RUMURUTI AND METAMORPHOSED, ORDINARY CHONDRITE CHONDRULE FRAGMENTS FROM COMET 81P/WILD 2.

D. R. Frank[1], G. R. Huss[1], K. Nagashima[1], E. Hellebrand[1], A. J. Westphal[2], Z. Gainsforth[2], dfrank@hawaii.edu, [1]Hawai'i Institute of Geophysics and Planetology, Dept. of Earth and Planetary Sciences, University of Hawai'i at Manoa, [2]Space Sciences Laboratory, University of California, Berkeley.

Introduction: Previous studies [1-9] showed that the vast majority of Wild 2 silicates have chemistry and O isotopes indistinguishable from chondrules, AOAs, and isolated matrix grains in chondrites. The Fe-rich olivine ($Fa_{>15}$) in Wild 2 has a wide range of Mn/Fe ratios that are consistent with type II chondrules in both ordinary and carbonaceous chondrites (OCs and CCs), and the low Cr content is consistent with a ~3.10 metamorphic grade [1]. Four tracks have Fe-rich olivine (Fa_{20-32}) with CaO content < 0.07 wt.%, requiring ≥ 3.5 petrologic grade [1]. These observations led [1] to infer that Wild 2 accreted a mixture of OC and CC type II chondrule fragments that underwent varying degrees of secondary thermal metamorphism. This previous work received two major criticisms:

1) We made TEM/EDXS measurements of many ~0.2 - 1µm crystallites in the Wild 2 samples and compared their compositions to EPMA measurements of 5-30µm isolated matrix grains in chondrites. The smaller Wild 2 olivines are more analogous to the micron and sub-µm chondrite matrix, and the low-Cr content in the Wild 2 olivine may not reflect secondary thermal metamorphism. Unfortunately, data sets with minor elements of the sub-µm matrix olivines are unavailable.

2) Of all the Fe-rich olivine grains that had a clear OC Mn/Fe signature, no O-isotope data were available, and an OC origin has been called into question.

We now present coordinated chemical and isotopic measurements of coarse, Fe-rich olivine and low-Ca pyroxene terminal particles from a new Stardust track (209) in order to address the above criticism.

Samples and Methods: Track 209 is a 7.4mm long carrot-shaped track with at least 9 terminal particles. The deepest particle (particle 1) is ~15µm x 12µm and was hand polished for EPMA and to preserve texture (fig. 1). A second terminal particle (particle 2) ~12µm x 6µm was ultramicrotomed and studied on an FEI Titan TEM at the National Center for Electron Microscopy (NCEM). Oxygen isotopes were measured with the UH Cameca ims 1280 ion microprobe in multi-collection mode, using a ~10pA Cs^+ primary ion beam (see [10] for details). The beam was rastered over 2µm x 2µm spots to obtain two measurements for each particle.

Results: Particle 1 is a homogeneous crystal of Fe-rich olivine (Fa_{26}). EPMA data are plotted in figs. 2-3.

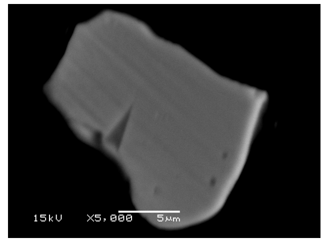

Figure 1: BSE image of track 209 particle 1. Fe-rich olivine (Fa_{26}) showing several voids preserved by hand polishing.

Figure 2 shows this particle with high Mn content (0.46-0.53 wt.% MnO) that is consistent with L/LL chondrite olivine but inconsistent with CM, CO, CV_{red}, and Acfer 094. A few CR olivines reach Mn content this high, but they are uncommon, and the Cr content of the track 209 olivine is only consistent with L/LL olivine, not CRs or other unmetamorphosed CCs. In fig. 3, the Cr content of particle 1 is compared with isolated matrix grains of comparable size (5-30µm) and is consistent with similarly sized LL3.10 matrix olivines and with TEM measurements of Wild 2 olivine [1]. Note that the Cr content of the track 209 olivine is near the upper end of the range of most TEM measurements. Therefore, crystal size dependence on Cr content appears to be small, and the low Cr values of previous TEM measurements are not merely due to their smaller sizes.

