MAGMATISM IN THE OUTER SOLAR SYSTEM: WHAT WE KNOW NOW FROM ISOTOPE FORENSICS OF CARBONACEOUS ACHONDRITES. M. E. Sanborn[1], and Q.-Z. Yin[1] [1]Department of Earth and Planetary Sciences, University of California-Davis, One Shields Avenue, Davis, CA 95616 (E-mail: mesanborn@ucdavis.edu).

Introduction: For a long time, the classical paradigm for carbonaceous materials, which ostensibly originated from the outer Solar System, was that they were entirely composed of undifferentiated objects (i.e., carbonaceous chondrites). However, this 'classical view' has been rapidly evolving in recent years. Early indication for the potential of differentiation activity in the carbonaceous region occurred with the measurement of the pallasite Eagle Station with a Cr isotopic composition similar to that of carbonaceous chondrites [1,2]. Later, the achondrite Northwest Africa (NWA) 3133, dubbed as CV7, was found whose oxygen isotopes and bulk composition were similar to that of CV chondrites [3]. Subsequent measurement of the ^{54}Cr and ^{50}Ti isotopic composition of the achondrite NWA 011/2976 further found excesses relative to Earth, similar to that of the carbonaceous chondrites [4,5]. Additionally, paleomagnetic evidence in CV chondrites [6] was used to infer the potential occurrence of evolved internal bodies in the carbonaceous region of the Solar System. Model calculation indeed showed that internal melting and partial differentiation of carbonaceous chondrite parent bodies was thermodynamically feasible [7].

More recently, there has been a rapid increase in the number of samples, nearly all originating from Northwest Africa, that have geochemical or oxygen isotope traits that have encouraged investigations as to their potential origin in the carbonaceous regions of the early Solar System. This influx of samples and the comprehensive effort to isotopically 'fingerprint' these materials using nucleosynthetic anomalies (^{54}Cr and ^{50}Ti) at the University of California-Davis (UC Davis) have begun to illustrate the complex evolution of planetesimals in the early, outer Solar System. Here, with the rapid increase in the data available, we discuss what the present state of knowledge is for the evidence of magmatic activity in the outer (carbonaceous) region of the Solar System. In particular, the advancement in our understanding of the extent and diversity of magmatic activity occurring in the outer Solar System.

Samples and Analytical Methods: The samples investigated within these studies have involved a wide range of material types. Samples include silicate inclusions from a pallasite (Milton) [8], achondrites with igneous or metamorphosed textures (NWA 011, 1839, 2788, 2976, 3133, 6693, 6704, 7822, 8186, 10132, 10503, 12264, Tafassasset) [9-14], and highly metamorphosed chondrites [9]. All sample preparation was completed and analytical measurements made at UC Davis using a Thermo *Triton Plus* TIMS for Cr and Thermo *Neptune Plus* MC-ICPMS for Ti measurements (see [9] for details of the analytical procedure).

Results: Figures 1 and 2 shows the current survey of differentiated materials known to have formed from the carbonaceous reservoir.

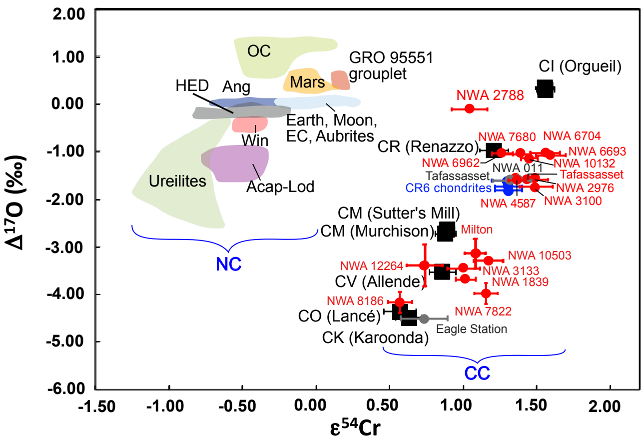

Fig. 1. Cr-O plot of non-carbonaceous (NC) and carbonaceous (CC) meteorite groups. Adapted from [9] where reference values can be found. Red and blue data points are CC achondrites and chondrites that have been analyzed at UC Davis [8-16]. Grey data points are CC achondrites analyzed prior to and concurrent to this study [2,4,5,17].

With the new data (shown in Figs. 1 and 2), it is evident that there is a significant degree of diversity of differentiated objects that formed from the carbonaceous reservoir of the outer Solar System.

Common carbonaceous chondrite and achondrite reservoirs. There is increasing evidence, based on combined Cr-Ti-O isotope data, for the occurrence of common reservoirs generating both undifferentiated carbonaceous chondrites and differentiated counterparts. This was first suggested based on Cr isotope measurements of the pallasite Eagle Station [1,2]. The potential CC-achondrite reservoir connection has now also been supported by several other achondrites, such as NWA 1839, NWA 3133, and NWA 12264 [10,13]. Importantly, possible common reservoirs have now also been seen for other groups including the CO/CK and CR chondrites [9,10,18].

New previously unsampled parent bodies and core formation evidence. During the study of the carbonaceous achondrites, one feature that has become clear is that some of the carbonaceous achondrites represent parent bodies for which no undifferentiated counterpart has been observed. One such sample is NWA 2788, which is isolated in both Cr-O and Ti-O space (Fig. 1 and 2). Another set of samples are the pallasite Milton and achondrites NWA 7822 and NWA 10503. This cluster of samples are important as this points towards samples of both a crustal and deeper metal-silicate component of a common parent body. The previously reported Eagle Station pallasite [3,19] also plots with the carbonaceous achondrite NWA 8186 and the CK Karoonda. Combining all these data provides us a snapshot of two different parent bodies for which we now have samples of the crust and core/mantle interface, both forming from a carbonaceous isotopic reservoir. Two distinct parent bodies, both with evidence for possible core formation and crustal differentiation, indicate planetesimal-scale differentiation processes in the outer carbonaceous region may be more prevalent than previous evidence suggested.

