OUTWARD MIGRATION OF DUST GRAINS FROM THE INNER TO THE OUTER SOLAR SYSTEM: EVIDENCE FROM RELICT GRAINS IN CV CHONDRITE CHONDRULES. D. L. Schrader1,2, J. Davidson1,2, and K. Nagashima3. 1Buseck Center for Meteorite Studies, 2School of Earth and Space Exploration, Arizona State University, 781 E. Terrace Rd, Tempe AZ 85287-6004, USA (devin.schrader@asu.edu), 3HIGP/SOEST, University of Hawai‘i at Mānoa, Honolulu, HI 96822, USA.

Introduction: In recent years it has become apparent that migration of sub-mm sized-particles occurred in the very early Solar System (e.g., [1–5]). The extent and direction(s) of grain migration throughout the protoplanetary disk is not yet known. Since the 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]), they have the potential to record grain migration in the disk. In fact, some minimally altered chondrites have recently been shown to contain evidence for grain migration (e.g., [2–5]).

Partially melted chondrules retain unmelted precursor silicates, termed relict grains; the chemical and O-isotope compositions of which can be used to determine their origins. Relict grains may show similarities to material from other chondrite groups and thus imply potential grain migration in the protoplanetary disk (e.g., [3,4]). As part of our ongoing efforts to understand grain migration (e.g., [2–4]), we have undertaken a search for chondrule precursors in multiple chondrite groups. We previously reported analyses of relict grains in unequilibrated ordinary chondrites (UCOs), and carbonaceous Renazzo-like (CR), Mighei-like (CM), and Ornans-like (CO) chondrites [2–4,8], and preliminary data for Vigaranolike carbonaceous (CV) chondrites [9]. Here we present O-isotope data for the CV chondrites, which likely formed in the outer Solar System, beyond the orbit of Jupiter, and slightly earlier than the other carbonaceous chondrites groups (e.g., [7]).

Results and Discussion: We identified relict grains in all CVs studied here, including FeO-poor relict grains in FeO-rich (type II) chondrules, and relict dusty-olivine grains in FeO-poor (type I) chondrules. Using Fe-Mn systematics, following the method described in [4,9,12], we also identified FeO-poor relict grains in FeO-poor chondrules and FeO-rich relict grains in FeO-rich chondrules, which would otherwise be difficult to identify (they are not apparent in BSE images).

We identified multiple CL features in FeO-poor chondrules in Leoville and in Kaba that correspond to higher abundances of CaO (e.g., 0.70 vs. 0.25 wt.%). A CL feature with an O-isotope composition that is indistinguishable from the rest of the host chondrule indicates a crystallization feature (e.g., [16]), while a CL feature with an O-isotope composition distinct from the host chondrule indicates a relict grain (i.e., [17,18]).

Due to the number of relict and potential relict grains identified, we selected a total of 17 chondrules (9 FeO-poor and 8 FeO-rich chondrules) from Bali, Kaba, and

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Figure 1. Dusty-olivine bearing chondrule in Leoville.

Sample Selection: Since relict grains only remain in the least altered chondrites and CV3s are generally of higher petrographic type (i.e., more heated) than the CR, CM, and some CO chondrites [6], CV3s with the lowest relative peak metamorphic temperatures were studied [10]. We studied polished sections of the type samples for each of the three CV subgroups, the oxidized CV_{OXA} Allende (ASU818_132_L1a) and CV_{OXB} Bali (USNM4839-1), and the reduced CV_{Red} Vigaranol (ASU590_C1) for comparison, and we also studied CV_{Red} Leoville (ASU821), CV_{Red} NWA 12772 (ASU2019), and CV_{OXA} Kaba (USNM1052-1). While Allende is known to be heated [10], we analyzed it to test the limits of relict grain survival.

