NUMERICAL MODELING OF CATASTROPHIC DISRUPTION OF MOLTEN AND PARTLY MOLTEN ASTEROIDS, WITH IMPLICATIONS FOR BREAKUP OF THE UREILITE PARENT BODY. P. Michel[1], C.A. Goodrich[2], M. Jutzi[3], L. Wilson[4], D.P. O'Brien[2], W.K. Hartmann[2] and S.J. Weidenschilling[2]. [1]Lagrange Lab., University of Nice-Sophia, CNRS, Observatoire de la Côte d'Azur, UMR 7293 Lagrange, BP 4229, 06304 Nice Cedex 4, France, michelp@oca.edu. [2]Planetary Science Institute, 1700 E. Ft. Lowell, Tucson, AZ 85719 USA. [3]Physics Institute, Space Research and Planetary Sciences Center for Space and Habitability, University of Bern, Switzerland. [4]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ UK.

Introduction: Catastrophic disruptions of asteroids have been modeled numerically [e.g., 1-3]. These events involve shattering, fragmentation and dispersal of the target, followed by gravitational reaccumulation of subsamples of the fragmented material to form a family of offspring. [1-3] found that the largest offspring are each dominated by materials derived from a restricted region in the original body. [4,5] suggested that results of this modeling could be applied to the ureilites, a group of carbon-rich ultramafic achondrites (mantle residues) whose parent body (UPB) is thought to have been catastrophically disrupted early in its history [6-10]. Some of the properties of ureilites may best be explained if all known samples are derived from a daughter body that formed in this event [8-10]. Knowing the degree to which that daughter is a select sample of the UPB, and the depth(s) from which that sample is derived, would help to constrain the petrologic structure of the UPB and therefore models of ureilite petrogenesis. However, [11] argued that the modeling of [1-3] was not relevant to breakup of the UPB because it pertained only to solid targets, whereas the UPB was partly molten at the time of breakup. We have now modeled catastrophic disruptions of asteroids in various states of melting. We compare the results with those for solid targets, and discuss implications for ureilite petrogenesis.

Numerical Modeling and Results: The radius of the target was 125 km. Four cases were considered: 1) fully molten; 2) half molten by mass (molten outer layer, 26 km thick); 3) solid except for a molten layer at 10 km depth (10% of asteroid mass); 4) fully solid. We use the material properties of basalt for the solid.

Simulations of catastrophic disruption of the target, using a 84 km-diameter projectile impacting at 5 km/s at a 45° angle, were carried out in two phases [1-3]: 1) the fragmentation phase is computed using the 3D SPH hydrocode of [12] in which several fragmentation models were introduced and validated; 2) the gravitational phase, in which fragments reaccumulate, is computed using the numerical code pkdgrav [13].

The number of SPH particles representing the target is ~800,000. The minimum particle size limited by resolution is ~3 km. The paths taken by the particles from their original positions in the target to their final ones in reaccumulated bodies are tracked. We can thus determine the original depths within the parent of the particles forming the offspring. This is the first time we have quantified such information [1-3]. Results are shown in Fig. 1. In the fully molten case, the material in each of the offspring represents essentially the entire parent. In the other cases, the 3 largest offspring each preferentially samples distinct regions (depths) of the parent (as predicted by [2]) with detailed differences depending on amount and location of melt.

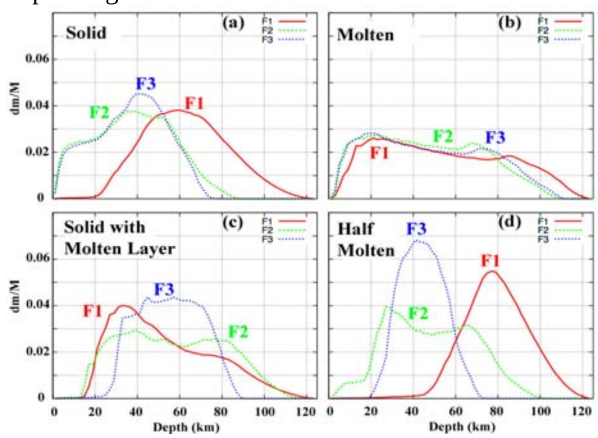

Fig. 1. Fraction of mass contained in the three largest offspring (F1, F2, F3 in decreasing size), as a function of original depth within the target. Bin size is 2 km and curves are normalized by the mass of the corresponding offspring.

Models for Ureilite Petrogenesis: Ureilites show a large variation in olivine Fo (molar Mg/[Mg+Fe]). The 2 main models to explain this variation are: 1) low-pressure smelting (reduction of $FeO \rightarrow Fe^0$ by C) on the UPB [8,14-16]; 2) nebular inheritance, with high-pressure suppression of smelting on the UPB [11,17]. The 2 models have different implications for the size of the UPB and depths of derivation of ureilites.

