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Title: Investigating the role of anhydrous oxidative weathering on sedimentary rocks in the Transantarctic Mountains and implications for the modern weathering of sedimentary lithologies on Mars

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Abstract

Alteration of the uppermost surfaces of geologic materials is a pervasive process on planetary surfaces that is dependent upon factors including parent composition and the environment under which alteration is occurring. While rapid and pervasive in hot and humid climates on Earth, chemical weathering of rock surfaces has also been found to dominate in some of Earth's coldest and driest landscapes as well. Specifically, surfaces dominated by resistant fine-grained igneous rocks in the Antarctic preserve evidence of oxidative weathering processes, which represent the initial immature surface alteration processes that stagnate due to the lack of available water and kinetics necessary for the production of more mature alteration phases. In this study, we test the hypothesis that oxidative weathering also dominates the surfaces of sedimentary rocks throughout the Antarctic. We investigated the chemistry and mineralogy of a suite of sedimentary rocks from the Transantarctic Mountains ranging from fine-grained tuffs to coarse-grained sandstones and conglomerates. Our results show that, like the previously studied fine-grained igneous rocks in the Antarctic, sedimentary rocks generally showed only minor chemical weathering signatures at their surfaces relative to their interiors. However, unlike the igneous rocks in this earlier study, the sedimentary rocks exhibited a wide variety of non-systematic differences between surface and interior compositions. This variability of surface weathering signatures is equally as complex as the physical properties and compositions inherently present within these different sedimentary lithologies. Based on these analyses, it is apparent that oxidative weathering products do not dominate the surfaces of sedimentary rocks throughout the Transantarctic Mountains, which instead exhibit a wide array of weathering signatures that are likely dependent on both lithological and environmental factors. Considering that sedimentary lithologies are widespread across a significant fraction of the martian surface, our results suggest that observed alteration signatures limited to the surfaces of martian sedimentary rocks are most likely to be minor and to vary as a result of the lithological properties of the specific rock unit and not as a result of the widespread influences of the modern cold and dry climatic conditions.

Introduction

The modification of parent rock materials as a result of subaerial exposure often produces alteration phases that can be used to infer the paleoenvironmental conditions present during their formation. For example, the formation of heavily leached laterite sequences and their preservation in the geologic record suggest tropical conditions, while caliche hardpans indicate desert environments (e.g., Sheldon and Tabor, 2009). Weathering coatings (deposits on the surfaces of rocks derived from external sources), patinas (deposits on the surfaces of rocks derived from elements source from the rock itself), and rinds (a zone of chemical alteration on a rock's surface from preferential removal of elements that penetrates to some depth within the rock) also preserve important paleoclimatic information, particularly in desert environments where aqueous alteration is minimal (Liu and Broecker, 2000; Dorn, 2009a, 2009b; Mahaney et al., 2012). Specifically in Antarctica, alteration rinds have been shown to preserve evidence for oxidative weathering processes in the absence of significant aqueous alteration, demonstrating that the rocks have been exposed to cold, dry, and stable environmental conditions for long durations (Weed and Ackert, 1986; Weed and Norton, 1991; Chevrier et al., 2006; Staiger et al., 2006; Salvatore et al., 2013; Cannon et al., 2015).

While relatively immature and mineralogically insignificant (Weed and Ackert, 1986; Salvatore et al., 2013; Cannon et al., 2015), the alteration rinds generated and preserved on Antarctic rocks significantly modify the spectral signatures of rock surfaces relative to their unaltered interiors. These rinds also preserve minor yet consistent elemental variations relative to their interiors, including a relative increase and decrease in monovalent and divalent cations, respectively. Salvatore et al. (2013) showed that similar elemental trends are preserved at the surfaces of igneous rocks in Gusev crater on Mars, and subsequent spectral investigations

suggested that oxidative weathering products may be a globally significant component of the martian surface (Salvatore et al., 2014). With the exception of just a few studies (e.g., Weed and Ackert, 1986; Weed and Norton, 1991; Cannon et al., 2015), however, previous investigations in the Antarctic have not focused on the formation or preservation of surface alteration in sedimentary lithologies. Sedimentary rocks are typically more friable and permeable than igneous rocks, and their compositions are also much more variable than the relatively homogeneous dolerites (diabase, or shallow intrusive basalt) that were previously studied (Salvatore et al., 2013).

To improve our understanding of rock weathering in cold, dry, and stable terrestrial environments, our study tests the hypothesis that oxidative weathering processes are the dominant alteration process acting on the surfaces of sedimentary rocks throughout the Transantarctic Mountains (TAM). We do so by characterizing the chemical, mineralogical, and spectral variations associated with carefully selected sedimentary samples collected from throughout the TAM. Should oxidative weathering processes dominate, we anticipate these compositional signatures to be consistent with those identified in Salvatore et al. (2013) for Antarctic dolerites. Should other trends be observed, we can confidently refute this hypothesis and instead investigate whether some other alteration process dominates sedimentary rocks in the cold and dry Antarctic. Our investigation specifically focuses on the wide variety of sedimentary rocks found throughout the TAM, and does not consider the effects of oxidative weathering processes on the diverse range of igneous (e.g., Kirkpatrick Basalt, Granite Harbour Intrusives) or metamorphic lithologies (e.g., Skelton Group, Duncan Formation) present throughout the Antarctic.

It is necessary to consider that the work of Salvatore et al. (2013) only focused on clasts

of the Ferrar Dolerite within the confines of Beacon Valley, a stable geologic surface (Marchant et al., 2002) located at high altitudes within the stable upland microclimate zone (Marchant and Head, 2007). We extrapolate the work of Salvatore et al. (2013) to a broader suite of geologic materials over a broader range of micro- and macro-environments within the TAM in an effort to understand the role of continental-scale oxidative weathering. Previous investigations have qualitatively described and documented the enhanced oxidation of older surfaces relative to younger surfaces throughout the TAM, even those dominated by sedimentary lithologies (e.g., Campbell and Claridge, 1987; Bockheim et al., 1989; Bockheim, 1990), which suggests that oxidative weathering is an important weathering process in the cold, dry, and stable Antarctic environments. However, is oxidative weathering the most dominant alteration process in these cold and dry environments, or are other processes equally as influential?

Our analytical methods were designed to be comparable to those on the Mars Science Laboratory (MSL) Curiosity rover. Gale crater, the site of Curiosity's explorations on the martian surface, is dominated by sedimentary rocks deposited in ancient alluvial, deltaic, and lacustrine environments (Grotzinger et al., 2014). If successful in identifying the dominant mode of "modern" surface alteration in the TAM using these analytical methods, it may be possible for Curiosity to distinguish between different modes of modern surface alteration on Mars. Such a capability could help to constrain the relative roles of physical erosion and chemical alteration in the modern martian environment.

Oxidative Weathering Processes on Earth and Mars

Subaerial oxidative weathering, like that dominating surfaces of dolerites in the McMurdo Dry Valleys (MDV) of Antarctica, is observed as discolored alteration rinds at the

surfaces of dolerite (shallow intrusive basalts, or diabase) clasts. The rinds appear reddish brown, while the rock interiors appear grey or black. No evidence for coatings or patinas is found on rock surfaces, which would indicate the deposition of materials at the surfaces. Instead, the alteration rinds penetrate to some depth into the rock where they eventually fade into the rock interior. Such morphologies indicate diffusion into the rock surface from the outside environment, with the depth of penetration a result of both the diffusivity of the rock itself as well as its exposure age. Staiger et al. (2006) showed that the approximate rate of oxidative weathering rind growth is 1.5 mm My^{-1} when compared to uncorrected cosmogenic nuclide exposure ages of glacial moraine sequences in Vernier Valley, Antarctica. These rinds represent modern and ongoing chemical weathering in the cold, dry, and stable Antarctic environment. While others have identified and characterized older episodes of chemical alteration in Antarctic lithologies, most are associated with more active geologic processes including magmatic intrusion (Vavra, 1989), continental-scale rifting (Fleming et al., 1992), and major glaciations (Passchier, 2004).

A brief summary of oxidative weathering products and processes in the Antarctic is provided below, and more detail can be found in Salvatore et al. (2013). Within the alteration rind, individual mineral phases and morphologies are preserved and relatively unaltered, which is consistent with X-ray diffraction (XRD) measurements that indicate no significant changes between rock surfaces and rock interiors. Chemically, alteration rinds exhibit elemental signatures that are inconsistent with typical aqueous alteration. For example, surfaces exhibit no appreciable variation in SiO_2 or Al_2O_3 abundances. In addition, cations that are typically mobile in aqueous environments behave differently in environments dominated by oxidative weathering. Monovalent (e.g., Na^+, K^+) and divalent (e.g., Ca^{2+}, Mg^{2+}) cations are both commonly mobile in

aqueous environments. However, during oxidative weathering, divalent cations are preferentially removed from the rock's surface relative to monovalent cations (with the exception of Fe^{2+}, which is preferentially oxidized to Fe^{3+}), as the oxidation potential from the removal of divalent cations is twice as large. The result is a relative enrichment of monovalent cations in rock surfaces relative to their unoxidized interiors, which is not typically observed as a result of aqueous alteration. At visible/near-infrared (VNIR) wavelengths, reflectance spectra of rock surfaces exhibit strong charge-transfer absorption features associated with ferric iron at wavelengths shorter than ~0.7 μm. Absorption features associated with hydrated mineral phases, OH^-, and H_2O are weak and comparable to those observed in rock interiors, suggesting minimal hydration during oxidative weathering.

Based on these observations, analytical results, and earlier lab experiments, Salvatore et al. (2013) concluded that oxidative weathering of dolerite surfaces in the MDV is driven by the migration of cations towards the rock surface (and replaced by the inward flux of electron holes) in response to the oxidizing environment. Divalent cations are preferentially mobilized relative to monovalent cations because of their greater charge, which allows for more oxidation to occur relative to the number of cations removed. As the cations reach the surface, they form soluble and friable oxide phases that are easily removed through aeolian abrasion and aqueous dissolution, which is why they are not observed at rock surfaces exposed to the environment. What remains is an oxidation rind and oxidation front that penetrates to some depth within the rock interior, determined largely by rock hardness/permeability and exposure age.

The rinds observed by Salvatore et al. (2013) are significantly different from weathering rinds that have been shown to form in Arctic environments (e.g., Dixon et al., 2002), which form as a result of dissolution and often result in significant disaggregation and fracturing and indicate

the significant influence of liquid water during the weathering process. This is consistent with the hypothesis that the primary difference between weathering processes in the Antarctic and other terrestrial environments is the lack of moisture and liquid water (Balke et al., 1991; Meiklejohn and Hall, 1997; Hall et al., 2002).

