EARLY DIFFERENTIATION IN THE CARBONACEOUS CHONDRITE FORMING REGION OF THE SOLAR NEBULA: NEW INSIGHT FROM THE ACHONDRITES NORTHWEST AFRICA 7680/6962.

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Introduction: The number and diversity of planetary materials (meteorites) identified in recent years have been increasing explosively, providing a treasure trove of information on the conditions and processes operating in the emerging early Solar System.

Northwest Africa (NWA) 7680 and NWA 6962 are examples of ungrouped achondrites whose origin remains ambiguous. NWA 7680 is composed of two main lithologies: (1) an Fe,Ni metal component and (2) a silicate-rich fraction composed predominantly of olivine and plagioclase along with chromite found as standalone grains and as inclusions [1,2]. The high abundance of Fe-rich olivine lead to an initial description of NWA 7680 as resembling brachinite-like meteorites with a notable difference of the olivine in NWA 7680 being more Fe-rich than typically seen in brachinites or brachinite-like meteorites [1,2]. Similar Fe-rich olivine is also seen in NWA 6962. This along with mineralogical, major, minor and trace element geochemisty and oxygen isotope similarities led to the suggested relationship between the two samples [1,2]. Both NWA 7680 and NWA 6962 have oxygen isotopic compositions that plot in the proximity of the acapulcoite-lodranite meteorites but also within the range of ureilites [1,3]. The compositions also fall near the carbonaceous chondrite anhydrous mineral line. This, along with supporting evidence, has recently been used to suggest a link between NWA 7680/6962 and carbonaceous chondrites [2].

Here, we work to address two questions regarding the origin and evolution of NWA 7680/6962. First, using anomalies in ε^{54}Cr, is it possible to determine a common provenance with any known meteorite or meteorite group of shared Cr-O reservoir. Second, can the short-lived ^{53}Mn-^{53}Cr system provide chronological constraints on the timing of formation and subsequent evolution of NWA 7680/6962.

Methods: Three samples of NWA 7680 and 6962 were processed: a whole-rock sample of NWA 6962, a silicate-rich sample of NWA 7680 (predominantly olivine, plagioclase, chromite), and a separate chromite sample of NWA 7680. Samples were initially fluxed in a 6 N HCl solution in order to dissolve Fe,Ni metal present to avoid cosmogenic spallation of Fe on ^{54}Cr (e.g., [4]). Using an aliquot of the silicate-rich fraction of NWA 7680, silicate and chromite were separated using a preferential dissolution technique. In this process, hotplate dissolution (3:1 HF:HNO_3 for 72 h at 140°C) dissolves silicates leaving chromite as a residue. A separate chromite fraction also underwent preferential dissolution to remove minor silicate grains attached to the chromite. The chromite residue from the silicate-rich fraction was combined with the separate chromite fraction after preferential dissolution and was placed into PTFE Parr bombs with a 3:1 HF:HNO_3 mixture and heated in a 190°C oven for 96 h. (subsequently referred to as NWA 7680 chromite). The silicates obtained from the preferential dissolution step of both the silicate-rich fraction and chromite fraction were combined and dried down for column chemistry (referred to as NWA 7680 silicate).

An aliquot of the dissolved samples (10%) was reserved for Mn/Cr ratio measurements while the remaining material was processed using a 3-column chemistry procedure to separate Cr [5]. ^{55}Mn/^{52}Cr ratios were determined using a Thermo *Neptune Plus* MC-ICP-MS at UC Davis. Chromium isotopic ratios were measured using a Thermo *Triton Plus* TIMS at UC Davis. All Cr isotopic values are reported at parts per 10,000 deviation from a terrestrial standard (NIST SRM 979) measured within the same analytical session.

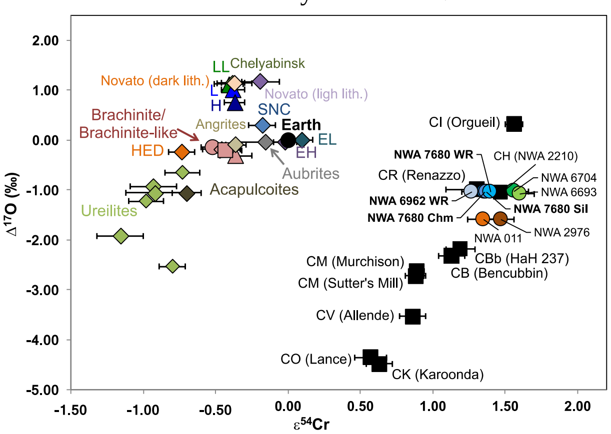

Fig. 1. ε^{54}Cr vs. Δ^{17}O diagram showing NWA 7680/6962 in comparison to other achondrite and chondrite meteorites. Literature data for ε^{54}Cr vs. Δ^{17}O are from [4,6] and references therein. Δ^{17}O data for NWA 7680 from [1] and NWA 6962 from [3].

