

# Crustal heat production and the thermal evolution of Mars

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**Abstract.** The chemical compositions of soils and rocks from the Pathfinder site and Phobos-2 orbital gamma-ray spectroscopy indicate that the Martian crust has a bulk composition equivalent to large-ion lithophile (LIL) and heat-producing element (HPE) enriched basalt, with a potassium content of about 0.5%. A variety of radiogenic isotopic data also suggest that separation of LIL-enriched crustal and depleted mantle reservoirs took place very early in Martian history (>4.0 Ga). Accordingly, if the enriched Martian crust is  $\geq 30$  km thick it is likely that a large fraction (up to at least 50%) of the heat-producing elements in Mars was transferred into the crust very early in the planet's history. This would greatly diminish the possibility of early widespread melting of the Martian mantle.

## Introduction

The thermal evolution of single plate planets, such as Mars, is strongly influenced by mantle convection that takes place within a 'stagnant lid' regime [Reese *et al.*, 1998; Grasset and Parmentier, 1998]. Under these conditions, thermal modeling suggests that Mars should have undergone early catastrophic melting, for which there is no evidence [Reese *et al.*, 1998]. There are effectively two solutions to this problem that allow for early release of heat from the Martian interior: Mars underwent an early phase of plate tectonics or there was a transfer of a substantial fraction of heat-producing elements (K, Th, U) into the crust [Reese *et al.*, 1998] early in the history of Mars. These alternatives, of course, are not mutually exclusive.

An early phase of plate tectonics on Mars has been suggested [Sleep, 1994, 2000; Connerney *et al.*, 1999] but there is certainly no consensus for this [e.g., Wadhwa, 2001]. In this paper, constraints on the chemical composition of the Martian crust are presented and the possibility that a substantial fraction of the heat-producing elements in Mars was transferred to the crust early in the planet's history is evaluated.

## Timing of Crust-Mantle Differentiation on Mars

Both short-lived and long-lived radiogenic isotopes ( $^{182}\text{Hf}$ - $^{182}\text{W}$ ,  $^{146}\text{Sm}$ - $^{142}\text{Nd}$ ,  $^{87}\text{Rb}$ - $^{87}\text{Sr}$ ,  $^{147}\text{Sm}$ - $^{143}\text{Nd}$ ,  $^{238}\text{U}$ - $^{206}\text{Pb}$ ,  $^{235}\text{U}$ - $^{207}\text{Pb}$ ,  $^{176}\text{Lu}$ - $^{176}\text{Hf}$ ,  $^{187}\text{Re}$ - $^{187}\text{Os}$ ) indicate that a large ion lithophile element-enriched reservoir differentiated from the primitive mantle very early in the history of Mars [Jagoutz, 1991; Harper *et al.*, 1995; Lee and Halliday, 1997; Blichert-Toft *et al.*, 1999; Brandon *et al.*, 2000]. The exact timing is less clear and generally model dependent but an age certainly in excess of 4.0 Ga and possibly approaching 4.5 Ga is most likely. Modeling isotopic data alone does not readily constrain crustal composition because, among other things, there is a trade-off between crustal mass and crustal composition [e.g., Norman, 1999]. Accordingly, within the context of the discussion in this paper, the major questions remaining are the size and overall composition of this "crustal" reservoir.

## Composition of the Martian Crust

On Earth, sedimentary materials have been used successfully to help evaluate the average composition of the upper continental crust [e.g., *Taylor and McLennan, 1985; McLennan, 2001*]. The relationships between sediments and upper crust for the major elements and many trace elements are not simple because various sedimentary processes (e.g., weathering, mineral sorting, organic/inorganic chemical precipitation) result in lithological diversity (carbonates, evaporites, sands, muds, etc.) and considerable geochemical variability within individual lithological types. A second important issue is that there is abundant evidence that the upper continental crust is considerably more felsic than the bulk continental crust due to intracrustal differentiation (partial melting, crystal fractionation) and so the upper crust is not representative of the bulk continental crust [*Taylor and McLennan, 1985*].

