A NEW MODEL FOR PLANETESIMAL FORMATION: CASE STUDY OF THE UREILITE PARENT BODY.

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Introduction: Asteroid 4-Vesta, parent body of the HED suite of meteorites, has a differentiated core-mantle-crust structure, and is commonly considered as a reference model for planetesimal formation and differentiation [1]. However, ureilites meteorites, the second most abundant type of achondrite meteorites, provide a different view of formation of asteroids and planetesimals [2,3].

Ureilites show correlations between oxygen isotope compositions and bulk silicate mg# and/or Fo content of constituent olivine, which are not evident in other achondrite groups, including the HEDs. As compared to ureilites, the bulk chemistry and oxygen isotope compositions of HED meteorites are well homogenized, probably because Vesta underwent a high temperature magma ocean stage during which its silicate mantle was mostly or completely molten [4,5]. This would have obliterated any earlier compositional variations in the Vestan mantle. In contrast, ureilites show a trend between Fe-rich compositions with high $\Delta^{17}O$ ratios and high-Mg com-positions with lower $\Delta^{17}O$ values [6,7,8]. Figure 1 shows this correlation, using mg# in olivine as a proxy for bulk rock Mg#. This correlation must be accounted for in any model of formation of the original parent asteroid of ureilite meteorites.

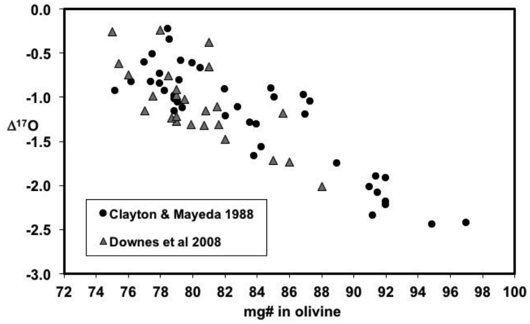

Figure 1. Correlation between mg# in olivines and Δ17O, in ureilite meteorites. Data from [6,8].

Approach: We used a Monte Carlo modelling approach to determine which combinations of primitive meteorites and meteoritic components could generate the observed trend of oxygen isotopes and bulk chemistry shown in Figure 1. A combination of a range of sampled chondritic materials as representatives of early nebular matter which included chondritic meteorite types (CH, CI, CK, CM, CO, CR, CB, EH, EL, H, L, LL, R), with Fe- and Mg-rich chondrules and CAIs were considered as building blocks for the original Ureilite Parent Body. Our modelling showed that all combinations of primitive C, O and E chondrites failed to generate the oxygen isotopes and bulk chemistry of ureilites. However, a model using a combination of Mg-rich and Fe-rich chondrules could perfectly generate the oxygen isotope trend found in ureilites. We then evaluated the possibility that the range of compositions generated on the basis of this combination of Mg-rich and Fe-rich chondrules could account for the bulk compositional trends of the ureilite parent planetesimal.

Results: Unlike HED meteorites, which are mostly fragments of the crust of Vesta, ureilites are ultramafic achondritic meteorites composed largely of olivine and pyroxenes, that would have derived as residues of partial melting within the mantle of a carbon-rich asteroid [7]. Their significant LREE-depletion is also indicative of this. Thus, ureilites are equivalent to the “depleted mantle” compositions of a terrestrial planetary body, i.e. one that has lost some proportion of silicate melt. Thus, it is essential to add back a silicate partial melt, basalt or trachyandesite [10], to the major element compositions of ureilites [7], in order to reconstruct the composition of the undepleted mantle of the ureilite parent asteroid. Furthermore, to achieve the bulk composition of the parent asteroid before the segregation of the Fe-rich metallic melt from the silicate portion, we also included a metallic core component. Using this approach, we propose a new compositional model for the ureilite parent asteroid which we call the “Proto-Ureilite Planetesimal”. Our model based on a combination of Mg-rich and Fe-rich chondrules can successfully generate both the observed range of oxygen isotope signatures and the reconstructed bulk chemistry of the Proto- Ureilite Planetesimal. The model also reproduces the trends seen in Figure 1, which also suggests simple two component mixing. Mg-rich and Fe-rich chondrules have been found to occur together in the same meteorite [11], so mixing between these componenets must have occurred in the early Solar System. However, the novel result of our modelling suggests a lack of matrix in the mixture, and also suggests a compositionally zoned or layered parent asteroid.

Discussion: Mg-rich chondrules have low $\Delta^{17}O$ values, whereas Fe-rich chondrules have higher $\Delta^{17}O$ values, thus this mixture can account both for the variation in oxygen isotope ratios and the co-variation of composition with oxygen isotopes. During condensation and accretion in the solar nebula, the Mg-rich end-members of silicate minerals such as olivine and pyroxene would have condensed at slightly higher temperatures compared to the more Fe-rich compositions. This would have led to the growth of a compositionally zoned planetesimal which would have formed with more Mg-rich minerals towards its centre and more Fe-rich minerals in its outer layers (Fig. 2), i.e. having a layered bulk chemical structure. Differences in $\Delta_{17}O$ of the chondrules would also produce a radial gradient in oxygen isotopes (Fig. 2).

