

**AQUEOUS ALTERATION OF ULTRAMAFIC ROCKS IN OMAN: AN ANALOG FOR UNDERSTANDING CARBONATE AND SERPENTINE ON MARS.** B.L. Ehlmann<sup>1,2</sup>, P.B. Kelemen<sup>3</sup>, P. Pinet<sup>4</sup>, J.F. Mustard<sup>5</sup>, P. Launeau<sup>6</sup>, G. Ceuleneer<sup>7</sup>. <sup>1</sup>Geological & Planetary Sciences, California Institute of Technology, <sup>2</sup>Jet Propulsion Laboratory, <sup>3</sup>Lamont-Doherty Earth Observatory, Columbia University, <sup>4</sup>IRAP/CNRS, OMP, Toulouse, <sup>5</sup>Geological Sciences, Brown University, <sup>6</sup>Laboratoire de Planétologie et Géodynamique, UMR-CNRS, Nantes, <sup>7</sup>GET/CNRS, OMP, Toulouse

**Introduction:** Both orbital investigation by the CRISM imaging visible/near-infrared (VNIR) spectrometer [1] and in-situ investigations by the Spirit rover [2] have detected Mg-rich carbonates intimately associated with a few olivine-rich igneous rock units on Mars. Imaging by Spirit shows the carbonate in the Comanche outcrop is hosted in a granular, veined rock (40 wt. % olivine; ~25 wt. % carbonate,  $Mg_{0.62}Fe_{0.25}Ca_{0.11}Mn_{0.02}CO_3$ ). Mg-carbonates viewed by CRISM from orbit are associated with heavily fractured olivine-bearing rock units, sometimes associated with serpentine [3] and possibly talc [4].

These findings suggest that the typical processes for large-scale carbonate formation on Earth, i.e. Ca- or Fe-rich carbonate precipitation from large water bodies, often biologically catalyzed, is not the appropriate analog to explain Martian carbonates. Rather, two more plausible scenarios are alteration of olivine-rich rocks under hydrothermal conditions, weathering in near-surface aqueous alteration, or both. Can future data analyses distinguish the environment in which the Martian carbonates were produced? How much carbonate could form on Mars via these mechanisms? What are the limits of our ability to find it via remote spectroscopic investigation?

**Methods:** To address these questions and support the interpretation of current and future data returned from Mars, we have begun a project of detailed remote sensing, field, and laboratory investigation of the aqueous alteration of olivine-rich rocks in Oman. In this case, the olivine-rich rocks are peridotites, variably serpentinized under hydrothermal conditions at the seafloor and then uplifted to form the Samail ophiolite complex. The rocks of the ophiolite are presently being altered to form carbonates (dominantly Mg- or Ca-rich) plus additional serpentine through both hydrothermal alteration and surface weathering [5]. Ancient Mars was likely substantially colder than Oman today and had lower atmospheric pressures. Nevertheless, there are also geochemical similarities between carbonate formation on early Mars and modern-day alteration of Oman peridotites. In both cases, fluids in contact with atmospheric CO<sub>2</sub> react with ultramafic rocks. They may provide an excellent chemical, mineralogical, and spectroscopic analog to Mars carbonates and are well-exposed over thousands of square kilometers.

Our program of study seeks to understand (1) the sequence of mineralogical changes through time as these ophiolite rocks are subject to different styles of alteration; (2) how these changes are expressed to multiple instruments that are likely to be utilized in future Mars missions, in particular VNIR reflectance characteristics at multiple spatial scales; and (3) how the effects of coatings and textures influence the detectability of secondary minerals, like carbonate and serpentine, indicative of aqueous alteration.

Our work builds on previous remote sensing investigations mapping mafic units in the ophiolite [6-9] and an ongoing project to understand the aqueous geochemical reactions and timescales of alteration [5]. We use existing airborne hyperspectral data to map zones of alteration; conduct fieldwork to field check and calibrate these data; gather outcrop-scale VNIR images with a portable hyperspectral imaging camera; and collect and analyze samples in the lab to determine their modal mineralogy (with XRD) and assess the textural characteristics of alteration (veins, rinds, coatings) and how these influence spectral properties.

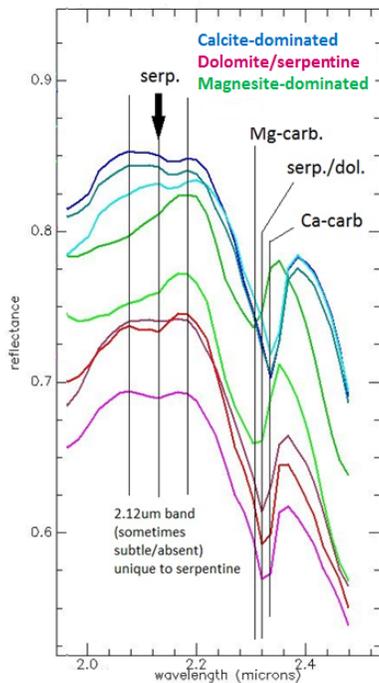
**First Results:** Samples collected in the course of [5] exhibit diverse suite of textures, including massive serpentinite, peridotite veined with magnesite at mm- to meter-scales, carbonate-cemented breccia, and travertine precipitates (Figure 1).



