**MAGMATIC EVOLUTION TRENDS WITHIN THE UNGROUPED ACHONDRITE METEORITE RECORD** Z. Vaci[1,2], C. B. Agee[1,2], K. Ziegler[1,2], and M. T. Heizler[3] Institute of Meteoritics[1], Department of Earth and Planetary Sciences[2], University of New Mexico, Albuquerque, NM, USA, New Mexico Geochronology Research Laboratory[3], New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, Socorro, NM, USA.

**Introduction:** Ungrouped achondrites can be defined by two categories: evolved and primitive. Evolved ungrouped achondrites are magmatically derived achondritic meteorites that do not fit into groups such as the HEDs, SNCs, or lunar meteorites. Primitive ungrouped achondrites likewise do not fit with any of the primitive achondrite groups, such as the acapulcoites, brachinites, lodranites, or winonaites, which occupy unique fields within triple oxygen isotope space. Ungrouped achondrites, whether primitive or evolved, are characterized by unique isotopic profiles, petrology reflective of an unidentified source composition, or singular geochemistry. As the meteorite record is continually being updated, so too must the categories which are used to systematically describe them. We examine here several unique achondrites that potentially warrant reclassification of both achondrite grouping and the nature of chondritic and achondritic parent bodies.

**Supra-TFL Achondrites:** The oxygen isotopes of several recently discovered ungrouped achondrites plot in the same field as the ordinary chondrites, with $\Delta^{17}O$ ~1 (Fig. 1). These include Northwest Africa (NWA) 4284 and 11042, both of which are ultramafic rocks that exhibit cumulate textures. Both rocks are composed primarily of unzoned, medium-grained olivine, enstatite, and albitic plagioclase/maskelynite, with minor augite and chromite, and trace troilite, kamacite/taenite, and chloroapatite. NWA 4284 has a higher augite to enstatite ratio and greater amounts of plagioclase/maskelynite than NWA 11042, so that they could represent two parts of a petrologic sequence in which NWA 4284 has a more evolved composition. NWA 11042 is heavily shocked, such that all plagioclase has been transformed to maskelynite, while NWA 4284 contains mostly plagioclase with only minor evidence of shock. This is evidence for the heterogeneity of shock effects rather than evidence against the pair being related [1]. $^{40}Ar/^{39}Ar$ dating of a maskelynite mineral separate from NWA 11042 yields an age of 483.3 ± 1.4 Ma, coinciding with the breakup of the L chondrite parent body [2]. This age is relative to Fish Canyon Sanidine with an assigned age of 28.201 Ma and a total $^{40}K$ decay constant of $5.463\times10^{-10}$ /a. The crystallization age is much older, with a Sm-Nd isochron showing a minimum age of 4.1 ± 0.160 Ga.

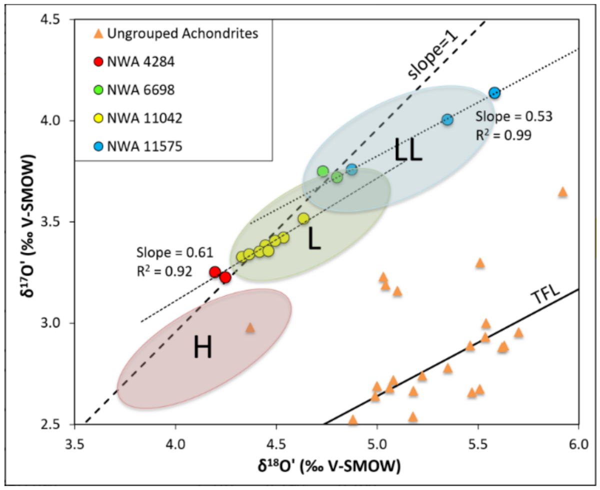


**Figure 1** showing triple oxygen diagram of "supra-TFL achondrites" plotted with ordinary chondrites (H, L, and LL fields). Other ungrouped achondrites are also shown, most of whom plot near the TFL. These are not necessarily related to each other, but also invite further research. Slope=1 line, which represents non-mass-dependent fractionation, is shown. Linear regression lines through Northwest Africa 11042 and 11575 are shown.

Two other ungrouped achondrites plot within the field of ordinary chondrites: Northwest Africa 6698 and 11575. NWA 6698 is a dioritic rock with 69 vol% albitic plagioclase, 27% augite and pigeonite, and 4 vol% accessory phases such as chromite, taenite, troilite, and chloroapatite [3]. Therefore, it represents the product of an even more evolved magma than that which produced NWA 11042 and 4284. Finally, NWA 11575 is felsic rock with mafic xenocrysts, composed of 90-95 vol% ophitic pyroxene and plagioclase, with ubiquitous potassium feldspar and silica [4]. This is the most petrologically evolved rock of the supra-TFL series. The petrology and oxygen isotopes of these supra-TFL achondrites is suggestive of a continuous petrologic series ranging from the ultramafic NWA 11042 to the felsic NWA 11575. The shock age of NWA 11042 suggests that magmatism resulting from the differentiation of the L chondrite parent body resulted in the emplacement of NWA 4284 and 11042. However, since NWA 6698 and 11575 have significantly different oxygen isotopes, they likely originated from different parent bodies.

