

ASSESSING AQUEOUS ALTERATION ON MARS USING GLOBAL DISTRIBUTIONS OF K AND TH.

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Introduction: One of the prime goals of the scientific exploration of Mars is to understand the abundance, distribution, and history of water on the planet. There is abundant evidence from morphology, surface compositions at the Viking, Pathfinder, and MER sites, and martian meteorites that aqueous processes have been active, at least intermittently, on Mars. The effects of such alteration may be recorded in the elemental composition of the Martian surface. Here we focus on using K and Th data from the Mars Odyssey Gamma Ray Spectrometer (GRS) to assess the effect of aqueous processes on elemental distributions. The data reduction methods are described by *Boynton et al.* [1].

Expected Effect of Aqueous Alteration on K/Th:

It is difficult to generalize about the behavior of elements during chemical weathering. Their mobility depends on the compositions of the igneous rocks composing the crust, dissolution rates of their host phases, temperature, water chemistry, pH, and rock/water ratio (governed by water supply and rock permeability). In general, K is more mobile than Th [e.g., 2-5], as shown in Fig. 1. Within each weathering profile studied, as weathering progresses, reflected in increasing CIA, the Chemical Index of Alteration [6], K decreases and Th tends to be unchanged or even increase, resulting in decreasing K/Th. This behavior is a consequence of the high solubility of K and low solubility of ThO₂. However, the details depend on whether secondary phases precipitate, such as kaolinite to trap K or iron oxides that adsorb Th, and whether the local regolith is open or closed. In some cases K and Th are redistributed in the column of weathering rock. Patino et al. [5] argue that no element ought to be considered immobile. Nevertheless, weathering usually fractionates K and Th.

Some alteration on Mars may have occurred on the floors of lakes or the hypothetical northern ocean. The elemental concentration changes that occur during submarine basalt weathering on Earth are driven by the concentrations of elements in the ocean and seafloor basalt, temperature, and water/rock ratio. Ocean water is rich in K (about 400mg/kg [7]) and severely depleted in Th (<0.5 ng/kg). This is likely also the case on Mars; experiments [8] show that martian brines are greatly enriched in K. Thus, we would expect enrichment of K and little change in Th, as shown, by studies of altered MORB basalts [9-10]. For example, [9]

show that K/Th in altered basalt is 3 to 90 times greater than in typical unaltered MORB.

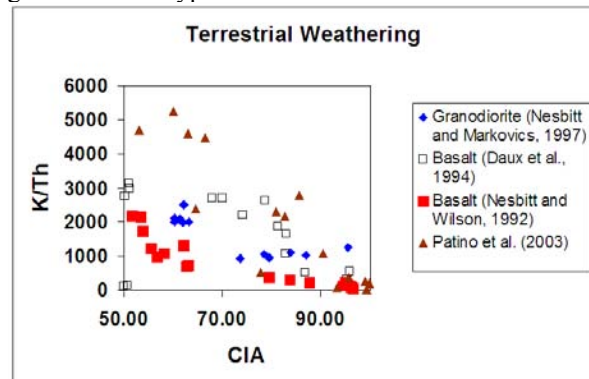


Fig. 1. K/Th decreases as the amount of weathering increases. $CIA = 100[Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)]$; see [6].

Results: K, Th, and K/Th are not uniform across the Martian surface (Figs. 2,3). The K/Th ratio varies by a factor of 2–3, but most of the surface area is between 4500 and 7000 (Fig. 2). K/Th is distinctly low west of Olympus Mons in Amazonis Planitia, in the region where Kasei Valles meets Chryse Planitia, in Arabia Terra, and in Syrtis Major Planum. K/Th is high in the region surrounding and in Valles Marineris, Terra Cimmeria, over much of Vastitas Borealis, and in the Hellas basin and in Malea Planum to the southwest of Hellas. Although K/Th varies, its variation is roughly independent of K concentration (Fig. 3).

Table 1 lists the K/Th ratio for several geologic regions representative of low, average, and high K/Th. Concentrations in these regions were determined from summed spectra. The spectra involve large counting times ($>3 \times 10^6$ seconds) and have correspondingly low statistical uncertainties. The uncertainty varies with the size of the region, hence with the total counting times in the summed spectra. The global mean (5750) provides a useful baseline for comparison. We highlight three regions with distinctly lower than average K/Th. These are Arabia Terra, the Medusae Fossae formation, and Syrtis Major. All might be sites of deposition, and the low K/Th would suggest that K had been leached from the sediments before or during transport. Two regions, the Hellas basin and Malea Planum, have distinctly high K/Th, although their small size leads to large uncertainties. The low K/Th might indicate deposition from water carrying K leached from rocks elsewhere in the highlands.

Table 1. K/Th in geologically-defined regions.

Region	K/Th
Global average	5750 ±250
Arabia Terra	5020 ±230
Medusae Fossae	5130 ±290
Syrtis Major	4620 ±420
Malea Planum	7660 ±1450
Hellas basin	7710 ±1270

^bUncertainty calculated from $(K/Th)[1 \pm ((\sigma_K/K)^2 + (\sigma_{Th}/Th)^2)^{1/2}]$, where K and Th are mean concentration of K and Th.