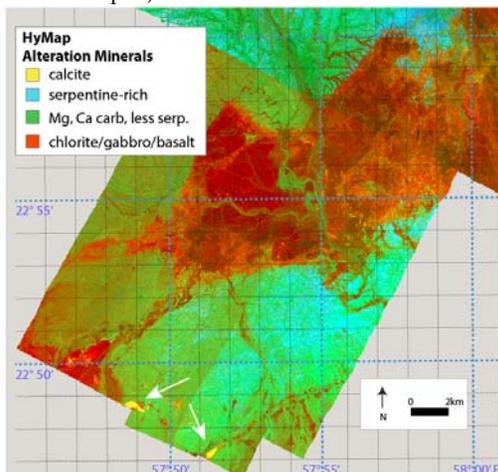
**Figure 1.** Samples measured with XRD and ASD field spectrometer data include (clockwise from upper left) magnesite-veined peridotite, peridotite fractured by magnesite precipitation, calcite-cemented breccias, and massive magnesite vein samples.

An ASD field spectrometer was used to measure VNIR properties of hand samples. Systematic variation in carbonate composition from magnesite to calcite,

checked with XRD, caused the 2.3 $\mu$ m absorption to shift from minima near 2.31 $\mu$ m to 2.34  $\mu$ m with increasing calcium content as has been observed in prior studies [10]. A small absorption at 2.12  $\mu$ m was a definitive indicator of serpentine whose stronger 2.32  $\mu$ m and 2.52  $\mu$ m absorptions were often obscured by carbonate absorption bands at the same wavelengths.



**Figure 2.** In VNIR spectra, the position of the 2.3  $\mu$ m absorption band indicates Mg- vs Ca-rich samples. An additional feature at 2.12 $\mu$ m indicates the presence of serpentine (up to 20% in this selection of samples).



**Figure 3.** HyMap color composite showing spatial variation in alteration minerals. (R: position of the 2.3  $\mu$ m minima; G: 2.3  $\mu$ m band depth; B: 2.1  $\mu$ m band depth).

The systematic variations observed in the laboratory were used with an airborne HyMap hyperspectral imaging dataset [6-9] to map variations in serpentine and carbonate across the Samail ophiolite (Figure 3). Initial efforts to groundtruth this HyMap data product

show excellent ability to distinguish calcium carbonates from the more widespread magnesium carbonates (Figure 4). This is important because the two types of carbonates form differently. Magnesite forms at depth as meteoric waters descend through the peridotite, reacting with the magnesium-rich host rock. Waters participating in serpentinization at depth lose Mg to serpentine and carbonate precipitates, produce hydrogen gas ( $H_2$ ), become highly alkaline ( $OH^-$ ), and acquire Ca from reaction with the pyroxene-bearing peridotite. Upon release of these waters back at the surface, Ca reacts with bicarbonate supplied by dissolution of atmospheric  $CO_2$  to form calcium-rich carbonates near springs [5, 11]. First results suggest that careful remote mapping of carbonate composition has the potential to illuminate the nature of subsurface geochemical reactions and groundwater flow paths.



**Figure 4.** Travertine (calcium carbonate) deposits formed by precipitation of spring waters are found at the locations mapped as calcite, and indicated with arrows, in Figure 3.

**Future work:** Continued groundtruthing efforts, trial of outcrop scale VNIR imaging and radiative transfer modeling to determine carbonate abundances, and petrographic examination of coatings and rinds that affect sample spectral properties are priorities in future work. We expect that this research project will add to understanding of the likely processes for carbonate formation on Mars and lead to better constraints on its extent and composition as mappable from orbit. Moreover, we expect that the combined remote outcrop-scale and laboratory hand-sample-scale investigations will lead to advances in techniques for relating orbital spectroscopic data to landed data and provide important lessons in support of synergistic analyses of multiple data sets from Mars.

**Acknowledgements:** This work is supported by the NASA Mars Fundamental Research program

**References:** [1] Ehlmann, BL et al., *Science*, 322, 1828-1832 [2] Morris, RV et al., *Science*, doi : 10.1126/science/1189667, 2010 [3] Ehlmann, BL et al., *GRL*, 37, L06201, 2010 [4] Brown, AJ et al., *EPSL*, doi : 10.1016/j.epsl.2010.06.018, 2010 [5] Kelemen, PB and Matter, J, *PNAS*, 105, 17295-17300, 2008 [6] Pinet, P et al, *LPSC* 37, #1346, 2006 [7] Combe, J.-P. et al. *G-cubed*, 7, Q8001, doi :10.1029/2005GC001214, 2006 [8] Roy, R. et al, *G-cubed*, 10, Q02004, doi : 10.1029/2008GC002154, [9] Clenet, H. et al., *Lithos*, 114, 265-281, 2010. [10] Gaffey, SJ *JGR* 92(B2), 1429-1440, 1987. [11] Barnes, I & O'Neil JR, *GSA Bull.*, 80, 1947-1960, 1969.