IGNEOUS AND AQUEOUS PROCESSES ON MARS: EVIDENCE FROM MEASUREMENTS OF K AND Th BY THE MARS ODYSSEY GAMMA RAY SPECTROMETER. G. Jeffrey Taylor[1], W. Boynton[2], D. Hamara[2], K. Kerry[2], D. Janes[2], J. Keller[2], W. Feldman[3], T. Prettyman[3], R. Reedy[4], J. Brückner[5], H. Wänke[5], L. Evans[6], R. Starr[7], S. Squyres[8], S. Karunatillake[8], O. Gasnault[9] and Odyssey GRS Team. [1]Hawaii Inst. of Geophys. and Planetology, 1680 East-West Rd., Honolulu, HI 96822 (gjtaylor@hawaii.edu). [2]Lunar and Planetary Lab, Univ. of Arizona, Tucson. [3]Los Alamos National Laboratory, Los Alamos, NM. [4]Inst. of Meteoritics, Univ. of New Mexico, Albuquerque, NM. [5]Max-Planck-Institü für Chemie, Mainz, Germany. [6]Computer Sciences Corp., Lanham, MD. [7]Dept. of Physics, Catholic Univ. of American, Washington, DC. [8]Center for Radiophysics and Space Research, Cornell Univ., Ithaca, NY. [9]Centre d'Etude Spatiale des Rayonnements, Toulouse, France

Summary: We report preliminary measurements of the concentrations of K and Th on Mars. Concentrations of K and Th and the K/Th ratio vary across the surface. Concentrations are higher than in Martian meteorites, suggesting that most of the crust formed by partial melting of enriched mantle. The average Th concentration (1.1 ppm), if applicable to the entire crust, implies a maximum thickness of about 65 km. The variation in the K/Th ratio suggests that aqueous processes have affected the chemistry of the surface.

Introduction: The concentrations of potassium and thorium on planetary surfaces reveal much of the story of crustal evolution. They are both incompatible elements, so they concentrate in magma. During igneous processing, the ratio of K to Th is approximately constant, so K/Th in igneous rocks reflects that ratio in the bulk silicate planet. However, aqueous processes can fractionate K from Th, in principle giving us a way to investigate the extent of aqueous alteration of a planetary surface.

Overview of Results: Date reduction techniques are described briefly in [1,2]. We present data from 45 S to 65 N only because high H concentrations at higher northern latitudes make corrections uncertain at present and because the data south of 45 S were obtained before boom deployment. K and Th are not uniformly distributed on Mars (Fig. 1-3). Some regions are richer in one or both of these elements than others. The northern plains from about 60 W to 180 E are rich in both, though the higher-than-average Th region extends much further south into the highlands. Both are generally medium to low over Tharsus, though there is a patch of higher K south of Olympus Mons. There is distinctly higher K and Th in Terra Sirenum in the region 30 to 45 S, 150 to 180 W, and in Terra Cimmeria (15 to 45 S, 150 to 189 E). The region west of Hellas contains average K, but has relatively high Th. The K/Th ratio varies widely. It is distinctly low west of Olympus Mons in Amazonis Planitia, in the region where Kasei Valles meets Chryse Planitia, in western Arabia Terra, and in Syrtis Major Planum. K/Th is high in the region surrounding and in Valles Marineris, Terra Cimmeria, and over much of Vastitas Borealis. These variations probably reflect a combination of bulk Martian K and Th concentrations, igneous processes, and aqueous alteration. We hope to deconvolve these effects, and present preliminary interpretations below.

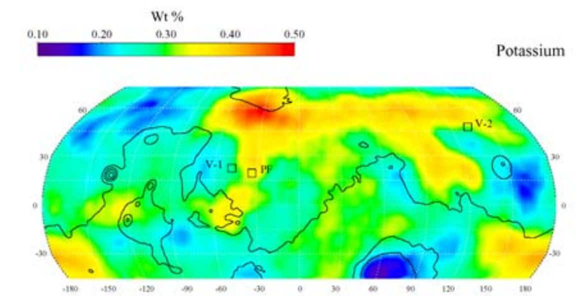

Fig. 1. K distribution on Mars. Data smoothed with 450 km boxcar filter.

