

**NEW SECONDARY MINERALS DETECTED BY MRO CRISM AND THEIR GEOLOGIC SETTINGS: KAOLINITE, CHLORITE, ILLITE/MUSCOVITE, AND THE POSSIBILITY OF SERPENTINE OR CARBONATE IN NILI FOSSAE.** B.L. Ehlmann<sup>1</sup>, J.F. Mustard<sup>1</sup>, J.L. Bishop<sup>2</sup>, G.A. Swayze<sup>3</sup>, S.M. Pelkey<sup>1</sup>, R.N. Clark<sup>3</sup>, R.E. Milliken<sup>4</sup>, F. Poulet<sup>5</sup>, W.M. Calvin<sup>6</sup>, S.L. Murchie<sup>7</sup>, L.H. Roach<sup>1</sup>, J.L. Griffes<sup>8</sup> and the MRO CRISM Team. <sup>1</sup>Dept. of Geological Sciences, Brown University (bethany\_ehlmann@brown.edu), <sup>2</sup>SETI Institute <sup>3</sup>U.S. Geological Survey, Denver <sup>4</sup>JPL-Caltech <sup>5</sup>IAS, Université Paris-Sud <sup>6</sup>Dept. of Geological Sciences and Engineering, University of Nevada, Reno, <sup>7</sup>JHU-Applied Physics Laboratory <sup>8</sup>CEPS, Smithsonian Institution

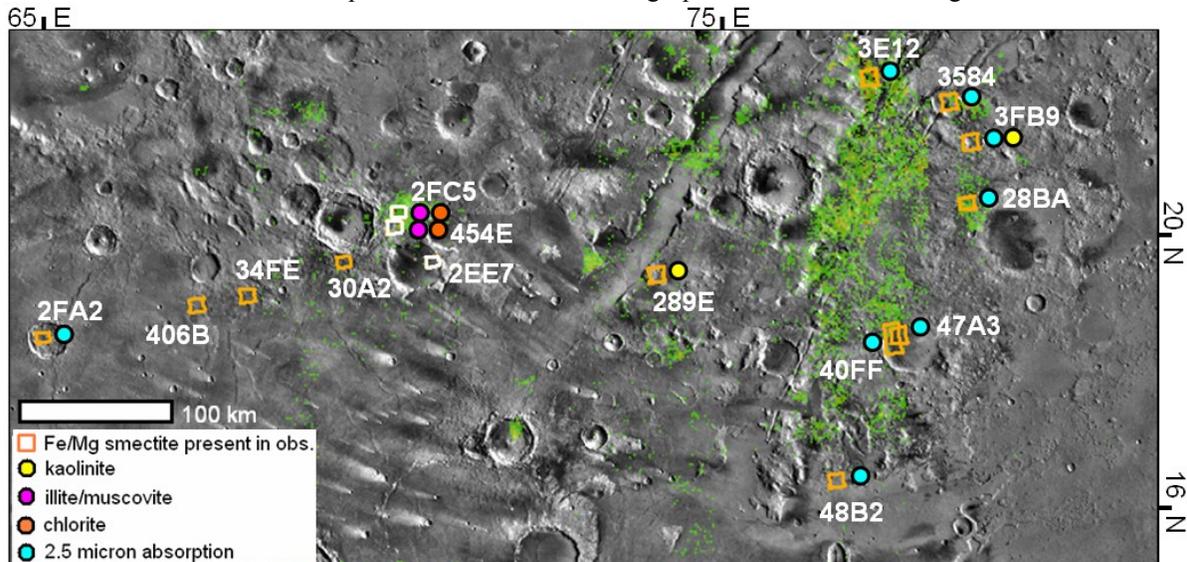
**Introduction:** The OMEGA instrument on Mars Express revealed extensive deposits of phyllosilicates, mainly associated with outcrops in ancient Noachian terrains [1,2]. These imply sustained contact of igneous materials with liquid water, likely in a moderate pH system different from the more acidic environment in which sulfates formed [2-4]. Geological relationships between phyllosilicates and unaltered ancient mafic units suggest their formation was restricted to a distinctly phyllosian era (in the early Noachian) [2,4,5-7]. A key question is the setting of phyllosilicate formation. Possible environments include: hydrothermal systems (possibly impact-related) [e.g. 8]; near-surface pedogenic processes, and deposition and precipitation of clays in standing bodies of water [e.g. 9]. We use the Mars Reconnaissance Orbiter CRISM imaging spectrometer to examine the mineralogically diverse Nili Fossae region, where phyllosilicates are associated with ancient Noachian crust, pre-dating the Isidis basin [5, 10]. Specifically, we focus on the geologic setting of new secondary minerals and what these might reveal about the alteration environment.