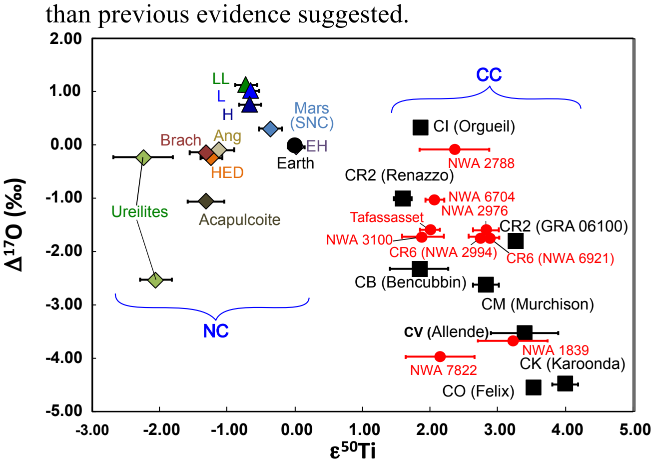

Fig. 2. Ti-O plot of NC and CC meteorite groups. Adapted from [9]. Red data points are CC achondrites that have been analyzed at UC Davis [9,11].

Chronology of magmatic activity. In addition to 'fingerprinting' the reservoirs of magmatic activity, new data has been obtained to place more stringent timing constraints for magmatism on parent bodies in the carbonaceous region. To date, timing of formation has been determined for 5 of the carbonaceous achondrites: NWA 2976/4587 [20,21], NWA 6704/6693 [9,22], NWA 7680/6962 [15], NWA 10132 [14,21], and Tafassasset [17], using a combination of Al-Mg, Mn-Cr and U-Pb chronometers. The ages for all of these meteorites cluster over a small time span of 1 Ma centered around 4563 Ma, meaning the current evidence for differentiation activity samples a compact time interval. This is in contrast with evidence for magmatic activity in the NC region as early as 4565 Ma in the Asuka 881394 and NWA 11119 achondrites [23-25]. One important caveat is that all of the CC achondrite meteorites dated also happen to sample a nearly common region, as all originated from a CR-like Cr-O isotopic composition (Fig. 1). We anticipate this will be improved as we move to date samples like NWA 7822, 10503, 11961, 12264, etc.

Conclusions: From the recent investigations of carbonaceous achondrites, significant advancement in our understanding of the extent and variety of magmatic activity in the early, outer Solar System have been made. Early suggestions of potential differentiation activity, based on chemical similarities or paleomagnetic evidence, have been supported by Cr and Ti isotopic evidence. The few samples studied early on have now been vastly expanded on, with 18 samples analyzed thus far. This increased sample set has provided a unique picture of early differentiation processes in the outer Solar System. From this data, we know that we can now associate differentiated objects with several carbonaceous chondrite groups in terms of Cr-Ti-O systematics (e.g., CV, CK/CO, and CR). We also have evidence for multiple potential parent bodies that we have not sampled previously through undifferentiated chondrite counterparts. There are at least two parent bodies, from the carbonaceous region, where there is evidence for metal-silicate segregation through the occurrence of pallasites as well as iron meteorites such as NWA 176 and Bocaiuva [3]. And lastly, we now have additional constraints, through multiple samples, for the timing of magmatic activity in portion of the outer Solar System that generated CR-like objects.

References: [1] Shukolyukov A. and Lugmair G. W. (2001) *LPS XXXII*, A1365. [2] Shukolyukov A. and Lugmair G. W. (2006) *EPSL, 250*, 200-213. [3] Irving A. J. et al. (2004) *EOS*, #P31C-02. [4] Bogdanovski O. and Lugmair G. W. (2004) *LPS XXXV*, A1715. [5] Trinquier A. et al. (2009) *Science, 324*, 374. [6] Carpozen J. et al. (2011) *PNAS, 108*, 6386-6389. [7] Elkins-Tanton L. et al. (2011) *EPSL, 305,* 1-10. [8] Sanborn M. E. et al. (2018) *LPS XLIX*, A1780. [9] Sanborn M. E. et al. (2019) *GCA, 245,* 577-596. [10] Sanborn M. E. et al. (2015) *LPS XLVI*, A2259 [11] Williams C. D. et al. (2016) *LPS XLVII*, A1539 [12] Agee C. B. et al. (2014) *MetSoc 77*, A5395. [13] Irving A. J. et al. (2019), *LPS L*, This meeting. [14] Sanborn M. E. et al. (2018) *MetSoc81*, A6279. [15] Sanborn M. E. et al. (2018) *LPS XLIX*, A2296. [16] Sanborn M. E. et al. (2018) *MetSoc 81*, A6279. [17] Göpel C. et al. (2015) *GCA, 156,* 1-24. [18] Srinivasan P. et al. (2015) *LPS XLVI*, A1472. [19] Dey S. et al. (2019), *LPS L*, This meeting. [20] Bouvier et al. (2011) *GCA, 75,* 5310-5323. [21] Huyskens et al. (2019) *LPS L*, This meeting. [22] Amelin Y. et al. (2019) *GCA, 245,* 628-642. [23] Wimpenny et al. (2019) *GCA, 244*, 478-501. [24] Huyskens M. et al. (2018) *LPS XLIX*, A2311. [25] Srinivasan et al. (2018) *Nat. Comm.*, 9, 3036.