Salvatore et al. (2013) also showed how oxidative weathering processes appear to dominate the modern weathering of basaltic surfaces in Gusev crater. Specifically, they used data from the Alpha Particle X-Ray Spectrometer (APXS, Gellert et al. (2006)), the Mössbauer spectrometer (Morris et al., 2006), and the Pancam imaging system (McSween et al., 2004) on rocks that were both brushed and ground into by the Rock Abrasion Tool (RAT) on the Mars Exploration Rover (MER) Spirit to show that the geochemical and spectral relationships between rock surfaces and interiors are identical to those observed in Antarctic dolerites. Salvatore et al. (2014) followed this initial investigation with a global martian VNIR and TIR spectroscopic investigation to determine whether oxidative weathering processes contribute significantly to the global spectral signatures observed on the planet. Their results demonstrated that most of Mars' classic low-albedo regions contain spectrally significant abundances (> ~10%) of oxidative weathering products, indicating the dominance of cold and dry oxidative weathering processes at play on the "modern" martian surface.

Methods

To relate our work to that of Salvatore et al. (2013), we utilized the same sample preparation methods and conducted a similar suite of spectral, chemical, and mineralogical analyses on our samples. In addition to the analyses from Salvatore et al. (2013), we also performed laser induced breakdown spectroscopy (LIBS) to measure sample chemistry and for

Table 1. Measurements performed on Antarctic sedimentary rocks in this investigation and their relevance to analytical techniques onboard the Curiosity rover.

Analytical Technique, Laboratory	Relevant Analytical Instrument, Curiosity Rover
Visible/Near-infrared reflectance spectroscopy	Mastcam, ChemCam (passive)
X-ray diffraction	CheMin
Laser-induced breakdown spectroscopy	ChemCam (active)
Inductively coupled plasma-optical emission spectroscopy	APXS, ChemCam (active)
Mössbauer spectroscopy	(None)

comparison to results from the Chemistry and Camera (ChemCam, Wiens et al., 2013) instrument on the Curiosity rover. All other analytical methods were selected for their comparability to instruments onboard past and present Mars rovers, specifically Curiosity in Gale crater (**Table 1**), allowing us to compare our results to measurements of the martian surface as well.

Sample Suite

We initially selected a total of 211 rock samples from throughout the Transantarctic Mountains, Marie Byrd Land, and the Antarctic Peninsula. Samples were originally selected to ensure a wide diversity of sedimentary rock types and depositional environments as well as volcanic rocks for comparison. The rock samples were retrieved from the Polar Rock Repository (PRR) at the Ohio State University, which is the National Science Foundation's repository for Antarctic

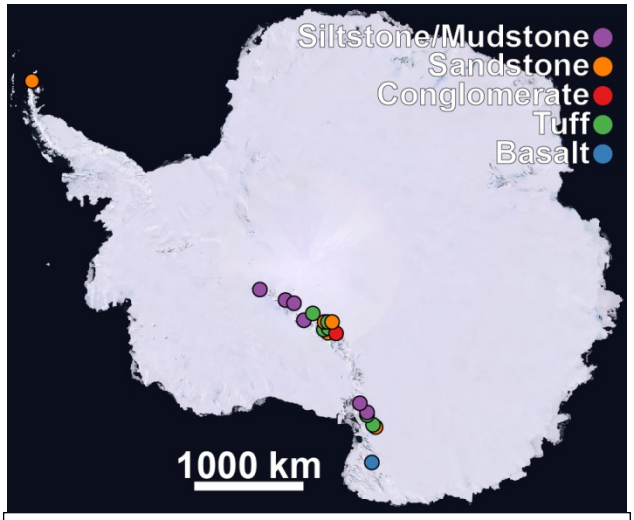

Figure 1. The location of 22 down-selected samples obtained from the Polar Rock Repository. Colors are representative of specific rock types.

samples collected during prior field seasons. The samples consisted of 30 siltstones/mudstones, 40 sandstones, 26 conglomerates, 59 tuffs and tuffaceous mudstones, 50 basalts, and 6 assorted sedimentary and igneous clasts. We then down-selected 22 representative samples from our initial collection of 211 for more detailed spectral, chemical, and mineralogical analyses (**Fig. 1**, **Table 2**). Our goal was to maintain a representative collection of different lithologies that were distributed throughout the Transantarctic Mountains during the down-selection process. Selected samples showed clear visual evidence for surface weathering, specifically oxidation, and preference was given to those with accompanying field notes that provided additional contextual information regarding field setting and reason for collection. We were also cognizant of identifying any samples with evidence for lichen or other biological materials present on the surface in an effort to avoid geochemical and mineralogical effects from biological weathering

Table 2. The 22 samples down-selected for further investigation in this study.

Type	Sample ID	Latitude/Longitude	Geographic Region	Geographic Feature
Basalt	13197	72.98º S, 162.90º E	NVL	Mt. Masley
Conglomerate	20642	63.42º S, 57.02º W	AP	Mt. Flora
	25796	84.23º S, 162.42º E	CTAM	Coalsack Bluff
Mudstone/ Siltstone	12393	86.37º S, 159.25º W	STAM	Roaring Cliffs
	12798	85.33º S, 119.20º W	STAM	Victor Cliff
	23553	85.20º S, 174.30º W	STAM	Thrinaxodon Col
	26210	76.88º S, 159.40º E	SVL	Carapace Nunatak
	30224	86.28º S, 147.27º W	STAM	Mt. Blackburn
Sandstone	05483	84.35º S, 164.70º E	CTAM	Mt. Falla
	26160	77.80º S, 160.55º E	SVL	Aztek Mountain
	26909	84.55º S, 163.60º E	CTAM	Kenyon Peaks
	27111	84.58º S, 164.00º E	CTAM	Storm Peak
	36193	75.62º S, 158.63º E	NVL	Shappard Rocks
Tuff	25633	85.73º S, 176.73º E	CTAM	Mauger Nunatak
	25908	84.52º S, 164.07º E	CTAM	Elliot Peak
	26951	84.37º S, 164.92º E	CTAM	Mt. Falla
	26975	84.37º S, 164.92º E	CTAM	Mt. Falla
	27109	84.85º S, 164.00º E	CTAM	Storm Peak
	34531	84.33º S, 164.43º E	CTAM	Golden Cap
	36150	75.62º S, 158.63º E	NVL	Sheppard Rocks
	36241	75.70º S, 158.78º E	NVL	Ricker Hills
	39262	76.73º S, 159.65º E	SVL	Allan Hills

AP = Antarctic Peninsula, CTAM = Central Transantarctic Mountains, STAM = Southern Transantarctic Mountains, NVL = Northern Victoria Land, SVL = Southern Victoria Land

processes, although no evidence for biological materials were present on any of the originally selected 211 samples. Through this down-selection process, we identified 9 tuffs, 5 sandstones, 5 siltstones/mudstones, 2 conglomerates, and 1 basalt for further investigation.

Selected samples were acquired primarily from Northern and Southern Victoria Land, and the Central and Southern Transantarctic Mountains, with one conglomerate sample from the Antarctic Peninsula. With the exception of the Antarctic Peninsula, all sampling locations fall within the "Cold katabatic" climatic zone as defined by Dalrymple (1966), where mean annual temperatures range from -30º C to -40º C, and mean annual precipitation ranges between 0 mm and 45 mm. The one sample from the Antarctic Peninsula was collected from Mt. Flora, which is located approximately 5 km from Hope Bay and the Argentinian Esperanza Base, with a recorded mean annual temperature of -4.6º C and a mean annual precipitation of 28.6 mm. These climatological data confirm that all samples were collected from hyper-arid polar desert environments.

While analyzing rocks that were previously collected and returned from the Antarctic is efficient and allowed us to perform this research without the need for costly field work, the use of these samples creates two causes for concern. First, the clasts originate from throughout the Antarctic and correspond to a wide range of environments, from low-elevation coastal regions to high-elevation mountainous and polar environments. Second, the exposure histories of these clasts are largely unknown, which precludes our ability to determine the length of time over which surface alteration processes have been occurring. Regardless, if we assume that the entirety of the Antarctic hosts cold, dry, and stable environmental conditions, and that surface alteration proceeds along the same alteration trends regardless of clast location or exposure history, we are still able to determine whether oxidative weathering processes dominate these

sedimentary clasts, whether oxidative weathering is overprinted by more mature alteration processes, or whether any alteration is seen at all.

Sample Preparation

Rock surfaces and interiors were subdivided into small (~3 cm^2) chips and fragments using a rock hammer to preserve natural surfaces and to avoid artificial cut surfaces. These chips were prepared for VNIR reflectance spectroscopy and LIBS analyses. Rock powders were created using a diamond-tipped rotary drill, which was used to extract material from rock interiors and rock surfaces in an identical manner. Material from rock interiors was acquired from near the center of the sample, well beyond any visible evidence for oxidation or other signs of alteration. When preparing rock surfaces, only the uppermost material was removed from a relatively large area of the rock surface, which minimized the sampling depth and ensured that only the outermost altered material was extracted (to a depth of ~0.5 mm, Salvatore et al., 2013). Surface and interior powders were then ground using a mortar and pestle and sieved to < 150 µm size fractions, which is the same size fraction analyzed by the Chemistry and Mineralogy (CheMin) XRD instrument on Curiosity (Blake et al., 2012), and prepared for powder XRD, bulk chemistry measurements, and Mössbauer spectroscopy.

Reflectance Spectroscopy

VNIR spectroscopy was performed on rock chips of all 22 samples using an Analytical Spectral Devices (ASD) FieldSpec4 spectroradiometer in a well-calibrated laboratory setup, a 0º illumination angle, and a 30º exitance angle outside of the plane of illumination (to avoid specular reflection). The instrument was calibrated every 10 minutes using a Spectralon white

reference in the same viewing and illumination geometry as the measured samples.

Mineralogy Measurements

XRD analyses were performed on 21 pairs of sample powders at the University of Michigan's Electron Microbeam Analysis Laboratory using a Rigaku Ultima IV diffractometer (3º - 65º 2θ) using a Cu-Kα radiation source at 40 kV and 44 mA. The goniometer radius is 285 mm, and the divergence, scattering, and receiving slits are 0.67º, 0.67º, and 0.6 mm, respectively. Data were acquired at a step of 0.05º at a speed of 1º per minute. Rietveld refinement was performed using the MDI Jade software subsequent to these analyses to quantify variations in mineralogy between sample interiors and surfaces.

Elemental Chemistry

Bulk chemistry of all 22 sample pairs was measured at Brown University using inductively coupled plasma-optical emission spectroscopy (ICP-OES) and the flux fusion dissolution method (Murray et al., 2000). Powdered samples were divided into 40 mg aliquots, mixed with 160 mg of $LiBO_2$ flux, and fused for 10 minutes at 1050º C. Melts were subsequently quenched in 20 mL of 10% HNO_3 and agitated to ensure thorough dissolution. Liquid samples were then filtered and diluted again prior to being analyzed using a JY2000 Ultrace ICP Atomic Emission Spectrometer. Samples, powdered standards, and blanks were run concurrently and analyzed for Si, Al, Fe, Mg, Ca, Na, K, P, Mn, and Ti. All samples were run and analyzed in triplicate to determine ensure accuracy and to determine analytical uncertainty.

