COMPOSITION AND CHEMICAL EVOLUTION OF THE MARTIAN CRUST AND MANTLE: INTEGRATING THE DATA FROM MISSIONS AND METEORITES. Scott M. McLennan, Department of Geosciences, State University of New York at Stony Brook, Stony Brook, NY, 11794-2100, U.S.A. (Scott.McLennan@sunysb.edu).

Introduction: Our understanding of the chemical composition and chemical evolution of the martian crust and mantle is now advancing rapidly. A critical challenge for the future will be the integration of the chemical and mineralogical data derived from:

1. Planetary-scale orbital missions that provide imaging, spectroscopic, geophysical and geochemical data on scales of meters to many kilometers (e.g., Global Surveyor, Mars Odyssey);
2. Localized landed missions that provide relatively good geological context but return limited varieties of geochemical data (Viking, Pathfinder and the imminent Beagle-2 and Mars Exploration Rovers);
3. Martian (SNC) meteorites that are comprehensively analyzed for petrology, geochemistry, and isotopes, but that have poorly understood geological context.

Among the most important findings over the past five to ten years, that are especially relevant to understanding martian crust-mantle evolution, are the following (by no means comprehensive):

1. Direct chemical measurements of martian rocks and soils by Mars Pathfinder that have confirmed, refined, and greatly extended previously available data from Viking [1-4]. Of special interest are the presence of high silica rocks and surprisingly high potassium contents in both rocks and soils at the Pathfinder site.
2. Thermal emission spectroscopy, while mapping the mineralogical character of the martian surface, has identified a global-scale mineralogical / chemical dichotomy approximately coinciding with the topographic break separating the heavily cratered southern (Surface Type 2) and less cratered northern hemispheres (Surface Type 1) [5]. The spectral signature of "andesite" that characterizes the northern hemisphere is controversial and has been interpreted as reflecting either a primary igneous composition [5] or as a consequence of basaltic alteration processes [6].
3. A variety of new geophysical constraints derived from orbital and landed missions. For example, data from Mars Pathfinder for the martian moment of inertia factor [7,8] constrains mass distribution (e.g., Fe content and Fe/Si) throughout the planet and combined gravity and topography data provide important constraints on crustal thickness [9].
4. Dramatically increased number of finds of martain meteorites, especially basaltic and picritic shergottites, resulting in more than doubling of the available collection. Geochemical and isotopic data that have been obtained from these samples have greatly improved our understanding of the magmatic history of Mars. It is also becoming increasingly clear that this sampling of the martian near-surface may provide an incomplete, and perhaps even seriously biased, view of the geochemistry of the martian crust-mantle system.
5. Arrival of the Mars Odyssey orbiter and especially the initiation of the mapping phase of the gamma-ray spectrometer (GRS). In addition to the well-publicized finding of widespread near surface water [10], preliminary GRS data generally have confirmed the very short-lived Phobos-2 GRS experiment [11] in showing an enrichment of the large ion lithophile elements (K, Th) in the martian crust [12,13]. Odyssey GRS also has generally confirmed the global petrological dichotomy recognized by Mars Surveyor thermal emission data [13].

Accordingly, the purpose of this paper will be to review and integrate some of these new findings and place them within the context of improved understanding of the composition and evolution of the martian crust-mantle system.

Martian Mantle: The primitive mantle (present-day mantle plus crust) of Mars generally is thought to be enriched in iron and in moderately volatile elements (e.g., K, Rb) by a factor of about two over the terrestrial primitive mantle (see Ref [14] for recent estimate). This model is based largely on the composition of martian meteorites. However, a number of recent results call into question several critical aspects of the current conventional wisdom about the martian primitive mantle. For example, the precise measure of the martian moment of inertia, obtained from the Mars Pathfinder mission [7], especially when combined with Global Surveyor gravity and topography that suggests a crust on the order of 50 km thickness [9], is inconsistent with the combination of an iron rich primitive mantle and a bulk Mars that has a chondritic Fe/Si ratio [8]. Recent experimental studies are also questioning whether an Fe-rich mantle is actually required to generate all of the SNC compositions (e.g., Ref. [15]).

The recent spate of new martian meteorite finds has also allowed us to begin to evaluate systematic geochemical variations that were simply unrecognizable when only a handful of martian meteorites were available. For example, systematic variations in REE, from patterns that are very highly LREE-depleted through to essentially flat, and Nd isotopic compositions of shergottites have been interpreted to reflect an origin by mixing of magmas derived from a highly depleted mantle source with an ancient LIL-enriched crustal component (e.g., Ref. [16,17]).

