MELT FORMATION, MIGRATION AND RAPID EXTRACTION FROM DIFFERENTIATED ASTEROID INTERIORS: LESSONS FROM UREILITES EXTENDED TO ALL ASTEROIDS. L. Wilson[1] and C. A. Goodrich[2] [1]Lancaster Environment Centre, Lancaster Univ., Lancaster LA1 4YQ, UK. (L.Wilson@Lancaster.ac.uk) [2]Planetary Science Institute, 1700 E. Ft. Lowell Dr., Tucson AZ 85719, USA.

Overview: We show that rapid extraction of partial melts from mantles of differentiated asteroids was not strongly dependent on gas being present. The highest degrees of partial melting (≥30%) require very early asteroid formation. Rapid melt transfer out of the mantle should have been the norm, rather than the exception, in early-forming asteroids of all sizes, casting doubt on the viability of thermal models that propose an extensive magma ocean.

Background: ^{26}Al was probably the major heat source that, along with some other short-lived radioisotopes, especially ^{60}Fe, influenced the thermal history of asteroids forming within ~ 3 Ma of the time of formation of CAIs [1]. The potential for this heat source to cause more than 50% partial melting in the mantles of the earliest-forming asteroids [2] led to the common acceptance of the idea that these asteroid mantles became "magma oceans" [3]. The ocean would occupy most of the interior of the asteroid between the core, if one separated, and the lithosphere (the conductively-cooled outer thermal boundary layer of the asteroid, ~10 km thick by the end of the ~1-3 Ma warm-up time [4]). Such models assume that, although some melt may have been extracted from the mantle to intrude within the lithosphere or erupt at the surface, much partial melt was retained in the magma ocean mantle and eventually solidified [5]. The chemical and mineralogical compositions of some of the howardite-eucrite-diogenite meteorites, commonly inferred to have come from the asteroid 4 Vesta, have been interpreted in the light of this model [6].

An alternative model has been proposed [7-9], in which an efficient network of melt veins develops, allowing melt to migrate rapidly after only a few % partial melting has taken place. This model explains [9] the unequilibrated oxygen isotope trend of the ureilite meteorites [10, 11], by indicating that melt extraction on the ureilite parent body (UPB) would have been a fractional process involving transit times (parcels of melt traveling from their mantle source regions to shallow depths) of less than ~1 year, much too short to allow significant chemical/isotopic interaction with the residual solids through which they passed [12]. The fast-transit model [9] was based on the basic physics coupled with evidence of efficient formation of interconnected melt vein and dike complexes in terrestrial ophiolites [13-17].

The hypothesis of smelting (pressure-dependent reduction of FeO by graphite, with production of CO) on the UPB [18-24, 12] suggested that melt extraction from the interior of this asteroid would have been significantly facilitated by the high positive buoyancy imparted to the silicate melts by entrained bubbles of CO gas. Assistance of melt migration by entrainment of gas bubbles was proposed for all asteroids on which explosive silicate volcanism was important [25] and has also been invoked to support surface eruptions of FeNi-FeS liquids explaining sulfur depletion in some iron meteorites [26]. However, the importance of equilibrium smelting on the UPB is uncertain [27-31], and so we have re-evaluated the process of melt generation and extraction in the absence of smelting.

Analysis: Equation (27) in [9] gives the time required to transfer a given batch of melt from any location within the zone where partial melting takes place to the top of that zone, at which point it is intruded into a sill or magma reservoir, or erupted at the surface. The transit time depends on the vertical extent of the melting zone, R_m; the distance from the base of the melting zone from which a given batch of melt starts, R_x; the acceleration due to gravity, g; the volume of melt being produced per unit time, ϕ_R; and the density difference between the melt and the host solids, $\Delta\rho$. The dependencies are proportional to $R_m^{3/2}$, $R_x^{-1/2}$, $g^{-1/2}$, $\phi_R^{-1/2}$ and $\Delta\rho^{-1/2}$ [9]. Ignoring small differences in asteroid bulk densities, the first three of the above parameters scale in proportion to the radius of the asteroid, R. The fourth depends on the total asteroid volume and hence scales as the cube of the asteroid radius, and the last depends on assumptions about the amount of gas entrained by the melt. Combining the dependencies, the transit time is proportional to R^{-1} and $\Delta\rho^{-1/2}$. [9] treated the case of the UPB, inferred to have a radius of 100 km (based on constraints from smelting), producing melt at its peak total rate of 100 $m^3 s^{-1}$ soon after melting started. They assumed that the smelting taking place on this body, caused the silicate melt to contain CO gas, reducing its bulk density to ~200 kg m^{-3}, and leading to a density difference from the residual solids of ~3100 kg m^{-3}. A typical melt transit time of ~30 days was found.