Chemistry was also determined on rock chips using LIBS analyses at Los Alamos National Laboratory (LANL). The LANL instrument is a replica of the ChemCam instrument on

the Curiosity rover, and uses a pulsed 1067 nm laser (repetition rate of 3 Hz, energy of 13 mJ/pulse, and stand-off distance of 3 m) to generate a plasma on the sample surface, the light from which is collected by the unit's telescope and directed to three spectrometers spanning from 240.1 nm through 906.5 nm. A total of 150 laser pulses (and, subsequently, spectra) were generated at three locations on each sample surface and interior. Each laser pulse bores slightly deeper into the rock, resulting in the generation of small depth profiles (on the order of ~100 μm, Lanza et al., 2012, 2015). The samples were measured under martian environmental conditions (CO_2 atmosphere at 7 Torr) to quantify elemental chemistry, a technique that is well-calibrated for Curiosity's ChemCam unit under martian environmental conditions. The lower atmospheric pressure also allows for the plasma to more effectively expand within the environmental chamber. Spectra were subsequently processed and converted to elemental chemistry using the techniques described in Wiens et al. (2013), Lanza et al. (2015), and Clegg et al. (2017).

Mössbauer spectroscopy was used to determine Fe^{3+} abundances in 5 sample interiors and surfaces (3 tuffs and 2 sandstones) and to quantify the distribution of iron among its ferric and ferrous phases. Analyses were performed at Mt. Holyoke College. Powder aliquots of 75 mg were analyzed at 295 K on a WEB Research Co. model WT302 spectrometer using a ^{57}Co source.

Elemental chemistry and comparisons between unaltered interiors and weathered surfaces can provide important clues regarding the alteration processes at work. Alteration processes and their resultant alteration products follow diagnostic pathways that allow for these processes to be identified and interpreted. For example, typical aqueous alteration under near-neutral conditions will preferentially leach divalent (e.g., Fe^{2+}, Ca^{2+}, Mg^{2+}) and monovalent cations (e.g., Na^{+}, K^{+}) out of a material relative to more stable elements like aluminum and silicon. This is the

foundation for the Chemical Index of Alteration (CIA, Nesbitt and Young, 1982), which uses molecular proportions and is defined as:

$$CIA = \frac{Al_2O_3}{(Al_2O_3 + CaO^* + Na_2O + K_2O)} \times 100$$

where CaO^* corresponds solely to the CaO contained within the silicates in the material. Oxidative weathering processes, however, are not easily characterized using the CIA, as divalent cations preferentially migrate towards the rock surface and are removed from the system relative to monovalent cations. The result is a relative increase in monovalent cations and decrease in divalent cations in rock surfaces relative to their interiors, which is unique from most forms of aqueous alteration. Lastly, the presence of coatings or patinas on rock surfaces is also not well represented by the CIA, as one or several elements significantly increase in concentration at the expense of other elements relative to the rock interiors. For example, the presence of a coating of gypsum (Ca-sulfate) on a rock surface would appear as an increase in CaO at the expense of most other elemental phases, particularly SiO_2, which is typically abundant in silicate rocks and is relatively stable under minor to moderate amounts of alteration. It should be noted that while we utilize the CIA on the scale of individual hand samples, it was originally developed to characterize chemical alteration on the landscape-scale (Nesbitt and Young, 1982).

While the CIA has long been used to investigate the extent of weathering where aqueous alteration dominates, it was not designed to differentiate between different types of alteration processes as described above. To help differentiate between traditional aqueous alteration, oxidative weathering processes, and the presence of coatings or patinas, we rely on the Weathering Intensity Scale (WIS, Meunier et al., 2013), which compares the molar proportions of several cation species. Specifically, the WIS compares M^+ ($Na^+ + K^+ + 2Ca^{2+}$), R^{2+} (Fe^{2+} +

Mg^{2+}), and 4Si (Si/4) on a ternary diagram. The elemental trends between a rock interior and surface towards or away from any of the three apices can be used to determine the dominant alteration process at work on the rock surface. To determine the proportion of Fe^{2+} in each sample, we utilize the results of our limited Mössbauer spectral analyses to estimate the relative proportion of Fe^{2+}/Fe_{Total} in all of our samples.

Results

The results from our analyses are presented in **Table 3** and discussed in detail in the sections below.

Spectral Signatures

Rock samples were originally selected from the PRR due to their visible weathering signatures (including oxidized red/brown surfaces relative to their less oxidized (less red) interiors). These oxidation signatures are confirmed through VNIR reflectance spectroscopy, appearing as strong charge-transfer absorptions at visible wavelengths (shorter than 0.7 µm, **Fig. 2**). At near-infrared wavelengths, anhydrous oxidative weathering processes typically result in little if any increase in the strength of absorption features related to hydration/hydroxylation, which would be seen as sharp absorptions near 1.4 µm, 1.9 µm, and between 2.1 µm and 2.5 µm, as well as a general decrease in reflectance towards the longest wavelengths (referred to as a "blue slope"). A classic oxidative weathering spectrum can be observed in the conglomerate PRR-20642, which shows

Table 3. Antarctic samples analyzed in this investigation using the full suite of analytical techniques, sorted by rock type. Reported are the differences observed in the rock surfaces relative to their corresponding interior measurements. For example, "> Hydration" indicates that the surface is more hydrated than the interior. The "dominant mode of alteration" is interpreted based on the full complement

of analytical techniques and results (see *Discussion* section).

Type	Sample ID	VNIR Spectroscopy	XRD	Chemistry	CIA Difference	Dominant Mode of Alteration
Basalt	13197	> Oxidation ~ Hydration	> Hydrated mineral phases	< CaO < MgO > K_2O	+2.2	Oxidative
Conglomerate	20642	> Oxidation < Hydration	None	> Al_2O_3 > FeO_T > K_2O < Na_2O < SiO_2	+4.2	Oxidative
	25796	> Oxidation > 1 μm crystal field feature ~ Hydration	None	None	+0.9	Oxidative
Mudstone/ Siltstone	12393	~ Oxidation > Hydration < Gypsum	< Gypsum	< CaO > Al_2O_3 > SiO_2	+4.1	Aqueous, Bleached*
	12798	> Oxidation ~ Hydration	None	< CaO < MgO > K_2O	-1.0	Oxidative
	23553	> Oxidation ~ Hydration	None	< CaO < MgO > K_2O	+1.0	Oxidative
	26210	~ Oxidation > Hydration	> Zeolites and phyllosilicates	< SiO_2 > Al_2O_3	+3.4	Unknown
	30224	> Hydration		None	+0.2	Aqueous, Bleached*
Sandstone	05483	> Oxidation > Hydration	> Zeolite	None	+2.0	Aqueous
	26160	> Oxidation ~ Hydration	None	> SiO_2 < Al_2O_3 < K_2O	-0.4	Aqueous
	26909	> Oxidation ~ Hydration	< Hydrated phases	None	-1.0	Oxidative
	27111	> Oxidation ~ Hydration	None	None	-0.7	Oxidative
	36193	> Oxidation > Hydration	None	None	+0.5	Unknown
Tuff	25633	> Oxidation > 1 μm crystal field feature ~ Hydration	> Gypsum < Zeolites < Amorphous material	> FeO_T < SiO_2	-3.3	Coating (goethite)
	25908	> Oxidation > Hydration	> Gypsum	> CaO > Na_2O < SiO_2	-17.8	Coating (gypsum)
	26951	> Oxidation ~ Hydration	None	None	-0.4	Oxidative
	26975	> Oxidation > Gypsum	> Gypsum	> CaO < Al_2O_3 < SiO_2	-16.6	Coating (gypsum)
	27109	> Oxidation	> Gypsum	> CaO	-27.3	Coating

		> Gypsum		< Al_2O_3 < SiO_2		(gypsum)
	34531	> Oxidation > Hydration	None	> CaO > P_2O_5 < SiO_2	-14.7	Coating (amorphous Ca-sulfate)
	36150	~ Oxidation ~ Hydration	None	> CaO < Al_2O_3	-0.4	Unknown
	36241	> Oxidation ~ Hydration	None	> FeO_T > MgO	+0.9	Unknown
	39262	> Oxidation ~ Hydration	> Zeolite > Chlorite	< CaO < MgO > K_2O > SiO_2	+0.5	Oxidative

*Surfaces consistent with bleaching due to exposure to ultraviolet radiation, as was first described in Tasch and Gafford (1969).

weakened hydrated absorption features relative to the rock's interior, a strong Fe^{3+} charge-transfer absorption at visible wavelengths, and an overall blue slope at near-infrared wavelengths (**Fig. 2d**). Only approximately half of the samples measured in this study exhibit VNIR spectral signatures that are consistent with oxidative weathering processes (**Table 2**).

In addition to these oxidized signatures, many sample surfaces also exhibit spectral signatures that are consistent with more mature alteration processes. For example, PRR-25633, a tuff from Mauger Nunatak in the Central Transantarctic Mountains (CTAM), exhibits broad absorption features near 0.64 μm and 0.92 μm that are associated with Fe^{3+} crystal field transitions (Morris et al., 1985). Other examples include a suite of tuffs collected from the Hanson Formation in the CTAM (including PRR-27109 from Storm Peak, **Fig. 2b**), almost all of which exhibit spectral signatures consistent with the calcium sulfate mineral gypsum at their surfaces but not in their interiors. Diagnostic gypsum signatures include "saw tooth" absorptions centered near 1.42 μm and 2.23 μm, as well as a prominent 1.78 μm absorption. These more mature alteration phases are not predicted for nor observed in the oxidative weathering previously identified in Antarctic samples (Salvatore et al., 2013, Cannon et al., 2015) and, instead, are more consistent with more extensive and mature aqueous alteration.

Mineralogy

As reported by Salvatore et al. (2013), XRD patterns of dolerites from the MDV do not show any significant variations between rock surfaces and interiors, suggesting little (if any) mineralogical variations as a result of oxidative weathering. This interpretation was supported through petrographic analyses, which showed unaltered minerals at the uppermost surface of oxidized dolerites in the absence of significant coatings, patinas, or other evidence for aqueous alteration. Mössbauer spectroscopy also confirmed this interpretation and suggested that the increased Fe^{3+} in rock surfaces (+14% on average) remains in its original primary mineralogical phases (most likely pyroxenes) as opposed to producing new crystalline oxides and oxy-hydroxides.

