

**EVIDENCE FOR CHONDRULE MIGRATION FROM DUSTY OLIVINE CHONDRULES.** D. L. Schrader<sup>1</sup>, K. Nagashima<sup>2</sup>, R. R. Fu<sup>3</sup>, J. Davidson<sup>4</sup>, and R. C. Ogliore<sup>5</sup>. <sup>1</sup>Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA (devin.schrader@asu.edu), <sup>2</sup>HIGP/SOEST, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA. <sup>3</sup>Lamont-Doherty Earth Observatory, Columbia University, PO Box 1000 Palisades NY 10964, <sup>4</sup>Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington DC 20015, USA. <sup>5</sup>Department of Physics, Washington University in St. Louis, USA.

**Introduction:** The nature of the chondrule formation process is a subject of significant debate, with numerous models being proposed [e.g., 1–7]. Regardless of the process(es), it is agreed that chondrule precursors were flash heated to peak temperatures on the order of seconds to minutes, and cooled on the order of hours to days [e.g., 8–10]. Chondrules formed either from complete or partial melts [e.g., 9], and those that were only partially melted retained portions of their solid precursors, termed relict grains [e.g., 11–14].

The chemical and O-isotope compositions, and morphology of these relict grains provide information about the nature of chondrule precursors. Typically, relict grains are thought to be fragments of earlier formed chondrules, although there are chemical differences between some relict grains and their apparent source chondrules. Their origin(s) remain unclear [e.g., 14–18]. Relict grain types include dusty olivine (grains that contain  $\mu\text{m}$ -sized Fe metal blebs, Fig. 1) [11,12], which are thought to form by solid-state reduction of more FeO-rich olivine during partial melting [e.g., 15,19]; potentially by reduced C in the chondrule precursor (graphite or organic C) [20]. This relatively FeO-rich olivine is considered to originate from a previous generation of chondrules, including both type I (FeO-poor) and type II (FeO-rich) chondrules [15].

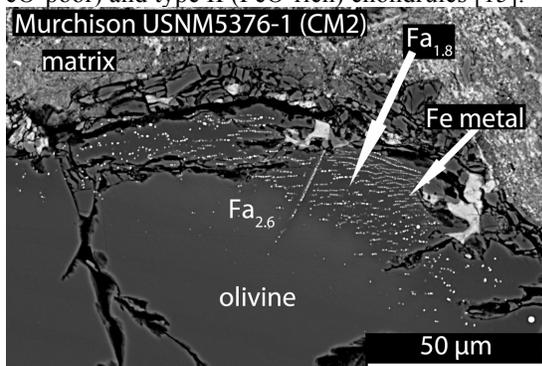


Fig. 1. BSE of dusty olivine chondrule in Murchison.

We report the chemical and O-isotope compositions of dusty olivine grains in different meteorite groups to determine the origin(s) of chondrule precursors and the chondrule formation mechanism(s). Meteorites from different groups were studied as their chondrules likely formed at different times [e.g., 21] and heliocentric distances [22].

**Samples and analytical procedures:** Chemical and O-isotope compositions of chondrule olivine in Murchison USNM5376-1 (CM2), Graves Nunataks (GRA) 95229,22 (CR2), and Meteorite Hills (MET) 00452,29 (L(LL)3.05; unequilibrated ordinary chondrite (UOC)) were studied with the University of Arizona Cameca SX-100 electron microprobe analyzer and the University of Hawai'i (UH) Cameca ims-1280 ion microprobe, respectively (details see [23]).

**Results:** Dusty olivine and melt grown olivine (i.e., phenocrysts), as well as type I and II chondrules, were analyzed in UOC, CM, and CR chondrites (Fig. 1, Tables 1–3). Error on  $\Delta^{17}\text{O}$  is typically 0.6–0.9‰ (2 $\sigma$ ).

Table 1: CM chondrite chondrules

Chondrule type	Fa range	$\Delta^{17}\text{O}$ range ‰	# analyses
type I <sup>a</sup>	0.2–0.7	–7.6 to –5.0	5
type I <sup>b</sup>	7.3–8.6	–0.2 to –0.2	2
type II	23.8–39.8	–2.6 to –2.0	6
type II <sup>c</sup> (relict)	0.6	–5.8±0.9	1
dusty olivine	0.7–10.0	–9.2 to 0.1	19

<sup>a</sup>low' Fa; <sup>b</sup>high' Fa; <sup>c</sup>FeO-poor relicts in type II

