GEOCHEMICAL MIXING RELATIONSHIPS BETWEEN BEDROCK LITHOLOGIES ON HUSBAND HILL, GUSEV CRATER, MARS. J. A. Hurowitz[1], S. M. McLennan[1], and The Athena Science Team[2], [1]Department of Geosciences, Stony Brook University, Stony Brook, NY 11794-2100, [2]Gusev Crater, Mars

Introduction: Two-component geochemical mixing relationships are expressed in a variety of geologic processes on Earth. Examples of mixing in igneous systems might include mixing between two or more magma bodies [1]. In sedimentary systems, mixing may be seen in rocks which are the product of the erosion of two different terranes bordering a depositional basin [2]. In impact systems, mixing between target lithologies may take place as rocks are excavated from the impact zone and mixed to form ejecta deposits [3].

On Husband Hill, in the Columbia Hills of Gusev Crater, the Mars Exploration Rover *Spirit* has encountered a startling variety of rock lithologies [4], whose chemical and mineralogical diversity has made their interrelationships a challenge to elucidate. There is indication, however, that some of the chemical variation amongst the lithologies encountered on Husband Hill can be explained by a two component mixing relationship, which we interpret to be the result of physical mixing caused by impact or volcaniclastic processes. One key line of evidence for such an origin lies in the observation that many of the lithologies encountered on Husband Hill exhibit clast-in-matrix textures at scales ranging from 100's of μm to 10's of cm. Such textures are common, though not necessarily unique, to impact and volcaniclastic deposits [3, 5]. Below, we discuss chemical evidence for two component mixing.

Methods: In an effort to minimize the effects of rock surface alteration and soil addition to rock surfaces, processes which were shown by [6] to be important components of rock surface chemistry, we have taken an approach which uses the deepest analysis (i.e., Rock Abrasion Tool (RAT) grind > RAT Brush > As Is) from each rock target analyzed by the Alpha Particle X-ray Spectrometer (APXS). This approach is necessary because after sol 416, RAT grinds were no longer possible due to wear out of the RAT's diamond impregnated grind heads [4].

Powerful constraints can be placed on two-component mixing relationships by plotting samples on elemental ratio-ratio diagrams, and demonstrating that: (1) samples lie along a hyperbolic mixing curve generated from two data points on the plot which are representative and well separated, and (2) samples maintain the same position relative to one another on all plots [1]. In order for a physical two-component mixing relationship to be valid it must be obeyed by all elements. For ratio-ratio diagrams, additional confirmation of the mixing relationship is provided by demonstrating a linear relationship between samples on "companion plots". These are constructed by plotting one of the ratios from the original diagram against the ratio of the denominators from that same diagram.

Results: We have demonstrated, for all elements, that a two component mixing relationship exists between the Wishstone and (tentatively named) Descartes Class. Intermediate compositions in the mixture are represented by rocks of the Watchtower Class. This relationship is well demonstrated by the hyperbolic mixing array and linear companion plot shown on Figure 1. We have also demonstrated that for all ratios examined thus far, the lithologic classes (Wishstone, Watchtower, and Descartes Classes) maintain the same position relative to one another on all diagrams. We observe considerable scatter within lithologic classes, most likely due to (1) the inherent differences between APXS analyses collected from RATed, Brushed, and As Is rock surfaces [6], and possibly (2) the effect of post-mixing alteration of rock interiors by processes more extensive than those affecting rock surfaces [e.g., 7]. Furthermore, by evaluating all other potential lithologic endmembers encountered by *Spirit* during her traverse to the summit of Husband Hill, we have been able to rule out other rock classes (e.g., Adirondack Class, Clovis Class, Peace Class, Backstay Class) as participants in the mixing relationship.

Discussion: Review of mixing arrays indicates that the relationship between the Wishtone, Watchtower, and Descartes lithologies is, first and foremost, a mixture between a high P_2O_5, high TiO_2 lithology (Wishstone Class), and a chemically similar lithology (Descartes Class) which is richer in MgO and SO_3. The sample-to-sample relationships shown on Figure 1 are inconsistent with simple addition of Mg-sulfate to Wishtone Class rocks as the sole explanation for the relative positions of the data points. If the samples did lie along the kieserite addition line depicted, one might suspect that the apparent mixing relationship is actually nothing more than an alteration relationship in which Mg-sulfate has been added to Wishstone Class rocks. Instead, our analysis indicates that the mixing relationship is the result of the combination of Wishstone Class materials with Descartes Class materials, which are richer in both Mg-sulfates and Mg-silicates.

Complicating interpretation of the mixing relationships is the previously mentioned issue of chemical differences between RATed, Brushed, and As Is surfaces. Figure 2 shows a mixing array for the ratios