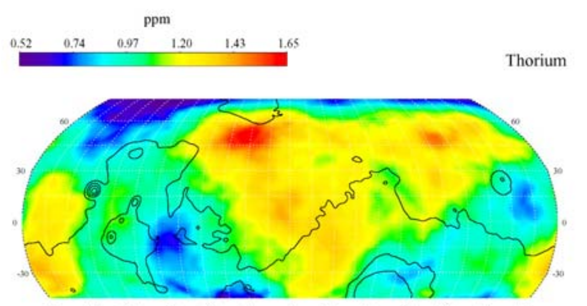

Fig. 2. Th distribution on Mars. Smoothed with 1200 km boxcar filter.

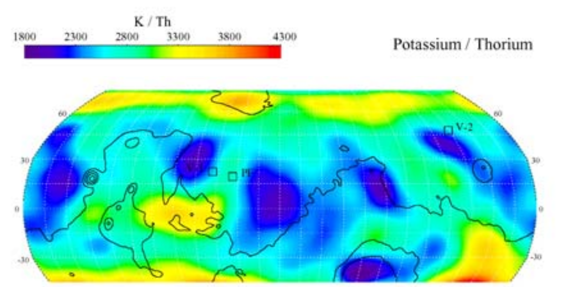

Fig. 3. K/Th varies significantly across Martian surface.

Bulk Martian Composition and Style of Primary Differentiation: K vs Th for the surfaces of Mars (unsmoothed 10-degree pixels) and the Moon (5-degree pixels[3]) is shown in Fig. 4. For a given Th content, the lunar surface contains much less K than does Mars. This reflects a large difference in K/Th in the bulk silicate portions of the two bodies, as we already knew from studies of SNC meteorites and lunar samples. The low lunar bulk K may reflect processes that operated during formation of the Moon by a giant impact [e.g., 4]. Martian meteorite data have been used to infer that Mars is enriched in moderately volatile elements such as K compared to Earth [5]. Because of the complexity of the surface, it is not yet possible to test the proposition that bulk silicate Mars has a higher K/Th than does the Earth. Nevertheless, the global data for K and Th are consistent with a somewhat higher K/Th for Mars, and Martian meteorite data clearly show that the Martian mantle was enriched in Mn and P, two other moderately volatile elements, compared to Earth [5,6].

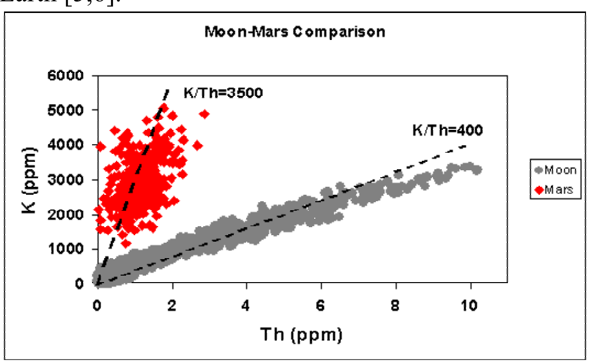

Fig. 4. K and Th variations on the lunar (5-degree pixels [3]) and Martian (10-degree pixels) surfaces. Dashed lines indicate constant K/Th ratios and are not fitted to the data.

The data in Fig. 4 can be used to probe the nature of the primary differentiation of Mars. The Moon has a much larger range in Th concentrations than does Mars. For the Moon this was caused by formation of a plagioclase-rich crust from a global magma system (called the magma ocean). Extensive fractional crystallization of the magma ocean also led to formation of materials enriched in Th and K (nicknamed KREEP). There is no evidence that extensive regions of exposed low-Th, low-K cumulates occur on Mars. Nor is there any evidence for the formation (or at least preservation) of extensively fractionalized products (the Martian equivalent of KREEP). This suggests that either a magma ocean did not form on Mars, that its characteristics (e.g., formation of garnet at its base, presence of water [7]) differed significantly from those of the lunar magma ocean, or that its products are not exposed at the surface.