Results and Discussion: The results of the ε^{54}Cr measurements for individual mineral phases and the whole-rocks are plotted in Δ^{17}O-ε^{54}Cr isotope space (Fig. 1). The ε^{54}Cr of both NWA 7680 and NWA 6962 range from +1.27 to +1.40, all overlapping within analytical uncertainties. These positive ε^{54}Cr values are well-resolved from acapulcoites-lodranites and ureilites, precluding formation from a common isotopic reservoir with these meteorite groups. Instead, NWA 7680/6962 appear to have originated from an isotopic reservoir that also produced CR- and/or CH-type carbonaceous chondrites and more recently identified carbonaceous achondrites, e.g., NWA 6704/6693 and NWA 2976/011 [7,8]. The identical ε^{54}Cr between NWA 7680 and NWA 6962 further confirms that they are in fact related and were probably generated on the same parent body.

The mineral separates and whole-rock fractions of NWA 7680 and NWA 6962 span a relatively narrow range of ^{55}Mn/^{52}Cr ratios from 0.008 to 0.577. However, even with this narrow range of ^{55}Mn/^{52}Cr, a resolved slope is obtained when plotting ε^{53}Cr versus ^{55}Mn/^{52}Cr (Fig. 2). The slope of the resulting isochron translates to a ^{53}Mn/^{55}Mn at the time of last isotopic closure of $(3.48\pm1.13)\times10^{-6}$. Anchoring to the angrite D'Orbigny [9-11] results in an absolute age for NWA 7680/6962 of 4563.76 ± 1.76 Ma (2σ) (assuming a single formation event for both).

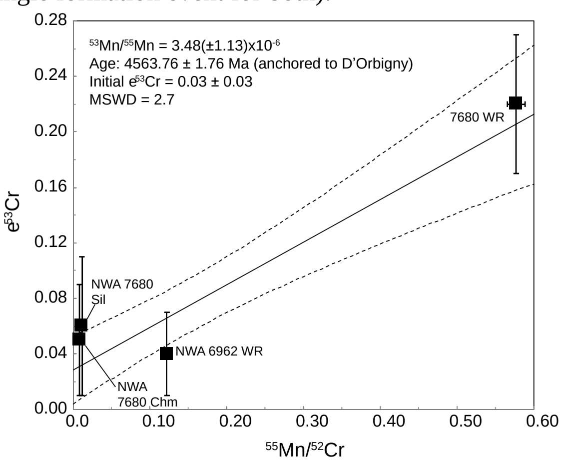

Fig. 2. ^{53}Mn-^{53}Cr isochron of NWA 7680/6962. Sil = silicate, Chm = chromite; WR = whole-rock.

Based on the Cr-O isotope systematics and the determined ^{53}Mn-^{53}Cr age, there is a strong similarity to the paired carbonaceous achondrites, NWA 6704/6693 [8] . Both meteorite pairs have indistinguishable ε^{54}Cr and Δ^{17}O composition suggesting their origin from a similar geochemical reservoir within the protoplanetary disk (Fig. 1). ^{53}Mn-^{53}Cr ages for both NWA 7680/6962 and NWA 6704/6693 [8] are the same, indicating a contemporaneous formation. Their occurrence provides evidence that melt generation in a region of the protoplanetary disk that also appears to have originated CR and/or CH chondrites was quite widespread. It should be noted that both NWA 7680/6962 and NWA 6704/6693 are just two pairs of now numerous carbonaceous achondrites confirmed using Cr-O and Cr-Ti isotope systematics (e.g., [7,12-15]). Some of these other carbonaceous achondrites have similar ε^{54}Cr to NWA 7680/6962 but slightly lower Δ^{17}O. Chronological data is limited to just one of these lower Δ^{17}O samples, NWA 2976/011 with a Pb-Pb, Al-Mg, and Mn-Cr ages of NWA 2976/011 concordant with NWA 7680/6962 and NWA 6704/6693 [8,16,17]. Coupling the Δ^{17}O-ε^{54}Cr observations with the chronology constraints determined to date suggests that melt processes and differentiation activity were ubiquitous in the carbonaceous chondrites forming region of the solar nebula. The relatively young Pb-Pb age of CR chondrules [18] is used to infer a late accretion for the CR chondrite parent body [19,20], resulting in lower abundance of short-lived ^{26}Al (half-life 0.705 Myr) as a heat source. However, with NWA 7680/6962 and the numerous other carbonaceous achondrites [7,8,12-15] and iron meteorites [21] and pallasites [22], there are now multiple lines of evidence that a wide range of melting environments generated from internal heating and/or impacts did occur early in the formation regions of carbonaceous chondrites. This would require an early onset of accretion to provide adequate abundances of short-lived radionuclides to induce melting, or bodies substantial enough to produce abundant impact melting. The similar Mn-Cr ages and ε^{54}Cr-Δ^{17}O distribution among NWA 7680/6962, NWA 6704/6693, and NWA 2976/011 provide evidence for a common geochemical source within the solar nebula that experienced a wide range of melting conditions contemporaneously [7,8,12,23].

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