MARS MAGMATIC EVOLUTION THROUGH TIME: IS IT REAL?. H. Y. McSween[1], [1]Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996-1410, mcsween@utk.edu.

Introduction: Orbital spectroscopic analyses of martian volcanic terrains of different ages have been interpreted to reflect compositional evolution of magmas. Temporal changes include decrease in modal low-Ca pyroxene/total pyroxene [1, 2] and decrease in K contents [2, 3] from Noachian to Hesperian time (Fig. 1), and decrease in SiO_2 and increase in Th contents (Fig. 2) and decrease in Fe [4] from Hesperian to Amazonian time. Are these patterns consistent with ground-truth data from Mars rover analyses and from martian meteorites, and if so, what do they mean?

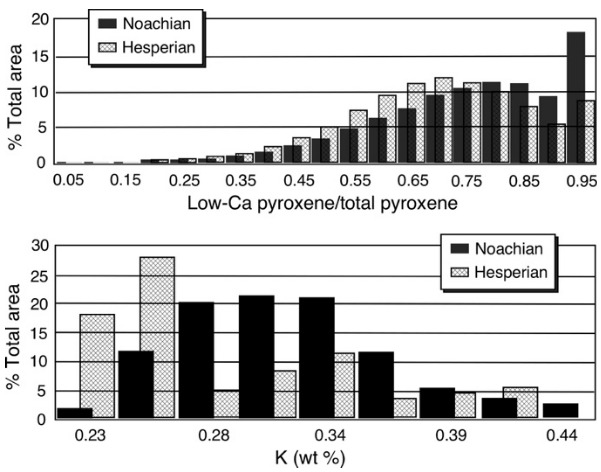

Fig. 1. Changes in the compositions of magmas from Noachian to Hesperian time inferred from remote-sensing VISNIR, TIR, and GRS data. Adapted from [2].

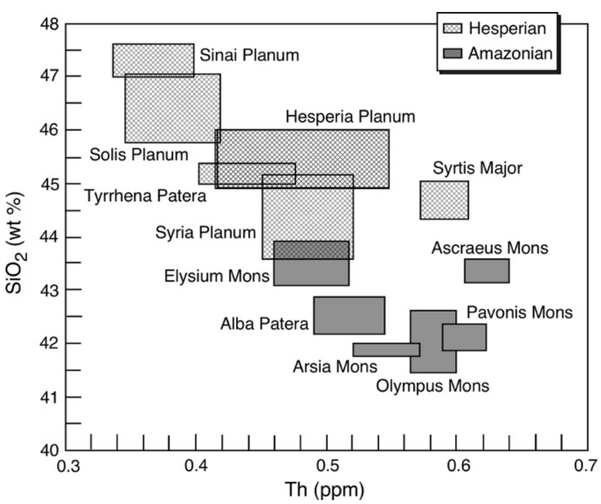

Fig. 2. Changes in the compositions of magmas from Hesperian to Amazonian time inferred from remote-sensing GRS data. Adapted from [4].

For the purposes of this comparison, the following ages are assigned to meteorites and igneous rocks at rover landing sites:

- Pre-Noachian (>4100 Ma): NWA 7034 and its pairs are the only samples of this age [5].
- Noachian (4100-3700 Ma): Igneous float rocks [6, 7] derived from Gale crater (Curiosity rover) walls likely predate crater formation in the Late Noachian. ALH 84001 (~4100 Ma) straddles the boundary.
- Hesperian (3700-3000 Ma): Igneous rocks in Gusev crater (Spirit rover) [8, 9] are Early Hesperian based on crater ages.
- Amazonian (<3000 Ma): Ages for shergottite, nakhlite, chassignite, and augite basalt meteorites span the Early to Late Amazonian period [10].

Comparison of datasets: A decrease in the ratio of low-Ca pyroxene to total pyroxene with time is consistent with most (but not all) surface samples. Low-Ca/total pyroxene ratios in Pre-Noachian NWA 7034 igneous clasts are 0.67-0.70 [5], and the Late-Noachian ALH 84001 meteorite is a low-Ca pyroxene cumulate. However, high-Ca pyroxene occurs almost exclusively in calculated norms of Late Noachian igneous rocks in Gale crater [6, 7]. Early Hesperian plains basalts in Gusev crater show low-Ca/total pyroxene ratios of 0.31-0.34, and alkaline igneous rocks in the Columbia Hills have ratios of 0.35-0.46 [11]. Early Amazonian augite basalt meteorites and Middle Amazonian nakhlites are completely dominated by high-Ca pyroxene, as predicted, but Late Amazonian shergottites contain subequal amounts of low-Ca and high-Ca pyroxenes.

A decrease in K contents of magmas with time appears to be on firmer ground. The compositions of martian meteorites and rover APXS-analyzed igneous rocks are shown in Fig. 3. The ancient (Pre-Noachian, Late Noachian, and Early Hesperian) rocks are clearly more alkaline than Amazonian meteorites (and Bounce Rock, a float rock similar to shergottites analyzed at Meridiani by the Opportunity rover). Although Fig. 3 combines K and Na oxides, a similar pattern would be observed if only K were plotted.

A decrease is silica abundance from Hesperian to Amazonian time is not obvious from inspection of Fig. 3, unless Noachian rocks from Gale crater are included. Martian meteorite compositions do extend into the picrobasalt field, so perhaps this suggests that remote-sensing has sampled more ultramafic compositions than have the launch sites for Amazonian-age meteorites. Because most Amazonian terrains are dust-covered, the orbital GRS analyses may also be contaminated.

