Remarkable Diversity of Refractory Inclusions in the Miller Range 090019 CO3.1 Chondrite. D. Kent Ross[1], J. I. Simon[2] and S. B. Simon[3], [1]University of Texas El Paso, Jacobs Technology, and NASA-JSC-ARES, Houston, TX 77058 USA (Daniel.Ross@nasa.gov), [2]NASA-JSC-ARES and the Center for Cosmochemistry and Geochronology, Houston TX, 77058, [3]Institute of Meteoritics, Univ. of New Mexico, Albuquerque NM 87131.

Introduction: We have characterized the mineralogy, textures, bulk compositions, modal abundances and some mineral compositions in a suite of ~ 140 refractory inclusions from the MIL090019 carbonaceous chondrite. All of these 140 inclusions are found in a single thin section of this CO3.1 chondrite. These inclusions range from grossite- and hibonite-rich varieties, melilite-, spinel-, fassaite-diopside- and anorthite-rich types, and include a subset of aluminous AOAs (amoeboidal olivine aggregates). Grossite- and hibonite-bearing inclusions were discussed briefly in previous abstracts [1, 2]. X-ray mapping by energy dispersive spectrometry has permitted us to extract the bulk compositions of these inclusions from hyperspectral x-ray datasets. The bulk compositions of these inclusions represent the full range of recognized CAI types.

Shapes and textures of these CAIs are quite variable, but appear to be dominantly consistent with condensation. Only a small subset of these inclusions are spherules that strongly suggest melting. Oxygen isotope ratios in one spinel-cored spherule were presented in [3]. Silicate glass has not been observed in any of these refractory inclusions. An equally small subset have quite fluffy textures with irregular shapes and considerable porosity.

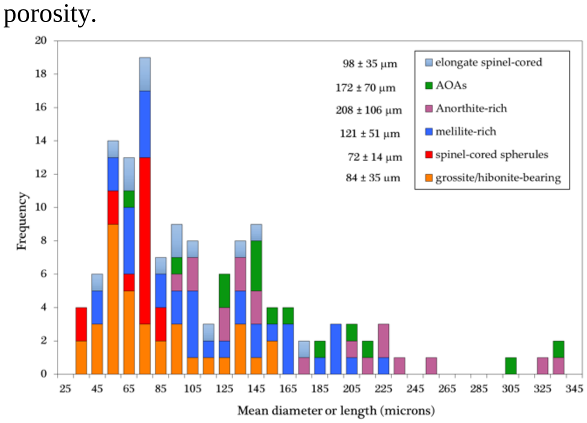

Figure 1. Size frequencies of various types of refractory inclusions. Aluminous AOAs and anorthite-rich inclusions tend to be larger than grossite/hibonite-bearing inclusions and spinel-cored spherules.

The inclusions in this CO chondrite are relatively small, typically ~ 50-250 microns in mean length or diameter. This size range is typical of CO chondrite CAIs, and in sharp contrast to the very large sizes of CAIs found in CV chondrites [4]. In Figure 1, we show the size ranges and frequencies for the inclusions characterized in this study.

The mineralogies of many of these inclusions are clearly not equilibrium condensate assemblages, with relict grossite and/or hibonite coexisting with minerals that formed at lower temperatures. It seems clear that in many cases, gas/solid reactions did not proceed to completion, leaving relicts of minerals formed earlier, at very high temperatures.

Methods: We used a JEOL 8530F, field emission electron probe, equipped with a ThermoFisher SDD-EDS system to chemically map ~ 140 refractory inclusions. The x-ray mapping data were acquired at 15 kV and 30 nA. The time-constant on the EDS detector was set to increase count rates, resulting in some diminishment of the energy resolution of the detector, but better counting statistics in each pixel. The silicon drift detector (SDD) can accommodate much higher count rates (~ 50 kcps in these mapping runs) than SiLi EDS systems, and this feature permitted the mapping of these inclusions over reasonable acquisition times. The refractory inclusions were digitized within the ThermoFisher NSS software, which extracts x-ray counts from the digitized pixels, resulting in a single x-ray spectrum that encompasses all the counts from the defined area. These gathered spectra were compared with standard data collected under the same acquisition conditions, and phi-rho-Z matrix corrections were applied to calculate the bulk compositions. The ThermoFisher software performs background fitting, and sum and escape peak removal. We quantified the compositions of these inclusions for SiO_2, Al_2O_3, TiO_2, CaO, MgO, FeO, Na_2O, ZnO and Cl. Grossite-rich inclusions have, in some cases, been altered, with grossite replaced by very iron-rich spinel, which is also Zn-bearing. Bulk analytical totals were typically in the range 98.5-101.5.

Diverse CAI Lithologies: Figures 2 through 5 illustrate some of the remarkable variety in mineralogy and texture displayed in this suite of refractory inclusions. Figure 2 shows a melilite-rich, anorthite- and spinel-bearing, compact inclusion, rimmed by diopside. Object A in Figure 3 is an anorthite-rich, melilite-, spinel-, and fassaite-bearing inclusion, rimmed by diopside, which has some remnant porosity and a convoluted margin. Inclusion 3B is a spinel-cored, anorthite-bearing CAI, with diopside rim. Figure 4 shows a porous cluster of spinel-cored grains, with melilite, fassaite and perovskite, and thin diopside rims. It appears that the rim-forming episode preceded assembly of the porous cluster. Figure 5 shows an olivine-rich, aluminous

AOA, in which spinel-cored spherules were engulfed, with alternating diopside and olivine growth.