**CM chondrites.** Thirty-three O-isotope analyses across four type I chondrules, three type II chondrules (one with an FeO-poor relict grain), and five dusty olivine chondrules were obtained in Murchison (Table 1). Dusty olivine grains in two chondrules with  $\text{Fa}_{0.7-1.5}$  are more  $^{16}\text{O}$ -poor than phenocrysts (e.g.,  $\Delta^{17}\text{O} = 0.0 \pm 0.9$  vs.  $-9.2 \pm 1.4$ ‰, 2 $\sigma$ , respectively). In one chondrule ( $\text{Fa}_{9.7-10.0}$ ) dusty olivine is more  $^{16}\text{O}$ -rich than phenocrysts ( $\Delta^{17}\text{O} = -5.9 \pm 0.8$  vs.  $-2.3 \pm 0.8$ ‰, respectively). One dusty olivine chondrule ( $\text{Fa}_{1.7-4.7}$ ) is homogeneous in  $\Delta^{17}\text{O}$ .

Table 2: CR chondrite chondrules

Chondrule type	Fa range	$\Delta^{17}\text{O}$ range ‰	# analyses	Ref.
type I	0.6–7.1	–23.1 to 0.1	56	18,21,23
type II <sup>a</sup>	13.0–57.1	–1.8 to 1.4	43	18,21,23
type II <sup>b</sup>	10.8–34.6	–4.3 to 0.6	21	18,21
type II <sup>c</sup> (relict)	0.4–8.6	–6.6 to –1.6	6	18,21
dusty olivine	1.3–7.5	–4.3 to –0.4	7	18; here

<sup>a</sup>type II (relict free); <sup>b</sup>type II (FeO-rich olivine, relict bearing)

<sup>c</sup>FeO-poor relicts in type II

**CR chondrites.** One dusty olivine chondrule from GRA 95229 was studied (n=3), and compared to literature data obtained from UH on one dusty olivine chondrule, 18 type I, 14 relict-free type II chondrules, and five relict-bearing type II chondrules from CR chondrites (130 analyses, Table 2) [18,21,23]. Dusty olivine in the chondrule with  $\text{Fa}_{7.0-7.5}$  is more  $^{16}\text{O}$ -rich than phenocrysts ( $\Delta^{17}\text{O} = -4.3 \pm 0.6$  vs.  $-0.4 \pm 0.6$ ‰, respec-

tively; [r]). One dusty olivine chondrule ( $Fa_{1.3-1.6}$ ) has homogeneous  $\Delta^{17}O$  in dusty olivines and phenocrysts.

**UOC.** Thirty-two O-isotope analyses across three type I chondrules, three type II chondrules, and four dusty olivine chondrules were obtained in MET 00452 (Table 3). Dusty olivine in one chondrule ( $Fa_{0.4-0.9}$ ) is more  $^{16}O$ -rich than phenocrysts (e.g.,  $\Delta^{17}O = -4.5 \pm 0.6$  vs.  $0.9 \pm 0.6\text{‰}$ , respectively). In another, dusty olivine ( $Fa_{0.9-19.6}$ ) is more  $^{16}O$ -poor than phenocrysts ( $\Delta^{17}O = 0.6 \pm 0.8$  vs.  $-2.3 \pm 0.8\text{‰}$ , respectively). Two dusty olivine chondrules ( $Fa_{0.9-9.7}$ ) are homogeneous in  $\Delta^{17}O$ .

**Table 3: UOC chondrules**

Chondrule type	Fa range	$\Delta^{17}O$ range ‰	# analyses
type I	0.7–10.9	0.3 to 1.8	7
type II	16.4–26.0	0.0 to 1.6	6
dusty olivine	0.4–19.6	-4.5 to 1.4	19

**Discussion and Implications:** Dusty olivine grains in chondrules are  $^{16}O$ -poor,  $^{16}O$ -rich, or homogeneous relative to phenocrysts. As dusty olivine grains avoided melting/dissolution during chondrule formation, these differences are likely due to distinct precursors (e.g., type I or type II chondrules, or another source).

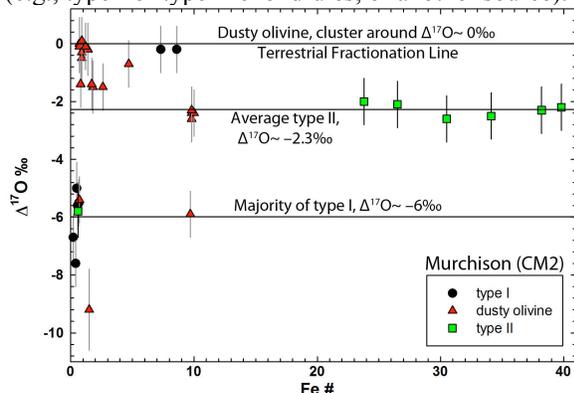


Fig. 2.  $\Delta^{17}O$  vs.  $Fe\#$  for olivine in Murchison.