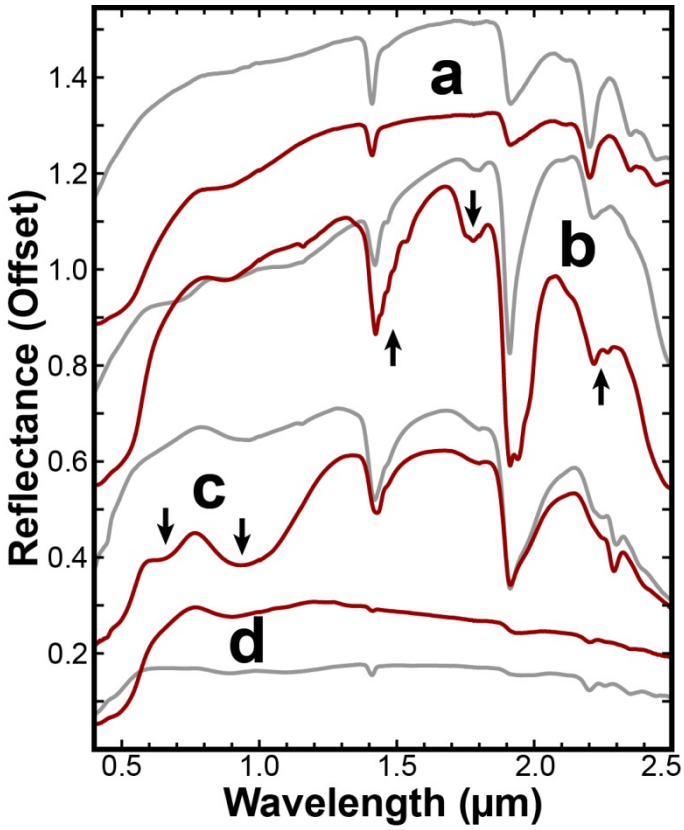

Figure 2. Visible/Near-infrared spectra of representative sample interiors (grey) and surfaces (red). Arrows indicate major differences in absorption features between interiors and surfaces. (a) PRR-26160 (Sandstone, offset +0.8) showing a strong ferric iron charge-transfer absorption at the surface; (b) PRR-27109 (Tuff, offset +0.4) showing strong gypsum absorption features at the surface (see arrows); (c) PRR-25633 (Tuff, offset +0.1) showing significant goethite absorptions at the surface (see arrows); and (d) PRR-20642 (Conglomerate, no offset) showing a strong ferric iron charge-transfer absorption at the surface.

The sedimentary rocks analyzed in this study, however, exhibit a wide diversity of mineralogical signatures (**Fig. 3**). For example, half (9) of the samples do not show any appreciable differences between their interiors and their surfaces, suggesting that the alteration

process acting on the rock's surface did not remove phases present within the bulk rock, nor did it produce new alteration phases. Such signatures are consistent with oxidative weathering, but can also occur as a result of congruent leaching or dissolution under aqueous conditions. Other samples show evidence for more mature alteration phases at their surface, including gypsum and goethite, which is consistent with VNIR spectral measurements. For example, the surface of sample PRR-25633 (**Fig. 3b**) exhibits a small XRD peak associated with goethite, which supports the VNIR observations discussed previously. The relatively small goethite peak is likely a result of the Cu-Kα radiation source, which causes significant iron fluorescence and a higher background that creates difficulty in identifying crystalline phases. In addition, the majority of XRD peaks observed in the interior of this sample are muted or entirely absent from the surface XRD pattern, suggesting that the surface mineralogy is less complex (dominated by only a few mineralogical species) than the interior. The surface pattern of sample PRR-26975 (**Fig. 3a**) also shows a weakening of the XRD peaks found in the sample interior in addition to the appearance of an XRD peak associated with gypsum. This observation is consistent with the corresponding VNIR spectra that suggest the presence of a gypsum coating on the surface of this sample and its absence in the sample interior.

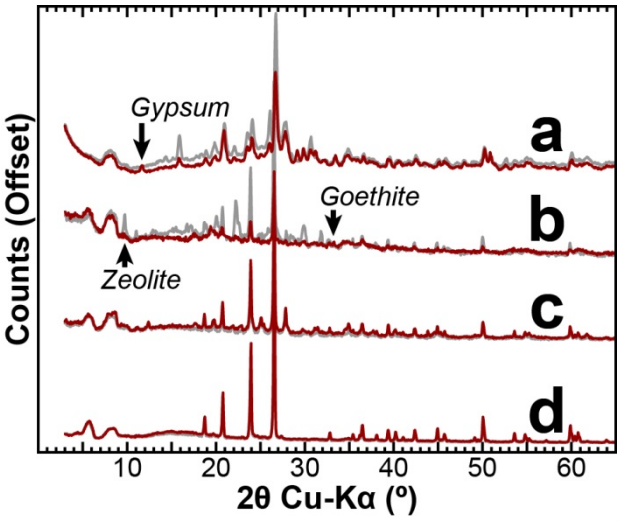

Figure 3. X-ray diffraction (XRD) patterns of representative sample interiors (grey) and surfaces (red). Patterns are offset for clarity and arrows represent significant differences between patterns. (a) PRR-26975 (Tuff) showing the presence of gypsum at the surface; (b) PRR-25633 (Tuff) showing the presence of zeolite and goethite in the interior and at the surface, respectively; (c) PRR-20642 (Conglomerate) and (d) PRR-26160 (Sandstone), both showing no significant mineralogical differences between the surface and interior.

Lastly, some samples also exhibit evidence for crystalline alteration phases within their interior (e.g., zeolites), with significantly weaker signatures at the surface. These interior alteration phases are likely indigenous to the sedimentary rocks and prevalent throughout the sedimentary unit. One possible reason for why these alteration minerals are not present at the rock surface is due to their dissociation by ultraviolet radiation, which has been previously observed in the Antarctic and shown to have significant influences on both the clay mineralogy and organic content of organic-rich sedimentary rocks (Tasch and Gafford, 1969).

Chemical Signatures

The diversity of the derived rock chemistries reflect the diversity of sedimentary rocks characterized in this investigation. This is demonstrated in the CIA values for rock interiors calculated using ICP-OES data, which range from 45.7 (sandstone sample PRR-26909) to 83.6 (siltstone sample PRR-30224). These CIA values reflect the concentration of mobile cations inherent within the parent lithologies, and indicate that some of these lithologies have experienced significant aqueous alteration prior to their most recent exposure to the Antarctic environment, while others likely did not. While CIA variations among interiors represent rock alteration prior to modern exposure, the CIA value of each rock surface relative to its interior identifies any cation removal within the current rock surface. Differences in CIA values between rock surfaces and their corresponding interiors are reported in **Table 3**. However, as previously noted, CIA is not ideal for identifying oxidative weathering processes.

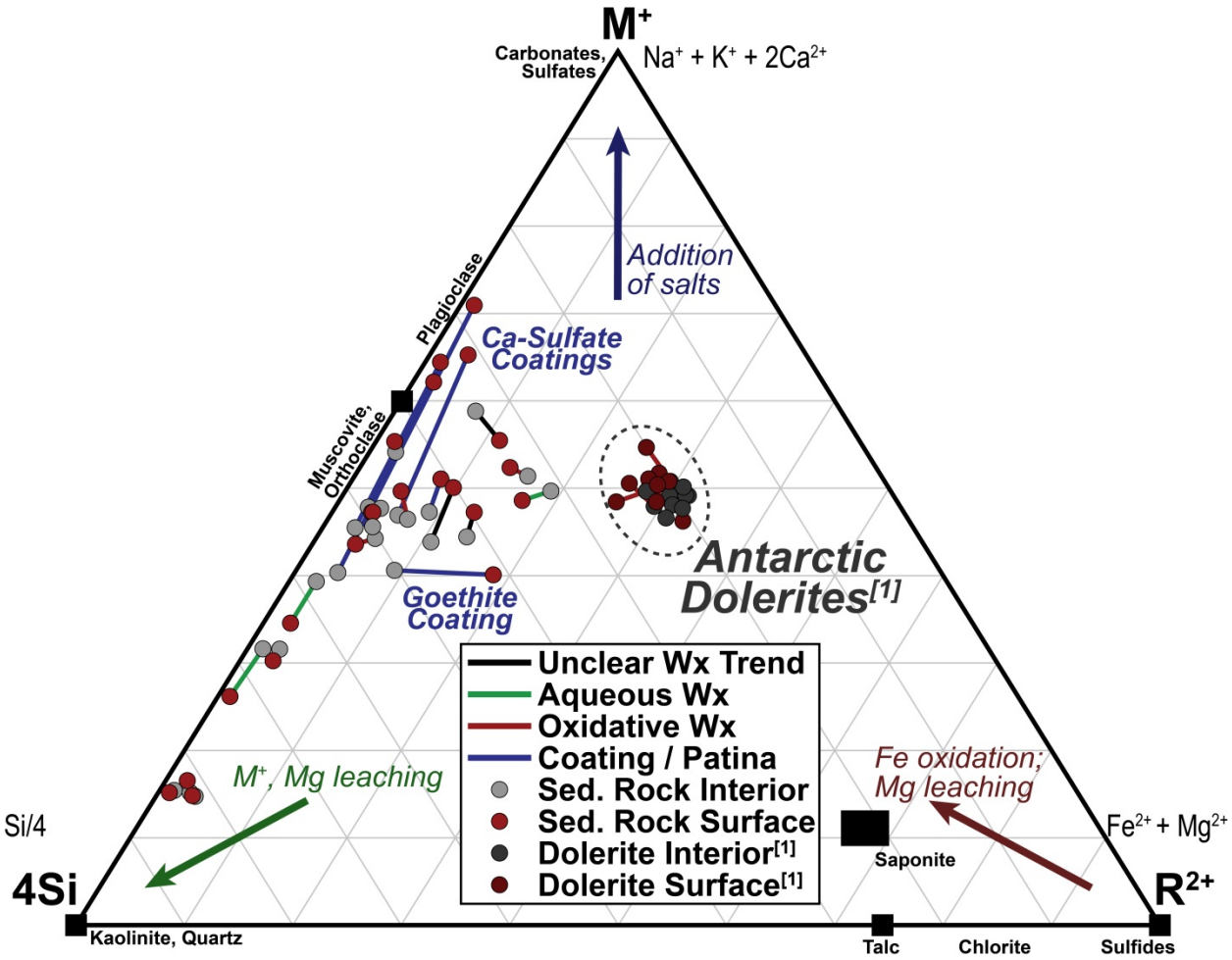

Figure 4. A Weathering Intensity Scale (WIS) ternary diagram showing the ICP-OES-derived chemistry and relationships between rock interiors (grey dots) and surfaces (red dots) for the Antarctic samples investigated in this study. The color of the joins between rock interior-surface pairs indicate the dominant weathering process interpreted based on available data. Antarctic dolerite interiors and surfaces are also shown for comparison, highlighting the trends caused by oxidative weathering in basaltic materials.