OMEGA revealed and CRISM confirms that Fe/Mg smectites such as nontronite and saponite are the areal-

ly dominant phyllosilicate type. In Mawrth Vallis, the Al smectite montmorillonite is also exposed at large (hundreds of km<sup>2</sup>) scale, although this is not the case in Nili Fossae [2, 5, 7]. OMEGA data analyses in Nili Fossae raised the possibility of serpentine and chlorite [5, 11] although these were difficult to confirm unambiguously. CRISM's targeted observations support a finding of additional diversity in Mars' phyllosilicate minerals down to the 15-20 m/pixel spatial resolution of the instrument [7, 12] (Fig. 1). New secondary minerals identified include kaolinite and chlorite whose detections are also supported by OMEGA [13-14] and illite/muscovite. Other spectra are potentially consistent with mixtures containing serpentine although this interpretation is tentative.

Nested CRISM, CTX (6 m/pixel) and HiRISE (25 cm/pixel) images provide a unique opportunity to examine mineralogy and geologic setting in tandem at high resolution. For each new secondary mineral in Nili Fossae, we provide spectra, maps of location, geologic exposure, and preliminary conclusions as to implications for the environment of formation.

**Methods:** CRISM is a visible/near infrared, imaging spectrometer which at highest resolution can ac-



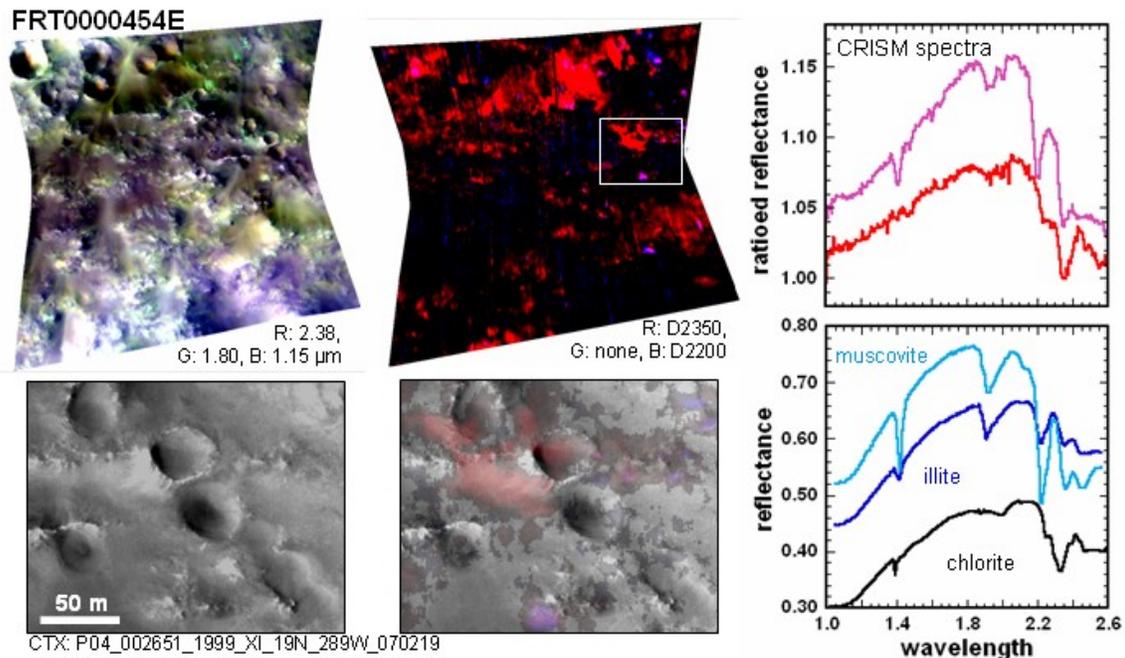
**Figure 1.** Outlines of targeted CRISM observations in the Nili Fossae region overlain on an OMEGA map of phyllosilicate based on depth of the 2.3  $\mu\text{m}$  absorption [16]. Labels are hexadecimal image ID with prefix, e.g. FRT0000\* omitted for clarity. Orange outlines indicate Fe/Mg smectites are present (white = negligible smectites). Circles indicate the presence of new secondary minerals or materials with the 2.5 micron feature (see text).

