FINAL REPORT

Title: Sedimentary Geochemistry of Martian Samples from the Pathfinder Mission

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The purpose of this research project was to evaluate the APXS data collected on soils and rocks at the Pathfinder site in terms of sedimentary geochemistry. Below are described the major findings of this research:

1. An influential model to explain the chemical variation among Pathfinder soils and rocks is a two component mixing model where rocks of fairly uniform composition mix with soil of uniform composition. The most likely mechanisms of mixing include soil and dust coatings on rock surfaces and admixture of rock fragments into the soils. This model has received additional support from spectroscopic data where a well defined positive correlation between the Red/Blue reflectance ratio (750nm / 440nm) measured by the Mars Pathfinder Imager (IMP) and the proportion of rock in the mixture, calculated from the sulfur content. My research has demonstrated that although rock-soil mixing clearly takes place, the Pathfinder (and Viking) results are inconsistent with a simple two component mixing model. The basic observations leading to this conclusion are that for a number of elements, calculated mixing lines between various rock - soil and rock - rock pairs do not correspond to the linear regressions (this general conclusion is also confirmed when the recently recalibrated data are used). In order to explain the chemical variation, additional components or additional processes affecting one or both of the end member compositions, or some combination are required.

   One important implication of these findings is that care must be taken in defining a "soil-free rock" composition using linear regressions. In principle, such a composition has no geological meaning. In practice, the "soil-free rock" from Pathfinder has a composition very close to the rock samples A3 and A17 and thus mimics the composition of the lowest sulfur rocks. These results have been published in McLennan (2000; reprint attached)
2. The very strong positive correlation between MgO and SO_3 points to a control by a $MgSO_4$ mineral however, spectroscopic data continue to suggest that Fe-sulfates, notably schwertmannite and jarosite, may be important components. On a ternary plot of mole fraction SO_3-MgO-FeO_T Pathfinder rocks and soils align along a linear array (also confirmed using recalibrated APXS data). Extrapolation of calculated mixing lines suggest that $MgSO_4$-type phases dominate the variations in S content, constituting on the order of 7-10% of the soil and thus limiting the role of Fe-sulfates. Viking soil data align along a slightly different linear trend, but extrapolate to the MgO-SO_3 tie line, thus again limiting the role of Fe-sulfates in explaining the sulfur variation (also reported in McLennan, 2000).
3. In an attempt to better understand the causes of complexities in mixing relationships, the possible influence of sedimentary transport has been evaluated. The abundant evidence for aeolian transport of sand sized particles in dunes and the occurrence of deflation surfaces at the Pathfinder site suggest the likelihood of hydrodynamic separation of heavy minerals. For the Martian surface where basaltic provenance likely dominates, minerals such as ilmenite,

titanomagnetite, magnetite, and chromite are potential candidates. Fe-Ti oxide fractionation can be tested with the available geochemical data and systematic variations in TiO_2 content are consistent with concentrations / depletions of ilmenite of up to about 1.0% (based on recalibrated APXS data), values well within the range of the concentration of such minerals in SNC meteorites. Similarly, the occurrence of very fine grained iron oxides are generally thought to be present in the Martian dust (e.g., hematite, maghemite, nanophase iron oxides, etc.) and adherence of such material to surfaces is a likely phenomenon. Such a process can also be evaluated from variations in the chemical data and the chemistry of rocks and soils is consistent with up to about 6% added Fe-oxide minerals, calculated as Fe_2O_3 (also reported in McLennan, 2000).