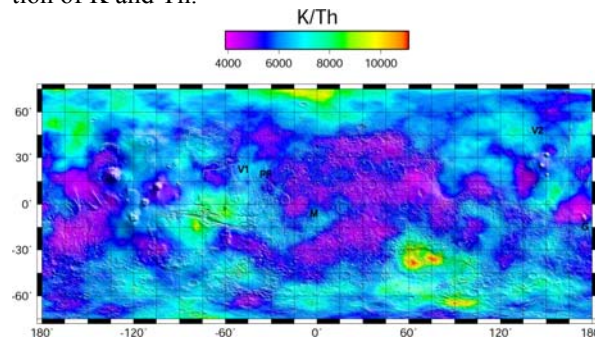


Fig. 2. K/Th variation on Mars.

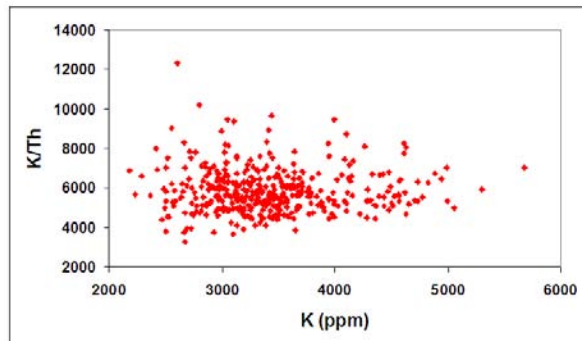


Fig. 3. K/Th and K variations; each point is a 10x10 degree resolution element.

Possible Causes of the Variation in K/Th: The variation in K/Th on Mars is modest, but distinct. Igneous processes might have caused these variations. K and Th are highly incompatible lithophile elements, so they ought to correlate strongly in igneous rocks, and in general they do. However, K/Th is far from constant. Terrestrial oceanic island basalts, for example, vary as much in K/Th (normalized to planet bulk K/Th) as do our global GRS data. The Hawaiian Reference suite [11] has normalized K/Th ranging from 0.9 to 2.3 compared to a range of 0.5 to 2.3 in our 10 x 10 degree dataset. Lunar rocks vary greatly in K/Th, and this must be due entirely to igneous processes as the lunar interior is anhydrous. Most are in the range 0.5 (normalized to the bulk Moon K/Th of about 360)

to 4. We do not know the extent to which igneous processes fractionated K from Th on Mars. SNC meteorites have normalized K/Th ranging from 0.5 to 1.9, but all but one is in the range 0.5 to 1.2. This is a much narrower range than shown by our GRS data, but it is unlikely that the SNC meteorites in our terrestrial collections are representative of igneous rocks on Mars. It is possible that all of the variation we observe is caused by igneous processes.

Impact gardening might have homogenized a closed-system weathering profile. Hartmann et al. [12] concludes that all but the youngest surfaces would have been gardened to depths of 2-12 meters. On the other hand, impact gardening would also have made the regolith prone to weathering by creating porosity and permeability, which would tend accentuate K-Th fractionation.

The modest variation in K/Th might also reflect dissolution kinetics. Using laboratory data on dissolution rates we calculated the time to dissolve feldspar and phosphates, the host minerals for K and Th, respectively. If we assume that Th is immobile and K is readily removed from the system once it is released from feldspar, then we can calculate the time it would take to begin to fractionate K from Th. At 25°C it takes 1000 years for K to begin to be leached significantly. (Phosphate minerals dissolve readily, but the released Th remains in the weathered regolith.) At 5°C it takes 5000 years for fractionation to begin. A factor of 2 decrease in K/Th takes 40,000 years. Dissolution rates determined from field studies are 100 to 10,000 times slower [13], so a significant fractionation of K/Th might take 10^6 to 10^7 years.

References: [1] Boynton, W. V. et al. (2004) *LPS XXXV*, abstract #1950. [2] Nesbitt, H. W. and R. E. Wilson (1992) *Am. J. Sci.*, 292, 740-777. [3] Daux et al. (1994) *Geochim. Cosmochim. Acta*, 58, 4941-4954. [4] Nesbitt, H. W. and G. Markovics (1997), *Geochim. Cosmochim. Acta*, 61, 1653-1670. [5] Patino, L. C. et al. (2003) *Chem. Geol.*, 202, 343-364. [6] Nesbitt, H. W. (1982) *Nature*, 299, 715-717. [7] Drever, J. I. (1997) *The Geochemistry of Natural Waters: Surface and Groundwater Environments*, Pearson Education, 436 pp. [8] Bullock, M. A. et al. (2004) *Icarus*, 170, 404-423. [9] Staudigel, H. et al. (1996) In *Subduction: Top to Bottom*, AGU Geophysical Monograph 96, 19-38. [10] Jochum, K. P. and S. P. Verma (1996) *Chem. Geol.*, 130, 289-299. [11] *Basaltic Volcanism Study Project* (1981). [12] Hartmann, W. K. et al. (2001) *Icarus*, 149, 37-53. [13] White, A. F. and Brantley, S. L. (2003) *Chem. Geol.*, 202, 479-506.