IMPLICATIONS OF MAGMA OCEAN CUMULATE OVERTURN FOR MARS. P.C. Hess and E.M. Parmentier, Department of Geological Sciences, Brown University, Providence, RI 02912.

We propose that the early differentiation of Mars, like that of the Moon, was dominated by the fractional crystallization of a planet-wide magma ocean which produced a buoyant anorthositic crust and a complementary mafic cumulate mantle. The cumulate mantle was compositionally stratified and gravitationally unstable. Solid state differentiation then carried dense, iron-rich and relatively cool cumulates into the Martian interior ultimately resulting in a lower mantle that is denser and chemically more evolved than the upper mantle. Similar processes were proposed for the evolution of the lunar mantle [1]. This model, if correct, leads to interesting geochemical and geophysical consequences.

A variety of evidence argues for the existence of a magma ocean on Mars. **1)** The parent liquids to the SNC meteorites are significantly depleted in Al_2O_3 and CaO relative to terrestrial basalts [2]. Only terrestrial komatiites, the products of more than 30% melting of the Archean mantle and the mare basalts and picrite glasses, derived by melting of the cumulate Lunar mantle have similarly low Al_2O_3 and CaO contents. **2)** Whole rock Rb-Sr isochrons for shergotites preserve the record of a major, Martian-wide differentiation event that depleted the mantle in Rb and other incompatible elements [3]. **3)** ^{182}W and ^{142}Nd anomalies and the apparent age of the Rb-Sr isochron place this differentiation event within 50 million years of the origin of the solar system [4,5]. **4)** The ^{143}Nd composition of the Martian mantle, assuming a single differentiation event at 4.5Ga, is more depleted than even the cumulate source regions of the mare basalts on the Moon [6]. The average thickness of the Martian crust is about 50 km [7] and, at least in the southern hemisphere, probably dates a massive differentiation event at about 4.5Ga.

A gravitationally stable compositionally stratified Martian mantle can also explain other important characteristics of Mars. **1)** Mars, like the Moon, is isotopically much more heterogeneous than the Earth [5,6]. While one might argue that the small size of the Moon or the absence of water to promote solid state creep inhibits thermal convection, such arguments do not apply to Mars. **2)** The presence of ^{142}Nd anomalies in some SNCs require that their source regions preserved their initial compositional heterogeneities [6]. **3)** The preservation of whole rock Rb-Sr isochrons and the ancient ^{182}W and ^{142}Nd anomalies argue against crustal recycling subsequent to stabilization of the magma ocean cumulates [5]. **4)** The isotopic evidence of early differentiation in the Martian mantle, in contrast to the evidence from the terrestrial mantle, indicates that the Martian mantle has successfully resisted homogenization by thermal convection. We argue that thermal convection is inhibited by a stably compositionally zoned mantle.

Fractionation of a magma ocean on Mars would have important similarities and differences with the Moon. On the Moon, the crystallization sequence of the magma ocean is dominated by olivine and orthopyroxene; the progressive enrichment of FeO over MgO in these phases makes the density of the cumulates increase upward with progressive fractionation leading to gravitational instability [1]. The concomitant FeO enrichment in the liquid and its saturation in normative plagioclase component leads to the crystallization and flotation of plagioclase and the stabilization of an anorthosite Lunar crust.

In contrast, the liquidus phase in the Martian magma ocean is mainly garnet-majorite at depths greater than about 1000 km [9,10]. For a core radius of about 1400 km, this region will extend over the lower 1000 km of the mantle. At these depths, majorite is predicted to be only slightly negatively buoyant [11]. It is likely that crystal-liquid fractionation will be inefficient in the strongly convecting magma ocean so that the lower mantle may initially approximate the whole Mars composition. Once convection ceases the remaining intergranular liquid with the majority of the highly incompatible elements, including the heat producing ones, will migrate upwards to the still liquid magma ocean. The net effect is to sequester Al_2O_3 (as garnet-majorite) in the lower mantle. Garnet-majorite will transform to eclogite in the upper mantle so that it should remain as a stable layer in the lower mantle being less dense than only dense FeO-enriched sinking cumulates from below the crust.