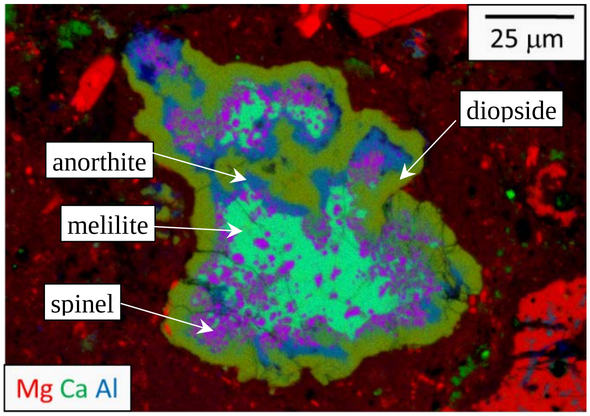

Figure 2. MIL090019-13-K3. Melilite, spinel, and anorthite bearing CAI, with fassaite, and rimmed by diopside.

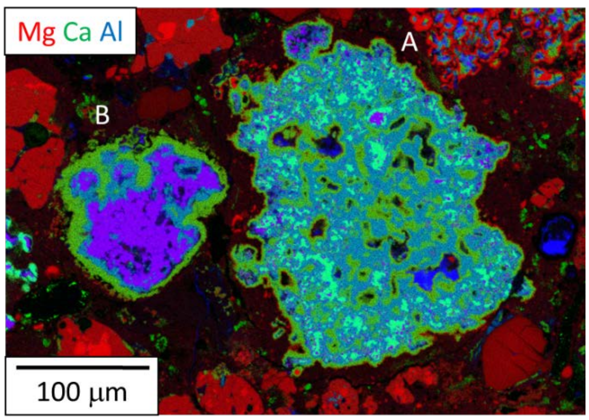

Figure 3. MIL090019-13-P. A. Anorthite-rich, melilite and spinel-bearing with diopside rim. B. Spinel-cored, anorthite-bearing CAI with diopside rim.

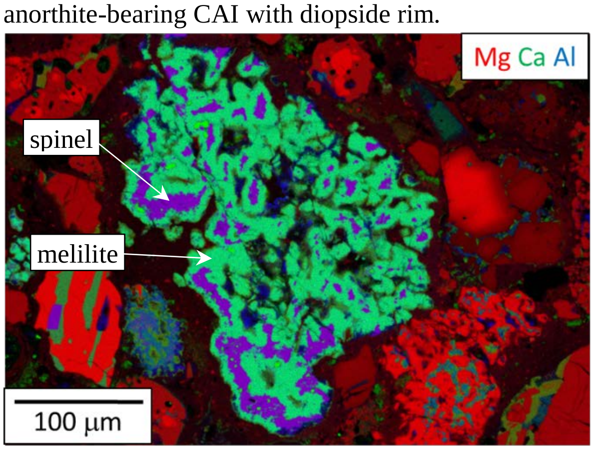

Figure 4. MIL090019-13-S. Porous cluster of spinel, perovskite and melilite-bearing sub-grains.

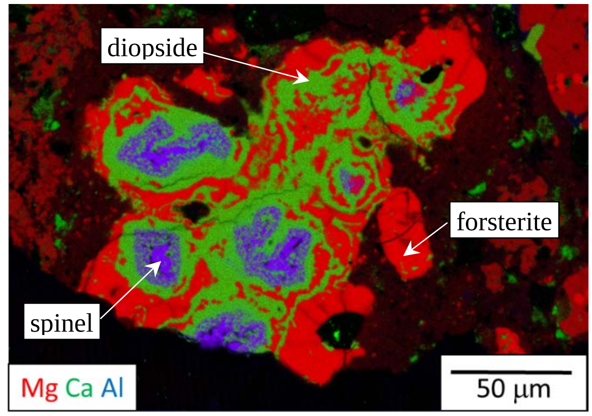

Figure 5. MIL090019-13-Z. AOA incorporating a group of spinel-cored spherules.

Bulk Compositions: Refractory inclusions in this data set exhibit a remarkable range of bulk compositions, reflecting their diverse mineralogical content. Silica abundances range from ~ 3 to 45 wt. %, alumina from 5 to 58 wt. %, and MgO from 1 to 45 wt. % (including aluminous AOAs). CaO ranges from ~3 to 38 wt. % and TiO2 from < 1 to 12.5 wt. % (in one particularly perovskite rich sample). FeO abundances also encompass a surprisingly large range of values, from < 1 to 19 wt. %! The highest iron abundances are in grossite-rich samples that have been altered, with grossite clearly replaced by FeO- and ZnO-rich spinel. Even in non-grossite-bearing inclusions, iron is often surprisingly high, reflecting various sources – FeO-rich diffuse veins, and matrix-filled pores that was difficult to exclude in the digitization process. The software used to extract x-ray counts required drawing one continuous line. Quantitative electron probe data on various primary phases in these inclusions shows 0.3-1.1 wt. % FeO, although some inclusions that aren't grossite bearing also show FeO-enriched spinel, according to qualitative data by EDS. FeO enrichments are also seen in CAIs in DOM CO3s and Acfer 094 [5].

The most interesting conclusion that can be drawn from this very diverse suite of refractory inclusions is that the process that delivered them into the region of CO chondrite assembly sampled such a wide range of CAI types. CAIs that were supplied to this chondrite represent a wide variety of CAI-forming conditions.

References: [1] Ross, D. K. and Simon J. I. (2018) *49th LPSC,* abstract # 2559. [2] Simon S. B. (2016) *79th Ann. Met. Soc. Meeting,* abstract # 6098. [3] Simon J. I., Simon S. B., Nguyen, A.N., Ross, D.K., and Messenger, S. (2017) *80th Ann. Met. Soc. Meeting,* abstract # 6123. [4] Scott, E.R.D. (2007) *Ann. Rev. Earth Planet Sci.*, 35, 577-620. [5] Simon S. B and Grossman, L. (2015) MaPS, 50, 1032.