The dominance of oxidative weathering processes in dolerites from the MDV can be more clearly seen in a WIS ternary diagram (**Fig. 4**), where rock surfaces trend away from the R^{2+} apex as Fe^{2+} is oxidized to Fe^{3+} and Mg^{2+} is preferentially removed from the rock surface. Some dolerite surfaces also trend slightly towards the M^{+} apex, indicating that the relative increase in Na^{+} and K^{+} is greater than the relative removal of Ca^{2+} in the dolerite surfaces. The relative distance between rock interiors and surfaces is small, which is consistent with the relatively minor elemental variations observed in rock surfaces that have undergone oxidative

weathering relative to their interiors. Each sample surface was assumed to have 14% more Fe^{3+} than their corresponding interior, a result based on the average difference in Fe^{3+}/Fe_{Total} of the three representative samples measured with Mössbauer spectroscopy in Salvatore et al. (2013).

In contrast to the tight clustering observed in the dolerites from the MDV, the lithologies investigated in this study span a wide range of interior and surface compositions (**Fig. 4**). The interior compositions reflect the wide variety of lithologies selected for this investigation, from siliceous clastic sedimentary rocks towards the bottom-left of **Fig. 4**, to the basalts and basaltic tuffs found towards the center of **Fig. 4**. Similarly, the surface compositions reflect a wide variety of alteration trends relative to the unaltered interior. The relationship between chemical signatures in some surfaces relative to their interiors point to dominance by oxidative weathering processes, which follow a similar path away from the R^{2+} apex as the dolerites. The oxidation of some samples without a significant change in mineralogy is also confirmed by Mössbauer spectroscopy in samples like PRR-39262 (**Fig. 5a-b**). However, oxidative weathering was not found to be the dominant alteration process in these sedimentary samples. Several samples also exhibit alteration trends that are more consistent with typical aqueous alteration, which trends towards the 4Si apex as mobile cations are leached from the rock surface (**Fig. 4**, Meunier et al., 2013). In addition, significant trends towards either the R^{2+} or M^{+} apices indicate an enrichment of mobile cations at the rock surface relative to its interior, which is not predicted for either aqueous alteration or oxidative weathering. Instead, these trends are most consistent with the presence of coatings or patinas on the surfaces (Meunier et al., 2013), which supports the spectral and mineralogical observations discussed above.

For example, the presence of a goethite coating on the surface of PRR-25633, as supported by spectral, mineralogical, and chemical analyses (e.g., **Fig. 2** and **Fig. 5c-d**). In **Fig. 4**, the surface of PRR-25633 is shown to trend towards the R^{2+} apex, indicating a significant enrichment in iron. Note that this enrichment in iron is predicted as Fe^{2+} because the average Mössbauer Fe^{2+} value was used in the generation of this figure; in reality, the surface of sample PRR-25633 was measured to be 100% Fe^{3+} using Mössbauer spectroscopy, and so no variation in Fe between rock interior and surface should be visible on a WIS diagram because none of the Fe is in a ferrous state. However, LIBS analyses confirm the presence of an Fe-rich phase at the surface of this sample. As shown in **Fig. 6**, the observed contribution of Fe in LIBS analyses of the surface of PRR-25633 generally decreases with increasing depth into the sample, with a maximum calculated FeO_T abundance of roughly 25%. The first ~20 laser pulses in two of the three LIBS analyses averaged on the surface of PRR-25633 show a significant increase in elemental Fe before decreasing with depth; this initial increase in Fe corresponds with a similar

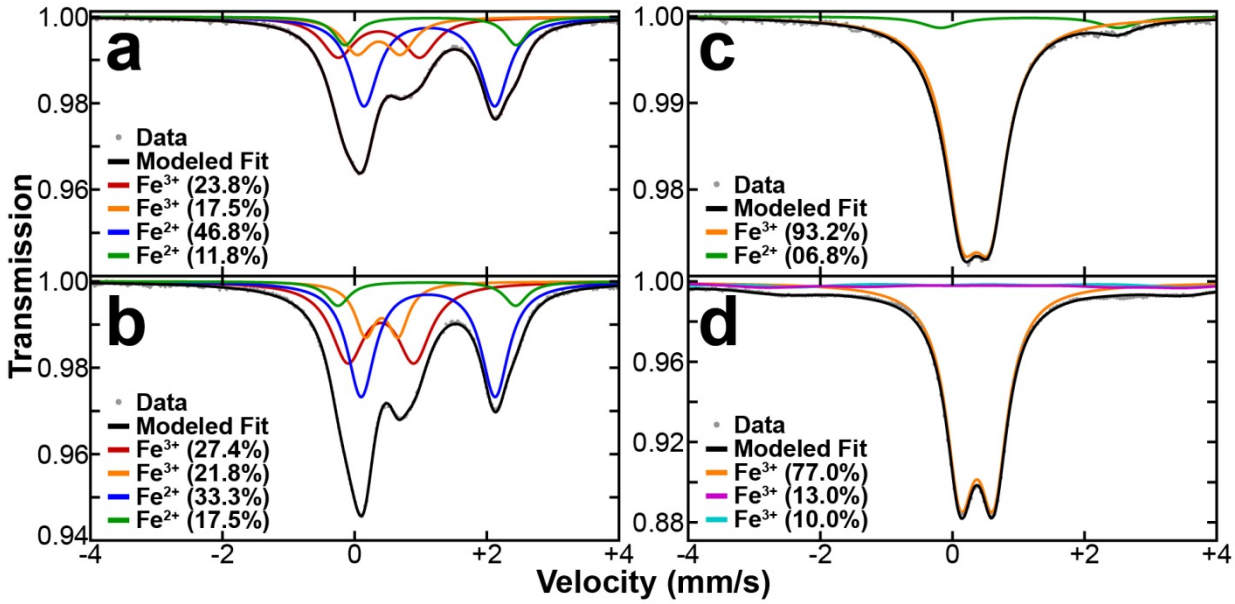

Figure 5. Mössbauer spectra of select samples measured in this study. The interior (a) and surface (b) of sample PRR-39262, exhibiting changes in relative abundances of Fe^{2+} and Fe^{3+}, although very little change in host mineralogy, which is consistent with oxidative weathering processes. Alternatively, the interior (c) and surface (d) of sample PRR-25633 exhibit significant spectral differences that are consistent with a coating of goethite on the sample surface.

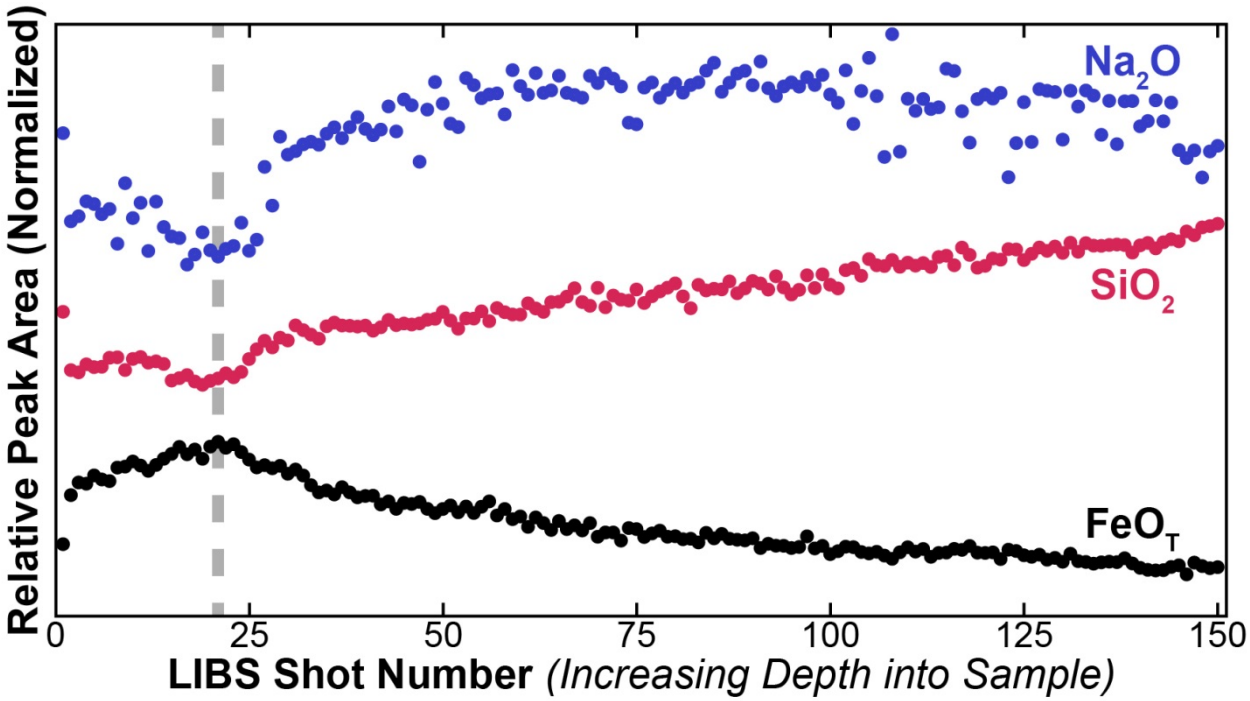

Figure 6. Normalized peak intensities (corresponding to relative oxide abundances) for sample PRR-25633S for elemental Fe, Si, and Na, measured as the peak area at 404.58 nm, 288.16 nm, and 589.59 nm, respectively. The vertical dashed grey line indicates the transition from a Si- and Na-rich coating at the uppermost surface to an Fe-rich coating just below the uppermost coating.

decrease in Si and Na before these two elemental phases begin to increase with depth into the sample. While the elemental trends after the first ~20 laser pulses are consistent with a goethite coating, the initial increase in Fe and decrease in Si and Na suggest that the uppermost ~20 µm of sample PRR-25633 contains a silicon- and sodium-rich coating that lies above a subsequent coating of goethite. This uppermost coating must be sufficiently thin as to not be evident in VNIR spectral measurements, or to be incorporated in significant volume into the powdered rock surfaces that were subsequently measured by XRD or Mössbauer spectroscopy. While an Fe-poor phase may not be visible to Mössbauer spectroscopy, even a non- or nano-crystalline silica-rich phase should be detected in XRD analyses through the presence of an amorphous hump.

The presence of gypsum coatings on the surfaces of several tuffs from the CTAM is indicated by a trend towards the M^+ apex in **Fig. 4**, as the presence of gypsum preferentially increases the concentration of calcium at the surface relative to silicon. LIBS analyses agree

with this observation and provide additional insight into the thickness and purity of the coatings and patinas observed in the other chemical, mineralogical, and spectral data (Lanza et al., 2012). For example, **Fig. 7** shows the comparison between ICP-OES measurements of sample PRR-27109 and LIBS measurements of the same sample surface on a WIS ternary diagram. A nearly identical pattern can be seen using both analytical methods. Consistent with the ICP-OES measurements, the LIBS analyses trend away from the M^+ apex, which corresponds to the decreasing concentration of Ca in the rock interior. The trend towards the 4Si apex also indicates that silicates are becoming more prevalent in the rock interior relative to the sulfate-dominated rock surface (Meunier et al., 2013). The derived compositions from both the initial and final LIBS shots are remarkably consistent with the compositions measured using ICP-OES for the rock surface and interior, respectively. This likely indicates that the LIBS pulses were able to completely penetrate through the gypsum coating and into the underlying tuffaceous substrate. A value of 82% Fe^{3+} was used for all LIBS shots, as that is the value derived from Mössbauer spectroscopy of the surface of PRR-26975, a similar gypsum-coated tuff collected from the same geologic unit as PRR-27109.

