THE SECOND SHERGOTTITE AGE PARADOX. J. B. Balta and H.Y. McSween, Planetary Geoscience Institute and Department of Earth & Planetary Sciences, University of Tennessee, Knoxville, TN 37996-1410, jbalta@utk.edu.

Introduction - the Shergottite age paradox: Shergottites are magmatic rocks that vary from basaltic to ultramafic in composition. Their provenance has proven difficult to explain as they are the most abundant martian meteorites, but their ages are younger (<500 m.a.) than the majority of Mars's surface [1]. This discrepancy has been termed the shergottite age paradox, and requires a bias towards younger rocks successfully arriving on Earth, as would be the case if, for example, older rocks had been highly altered or fractured.

Since this issue was first noted, a variety of new data types have been obtained from Mars that can be used to construct a relative chronology of martian magmatism based on chemostratigraphy, rather than an absolute chronology based on age dates. Interpreting the chemostratigraphy of martian magmatism could provide constraints on the origin of the shergottites, the origin of other martian igneous rocks, and the evolution of the martian mantle.

Here we present an overview of recent stratigraphic constraints on the timing and composition of martian volcanism. We combine these constraints with models for the evolution of the martian mantle, and attempt to explain the origin of the shergottites. We find instead a second age paradox associated with their chemostratigraphy, and finally propose an alternate method of shergottite generation based around the melting of a hydrous martian mantle.

Spacecraft data: The large volcanic edifices of the Tharsis and Elysium plateaus represent the youngest volcanic terranes on Mars and the most likely sources for young igneous rocks such as the shergottites [2]. Two recent instruments provide mineralogical and compositional constraints on the these volcanoes. The OMEGA instrument on the Mars Express orbiter provides mineralogical and some compositional information using visible and near-IR reflectance spectra [3], and the GRS instrument on Mars Odyssey measured several elements, including Si and Th, using gamma ray spectroscopy [4]. In both cases, we find that the compositions of the young volcanoes are difficult to reconcile with the young age of the shergottites. The martian chemostratigraphy therefore creates a second paradox in the shergottite ages.

OMEGA results:

The OMEGA instrument is sensitive to features such as abundance of low-calcium pyroxene (lcp), high-calcium pyroxene (hcp), and olivine. The instrument's results demonstrate that much of Mars's surface, including the recent volcanic constructs, is dominated by igneous rocks composed mostly of hcp and plagioclase, with limited olivine and lcp exposures. These results contrast with the chemistry of the shergottites, which lcp- and sometimes olivine-rich. The only region with elevated lcp and olivine contents which comes close to matching the shergottite compositions is in the southern highlands, composed of older Noachian rocks. Consequently, the OMEGA instrument team suggested that the young shergottite ages may be a poor match for their surface spectra [3].

GRS results:

GRS is sensitive to elements such as Si and Th, which can be compared to measurements of shergottite compositions. GRS results for the young volcanoes suggest that Th contents increase and Si contents decrease in younger volcanic rocks. This conclusion motivated the creation of a model for the evolution of the martian mantle focused on increasing crustal thickness with time. In this model, as crustal thickness increases, melt fractions would decrease and melting pressures would increase, leading to decreasing Si and increasing Th abundances [4].

Both the GRS results and the thickening crustal model predictions fail to match the measured shergottite compositions (Fig. 1). The shergottites are low in Th and high in SiO_2 compared with even the oldest volcanic edifices, and no fractionation, mixing, or shallow crustal contamination path reproduces the volcanic trends from a shergottite parent magma.

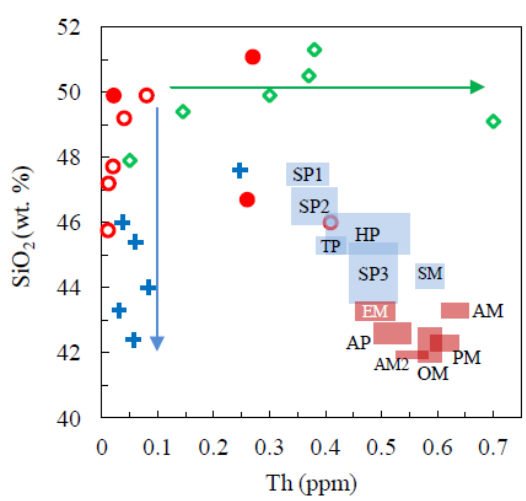

Figure 1: Shergottite whole-rock compositions (crosses are lherzolitic, diamonds are basaltic, and circles are olivine-phyric) compared with GRS data. Filled circles represent

plausible parental magma compositions [5]. Blue boxes show representative GRS compositions for older (Hesperian) volcanism, red boxes show compositions for younger (Amazonian) Tharsis and Elysium volcanoes [4]. Blue arrows show direction of compositional changes from olivine accumulation (lherzolitic shergottites), green arrows show shallow crustal AFC processes (basaltic shergottites). Abbreviations: SP1 – Sinai Planum, SP2 – Solis Planum, HP – Hesperia Planum, TP – Tyrrhena Planum, SP3 – Syria Planum, SM – Syrtis Major, EM – Elysium Mons, AM1 – Ascraeus Mons, AP – Alba Patera, AM2 – Arsia Mons, OM – Olympus Mons, PM – Pavonis Mons. X marks "Bounce" rock

Alternative model - impact of water:

To attempt to explain these compositional, mineralogical, and stratigraphic constraints in the context of the measured shergottite ages, we instead consider the effect of water on the melting of the martian mantle.

