METAMORPHISM WITHIN THE MARTIAN CRUST, AS CONSTRAINED BY KNOWN MARS ROCK COMPOSITIONS. H. Y. McSween[1], T. C. Labotka[1], and C. E. Viviano[2], [1] Department of Earth & Planetary Sciences, University of Tennessee, Knoxville, TN 37996, mcsween@utk.edu, [2]Johns Hopkins Applied Physics Laboratory, Laurel MD 20723.

Introduction: The chemical compositions of basaltic and ultramafic rocks analyzed by Mars rovers and occurring as martian meteorites permit predictions of metamorphic mineral assemblages that would form under various conditions in the martian crust. We use a traditional approach (phase diagrams) to assess equilibrium assemblages and compare these with assemblages inferred from orbital spectroscopy of terrains thought to have formed by low-grade or hydrothermal metamorphism [1,2]. This approach allows new insights into the compositions of protoliths and the conditions of metamorphism, predicts candidate metamorphic minerals not yet identified on Mars using remote sensing techniques, and constrains past geothermal gradients in the martian crust.

Results: ACF diagrams (Fig. 1) predict equilibrium mineral assemblages for metabasalts. Known martian basaltic rock compositions (basaltic shergottites, the nakhlite parental magma, NWA 7034 breccia, Meridiani's Bounce Rock, most Gusev crater basalts, and Gale crater alkaline basalts) should produce chlorite + actinolite + albite + silica, accompanied by laumontite, prehnite, or pumpellyite, depending on temperature and pressure. These assemblages correspond to the zeolite (ZEO), prehnite-actinolite (PrA), and pumpellyite-actinolite (PA) facies (Fig. 1). Albite and silica do not project on ACF diagrams but are assumed to be present.

The generally lower Al_2O_3 contents of Mars rocks equate to lower A components, precluding the formation of zoisite (epidote) or lawsonite. Olivine-bearing shergottites have higher F components (Fig. 1) and thus should not form laumontite, prehnite, or pumpellyite; instead, they would form chlorite + actinolite + an F phase, assessed below.

The ultramafic rock compositions considered are lherzolitic shergottites (peridotites), nakhlites (clinopyroxenites), chassignites (dunites), and ALH 84001 (orhtopyroxenite); olivine-phyric shergottites are also modeled to determine their F phase. These rocks produce serpentine or talc + magnesite under conditions similar to those of metabasalts in Fig. 1. These minerals are relatively insensitive to pressure, but their temperature of formation depends greatly on fluid composition, with serpentine transforming to talc with increasing X_{CO2} (Fig. 2).

Comparison to Mars: The Noachian Nili Fossae region has been well studied and is proposed to have experienced hydrothermal metamorphism [1]. Spectroscopy provides information on one dominant mineral, but a map of adjacent mineral distributions allows mineral assemblages to be inferred. ZEO assemblages are inferred from the identification of analcime and from smectite + chlorite + silica. The assemblage prehnite + chlorite + albite + silica represents the PrA facies, although actinolite has not been identified. Serpentine [1] and talc + magnesite [3] are consistent with these metamorphic conditions, but require varying fluid X_{CO2}. Absence of brucite indicates temperatures <350 ^{o}C at low X_{CO2}.

Widespread occurrences of prehnite, chlorite, serpentine, and unspecified zeolites [2] suggest that these metamorphic conditions may be common within the martian crust.

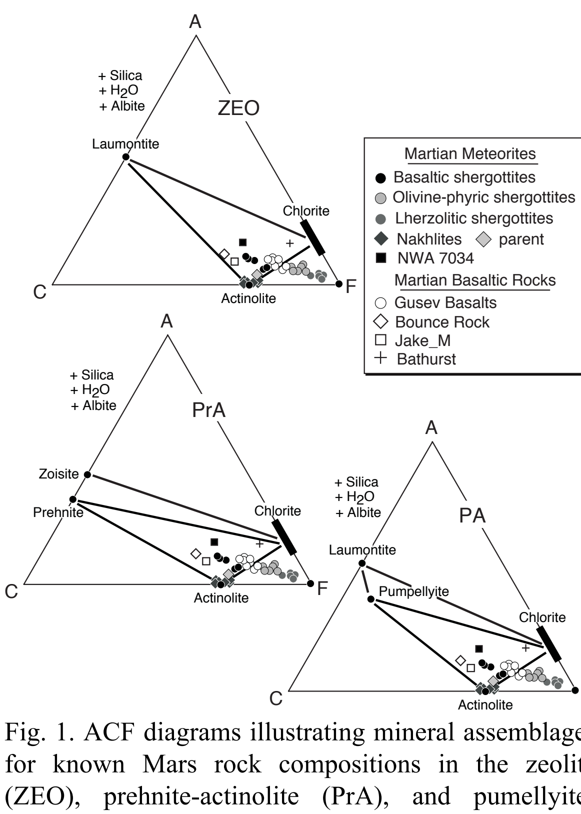

Fig. 1. ACF diagrams illustrating mineral assemblages for known Mars rock compositions in the zeolite (ZEO), prehnite-actinolite (PrA), and pumellyite-actinolite (PA) facies.