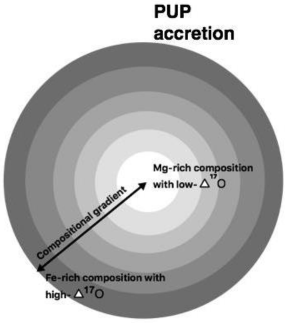

Figure 2. Initial concentric structure of the Proto-Ureilite Planetesimal (PUP) with Mg-rich silicate interior and more Fe-rich silicate outer shells, and a gradient in oxygen isotopes.

Geothermometry suggests that the Mg-rich centre of the Proto-Ureilite Planetesimal reached temperatures of ~1320 ºC, while the Fe-rich outer parts reached ~1190 ºC [7]. These temperatures are above the solidus of the Fe-FeS system, so that small amounts of metal-sulfide melt would have been formed. Being denser than the surrounding silicate portion, this metallic melt would have percolated towards the centre of the body to form a metallic core. The temperatures are also near the onset of melting of peridotite at low pressures, so that low-density silicate partial melts would have formed and moved upwards towards the surface of the body. Differences in degree of partial melting related to different *P*-*T* regimes with-in the planetesimal would have produced different silicate melt compositions. Formation and percolation of the metal and silicate partial melts did not destroy the original layered structure of the planetesimal. It is possible that all differentiated planetesimals began with an initial compositionally layered structure as described above, but they continued to heat up (by decay of ^{26}Al or by kinetic energy of impact) to a point where the peridotite liquidus was approached leading to large scale or complete melting in a magma ocean scenario. In this case, all evidence of the previous layered silicate structure would be destroyed. However, the Proto-Ureilite Planetesimal did not reach this point. Instead, while the body was still hot and in a few regions still partially molten, it was disrupted and destroyed by an impact with another body.

A large proportion of the Proto-Ureilite Planetesimal was reaccreted as fragments, producing a daughter body from which our collection of ureilite meteorites has been derived (the present-day Ureilite Parent Body). This daughter asteroid has a distinctive compositional variation in which there is significantly more Fe-rich ureilite material than Mg-rich (Fig. 3), i.e. more of the outer layers of the Proto-Ureilite Planetesimal were preserved than the internal ones.

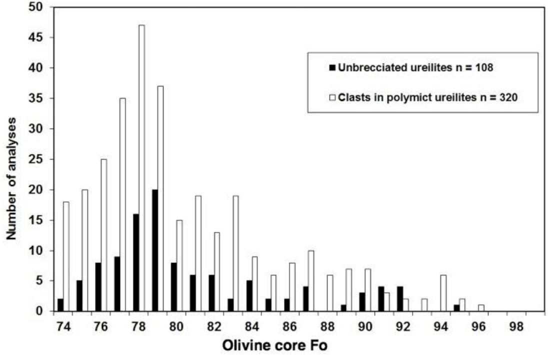

Figure 3. Histogram of distribution of Fe-rich and Mg-rich silicates in ureilites. Data from [2,8].

Conclusions: Ureilite meteorites are derived from the mantle of a differentiated planetesimal which did not experience a magma ocean stage and which therrefore did not become homogenized in terms of bulk composition and oxygen isotopes. Thus they give us a window into the early planetesimal accretion process, prior to magma ocean formation. We propose that a layered body formed from early condensed Mg-rich chondrules with low $\Delta_{17}O$ mixing with later con-densed Fe-rich chondrules with higher $\Delta_{17}O$. The body underwent heating to a temperature at which it formed a metallic liquid core and silicate melts, but the degree of partial melting was sufficiently low that the original layered structure of the silicate part of the planetesimal was preserved until the point when it was destroyed by impact. Reaccretion of a daughted asteroid (the present day UPB) preserved jumbled fragments of the compositionall layered structure.

References: [1] McSween H et al. (2014) *Elements* 10: 39-44. [2] Goodrich CA et al. (2004). *Chemie der Erde* 64, 283-327. [3] Sanders IS et al. (2017) *MAPS* 52, 690-708. [4] Greenwood RC et al. (2005) *Nature* 435: 916-917. [5] Steenstra ES et al. (2016) *GCA* 177, 48-61. [6] Clayton RN and Mayeda TH (1998) *GCA* 52: 1313-1318. [7] Warren PH (2012) *MAPS* 47: 209-227. [8] Downes H et al. (2008) *GCA* 72, 4825-4844. [9] Goodrich CA et al. (2009) *GCA* 73: 3055-3076. [10] Bischoff A et al. 92014) *PNAS* 111, 12689-12692. [11] Ruzicka A (2012) *MAPS* 47: 2218-2236.