quire targeted observations at 544 wavelengths and 15-19 m/pixel [15]. Spectral data from targeted observations (Fig. 1) are used in this abstract. These are ~10 km across at the narrowest point. Data were processed to cosine-corrected I/F and then atmospherically corrected using an elevation-scaled atmospheric transmission spectrum derived from observations of Olympus Mons [as in 1]. Areas with diagnostic spectral signatures were identified using maps of spectral summary parameter values [16], and representative spectra from these surface units were collected. Spectra of interest were ratioed to similar albedo, spectrally bland pixels in the same column to highlight spectral features.

**Overview of findings:** Phyllosilicates are widespread, found in 14 of 15 CRISM scenes examined in Nili Fossae (Fig. 1). The lone exception is HRS0002EE7, which is dominated by high calcium pyroxene bearing flows from Syrtis Major. The phyllosilicate exposures are often areally small, and thus CRISM finds phyllosilicate exposures at sub-OMEGA pixel scale. In 12 images, Fe/Mg smectites such as nontronite and saponite are present and are usually the dominant secondary mineral, identified based on 1.4, 1.9, and 2.28-2.32  $\mu\text{m}$  absorption features. In two images acquired near a 50 km impact crater, phyllosilicates more consistent with chlorite dominate; and illite or muscovite is present as well. There are also small (<1 km<sup>2</sup>) exposures of kaolinite in two geographically separate scenes, FRT0000289E and FRT00003FB9. Particularly in the eastern part of Nili Fossae, a 2.5  $\mu\text{m}$

absorption feature is present in some spectra. Spectra with the 2.5  $\mu\text{m}$  absorption along with Si glass-like spectra are also seen within a crater to the west of Nili Fossae (HRS00002FA2), identified by [17] as having TES spectra consistent with quartzfeldspathic materials. Below, each new secondary mineral and the mineralogic significance of the 2.5 micron absorption is considered.

**Chlorite and illite/muscovite:** West of Nili Fossae near a 50 km crater, chlorite is the dominant phyllosilicate. In CRISM image FRT0000454E, there are numerous fresh craters (<100 m) in the north of the scene and degraded craters to the south (Fig. 2). Chlorite is identified based on a strong absorption feature at 2.34  $\mu\text{m}$ , a shoulder at 2.26  $\mu\text{m}$ , and minor to absent absorptions at 1.4 and 1.9  $\mu\text{m}$ . In a few locations, there is a different spectral signature with prominent 1.4, 1.9, 2.2, and 2.35  $\mu\text{m}$  absorptions, characteristic of either illite or muscovite. Distinction between the two is difficult given the similarity of the library spectra, although the greater depth of the 1.4 relative to the 1.9  $\mu\text{m}$  feature slightly favors muscovite, perhaps in a mixture with chlorite. Mapping shows that chlorite is found near small craters and in topographically higher ridges, probably degraded crater rims. The strongest signatures are associated with fresh craters. Tails of chlorite-rich debris extending from higher areas suggest mass-wasting. Fading of signatures with distance from outcrops suggests covering by dust and sands or removal by



**Figure 2.** CRISM image FRT0000454E is dominated by phyllosilicates (yellow/green in RGB composite) and pyroxene (blue/purple). Spectra and maps of the depth of absorptions at 2.35 and 2.20  $\mu\text{m}$  reveal chlorite (red) is spatially the most abundant phyllosilicate with a few outcrops of muscovite or illite (magenta). Phyllosilicate detections overlain on CTX indicate an association with craters.

winds. Illite/muscovite is found in isolated patches in small topographic high points with bright material.

