

**CORUNDUM-HIBONITE INCLUSIONS AND THE ENVIRONMENTS OF HIGH TEMPERATURE PROCESSING IN THE EARLY SOLAR SYSTEM.** A. W. Needham<sup>1,2</sup> and S. Messenger<sup>2</sup>. <sup>1</sup>Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058, USA. E-mail: [andrew.w.needham@nasa.gov](mailto:andrew.w.needham@nasa.gov). <sup>2</sup>Robert M. Walker Laboratory for Space Science, ARES, NASA JSC, 2101 NASA Parkway, Houston TX 77058, USA

**Introduction:** Calcium, Aluminum-rich inclusions (CAIs) are composed of the suite of minerals predicted to be the first to condense from a cooling gas of solar composition [1]. Yet, the first phase to condense, corundum, is rare in CAIs, having mostly reacted to form hibonite followed by other phases at lower temperatures. Many CAIs show evidence of complex post-formational histories, including condensation, evaporation, and melting [e.g. 2, 3]. However, the nature of these thermal events and the nebular environments in which they took place are poorly constrained. Some corundum and corundum-hibonite grains appear to have survived or avoided these complex CAI reprocessing events. Such ultrarefractory CAIs may provide a clearer record of the O isotopic composition of the Sun and the evolution of the O isotopic composition of the planet-forming region [4-6].

Here we present in situ O and Mg isotopic analyses of two corundum/hibonite inclusions that record differing formation histories.

**Methods:** A thin section of ALH77307, a highly unequilibrated CO3.0 chondrite, was mapped for Ca, Al-rich, and Si-poor phases with a JEOL 7600F field-emission scanning electron microscope. Energy-dispersive X-ray (EDX) maps were obtained at 1.5 $\mu$ m per pixel resolution. Identified corundum-bearing CAIs were subsequently analyzed using a Cameca SX100 electron microprobe to confirm their mineralogy and provide quantitative element compositions (by wavelength-dispersive X-ray spectrometry), including accurate Al/Mg ratios relevant to the associated Mg isotope analyses.

Selected CAIs were subjected to O isotopic imaging with the JSC NanoSIMS 50L ion microprobe. Isotopic images of <sup>16,17,18</sup>O, <sup>12</sup>C<sub>2</sub>, <sup>27</sup>Al and <sup>28</sup>Si were acquired in multidetection from 5-20  $\mu$ m fields of view with electron multipliers. The data were normalized to a San Carlos olivine standard. An electron flood gun was used for charge compensation.

Isotope images of <sup>24,25,26</sup>Mg, <sup>27</sup>Al, <sup>28</sup>Si, <sup>40</sup>Ca and <sup>48</sup>Ti<sup>16</sup>O were subsequently obtained from these same CAIs. In all cases the O isotope analyses were conducted prior to the use of an O<sup>-</sup> primary ion beam used for Mg isotope analyses. Madagascar hibonite and terrestrial corundum were used to determine relative sensitivity factors and all data were normalized to a San Carlos olivine standard.

**Results:** EDX maps of ALH77307 identified numerous CAIs ranging from sub- $\mu$ m to >500 $\mu$ m. We selected two corundum-bearing CAIs for further study.

*CAI-61* (24 x 12 $\mu$ m; Fig 1a) is unusual, having a hibonite core, corundum mantle and an incomplete spinel and melilite rim. Oxygen isotope compositions of the hibonite and corundum are indistinguishable within error: ( $\delta^{17}\text{O} = -49 \pm 7\%$ ,  $\delta^{18}\text{O} = -41.5 \pm 2.5\%$ ; Fig 2). <sup>26</sup>Mg excesses were detected in both hibonite and corundum. An Al-Mg plot (Fig 3) of the corundum and hibonite analyses defines a straight line numerical fit corresponding to an initial <sup>26</sup>Al/<sup>27</sup>Al of  $4.2 \times 10^{-5}$ .