Discussion

Surface Weathering of Sedimentary Rocks in Antarctica

The combination of our spectral, mineralogical, and chemical analyses does not support the hypothesis that oxidative weathering is the dominant alteration process occurring on sedimentary rock surfaces throughout the TAM. While the relationship between rock surfaces and interiors is generally well-defined in Antarctic dolerites (Salvatore et al., 2013), the

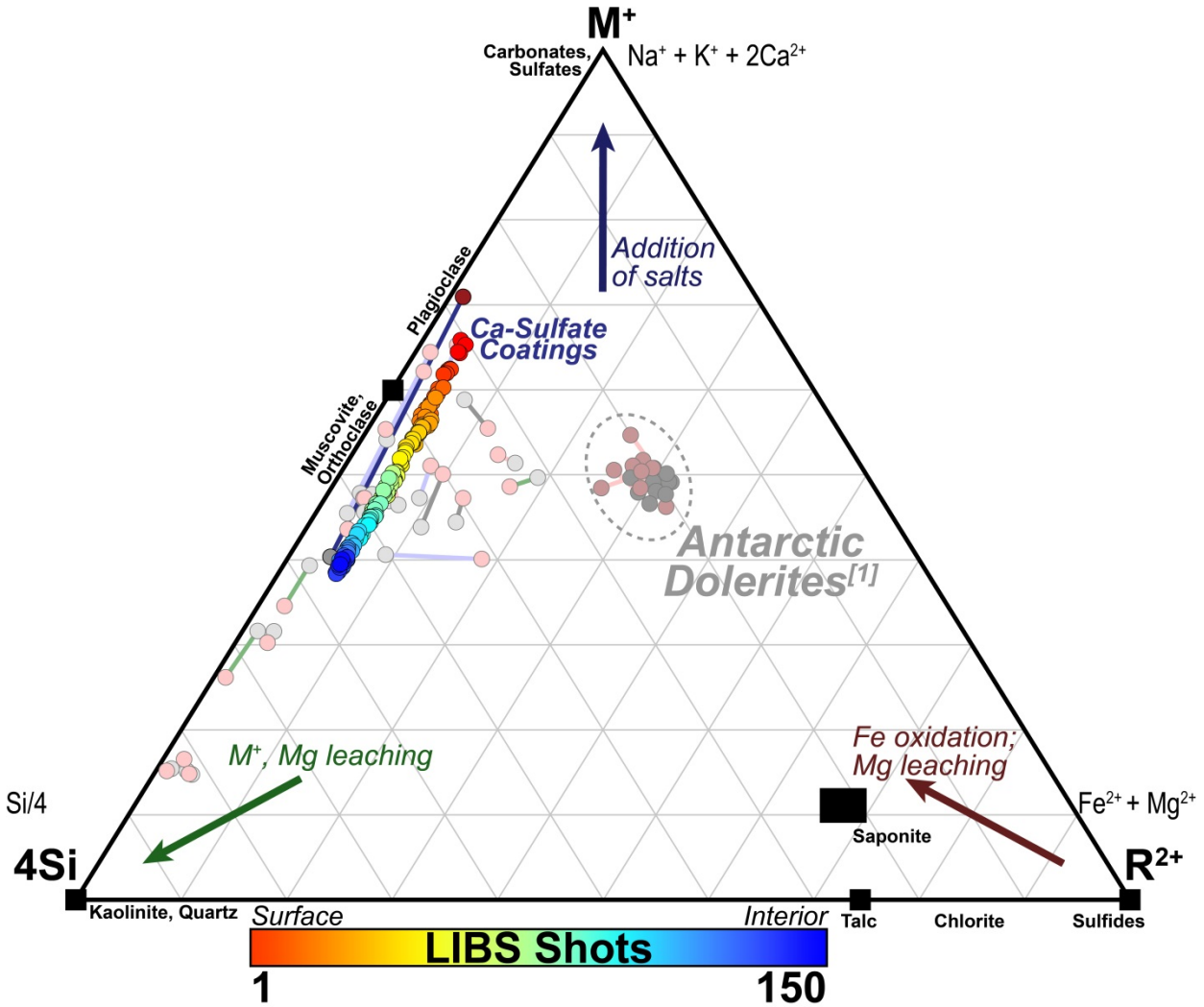

Figure 7. A Weathering Intensity Scale (WIS) ternary diagram highlighting the laser induced breakdown spectroscopy (LIBS) 150-shot analysis of sample PRR-27109 (tuff), which was shown to have a sulfate-rich coating at its surface. The ICP-OES-derived surface-interior trend is also highlighted for this sample in the background. Both techniques show notably similar chemical trends between the surface and the interior, as the measurements trend away from the M^+ apex with increasing depth into the sample, which is consistent with the presence of a Ca-sulfate coating at the surface and decreasing Ca-rich compositions with depth.

relationships observed in sedimentary rocks cannot be explained with a single weathering process. Instead, it appears as if at least three separate alteration processes are occurring on the 22 samples analyzed as part of this investigation (**Fig. 4**, **Table 3**).

Based on our interpretation of the results presented above, we have identified oxidative weathering processes preserved at the surfaces of 9 of the 22 samples analyzed in this investigation. This process is identified through the presence of Fe^{3+} charge-transfer absorption

features and the lack of new alteration phases as observed in VNIR spectroscopy, a general similarity between XRD patterns of rock surfaces and interiors, and chemical signatures that indicate a depletion of divalent cations relative to monovalent cations at rock surfaces. Evidence for aqueous alteration is observed in 4 of our samples, which can be identified by strengthened hydration features at VNIR wavelengths, the presence of crystalline secondary phases (e.g., phyllosilicates) in XRD data, and the depletion of both monovalent and divalent cations and a relative increase in SiO_2 and/or Al_2O_3 at rock surfaces. Lastly, evidence for coatings or patinas is observed on 5 of the 22 rock surfaces, which can be observed as significant increases in elemental phases at the surface that should otherwise be mobile under aqueous or oxidative weathering processes. In addition to these three dominant modes of surface alteration, 4 of the 22 sample surfaces exhibit alteration patterns that are not consistent with any of these three modes, suggesting that an unknown alteration processes is (or combination of alteration processes are) dominating these rock surfaces. None of the 22 samples showed evidence for biological weathering processes, which would lead to the disintegration and physical weakening of sample surfaces as well as the preferential redistribution of metal cations from the actions of organic acids (Banfield et al., 1999).

Two samples that exhibit evidence for both aqueous alteration as well as an additional alteration process are PRR-12393 and PRR-30224, two dark grey Permian-aged mudstones with bright surface rinds more than one centimeter in thickness (**Fig. 8**). The dark nature of these mudstones is likely due to an abundance of organic carbon within the sample, which is consistent with other members of the carbon-rich Victoria Group from the southern Transantarctic Mountains (Barrett et al., 2013). VNIR spectra of both sample surfaces indicate stronger 2.2 μm absorption features associated with Al- or Si-OH bonding, and the PRR-30224 spectra exhibit

the diagnostic doublet absorption features at 1.4 µm and 2.2 µm that are diagnostic of kaolinite (**Fig. 8c**). The strengthening of vibrational absorption features in the surface spectra is consistent with aqueous alteration processes modifying the rock surfaces. The unique lightening at the surface is most consistent with the oxidation and bleaching of the surface under the enhanced ultraviolet (UV) radiation in the Antarctic due to the relative depletion of the ozone layer, a geologic phenomenon that was first identified by Tasch and Gafford (1969). They showed that the increased UV radiation is able to bleach, oxidize, and remove essentially all organic carbon from the rock surface, leaving it in stark contrast to the rock's interior. No other samples in our suite demonstrate a similar weathering pattern, possibly because PRR-12393 and PRR-30224 are the most enriched in organic carbon, resulting in both their dark interior as well as providing the contrast necessary to observe this UV bleaching.

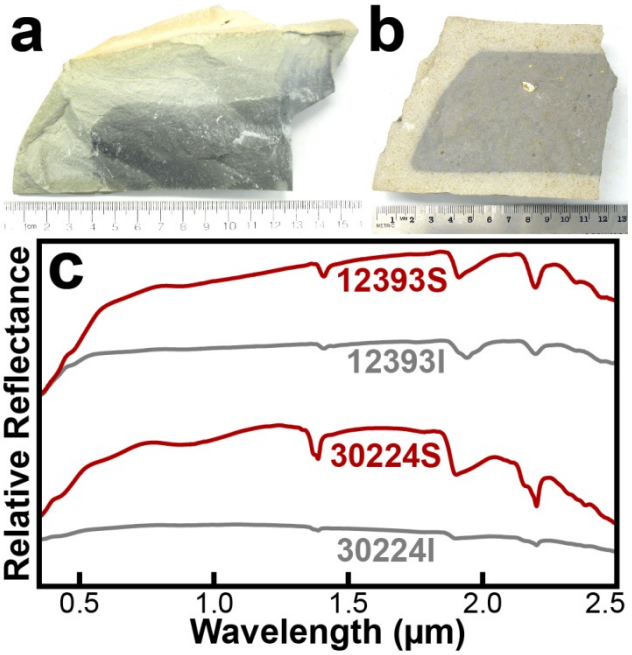

Figure 8. Photographs of samples PRR-12393 and PRR-30224, showing the thick bleached rinds and the darker interiors. Images courtesy of the Polar Rock Repository. (b) Visible/Near-infrared (VNIR) spectra of the interiors and surfaces of the two samples, showing the distinct brightening of the surfaces at visible wavelengths and the strengthening of hydration features.

There are several possible reasons as to why oxidative weathering processes like those found in Antarctic dolerites (Salvatore et al., 2013) dominate the surfaces of some but not the majority of samples studied here. The oxidative weathering products studied by Salvatore et al. (2013) were found on hard, fine-grained, and impermeable igneous rocks that can readily preserve alteration rinds (Glasby et al., 1981; Campbell and Claridge, 1987; Staiger et al., 2006).