**Kaolinite:** OMEGA detects kaolinite near 32 S and 102 E [13, 14], and CRISM detects kaolinite in two scenes in Nili Fossae. In scene FRT00003FB9, the doublet at 2.2  $\mu\text{m}$  can be resolved in 7 distinct locations. Spectra have characteristic absorptions at 1.41, 1.91, 2.164, and 2.205  $\mu\text{m}$ . In this scene the dominant surface materials are olivine sands and a spectrally bland unit (Fig. 3). Phyllosilicates are exposed intermittently from beneath the rocks of the bland unit and beneath the cover of sand. Kaolinite is in the uppermost phyllosilicate unit which sometimes appears layered (left blue patch in HiRISE of Fig. 3). It overlies a unit of Fe/Mg rich smectites which is often eroded into a rough texture. The smectites have absorptions at 1.4, 1.9, and 2.31  $\mu\text{m}$  and overlie a polygonally fractured unit which in many places has a 2.5  $\mu\text{m}$  absorption in addition to 2.3  $\mu\text{m}$  (discussed further in the next section). The contact between the smectites and 2.5  $\mu\text{m}$ -absorption unit is in many places indistinct, however, the texture of units is different with the former having raised ridges while the latter is flat-lying and has only <10m polygonal cracks. In all cases, the exposures of secondary minerals are no more than a 1km<sup>2</sup>.

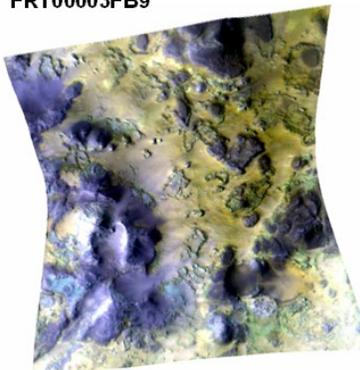
**2.5 micron feature:** Some materials with phyllosilicate-like absorptions at 2.30-2.31  $\mu\text{m}$  have an additional absorption from 2.50-2.52 (Fig. 3 and 4). In phyllosilicates within and near a fan in a crater (FRT000047A3 and HRL000040FF) [18], materials

with a 2.5  $\mu\text{m}$  feature are the dominant secondary mineral. In most cases, however, the 2.5 feature is restricted to a few isolated locations as in FRT00003FB9 and FRT00003E12 (Fig. 3 and 4). In FRT00003E12 [7], a spectrally bland rock unit with a thin olivine layer at its base and olivine sand dunes overlie Fe/Mg smectites. In small exposures (<0.5 km<sup>2</sup>) are materials with the 2.5  $\mu\text{m}$  feature with spectra different from surrounding smectites and olivine (Fig. 4). Based on examination of existing library spectra, three interpretations of this feature were considered:

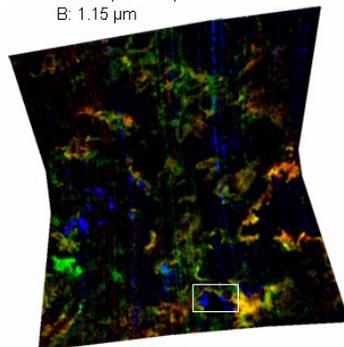
**Carbonate:** Fe/Mg carbonates such as siderite and magnesite have narrow absorption features at 2.3 and 2.5  $\mu\text{m}$  and a broad absorption between 1.0 and 1.5  $\mu\text{m}$ . CRISM spectra shortward of 3  $\mu\text{m}$  are largely consistent with these features. CRISM spectra also have an absorption at 1.9  $\mu\text{m}$  not seen in carbonate. This absorption could result from a physical mixture of smectites and carbonate materials, with the smectites contributing the strong hydration signature. However, carbonates have strong overtone bands at 3.4 and 3.95  $\mu\text{m}$ , and these are not observed in the CRISM data. This indicates the 2.5  $\mu\text{m}$  feature is due to a different mineral.