Particle 2 appears to be a single crystal of low-Ca pyroxene ($Fs_{15}Wo_{0.8}$). Pyroxene with $Fs_{>10}$ is rare in CCs but occurs frequently in OCs [11] and R chondrites [12-13]. The minor element (Mn, Cr, Ca) contents of the track 209 pyroxene all fall within the ranges for LL3 pyroxene.

Oxygen-isotope measurements of track 209 and literature values of Wild 2 olivine and pyroxene [3-9] are shown in fig. 4 along with olivine and low-Ca pyroxene data from type II chondrules in LL3 [14], R [15], and CR [16-17] chondrites. The $\delta^{17}O$ uncertainties associated with track 209 olivine permit consistency with either CR or LL3 chondrules. The O values for pyroxene are unambiguously not CC, and the $\delta^{18}O$ values are too low to be an LL type II chondrule. Type II chondrules in R chondrites, however, have O isotopes consistent with the track 209 pyroxene.

Discussion: The track 209 olivine has a Mn/Fe ratio and oxygen isotopic composition that is consistent with both CR and OC chondrule olivine, but the Cr content is only consistent with mildly metamorphosed OC olivine (~3.10). We also note the wedge-shaped void (fig. 1), which appears to be crystallographically controlled. The close proximity to the grain boundary resembles void space created by recrystallization of subgrains during thermal metamorphism.

The oxygen composition of the track 209 pyroxene unambiguously precludes a CC origin. When considering the Fe content (Fs_{15}) and low $\delta^{18}O$ values, the combined compositional signature strongly implies an R chondrite origin.

We infer the track 209 silicates are derived from two distinct type II chondrules: one that shares a common origin with R chondrules, and one OC chondrule that experienced secondary thermal metamorphism. The size of the track 209 olivine permits comparison to the EPMA measurements of matrix olivine in [1], confirming a ~3.10 metamorphic grade for much of the Fe-rich olivine from Wild 2.

The presence of R- and OC-derived materials in Wild 2 demonstrates that Jupiter did not prevent mixing of inner and outer solar system solids >1 Myr after CAIs. Although we cannot rule out transport of fine-grained R and OC material to the Kuiper Belt, fine-grained transport requires invoking an uncertain mechanism to account for secondary thermal metamorphism, either in the nebula or within Wild 2 itself. We therefore speculate that parent asteroid metamorphism preceded delivery of whole, inner solar system asteroids to the Kuiper Belt, and that subsequent impacts dispersed their material widely. We suspect that such physical mixing between asteroids and KBOs was common, driven by giant planet growth and/or migration.

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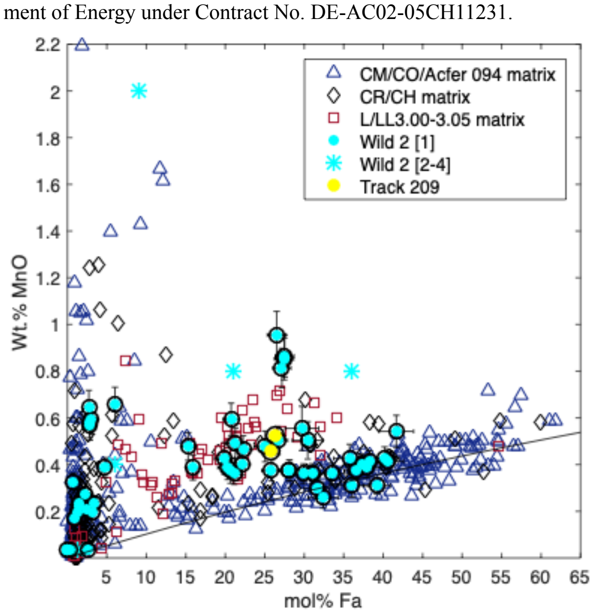

Figure 2: Mn vs. Fe in Wild 2 olivine and matrix olivine grains [1].

