OLIVINE FROM THE "FORBIDDEN TRIANGLE": EVIDENCE FOR CHONDRULE MIGRATION TO THE COMET FORMING REGION?

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Introduction: Chondrules formed from either complete or partial melts, and those that were only partially melted retained portions of their solid precursors, termed relict grains [e.g., 1]. Rare relict grains in chondrules, and some whole chondrules, have been identified with distinct chemical and/or O-isotope compositions relative to their host that imply a non-local origin. This implied non-local origin may be evidence for migration of earlier formed chondrules or chondrule fragments between groups prior to asteroidal accretion [e.g., 2–5]. The identification of chondrules and chondrule fragments that may have migrated is important because it provides insights into the dynamical transportation of material in the early Solar System.

Chondrules from distinct chondrite groups often have characteristic Fe-Mn systematics of their olivine [e.g., 4,6–11]. Olivine from Comet Wild 2 exhibits a wide range of Fe-Mn compositions that encompass most known olivine compositions from chondrules [11]. During a study of Comet Wild 2 olivine and a literature survey of chondrule olivine data from numerous groups and olivine in interplanetary dust particles (IDPs) [e.g., 7–9], a range of Fe and Mn compositions represented by Comet Wild 2/IDP olivine that were apparently not observed in chondrites was identified by [11], which they termed the "forbidden triangle" on a plot of Fe vs. Mn. [11] interpreted that: (1) the large compositional variation in Comet Wild 2 olivine implies that the olivine formed in a wide range of formation regions within the inner Solar System and then migrated to the comet forming region in the outer Solar System, and (2) that the "forbidden triangle" represents a chondrule population previously unsampled by known chondrite groups. Recently, a single olivine analysis from an agglomeratic-olivine chondrule from a CR chondrite was found to be within this "forbidden triangle" [10]. In addition, two chondrule olivine analyses reported by [8] for an unequilibrated ordinary chondrite (UOC) may also be near or within this "forbidden triangle". The dearth of olivine in the chondrite record with compositions in this "forbidden triangle" could mean that Comet Wild 2 sourced a compositional reservoir not well represented by chondrites, and/or the formation conditions (e.g., precursor composition, oxygen fugacity, peak metamorphic temperature) required to form this olivine were exceptionally rare in the chondrule forming regions.

Our goals are: (1) to determine if olivine from UOCs plots in the "forbidden triangle", and if so, (2) what are the implications for olivine sources of Comet Wild 2/IDPs?

Samples and analytical procedures: High-resolution images (e.g., Fig. 1) and chemical compositions of chondrule olivine from thin sections of Roosevelt County (RC) 075 AML4 (H3.1), Queen Alexandra Range (QUE) 97008,63 (L3.05), Meteorite Hills (MET) 00452,29 (L[LL]3.05), and Semarkona USNM 1805-17 (LL3.00) were obtained with the Arizona State University JEOL-8530F Hyperprobe electron microprobe analyzer (EPMA) and the University of Arizona Cameca SX-100 EPMA.

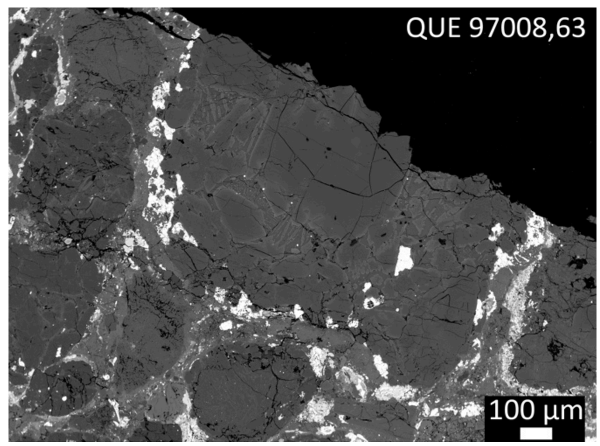

Figure 1. Compositionally distinct porphyritic olivine pyroxene type I chondrule (Ch6) from QUE 97008,63 (L3.05).

Results: We obtained a total of 528 olivine analyses from 40 UOC chondrules. Chondrule textural types analyzed include barred olivine, porphyritic olivine, and porphyritic olivine pyroxene.

RC 075 AML4 (H3.1): We obtained 64 olivine analyses from five chondrules: two type I chondrules ($Fa_{1.5\pm1.5}$, $Fa_{0.7–6.0}$; n=16); and three type II chondrules ($Fa_{21.1\pm6.1}$, $Fa_{9.6–34.0}$; n=48).

QUE 97008,63 (L3.05): We obtained 227 olivine analyses from 19 chondrules: eight type I chondrules ($Fa_{7.9\pm4.0}$ [avg±1σ], $Fa_{0.7–22.4}$ [min–max]; n= 89 olivine analyses); seven type II chondrules ($Fa_{15.7\pm6.0}$, $Fa_{0.5–37.2}$; n= 104; includes FeO-poor relict grains); and four dusty olivine chondrules ($Fa_{3.0\pm3.0}$, $Fa_{0.5-8.9}$; n= 34).

