CARBONACEOUS CHONDRITE-LIKE XENOLITHS IN POLYMICT UREILITES: A LARGE VARIETY OF UNIQUE OUTER SOLAR SYSTEM MATERIALS.

C. A. Goodrich[1], M. Zolensky[2], I. Kohl[3], E. D. Young[3], Q.-Z. Yin[4], M. E. Sanborn[4] and M. H. Shaddad[5]. [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston TX 77058 USA goodrich@lpi.usra.edu; [2]ARES, NASA-JSC, Houston TX 77058 USA; [3]Univ. of California at Los Angeles, Los Angeles CA 90095 USA; [4]Univ. of California at Davis, Davis CA 95616 USA; [5]Univ. of Khartoum, Khartoum 11115 Sudan.

Introduction: Dark, carbonaceous chondrite (CC)-like xenoliths are common in typical polymict ureilites and have been described as mineralogically similar to CI chondrites [1-5]. However, the bulk oxygen isotope composition of one CC-like clast from the Nilpena polymict ureilite (Fig. 1) showed it to be unlike CI or any other known CC [2]. In addition, D/H ratios and S isotope compositions of several of these clasts have been found to be distinct from those of CI [6,7].

The anomalous polymict ureilite Almahata Sitta (AhS) also contains unique CC lithologies. AhS 202 is a magnetite-rich (>10%) C2 that has oxygen isotope composition in the range of CR or CM (Fig. 1) but is mineralogically unlike any known CC [8,9]. AhS 91A and 671 are breccias that consist of C1 matrix material enclosing fragments of ureilitic minerals, as well as chondrule and chondrule fragments from OC and metal-sulfide from EC [9,10]. Breccias like AhS 91A and 671 may have comprised a large fraction of 2008 TC$_3$, the immediate source asteroid of AhS [10].

These CC-like materials are of great interest because they constitute direct evidence for mixing of inner solar system (ureilite) and outer solar system (CC) materials [11,12] and provide the opportunity to test dynamical models such as the Grand Tack, the Nice Model, and others [13-15]. They also provide samples of CC-like lithologies not sampled as whole meteorites, increasing knowledge of the range of volatile-rich materials in the early Solar System.

We are studying the mineralogy and oxygen and Cr isotopes of CC-like clasts in typical polymict ureilites, focusing here on two main goals: 1) determine the variety of CC-like materials in polymict ureilites and compare them with known CC; and 2) compare the CC-like lithologies in AhS with those in typical polymict ureilites, to test the hypothesis that AhS and typical polymict ureilites are derived from the same body [16] and constrain their formation mechanism [16,17]. We report on 9 new clasts from polymict ureilite Northwest Africa (NWA) 10657.

Methods: Back-scattered electron imaging (BEI), X-ray mapping, electron microprobe analysis (EMPA), and transmission electron microscopy (FIB/TEM) were conducted at ARES, JSC. Bulk oxygen isotope analysis was conducted at UCLA. Cr isotope analysis was conducted at UC Davis. Oxygen isotope analyses of magnetite by SIMS are reported in [18].

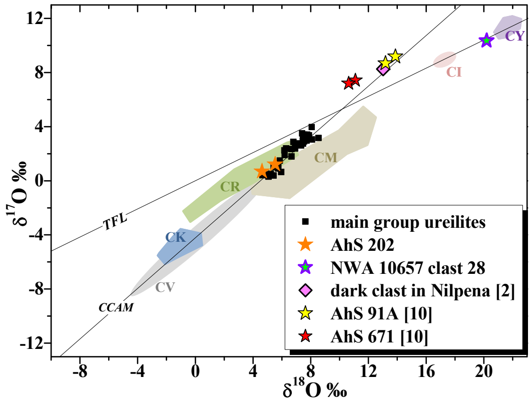

Fig. 1. Oxygen three isotope plot showing bulk compositions of AhS 91A, 671, and 202, and NWA 10657 clast 28, compared with ureilites and major groups of CC.