The likelihood of crust-mantle mixing is also apparent in Fig. 1 where K/Th is plotted against K content for martian meteorites and orbital GRS data (adapted from Ref. [18]). The range of K content in Pathfinder soils and rocks is also shown for comparison. There is a clear systematic relationship of decreasing K/Th ratio with increasing K abundances (similar trends are seen for K/U and K/La). The trend is also consistent with derivation of magmas from a highly depleted (low K) mantle source, with high K/Th ratios, and an enriched (high K) crustal source such as that sampled on the martian surface by Phobos-2 and Odyssey GRS [11,12] and Pathfinder APXS [3,4].

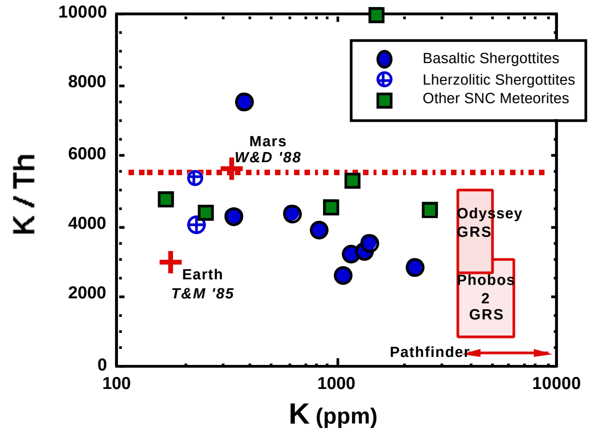

Figure 1. *Plot of K/Th vs. K for martian meteorites and the martian surface. Also shown for comparison is the range in K content for Pathfinder soils and rocks. The trend for shergottites is consistent with mixing of magmas derived from a highly depleted (low K) mantle source with an enriched crustal reservoir. There is considerable fractionation of the K/ Th (and K/U, K/La) ratio between depleted mantle and enriched crust. Any reasonable mix between these reservoirs results in a K/Th ratio considerably lower than previously suggested for the martian primitive mantle. Adapted from Ref. [18].*

An important implication of these trends is that there is considerable fractionation among highly incompatible elements between crust and mantle. Accordingly, great caution is warranted in interpreting ratios such as K/Th, K/La and K/U in terms of relatively enriched moderately volatile element content of the primitive mantle. Indeed, when the orbital GRS, Pathfinder and martian meteorite data are considered together, they suggest a martian primitive mantle that at most is only slightly more enriched in moderately volatile elements than is the Earth [18].

Although the shergottites appear to be reasonably well explained, at least to a first approximation, by mixing of depleted mantle and enriched crust, the martian primitive mantle may not necessarily fall anywhere along this trend. Assuming that refractory lithophile elements are in chondritic proportions, mass balance among all of the crust-mantle chemical reservoirs must be chondritic for these elements. Although this appears to be the case for many refractory lithophile element pairs (e.g., Th/U, La/Sm) it is not the case for all (Fig. 2) [18,19]. The element pairs, La/Th, Sm/Hf and Ba/La, are not readily balanced by the end member compositions defined by the shergottites. Mass balance calculations indicate that at least 20-30% of the REE budget of the martian primitive mantle is unaccounted for. Mantle sources sampled by nakhlites (±Chassigny) may represent this complementary mantle reservoir but this is not entirely clear (for example, it is consistent with La/Th and Sm/Hf ratios but not Ba/La ratios).

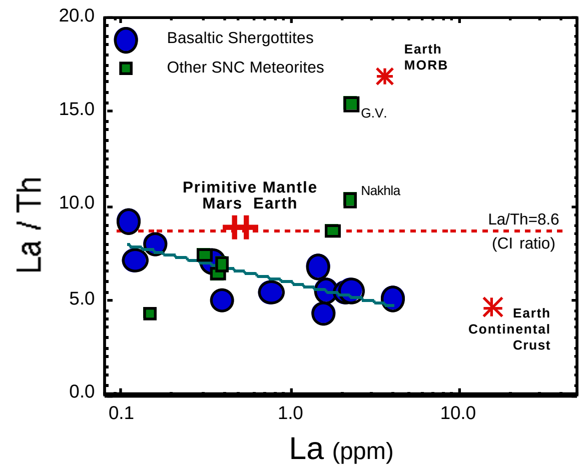

Figure 2. *Plot of La/Th vs. La for martian meteorites. The trend defined by shergottites is likely to be related to mixing between magmas derived from a highly depleted mantle source and an enriched crust. No reasonable mass balance between these reservoirs is consistent with a chondritic primitive mantle La/Th ratio and another major mantle reservoir with high La/Th is required. Nakhlites may be sampling this additional reservoir but this is not entirely clear.*

