BREAKUP AND REASSEMBLY OF THE UREILITE PARENT BODY, FORMATION OF 2008 TC$_3$/ALMAHATA SITTA, AND DELIVERY OF UREILITES TO EARTH. 1William K. Hartmann, 1Cyrena A. Goodrich, 2David P. O'Brien, 2Patrick Michel, 3Stuart J. Weidenschilling and 1Mark V. Sykes. 1Planetary Science Institute, 1700 E. Ft. Lowell Dr., Tucson AZ 85719, USA. 2Observatoire de la Côte d’Azur, CNRS/UMR 6202 Cassiopee, Bd de l’Observatoire, B.P. 4229, 06304 Nice cedex 4, France.

Introduction: Ureilites form the 2nd largest group of achondrites. Main group ureilites (94%) are ultramafic rocks thought to represent the residual mantle of a partially differentiated, carbon-rich asteroid [1]. They exhibit a large range in olivine composition (Fo 75–95) that cannot be explained by normal igneous fractionation [1-3]. Several lines of evidence strongly suggest a single parent body [4,5]. Approximately 6% of ureilites are polymict breccias, thought to represent a regolith [1]. More than 97% of the material in polymict ureilites is indistinguishable from main group ureilites [4,5]. The remainder includes feldspathic clasts that may represent basalts from the ureilite parent body (UPB), and a variety of foreign (angritic, R-, E- and O-chondritic) materials [4-6].

On October 7, 2008, a small asteroid (~4 m diameter) called 2008 TC$_3$ exploded over Sudan [7,8]. More than 600 stones were recovered and named Almahata Sitta [7,8]. The first samples studied were fine-grained, porous ureilite material [7]. Additional samples included compact olivine-pyroxene assemblages similar to the entire range of main group ureilites, plus various non-ureilitic materials [8-13]. The latter appear to be mainly E chondrites (EH, EL and breccias), with lesser O-, R- and unique chondrite types. Thus, 2008 TC$_3$ was a complex meteoritic breccia.

Complete petrographic characterization of 2008 TC$_3$ is critical to understanding its origin. All recovered Almahata Sitta (AHS) samples are small fragments (0.2-379g), and all of those studied so far (~75) are single lithologies (no contacts). Based on estimates of the pre-atmospheric mass of 2008 TC$_3$ (~83t to ~42t [7,14,15]), and a total fallen mass of 39±6 kg [8], >99.9% of the mass of the asteroid was lost in Earth's atmosphere. Combined with estimates of 20-55% macroporosity [14-16], this suggests that the asteroid consisted largely of fine-grained matrix weakly cementing together a small fraction of isolated, cm-sized fragments (the recovered samples). The composition of the matrix is unknown. Based on [7-13], 2008 TC$_3$/AHS shows important differences from normal polymict ureilites: 1) The clast/matrix ratio is much lower, and the bulk rock less coherent; 2) The fraction of non-ureilitic material is much higher (20-30% vs. ≤1%), at least among the clasts; 3) Among non-ureilitic materials, no achondritic materials are found; 4) The feldspathic component has not been observed; 5) AHS may have a higher proportion of fine-grained, porous and highly magnesian material.

UPB Origin: Oxygen, Cr and Os isotopic compositions, as well as several bulk compositional parameters [17-20] indicate that ureilite precursor material was similar (though not identical) to known CCs, which suggests (via asteroid spectra and theoretical considerations) that the UPB accreted in the outer asteroid belt. Petrological evidence indicates that ureilites were heated to ~1300°C and lost their entire basaltic component [1]. Current accretion models predict the rapid formation of bodies large enough to melt in the outer belt, and are consistent with the UPB having accreted and begun to melt within ~1 Myr of CAI [21]. Jenikens et al. [7] suggested that the UPB originated in the terrestrial region, and was later swept into the asteroid belt. This is unlikely because O-isotopes of ureilites are inconsistent with most materials from the inner asteroid belt or terrestrial region [17].

Breakup of the UPB: All ureilites show petrological evidence of extremely rapid cooling (10-20°C/hr), along with a drop in pressure, through ~1100-600°C [1]. This could result from catastrophic disruption of the UPB while still hot [4,10,22,23]. A radiometric age of ~5 Myr after CAI from $^{26}$Al-$^{26}$Mg and $^{53}$Mn-$^{53}$Cr chronometry may record this event [24]. The existence of polymict ureilites and observation that they show the same distribution of Fo as main group ureilites on the whole [4,5], suggest that these meteorites resided together in an offspring body that formed in the aftermath of the catastrophic disruption [4].