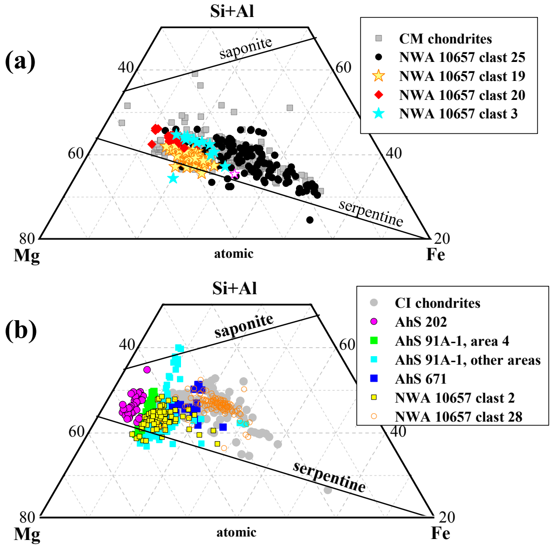

Fig. 2. Ternary compositions of phyllosilicates comparing CC-like clasts in AhS and NWA 10657 with CM and CI chondrites. Data for AhS 91A, 671 and chondrites from [10].

Results: All clasts studied (~0.2-3.4 mm in size) are hydrous CC matrix-like lithologies consisting dominantly of phyllosilicates (serpentine + saponite) with highly varying proportions and compositions of magnetite, carbonates, sulfides, fayalitic olivine, and relict anhydrous silicates (mainly olivine). Phyllosilicates vary in Fe/Mg ratio and apparent serpentine/saponite ratio (Fig. 2). Four of the clasts (e.g., Fig. 3) have phyllosilicate compositions distinctly more like those of CM than CI (Fig. 2a). One of these contains a phase tentatively identified as tochilinite, which is characteristic of CM2, and two contain dolomite, consistent with CMs and CIs [19,20]. However, they all contain significant magnetite, which is more common in CIs [19,20]. These 4 clasts all have rims enriched in Fe and S (Fig. 3), whereas none of the other clasts studied show rims.

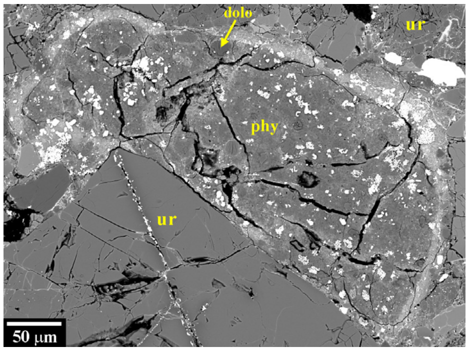

Fig. 3. BEI of CM-like (?) clast 19 in NWA 10657, containing phyllosilicates (phy), dolomite (dolo), and sulfides and magnetite (bright). Rim is enriched in Fe & S.

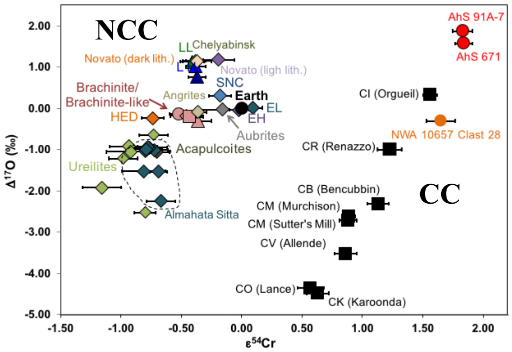

Fig. 4. Plot of ε^{54}Cr vs. Δ^{17}O showing dichotomy between inner (NCC) and outer (CC) solar system materials. Clasts in polymict ureilites increase the variety of CC materials.

Of the other 5 clasts studied, each is distinct. We highlight two. Clast 28 has CI-like phyllosilicate compositions (Fig. 2b), with magnetite and common relict anhydrous silicates (Fo ~99 and Fo ~75 olivine). It appears to have extremely low S content (no sulfides observed and matrix analyses show low S) compared with known CIs. Its oxygen isotope composition (Fig. 1) is close to TFL (Δ^{17}O = –0.307±0.006) and plots between the fields of CI and Y82162-like (thermally metamorphosed) CC [21]. Its Cr isotope composition (Fig. 4) is unique but most similar to CI.