*CAI-160* consists of a 13 $\mu$ m corundum grain with three <3 $\mu$ m regions of hibonite (Fig 1b). O isotopic images showed the corundum and hibonite to have indistinguishable  $\delta^{17}\text{O}$  (-15 $\pm$ 12‰) and  $\delta^{18}\text{O}$  (-17 $\pm$ 9‰) values, falling on the CCAM line (Fig 2). Corundum and hibonite regions are similarly homogeneous with respect to Mg isotopes, neither showing evidence for decay of <sup>26</sup>Al (Fig 4).

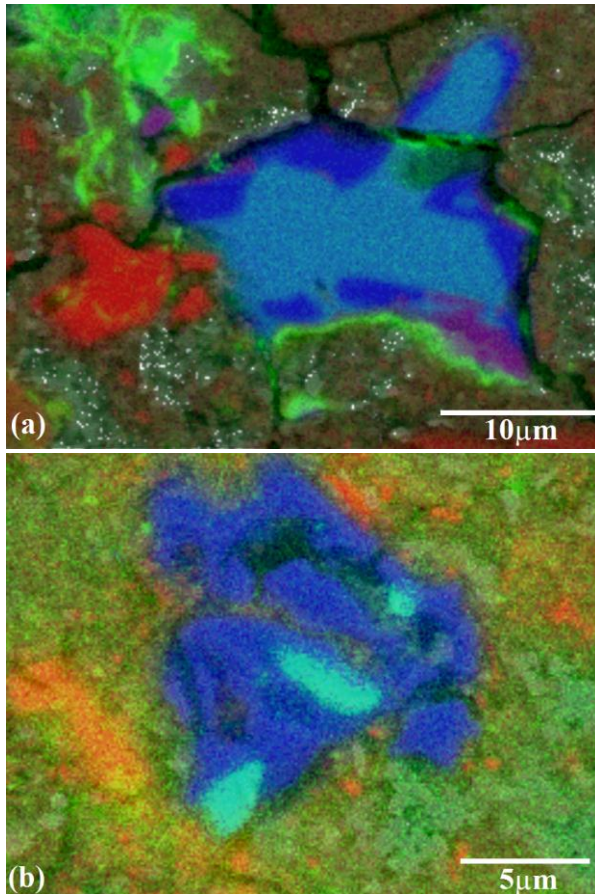
**Discussion:** Both CAIs have O isotopic compositions in the observed range of meteoritic hibonite and corundum [6-9]. Both CAIs fall within error of a slope-1 line but do not share a single mass-dependent fractionation line. This suggests the CAIs formed, or were later altered, in distinct oxygen isotopic reservoirs.

Of the two CAI discussed here CAI-160 is the mineralogically simpler object. It contains only two mineral phases and these are observed to be in a crystallization sequence expected from a cooling gas of solar composition i.e. corundum followed by hibonite. This CAI has O isotope compositions intermediate to terrestrial and solar wind <sup>17,18</sup>O compositions [5]. This intermediate composition could have resulted from either direct condensation from a gas of this original composition, or through later O isotope exchange during perhaps multiple episodes of heating. Later exchange with different gas reservoirs may also explain the lack of <sup>\*26</sup>Mg observed in this CAI.

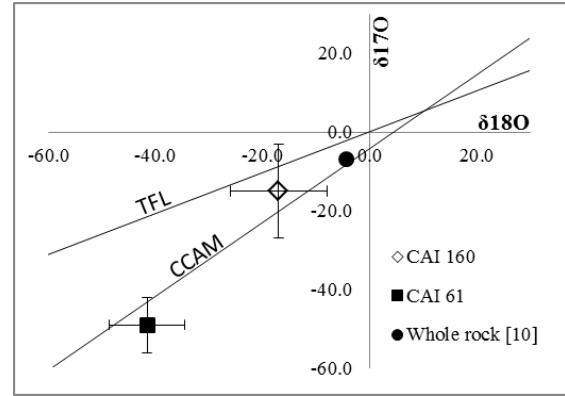
*CAI-61* preserves strong evidence of multi-stage heating. The initial predicted condensation of corundum followed by reaction to form hibonite appears to have been followed by a secondary heating event that evaporated CaO from the surface to form a CaO-free corundum mantle. Further interaction with a cooler gas resulted in an incomplete rim of melilite and spinel (in places less than 200nm thick). This CAI, in contrast to

CAI 160, underwent this multi-stage heating in the presence of gases of solar rather than planetary-like or intermediate compositions. The preservation of excess  $^{26}\text{Mg}$  also indicates that these reheating events occurred early in the solar system.