Neither of these issues may be as important for Mars. Although data are meager, thus far there is reasonable uniformity for sediments (soils) analyzed from three widely spaced Viking and Pathfinder sites [e.g., *Clark et al., 1982; Rieder et al., 1997*]. These materials may well have been affected by "sedimentary" processes, for example, to give rise to the exceptionally high sulfur and chlorine contents, but their relative uniformity provides at least some level of confidence that the erosional products of the Martian upper crust have been reasonably homogenized.

Although there may well be vertical differentiation within the Martian crust, it is likely to be far less profound than that seen for the continental crust of the Earth [e.g., *Taylor, 1999*]. Intracrustal differentiation of the Earth's continental crust is intimately related to plate tectonics and results in the production of abundant granitic rocks. Early suggestions of andesites on Mars [*Rieder et al., 1997*] appear far less secure with recent re-calibration of the Pathfinder geochemical results [*Brückner et al., 2001; Foley et al., 2001*] and no evidence for even more differentiated materials has been recognized. Thus, in spite of caution being warranted in extrapolating upper crustal compositions to the entire Martian crust, it provides a reasonable starting place for such discussions.

Geochemical evidence, from surface samples at the Pathfinder site [*Rieder et al., 1997; Brückner et al., 2001; Foley et al., 2001*] and orbital gamma ray spectroscopy [*Surkov, 1989, 1994*], is consistent with the Mars crust being an LIL-enriched basaltic composition on average. Figure 1 compares Martian soils at the Pathfinder site with non-basaltic (i.e., ultramafic) SNC meteorites (Fig. 1a) and basaltic shergottites (Fig. 1b). Pathfinder data are from the recent recalibration of the APXS data [*Brückner et al., 2001; Foley et al., 2001*]. The two data sets were averaged, except for Na<sub>2</sub>O, where the alpha/proton-mode data of *Foley et al. [2001]* were adopted ahead of x-ray mode data. Final compositions were also recalculated to SO<sub>3</sub> and Cl contents (0.44% and 0.01%, respectively) equal to typical SNC meteorites since high concentrations of these elements in the soils are thought to result from secondary processes [e.g., *Clark, 1993; Rieder et al., 1997; McSween and Kiel, 2000*]. SNC meteorite data were compiled from a variety of sources [*Meyer, 1998; Lodders, 1998; Dreibus et al., 2000; Rubin et al., 2000; Zipfel et al., 2000*].

There is little correspondence between soils and the ultramafic SNC meteorites but there is a very good correspondence with the basaltic shergottites apart from the soils being considerably enriched in the incompatible elements K and Na. Enriched levels of incompatible elements are also consistent with available orbital gamma ray spectroscopy (GRS). In Fig. 2, average Pathfinder soils are compared to the average of ten

overlapping regional GRS analyses collected at equatorial latitudes by the Phobos-2 mission [Surkov *et al.*, 1994]. Again, reasonable correspondence between these compositions is seen, including the high levels of K and Na. Of some interest is that the Pathfinder soils have lower levels of titanium and higher levels of iron, consistent with the hydrodynamic separation of iron and titanium oxides in the Martian soils [McLennan, 2000].

Although there are no Th or U data for Martian soils, Fig. 3 plots K vs. U and K vs. Th for SNC meteorites, GRS measurements, and various models for the Martian primitive mantle. Also shown are the average K abundances for Pathfinder and Viking soils and rocks. All of the available large-scale crustal analyses (soils and GRS) indicate high levels of HPE, with K in the range of 1,200-7,000 ppm and Th and U in the ranges of 1.4-4.3 ppm and 0.6-1.1 ppm, respectively. Accordingly, available evidence indicates that the Martian crust has a composition approximating an LIL-enriched (and HPE-enriched) basaltic composition [also see Norman, 1999], perhaps analogous to terrestrial hotspot-related basaltic volcanism.