Geothermal Gradients: Noachian radiogenic heat production was 5 times greater than for present-day Mars [4], and predicting thermal gradients for specific locations is complicated by significant variations in different provinces. Previous estimates for surface heat flow correspond to gradients ranging from 14-20

°C/km, with Nili Fossae having the highest gradient. A geotherm for Nili Fossae calculated from GRS measurement of heat-producing elements, adjusted for relevant half-lives, is ~12 °C/km [4]. This gradient would never produce prehnite (shaded PrA facies in Fig. 3), but would instead form pumpellyite (Fig. 3). However, a gradient of >20 °C/km [5] would reach the PrA facies (Fig. 3). Under that gradient, prehnite would form at >12 km depth (Fig.1). The maximum sizes of craters (<50 km diameter) that expose these rocks in Nili Fossae limit the depth of excavation to ~5 km. The hotter geothermal gradients implied by these exposed rocks require an extra heat source, such as a regional hydrothermal or nearby magmatic system. Mineral assemblages formed along a lower geothermal gradient might occur within the ancient martian crust, if no other heat sources besides radioisotope decay were available.

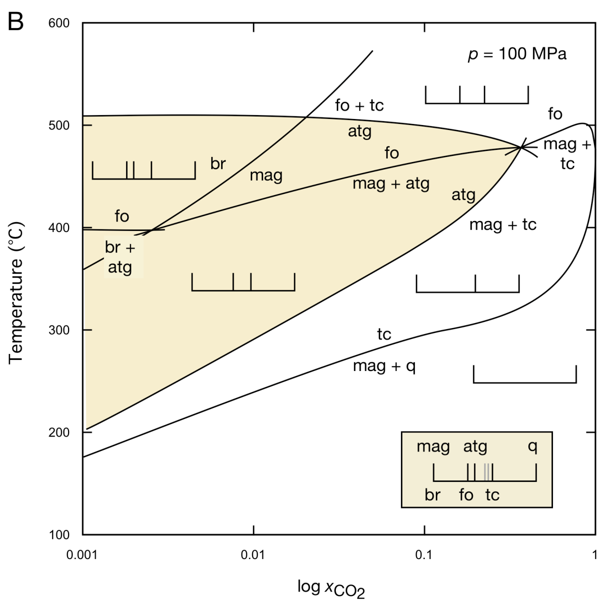

Fig. 2. Temperature vs. X_{CO2} diagram for ultramafic rocks at 1 kbar showing assemblages stable in H_2O-rich fluids. Inset shows the identities and compositions of minerals, and bars illustrate metamorphic assemblages under different conditions. Shaded region shows the stability field for antigorite.

References: [1] Ehlmann B. L. et al. (2011) *Clay & Clay Min.* 59, 359-377. [2] Carter J. et al. (2013) *JGR* 118, 831-858. [3] Viviano C. E. et al. (2013) *JGR* 118, 1-15. [4] Hahn B. C. et al. (2011) *GRL* 38, L14203. [5] McGovern P. J. et al. (2002) *JGR* 107 (E12), 5136.

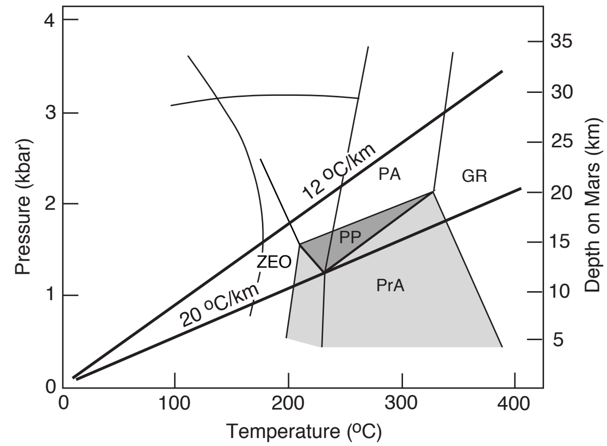

Fig. 3. Petrogenetic grid for metamorphosed basaltic rocks, showing facies and estimated Noachian geothermal gradients.