MISMATCHED PHYSICAL AND CHEMICAL WEATHERING OF ROCKS ON MARS: CLUES TO PAST CLIMATE.

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Summary: Here we quantify the degree of weathering experienced by the Adirondack-class basalts at the Mars Exploration Rover Spirit site by performing comparative analyses on the strength and chemistry of a series of progressively weathered Columbia River Basalt (CRB) samples. In comparison with the terrestrial samples, the strength of Adirondack-class basalts as inferred from Rock Abrasion Tool (RAT) grinds are most similar to the weakest CRB samples. However, they do not exhibit a commensurate amount of chemical alteration. This mismatch between their strength and chemistry indicates that Adirondack-class basalts may possess a several mm-thick weak outer rind encasing an interior that is more pristine than otherwise indicated, and also suggests that long rock residence times may be the norm.

Introduction: Basalt physical properties such as compressive strength and density are directly linked to their chemistry and mineralogy; as weathering progresses, basalts gradually become weaker and transition from intact rock to saprolite and ultimately, to soil. Understanding the material strength of rock, outcrop, and soil targets encountered by landed spacecraft on Mars is an essential part of our knowledge of present and past environmental conditions.

This study extends our previous work in which the RAT specific grind energy was used infer the compressive strength of rocks in Gusev crater [1]. The goal of this present investigation is to investigate the linked chemical and strength changes undergone by basalt during weathering, which is the most abundant rock type on Mars [e.g., 2]. Establishing an empirical linkage between strength and chemistry of basalt undergoing weathering will permit greater insight into the nature and degree of weathering processes on Mars as inferred from *in situ* measurements.

Methods: All of the terrestrial basalt samples described in this work were obtained from flows of the Columbia River Basalt Group in eastern Washington and Idaho. Our focus is on the entombed paleosol horizons that developed on top of basalt flows during interflow intervals. Their subsequent burial in later flows provides a unique snapshot of weathering processes from that interval [3, 4].

At each sample locality, relatively intact blocks of basalt were selected at regular intervals below the paleosol layer. The objective was to sample the transition from intact basalt to progressively more weathered material. Drill cores (mean diameter of 24.6 mm) were extracted in the field using a portable water-cooled drill. Once the samples were returned to the laboratory, three sets of tests were performed on each sample (N = 24 samples): compressive strength tests on the drill cores, RAT grind tests on adjacent cut slabs, and chemical analyses of rock chips from the same slab. A detailed account of the test procedures is given in [5].

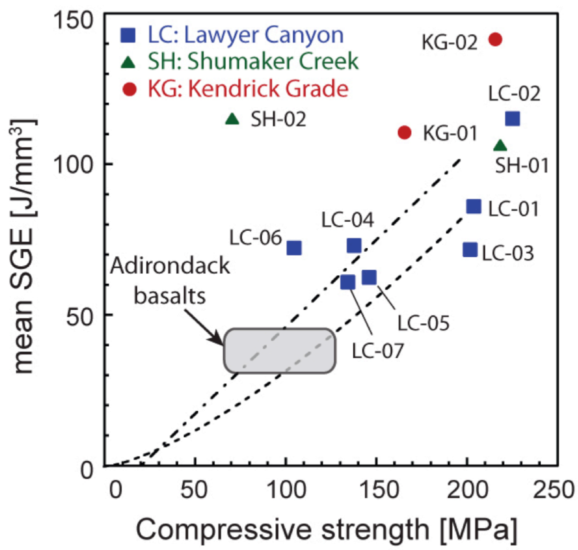

Figure 1. Mean compressive strength values (in MPa) plotted against mean specific grind energy (SGE) values (in J/mm^3). Dashed and dot-dashed lines give power law and linear fits to the calibration data of [1]. Shaded field on right-hand plot is measured SGE values and inferred UCS values of Adirondack-class basalts in Gusev crater.

Results of grind and compressive strength tests: The samples from Lawyer Canyon are reasonably consistent with the previously determined correlation [1] (**Fig. 1**). The Adirondack-class basalts Adirondack, Humphrey, and Mazatzal have recorded SGE values that range from ~30 to 45 J/mm^3; their inferred compressive strengths range from about 70-130 MPa. In terms of strength, Adirondack-class basalts are similar to samples LC-05 and LC-07, which are the most weathered but intact basalt samples measured in this study (excluding paleosols or saprolite).

Mobility ratio results: To assess the degree of chemical alteration that Adirondack basalts have experienced, we calculated mobility ratios [6] using Ti as an index element to facilitate direct comparison with the CRB samples. As given by the gray shaded field in **Fig. 2**, the range of mobility ratio values for most cations of the brushed versus RAT-abraded surfaces of Adirondack and Humphrey are within plus or minus 0.2 (excluding enrichments in K_2O). Considering Mg as our most sensitive tracer of alteration, Adirondack-class basalts are therefore intermediate in Mg loss (mobility ratio of -0.14) between LC-03 and LC-04 (mobility ratios of -0.05 and -0.3, respectively). These results indicate that the brushed vs. abraded surfaces of Adirondack-class basalts do not encompass the same degree of alteration evidenced by the transition from LC-01 to LC-07.