3. A third aspect of my research has been to examine the possibility of sedimentary silica being a significant phase on Mars. Evidence for the influence of water in governing the mineralogical and chemical composition of the Martian surface is persuasive. The strong correlation between MgO and sulfur content in soils strongly suggest the presence of magnesium sulfates. Spectroscopic evidence also points to a major role for iron oxide phases in the dust and soils. For example, recent TES mapping has revealed major regions of the Martian surface in Sinus Meridiani that have substantial concentrations (>15%) of hematite and the most likely origin for such deposits involves interaction with water . Evaluation of a variety of low temperature alteration processes affecting terrestrial basalts indicates that silica is almost universally mobile. Accordingly, simple mass balance suggests that significant amounts of excess silica are likely to be present at or near the surface of Mars. Working with recalibrated APXS data calculations indicate that as much as 17% of altered basaltic material could be in the form of free SiO_2 (likely amorphous) and less than 16% amorphous silica (as surface coatings, pore/fracture filling, etc.) would be required to explain the silica 'enrichment' in Pathfinder rocks. Low temperature processes resulting in liberation of significant amounts of free silica also provide an alternative explanation for the planetary scale north-south dichotomy in TES characteristics. This work is being prepared for publication
4. On Earth, the geochemistry of sedimentary rocks has been used to constrain the chemical composition of the continental crust and an important part of my research was to evaluate this approach for Mars. The composition of the Pathfinder soils, recalculated to a S- and Cl-free basis (using recently recalibrated APXS data) are most similar to an incompatible element-enriched basalt (similar to average basaltic shergottite but enriched in Na and K). The available orbital gamma-ray spectroscopy data further confirm this and point to a Martian crust with K abundance of about 5,000 ppm (and correspondingly high Th and U). Such high abundances of heat-producing elements, coupled with known geochronology, indicates that on the order of 50% of the heat production on Mars was transferred into the crust very early in Mars' history (>4.0 Ga). This result has important implications for the geological history of Mars, including the possible role of plate tectonics, mantle convection history, and history of the magnetic field and dynamo. For example, such an early differentiation of heat producing elements into the Martian crust would make it less likely that the planet underwent early catastrophic melting as has been suggested by some thermal modeling. These results have been published in McLennan (2001; reprint attached).

Project-Related Publications

McLennan, S. M. (2000) Chemical composition of Martian soil and rocks: Evidence of complex mixing and sedimentary transport. *Geophys. Res. Lett.*, 27, 1335-1338.

McLennan, S. M. (2001) Crustal heat production and the thermal evolution of Mars. Geophys. Res. Lett., 28, 4019-4022. *(also supported by NAG5-10583 - the renewal of this grant)*

In addition, a third paper is in preparation that evaluates the possibility that sedimentary silica plays a role in the surficial processes of Mars.

Project-Related Abstracts

McLennan, S. M. (1999) Sedimentary geochemistry on Mars: Major element evidence from Pathfinder and Viking. In *Lunar Planet. Sci.* XXX, Abst. #1700, The Lunar & Planetary Institute, Houston (CD-ROM).

McLennan, S. M. (1999) Geochemical constraints on the surface (sedimentary) mineralogy on Mars. *5th International Conference on Mars*, Abst. #6148, LPI Contribution No. 972. Lunar and Planetary Institute, Houston (CD-ROM).

McLennan, S. M. (1999) Geochemical evidence for sedimentary silica on Mars. *9th V. M. Goldschmidt Conference*, Boston, p. 194-195. LPI Contribution No. 971, Lunar and Planetary Institute, Houston.

McLennan, S. M. (1999) Chemical composition of the Martian surface: A sedimentary perspective. In *Workshop on Mars 2001: Integrated Science in Preparation for Sample Return and Human Exploitation,* pp. 59-61. Lunar and Planetary Institute, Houston.

McLennan, S. M. (2000) Silica mobility during surficial processes on Mars. In *Lunar Planet. Sci.* XXXI, Abst. #1460, The Lunar & Planetary Institute, Houston (CD-ROM).

McLennan, S. M. (2001) Sedimentary geochemistry and crustal evolution on Mars. *Geol. Assoc. Canada Ann. Mtg. Abst.*, 26, 100. *(also supported by NAG5-10583 - the renewal of this grant)*

McLennan, S. M. (2001) Crustal heat production and the thermal evolution of Mars. In *Lunar Planet. Sci. XXXII*, Abst. #1349, The Lunar & Planetary Institute, Houston (CD-ROM). *(also supported by NAG5-10583 - the renewal of this grant)*

Project-Related Lectures and Public Outreach Presentations

"The Surface of Mars: From Canals to Channels - From Civilizations to Microbes" Geology Open House, SUNY at Stony Brook, Stony Brook NY, October 29, 2000.

"Sedimentary Geochemistry on Mars" Lamont-Doherty Earth Observatory, Columbia University, March 31, 2000.

"The Surface of Mars: From Canals to Channels - From Civilizations to Microbes" Twenty-first Annual Astronomy Jamboree, Custer Institute, Southold, NY, May 6, 2000.

"Relationships Between the Composition of Sedimentary Rocks and the Upper Continental Crust: Lessons for Mars?" University of Tennessee, Dept. of Geological Sciences, Nov. 9, 2000.

"Sedimentary Geochemistry and Crustal Evolution on Mars" University of Tennessee, Dept. of Geological Sciences, Nov. 9, 2000.

"Sedimentary Geochemistry and Crustal Evolution on Mars" University of Rhode Island, Graduate School of Oceanography, Feb. 16, 2001.