NO MAGMA OCEAN ON VESTA (OR ELSEWHERE IN THE ASTEROID BELT): VOLATILE LOSS FROM HEDS.

John T. Wasson, Departments of Earth and Space Sciences and Chemistry and Biochemistry, University of California,
Los Angeles, CA 90095-1567, USA

p

Introduction. The view that the Earth and Moon had a magma ocean (MO) early in their history receives much support from studies of O and other isotopic systems. The heat source for these large volumes of melt was surely impacts.

Several research teams have speculated about the possibility of a magma ocean on Vesta (or the HED parent asteroid, if not Vesta). Righter and Drake [1] argued that it best explained the distribution of eucrite types and the diogenites. Greenwood et al. [2] stated that the observation that almost all eucrites and diogenites formed a tight cluster in Δ^{17}O required formation of these meteorites in a magma ocean.

In fact, the Δ^{17}O cluster only indicates that these HED samples formed from the same magma body, but offers no evidence regarding the presence of a global magma ocean. Formation of a magma ocean requires rates of heat input that were not available in the Asteroid Belt; ^{26}Al contents of known chondrites were too low and the few impacts that imparted enough energy to melt an entire asteroid would have destroyed and dispersed the asteroid. Even if the speculation that HEDs formed from special chondritic materials with high ^{26}Al/^{27}Al ratios were correct, internal heat sources release heat at rates that are too slow to produce magma oceans; strong internal heat sources can produce internal magma bodies but cannot generate enough steady-state energy to match the rate of heat loss from a magma ocean.

A major chemical feature of the HED meteorites and angrites is their very low contents of the alkali elements Na, K and Rb compared to those in chondritic meteorites. Righter and Drake [1] argued that this reflected loss during a magma-ocean stage in the parent asteroid. If there was no magma ocean, another explanation is required. Internal heat sources are not easily able to produce the loss of trace volatiles because the gas volume is too small to generate the eruptions needed to expel the gas from the system; a slow leakage of gas from the surface is implausible at the low temperatures present in the Asteroid Belt.

Radioactive internal heat unlikely to make a magma ocean. The ^{26}Al/^{27}Al ratios recorded in chondrites are too low to produce melting [3]. However, most modelers still use ^{26}Al as an asteroidal heat source because it is easy to model and they question the viability of impact heating. The common rationalization is that the existence of very old differentiated meteorites shows that early melting occurred and, therefore, that it is reasonable to assume that the chondrites parental to the differentiated meteorites had ^{26}Al/^{27}Al ratios similar to those in CAIs.

There is no doubt that, if asteroids with radii (R) >10 km formed with ^{26}Al/^{27}Al ratios similar to initial ratios in CAIs, extensive melting would have occurred. However, the rate of heat input by ^{26}Al appears to be an order of magnitude too low to produce a magma ocean, here defined to be magma on >20% of the surface (later covered by an unstable frozen skin) of the asteroid and having a depth >0.05R. Slow internal heating is not able to liberate heat fast enough to create such a structure. The problem arises because as soon as the fractional volume of melt reaches a critical value, perhaps ~30%, the metallic melt will form a core and the silicate melt will migrate to the surface and take the Al with it. At this point, with the ^{26}Al near the surface, the differentiated materials will cool rather than heat. This melt redistribution problem is aggravated by the high rate of impacts that would have been present during the first 100 Ma. Note that this model can form basalts such as HEDs, just not a magma ocean. However, such basalts should have still had very high ^{26}Al/^{27}Al ratios, only 5 to 10 times lower than CAI values, not the 100× lower (~4E-7) ratios found in eucrites [4].

Radioactive internal heat and volatile loss. Because heat is liberated very slowly by the decay of ^{26}Al, the phases that are easily volatilized (such as CO, CH_4 and H_2O) are lost at low temperatures, long before large fractions of the alkali elements enter the gas phase at temperatures >1200 K. The prime mechanism for volatile loss from internally heated asteroids is explosive loss of clouds of gas such as H_2O but, in the absernce of a carrier, trace gases will either not nucleate bubbles in magmas or will form small bubbles that are inefficiently lost from the basaltic melt during extrusion (such as those in the Ibitira anomalous eucrite).

Impact heating and melting in the inner Asteroid Belt. Although low impact velocities and low escape velocties make it impossible to produce a magma ocean on asteroids, it is possible to produce magmas by impacts. Although Keil et al. [5] argued thated that this was not possible, their study relied heavily on Earth analogues in which the target materials have low porosities. In addition, the goal of the model was to produce global magmas rather then regional magmas. However, asteroids have high porosities today and laboratory and modeling studies [6] show that porosities may have uniformly exceeded 50% immediately after accretion. And there is no evidence that the parental magmas of the HEDs or of the magmatic iron meteorites were global in extent. Numerical modeling by Davison et al. [7} showed that local impact melting of porous asteroids can occur at impact velocities as low as 5 km s^{-1} (the mean impact velocity in the inner Asteroid Belt); at this velocity a small porous projectile can melt a volume twice as large as its own volume. As noted by Wasson et al. [8] 20% of impacts in the inner asteroid belt occur at velocities >7 km s^{-1}, and thus an identical projectile would produce twice as much heat as one impacting at 5 km s^{-1}. In addition, because of the high relative flux of transJovian materials, the mean impact velocity was surely higher during the first 100 Ma of solar-system history.

