The O-isotope compositions of chondrules from an H3.1 chondrite: The origins of chondrule precursors and implications for grain migration in the early Solar System

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Introduction: In recent years, it has become increasingly evident that sub-mm sized-particles migrated within the early Solar System (e.g., [1–5]). However, the extent and direction(s) of grain migration throughout the protoplanetary disk are not well constrained. Different chondrite groups have distinct chemical and isotopic characteristics (e.g., [6]) and are believed to have formed at different heliocentric distances and at slightly different times [e.g., 7,8], making them valuable records of grain migration in the disk. In fact, studies of minimally altered chondrites have revealed compelling evidence for grain migration (e.g., [2–5,9–16]). Partially melted chondrules often preserve unmelted precursor silicates, known as *relict* grains, whose chemical and O-isotope compositions can be used to determine their origins. These relict grains may exhibit similarities to chondrule silicates from other chondrite groups and/or refractory inclusions, and thus imply potential grain migration in the protoplanetary disk (e.g., [3]). As part of our ongoing efforts to constrain the extent and direction(s) of grain migration throughout the protoplanetary disk, we have undertaken a search for chondrule precursors in multiple different chondrite groups [2–4,12,14–18]. Most of our work to date has focused on carbonaceous chondrite groups from the outer Solar System.

The unequilibrated ordinary chondrites (UOCs) formed in the inner Solar System [e.g., 7]. Some UOC chondrules contain olivine that is a unique compositional match to that from Comet Wild 2, 'the forbidden triangle' [4,16]; originally named so by [19]. This unique composition shared between UOCs and Comet Wild 2 may suggest that UOC chondrule fragments migrated from the UOC chondrule-forming region in the inner Solar System to the comet-forming region [4,16]. Here we present O-isotope data for UOC chondrules from one of the least thermally altered H3 chondrites (an H3.1) to constrain the origins of their chondrule precursors and investigate the origin(s) of olivine from the so-called 'forbidden triangle'.

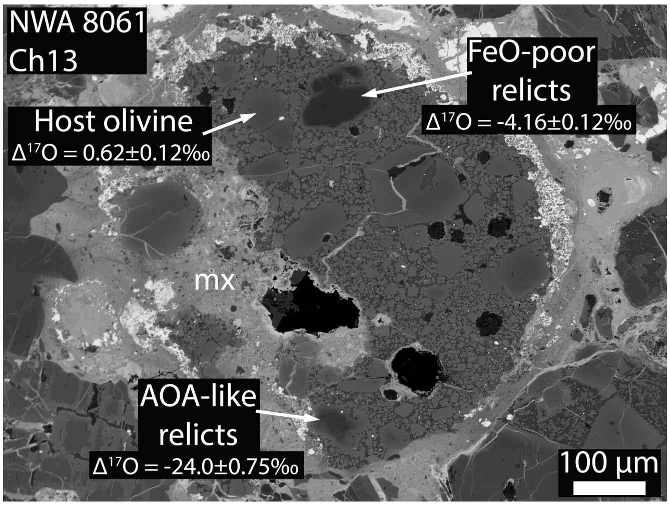

Figure 1. Back scattered electron (BSE) image of NWA 8061 Ch13. mx = matrix. Uncertainty = 2SE (standard error).

Samples and Analytical Procedures: We studied polished sections of Roosevelt County (RC) 075 (H3.10), Los Vientos (LoV) 266 (H3.15), Northwest Africa (NWA) 8061 (H3.10), and NWA 13501 (H3.10); preliminary data was presented in [15]. Samples were first studied via an optical microscope to identify petrographically identifiable relict grains (e.g., dusty olivine and agglomeratic olivine [AO] chondrules). Backscattered electron (BSE) images and X-ray element maps, which were used to identify mineral phases for quantitative analysis, were obtained on polished sections using the JEOL JXA-8530F Hyperprobe field emission electron probe microanalyzer (EPMA) at Arizona State University (ASU). The ASU EPMA was also used to obtain monochromatic cathodoluminescence (CL) maps of chondrules with Fa<2. Quantitative compositional analyses of silicate phases were subsequently performed on the Cameca SX-100 EPMA at the University of Arizona using similar conditions to those reported in [18,20]. Based on the number and diversity of relict grains identified, and identification of a 'forbidden triangle' olivine-bearing chondrule, we selected NWA 8061 for detailed O-isotope analyses. The O-isotope analyses were conducted with the University of Wisconsin-Madison Cameca IMS 1280 SIMS (secondary ion mass spectrometer; WiscSIMS [21–23]), with beam sizes of 13 µm and 5 µm with typical external reproducibility of oxygen 3-isotope ratios ($\delta^{18}O$, $\delta^{17}O$, $\Delta^{17}O$) of ~0.2‰ and ~0.8‰, respectively. Uncertainties of instrumental bias correction are 0.3‰ for $\delta^{18}O$ and 0.15‰ for $\delta^{17}O$ [e.g., 24]. After O-isotope analyses, each spot was inspected on the ASU EPMA to verify spot location and that it was not over multiple phases or cracks (all spots were cleared).

