SYSTEMATIC OXYGEN ISOTOPE VARIATIONS WITHIN A SINGLE VIGARANO CAI SURROUNDED BY A UNIFORMLY 18O-RICH WARK-LOVERING RIM. A. W. Needham\textsuperscript{1,2}, S. Messenger\textsuperscript{2}, L. P. Keller\textsuperscript{2}, J. I. Simon\textsuperscript{2}, J. Han\textsuperscript{2,3}, R. K. Mishra\textsuperscript{2,1}. Oak Ridge Associated Universities (andrew.w.needham@nasa.gov), \textsuperscript{2}NASA-Johnson Space Center, \textsuperscript{3}Lunar and Planetary Institute.

**Introduction:** Ca-Al-rich inclusions (CAIs) in chondritic meteorites, exhibit a wide range of O isotopic compositions \[1\], both in their interiors and across their multi-mineral rim sequences, known as Wark-Lovering (WL) rims \[2\]. A major unsolved issue is whether the isotopic variations in CAIs record major reservoirs that existed at different times or locations within the early solar system.

Recent studies have revealed O isotopic variations across some WL rims \[3, 4\], suggesting that the host CAIs experienced high temperature processing at isotopically and spatially distinct regions of the inner solar nebula. If so, this would be compelling evidence that isotopically distinct reservoirs were present at the same time in the early solar system. However, these isotopic records must be interpreted with caution due to potential overprints of parent-body processing.

Here we present in situ O isotopic analyses of a CAI from the Vigarano CV3 chondrite. The goal of this study was to determine whether O isotope variations were preserved in a minerallogically complex CAI from a relatively unaltered parent body.

**Methodology:** Sequential thin sections were produced from a fragment of Vigarano (\#447, USMNH). Backscatter electron and energy dispersive X-ray maps of one of these sections were generated using the JSC JEOL 7600F field-emission scanning electron microscope. Candidate CAIs were identified in X-ray maps and subsequently examined using the JSC Cameca SX-100 electron microprobe to obtain quantitative mineral compositions.

Oxygen isotope analyses were conducted using the JSC NanoSIMS 50L. A 16-18pA Cs+ beam was rastered over 7 x 7 \( \mu \)m areas to presputter regions of interest, followed by 5 x 5 \( \mu \)m or 3 x 3 \( \mu \)m areas for analysis. \( ^{16} \text{O} \) was measured with a Faraday cup (FC) and \( ^{17} \text{O} \), \( ^{18} \text{O} \), Si, MgO, AlO- and CaO- were measured with EMs. Measurements typically consisted of 20 cycles acquired over periods of 14 minutes. San Carlos olivine standards were analyzed in the same analytical sessions using the same analytical procedures. An electron flood gun was used for charge compensation. One full transect of Big Guy was conducted, consisting of 20 spot O isotopic measurements, followed by a second partial transect of the core and mantle (20 spots). We also obtained several additional analyses in the core and mantle, two transects of the Wark Lovering rim, and several analyses within the accretionary rim.

**Results:** Mineralogy - The CAI Big Guy (Fig 1) is a 1200 \( \mu \)m x 750 \( \mu \)m Type B1 inclusion that appears to be a fragment of a larger object. It is composed of a fassaite core and thick, zoned melilite mantle, partially surrounded by a WL rim. The melilite mantle is zoned from Åk55Gh45 at the interface with the fassaite core to Gh94Åk6 at the base of the WL rim sequence. The fassaite core is also zoned from Ti, Al-rich compositions in the core to more Mg-rich compositions and partial melts at the interface with melilite mantle. Euhedral, Mg-rich spinels occur in both the core and mantle. The WL rim sequence has a base layer of hibonite+spinel+perovskite, followed by layers of: gehlenite, anorthite, zoned pyroxene, and lastly, forsterite. There is an accretionary rim on part of the CAI that is dominated by fine-grained forsterite, minor metal. Several micro-CAIs occur in the accretionary rim.

**Oxygen isotopes** - All analyses of spinel in the CAI interior, whether surrounded by fassaite or gehlenite, are isotopically indistinguishable with an average composition of \( \Delta^{17} \text{O} = -23.2 \pm 3.4 \)‰ (2 s.d.).