Semarkona USNM 1805-17 (LL3.00): We obtained 61 olivine analyses from four chondrules: two type I chondrules ($Fa_{4.6±3.0}$, $Fa_{0.6–6.9}$; n=6); and two type II chondrules ($Fa_{16.3±6.8}$, $Fa_{0.7–33.4}$; n=55).

MET 00452,29 (L[LL]3.05): We obtained 176 olivine analyses from 12 chondrules: four type I chondrules ($Fa_{4.5±3.7}$, $Fa_{0.5–16.1}$; n=66); and eight type II chondrules ($Fa_{21.2±7.2}$, $Fa_{3.1–52.3}$; n=110).

Discussion: All chondrules from RC 075, MET 00452, and Semarkona, and most chondrules from QUE 97008, are within the Fe-Mn compositional range of olivine from UOCs [e.g., 6–8]. However, three type I chondrules from QUE 97008 have olivine grains with Fe and Mn compositions that are outside the UOC field and within the "forbidden triangle" identified by [11]. Furthermore, one of these chondrules has olivine with compositions that are outside the range of olivine compositions of Comet Wild 2/IDPs. This type I chondrule appears to have an Fe-Mn composition unlike those reported to date in olivine from chondrules, Comet Wild 2, and IDPs (Fig. 2), and may indicate a formation history distinct from other chondrules in UOCs and/or it may be a chondrule with a non-local origin. One type II chondrule plots outside the UOC field and the "forbidden triangle", but is likely an extension of the UOC field (Ch14; Fig. 2).

Compared to other UOC chondrules, these three non-UOC field chondrules may: (1) represent distinct precursor composition(s), (2) and/or distinct formation histories, (3) and/or imply a non-local origin (i.e., represent chondrule migration from another region). Other than the distinct Fe-Mn compositions of these three type I chondrules, there are no petrographic indicators (i.e., size, texture, associated minerals) to suggest they are distinct from other chondrules in UOCs. Therefore, it is perhaps more likely that these are L chondrite chondrules with an uncommon formation history.

The identification of UOC olivine that compositionally lies within the "forbidden triangle" poses a potential solution to the source of olivine from Comet Wild 2 posed by [11], or at least indicates shared formation conditions at different times and radial distances in the protoplanetary disk. Additional analyses of chondrules in UOCs, as well as *in situ* O-isotope analyses of the three chondrules in QUE 97008 that are outside the Fe-Mn compositional range for UOCs, may be needed to resolve if these chondrules have a local origin in the L chondrite chondrule formation region(s), or a non-local origin(s) and provide additional evidence for chondrule migration in the protoplanetary disk. If the O-isotope compositions of the chondrule with olivine in the "forbidden triangle" are found to be consistent with a local origin among L chondrite chondrules, it would support the conclusion of [11] that Comet Wild 2 olivine may include olivine that formed in the inner Solar System but does not require the existence of an unsampled chondrule population.

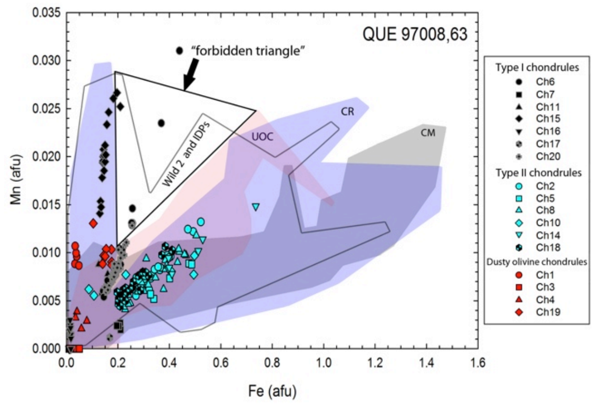

Figure 2. Fe vs. Mn (afu) of type I, type II, and dusty olivine chondrules from QUE 97008,63. Multiple chondrules have compositions outside the UOC field; Ch6, Ch15, and Ch20 plot compositionally within the "forbidden triangle". Compositional ranges for CR [7,9] and CM [4] chondrites, UOCs [6,7; this study], and Wild 2 and IDPs [8,11] shown. "Forbidden triangle" identified by [11].

Implications: The non-UOC field QUE 97008 chondrules: (1) are most likely L chondrite chondrules with distinct compositions/formation histories – *in situ* O-isotope analyses may be needed to confirm; and (2) provide a solution to the "unsampled chondrule population" suggested by [11].

Comet Wild 2 and IDPs: (1) may have sampled L chondrite chondrules and/or fragments that migrated from the inner Solar System (formation region of OCs) to the outer Solar System (formation region of comets/IDPs); or (2) formed from similar precursors and formation conditions as L chondrite chondrules.

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Acknowledgements: We thank the Smithsonian Institution, ANSMET/JSC, and AML for the samples used in this study, and the Center for Meteorite Studies at Arizona State University for funding a portion of this research.