

BULK COMPOSITIONS OF THE UREILITE PARENT BODY AND VESTA: CONSTRAINTS FROM OXYGEN ISOTOPES. N. Rai^{1,2}, H. Downes^{1,2}, C.L. Smith² ¹Centre for Planetary Sciences, Birkbeck-UCL, Malet Street, London WC1E 7HX, UK; ²Natural History Museum, Cromwell Rd, London SW7 5BD, UK. n.raai@ucl.ac.uk

Introduction: A common approach to constraining the building blocks of terrestrial planetary bodies is to use oxygen isotope signatures [1,2]. Oxygen isotopes are one of the major constraints given that oxygen is the most abundant element in silicate rocks and is also the first or second most abundant element in any terrestrial planet [1]. Such models based on oxygen isotope signatures have previously been applied to estimated compositions of large planetary bodies such as the Earth and Mars. Additional constraints are provided by the estimated bulk planetary compositions as derived from studies of meteorites believed to have originated from those bodies (e.g. Mars, Moon, Vesta). This multi-component approach was used by [3, 4, 5].

Estimating bulk planetary compositions is challenging. The bulk composition of the Earth's mantle (66% of the total planet) is considered to be well constrained because of the abundance of terrestrial mantle xenoliths available and geophysical constraints [6]. However, even for Mars and the Moon, the meteorites available originated from the crust of the respective planets, and were only indirectly derived from the mantle by processes such as partial melting and fractional crystallization. We lack direct evidence of the mantle composition because we have no lunar or martian meteorites that are equivalent to a terrestrial mantle xenolith. We therefore need to apply the modeling approach to (i) a planetary body for which we have a good estimate of the mantle composition, e.g. the Ureilite Parent Body (UPB), and (ii) a planetary body for which we have only crustal samples, e.g., Vesta. Ureilites and Vesta represent ideal candidates for understanding the processes prevalent during the earliest stages of terrestrial planet formation.

Ureilites are ultramafic achondritic meteorites composed largely of olivine and pyroxenes, that are formed to have been derived as residues of partial melting within the mantle of a carbon-rich asteroid [7]. 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. This melt was originally expected to be basaltic, but the recent discovery of a trachyandesite derived from the UPB has revised this expectation [8,9]. Ureilites show a wide range of oxygen isotope compositions [12], possibly derived from a range of accreted material from the Solar Nebula. This suggests that the UPB did not pass through a magma ocean stage of homogenization.

Vesta has an internally differentiated structure consisting of an iron-rich core, silicate mantle and a basaltic crust [10]. Visible-IR spectral data of Vesta matches very well to the laboratory spectra of the Howardite-Eucrite-Diogenite (HED) meteorites leading to the hypothesis that Vesta is the parent body of the HEDs [11, 5]. Like those of Earth, Moon and Mars, oxygen isotopes of Vesta have been largely homogenized by a magma-ocean stage.

Here we use the oxygen isotope signatures of a range of chondritic materials to constrain the possible building blocks for the UPB and Vesta.

Approach: In our modeling we used a combination of a range of sampled chondritic materials as representatives of early nebular matter. This included chondritic meteorite types (CH, CI, CK, CM, CO, CR, CB, EH, EL, H, L, LL, R), with Fe- and Mg-rich chondrules [13] and CAIs as additional building blocks for the UPB and Vesta. Using a Monte Carlo approach we determined possible two, three and four end-member combinations from this range of materials that could provide a simultaneous match for the three oxygen isotope ratios ($\Delta^{17}\text{O}$, $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$) for the UPB and Vesta respectively.

Results I (Ureilites): Based only on the three oxygen isotope ratios, we could find numerous two and three end-member combinations of chondritic meteorites that could satisfy subsets of the oxygen isotope signature of the UPB. This is unsurprising, given the well-known similarity between ureilites and carbonaceous chondrites in terms of their oxygen isotope characteristics [12]. We also found that the two end-member combination of the Fe- and Mg-rich chondrules could account for the entire range of oxygen isotope signatures exhibited by ureilites. However, for a unique solution set, it is necessary to find a match for the elemental ratios in addition to the oxygen isotopes. A range of possible compositions of the bulk silicate portion of the original UPB was derived by adding 20% of a trachyandesitic magma composition from [9] to the average composition of ureilites (recalculated without Fe metal and sulfides) derived by [14]. Additionally two extreme end-member compositions were calculated by addition of trachyandesite to the most Fe-rich (mg#=75) and the most Mg-rich ureilite (mg#=92), and a further set of possible bulk-silicate UPB compositions were obtained using the two most-frequently occurring ureilite compositions (with mg#s of 78 and 88). In our modelling, we

tried to determine possible matches that could simultaneously satisfy the oxygen isotope characteristics ($\Delta^{17}\text{O}$, $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$) and elemental ratios (Mg/Si, Al/Si, Fe/Si, Fe/Al) from our derived bulk-UPB compositions. We did not find any valid solutions with two or three end-members that could provide a simultaneous match for oxygen isotopes and elemental ratios for our range of derived bulk-UPB compositions. We found only end-member solutions with four constituents (CI, CM, EH and Mg-rich chondrules) that can form the UPB, satisfying the oxygen isotopes and the major element ratios of Mg/Si and Al/Si. We found the Fe/Si and Fe/Al ratios of our calculated bulk Ureilite silicate composition to be too low to be satisfied by this four end-member combination. However, if we add back a 25-30 wt.% Fe-rich core component to the bulk silicate ureilite composition, we find that this four end-member combination can simultaneously match the major element chemistry and the oxygen isotope signatures (Figure 1).