![Figure 1. False color EDS map of the Vigarano inclusion Big Guy (Mg = red, Ca = green, Al = blue). NanoSIMS spots are small white squares.](2865-1.jpg)
Two spot analyses of spinel in the WL rim ($\Delta^{17}\text{O} = -23 \, \%$ and $-19 \, \%$) appear to have overlapped with adjacent minerals but are apparently also $^{16}\text{O}$-rich. Fassaite is marginally less $^{16}\text{O}$-rich than spinel, with $\Delta^{17}\text{O} = -17.8 \pm 4.5 \, \%$. Gehlenite exhibits a very wide range of $\Delta^{17}\text{O}$ compositions, from $\Delta^{17}\text{O} = 1.2 \pm 3.1 \, \%$ to $-19.8 \pm 3.3 \, \%$, with a continuum of intermediate compositions. These variations are observed to range from $^{16}\text{O}$-poor at the fassaite core - gehlenite mantle boundary, to $^{16}\text{O}$-rich at the center of the gehlenite mantle, returning to $^{16}\text{O}$-poor approaching the gehlenite interface with the WL rim. The WL rim, in contrast to the adjacent $^{16}\text{O}$-poor gehlenite interior, is dominated by $^{16}\text{O}$-rich compositions of spinel, pyroxene, akermanitic melilite and hibonite, with combined average compositions of $\Delta^{17}\text{O} = -22.0 \pm 4.6 \, \%$. O isotope data for all minerals, from fassaite core to WL rim, are shown in Fig. 2.

**Discussion:** Vigaran CAI Big Guy O isotope compositions range from CAI endmember to terrestrial composition. Spinel is uniformly $^{16}\text{O}$-rich across the CAI. Since spinel is highly resistant to O isotope exchange [5] we interpret this to record the composition of the reservoir in which the CAI first formed (including when the fassaite relict and gehlenite mantle combined). Mellite is less resistant to alteration than spinel and the variable O isotope compositions of the gehlenitic mantle attest to this. Although disturbed O isotope compositions are known in other CAIs [6] it is typically unclear whether this alteration occurred soon after CAI formation or at a significantly later time – perhaps caught up in the chondrule formation region or altered shortly before/during accretion of the parent body [4]. Regardless, such CAIs clearly encountered a $^{16}\text{O}$-poor reservoir at a later time than the initial $^{16}\text{O}$-rich reservoir – though this does not explicitly imply any chronology of the two reservoirs themselves.

The O isotope variations across the interior and rim of Big Guy reflect a complex history. The gehlenite mantle is $^{16}\text{O}$-poor at the margin directly beneath the WL rim, which is itself exclusively $^{16}\text{O}$-rich. If the CAI encountered a $^{16}\text{O}$-poor reservoir after WL rim formation it is possible that the interior could exhibit evidence of this even where most alteration-resistant minerals in the rim do not, due to the higher diffusivity rate in mellite. However, the akermanitic melilite in the WL rim is also $^{16}\text{O}$-rich, effectively precluding a simple diffusion-rate explanation.

One explanation for the O isotopic variations is that the CAI originally formed in a $^{16}\text{O}$-rich environment (as recorded by spinel) and was subsequently altered in a $^{16}\text{O}$-poor environment (leading to zoning across the gehlenite mantle from $^{16}\text{O}$-rich center to $^{16}\text{O}$-poor edges). A later high-T event in a $^{16}\text{O}$-rich environment would be required to form the WL rim, such as in [4]. Alternatively, the complex O isotopic distribution within the CAI may reflect that the fassaite core is relict as suggested by the petrography. Either scenario would require that $^{16}\text{O}$-rich and $^{16}\text{O}$-poor reservoirs existed contemporaneously in the early solar system and that the reservoirs remained separated over timescales sufficient for individual particles to travel between reservoirs multiple times.

**Conclusion:** Multiple isotopic reservoirs were involved in the formation and alteration of a large CAI in the CV3 chondrite Vigaran. The complex isotopic zoning within the CAI interior, coupled with solar-like $^{16}\text{O}$-rich WL rim, suggest that distinct reservoirs were extant contemporaneously and that particle transport in the nebula was dynamic.