For this study, the average K abundance of Pathfinder soils and GRS measurements, 5,000 ppm, is adopted for the Martian crust. The GRS Th and U data indicate K/U and K/Th about a factor of two lower than that proposed for the bulk composition of Mars by Dreibus and Wänke [1985], leading to relatively high crustal Th and U abundances (and high heat production). However, for this study, the K/U (20,000) and K/Th (5,600) of Dreibus and Wänke [1985] are accepted, thus minimizing the effects discussed below. This leads to Martian crustal levels of Th=0.9 ppm and U=0.25 ppm (Table 1).

## Discussion

On Earth, the continental crust, averaging 40 km thick and covering about 40% of the surface, comprises less than 0.5% of the mass of the planet. If oceanic crust is included, the overall terrestrial crust averages about 20-22 km in thickness and is less than 0.7% of the mass. In spite of the small mass, some 30-40% of the Earth's heat producing elements have been transported into the crust [Taylor and McLennan, 1985] episodically over geological time, as the continental crust has grown, but mostly during the interval of about 3.8-1.8 Ga [Taylor and McLennan, 1985].

Mars is a much smaller planet and so a crust of comparable thickness is a greater fraction of the mass of the planet. For example, a 20 km crust equates to about 1.3% of the mass of the planet and 50 km thick crust to 3.2% of the mass. Accordingly, as seen in Fig. 4, the efficiency by which the Martian crust sequesters radiogenic heat production, as a function of crustal thickness, is greater than that seen for the terrestrial crust, despite lower HPE concentrations.

The thickness of the Martian crust is now reasonably well established. Improved constraints from Mars Global Surveyor gravity and topography data suggest a minimum average thickness of 50 km [Zuber *et al.*, 2000]. In general, geophysical constraints place crustal thickness certainly between 30 and 100 km and most likely between 50 and 80 km [Nimmo and Stevenson, 2001; Turcotte *et al.*, 2001]. Norman [1999] modeled Martian crustal thickness using rare earth element and Nd-isotopic constraints from SNC meteorites and concluded that the thickness of the 'enriched' crust was likely to be between 10 and 45 km. These estimates are not necessarily in conflict since crust that is defined by geophysical constraints need not be composed entirely of 'enriched' components. From Fig. 4,

it is apparent that a 30 km thick crust, that is the composition shown in Table 1, would contain some 50% of the planet's HPE. If the Martian crust has lower K/U and K/Th than SNC meteorites (Fig. 3), as suggested by the GRS data, the Mars trend in Fig. 4 would be even steeper resulting in even greater crustal HPE enrichment.

Such a massive early transfer of HPE into a crustal reservoir may have far-reaching implications for the geological history of Mars, including the possible role of plate tectonics [e.g., Sleep, 2000], mantle convection history [e.g., Reese *et al.*, 1998], and the history of the dynamo and magnetic field [e.g., Nimmo and Stevenson, 2000]. In contrast to the Earth, where the concentration of HPE in the crust is relatively modest (<40% of planet's budget) and late (average crustal age < 3.0 Ga), on Mars it appears to be more substantial ( $\geq 40\%$ ) and early ( $\geq 4.0$  Ga). One consequence may be that the mantle of Mars may have been less likely to have undergone early widespread melting, as some thermal modeling has suggested [Reese *et al.*, 1998].

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**Figure 1.** Comparison of the chemical composition of average Pathfinder soil and SNC meteorites. Bars representing one standard deviation are shown to illustrate compositional variability. (a) Comparison between Pathfinder soils and non-basaltic SNC meteorites illustrating a poor correspondence between the compositions. (b) Comparison between Pathfinder soils and basaltic shergottites. Note that there is a good correspondence for all available elements, except K and Na, which are strongly enriched in the soils.

**Figure 2.** Comparison of ten overlapping orbital gamma-ray spectrometer (GRS) measurements and average Pathfinder soils. Note the general correspondence between these compositions, including high K and Na abundances, indicating that the available gamma-ray data are also consistent with an LIL-enriched basaltic composition for the average Martian surface.

