MARTIAN CLAY MINERALS FROM ORBIT TO THE SURFACE: MSL AND MER ROVER INVESTIGATIONS OF CRISM SMECTITE DETECTIONS. V.K. Fox[1], K. A. Bennett[2], R. E. Arvidson[3], B. L. Ehlmann[1,4], K. Stack[4], E. Dehouck[5], J. P. Grotzinger[1,4], T. Bristow[6], M. Salvatore[7], J. Catalano[3] [1]California Institute of Technology, Pasadena, California (vfox@caltech.edu), [2]USGS Astrogeology Science Center, Flagstaff, Arizona, [3] Washington University in Saint Louis, Missouri, [4]Jet Propulsion Laboratory, Pasadena, California, [5]LGL-TPE, Université de Lyon, France, [6]NASA Ames Research Center, Mountain View, California, [7]Northern Arizona University, Flagstaff, Arizona

Introduction: Smectite clay minerals are among the most common alteration minerals detected in ancient Martian surface materials [1–3] and are an important indicator of past aqueous conditions. If discernable, the properties of the clay minerals, particularly composition and structure, can be used to better constrain the environmental conditions in which they formed. This can inform interpretations about hydrological systems on early Mars [4]. Initial mineralogical mapping of phyllosilicate distribution developed a paradigm in which early Mars hosted an active hydrological cycle during the Noachian that gradually gave way to increasingly water-limited and acidic conditions during the Hesperian. However, further investigation of Martian clay minerals by both orbital and surface assets has demonstrated a variety of phyllosilicate-favorable aqueous alteration pathways active during both the Noachian and Hesperian periods, and shown that a synergistic approach combining information obtained at many spatial scales is critical to determining geologic context and aqueous conditions as indicated by the presence of clay minerals.

Spectral detection of clay minerals: Orbiting infrared imaging spectrometers OMEGA and CRISM have enabled detections of thousands of occurrences of smectite clay minerals on the Martian surface [1,5]. Characteristic absorptions are caused by cation-OH vibrational modes within the clay mineral structure and vary as a function of composition between 2.2 and 2.5 µm [6,7]. Most commonly detected on Mars are Fe^{3+}/Mg smectites, with key absorptions centered near 2.3 µm. Saponites (Mg-rich endmember) have an absorption shifted towards 2.31 µm whereas absorptions in nontronites (Fe^{3+} endmember) are closer to 2.28 µm. These clay minerals form readily from basaltic materials in both open and closed systems, but do not require cation transport due to fluid flow. Montmorillonite (Al-rich endmember) also occurs and is identified by a 2.2 µm absorption. Al-phyllosilicates indicate more extensive cation fractionation and are typically associated with fluid flow and leaching. Other diagnostic clay minerals, such as kaolinite, illite and chlorite, have been detected from orbit as well [5].

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) has a standard resolution of 18 m/pixel, which makes it an important bridge between orbital and surface observations, enabling mapping of mineral assemblages on the regional to outcrop scale. Mineralogy identified by CRISM, together with visual imagery, has been critical in determining landing site locations and enables comparison between disparate stratigraphic sections. Conversely, understanding local contributions of dust cover, sand, and surface texture is of key importance in interpreting the spectroscopic signatures, and in-situ exploration of areas with mineral detections provide critical context to orbital interpretations.

Mt Sharp and Curiosity: The Curiosity rover has begun characterization of the clay-bearing Glen Torridon region on Mt Sharp, where CRISM detected Fe^{3+} smectites associated with a ~15-km lateral stratigraphic exposure. Glen Torridon is just south of the hematite-bearing Vera Rubin ridge and is overlain by thick sulfate-bearing layered deposits. This mineralogical sequence suggests that the Mt Sharp stratigraphy records significant environmental change and a variety of aqueous environments on early Mars, and was a key reason that Curiosity landed in Gale Crater [8,9].

Curiosity observations of Glen Torridon show that the region is composed primarily of low-lying mounds and ridges covered in locally-sourced pebbles with only intermittent exposures of intact bedrock. Where this intact bedrock is exposed, Curiosity has observed heterolithic mudstones sometimes exhibiting alternating thin-thick couplets, and very fine sandstones exhibiting trough cross-stratification. The facies observed in Glen Torridon are consistent with facies observed previously in the Murray formation lacustrine sediments. MSL data of elemental abundances also indicate Glen Torridon targets are compositionally in family with previous Murray formation observations. Resistant

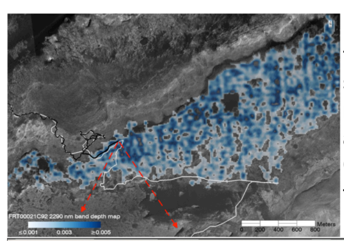

Figure 1. Left: CRISM map of Fe3+ smectites in Glen Torridon, on the northwest slopes of Mt Sharp. Below: Mastcam mosaic looking to the south (within red arrows). Regions associated with the CRISM smectite detections are in the foreground. MCAM 12542, NASA/JPL/Caltech/MSSS

knobs and ridges of cross-laminated sandstone overlie the more recessive heterolithic facies.

