SEDIMENT MIXING AND AMORPHOUS WEATHERING PRODUCTS IN A GLACIATED MARS-ANALOG SYSTEM. N. A. Scudder[1], B. Horgan[1], E. B. Rampe[2], E. R. Bamber[3], A. M. Rutledge[1], [1]Dept. of Earth, Atmospheric, and Planetary Sciences, Purdue University (nscudder@purdue.edu), [2]NASA Johnson Space Center, [3]Department of Earth Sciences, University of Oxford, UK.

Introduction: Modern climate models of Mars tend to predict a colder, icier early climate than previously imagined [*e.g.,* 1]. While alteration of mafic terrain under warm, wet conditions is relatively well understood, a significant knowledge gap exists in how weathering might occur under predominantly glaciated environments on Mars. In such conditions, it is unclear whether all or any of the variety of aqueous alteration phases [2] expressed in contemporaneous early martian surfaces could be formed, or how erosion of mafic bedrock and transport of sediment would comparatively change.

To test this, we collected sediment and bedrock samples from the Three Sisters volcanic complex in Oregon. The Three Sisters is the most mafic glaciated terrain in the continental U.S. [3], and the glaciers there have retreated rapidly in the past century, making it a good site to examine freshly exposed glacial material in a Mars-analog environment. This study uses thermal infrared (TIR) emission spectroscopy to examine sediment transport from source units and search for signs of alteration in bulk mineralogy.

Methods: TIR emission spectra of rock and pelletized sediment samples were acquired at Arizona State University using a Nicolet Nexus 670 FTIR spectrometer modified to measure emitted energy. All samples were heated to and maintained at 80°C for the duration of the measurements. For each measurement, 512 scans were averaged at 4 cm^{-1} spectral resolution, then converted from radiance to emissivity [4].

To analyze mineral abundances, we developed a TIR emission spectral library of minerals commonly found in volcanic environments using published spectra [4-10]. TIR sample spectra were analyzed using a non-negative least-squares spectral deconvolution technique [11, 12] between 350 and 1250 cm^{-1}. TIR deconvolution methods can accurately model abundances of minerals in igneous rocks to within 15% [13].

Validation of TIR measurements with XRD: Quantitative mineralogy of 7 rock samples was also acquired using Rietveld refinement of X-ray diffraction patterns collected at Johnson Space Center [14, 15]. For each sample, modeled mineral abundances were then grouped by type, and the magnitude of the difference between XRD- and TIR-derived abundances was summed to provide a measure of the variance of TIR models from XRD. We find that TIR abundances for individual minerals generally stay within ~15% of XRD abundances. The RMS error of the TIR models positively correlates with increasing TIR-XRD difference,

suggesting that more accurate mineral abundances can be expected with better model fits for a given TIR spectrum.

Comparison of sediments vs. source rocks using TIR: The sediments in the glacial valleys at the Three Sisters are sourced from a heterogeneous collection of volcanic rock units, but homogenize downvalley. At Collier glacier, andesite and vitrophyric dacite form steep walls along the southwestern valley edge (Fig. 1), represented in the TIR spectra of nearby sediment (sample A; Figs. 1 & 2) by high amounts of feldspar and high-silica glass alongside low amounts of olivine and pyroxene. Along the eastern side of the valley, basaltic andesite dominates, and is reflected in the relative lack of high-Si glass and significant increase in olivine and pyroxene at sample B. Downvalley along the western side, mixing of these units is apparent in sample C by higher olivine and pyroxene but retention of high-silica glass. Far enough downvalley, sediment spectra look identical to those near the basaltic andesite (D), indicating that the basaltic andesite is the major sediment contributor in the valley. At Diller glacier, a basaltic andesite unit is the major sediment contributor both near the unit and in downvalley moraines (E and F).

In addition to modeling sediments with mineral endmembers, we also used spectra of local rock units as endmembers in order to track the relative contributions of each unit to the sediment throughout the valleys. However, we find in models including all minerals and all rock units that mineral endmembers are preferred to the near exclusion of rock units. In models including only rock units with or without x-ray amorphous phases, good model fits nearly ubiquitously require significant addition of amorphous material (e.g., tephra units). However, while local altered and/or glassy units do exist at Collier and Diller, they are small and cannot easily explain the widespread modeling of amorphous material in both systems. As the library contains at least 2-3 samples of each major contributing unit mapped in [3], it seems unlikely that this is because a major glass-rich sediment-forming unit is unrepresented in the models.

