UREILITES: MIXES OF A VESTA-LIKE PARENT BODY AND AN IMPACTOR FROM PROTO-MARS.

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Ureilites: Ureilites are unusual and enigmatic meteorites. They are as carbon-rich (~3 wt% C [1]) as carbonaceous chondrites, but compositionally resemble ordinary chondrites [2]. Their ^{50}Ti and ^{54}Cr abundances place them in the inner solar system [3], near 2.7 AU [4]. They are achondrites but saw only partial (~15%) extraction of melt [2]. Most (95%) ureilites are monomict with olivines of uniform Mg# varying from 74 to 96, strongly peaked at 80. Several properties (e.g., Δ^{17}O and δ^{18}O, Fe/Mn ratios), correlate with Mg# [5]. The range of Mg# has been attributed to "smelting": $(Mg,Fe)_2SiO_4$ + CaO (melt) + SiO_2 (melt) + C $\rightarrow$ $(Mg,Ca)SiO_3$ + Fe + CO (gas). The equilibrium Mg# depends on pressure and depth in the ureilite parent body (UPB) [6,7], but why ureilites would so preferentially sample Mg# of 80 is a mystery [8]. C content does not correlate with Mg# [9]. Pyroxene thermometers suggest the UPB last equilibrated at about 1050-1100°C [10], after peak temperatures ≈1200-1300°C [2,11,12]. Thermal models including melt migration reproduce these temperatures if the UPB had radius ≈ 100-250 km and formed at t=0.6 Myr (relative to CAIs) [13]. Soon after t=5 Myr [14], the UPB was catastrophically disrupted by impact at ~5 km/s (consistent with typical S4 shock stages; [15]), as inferred from reduction rims around olivines attributed to "smelting" initiated by release of pressure by an unroofing event, followed by a quench in temperatures. The UPB must have broken into chunks < 10 m in size [16] that reassembled into ureilite daughter bodies (UDBs) [2,17], from which ureilites derive. Impact shock would have produced the copious nanodiamonds in ureilites [18], but this does not explain the large (100 μm) sngle-crystal diamonds with δ^{15}N zoning observed in the polymict ureilite Almhata Sitta MS-170, which formed in metallic melt in a planetary mantle at pressures ≈ 4 GPa [19,20].

Model for Ureilite Origins: We hypothesize the following. The UPB formed at 2.7 AU at t=0.6 Myr. Disk models predict it was 1.3wt% CAIs [21]. Its initial composition was like 0.63 H+0.33 CV+0.04 CI chondrites, similar to the 0.75 H+0.25 CV mix inferred for Vesta [22]. This composition yields Mg# 80 olivines and ~1wt% C. Some silicates at low pressures underwent equilibrium smelting, forming high-Mg# olivines. The smelted fraction constrains the peak pressure; we infer the UPB radius was 173 km. We interpret the ≈25% of olivines with Mg# < 80 to be from the impactor, mixed in during the impact. Its composition corresponds to end-member "A" of [5]. The impactor had 30% the mass of the UPB, consistent with [8], and had radius ≈115 km. It delivered metal and abundant C, including large diamonds. During reassembly into UDBs, temperatures were ≈1100°C, so that silicates did not melt, but metallic melts from both bodies mixed, explaining HSE abundance trends [23]. Carbon was redistributed by the melt.

Largest Daughter Body: We further hypothesize that 15 Eunomia at 2.64 AU is the largest UDB. Based on the radii above and the 5 km/s impact speed, using [24] we estimate a radius of the largest UDB ≈139 km; Eunomia's radius is 132 km. Although the polymict ureilite Almahata Sitta derived from the F-type asteroid 2008 TC_3 [25], most ureilites are spectrally associated with S-type asteroids [26]; Eunomia is the largest S-type asteroid. 15 Eunomia has an extensive and ancient collisional family with a dynamical pathway to deliver fragments to 2.55 AU [27]. We suggest the F-type asteroid 438 Zeuxo at 2.55 AU is from the Eunomian family, and 2008 TC_3 derived from it and underwent drifted to the 3:1 resonance at 2.5 AU to reach Earth, consistent with its inferred dynamics [25].

Impactor Origin: Finally, we suggest the impactor derived from the proto-Martian surface at t~5 Myr, after magma ocean crystallization but before mantle overturn [28]. It would be Fe-rich bulk Mars, plus late-accreted carbonaceous chondrite material, with Mg# ≈74-80. We find in oxygen isotopes, Mg#, and Fe/Mn it would match end-member "A" of [5]. The compositional similarity between the UPB (Mg# = 80) and the impactor is somewhat coincidental, but they did derive from similar starting materials. Ejection by the Borealis basin impactor would have generated > 100 fragments larger than 100 km in radius that would have impacted objects out to 2.9 AU at 5 km/s [29]. The impactor could have delivered diamonds, formed in Mars's mantle at P > 4 GPa, to the UPB and UDBs.

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