ALMAHATA SITTA IS NO MORE EXOTIC THAN ANY OTHER POLYMICT UREILITE.

C. A. Goodrich,[1] W. F. Bottke[2], K. J. Walsh[2], and R. T. Daly[3], [1]Lunar and Planetary Institute, USRA-Houston, 3600 Bay Area Blvd, Houston TX 77058 USA, goodrich@lpi.usra.edu; [2]Southwest Research Institute, Boulder CO 80302 USA; [3]Johns Hopkins University Applied Physics Laboratory, Laurel MD 20723 USA.

Introduction: Almahata Sitta (AhS) fell in 2008 when asteroid 2008 TC_3 (~4 m) disintegrated over Sudan [1,2]. The recovered ~cm-sized stones (<1% of the mass of the asteroid) include ureilites (achondrites) and diverse chondrites (OC, EC, RC, CC) [3,4]. Based on the predominance of ureilites among stones studied so far, AhS is classified as an anomalous polymict ureilite [1]. However, how the recovered stones were related to one another in the asteroid, and the composition of the missing 99% of its mass, are unknown [4,5]. The "extraordinary" mix of meteorite types in AhS has led to "exotic" models for formation of 2008 TC_3 [3,6].

Main group ureilites are carbon-rich ultramafic achondrites that represent the mantle of a partially differentiated asteroid [7]. They show a characteristic range and distribution of compositions (Fig. 1), and low to high shock levels. Typical polymict ureilites (TPUs) (~7% of all ureilites) are fragmental and regolith breccias consisting of clasts of mixed main group ureilite materials with the same range and distribution of compositions, as well as shock states, as main group ureilites [8-10]. They also contain a few % feldspathic clasts representing ureilitic crustal rocks [10,11], and ~10% xenoliths [12]. They are interpreted as having formed in ureilitic regolith, with the xenoliths being impactor remnants [4,8,9,13,14].

While AhS/2008 TC_3 is famous, TPUs are too often ignored. We argue here that AhS and TPUs are similar and most likely share a common origin.

Almahata Sitta vs. TPUs – Compositions: The range and distribution of compositions of AhS ureilitic stones studied so far is nearly identical to the range and distribution shown by ureilitic clasts in TPUs and main group ureilites (Fig. 1). AhS also contains feldspathic ureilites with distinctive compositions like those of the feldspathic clasts in TPUs [15].

The range of types of non-ureilites in AhS is no more extraordinary than that in TPUs, which are noted for containing xenoliths from every major chondrite class (OC, EC, RC, CC), including multiple groups (i.e., H, L, LL, EH, EL) and petrologic types (1-6) of each [13]. There are differences, however, in relative abundances. CC clasts are the most common in TPUs, while EC are only found as mineral fragments [16,17]. Conversely, CC are rare in AhS while EC are the most abundant non-ureilites. In addition, the achondrite types found as rare xenoliths in TPUs (angrites and NWA 7325-like) have not been found in AhS.

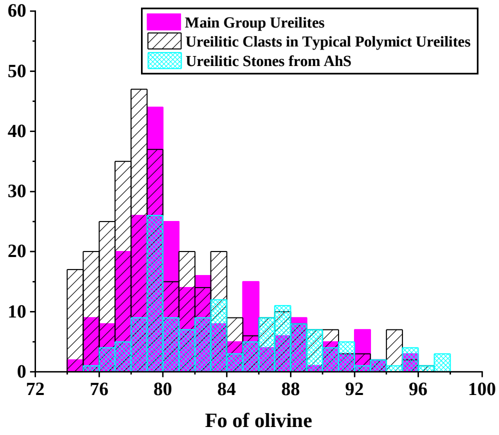

Fig. 1. Histogram of olivine Fo (100 x molar Mg/[Mg+Fe]) in main group ureilites, ureilitic clasts in typical polymict ureilites, and ureilitic stones from AhS.

The abundance of non-ureilites in AhS/2008 TC_3 been regarded as anomalously high [3] compared with the abundance of xenoliths in TPUs (19-35% of AhS stones studied so far are non-ureilites). However, if 2008 TC_3 was mainly ureilitic, as has been argued from the asteroid reflectance spectrum [18], the abundance of non-ureilitic clasts must have been much lower than among the surviving stones, possibly similar to or even lower than that in TPUs.

Almahata Sitta vs. TPUs – Structure: The AhS stones, which were clasts in 2008 TC_3, are ~0.5 to 6 cm in size, larger than clasts in TPUs (<1-2 cm, most being μm to a few mm). The significance of this difference is unknown. Most of 2008 TC_3 could have had smaller clast sizes than the recovered stones (larger clasts are more likely to have survived), and given that TPUs are usually studied in small sections (1-inch diameter), their largest clasts may not have been recognized (e.g., some sections consist of single ureilitic clasts).

Nevertheless, an obvious difference between AhS and TPUs is that 2008 TC_3 was weak and disintegrated in the atmosphere [19,20]. This may be because the matrix of the asteroid was similar to the fine-grained, porous, highly-shocked ureilitic stones [3], which are also a plausible spectral match to the asteroid [18]. This suggests the possibility that 2008 TC_3 was derived from shallow, loosely-consolidated regolith, while typical polymict ureilites were derived from deeper, more mature regolith, on the same ureilitic body [4].

Alternatively, the matrix of the asteroid may have been similar to AhS stone 91A, which is a very friable, phyllosilicate-rich CC xenolith [5]. AhS 91A provides an even better match to the asteroid's spectrum, as well as its density and porosity, than the fine-grained ureilites [5]. This suggests the possibility that 2008 TC_3 was derived from a volume consisting mainly of xenolithic CC material in the same regolith as that sampled by TPUs (CC are the largest xenoliths in typical polymict ureilites), analogous to some dark regions on Vesta [22].