Evidence of amorphous material in glacial sediment: One possible explanation for the widespread amorphous material is secondary formation via alteration in the glacial system. Our TIR models suggest on average 21% more amorphous material in sediments than in rock units, and XRD also finds elevated amorphous abundances in sediments compared to nearby rock units [15]. Secondary amorphous phases could

form via low-temperature interactions with ice and meltwater, and this hypothesis is consistent with findings of high amounts of amorphous material in cold-climate soil weathering [16,17]. The highest amorphous abundances tend to be modeled in sediments found at moraine springs where water geochemistry measures the highest dissolved silica in the glacial system, suggesting that dissolution processes, and perhaps subsequent precipitation of amorphous silicate phases, contribute to the elevated amorphous signature. Hydrated silica-like phases are also weakly apparent in VNIR spectra of glacial sediments and in glacier-formed rock coatings [18]. Transmission electron microscopy of glacial sediment samples finds evidence of a variety of amorphous silicates as well as nanophase iron oxides and proto-clays [14,17].

Implications for Mars: Evidence from multiple techniques suggests that amorphous material forms as a weathering product in mafic alpine glacier systems. If similar conditions existed on early Mars in the form of glaciers and ice sheets, we predict such systems could have formed similar amorphous weathering products that may be detectable from orbit. However, there is little evidence that cold systems can form the crystalline alteration minerals preserved from early Mars.

In small alpine systems like the Three Sisters, sediments sourced from chemically distinct rock units appear to largely homogenize within 1-2 km of transport. Under large glaciers or ice sheets, sediment from regional units may become well-mixed over larger spatial scales [19]. Such sediment mixing might be expected for a cold, icy early Mars environment regardless of glacier thermal regime, as on Earth even cold-based glaciers erode and deposit significant material [20].

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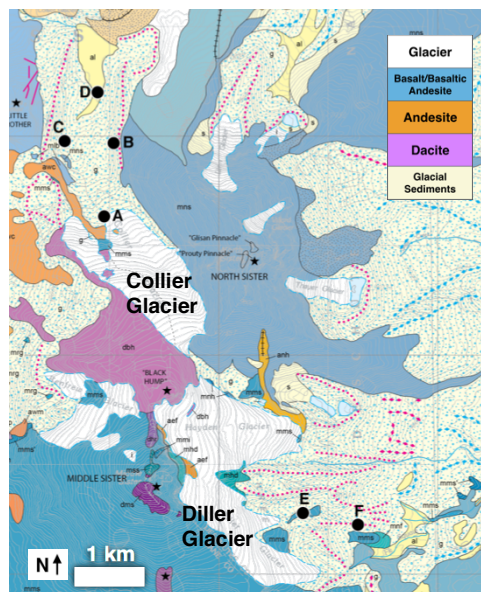

Fig. 1. Geologic map of North and Middle Sister modified from [3], with a simplified unit description. Spectra from Fig. 2 are marked with their sample location.
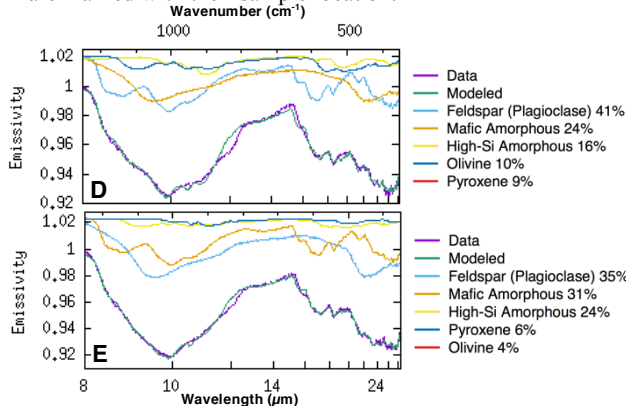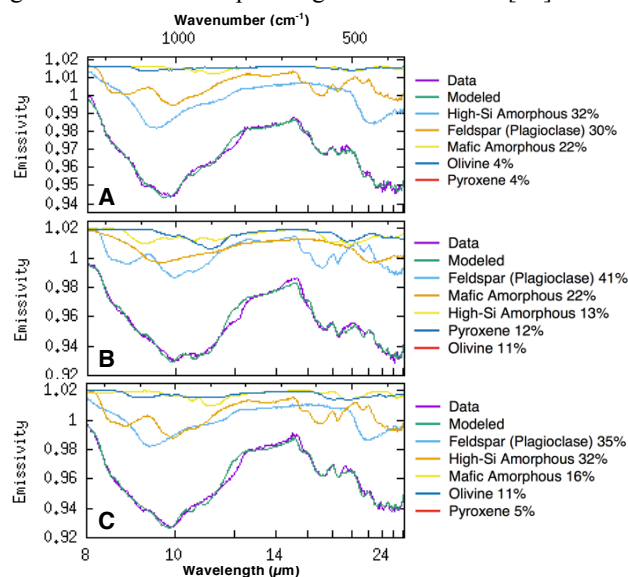

Fig. 2. TIR deconvolutions of samples A-E as located in Fig. 1, grouped by mineral category. Sample F is highly similar to E and its spectrum is not shown.