Oxygen Isotopic Measurements of Phenocrysts in Chondrules from the Primitive Carbonaceous Chondrite Yamato 81020: Evidence for Two Distinct Oxygen Isotope Reservoirs. T. J. Tenner[1], T. Ushikubo[1], E. Kurahashi[2], N. T. Kita[1], and H. Nagahara[3], [1]WiscSIMS, Department of Geoscience, University of Wisconsin-Madison, Madison, WI 53706 (tenner@wisc.edu), [2]Department of Mineralogy, Natural History Museum, London, UK, [3]Department of Earth and Planetary Science, The University of Tokyo, Japan.

Introduction: Chondrules in primitive meteorites are sub-millimeter melted spherules that likely formed in the dust-rich protoplanetary disk of the early solar system. However, relatively little is known about the environment of chondrule forming regions, including the degree of source mixing and spatial distribution of sources over time. The oxygen isotopic signature of chondrules is a valuable proxy because observed variability is related to precursors of chondrules, as well as the environment from which chondrules formed [1]. Ushikubo et al. [2] found that chondrules in Acfer 094 (ungrouped C) exhibit bimodal distribution of oxygen three isotopes with the Δ^{17}O (=δ^{17}O-0.52×δ^{18}O) values at −5‰ and −2‰. However, the ^{26}Al ages of type I chondrules in Acfer 094 do not correlate with Δ^{17}O values [3]. In this study we report and interpret O isotope ratios of phenocrysts from chondrules in Yamato 81020, which is one of the least altered carbonaceous chondrites (CO3.0). We also discuss the correlation between the oxygen isotope ratios and the relative ^{26}Al ages [4] of corresponding chondrules in Y-81020.

Samples and Methods: We analyzed a total of 32 chondrules, consisting of 22 type I (Mg#$_{silicate}$ > 90) and 9 type II (Mg#$_{silicate}$ < 90) chondrules (Fig. 1), and 1 Al-rich chondrule. Of these, 20 (14 type I, 5 type II, 1 Al-rich) have been previously measured by Al-Mg systematics to determine their relative ages [4]. Oxygen isotope measurements are limited to olivine and pyroxene phenocrysts, as high-precision SIMS requires a spot size of ~15µm. Petrographic observations were performed with a Hitachi S-3400N SEM, and major element concentrations of silicate phases were measured with a Cameca SX51 EMP at UW-Madison. Oxygen isotopes were analyzed with a Cameca-IMS 1280 ion microprobe at the WiscSIMS Laboratory using multi-collector Faraday Cups similar to the method in [5]. Primary Cs$^+$ ion intensity was 3 nA and the external reproducibilities (2SD) of a San Carlos olivine standard were typically at 0.5, 0.4, and 0.4 ‰ for δ^{18}O, δ^{17}O, and Δ^{17}O, respectively.

Results and Discussion: We obtained 169 O isotope analyses of olivine, low-Ca and high-Ca pyroxene from Y-81020 chondrules (1 to 11 spots each). All data fall between CCAM [6] and Young & Russell [7] lines (Fig. 2). Generally, Δ^{17}O values of multiple analyses from a chondrule are within external reproducibility. However, ten chondrules contain olivine grains that exceeded the external reproducibility, with distinct Δ^{17}O values relative to the other minerals. These olivines are likely unmelted "relicts" from a solid precursor of the chondrule, in which their O isotopes did not equilibrate during final-stage melting.

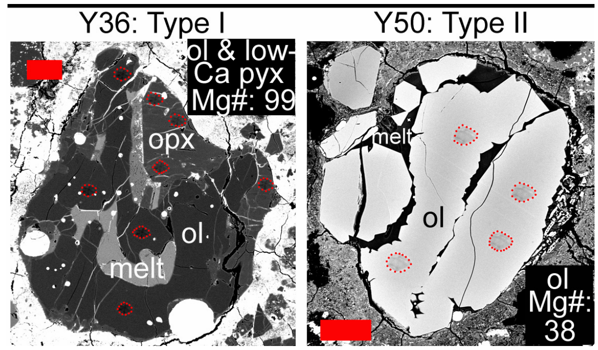

Fig. 1: BSE images of a typical type I and II chondrule from chondrite Y-81020. Dotted circles are SIMS pits from O isotope analyses. Mg#$_{silicate}$ = Mol. % (MgO/(MgO+FeO)). Scale bars = 50 µm.