**Figure 3.** Plots of (a) K vs. U and (b) K vs. Th for various SNC meteorites and other compositions from Mars. Primitive Mars' mantle models include: LF - *Lodders and Fegley* [1997], DW - *Dreibus and Wänke* [1985] and MA - *Morgan and Anders* [1979]. See text for other data sources. Large regions of the Martian surface (soils, GRS) indicate K abundances >1,000 ppm and mostly >4,000 ppm. GRS data also suggest significantly lower K/U and K/Th ratios than do SNC meteorites. The crustal composition for Mars, adopted in this study, is also shown.

**Figure 4.** Plot of the amount of radiogenic heat production sequestered into the crust, as a function of crustal thickness. Compositions for Earth taken from *Taylor and McLennan* [1985, in press]. Mars primitive mantle and crustal abundances taken from Table 1. Core/mantle boundary on Mars is assumed to be 1760 km. Geochemical constraints on thickness of 'enriched' crust from *Norman* [1999]; geophysical constraints on crustal thickness discussed in text.

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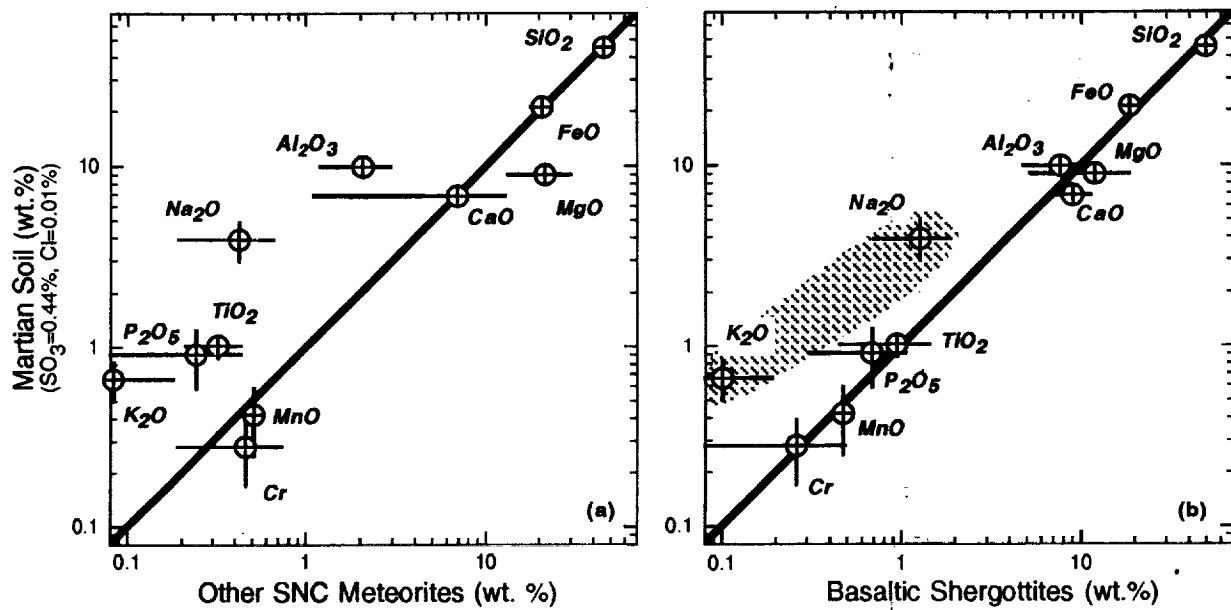
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**Table 1.** Heat producing elements in Mars and Earth

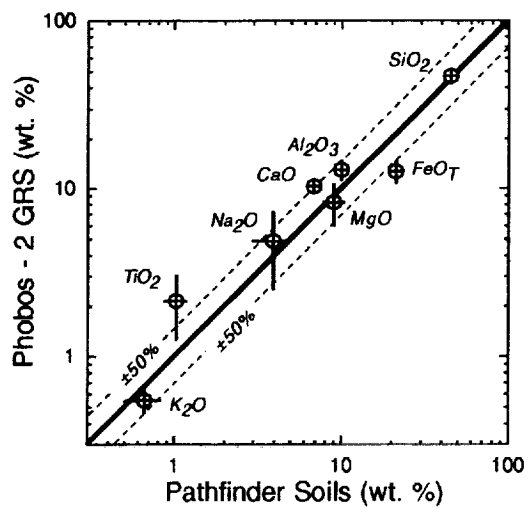
		Earth Continental Crust*	Earth Total Crust*	Mars Crust†	Mars Primitive Mantle^
K	(ppm)	11,000	8,200	5,000	315
Th	(ppb)	4,200	3,000	900	56
U	(ppb)	1,100	800	250	16
K/U	(X10 <sup>4</sup> )	1.0	1.0	2.0	2.0
K/Th	(X10 <sup>3</sup> )	2.6	2.7	5.6	5.6
Th/U		3.8	3.8	3.6	3.5