This scenario has several appealing features. The fractionation of majorite will decrease the Al_2O_3/CaO ratio in the remaining cumulates, a feature characteristic of Shergotite parent liquids [2]. The remaining liquids of the magma ocean will have less normative plagioclase resulting in delayed crystallization of plagioclase. The buildup of H_2O in the residual magma ocean will also delay the onset of plagioclase crystallization. The net effect is that the anorthosite crust on Mars should be relatively thinner than that on the Moon. The progressive build up of H_2O and other fluids in the residual liquids of the magma ocean may cause plagioclase to become negatively buoyant. The anorthosite crust would no longer float resulting in the eruption of volatile-rich residual melts onto the Martian surface. The upper Martian crust, in this model, would be formed by

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products of the late stage magmas. The lower crust would be anorthosite-rich and would have acted as the platform on which subsequent magmatism was deposited.

Finally, the Lu/Hf garnet signature in the SNC parent liquids [5] may arise by the remobilization and melting of depleted majorite bearing cumulates. The parent liquids are reminiscent of Al depleted komatiites on Earth which appear to coexist with garnet at 5-6 GPa [12,13]. Alternatively, the garnet signature may arise partly from ecogite layers within the upper cumulates; the eclogite layers may represent plagioclase-olivine carried downwards by sinking cumulates into the eclogite stability field.

Besides preserving the isotopic and compositional heterogeneity, overturning of an initially unstably stratified cumulate mantle may explain additional aspects of the evolution of Mars. After the overturn, the mantle would be stably stratified. Since thermal convection would then be inhibited by the compositional stratification, the primordial and radiogenically generated heat in the Martian interior would be slow to dissipate only by conduction. Similarly, the infertility of the cumulate mantle and the inhibition of thermal convection could limit magma production by adiabatic decompression, perhaps explaining in part the preservation of ancient crust.

The crustal dichotomy may be the product of the overturn of initially unstable magma oven cumulates. Horizontal convergence would thicken the crust above long wavelength (spherical harmonic degree one) downwelling of dense late stage cumulates. Thinning due to extension or delamination of the lithosphere in the opposing (northern) hemisphere could induce pressure-release melting and resurfacing. A similar catastrophic resurfacing model has also been suggested for the Venus [8].

Regardless of the origin of the crustal dichotomy, variations in the thickness of the Martian crust are well established by gravity and topography data [7] and it is at least plausible that these variations have persisted from the very early evolution. To preserve this crustal thickness variation over a substantial fraction of Mars' evolution requires low temperatures at the base of the crust. Evolution models including heat transfer by thermal convection suggest lower crustal temperatures high enough that crustal thickness variations may not be preserved [14]. The absence of thermal convective heat transfer due to stable compositional stratification would allow conductive cooling to result in lower crustal temperatures.

Remnant magnetism [15] in a portion of the ancient, heavily cratered Martian crust argues for the existence of an internally generated magnetic field early in the evolution. The generation of a magnetic field requires sufficiently rapid cooling of a molten metallic core. It has been argued that thermal convection beneath a cool, stagnant, conducting lithospheric lid would not cool the core rapidly enough, prompting the suggestion that the more rapid heat transfer associated with plate recycling may be required during the evolution of Mars [16]. Mantle overturn that transports relatively cool, dense cumulates to the mantle-core boundary may provide an alternative way to cool the core rapidly enough to sustain a magnetic dynamo. This cooling might induce a transient magnetic field for a part of early Martian history, consistent with the observation that not all ancient cratered terrain is magnetized; stable mantle stratification after overturn could prevent subsequent convective heat transfer and suppress continued magnetic field generation.

References: [1] Hess, P.C. and Parmentier, E.M. (1995) *EPSL*, 134, 501. [2] Longhi, J. et al., (1992) *Mars* 184, U. Arizona Press. [3] Jagoutz, E. (1991) *Space Sci. Rev.* 56, 13. [4] Lee, D-C and Halliday, A.N. (1997) *Nature* 388, 854. [5] Blichert-Toft, J. et al., *EPSL*, 173, 25. [6] Borg, L.E. et al., (1997) *GCA* 61, 4915. [7] Zuber, M.T. et al., (2000) *Science* 287, 1788. [8] Parmentier, E.M. and Hess, P.C. (1992) *GRL* 19, 2015. [9] Bertka, C.M. and Fei, Y. (1997) *JGR* 102, 5251. [10] Zhang, J. and Herzberg, C. (1994) *JGR* 99, 17729. [11] Miller, G.H. et al., (1991) *JGR* 96, 11831. [12] Blichert-Toft, J. and Arndt, N. (1999) *EPSL* 171, 439. [13] Wei, K. et al., (1990) *JGR* 95, 15817. [14] Parmentier, E.M., and Zuber, M.T., this volume. [15] Acuna, M.H., et al. (1999) *Science* 284, 790. [16] Nimo, F., and Stevenson, D.J. (2000) *JGR* 105, 11969.