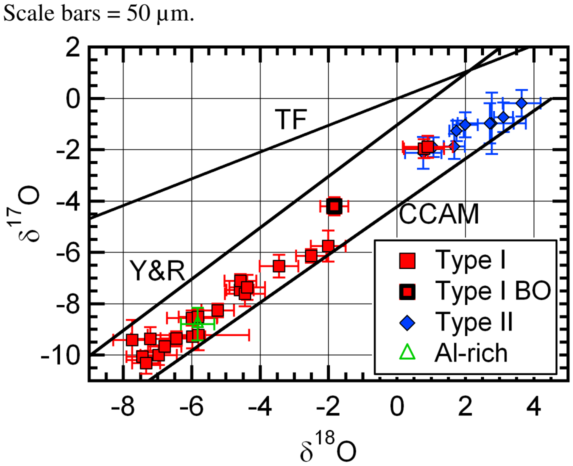

Fig. 2: Average isotopic compositions of individual chondrules excluding relict olivine grains from Y-81020. TF, Y&R, and CCAM represent the terrestrial fractionation line, Young & Russell line, and the carbonaceous chondrite anhydrous mineral line, respectively. Error bars are in 2σ.

Excluding relicts, phenocrysts in chondrules of Y-81020 are mainly distributed into two subgroups (Fig. 2) with Δ^{17}O values of ~−2 and ~−5 ‰ (Fig. 3a&b). These subgroups correlate with Fe-content of olivine and pyroxene, as 20 of 21 chondrules with Mg#>98 phenocrysts are ^{16}O-rich (Δ^{17}O: −5.5±1.0 ‰) while all chondrules with Mg# 36-95 phenocrysts are ^{16}O-poor (Δ^{17}O: −2.4±0.3 ‰) (Fig. 3a&b). These results are very similar to those found in Acfer 094 [2]. One chondrule with a Mg# 99 barred-olivine texture has an intermediate $\Delta^{17}O$ of −3.2 ‰ (Fig 3a).

Relict olivines in 9 of 10 chondrules have $\Delta^{17}O$ between −2 and −6 ‰ (Fig. 3c) suggesting they are related to one of the two isotope reservoirs common to the majority of chondrules in Y-81020. Two chondrules contain relicts that have $\Delta^{17}O$ of −11 and −14 ‰, respectively, suggesting that the relicts derive from highly ^{16}O-rich precursor material. One chondrule only contains very ^{16}O-poor ($\Delta^{17}O$~−0.4‰) relicts, suggestive of precursor material from the ordinary chondrule O isotope reservoir (Fig. 3a). Additionally, LL3 chondrules contain ^{16}O-rich relicts [5] with similar oxygen isotope ratios to carbonaceous chondrite precursors (Fig. 3c), so it is likely that some overlap in precursor material between ordinary and carbonaceous chondrules occurred.

Implications of ^{16}O-rich and ^{16}O-poor reservoirs in carbonaceous chondrites. The high Mg#'s (>98) of ^{16}O-rich phenocrysts in chondrules of Y-81020 imply that they formed under reducing conditions (log fO_2: −12) [8]. Phenocrysts in ^{16}O-poor chondrules, however, are more Fe-rich (Mg# 36-95), implying more oxidizing conditions (log fO_2 between −9 and −11), assuming that temperature and bulk chondrule compositions remain constant [8]. The degree of H_2O and/or dust-enrichment can have a considerable effect on fO_2 in chondrule-forming regions [9]. Anhydrous, low-dust conditions in precursor material are reducing and favor the formation of Mg-rich chondrules, while increasing dust-enrichment and bulk H_2O concentration aids in a more oxidizing environment that promotes forming Fe-enriched silicates in chondrules [9].