Elemental compositions measured by the ChemCam and APXS instruments demonstrate the intact bedrock and widely dispersed rubbly and pebble forming materials are compositionally distinct, such that the intact bedrock is enriched in MgO and the rubbly material is enriched in K. All samples have elevated CIA values consistent with increased weathering [10]. Initial results indicate that the two drilled samples (Aberlady and Kilmarie) are the most clay-mineral rich to date [11,12]. These samples are located within one of the CRISM smectite "hotspots" close to the contact with the Vera Rubin ridge, and were drilled from an isolated block of intact bedrock. Future exploration will continue to investigate how orbital signatures correlate with surface expression throughout Glen Torridon.

Endeavour Crater and Opportunity: The Opportunity Rover characterized several occurrences of smectite clay minerals while investigating the Noachian-aged Endeavour Crater. Given that at the time of exploration Opportunity lacked an explicit means of measuring mineralogy, these discoveries were dependent on the combination of orbital and in-situ observations.

On Cape York, CRISM detected a small patch of Fe^{3+} smectite clays, which rover investigation found to be be associated with fine-grained layered rocks interpreted to pre-date Endeavour Crater's formation. Nearby, Opportunity also found a fracture system with chemical evidence for Al-rich smectites as a product of chemical leaching, at a scale too small for observation by orbital spectrometers. These observations, together with cross-cutting calcium sulfate veins, demonstrated multiple iterations of aqueous fluid alteration both pre and post the Endeavour Crater impact [13].

On Cape Tribulation, 3 km to the south, Opportunity also investigated an Fe^{3+}/Mg smectite detection, confirmed using five overlapping CRISM observations, within a morphological feature cutting through the crater rim called Marathon Valley [14]. Rover compositional measurements demonstrated that the

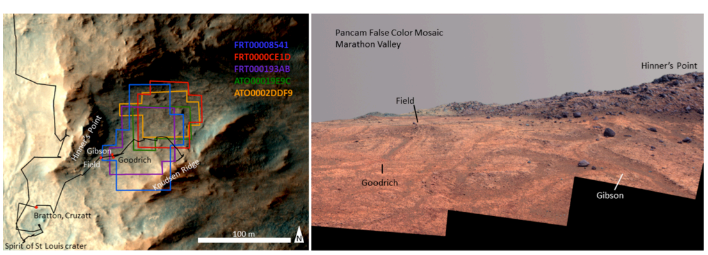

Figure 2. Opportunity exploration of smectites in Marathon Valley. Left: Pixel locations of Fe3+/Mg smectite clay minerals as detected in five overlapping CRISM scenes. Right: Pancam false color mosaic looking west from inside Marathon Valley showing the surface texture of a region where CRISM detected smectites. NASA/JPL/Caltech/MSSS

brecciated, fractured bedrock within Marathon Valley was consistent with that of the previously observed Shoemaker impact breccia formation [13], of which most of Cape Tribulation is composed, and supporting the interpretation that the Shoemaker breccia was likely pervasively isochemically altered by post-impact fluid permeation, particularly along fracture systems. That the smectite spectral signal detected from orbit was isolated within Marathon Valley was likely controlled by surface texture, dust content and bedrock exposure, as well as alteration mineral abundances[14].

Synergistic Results: In every case where a landed or rover mission explores a region identified as scientifically interesting from orbit, the added context from both scales provides reciprocal information when developing interpretations of the aqueous history of a region. In-situ observations about the outcrop expression and surface cover enable much more nuanced understanding of the orbital detections over larger spatial scales. The rubbly, broken-down surface texture in Glen Torridon, for instance, is distinct from much of the rest of the lower Mt Sharp strata and likely plays an important role in explaining why the smectite mineral signature is so clearly associated with this particular stratum, in addition to variation in the mineral abundance. Nearly every other Curiosity drill sample has contained smectite clay minerals, but rover imaging shows that the ground from which these previous samples were taken had a greater proportion of sand or dust-covered bedrock which would obscure the orbital signatures. Alteration to smectite minerals is demonstrably more widespread than the positive CRISM identifications. Similarly, the surface of Marathon Valley was windswept, and altered material within fractures was broken down into smaller stones, but from an elemental compositional perspective was non-unique. The orbital mineralogy provided critical evidence to support pervasive aqueous activity, and enabled the understanding the alteration history of Cape Tribulation as a whole. Extended to the rest of Mars, this implies the thousands of clay-mineral detections seen from orbit represent only a fraction of the true extent of aqueous alteration.

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