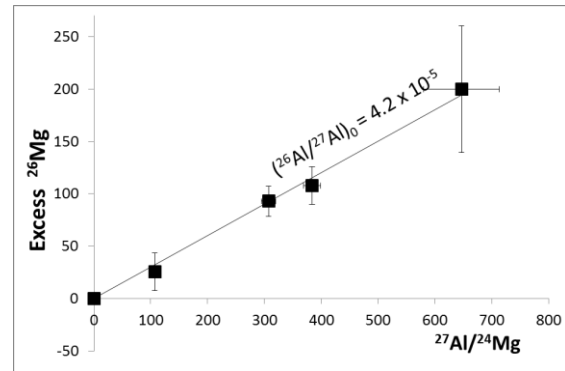
**Conclusion and future work:** Diverse nebular conditions have been recorded in the mineralogy, O and Mg isotopes of the two corundum-bearing CAI reported here. The intermediate O-isotope composition and lack of resolvable initial abundances of  $^{26}\text{Al}$  in CAI 160 may indicate late-stage formation and/or alteration in a planetary rather than near-solar environment. By contrast, the multiple thermal events experienced by CAI 61 (at the upper temperature limits of stability for these highly refractory minerals) occurred in environments of solar O-isotope composition and in the presence of abundant  $^{26}\text{Al}$ . These conditions are consistent with an early formation and alteration near the Sun. Further O and Mg isotope analyses of corundum-bearing CAI, combined with trace element analyses, will help reveal the mechanisms of formation (and any later alteration) and provide insights into the solar and planetary context of these earliest solar system solids.



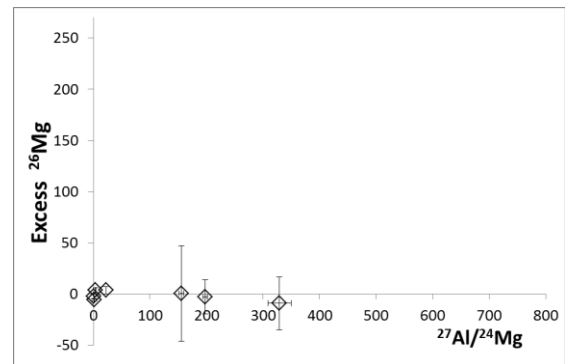
**Figure 1:** False color (Red = Mg, Green = Ca, Blue = Al) EDX maps of (a) CAI 61 and (b) CAI 160.



**Figure 2:**  $\delta^{17}\text{O}$  vs.  $\delta^{18}\text{O}$  plot of CAI 61 and CAI 160



**Figure 3:**  $^{27}\text{Al}/^{24}\text{Mg}$  vs.  $^{*26}\text{Mg}$  plot of CAI 61 reveals a resolvable excess of  $^{26}\text{Mg}$  consistent with an initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio of  $4.2 \times 10^{-5}$



**Figure 4:**  $^{27}\text{Al}/^{24}\text{Mg}$  vs.  $^{*26}\text{Mg}$  plot of CAI 160. All data are within error of zero excess  $^{26}\text{Mg}$

**References:** [1] Grossman L. (1972) *GCA* 36, 597. [2] Wark D.A. & Lovering J.F. (1977) *Proc. Lunar Planet. Sci.* 8, 95. [3] Yurimoto H., et al. (1998) *Science* 282, 1874. [4] Clayton R.N. (1993) *Ann. Rev. Earth Planet. Sci.* 21, 115. [5] McKeegan K.D. et al. (2011) *Science* 332, 1528. [6] Makide et al. (2009) *ApJ* 706, 142. [7] Liu M-C. et al. (2009) *GCA* 73, 5051 [8] Virag A. et al. (1991) *Geochim. Cosmochim. Acta* 55, 2045 [9] Huss, G. R. et al. (1995), *Lunar Planet Sci.*, 26, 641 [10] Clayton and Mayeda (1999) *GCA* 63, 2089