Crustal Evolution and Thickness: Global K and Th concentrations are generally higher than those in SNC meteorites (Fig. 5). Assuming the surface is representative of the entire crust, this suggests that the igneous rocks in most of the Martian crust are enriched compared to SNC basaltic meteorites in incompatible elements. This is consistent with models of Martian crustal evolution [8-12] that call on enriched and depleted reservoirs. The enriched component appears to have formed early in the history of Mars [10,11,13]. The high concentrations of K and Th in the Martian crust, especially if the crust formed early in Martian history, places constraints on the extent of melting after crust formation and the total heat production on Mars [14-15].

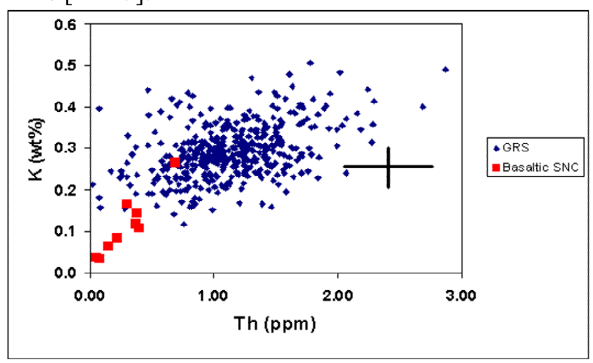

Fig. 5. K, Th variations on Mars compared to Martian (SNC) basaltic meteorites. Typical statistical uncertainty shown on right.

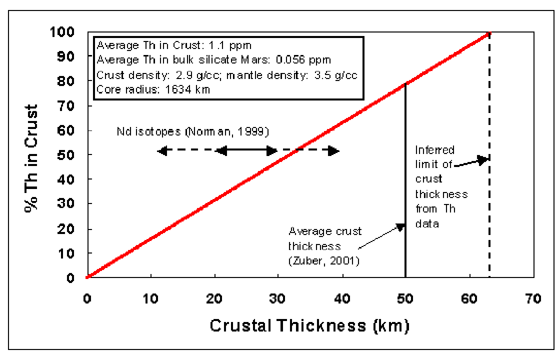

Fig. 6. Crustal Th vs. thickness of the crust.

We can use the average Th content of the surface to estimate the thickness of the crust (defined geochemically as the complement to the mantle). The average Th is 1.1 ppm. We assume that this surface average applies to the entire crust. Though not certain, there is no evidence to the contrary. Impacts early in Martian history churned over the highlands, producing a megaregolith that mixed the upper tens of kilometers of the crust, as we suspect happened on the Moon. Dust and soils might represent at least a rough average of the upper crust. Finally, lava flows exposed on the surface might be similar in composition to magmas intruded at depth.

Assuming that this applies to the entire crust and that the primitive mantle had a Th concentration of 0.056 ppm [5], we find that 100% of the Th would be in a crust 65 km thick (Fig. 6). Since 100% partitioning of Th is unlikely, this is the maximum crustal thickness. If the average crustal thickness is 50 km [16], then the crust contains about 65% of the planet's bulk Th, in agreement with Norman's [8] estimate that 50-55% of the Nd is in the crust. This level of differentiation is not greatly different from that of the Earth.

K and Th as Monitors of Aqueous Alteration: The K/Th ratio varies considerably on Mars (Fig. 3, 5). These elements behave reasonably conherently during igneous processing. Although they do vary somewhat among major groups of igneous rocks on Earth, their geochemical behavior during partial melting and fractional crystallization are very similar compared to their behavior during aqueous processing. We cannot rule out fractionation by igneous processes, especially at the extremes of fractionation [S. McLennan, personal communication]. K/Th varies among basaltic SNC meteorites (Fig.5), though not to the extent it varies in our global data set. The Moon provides an excellent example of fractionation under extensive igneous processing, and the global data obtained by Lunar Prospector indiates that K/Th is relatively constant (Fig. 4). Thus, we are pursuing the idea that the variation in K/Th is caused at least in part by aqueous processes. We hope this ratio, and U data when counting statistics improve, will be a useful tool for studying aqueous processes on a global scale.