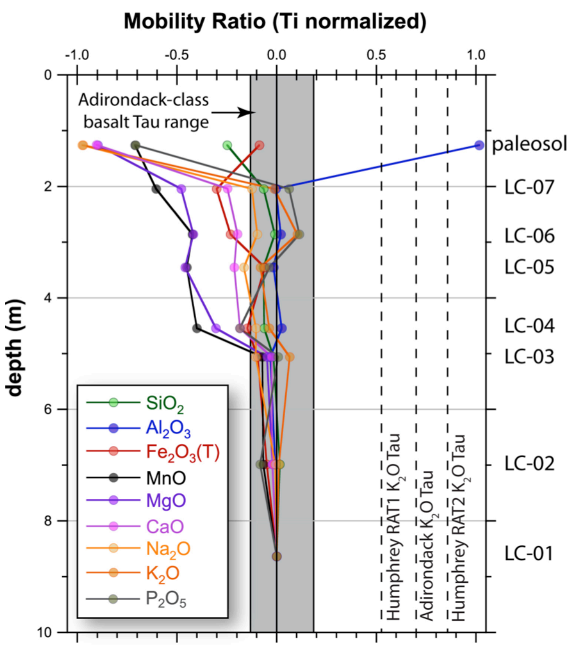

Figure 2. Mobility ratio [6] calculated for Lawyer Canyon (LC) samples indicating cation gain or loss compared to least weathered material (LC-01). Index element (assumed to be immobile) is Ti. Gray shaded field represents maximal cation gain or loss (excluding K_2O) of Adirondack-class basalts comparing brushed surfaces to those abraded by the RAT.

Discussion: What can we infer about the nature of weathering on Mars from the strength and chemistry of Adirondack basalts? While Adirondack basalts have a comparable strength to the weakest, most weathered non-paleosol samples measured in our study (LC-05, LC-07), they do not appear to have lost a corresponding amount of mobile cations (such as 54% of MgO, 38% of Fe_2O_3(T), and 34% of the initial CaO).

We can envision three possible explanations for the observed weakness of the Adirondack class basalts. First, the weakening may be entirely attributable to physical weathering such as shock effects [e.g., 7] during the emplacement process or subsequent salt weathering [8]. Second, Adirondack basalts may be samples from a soil-like weathering profile developed in a basalt layer reflective of deep (i.e., meter length scale) downward percolation of fluids [e.g., 9], followed by later disaggregation into isolated blocks. A third alternative is that the observed weakening is limited to a several mm to cm-thick rind on exposed basaltic clasts sampled by Spirit. In this case, we are looking at a moderately weathered, weak layer that encases more pristine (and unsampled) corestones.

Although we consider it unlikely that shock-induced weakening is solely responsible due to geometric considerations (especially given the self-similarity of the four Adirondack basalt samples), some degree of shock-related weakening is to be expected. Assuming that all of the weakening is not attributable to physical weathering, the reason that a distinction between the second and third scenarios matters is one of timing. If Adirondack basalts were weathered and weakened in a soil-like context, then these effects are likely related to an early phase of weathering on Mars (but still in the Hesperian since it had to have occurred after the lava flows that filled Gusev crater were emplaced [10]). However, if the third scenario is correct, this provides little to no age control for the weathering. It could be recent, or it could be significantly older. Exactly how old it could be is unclear, as this has to do with how long one would expect a rock to last on the surface of Mars.

A key discriminator between the second and third scenarios is the mismatch between strength and chemical data. If the physical and chemical weathering were due to the development of a soil-like weathering profile in a basalt layer, we would not expect a mismatch between the degree of weathering implied by the mechanical strength versus that implied but the degree of chemical alteration. Though such a process may have been active, one or both of the other two explanations (i.e., additional physical weathering or thick rinds) are necessary to explain the totality of available evidence.

In summary, this third hypothesis (i.e., Adirondack basalts are encased in a several mm-thick weak weathering rind) appears most consistent with the available evidence and known history of activity in Gusev crater.

References: [1] Thomson B.J. et al. (2013) *JGR*, *118*, 1233-1244. [2] McSween H.Y. et al. (2009) *Science*, *324*, 736-739. [3] Sheldon N.D. (2003) *GSA Bull.*, *115*, 1377-1387. [4] Hobbs K.M., (2010), MS, Univ. of Idaho. [5] Thomson B.J. et al. (2014) *EPSL*, in revision (pre-print link). [6] Brimhall G.H. et al. (1992) *Science*, *255*, 695-702. [7] French B.M. (1998) *Traces of Catastrophe*, LPI Contribution No. 954, 120 pp. [8] Malin M.C. (1974) *JGR*, *79*, 3888-3894. [9] Amundson R. et al. (2008) *GCA*, *72*, 3845-3864. [10] Milam K.A. et al. (2003) *LPSC 34*, 1071.