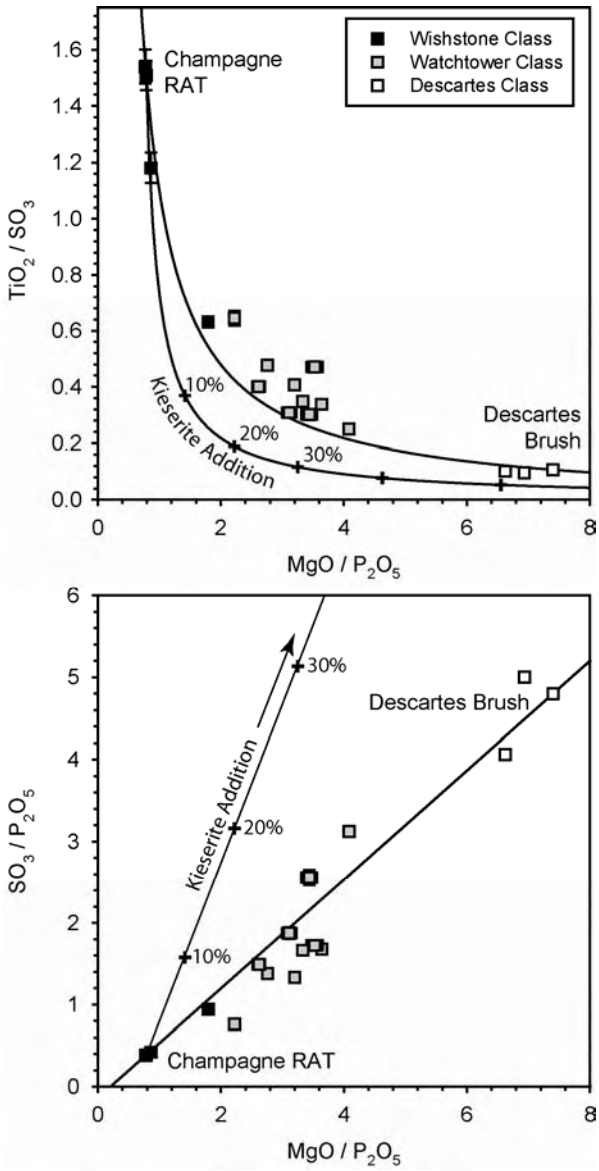

Figure 1: *(Top) Mixing array generated from the samples Champagne RAT_1 and Descartes Brush. (Bottom) Companion plot demonstrating linear relationship between samples. Kieserite addition to sample Champagne RAT_1 shown, crosses = 10% addition.*

TiO_2/SiO_2 vs. Al_2O_3/P_2O_5. The process of phosphate loss (due to the acidic dissolution of Ca-phosphate minerals from rock surfaces, see [6]) causes horizontal scatter away from the mixing array, while the addition of soil to rock surfaces mimics the mixing trajectory. The overall effect of these processes is to cause scatter away from the mixing array, with each sample affected to varying degrees, depending on how extensively they have undergone acid attack and soil coating. Unfortunately, evaluation of the extent of chemical alteration of rock surfaces is possible only where RATed and

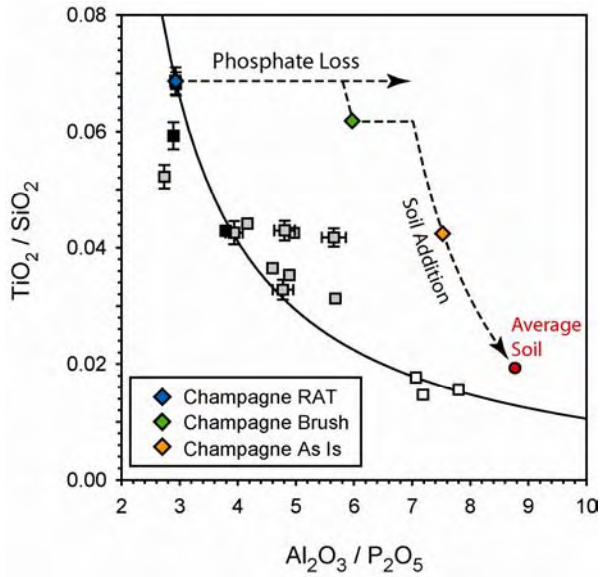

Figure 2: *Mixing array generated from Champagne RAT_1 and Descartes Brush. Dashed lines demonstrate phosphatic mineral dissolution and soil addition to the surface of Champagne RAT_1.*

Brushed surface analyses are available [6]. Soil coverage, however, can be readily evaluated by visual inspection of Pancam and Microscopic Imager images.

The alteration processes discussed (Mg-sulfate addition, acid deposition on rock surfaces, soil addition) highlight the unique complexities of weathering on Mars. Under the low-pH conditions thought to prevail in much of the Martian weathering regime, alteration largely involves near stoichiometric mineral dissolution [6], and so weathering processes are difficult to unravel from primary compositional variations and processes such as mixing between primary igneous lithologies. Nevertheless, our analysis leads us to the conclusion that much of the geochemical variability present in the rocks encountered by *Spirit* on Husband Hill is consistent with a two component mixing process. The existence of such a mixing relationship implies an important role for impact and/or volcaniclastic processes in the formation of the Columbia Hills.

References: [1] Langmuir, C.H., et al., (1978), *EPSL, 37*, 380-392. [2] Hurowitz, J.A. and S.M. McLennan, (2005), *J. Geol., 113*, 571-587. [3] French, B.M., (1998), LPI Contribution No. 954, LPI, 120 pp. [4] Squyres, S.W., et al., (2006), *JGR, 111*, doi:10.1029/2005JE002584, in press. [5] Raymond, L.A., (1995), *Petrology: The Study of Igneous, Sedimentary and Metamorphic Rocks*. Wm. C. Brown Publishers, 742 pp. [6] Hurowitz, J.A., et al., (2006), *JGR, 111*, E02S19, doi:10.1029/2005JE002515. [7] Ming, D.W., et al., (2006), *JGR, 111*, doi:10.1029/2005JE002560, in press.