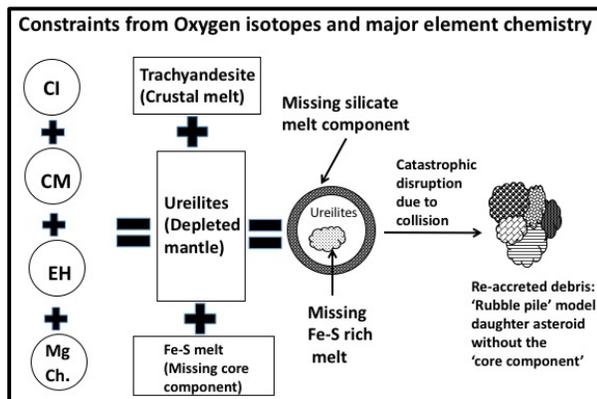


Figure 1: Combination consisting of CI, CM, EH and Mg-rich chondrules can simultaneously match the oxygen isotope ratios and major element chemistry of the calculated UPB.

Results II (Vesta): In the absence of mantle samples from Vesta, we only modelled the three oxygen isotope ratios based on measurements of HEDs [15,16] to determine possible building blocks for Vesta.

Our results indicate that the two end-member combinations of H and CV chondrites, and H and CR chondrites respectively can reproduce the oxygen isotope signatures of HEDs (Figure 2). We also find that any combination of H and CM chondrites cannot produce the HED oxygen isotope signatures.

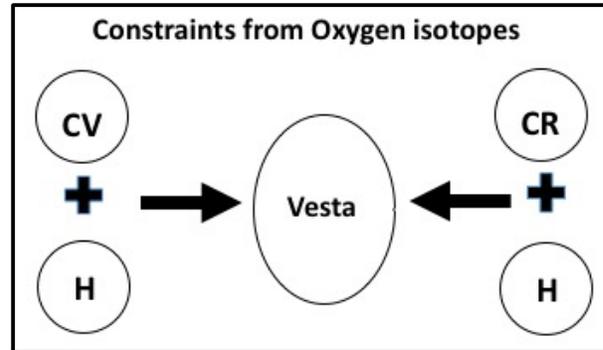


Figure 2: Two end-member chondritic combinations of either H+CV or H+CR can simultaneously match the oxygen isotope ratios of Vesta based on oxygen isotope measurements of HEDs [15,16].

Discussion: Oxygen isotopes give important constraints but may be non-unique as exemplified by the case of the UPB. Using just the oxygen isotopes we found numerous solutions for the UPB, all equally valid. This made it necessary to satisfy other available constraints such as major element chemistry. Our results indicate that the oxygen isotope signatures and our reconstructed bulk chemistry of the UPB can be reproduced based on a mixture of existing chondritic material.

For Vesta we found valid solutions in combinations of H+CR and H+CV chondrites respectively. However considering the core radius and core density constraints [5], the H+CV model appears more robust.

References: [1] Lodders K. & Fegley B. Jr. (1997) *Icarus* 126, 373-394; [2] Sanloup C. et al. (1999) *Phys. Earth Plan. Int.* 112, 43-54; [3] Korotev R. (1997) *Meteoritics & Planet. Sci.* 32, 447-478; [4] Burbine T. H. & O'Brien K. M. (2004) *Meteoritics & Planet. Sci.* 39, 667-681; [5] Toplis M. J. et al. (2013) *Meteoritics & Planet. Sci.* 48, 2300-2315; [6] McDonough W. F. (2014) *Treatise on Geochemistry 2nd Ed.*, 3, 559-577; [7] Mittlefehldt D. W. et al. (1998) *Planetary Materials, Rev. Mineral.* 36, 4-1 – 4-195; [8] Cohen B. et al. (2004). *Geochim. Cosmochim. Acta* 68, 4249-4266. [9] Bischoff A. et al. (2014) *Proc. Nat. Acad. Sci.* 111, 12689-12692; [10] Steenstra et al (2016) *Geochim. Cosmochim. Acta* (Accepted manuscript) [11] Binzel, R.P. & S. Xu (1993) *Science* 260, 186-191. [12] Clayton R. N. & Mayeda T. K. (1988) *Geochim. Cosmochim. Acta* 52, 1313-1318; [13] Krot A. N. et al. (2006) *Geochim. Cosmochim. Acta* 70, 767-779; [14] Warren P. H. (2011) *Geochim. Cosmochim. Acta*, 75, 6912-6926; [15] Weichert et al. (2004) *EPSL*, 221, 373-382; [16] Greenwood et al. (2014) *EPSL*, 390, 165-174.