Results: We analyzed the major and minor element compositions of 25 chondrules from NWA 8061, primarily of olivine (653 analyses) but with minor pyroxene (37 analyses). Relict grains were identified from petrographic indicators (e.g., dusty olivine) and potential relict grains were identified from their chemical compositions (e.g., FeO-poor relict grains in type II chondrules, grains with distinct Fe/Mn ratios from their host chondrules, and/or CL features in type I chondrules with Fa<2). We analyzed the O-isotope compositions of 20 chondrules in NWA 8061, for a total of 189 spots (181 olivine and 8 pyroxene; 104 analyses at 5 μm and 85 at 13 μm). Eight of the 20 chondrules were type I chondrules, five of which are also dusty olivine-bearing chondrules. Five of the type I chondrules studied had CL features. The 12 type II chondrules include four FeO-rich AO chondrules, which typically contain FeO-poor olivine relict grains. Eight of the chondrules studied (2 type I and 6 type II) contain relict olivine grains with O-isotope compositions distinct from their host chondrules (i.e., a relict grain via O-isotope composition is defined as being 3σ outside of analytical uncertainty in $\Delta^{17}O$ [i.e., 21]).

Discussion: The host compositions of the H3.1 chondrules analyzed (weighted mean $\Delta^{17}O$ = 0.84±0.04‰ [2SE], n = 145) have $\Delta^{17}O$ values consistent with UOC chondrules; $\Delta^{17}O$ values between approximately 0 and 1‰, within analytical uncertainty (LL3s: [9,25] and L3s [16]). The 'forbidden triangle' olivine-bearing chondrule is O-isotopically homogeneous and consistent with the host $\Delta^{17}O$ values of the other H3.1 chondrules. Eight chondrules analyzed have relict grains identified via their O-isotope compositions, all of which are ^{16}O-rich compared to their host compositions. The $\Delta^{17}O$ compositions of relict grains can mostly be placed into three broad 'bins' with $\Delta^{17}O$ ranges of approximately –2‰ to –3‰, –4‰ to –6‰, and –20 to –24‰ (relicts are not exclusive to these 'bins', there are relict grains with $\Delta^{17}O$ values outside these broad ranges, e.g., $\Delta^{17}O$= –15‰). There is no observed relationship between Fe# and $\Delta^{17}O$, or between CL features and O-isotope compositions.

Of the five dusty olivine chondrules analyzed, only one contains dusty olivine with distinct $\Delta^{17}O$ compositions (relict with ~ –2‰ vs. host compositions of 0‰ to +2‰). The composition of this relict grain indicates that the relatively FeO-rich precursor olivine that underwent solid state reduction to become this dusty-olivine grain was not an UOC chondrule fragment (i.e., $\Delta^{17}O$ = 0 to 1‰) and therefore has a non-local origin. Type II chondrules with $\Delta^{17}O$ of ~ –2.0‰ to –2.5‰ include those from both the Mighei-like carbonaceous (CM) and Ornans-like carbonaceous (CO) chondrites [3,26,27].

NWA 8061 Ch13 (Fig. 1) is remarkable as it contains at least four 'generations' of olivine. It contains: (1) an amoeboid olivine aggregate (AOA)-like texture that has $\Delta^{17}O$ = –21‰ to –24‰; (2) FeO-poor olivine ($Fa_{0.5–5.3}$) grains with $\Delta^{17}O$ = –2.6‰ to –5.0‰, but mostly near $\Delta^{17}O$ ~ –4‰; (3) it has an FeO-rich relict grain ($Fa_{20.5}$) of a grain core with –1.4‰; and (4) the host weighted mean of $\Delta^{17}O$ = 0.65±0.13‰ [2SE] (n = 11). These compositions imply that AOAs were a precursor for this chondrule, and potentially other chondrules in UOCs. The FeO-poor relict olivine with $\Delta^{17}O$ ~ –4‰ is within a range of FeO-poor olivine from CO or CM chondrite type I chondrules (i.e., which have $\Delta^{17}O$ values between –6‰ to –4‰ [3,26,27]). Therefore, Ch13 is a complex chondrule with multiple origins for its precursors.

Most studies have indicated outward migration of $\Delta^{17}O$ ~0‰ olivine from the inner to outer Solar System [3–5,13,28]. However, as the earliest formed CO and CM chondrule ages overlap with the last formed UOC chondrules [8], it is plausible that the H chondrite chondrule forming region included inwardly migrated CO and/or CM chondrule fragments.

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