Formation of Polymict Ureilites: All scenarios for formation of polymict ureilites begin with the catastrophic disruption of the ureilite parent body (UPB) at ~5-5.4 Myr after CAI [4,8,9,14,21,23]. This event produced ureilite daughter bodies (UDB) made of jumbled materials from various parts of the UPB [24]. The observation that TPUs show the same range and distribution of compositions as main group ureilites (Fig. 1) suggests that TPUs developed on one of these daughters – not on the UPB – because the observed distribution is not igneous and so likely represents selective sampling that occurred during disruption and reassembly [24]. But, where and how did AhS form?

The timing and high-energy impact conditions required for the catastrophic disruption of the UPB led [6,25] to suggest that the impactor was a C-type body driven into the inner Solar System during giant planet migration, as in the Grand Tack dynamical model [26]. [3,6] argued that the non-ureilites in AhS represented local debris (generated in the high impact frequency environment of the Grand Tack) that accreted along with ureilitic material during formation of the UDB. However, many of the observed xenolith types (higher petrologic types of OC, EC, and RC) did not come into existence until ~40-60 Myr after CAI [12]. Thus, most of the xenoliths in polymict ureilites had to be implanted into ureilitic regolith at or more recently than 40-60 Myr after CAI, not during UDB formation [12].

TPUs show clastic textures and a wide range of shock levels of clasts. This indicates an extended history in a regolith environment, involving multiple impacts of various severities, extensive comminution, and mixing. Although impact glasses are rare, these breccias are coherent, which suggests that they were lithified by localized shock melting at grain corners and edges. Formation of consolidated breccias is thought to require the kinds of shocks produced in the breccia lens of a 10 km diameter or larger crater, and that means they need to form on a body large enough to sustain such impacts without disruption [27,28]. Accordingly, we postulate that TPUs developed as regolith on a relatively large UDB.

While it is possible, as discussed above, that 2008 TC_3 represents a loosely-consolidated region within this same regolith, we must also consider the possibility that it instead formed in a manner similar to that proposed for Bennu (0.5 km) and Ryugu (1 km), two CC asteroids with exogenic boulders [29,30]. These asteroids took hundreds of Myr to escape the main belt, and their transit involved numerous cratering/disruption events. Such events might add new exogenic material via a collisional cascade, perhaps enough to explain the non-ureilites in 2008 TC_3 [28,31]. As discussed above, such small bodies would be unable to sustain large enough impacts to produce lithified breccias (like TPUs), and thus would remain loosely consolidated and weak.

The question is whether two evolutionary paths are needed for AhS and TPUs. By Occom's razor, the overall similarity in the clast populations between the two largely argues against this option. Instead, it seems more likely that AhS/2008 TC_3 formed in the same regolith as TPUs. Differences in the abundances of xenolith types could be explained by heterogeneous distribution of impactor remnants in the regolith or sampling biases (although they could also be explained by two different evolutionary paths). Differences in coherency and clast size could be explained by derivation from different regions or depths in regolith.

Conclusion: Although the composition and structure of 2008 TC_3 are unknown (and may never be known for certain), available data indicate that AhS and TPUs were probably derived from the same regolith.

References: [1] Jenniskens P. et al. (2009) *Natur* 458, 485-488. [2] Shaddad M.H. et al. (2010) *M&PS* 45, 1618-1637. [3] Horstmann M. & Bischoff A. (2014) *ChEG* 74, 149-183. [4] Goodrich C.A. et al. (2015) *M&PS* 50, 782-809. [5] Goodrich C.A. et al. (2019) *M&PS* 2769-2813. [6] Scott E.R.D. et al. (2018) *ApJ* 854:164. [7] Mittlefehldt D.W. et al. (1998) in *RIM* 36, 195 pp. [8] Goodrich C.A. et al. (2004) *ChEG* 64, 283-327. [9] Downes H. et al. (2008) *GCA* 72, 4825-4844. [10] Ikeda Y. et al. (2000) *AMR* 13, 177-221. [11] Cohen B. et al. (2004) *GCA* 68, 4249-4266. [12] Goodrich C.A. et al. (2020) *PSJ*, in press. [13] Bischoff A. et al. (2006) in *MESS II*, 679-712. [14] Herrin J. et al. (2010) *M&PS* 45, 1789-1803. [15] Bischoff A. et al. (2015) *PNAS* 111, 12,689-12,692. [16] Goodrich C.A. et al. (2015), *78th MSM*, #5018. [17] Boleaga Y. & Goodrich C.A. (2019) *LPSC* 50, #1622. [18] Hiroi T. et al. (2010) *M&PS* 45, 1836-1844. [19] Welten K.C. (2010) *M&PS* 45, 1728-1742. [20] Boroviĉka J. & Charvát Z. (2009) *A&S* 507, 1015-1022. [21] Keil K. et al. (1994) *P&SS* 42, 1109-1122. [22] Reddy V. et al. (2012) *Icar* 221, 544-559. [23] Goodrich C.A. et al. (2010) *E&PSL* 295, 531-540. [24] Michel P. et al. (2015) *P&SS* 107, 24-28. [25] Johnson B.C. et al. (2016) *SciA* 2, e1601658. [26] Walsh K.J. (2012) *M&PS* 47, 1941-1947. [27] Scott E.R.D. & Bottke W.F. (2011) *M&PS* 46, 1878-1887. [28] Bottke W. et al. (2020) *DPS* 52, 402.02. [29] DellaGiustina D.N. et al. (2020) *NatAs (Aug. 31)*. [30] Tatsumi E. et al. (2020) *NatAs (Aug. 31)*. [31] Walsh K.J. et al. (2020) *LPSC* 51, #2253.