Water has important consequences for the melting chemistry. Most notably, the melting of average peridotite in the presence of water leads to a magma that, after degassing, is SiO_2-rich compared to a magma produced from a dry peridotite [6]. Thus, compared to the GRS measurements, the shergottite SiO_2 contents could be consistent with the effects of magmatic water.

Requirements: To adequately explain this chemostratigraphy, a model for the martian mantle must explain: the shergottite ages and chemistries, the presence of shergottite-like, lcp rich rocks in the Noachian highlands, the presence of hcp-rich rocks in the volcanic provinces, and the compositional evolution measured by GRS in the volcanoes. Multiple lines of evidence suggest that shergottite magmas contained water, which could also impact these chemistries [7-8]. Wet melting, in the context of a thickening crust and a mantle that gradually dewaters over time, can potentially explain all of these characteristics.

Fitting chemostratigraphy using wet melting:

If the martian mantle initially was hydrous, at least at the level of Earth if not substantially more, then its earliest melts would be water-rich (>1 wt. %), high-SiO_2 magmas. Crystallization of these magmas at the surface would give rise to shergottite-like compositions, producing the lcp-rich rocks measured in the southern highlands. These compositions would be particularly abundant early in Mars's history as high water contents in a convecting mantle would lead to large volumes of melts delivery to the surface.

Because Mars does not have active subduction, there would be no way of resupplying water to the martian interior, leading to a gradual dewatering of the mantle, as water is incompatible during melting and would be nearly quantitatively removed from any portion of mantle that underwent partial melting. Water could be reintroduced to previously melted mantle through metasomatic processes or diffusion, but the mantle as a whole would dewater with time.

Decreasing mantle water abundances would lead to dryer magmas later in martian history, with lower melt volumes and less delivery of volatiles to the surface. These dryer magmas would be SiO_2-poor, due to the lack of water. Lower SiO_2 contents would lead to greater abundances of hcp and plagioclase in later rocks, as observed in the recent volcanic provinces. Lower melt fractions combined with increasing contamination due to thickening crust would produce the elevated Th contents measured in the SiO_2 poor magmas by GRS. Thus, a dewatering mantle combined with a thickening crust can fit these chemostratigraphic trends.

Finally, the young ages for the shergottites can be readily produced in the context of a dewatering mantle. If a portion of Mars's mantle remains hydrated, as might be the case in a chemically distinct lower mantle, then water-driven melting could resume if near-pristine wet mantle were entrained in the recent upwellings. Small amounts of wet mantle, perhaps isolated in the martian lower mantle, could then produce rare eruptions of shergottite-like magmas in the recent volcanic provinces. The provinces would be dominated by trace element- and hcp-rich rocks, perhaps similar to the naklite meteorites, and intersperced with shergottites at a scale too fine to be detected from orbit.

Implications for future missions:

At present, no mission to Mars has located any igneous rock close in composition to the samples available on Earth in stratigraphic sequence. This lack of context for the samples available to laboratories on Earth is a major impediment to our understanding of the evolution of volcanism on Mars and the delivery of volatiles to the atmosphere. A major implication of this model is the delivery of substantial quantitites of magmatic water to the martian surface early in its history, at the same time as life was evoliving on Earth. While we recognize that igneous stratigraphy is not the primary goal of the Mars exploration program, we hope that future missions, such as the recently announced 2020 lander, will consider developing an igneous stratigraphy as a mission goal, particularly given the connections between igneous rocks, atmospheric volatiles, and the elements necessary for life.

References: [1] Nyquist et al. (1998) *JGR, 103,* 31445-31455. [2] Lang. et al. (2009) *JVGR 185,* 103-115. [3] Poulet et al. (2009) *Icarus 201*, 84-101. [4] Baratoux et al. (2011) *Nature 472*, 338-341. [5] Filiberto and Dasgupta (2011) *EPSL 304*, 527-537. [6] Balta et al. (2009), *J. Petrol. 52,* 2079-2105. [7] McCubbin et al. (2012) *Geology 40*, 683-686. [8] McSween et al. (2001), *Nature* 409, 487-490.