Difficulties with magma ocean formation on asteroids. The magma oceans on the Earth and Moon seem to have been formed from local materials having similar O-isotopic compositions in the target and projectile. They thus probably formed at impact velocities in the range 12 to 20 km s^{-1}, between the escape velocity of the Earth and the typical impact velocity on the Earth today. A minor fraction of the impact velocities occurring in the inner Asteroid Belt during the first 100 Ma of Solar System historywere in this range, and thus high enough to melt the entire target asteroid. The problem is that asteroids have low escape velocities (that on Vesta, the second largest asteroid, is only 0.35 km s^{-1}), and that much second largest asteroid, is only 0.35 km s^{-1}), and that much of the debris resulting from collisions between bodies similar in mass would have escaped the combined gravitational field of the system.

If we accept the Occam's razor conclusion that, since known chondrites never contained enough ^{26}Al to produce melt, the extensive melting on Vesta must be the result of impact heating. This raises the question of why all parts of Vesta show basaltic reflection spectra. A possible trivial answer I have suggested in the past is that the very fresh (scarcely space weathered) spectra observed on Vesta must be the result of a recent "dusting" of the entire planet by an impact into basalt.

However, if we assume that basalts were extruded on all parts of Vesta, then the heat source must have been a massive impact, with much of the debris having been lost from the system and Vesta being the residue. Such an open-system event would not have retained enough heat to produce a magma ocean but could have resulted in magma bodies scattered around much of the body. And, as discussed in the following section, high temperatures generated by collisions into porous targets could have resulted in the extensive loss of volatiles, including from the HED and IVA-iron [8] parent asteroids.

Impact heating and volatile loss in the inner Asteroid Belt. Volatile loss associated with internal heating seems to require the formation of high-pressure gas pockets (largely composed of H_2O, CO or H_2O but also containing trace volatiles) below an impermeable cap followed by explosive loss of the gas. However, given the numerous fractures that must have been present in all asteroids in the chaotic environment during the first 100 Ma it seems certain that these carrier phases would have already escaped before internal heat sources generated temperatures high enough to volatilatize alkalis. In contrast, impacts into porous primitive bodies can provide both the heat source for the transfer of major volatiles into the gas phase and have simultaneously vaporized the trace volatiles and introduced them into the carrier gas.

As discussed by [9], during chondrule formation there is a gradual transfer of volatile elements from coarser grains to finer grains (i.e., nebular fines). Thus, in primitive chondrites a large fraction of the volatiles will have been present in micrometer-size fines or be present as surficial coatings on larger grains including chondrules.

Impact events produce a sharp spike in temperatures in compressible matter such as fines. Heat is then slowly transferred to the interiors of larger grains by conduction. Those elements sited in the fines or in thin surficial coatings will experience the highest temperatures and thus be more likely to volatilize than those located in the interiors of grains (or chondrules).

Because impact heating can cause gas temperatures to rise from <300 K to >1000 K very quickly, the flash volatilization of organics and hydrated minerals will occur at the same time as the vaporization of volatile trace elements. There is thus a carrier phase for the volatiles and the mechanical separation of gas from solids would have been efficient.

Summary. It seems highly unlikely that there were magma oceans in the Asteroid Belt. Radionuclide heating releases energy at too low a rate and leads to differentiation and extrusion of shallow melt layers. There is strong evidence that the Earth and Moon had magma oceans produced by massive impact events. However, to retain impact-heated debris one needs relatively high escape velocities >2 km s^{-1}, far higher than those on Vesta, the second largest asteroid. The very narrow range of Δ^{17}O in most HEDs implies formation of these within a single magma chamber but this chamber could have been local, not a deep magma ocean. Known chondrites have too little ^{26}Al to produce melting. Hypothetical chondrites with ^{26}Al/^{27}Al ratios similar to those in CAIs could produce internal melting but the rate of heat production is too low to produce magma oceans.- Internal heating also appears inadequate to produce extensive loss of trace volatiles. Impact heating which vaporizes both the trace volatiles and carrier volatiles such as H_2O are the probable mechanism for the loss of volatiles from HEDs and from the IVA irons.

References: [1] Righter K. and Drake M. J. MPS **32**, 929. [2] Greenwood R. C. et al. (2005) Nature **435**, 916. [3] Kunihiro T. et al. GCA **68**, 2947 [4] Nyquist L. et al. (2009) GCA **73**, 5115. [5] Keil K. et al. MPS 32, 349. [6] Blum J. and Wurm G. (2008) ARAA **46**, 21. [7]Davison T. M et al. (2010) Icarus **208**, 468. . [8] Wasson J.T. et al. (2006) *GCA* **70,** 3149-3172. [9] Wasson J. T. (2008) *Icarus* **195**, 895