An increase in incompatible elements like Th (Fig. 2) could reflect heterogeneous (enriched and depleted) mantle sources, as already recognized from martian meteorites [e.g. 12]. However, augite basalts and nakhlites are depleted, and shergottites are both depleted and enriched, so Amazonian samples do not show a consistent enrichment as implied by Fig. 2. Given that Pre-Noachian NWA 7034 is enriched and Early Noachian ALH 84001 is depleted, it is apparent that mantle heterogeneity was established very early.

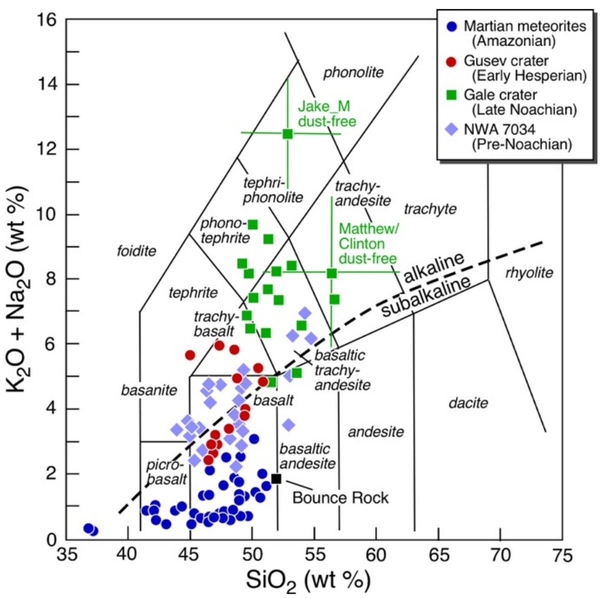

Fig. 3. Changes in the compositions of igneous rocks of various ages analyzed by Mars rovers and occurring as martian meteorites. Adapted from [9].

So are the variations real?: Ground-truth data appear to support the purported temporal evolution in alkalis and perhaps silica in martian magmas, but not the purported Th increase, as enriched and depleted meteorites formed throughout martian time. Although the variation in low-Ca/total pyroxenes inferred from orbital data is not consistently supported by studies of surface rocks, that does not mean the trend may not be not real. The surface rocks considered here represent ~9 launch sites for meteorites (known to be chronologically biased) and 2 rover sites – perhaps an unrepresentative sampling. On the other hand, it is difficult to isolate volcanic units of specific ages for orbital spectroscopy, and none of orbital measurements likely comprises a single igneous unit.

What do the variations mean?: Global convective cooling over time is plausible for Mars. A change in the proportions of low-Ca and high-Ca pyroxenes, as well as changes in SiO_2 and Th, have been predicted by a thermal model [4, 13] that assumes a homogeneous mantle with differences in magma compositions explained by an evolving thermal structure and lithospheric thickness. Magma generation has also been evaluated in terms of mantle potential temperatures calculated from martian meteorites and rover-analyzed rocks [14]. That study concluded that global cooling occurred from Noachian to Hesperian time, but a higher potential temperature during the Amazonian may represent localized plume melting.

A caveat is that a homogeneous mantle cannot readily account for the coupled variations in incompatible elements, radiogenic isotopes, and oxidation state seen in the meteorites. Furthermore, the model of [4] assumes that martian magmas are primary melts, although many martian meteorites contain 20% or more cumulus material [14]. A heterogeneous mantle [12] can potentially account for variations in source region Ca/Al (which could affect pyroxene type), silica, and alkali contents. A heterogeneous mantle also is compatible with an early magma ocean [15]; it is difficult to see how such a magma ocean could have produced a compositionally homogeneous mantle.

Conclusions: Comparison of Mars remote-sensing data with analyses of surface samples confirms that magma compositions have evolved over time, although not all changes found by remote sensing are consistently supported. These evolutionary changes likely reflect global cooling, with decompression melting acting on a compositionally heterogeneous mantle.

References: [1] Poulet F. et al. (2007) *JGR, 112,* Eo8S02. [2] Rogers A.D. and Hamilton V.E. (2014) *JGR, 120,* 62-91. [3] Taylor G. J. et al. (2007) *JGR, 111,* E03S06. [4] Baratoux D. et al. (2011) *Nature, 475,* 338-341. [5] Santos A.R. et al. (2015) *GCA, 157*, 56-85. [6] Stolper E, et al, (2013) *Science*, 341, 10.1126/science. 1239462, [7] Schmidt M.E. et al. (2018) *JGR, 123*, 1649-1673. [8] McSween H.Y. et al. (2004) *Science, 305*, 842-845. [9] McSween H.Y. et al. (2006) *JGR, 111,* E06S04. [10] McSween H.Y. (2015) *Am. Mineral., 100,* 2380-2395. [11] McSween H.Y. et al. (2008) *JGR, 113,* E06S04. [12] Borg L.E. and Draper D.S. (2003) *MAPS, 38*, 1713-1731. [13] Baratoux et al. (2013) *JGR, 118*, 59-64. [14] Filiberto J. and Dasgupta R. (2015) *JGR, 120*,109-122. [15] Elkins-Tanton L.T. et al. (2003) *MAPS, 38*, 1753-1771.