Consequences of No Smelting: If no gas had been available on the UPB, from smelting or any other source, melt bulk density would have been ~10% less than host rock density, a 9-fold smaller density difference than for a CO-rich melt. The $\Delta\rho^{-1/2}$ dependence then means that transit times in the absence of gas would have been $\sim 10^{1/2} = \sim 3$ times longer than the ~30 days originally found, i.e. ~3 months.

In the absence of smelting, there are no constraints on the size of the UPB. It could have been smaller than the 100 km radius inferred in [9] but was probably not bigger than 1 Ceres, radius ~475 km. A lower size limit of ~20 km is dictated by the fact that large-scale melting requires the radius to have been significantly greater than the ~10 km thickness of the conductively cooled lithosphere. With 20 and 475 km as extremes, melt migration times in the absence of gas could have been from ~15 months (smaller body) to ~20 days (very large body). Neither of the above consequences changes the conclusion that the timescale for melt transit is so short that no significant chemical/isotopic interactions between migrating melt and surrounding mantle solids would have taken place on the UPB [12].

Implications: As melting progresses, the ^{26}Al heat source migrates preferentially into the melt, and the efficient extraction of melt from the interior makes it very difficult to reach high degrees of melting [9]. For the UPB, a formation time of ~0.5 Ma after CAI time was required [9] to allow the asteroid to reach the peak temperatures of 1200-1300 ºC inferred from the rocks [32-35, 24] – equivalent to ~30% melting. This result does not depend on smelting, because very efficient melt extraction occurs on asteroids of all sizes whether or not smelting is involved, and because the timescale of heating of the asteroid does not depend strongly on the effects of smelting on the melting sequence [see 12]. An earlier formation time would not have led to significantly higher peak temperatures or degrees of melting, because all of the Al is removed from the mantle long before ~30% melting is reached [9]. The implication is that a high degree (>50%) of partial melting in the deep interior of any asteroid is not possible unless it forms so early that the weaker heat source ^{60}Fe also contributes significantly to the thermal history; and even this source is not directly available for mantle heating if much of the iron segregates efficiently into a core. These factors argue very strongly that high degrees of mantle melting never occurred in any asteroids and that melt retention in the mantle was minimal. Instead, the locations in asteroids where nearly completely molten extracts of the mantle will have been present are the massive intrusions formed at the base of the lithosphere by accumulation of the melts transferred from the mantles [9, 36].

Summary: (1) The presence or production of gases in asteroid interiors had minimal effect on the speeds at which mantle melts were transferred upward into the lithosphere. (2) Melt transit times early in the melt production period in differentiated asteroids ranged from ~15 months (small bodies, no gas) to ~1 week (large bodies, copious gas), severely limiting chemical/isotopic interactions between melt and residual solids. (3) No more than a few % of melt will have been present in the melt zone of an asteroid at any one time. (4) The degree of partial melting reached in an asteroid interior will have depended critically on the asteroid formation time, with ~30% melting being close to the maximum possible, requiring formation ~ 0.5 Ma after CAIs. (5) The results of [9] regarding early accretion and rapid melt migration for the UPB do not depend on smelting. (6) Severe doubt is cast on the concept of magma oceans in asteroids. Instead, large intruded melt bodies will have accumulated near the base of the lithosphere. We suggest that meteorites (such as the HEDs) that are currently thought to be products of magma oceans should be reexamined petrologically and chemically to see if they might instead have been derived from such intrusions.

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