ONSET OF METAMORPHISM IN THE MARTIAN CRUST. H. Y. McSween[1], B. C. Hahn[1], C. E. Viviano[1], and J. Moersch[1], [1]Planetary Geoscience Institute and Department of Earth & Planetary Sciences, University of Tennessee, Knoxville, TN 37996, mcsween@utk.edu.

Although most of the Martian surface is covered with basalts [1], OMEGA and CRISM spectra demonstrate that the crust contains abundant phyllosilicates and other secondary minerals [2] and may be metamorphosed [3]. Remarkable progress has been made in identifying alteration minerals and placing them into geologic context [e.g. 4, 5]. Diagnostic VNIR spectra are usually used to identify a single dominant mineral in each pixel or pixel group. Although individual minerals can provide insights into formation conditions, mineral *assemblages* provide more rigorous constraints. Spectroscopy, however, cannot identify all the phases present, especially if they have no diagnostic spectral features or are in low abundance. Comparison with what is known about low-grade metamorphism of basalts may allow further insight into minerals not yet identified by remote sensing, the compositions of protoliths, and the conditions of alteration.

A comprehensive CRISM study of the Nili Fossae region [5] provides sufficient mineralogical information to investigate protoliths and the metamorphic field gradient. We will assume that minerals found in the same general area constitute an assemblage. Craters west of Nili Fossae contain analcime, smectite (saponite?), and chlorite. Farther east, rocks contain chlorite, prehnite, and possibly pumpellyite (the latter is spectrally similar to chlorite and was not identified by [5], but was suggested by radiative transfer modeling [4]). Amorphous silica occurs widely, and illite/muscovite occurs locally.

The zeolite analcime is only stable at temperatures <180 ^{o}C, and its presence indicates pre-metamorphic (diagenetic) conditions. The reaction analcime + quartz = albite occurs at P <3 kbar. Albite cannot be detected using VNIR spectra, but a global assessment of feldspar compositions from deconvolutions of TES spectra [6] indicates that the average plagioclase composition in the western Nili Fossae region (An_{60}) is more sodic than to the south in Syrtis Major (An_{64}). This difference may reflect mixture of albite excavated by craters with the dominant igneous plagioclase. We thus assume that this reaction has occurred as we transition eastward.

Conditions for the assemblage smectite + chlorite + albite, inferred to occur to the east of the analcime-bearing region, are not well constrained, because smectite can persist at temperatures up to 600 ^{o}C under certain conditions. The prehnite-bearing assemblage clearly indicates metamorphic conditions. Prehnite is stable at T >200^{o}C and P <2 kbar at low XCO_2. Fig. 1 is a projection from SiO_2 and H_2O onto the plane ACF (molar end members are defined as A=Al_2O_3-Na_2O-K_2O, C=CaO-3.3P_2O_5, F=MgO+FeO+MnO); A is adjusted for feldspar, C for phosphate, and F for ferric oxide. The compositional fields for prehnite + chlorite + actinolite and prehnite + chlorite + pumpellyite are shown. Also projected are the compositions of Martian meteorites (shergottites and nakhlites) and basaltic rocks in Gusev Crater analyzed by the Spirit rover APXS [7]. Only the basaltic shergottite and Gusev basalt compositions are consistent with the occurrence of prehnite, and none of these rocks plot in the field containing pumpellyite. This suggests that the protoliths had higher C and possibly A components (more high-Ca pyroxene and plagioclase) than presently sampled Martian basalts, consistent with spectral observations of Nili Fossae that indicate basalts dominated by high-Ca pyroxene [8]. Actinolite, which Fig. 1 suggests should be present, has not been recognized; its spectra might be identified as other Mg-OH tri-octahedral minerals with similar longer-wavelength absorption features (Fig. 2b). However, spectral discrepancy may be resolved using data from the CRISM S detector, which spans the visible wavelength range (0.4-1.0 μm).