Relative chondrule ages vs. $\Delta^{17}O$: By combining our data with the corresponding Al-Mg systmatics of [4], we find that ^{16}O-rich and ^{16}O-poor chondrules in Y-81020 yield ages of 1.7-2.3 Ma, and 2.1-3.0 Ma after the formation of CAIs, respectively. If indeed ^{16}O-poor chondrules are systematically younger than ^{16}O-rich chondrules in Y-81020, it could suggest that the source reservoir O isotopic composition changed over time. For instance, relatively low dust enrichment without H_2O condensation early on could favor forming high Mg# chondrules with ^{16}O-rich signatures. Later, the reservoir region may have accreted a higher dust density and cooled to the point where ^{16}O-poor H_2O condensed. Homogenization of dust and H_2O in this environment would then favor forming Fe-rich, ^{16}O-poor chondrules. However, due to errors in relative ages (0.2- 1Ma) (Fig. 3a), it is equally likely that both ^{16}O-rich and ^{16}O-poor reservoirs coexisted within the carbonaceous chondrule-forming region, and were separated spatially, as suggested by [4] according to contemporaneous formation of chondrules from LL3 and CO3. This argument is strengthened by Acfer 094 data [3], where ^{16}O-rich and ^{16}O-poor chondrules exist on a tighter timescale. As indicated from O isotopes in relict olivines, local turbulence in the disk would result in minor mixing between these reservoirs [10]. More data combining oxygen three isotopes and ^{26}Al ages of chondrules with high precision for multiple chondrite classes are necessary to fully understand the dynamics of chondrule formation throughout the protoplanetary disk as a function of time.

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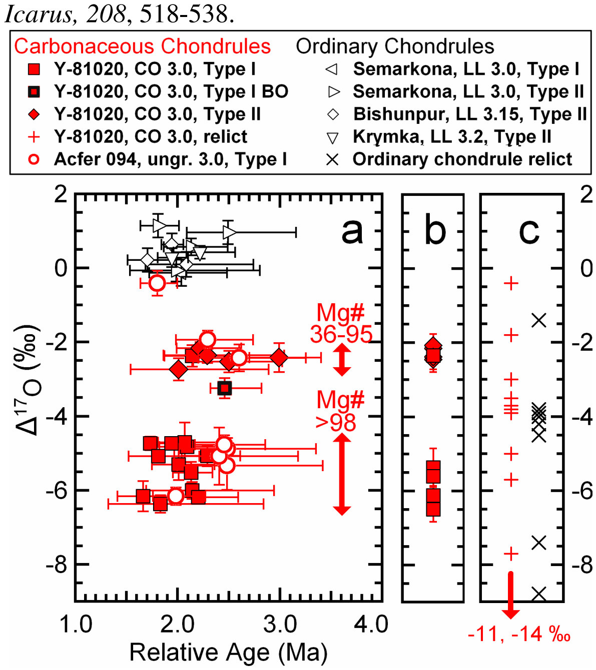

Fig. 3: a) $\Delta^{17}O$ versus the ^{26}Al age relative to CAI. Relative ages are from [2, 4, 5]. Chondrules from Y-81020 form 2 distinct subgroups ($\Delta^{17}O$: ~-5 and -2 ‰) that differ from the ordinary chondrule-forming reservoir [5]. **b)** $\Delta^{17}O$ values from Y-81020 chondrules that were not dated by [4] cluster into the same O-isotopic subgroups, with the same Mg# correlation as carbonaceous chondrules in Fig 3a. **c)** $\Delta^{17}O$ values in relict olivine from Y-81020 ("+", this work) and ^{16}O-rich relict olivine and chondrules from LL3 chondrules ("×", [5]).