Only a handful of samples analyzed in our investigation share similar physical attributes to those investigated by Salvatore et al. (2013). Increased erodibility of our samples may allow physical erosion to outpace chemical weathering, resulting in the rapid flaking and removal of altered surfaces. In addition, the dolerite samples investigated by Salvatore et al. (2013) had similar compositions, allowing for the composition of surfaces relative to their interiors to be easily determined. The samples analyzed in our study vary widely in composition, from basaltic to silica-rich, which may play a significant role in the availability and behavior of cations as well as our ability to confidently identify and track the behavior of different cation species using our analytical techniques. We are confident, however, in our ability to differentiate between typical aqueous alteration, oxidative weathering processes, and other forms of alteration, because of their consistent geochemical signatures. For example, nearly all compositions of igneous rocks have been shown to aqueously weather in the same manner, first with the leaching of CaO, Na_2O, and K_2O, followed by the leaching of FeO_T and MgO, with a steady enrichment in Al_2O_3 and SiO_2 (Nesbitt and Young, 1982, 1984; McLennan et al., 2002; Hurowitz and McLennan, 2007; Meunier et al., 2013). This consistency in weathering trends allows us to differentiate between alteration processes regardless of the parental chemistry of the rock.

Significant differences in parental composition as well as their original formation environments may also minimize any oxidation gradient that is present between rock interiors and the surrounding Antarctic environment. For example, the dolerites studied by Salvatore et al. (2013) were likely emplaced near the quartz-fayalite-magnetite (QFM) redox buffer, which is extremely reducing relative to the oxidizing Antarctic environment and establishes the oxidation gradient that is required for oxidative weathering processes to dominate. If these sedimentary lithologies were deposited under relatively oxidizing environmental conditions, the redox

gradient between the rock interior and the Antarctic environment may not be sufficient to promote surface oxidation and the preservation of oxidation rinds.

Lastly, the dolerites studied by Salvatore et al. (2013) were collected from the same valley and likely underwent similar geologic and alteration histories during their exposure to the Antarctic environment. The samples investigated in our study, however, were sourced from throughout the Antarctic continent and were likely exposed to a wide range of environmental conditions. Although all of the samples were collected from hyper-arid regions of the TAM, Marchant and Head (2007) showed that microclimatic variations can occur within very small geographic distances, resulting in significant differences between micro-, meso-, and macro-scale landscape and lithologic properties. In addition, the micro-geographic settings of these rocks (e.g., their orientation relative to other rocks or surfaces) and the impetus for their collection (e.g., were they a "typical" clast or was there some unique characteristic) are also poorly constrained for most of the samples analyzed here. The result is the inability to control for or even to confidently identify the relatively minor environmental, geologic, and geographic variables that might influence the formation and preservation of alteration products on these rocks.

While unlikely, it is possible that the gypsum coatings present on some tuffs are consistent with oxidative weathering processes. Cooper et al. (1996) were the first to show that oxidative weathering of basaltic glass in the laboratory resulted in the formation of crystalline CaO on sample surfaces. The calcium is sourced from the sample interior, as a result of divalent cations migrating outwards to the sample surface in response to the inward migration of electron holes (Cooper et al., 1996). However, in field settings where physical erosion and dissolution influence rock surfaces, the extremely friable and soluble CaO coatings are unlikely to be

preserved for any significant period of time (Salvatore et al., 2013). Is it possible that the local chemical environment promotes the formation of Ca-sulfates at rock surfaces instead of CaO as a product of surface oxidation? In addition, is it possible that the local microenvironment where these samples were collected was capable of protecting these rocks from physical erosion and dissolution to preserve these surface coatings? While no additional evidence suggests that these gypsum coatings are directly related to surface oxidation (e.g., clear gradients of discoloration, or significant differences in monovalent cation abundances between surfaces and interiors), we cannot wholly refute this possibility.

This work also provides evidence to suggest that some of the coldest and driest terrestrial environments are capable of aqueously altering the surfaces of sedimentary rocks. Mean annual temperatures throughout the TAM range from -30º C to less than -50º C (Dalrymple, 1966) and mean annual precipitation rivals that of the world's most arid deserts (Bull, 1971). The arid conditions and frequent katabatic winds also result in the rapid sublimation of most snow that falls onto ice-free surfaces, prohibiting liquid water from interacting with geologic surfaces for any extended periods of time (Campbell and Claridge, 1987). Despite these conditions that are adverse to the availability and activity of liquid water, aqueous alteration is possible due to the seasonal availability of small amounts of meltwater on the surfaces of rocks (Allen and Conca, 1991; Staiger et al., 2006; Marchant and Head, 2007) as well as the stability of the landscapes, which keeps geologic features and rock surfaces preserved and intact well longer than most terrestrial environments (Marchant and Denton, 1996). Given enough time, sufficient energy, and a source of both liquid water and geologic materials susceptible to chemical weathering, our work has demonstrated that aqueous alteration is possible even in the coldest and driest terrestrial environments. These are important considerations when studying martian sedimentary

landscapes and the degree to which they are chemically altered.

This study also helps to reinterpret the work of Salvatore et al. (2013) and their conclusion that oxidative weathering processes dominate dolerite surfaces in Beacon Valley. Do these new analyses of other lithologies throughout the TAM suggest that oxidative weathering is unique to Beacon Valley and/or dolerites, and not as widespread as originally anticipated? Based on theory and the occurrence of oxidative weathering in other locales, we believe that while the dolerites of Beacon Valley are uniquely optimized to preserve oxidative weathering signatures, oxidative weathering processes are still broadly at work throughout the TAM. Our study and previous work has shown that oxidative weathering can be easily overprinted by more mature alteration processes, but that oxidative weathering still occurs wherever an oxidation gradient and sufficient Fe^{2+} is present within a rock. While oxidative weathering may initially dominate rock surfaces throughout the TAM, the interaction of rocks with their local microclimates (in addition to their individual geologic histories) is far more influential on the overarching alteration signatures than the easily overwhelmed oxidative weathering processes that may also be at work. The composition, hardness, and exposure histories of the dolerites of Beacon Valley, along with the cold, dry, and stable microclimatic environment, are perfectly suited to form and preserve oxidative weathering signatures while retarding the progression of more mature alteration processes. While this perfect combination of physical, chemical, and environmental properties may be present elsewhere throughout the TAM, our study demonstrates that such conditions are not the norm and, instead, more mature alteration processes are able to overprint oxidative weathering signatures in many Antarctic environments.

Implications for the Weathering of Sedimentary Rocks on Mars

Chemical weathering of rocks at the martian surface has been investigated in the past, particularly using the results of the Mars Exploration Rovers Opportunity and Spirit. McSween et al. (2004, 2006) and Haskin et al. (2005) identified evidence for minor amounts of surface alteration on the olivine-bearing basaltic clasts on the floor of Gusev crater, suggesting that chemical weathering is occurring in the modern martian environment. Salvatore et al. (2013) showed that the elemental chemistries and trends between rock interiors and surfaces are consistent with the dominance of relatively immature anhydrous oxidative weathering processes, and Salvatore et al. (2014) demonstrated that global spectral signatures are also consistent with the presence of doleritic oxidative weathering products. Furthermore, the investigation of meteorites on the martian surface confirms that chemical weathering on Mars is relatively minor with little evidence for significant recent aqueous alteration (e.g., Schröder et al., 2008; Fairén et al., 2011). Studies also suggest that physical erosion is likely to significantly outpace chemical weathering in the modern martian environment, which should result in the identification of chemical weathering products on rock surfaces being the exception rather than the norm (Golombek and Bridges, 2000; Golombek et al., 2006).

Few studies have investigated the role of modern chemical alteration on the surfaces of sedimentary rocks on Mars. Knoll et al. (2008) identified and investigated the presence of veneers and thick rinds in Meridiani Planum that were investigated by the Opportunity rover and showed that rock surfaces differed significantly in composition relative to their interiors. These veneers were interpreted to form through the interaction of these rock surfaces with small amounts of liquid water that resulted in an increased Si and NaCl concentration at rock surfaces (Knoll et al., 2008). Cannon et al. (2015) investigated oxidative weathering processes in an Antarctic sandstone and suggested that similar processes may be at work in sedimentary

landscapes on Mars, particularly in Meridiani Planum.

The rocks under investigation in Gale crater by the Curiosity rover are dominantly sedimentary in nature (e.g., Grotzinger et al., 2014). These sedimentary units were emplaced in alluvial, deltaic, lacustrine, and aeolian environments several billion years ago, and were likely re-exposed as a result of physical erosion and landscape evolution in the more recent geologic past. CIA values associated with these sedimentary units vary from < 35 (Hurowitz et al., 2017) to > 60 (Frydenvang et al., 2018) which, if assumed that all sedimentary rocks were basaltic to start (Taylor and McLennan, 2009), indicates little to moderate amounts of aqueous alteration has likely occurred under fluctuating climate and environmental conditions during transport, deposition, and lithification (Hurowitz et al., 2017). Based on these and additional data from the instruments onboard Curiosity (Vaniman et al., 2014; Johnson et al., 2016; Treiman et al., 2016; Hurowitz et al., 2017; Rampe et al., 2017; Wellington et al., 2017; Frydenvang et al., 2018), it is clear that the oxidation state of sedimentary rock interiors in Gale crater varies widely (**Fig. 9**). Should we expect oxidative weathering to dominate the sedimentary rock surfaces under investigation by the Curiosity rover in Gale crater and, if so, might these weathering processes influence our ability to accurately characterize surface compositions?

Unfortunately, determining the specific role of oxidative weathering in Gale crater is a difficult task, as Curiosity's payload does not include a Mössbauer spectrometer and is thus not capable of quantifying the Fe^{3+}/Fe_{Total} ratio of geologic materials. This makes it impossible to quantify the oxidation gradient present between the rock interiors and the current martian environment. In addition, estimates of physical erosion in Gale crater are surprisingly high (~0.75 m My^{-1}, Farley et al., 2014) and comparable to (and, in some cases, far greater than) those found in parts of the Antarctic interior (e.g., ≤ 0.31 m My^{-1}, Margerison et al., 2005). This

suggests that the likely low rates of oxidative weathering (the current martian atmosphere is more than two orders of magnitude less oxidizing than Earth's atmosphere, Owen, 1992) would probably be outpaced by physical erosion, preventing the formation of measurable oxidative weathering rinds on the surfaces of sedimentary rocks in Gale crater.