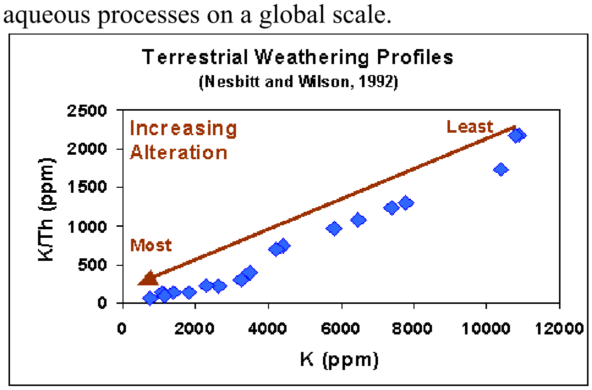

Fig. 7. Weathering of terrestrial basalt causes a depletion of K while Th remains constant, leading to reduction in the K/Th ratio.

Dissolution of K and Th depends on the solubility of the phases they are in: K in feldspar (plagioclase and K-feldspar) and volcanic glass, and Th in phosphates, volcanic glass, and possibly in other accessory phases such as zircon and monazite. Experiments and measurements of weathering profiles illustrate the different behavior of K and Th. Nesbitt and Wilson [17] studied a terrestrial weathering profile in basalt (Fig. 7). Th is resistant to transport while K is very mobile. In this example, both K and Th were concentrated in residual glass in the lava flow studied.

Dreibus et al. [18; also Dreibus and Wanke, unpublished data] did leaching experiments on the Martian meteorites. They put pulverized meteorite powders in slightly acidic, saturated solutions of Mg_2SO_4, and allowed the powders to be leached for minutes to hours. The results (Fig. 8) show that the REE and U were almost completely removed from the residue, while almost all of the K remained undissolved. They interpreted this to indicate that the leached elements were all contained in phosphates, while K was confined to plagioclase. This is another illustration that aqueous processes can fractionate K from U, and presumably from Th. (Th could not be measured by the INAA technique used, but would probably have behaved like U because it is contained in phosphates, too. Its behavior in the solutions might be very different from that of U, however.) Because P is abundant in SNC meteorites (and by inference in the Martian mantle), phosphate dissolution might be important in fractioning K from Th.

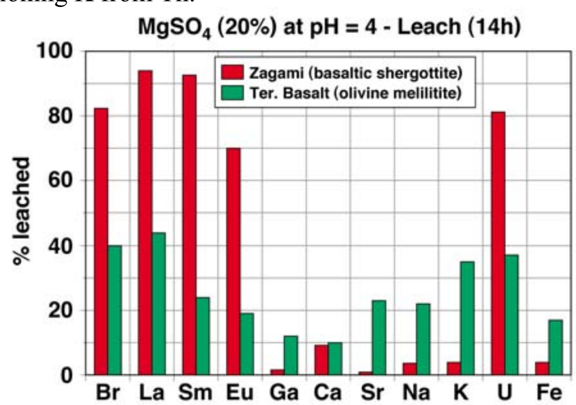

Fig. 8. Leaching experiments [18] on Martian meteorites show that mildly acidic solutions rapidly dissolve phosphate minerals, removing REE, U, and (presumably) Th from the residual solid. Terrestrial basalts may behave differently because of differences in siting of these trace elements.

Differential solubility of K-bearing phases and Th-bearing phases may have led to large-scale fractionation of K and Th, as shown in Fig. 3. The K/Th ratio and total abundances of each might serve as a monitor of global fractionation caused by aqueous processes (weathering, hydrothermal alteration, fumerolic activity, etc.). However, to use this tool, we need more experiments and detailed geochemical modeling of trace element fractionation under Martian environmental conditions.

Conclusions: Although our data should still be considered preliminary, we can make some tentative conclusions: (1) The concentrations of K and Th and the K/Th ratio vary across the Martian surface. (2) The concentrations are significantly higher than those in SNC meteorites, suggesting different mantle sources for the meteorites compared to the bulk of the crust. (3) Most of the crustal igneous rocks could have formed from enriched mantle sources. (4) The concentration of Th on Mars does not vary as much as it does on the Moon, suggesting that the primiary differentiation of Mars differed from that of the Moon. (5) If the average Th concentration of the surface is equal to the average of the entire crust, the crust cannot be thicker than 65 km. (6) The mean Th concentration is consistent with a crust 10s of km thick. (7) Aqueous processes have played an important role in the fractionation of K from Th.

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