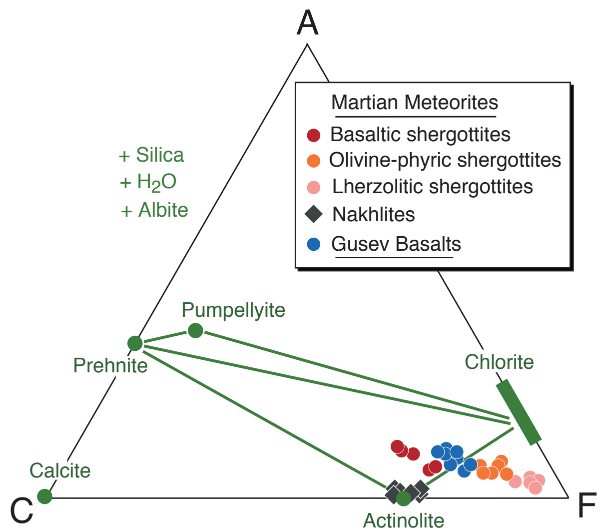

Fig. 1. ACF projection of phases identified spectrally (except actinolite) in the Nili Fossae region [4, 5]. Tie-lines connect metamorphic phases that would co-exist at equilibrium. Also shown are the bulk compositions of Martian basaltic meteorites and basaltic rocks analyzed in Gusev Crater by the Spirit rover [7].

Now consider the transition from analcime-bearing basalt to the metamorphic prehnite-bearing assemblage. A portion of the petrogenetic grid for low-grade metamorphism of mafic rocks [9, modified by 10] is illustrated in Fig. 3. Metamorphic assemblages in each field are indicated schematically by ACF diagrams. Note that the zeolite facies (ZEO = rocks bearing laumontite, whose first appearance defines the facies) is lodged between the analcime-bearing and prehnite-bearing rocks. Laumontite has not been identified in Nili Fossae, although there is spectral evidence for unspecified zeolites [5], many of which are spectrally non-unique (Fig. 2a). Next, the small prehnite + pumpellyite + chlorite stability field (prehnite pumpellyite facies, PP) tightly constrains temperature and pressure, and the absence of pumpellyite limits P to <2 kbar. Although some of these rocks may represent the prehnite actinolite facies (PA), actinolite has not been identified (as noted earlier), nor has zoisite [5] despite spectrally unique absorption features (Fig. 2c), limiting T to <230^{o}C. The common occurrence of smectite at all grades suggests that it may be a relict phase from an earlier period of weathering. Finally, the localized occurrence of illite/muscovite is inconsistent with isochemical metamorphism of basalt and suggests chemical leaching.

A Noachian (3.9 Ga) crustal geothermal gradient for the GRS pixel encompassing northern Syrtis, calculated from heat flow [11] based on measured K and Th and inferred U abundances [12], is ~12 ^{o}C/km (Fig. 4). The gradient calculation follows the method of [13]. The minimum metamorphic field gradient necessary to form prehnite or pumpellyite is ~13 ^{o}C/km, a virtually identical result. However, higher metamorphic field gradients of 17 or 20 ^{o}C/km provide more reasonable trajectories through the PP and PA facies, respectively (Fig. 4). Rocks on the estimated Noachian field gradient would reach 200 ^{o}C, required to form prehnite or pumpellyite, at ~15 km depth (Fig. 4). The 20 ^{o}C/km gradient would reach 200 ^{o}C at ~10 km depth. The diameters of craters that exposed these rocks (<50 km) may limit the maximum depth of excavation to only ~5 km. This difference suggests either significant erosional stripping of this region before cratering or a hotter gradient within a geothermal system of regional scale, possibly related to early Nili volcano magmatism. The latter may be supported by an apparent increase in metamorphic grade from west to east towards Nili Fossae.