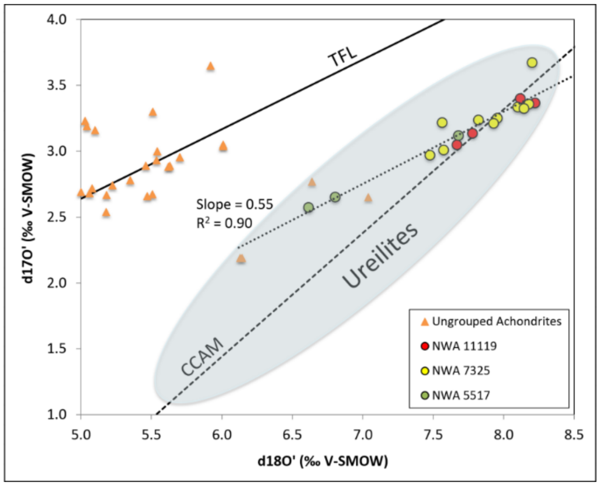


**Figure 2** showing triple oxygen diagram of "sub-TFL Achondrites" plotted within the ureilite field. TFL, CCAM line, and a linear regression of the sub-TFL achondrites are shown, along with the other ungrouped achondrites which again concentrate close to the TFL.

**Sub-TFL Achondrites:** A second group of achondrites feature oxygen isotopes that intersect the carbonaceous chondrite anhydrous mineral line (CCAM) within the region of the ureilites (Fig. 2). Northwest Africa (NWA) 5517, 7325, and 11119 form a trend in triple oxygen space whose slope implies mass-dependent fractionation, and thus they might share a parent body and be potentially implicated with the ureilites as well. NWA 5517 contains mostly olivine and clinopyroxene, and minor amounts of troilite and FeNi metal [5], and it thus forms a mafic endmember of the sub-TFL series. NWA 7325 is more evolved and composed of Al- and Cr-bearing diopside, calcic plagioclase, and some forsteritic olivine [6]. NWA 11119, meanwhile, is one of the most silica-rich achondrites yet identified, composed of 39 vol% pyroxene, 38 vol% plagioclase, 22% silica, and 1% ulvöspinel, ilmenite, troilite, and zircon [7].

$^{26}$Al dating of NWA 11119 gives an age of 4564.9 ± 0.3 Ma, indicating that is is the oldest example of silicic magmatism in the solar system, crystallizing over 2 million years before NWA 7325 [8]. If the two meteorites, and potentially NWA 5517, are sources from the same parent body, then this magmatic series suggests the presence of extremely complex volcanic events over long periods of time on a differentiated body in the early solar system. While the supra-TFL achondrites could represent differentiation of ordinary chondrite material, or even a yet to be discovered parent reservoir, the sub-TFL achondrites cannot be simply derived from known carbonaceous chondrites and must represent a newly characterized parent reservoir.

The degree of magmatic differentiation in NWA 11119 and 7325 is reflected in the linear trend formed by their oxygen isotopes, and this stands in contrast to the ureilites, which show a much more scattered triple oxygen profile. Meanwhile, Cr isotopes of NWA 7325 rule out derivation from any carbonaceous chondrite source, as they plot with the other major reservoir that includes ordinary chondrites, HEDs, and SNCs [9]. Other sub-TFL achondrites, such as Northwest Africa 011 and 8186, have Cr isotopes that do plot with the carbonaceous chondrites [10]. NWA 8186 is an olivine-rich rock that seems to be highly oxidized, and its oxygen isotopes plot with the CK and CV chondrites on the CCAM, in a much more $^{16}$O-rich region of the triple oxygen diagram [11]. NWA 011, meanwhile, has a petrology similar to that of eucrites but oxygen isotopes that plot with the acapulcoite/lodranite clan. As a basaltic melt of the acapulcoite/lodranite parent body would produce higher Fe/Mg ratios, its origin lies neither with the HED parent body nor the acapulcoite/lodranite parent body [12]. There are thus likely at least two distinct and unique reservoirs within the sub-TFL achondrites, one of which is associated with carbonaceous chondrite material, and the other which is entirely unique in origin.

**References:** [1] T. G. Sharp and P. S. DeCarli (2006) *Meteorites II* 653-677. [2] E. V. Korochantseva et al. (2007) *MaPS* 42, 113-130. [3] *MetBul Database #NWA 6698.* [4] *MetBul Database #NWA 11575.* [5] *MetBul Database #NWA 5517.* [6] *MetBul Database #NWA 7325.* [7] P. Srinivasan et al. (2017) *MetSoc 80*, #6129. [8] D. R. Dunlap et al. (2017) *MetSoc 80*, #6268. [9] N. T. Kita (2014) *LPSC 45*, #1455. [10] M. E. Sanborn (2014) *LPSC 45*, #2032. [11] C. B. Agee et al. (2014) *LPSC 45*, #5285. [12] F. Floss et. al (2005) *MaPS* 40, 343-360.