Clast 2 has important similarities to AhS 91A/671. The latter is heterogeneous, with some areas being CI-like and others rich in flaky, fayalitic olivine [10]. Most of clast 2 resembles such fayalite-rich areas (Fig. 5). Phyllosilicates in clast 2 are Mg-rich and similar to those in AhS 91A/671 (Fig. 2b). Clast 2 also contains bruennerite as in AhS 91A/671 [10]. Notably, the CC material in clast 2 encloses fragments of ureilitic olivine (Fig. 5b), similar to AhS 91A/671 [10].

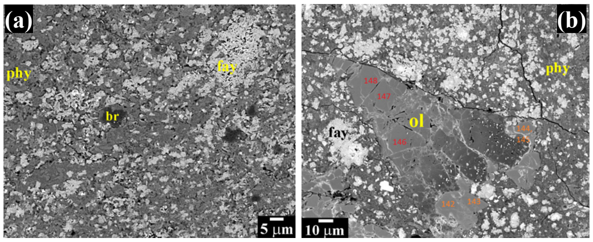

Fig. 5. (a) AhS 671, showing area of phyllosilicates (phy), flaky fayalitic olivine (fay), and bruennerite (br); (b) NWA 10657 clast 2, showing similar mineralogy as [a], with enclosed fragment of ureilitic olivine (ol), identified by composition and characteristic reduction zones.

Discussion: The variety of CC-like lithologies found in polymict ureilites continues to increase. The possibility that some are more like CM than CI contrasts with [5]. Similar clasts having Fe- and S-enriched rims (Fig. 3) may derive from a common impactor; the rims may have formed by reaction with a transient volatile-rich atmosphere during impact.

NWA 10657 clast 2, with its essential similarities to unique AhS breccias 91A and 671, could be critical to distinguishing secondary accretion vs. regolith models for formation of AhS [16,17]. [10] hypothesized that AhS 91A/671 represent a volume of ureilitic regolith in which a CC-like body impacted an already well-gardened mixture of ureilitic + impactor-derived (e.g., OC, EC) fragments. The discovery of similar breccias in typical polymict ureilites, which are regolith and fragmental breccias thought to have formed as regolith on a ureilitic asteroid [4,22], supports this hypothesis.

References: [1] Prinz M. et al. (1987) *Meteoritics* 22, 482-483. [2] Brearley A.J. & Prinz M. (1992) *Geochim. Cosmochim. Acta* 56, 1373-1386. [3] Ikeda Y. et al. (2003) *Antarctic Meteorite Research* 16, 105–127. [4] Goodrich C.A. et al. (2004) *Chemie der Erde* 64, 283–327. [5] Patzek M. et al. (2018) *Meteorit. Planet. Sci.* 53, 2519-2540. [6] Patzek M. et al. (2017) 80th MSM, #6183. [7] Visser R. et al. (2018) 81st MSM, #6190. [8] Fioretti A.M. et al. (2017) LPSC 48 #1846. [9] Goodrich C.A. et al. (2018) LPSC 49, #1321. [10] Goodrich C.A. et al. (2019) *Meteorit. Planet. Sci.*, submitted. [11] Yin Q.-Z. et al. (2018) LPSC 49, #1810. [12] Sanborn M. et al. (2017) 80th MSM, #6277. [13] Morbidelli A. et al. (2015) In *Asteroids IV*, 493-508. [14] Walsh K. et al. (2011) *Meteorit. Planet. Sci.* 47, 1941-1947. [15] Izidoro A. et al. (2018) DPS 50, 308.02. [16] Goodrich C.A. et al. (2015) *Meteorit. Planet. Sci.* 50, 782-809. [17] Horstmann M. & Bischoff A. (2014) *Chemie der Erde* 74,149-183. [18] Goodrich C.A. et al., this meeting. [19] Zolensky M. et al. (1997) *Geochim. Cosmochim. Acta* 61, 5099-5115. [20] Rubin A. et al. (2007) *Geochim. Cosmochim. Acta* 71, 2361-2382. [21] Tonui et al. (2014) *Geochim. Cosmochim. Acta* 126, 284-306. [22] Downes H. et al. (2004) *Geochim. Cosmochim. Acta* 72, 4825–4844.