Martian Crust: Although martian meteorites indicate that magmatism has occurred periodically throughout >4 billion years of martian history, the crust of Mars appears to be mostly ancient. Essentially all of the radiogenic isotope systems, including the short-lived ones, are consistent with very early differentiation of crust-mantle-core (e.g., Refs [20-24]). Recent improvements in understanding the cratering history of the northern plains further support this notion [25]. Although there is a clear bimodality in the planet's hypsometry, superficially similar to the continental crust – ocean crust dichotomy on Earth, in detail, the surface topography differs [26] and on balance, there is no evidence for anything comparable to continental crust on Mars.

The bulk composition of the martian crust is of considerable importance but at present is not readily obtained beyond the major elements and a few selected trace elements. This situation is due to change as Odyssey GRS data begin to arrive and accumulate. Nevertheless, a variety of approaches appear to converge on a crust that is basaltic in character, but a basaltic composition that is relatively enriched in incompatible elements (including heat producing elements), perhaps similar to terrestrial hot spot volcanism [27].

Soils from the three separated Viking and Pathfinder landing sites have broadly similar composition. Geochemical relationships among soils and rocks clearly indicate that a variety of sedimentary processes, such as sorting, evaporative processes and various types of alteration, may have affected the soils (e.g., [28,29]. Nevertheless, sedimentary processes may well homogenize upper crustal martian rocks, like they do on Earth [30], and so it may be possible to extract an estimate for the exposed crust of Mars from the soil data. Since there is no evidence for substantial intracrustal differentiation processes (giving rise, for example, to granitic rocks), such a composition also may be broadly representative of the entire martian crust.

The Pathfinder data are the most reliable and complete and compare favorably with average basaltic shergottites except that they are more enriched in K and Na (Fig. 3) [27]. Although the Viking soils appear to have lower K concentrations (<1,250 ppm), perhaps suggesting regional variations in detail, the orbital GRS data (see below) appear to confirm the K-rich nature of the martian upper crust.

Both Phobos-2 and Mars Odyssey GRS data indicate considerably higher K, Th and U abundances (see Fig. 1) than seen in the martian meteorite suite. These data provide very persuasive evidence for a far more incompatible-element enriched crust than indicated by the martian meteorite suite.

Modeling of REE and Nd isotope data in martian meteorites also is consistent with a LREE-enriched martian crust [16,17]. Accepting that the shergottites reflect a mixture of magmas derived from depleted mantle that have assimilated martian crust during ascent and eruption, it is possible to constrain the REE characteristics of the crustal end member through simple mass balance calculations. The calculations have a trade-off between crustal mass and crustal REE content and are sensitive to the depleted mantle end member that is adopted. Nevertheless, within any reasonable uncertainties, the modeling indicates a LREE-enriched crust.

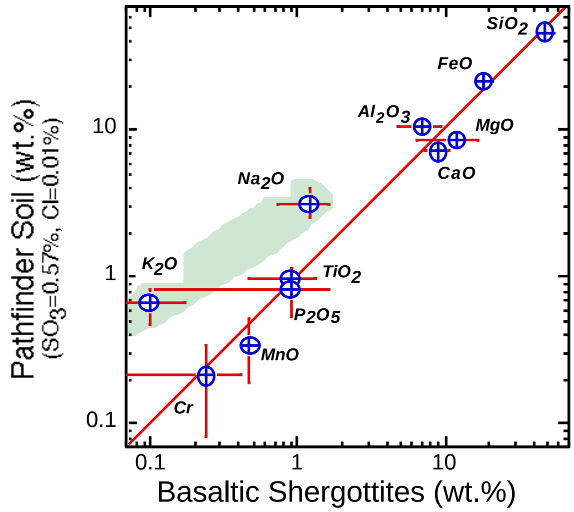

Figure 3. *Comparison of average Pathfinder soil (recalculated to S and Cl abundances comparable to shergottites) to average basaltic/picritic shergottite. "Error" bars represent one standard deviation. On average, martian soils have a bulk composition broadly comparable to typical basaltic rocks that have erupted on Mars with the exception of being greatly enriched in the incompatible elements K and Na. Adapted from Ref. [27].*

Although prone to considerable uncertainty, deconvolution of thermal emission spectra into mineralogical end members and chemical composition for both Surface Types 1 and 2 indicate relatively evolved compositions [31]. Although the interpretation of "andesite" for Surface Type 2 (northern plains) remains controversial, Surface Type 1 is more likely to relate in a relatively simple manner to martian upper crustal compositions. Although the composition may be more evolved (basalt to basaltic andesite, depending on deconvolution approach) than suggested by the soil data, the composition is characterized by high levels of alkali elements compared to martian meteorites [31].