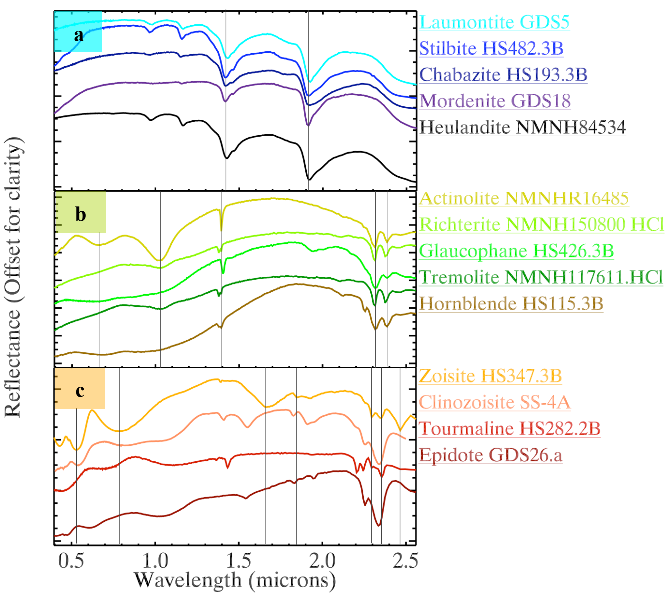

Fig. 2. a) Similarity of laumontite to other zeolite-group mineral spectra, exhibiting diagnostic 1.42- and 1.92-µm H_2O features. **b)** Actinolite laboratory spectrum with 2.31- and 2.38-µm Mg-OH absorption feature and 1.39-µm OH feature, similar to other hornblende-group minerals. Unique broader Fe^{2+} and Fe^{3+} absorption features at 0.65- and 1.02-µm. **c)** Laboratory zoisite spectrum with diagnostic 2.47-µm Al-OH feature, 2.29- and 2.35-µm Fe-OH feature, 1.65-µm OH feature, 0.78-µm Mn^{3+} feature, and 0.43- and 0.53-µm Fe^{3+} feature. Laboratory reflectance spectra from [14] and spectral absorption feature identification from [15]. Absorption features discussed are indicated by vertical black lines.

This exercise demonstrates that mineral assemblages in altered rocks can provide quantitative information about the conditions of alteration, the thermal gradient in the crust, and the compositions of protoliths. The recognition that some Martian rocks formed by metamorphism within the crust means that the minerals they contain cannot be used to assess surficial weathering processes or changes in climate.

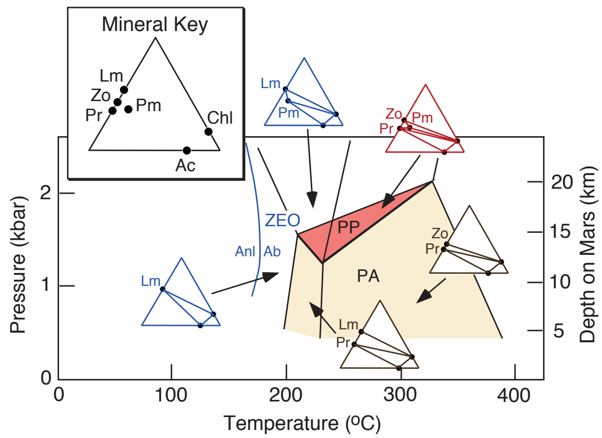

Fig. 3. Petrogenetic grid for low-grade metamorphism of mafic rocks [9, 10], showing the zeolite (ZEO), prehnite-actinolite (PA), and prehnite-pumpellyite (PP) facies. Mineral assemblages in each area are indicated by small ACF diagrams, and mineral identities are shown in the Mineral Key.

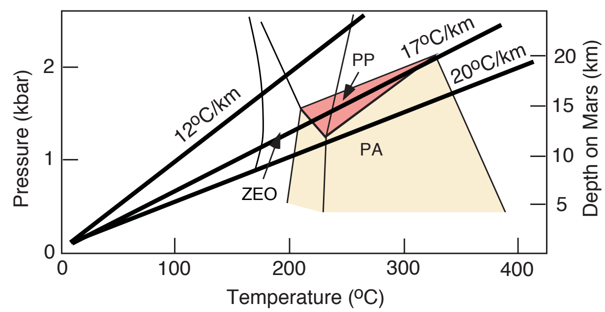

Fig. 4. Geothermal and metamorphic field gradients: The 12 ^{o}C/km geothermal gradient is calculated from crustal heat flow for Nili Fossae at 3.9 Ga [11]. Hotter gradients of 17 and 20 ^{o}C provide more reasonable paths through the PA and PP facies. Depths of exhumation necessary to expose these metamorphic rocks are given on the right-hand axis.

References: [1] McSween H.Y. et al. (2009) *Science* 324, 736-739. [2] Carter J. et al. (2010) *Science* 328, 1682-1686. [3] Murchie S.L. et al. (2009) *JGR* 114, E00D07. [4] Poulet F. et al. (2008) *Astron. Astrophys.* 487, L41-44. [5] Ehlmann B.L. et al. (2009) *JGR* 114, E00D08. [6] Milam K. A. et al. (2010) *JGR* 115, E09004. [7] McSween et al. (2008) *JGR* 113, E06S04. [8] Mustard J.F. et al. (2009) *JGR* 114, E00D12. [9] Liou J.G. et al. (1987) *Low-Temperature Metamorphism,* 59-113. [10] Beiersdorfer R.E. and Day H.W. (1995) *GSA Sp. Paper 296*, 5-28. [11] Hahn B. C. and MeLennan S. M. (2011) *GRL*, submitted. [12] Taylor G. J. et al. (2006) *JGR* 111, E03S06. [13] Turcotte D. L. and Schubert G. (2002) *Geodynamics*, 2nd ed. [14] Clark, R.N. et al. (2007) *USGS*, Digital Data Series 231. [15] Clark, R.N. et al. (1990) *JGR* 95, 12,653-12,680.