Analytical Techniques: 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) (operating conditions: 20 kV and 15 nA). Quantitative compositional analyses of silicate phases were subsequently performed on the Cameca SX-100 EPMA at the University of Arizona (UAz) using similar conditions to those reported in [11,12]. The ASU EPMA was also used to obtain cathodoluminescence (CL) maps of chondrules with Fa<2. To precisely target selected spots via SIMS, we used a focused ion beam (FIB) marking technique (e.g., [13,14]) at UAz to remove a 2×2 µm square of C-coat at each planned SIMS spot (operating conditions; 30 kV and 7.7 pA); which are then visible by 16O secondary ion imaging with the SIMS [15]. O-isotope analyses were conducted with the University of Hawai‘i (UH) Cameca ims-1280 ion microprobe (details see [2,3]), with beam sizes of 10 µm and 3 µm.

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Figure 1. Dusty-olivine bearing chondrule in Leoville.
Leoville for in situ O-isotope analyses. The O-isotope compositions of olivine from FeO-poor (including dusty olivine; Fig. 1) and FeO-rich chondrules analyzed in Bali, Kaba, and Leoville ranges from $\Delta^{17}O = -22.6\pm 0.5 \%$ (2σ; 10 µm spot) to $1.6\pm 2.0 \%$ (2σ; 3 µm spot). We identified numerous chondrule-hosted relict grains by their distinct O-isotope compositions (e.g., outside 3σ of the host mean). Petrographically identified relict grains and relict grains identified via Fe-Mn systematics were confirmed to be relict grains via O-isotope analyses. In contrast, CL bright features in chondrules with FeO<2 were found to have the same O-isotope compositions as CL dark regions, indicating the CL bright features may be due to crystallization instead of being relict grains.

A common relict grain in chondrules from Bali and Kaba are those with AOA-like morphologies (Fig. 2) and/or compositions (e.g., $\Delta^{17}O \sim -20 \%$), indicating incorporation of AOAs or AOA-like precursors during chondrule formation; also seen in Kaba by [19].

**Figure 2.** Relict grains in FeO-rich chondrule in Bali.

The O-isotope compositions of other relict grains (not AOA-like) are consistent with an origin from CV FeO-poor and FeO-rich chondrules (e.g., [5,16,19–22, this study]), indicating CV chondrule recycling. Interestingly, we identified three chondrules with olivine O-isotope compositions at and above the terrestrial fractionation line, $\Delta^{17}O \sim 0 \%$ (a dusty olivine chondrule in Leoville, and a FeO-poor and a FeO-rich chondrule in Kaba). Their O-isotope compositions are unlike those of typical chondrules from CV chondrites (e.g., [5,16,19–22]), and are more similar to those of ordinary chondrite chondrules than carbonaceous chondrite chondrules (e.g., [18,23]). This $\Delta^{17}O \sim 0 \%$ composition is similar to those of some exogenous dusty olivine and FeO-poor chondrules found in CM chondrites by [3] and the three OC-like chondrules found in Kaba by [5], and similarly we suggest these chondrules/olivine grains are exogenous to the CV chondrule-forming region. The dusty olivine chondrule contains relatively FeO-rich olivine grains (Fa7 vs. Fa<3) with O-isotope compositions ($\Delta^{17}O \sim -4 \%$) similar to those of some CV chondrules (16,21), suggesting the chondrule is a mixture of CV chondrule material and mostly OC-like material that underwent solid state reduction. One of these $\Delta^{17}O \sim 0 \%$ chondrules has major and minor element compositions unlike those of other CV chondrules, but is similar to those of OC chondrules and is compositionally within the ‘forbidden triangle’ of [24]. In addition to olivine from Comet Wild 2 and interplanetary dust particles [24], we previously found this ‘forbidden triangle’ compositional space is also populated by some OC chondrule olivine [4].

**Summary:** We propose that olivine in the $\Delta^{17}O \sim 0 \%$ chondrules migrated from the OC region in the inner Solar System to the CV chondrule forming region in the outer Solar System (e.g., [5]). This migration must have occurred after the formation of OC chondrules, and therefore after the formation of the Disk Gap (e.g., [3,4,5]). The AOA-like olivine found in CV chondrules here also migrated from the inner Solar System to the CV chondrule forming region before/during chondrule formation (e.g., [2,19]), but this migration could have occurred before or after the formation of the Disk Gap.


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