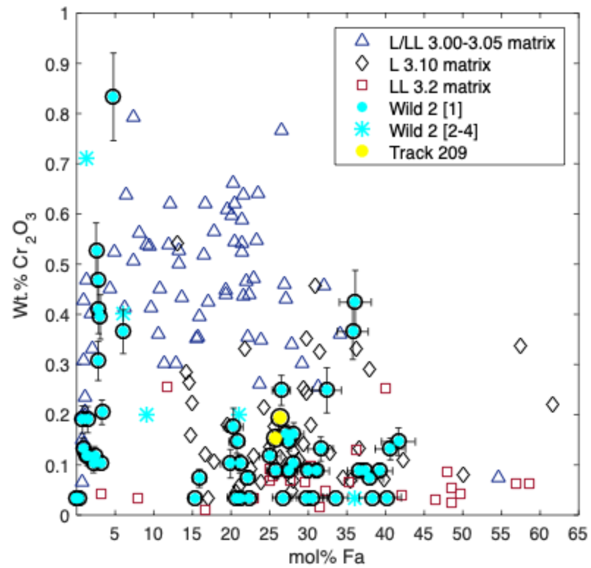

Figure 3: Cr vs. Fe in Wild 2 and matrix olivine grains from [1].

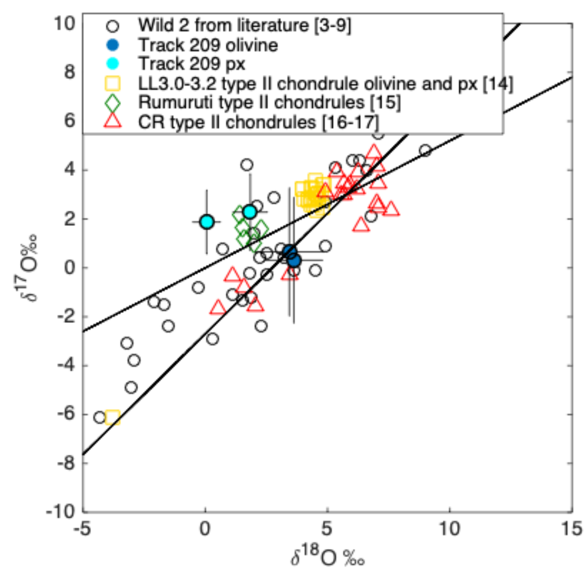

Figure 4: Oxygen isotopes in track 209 olivine and pyroxene compared with literature values and chondrites. The primitive chondrule mineral line (PCM) line is drawn for reference.

References: [1] Frank D. R. et al. 2014. *GCA* 142:240-259. [2] Joswiak D. et al. 2012. *MAPS* 47:471-524. [3] Ogliore R. C. et al. 2015. *GCA* 166:74-91. [4] Nakamura T. et al. 2008. *Science* 321:1664. [5] McKeegan et al. 2006. *Science* 314:1724. [6] Nakashima D. et al. 2012 *EPSL* 357-358:355-365. [7] Gainsforth Z. et al. 2015. MAPS 50(5):976-1004 [8] Defouilloy C. et al. 2017. 465:145-154. [9] Joswiak et al. 2015. *GCA* 144:277-298. [10] Makide K. et al. 2009. *GCA* 73:5018-5050. [11] Frank D. R. et al. 2014 *LPSC* Abstract #2643. [12] Schulze H. et al. 1994. *MAPS* 29-2:275-286. [13] Bischoff A. et al. 2011. *Chemie der Erde* 71-2:101-133. [14] Kita N. et al. 2010. *GCA* 74:6610-6635. [15] Miller K. et al. 2017. *GCA* 209:24-50. [16] Connolly H. C. and Huss G. R. 2010. *GCA* 74:2473-2483. [17] Schrader D. L. et al. 2013. *GCA* 101:302-327.