In Murchison, one dusty olivine chondrule ( $Fa_{9.7-10}$ ) has  $\Delta^{17}O$  ( $\sim -2\text{‰}$ ) identical to those of olivine in type II chondrules, potentially indicating it originated from these type II chondrules. In contrast, the O-isotope compositions of some dusty olivine chondrules ( $Fa_{.1}$ ) are tightly clustered at  $\Delta^{17}O \sim 0\text{‰}$ , and are distinct from the dominant populations of both type I ( $\Delta^{17}O \sim -6\text{‰}$ ) and type II ( $\Delta^{17}O \sim -2\text{‰}$ ) chondrules (Fig. 2; consistent with [24,25]). This suggests these chondrules contain components formed with an O-isotope reservoir unrelated to CM type I or type II chondrules.

The *in situ* O-isotope compositions of some dusty olivines in UOCs and CR chondrites are similar to their respective type I and type II chondrules (Tables 2 and 3), perhaps due to a petrogenetic relationship via reduction. However, most CR type II chondrules are near  $\Delta^{17}O \sim 0\text{‰}$ , while dusty olivine chondrules are often  $\Delta^{17}O < 0\text{‰}$ ; suggesting they are not reduced type

II chondrules. Some grains in the UOC dusty olivine chondrules are  $^{16}O$ -rich compared to type I and II chondrules, indicating a distinct origin.

The O-isotope compositions of some dusty olivine bearing chondrules can be explained by reduction of either type I or type II chondrules. However, some dusty olivine chondrules in each group have O-isotope compositions that cannot be explained by reduction of that group's type I or type II chondrules (e.g., CM chondrites, Fig. 2). The major and minor element compositions of some dusty olivine chondrules also cannot be explained by reduction of that group's type I or II chondrules (i.e., Fe/Mg–Fe/Mn systematics [26]). These dusty olivine chondrules may require a population of relatively FeO-rich olivine precursors of a non-local origin. This implied non-local origin might be evidence for migration of earlier formed chondrules [e.g., 27,28] between groups, or for incorporation of FeO-rich olivine fragments from planetesimal(s).

The diverse O-isotope compositions of chondrules indicate their precursors were O-isotopically heterogeneous, inconsistent with formation solely in impact splashes from melted (i.e., homogenized) bodies. Additional analyses of dusty olivine and CM chondrite chondrules (perhaps correlated O-isotope and  $\epsilon^{54}Cr$  analyses [e.g., 29]) may help resolve these issues. Implications for other models of chondrule formation will be discussed.

**References:** [1] Hood and Horanyi (1991) *Icarus*, 93, 259. [2] Shu et al. (1996) *Science*, 271, 1545. [3] Pilipp et al. (1998) *Astron. Astrophys.*, 331, 121. [4] Desch et al. (2012) *MAPS*, 47, 1139. [5] Hubbard et al. (2012) *ApJ*, 761, 58. [6] McNally et al. (2013) *ApJ. Lett.*, 767, L2. [7] Johnson et al. (2015) *Nature*, 517, 339. [8] Connolly et al. (1998) *GCA*, 62, 2725. [9] Hewins et al. (2005) *CPD*, 286. [10] Alexander et al. (2008) *Science* 320, 1617. [11] Nagahara (1981) *Nature* 292, 135. [12] Rambaldi (1981) *Nature* 293, 558. [13] Jones et al. (2005) *CPD*, 251. [14] Jones (2012) *MAPS* 47, 1176. [15] Jones and Danielson (1997) *MAPS* 32, 753. [16] Kita et al. (2010) *GCA* 74, 6610. [17] Hewins and Zanda (2012) *MAPS* 47, 1120. [18] Schrader et al. (2013) *GCA*, 101, 302. [19] Leroux et al. (2003) *MAPS* 38, 81. [20] Connolly et al. (1994) *Nature* 371, 136. [21] Schrader et al. (2017) *GCA*, doi.org/10.1016/j.gca.2016.06.023. [22] Ghosh et al. (2006) *MESS II*, 555. [23] Schrader et al. (2014) *GCA* 132, 50. [24] Jenniskens et al. (2012) *Science* 338, 1583. [25] Chaumard et al. (2016) *79<sup>th</sup> MetSoc* #6408 (abstr.). [26] Goodrich and Delaney (2000) *GCA* 64, 149. [27] Kita et al. (2010) *GCA* 74, 6610. [28] Weisberg et al. (2011) *GCA* 75, 6556. [29] Sanborn et al. (2015) *LPSC XLVI* #2259 (abstr.).

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