Catastrophic disruptions involve shattering, fragmentation and dispersal, followed by gravitational re-accumulation of some of the fragments to form a family of offspring [25-27]. The few largest offspring tend to consist of materials derived from well-defined, restricted regions within the parent [26]. We suggest that one such daughter, probably a selective sample of the UPB, became the source of all materials that have made it to Earth as ureilites and AHS.

Evolution of the UPB Daughter: AHS contains a significant amount of E- and O-chondrite material, which spectral evidence suggests is well-separated from CC material in the belt [28]. Oxygen isotopes also associate these materials with the inner asteroid belt and terrestrial region [17]. Thus, it is unlikely that these materials were acquired during assembly of the UPB daughter (as suggested by [12]), if the catastrophic disruption occurred in the outer belt. It is also unlikely that a regolith rich in E- and O-chondrite ma-
mterial developed on a UPB daughter in the outer belt, so we infer that the UPB daughter must have spent sufficient time in the inner asteroid belt and/or terrestrial region to accrete this material. Some models [29-31] suggest that at 5 Myr after CAI the asteroid belt was still massive and had planetary embryos in it. If the UPB broke up in the outer asteroid belt at this time, interactions with the embryos over the next ~10-100 Myr would scatter the daughters in semimajor axis and drive many into resonances that would eject them from the belt. Most bodies that remained would only be scattered ~0.1 AU, but a few would be scattered more than 1 AU, perhaps to the inner main belt. This may have been the fate of one of the largest UPB daughters.

Alternatively, a combination of gas drag and resonances could have led to rapid migration of ~100 km-scale bodies from the outer asteroid belt inwards, within the first few Myr of Solar System history when significant nebular gas was present [32]. In this case the UPB could have migrated intact to the inner asteroid belt and broken up there (at 5 Myr after CAI). Subsequent scattering and depletion [29-31] could then remove most of the daughters, leaving just one or a few capable of delivering meteorites to Earth today.

After being emplaced or created in the inner belt by one of these mechanisms (or a different one), the daughter would have suffered repeated bombardment by local materials. A deep regolith, consisting of an intimate mix of the different ureilitic materials in the daughter and local non-ureilitic materials (dominated by a variety of E-, with lesser O- and R-chondrites), could have developed over time. In this model, 2008 TC$_3$/AHS would be derived from shallow regolith (highly pulverized, high proportion of impactor materials), while normal polymict ureilites would be derived from deeper regolith (better lithified, coarser-grained, lower proportion of impactor materials), and main group ureilites from the interior.

Formation of 2008 TC$_3$: The regolith-encrusted UPB daughter must then have suffered an impact sufficient to break it up, with the resulting fragments subsequently drifting due to the Yarkovsky effect into a resonance that kicked them onto Earth-crossing orbits. One of these fragments would be 2008 TC$_3$. This second breakup may be dated by the ~0.05-35 Myr cosmic ray exposure ages of ureilites and AHS [15,33].

Outstanding Issues: There are some potential problems in the scenario discussed. (1) In order to survive as clasts in regolith, foreign material must be implanted at low velocity, but at impact velocities typical in the main belt (~5 km/s [34]), impactors may be mostly destroyed. On the other hand, 99.9% of the mass of 2008 TC$_3$ is inferred to have been extremely fine-grained material, so perhaps the regolith need only contain a small fraction of intact impactor material. (2) The apparent large ratio of enstatite to ordinary chondrite material in AHS [12] is inconsistent with asteroid spectral studies suggesting that enstatite material is relatively rare in the present-day inner belt [35]. This apparent inconsistency may disappear when the enstatite/ordinary chondrite ratio in AHS is better constrained. Otherwise, it might require a period of residence in the terrestrial planet zone or a primordial inner belt much richer in enstatite material than it is today [36]. Alternatively, the breakup of the UPB might have been a stochastic event involving an enstatite breccia impactor. (3) Differences between clast types in AHS and normal polymict ureilites (absence of feldspathic and angritic materials in AHS) may not be explained. Feldspathic clasts in polymict ureilites are typically very small, so those in AHS may have been lost in Earth’s atmosphere, and angrites may yet be found in AHS. Nevertheless, continued studies of AHS and normal polymict ureilites are needed to test this scenario.

Conclusion: Almahata Sitta provides clues not only to ureilite history but also to the dynamics and evolution of the asteroid belt, impact fragmentation, and delivery of meteorites to Earth.