**Ferrosaponite:** Fe/Mg smectites are sometimes observed to have a 2.5 micron band either in volcanic terrains [19] or when dehydrated at T>200°C [20] so that the masking influence of the 3  $\mu\text{m}$  water band is removed. However, the 2.5  $\mu\text{m}$  feature is usually accompanied by an equally strong 2.4  $\mu\text{m}$  feature and a 1.4

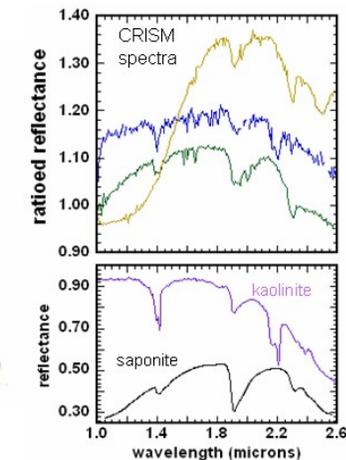
FRT00003FB9



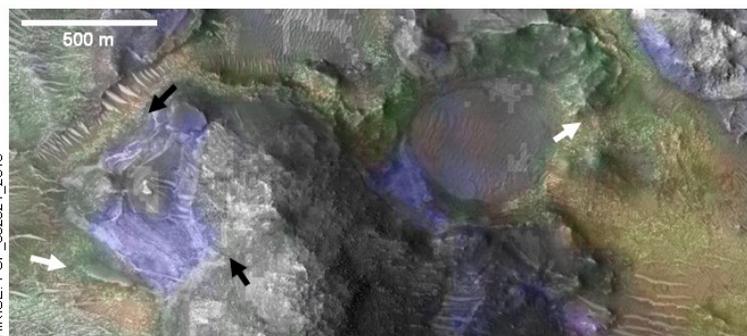
R: 2.38, G: 1.80,  
B: 1.15  $\mu\text{m}$



R: BD2500, G: D2300, B: BD2200



**Figure 3.** CRISM image FRT00003FB9 surface materials include olivine sands (yellow in RGB composite), a spectrally neutral unit (purple), and phyllosilicates (green, cyan). Spectra and band depth maps reveal three phyllosilicate types. Combining CRISM parameter maps with HiRISE shows kaolinite (depth at 2.2  $\mu\text{m}$ , blue) beneath the bland unit and above an Fe/Mg smectite unit (depth at 2.3  $\mu\text{m}$ , green) (black arrows). The smectite unit overlies a polygonally fractured unit with 2.3 and 2.5  $\mu\text{m}$  absorptions (yellow; white arrows). In both spectral plots the smectite and kaolinite spectra are of similar albedo and have been offset for clarity.



HiRISE: PSP\_002321\_2015

$\mu\text{m}$  feature. The 2.4 band is extremely weak and the 1.4  $\mu\text{m}$  band is absent in CRISM data but the possibility of masking both of these in a mineral mixture cannot be discounted.