In the smelting model, Fo values, combined with equilibration temperatures (T), constrain pressures (therefore depths) of derivation. Using T from [15] for the ureilite Fo range (74-95), we calculate a pressure range of ~87 to 34 bars. The maximum size of the UPB can then be constrained from thermal modeling (^{26}Al heat source) by requiring that peak T are reached at the depth corresponding to 34 bars [18]. Previously we determined a maximum radius of 125 km, assuming a 10 km thick cold outer shell [18]. New ideas about the density [19] and thermal properties [20] of the cold outer shell indicate that it was likely only ~6 km thick. This value, plus a more detailed density model for the asteroid, leads to a new maximum radius of ~214 km with a metallic core or ~270 km without.

The distribution of ureilite Fo values is strongly peaked at 79-80 [8]. In smelting, this implies that the majority of ureilites are derived from a limited range of depths [4,11]. Calculated depth distributions (232 main group ureilites) for 125 km radius and 214 km radius UPB (with cores) show that the majority of ureilites are derived from ~18 km depth in the former and ~11 km depth in the latter (Fig. 2).

In the nebular inheritance model (assuming C is present), each ureilite must be derived from a depth (pressure) above the smelting limit for its Fo. For the peak (Fo 79-80), this limit is ~80 bars at 1200°C [11] or 150 bars at 1300°C. The latter (peak T) leads to a minimum UPB size of ~95 km radius with no core (ureilites at center of asteroid) or 89 km with core (ureilites at core-mantle boundary). If ureilites are derived from the top of the mantle, asteroids >400 km radius are required. If the radius is 225 km, then ureilites must be derived from >18 km depth.

Evidence for an Early Major Impact on the UPB: All ureilites show evidence of rapid cooling (~0.05 to 10°C/hr) and a drop in pressure through ~1100-600°C [8,10]. This is interpreted to result from excavation by a large impact while the UPB was still hot [8-10]. An age of ~5 Ma after CAI may record this event [21]. The 0.05-32 Ma exposure ages of ureilites [22] require that they were then stored somewhere before delivery to Earth. Whether this was a reassembled daughter or a layer of rubble reaccreted to the UPB has been debated [8-10,23], with opinion favoring the daughter.

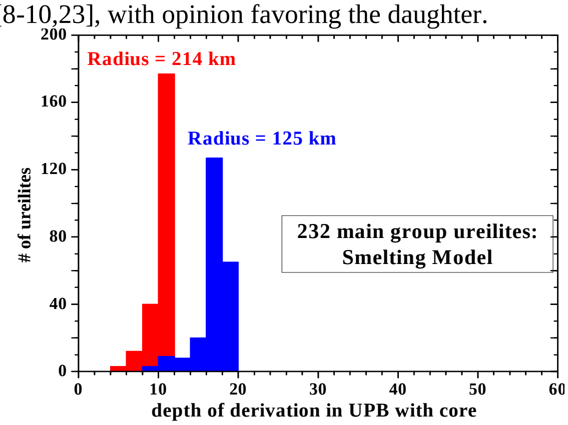

Fig. 2. Depth distributions for ureilites in smelting model.

Discussion: We compare results of the numerical modeling of catastrophic disruption (depths of derivation in parent for material in offspring) and the petrologic modeling (depths of derivation of ureilites in various petrogenetic models). The numerical modeling strictly applies only to targets of 125 km radius. At 5 Ma after CAI the UPB probably had a near solid mantle (<0.2% melt), with a layer of melt ~1.4 km thick, at ~ 6 km depth [18], so the case of solid target with molten layer (Fig. 1c) is most relevant to the UPB.

Comparing Fig. 1c with Fig. 2 (125 km radius in smelting model), the 3 largest offspring all derive the majority (peak) of their material from greater depths than those represented by ureilites. They also derive most of the rest of their material from deeper than the peak, whereas most of the rest of the ureilites are derived from shallower. A better match of peak depths might be obtained with a slightly smaller asteroid (e.g., 90 km radius), but this slight change in target size might not change the result that the rest of the material in the offspring is derived from deeper than the peak. If the UPB was its maximum size of 214 km radius (Fig. 2), then ureilites would represent shallower depths (peak ~11 km). Thus, if results of the numerical modeling are similar for larger targets (the majority of material in the offspring is derived from deep), then there would be an even greater mismatch to ureilites. Results so far do not support the smelting model in a catastrophic disruption and reassembly scenario. On the other hand, the new estimates of the size of the UPB in the smelting model indicate larger sizes and shallower derivation of ureilites than previously [18]. This suggests that the excavation inferred for ureilites [6-10] could have been a sub-catastrophic impact.

The nebular inheritance model provides fewer constraints than smelting, but most likely requires larger UPB sizes (>200 km radius). It also permits (but does not require) ureilites to be derived from deeper in the UPB. Thus, if the results of the numerical modeling remain similar for larger targets, they could be consistent with the nebular inheritance model.

Future Work: So far our numerical modeling of catastrophic impacts has explored only a small part of parameter space. Our next step will be to model larger targets. We will also explore sub-catastrophic impacts.

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