While observing and measuring oxidative weathering products similar to those observed on Antarctic dolerites would be difficult in Gale crater using the Curiosity rover, our work discussed above suggests that oxidative weathering is unlikely to dominate sedimentary lithologies in the first place. Considering the observed diversity in rock chemistry, physical properties, exposure histories, and the environmental conditions present during sediment deposition, lithification, and burial, we hypothesize that the products of oxidative weathering are unlikely to dominate the composition of sedimentary rock surfaces in Gale crater. Additional work is necessary to critically evaluate compositional differences between rock surfaces and interiors as measured by the Curiosity rover. However, given the inability for Curiosity to quantify ferric vs. ferrous iron, the only way to definitively identify oxidative weathering products would be through the subtle

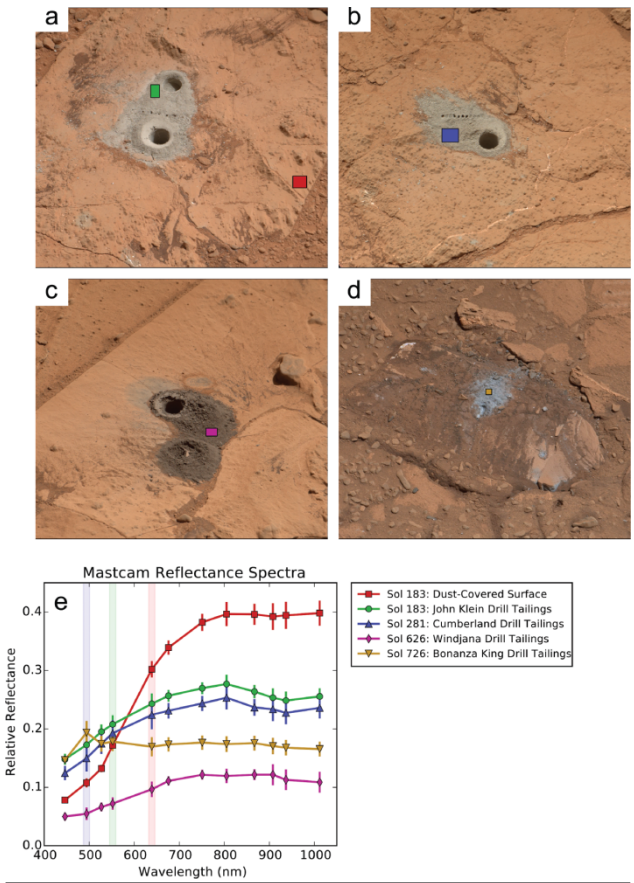

Figure 9. Mastcam multispectral data derived from various drill tailings in Gale crater. Spectra of drill tailings (representing rock interiors) are compared to the dust-covered surface (red spectrum). The depth of the short wavelength (< 600 nm) absorption feature and steepness of the slope between 550 and 700 nm indicate the relative spectral contribution from Fe^{3+}. Drill holes are approximately 1.6 cm in diameter for scale. From Wellington et al. (2017).

chemical patterns identified by Salvatore et al. (2013). Our work shows, however, that such chemical patterns are not preserved in the diverse suite of Antarctic sedimentary lithologies investigated here.

The hypothesis that oxidative weathering is not expected to dominate the surfaces of sedimentary rocks in Gale crater is supported by the only documented case of surface alteration identified on a rock clast within Gale crater, which was discovered on the "Bathurst Inlet" target by the ChemCam instrument near the Bradbury Landing site on sol 55 (Ollila et al., 2014; Mangold et al., 2015). Bathurst Inlet is a fine-grained layered sedimentary rock (fine sandstone or siltstone) with a composition comparable to hawaiite (Schmidt et al., 2013; Mangold et al., 2015) and uniquely high Li abundances (> 30 ppm) observed at the surface (Ollila et al., 2014). Li abundance, along with Rb, Na, and K, are also shown to systematically decrease with increasing ChemCam shot number, suggesting an enrichment of these elements at the uppermost surface. Ollila et al. (2014) interpreted this enrichment of alkali elements at the surface as evidence for modern aqueous alteration on the uppermost surface of the rock, potentially caused by processes like frost deposition, melting, and subsequent alteration. The preservation of these alteration signatures on Bathurst Inlet is thought to be the result of the resistant nature of the rock and the sheltering of these ChemCam analysis points by a slight overhang on the rock, which may have reduced the amount of physical erosion and removal of these alteration products (Ollila et al., 2014).

Lastly, while our study was able to isolate the uppermost surfaces of rocks and investigate them using XRD techniques, the XRD capabilities of the Curiosity rover are unable to sample just the uppermost millimeters of rock surfaces, precluding our ability to quantify differences between rock surface and interior mineralogies on Mars. Regardless, Salvatore et al.

(2013) found that oxidative weathering products, which primarily manifest themselves as chemical and not mineralogical variations, do not result in significant differences in XRD patterns between rock surfaces and interiors. Our XRD analyses on Antarctic sedimentary rocks confirm the results from Salvatore et al. (2013), showing little differences between rock surfaces and interiors where oxidative weathering is found to dominate. Instead, diffraction patterns are widely variable, from no observable changes between interiors and surfaces, to an increase in crystalline alteration phases in surfaces, to a decrease in crystalline alteration phases in surfaces. Such variability clearly demonstrates that oxidative weathering does not dominate the surfaces of sedimentary rocks throughout the TAM. Alternatively, the XRD data are consistent with each clast undergoing its own unique geologic and alteration history, thus resulting in their own alteration signatures.

The results of our investigation have significant implications for the weathering of sedimentary rocks in the modern martian environment. First, the diversity of alteration products found throughout the TAM, including those consistent with aqueous alteration, suggests that a diversity of alteration processes are also able to dominate rocky landscapes under hyper-arid and hypo-thermal environments on modern Mars. While liquid water is more stable and prevalent throughout the TAM than it is on the martian surface, Mars has experienced numerous significant climatic shifts in the recent geologic past as a result of variations in the planet's obliquity (Jakosky and Carr, 1985; Laskar and Robutel, 1993; Head et al., 2003; Forget et al., 2006). Second, should similar alteration processes and products be at work on Mars and generated at the surfaces of rocks, respectively, estimates of modern martian erosion rates from Gale crater indicate that the products of surface alteration may not remain preserved at the rock's surface for prolonged periods of time. For example, the rate of siliceous alteration rind

formation in sandstones in Arena Valley, Antarctica, is on the order of 0.05 mm My^{-1} (Weed and Ackert, 1986; Weed and Norton, 1991), which is more than four orders of magnitude slower than the measured erosion rate of 0.74 m My^{-1} in Gale crater by Farley et al. (2014). At these rates of surface alteration, it is unlikely that evidence for significant chemical alteration would survive the physical erosion that currently dominates the martian surface.

Relationship to Global Oxidative Weathering Processes on Mars

Oxidative weathering products were identified using VNIR and TIR spectral datasets as globally significant components of the martian surface (Salvatore et al., 2014). Considering that much of the martian surface is composed of sediments and sedimentary rocks (e.g., Grotzinger et al., 2011; Le Deit et al., 2015; Edgett, 2016), which we show are not likely to be dominated by oxidative weathering processes on their surfaces, why might oxidative weathering products be a spectrally significant component of the martian surface, as proposed by Salvatore et al. (2014)? To address this seemingly incongruent set of observations, one must consider processes at both the scale of individual rocks (as we have done in this current investigation) as well as those that dominate broader geologic landscapes.

For example, our investigation here suggests that oxidative weathering processes, while almost certainly occurring in the modern Antarctic environment, are either being overprinted by more mature alteration phases or are undergoing physical erosion at a rate that outpaces oxidative weathering processes. While our investigation only considered weathering that occurred on rock surfaces, chemical weathering processes continue to alter rock fragments and sediments after they are separated from their host rock. Campbell and Claridge (1987) showed how the age of soils and sediments throughout the Transantarctic Mountains could be readily

distinguished based largely on the extent of oxidation, and how soil oxidation does not necessarily correspond to the weathering patterns of surface clasts. This is an important observation when relating the weathering of individual rocks to spectral signatures identified from orbit.

Sediments on the martian surface are derived from a range of parental materials, including igneous rocks, impact ejecta, and sedimentary rocks. Unlike the Earth, where sediments undergo a wide range of physical and chemical sorting during their formation and evolution, martian rovers and landers have shown that sediments are both physically and chemically immature (e.g., Grotzinger et al., 2011; McLennan, 2012). Considering the cold, dry, and stable modern environment on Mars, as well as the recognized physical and chemical immaturity of these sediments, it is likely that the dominant form of chemical alteration capable of acting upon martian sediments is oxidative weathering. It is no wonder, therefore, that oxidative weathering products are identified from orbit across the martian surface. While physical erosion may outpace the weathering of rock surfaces in the modern martian environment, the initial oxidation of rock surfaces prior to physical erosion, the accumulation of immature sediments on the surface, and their constant exposure to the oxidizing martian environment would promote oxidative weathering in the modern martian environment on the scale of geologic landscapes.

Summary & Conclusions

In this study, we tested the hypothesis that anhydrous oxidative weathering (caused by the long-term exposure of iron-bearing rocks to the cold, dry, stable, and oxidizing Antarctic environment) dominates the surfaces of sedimentary rocks exposed throughout the TAM, as it

does to doleritic lithologies in the MDV. Samples were prepared and analyzed using a suite of analytical techniques to determine the effects of subaerial weathering on the surfaces of rocks obtained from the Polar Rock Repository. The sedimentary rocks investigated here show a diverse range of surface mineralogy and chemistry relative to their interiors. While some rock surfaces do exhibit geochemical, mineralogical, and spectral signatures that are consistent with oxidative weathering, others show evidence for more traditional aqueous alteration like that observed in warmer and wetter environments. A subset of samples also shows evidence for alteration mineral coatings on the surfaces of the rocks, suggesting that these mineral phases either precipitated out of solution or altered *in situ* at the rock surfaces as a result of frequent and repeated exposure to liquid water. Unlike the doleritic rocks studied in Salvatore et al. (2013), these observations are instead more consistent with a wide variety of alteration processes influencing these rock surfaces and not a single process dominating the surfaces of sedimentary rocks throughout the TAM.

The results of our laboratory investigation also have significant implications for the chemical weathering of sedimentary lithologies on the martian surface. First, with few exceptions, the magnitude of surface weathering observed in sedimentary rocks throughout the TAM is relatively small compared to that of more temperate or tropical environments on Earth. In fact, with the exception of some of our samples shown to have significant coatings, it is unlikely that the bulk composition and extent of weathering of any of the samples analyzed in this study would be misinterpreted if only the surface were measured and not the less altered rock interior. Additionally, LIBS measurements show that coatings of the compositions and thicknesses found in this study would be easily identified on Mars using the ChemCam instrument onboard Curiosity or the SuperCam instrument to fly on the Mars 2020 rover mission

(Wiens et al., 2014). Second, previously reported rates of surface weathering in the Antarctic compared to modern estimates of erosion rates in Gale crater suggest that physical erosion on Mars may substantially outpace the rate of chemical weathering of rock surfaces in Gale crater. If so, it is possible that the products of surface weathering may never be identified on martian sedimentary rocks due to the dominance of physical erosion at the surface, although they may be present in martian soils where they can accumulate over geologic timescales.

In conclusion, our results suggest that "modern" (i.e., Amazonian) chemical weathering of sedimentary rocks on Mars is unlikely to be a significant geological process that would inhibit the investigation of rock compositions in Gale crater. While previous studies have shown that oxidative weathering products are spectrally dominant components at the regional and global scales of orbital investigations (Bibring et al., 2006; Salvatore et al., 2014), the results presented here demonstrate how differences in bulk composition, friability, porosity/permeability, and geologic histories of individual sedimentary rocks can lead to differing extents and types of geochemical alteration preserved at the surfaces of these rocks even in the coldest and driest of terrestrial environments.

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