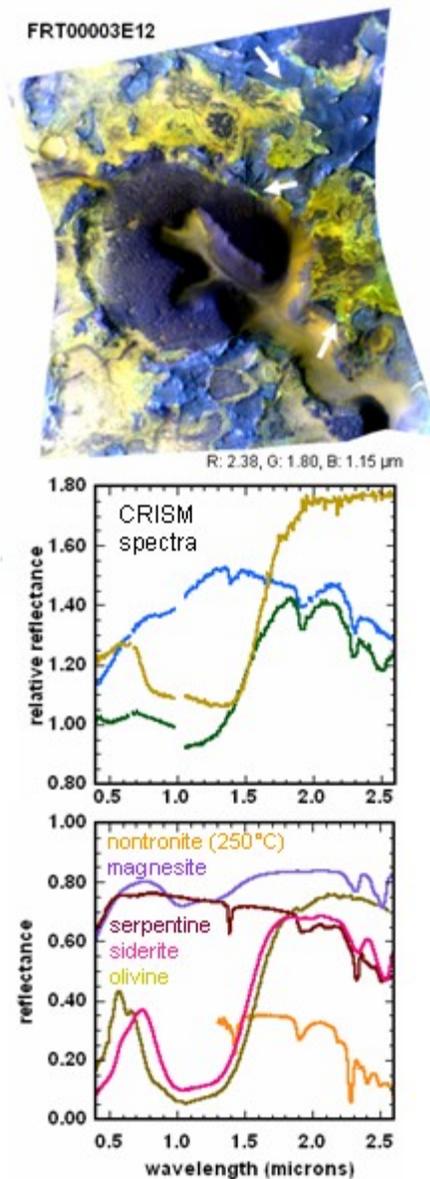
**Serpentine:** A third possibility is a mixture containing serpentine. The general shape of the serpentine spectrum is not very consistent with the CRISM spectra from 0.4 to 2.6  $\mu\text{m}$ . Serpentine has no broad absorption short of 1.5  $\mu\text{m}$  and does have a narrow absorption at 1.4  $\mu\text{m}$  due to structural OH which is absent in the CRISM data. However, serpentine also has characteristic absorptions at 2.3 and 2.5  $\mu\text{m}$ . Spectra of iron-rich serpentine may provide a good fit [5] to these features and olivine has a broad absorption at 1.0  $\mu\text{m}$  which could serve to mask a 1.4  $\mu\text{m}$  band. A serpentine-olivine mixture could represent simple physical mixing or partial alteration of an olivine parent mineral to serpentine.

**Implications:** (i) Illite/muscovite and chlorite are consistent with pedogenic or hydrothermal processes. The geology of the region with these minerals is extremely complex due to superposition of ejecta from multiple craters. Ongoing work examines ejecta and interiors of nearby craters to find additional exposure of these minerals. (ii) Predominance of smectite clays on Mars rather than kaolinite has been used to argue for limited abundance of water or length of weathering processes. While CRISM and OMEGA-detected kaolinite deposits are not extensive, their presence suggests that, locally, the action of water in pedogenic or hydrothermal processes may have been more intense than observed regionally. (iii) At present, we cannot conclusively determine the origin of the 2.5 micron feature. However, it is interesting that, regionally, the high resolution CRISM images with the 2.5 micron feature are co-located in areas with the highest olivine concentration on the planet, adjacent to the Isidis basin [21-23]. The mineralogy and geologic setting of secondary minerals discussed herein will continue to be refined as new MRO images are acquired and as more detailed analyses of calibrated CRISM spectra are undertaken.

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**References:** [1] Bibring, J-P et al. (2005) *Science*, 307, 1576-1581. [2] Poulet F. et al. (2005) *Nature*, 438, 623-627. [3] Gendrin, A. et al. (2005) *Science*, 307, 1587-1591. [4] Bibring J-P et al. (2006) *Science*, 312, 400-404. [5] Mangold N. (2007), *JGR*, in press. [6] Loizeau, D. (2007), *JGR*, in press. [7] Mustard, J.F. et al. (submitted) *Science* [8] Hagerly, J.J. and Newsom, H.E. (2003) *MAPS* 38(3), 365-381. [9] Velde, B., ed. (1995) *Origin and Mineralogy of Clays*, Springer, Berlin, 1995 [10] Mustard J.F. et al. (2007) *JGR*, in press. [11] Poulet, F. et al. (2005) *LPSC abs.* #1819. [12]

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**Figure 4.** In FRT00003E12 spectrally bland rock materials (purple) and olivine sand dunes (yellow) overlie phyllosilicates (blue). There are a few small exposures of materials with a 2.5 micron absorption (green, arrows). Library with a 2.5 micron feature are included as well as a nontronite dehydrated at 250°C. Nontronite spectrum is from [20]