\*- *Taylor & McLennan* [1985; in press]; †- this study;

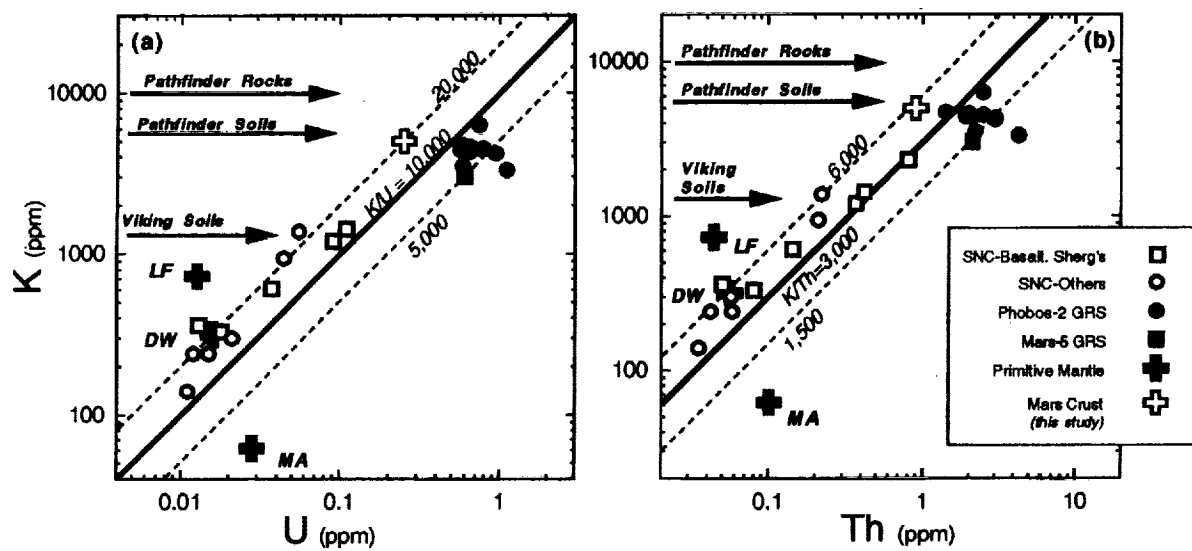
^- *Dreibus & Wänke* [1985]



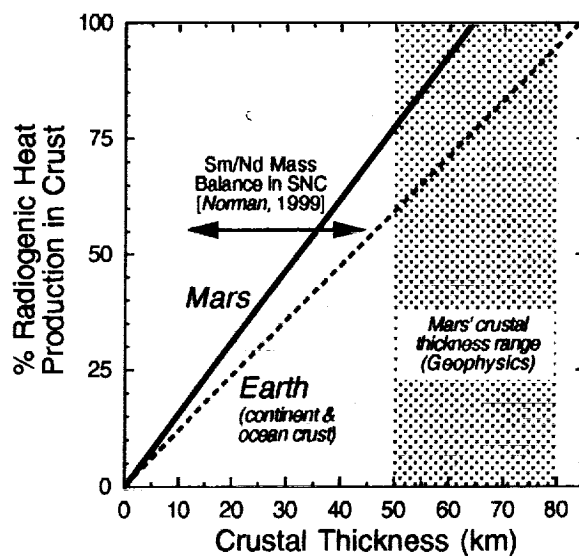
McLennan Fig. 1



McLennan Fig. 2



McLennan Fig. 3



McLennan Fig. 4