Olivine from the "forbidden triangle": Evidence for chondrule migration?

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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., Jones, 2012). Rare relict grains in chondrules, and some whole chondrules, have been identified with distinct chemical and/or O-isotope compositions 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., Kita et al., 2010; Weisberg et al., 2011; Schrader and Davidson, 2017; Schrader et al., 2017). 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 (Berlin et al., 2011; Schrader et al., 2015; 2018; Brownlee and Joswiak, 2017; Schrader and Davidson, 2017). Olivine from Comet Wild 2 exhibits a wide range of Fe-Mn compositions that encompass most known olivine compositions from chondrules (Brownlee and Joswiak, 2017). During a study of Comet Wild 2 olivine and a literature survey of chondrule olivine data from numerous groups (e.g., Berlin et al., 2011; Frank et al., 2014; Schrader et al., 2015), Brownlee and Joswiak (2017) identified a range of Fe and Mn compositions represented by Comet Wild 2 olivine that were apparently not observed in chondrites, which they termed the "forbidden triangle" on a plot of Fe vs. Mn. Brownlee and Joswiak (2017) 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" (Schrader et al., 2018). In addition, two chondrule olivine analyses reported (Frank et al., 2014) 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 compositions, oxygen fugacity, peak metamorphic temperature) required to form this olivine were exceptionally rare in the chondrule forming regions.

We report the major and minor element compositions of chondrules in the highly unequilibrated ordinary chondrite Queen Alexandra Range (QUE) 97008 (L3.05), and focus on two chondrules whose Fe-Mn systematics appear to be unlike other chondrules from ordinary chondrites reported to date.

Samples and analytical procedures: High-resolution images (Fig. 1) and chemical compositions of chondrule olivine from a thin section of QUE 97008,63 were obtained with the Arizona State University JEOL-8530F Hyperprobe electron microprobe analyzer (EPMA) and the University of Arizona Cameca SX-100 EPMA, respectively.

Results: We obtained a total of 132 olivine analyses from twelve chondrules: 32 olivine analyses from four type I chondrules ($Fa_{9.7\pm3.5}$, $Fa_{6.3\text{-}22.4}$); 75 olivine analyses from five type II chondrules ($Fa_{16.9\pm6.5}$, $Fa_{0.5\text{-}37.2}$; mean and range includes FeO-poor relict grains); and 25 olivine analyses from three dusty olivine chondrules ($Fa_{1.3\pm0.9}$, $Fa_{0.5\text{-}3.9}$). Chondrule textural types studied include barred olivine, porphyritic olivine, and porphyritic olivine pyroxene.

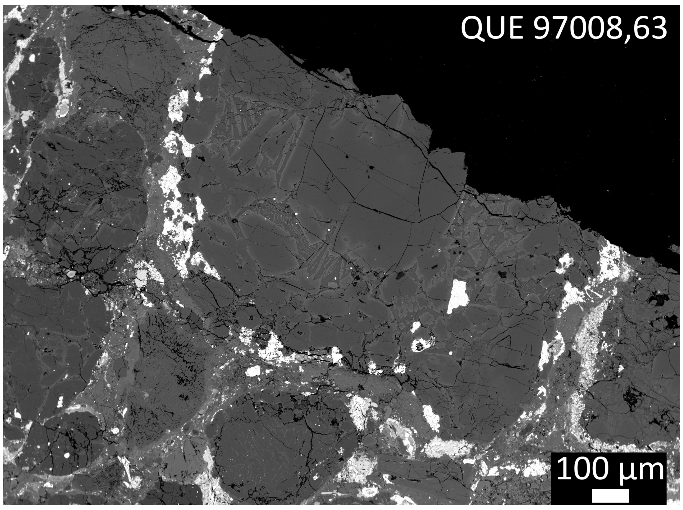

Figure 1. Compositionally distinct porphyritic olivine pyroxene type I chondrule from QUE 97008,63 (L3.05).

Discussion: Most chondrule olivine analyzed in QUE 97008 is within the Fe-Mn compositional range of olivine from UOCs (e.g., Jones, 1990; Berlin et al., 2011; Frank et al., 2014), which is to be expected as Berlin et al. (2011) also analyzed chondrules from QUE 97008 to define this range. However, two type I chondrules from QUE 97008 have olivine grains with Fe and Mn compositions that are distinct. One of these chondrules (Fig. 1) has olivine with Fe and Mn compositions that are within the "forbidden triangle" identified by Brownlee and Joswiak (2017), and olivine with compositions that are outside the range of olivine compositions of Comet Wild 2 and UOCs. This chondrule appears to have an Fe-Mn composition unlike that reported to date in chondrule and Comet Wild 2 literature, and may indicate a formation history distinct from other chondrules in UOCs and/or it may be a chondrule with a non-local origin. In the latter case, the chondrule may have migrated from another chondrule formation region into the accretion region of chondrules from QUE 97008. Other than the distinct Fe-Mn compositions of these two 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 olivine from a UOC that compositionally lies within the "forbidden triangle" poses a potential solution to the source of olivine from Comet Wild 2 posed by Brownlee and Joswiak (2017), 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 two chondrules in QUE 97008 that are outside the Fe-Mn compositional range for UOCs, are 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 Brownlee and Joswiak (2017) 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.

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