Combining insight from these data leads to a very preliminary estimate for the composition of the martian crust that is slightly LIL-enriched basaltic in composition. Major and minor elements (Mn, P, Cr) are derived from average Pathfinder soil corrected to S and Cl contents comparable to basaltic shergottites. Potassium is derived from Phobos-2 GRS, preliminary Odyssey GRS and Pathfinder soil data. Thorium is derived from preliminary K/Th for Odyssey GRS (and consistent with Phobos-2). Uranium is taken from a chondritic Th/U ratio that is seen for all martian meteorites unaffected by terrestrial weathering processes [18]. Lanthanum is derived from a La/Th ratio of 5, as suggested from Fig. 2, and the shape of the REE pattern is derived from the modeling of Norman [16,17].

The composition so derived can be characterized by SiO_2 = 50%, K = 4,500 ppm, Th = 1.3 ppm, U = 0.35 ppm, La = 7 ppm, Yb ~ 2 ppm, Cr = 2,000 ppm.

Discussion: Such a crustal composition is only modestly enriched in LIL elements and heat producing elements. For example, the continental crust of the Earth has LIL concentrations that are more than a factor of 2 higher [30]. However, as pointed out by McLennan [27], because the crust of Mars is such a large fraction of the martian primitive mantle (3.2% for a 50 km thick crust), the effects on the mass balance of LIL and heat producing elements are very large and >50% (and perhaps much more) of these elements has been concentrated into the martian crust for most of the planet's history (Fig. 4).

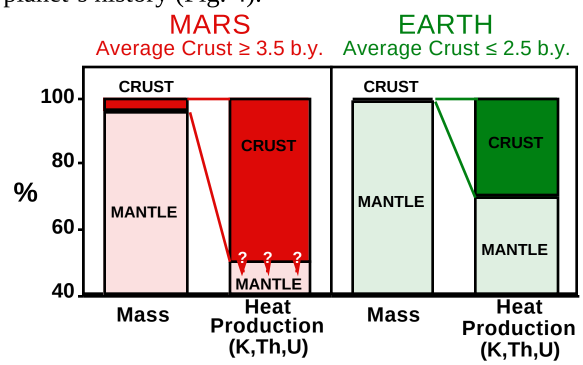

Figure 4. Comparison of the crust on Mars to the continental crust on Earth. The martian crust, at about 50 km thickness, is a much larger fraction of the planet than is the terrestrial crust. Although the concentration of incompatible elements in the martian crust is significantly less than the Earth's crust, a far greater fraction of the planetary complement resides in the martian crust and was differentiated much earlier. This contrast has considerable implications for understanding the geochemical and thermal evolution of Mars.

Such profound differences in the timing and scale of LIL and heat producing element transfer into the outer portions of Mars compared to the Earth have important implications for the thermal and tectonic evolution of Mars. A number of workers have begun to address such issues in thermal modeling (e.g., Ref. [32]) but more work is needed.

It is also worth pointing out that because the crust has such a large component of incompatible elements, understanding the chemistry and differentiation processes of the remaining mantle may be very difficult. For example, the modeling of Norman [16,17] and others only considers a three-end member crust-mantle system (primitive mantle – depleted mantle – crust). However, trace element systematics of martian meteorites (e.g., Fig. 2; Ref. [18,19]) indicate an additional reservoir that may contain up to 30% of the LREE budget of Mars. Thus, the depleted mantle sampled by shergottites, while perhaps being volumetrically dominant, may contain a relatively small fraction of the incompatible trace elements of Mars.

A major conclusion that comes from integrating the data now available from missions and meteorites is that many aspects of our current understanding of crust-mantle geochemistry on Mars require revision. The ever increasing number of martian meteorite finds, and improved understanding of their petrogenesis, coupled with the flood of mineralogical / geochemical data expected from both current and planned missions is bound to result in major strides in constraining the composition and evolution of Mars.

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