COUPLED O AND MG ISOTOPIC INVESTIGATIONS OF COMPACT TYPE A REFRACTORY INCLUSIONS. J. Alén1,2, J. Marin-Carbonne3 and K. D. McKeegan1, CSNSM, Bat 104, 91405 Orsay Campus, France, 2IMPMC, MNHN 61 rue Buffon 75005 Paris, France (jerome.alen@mnhn.fr), 3LMV, Univ. Jean Monnet 23 rue du Dr Paul Michelon 42023 St-Etienne, France, 4UCLA, Dept. of Earth, Planetary, and Space Sciences, Los Angeles, CA, 90095-1567, USA.

Introduction: Ca-Al-rich inclusions (CAIs) show a large range of $^{16}$O variations between the $^{16}$O-rich solar and $^{16}$O-poor planetary compositions, and the astrophysical origin of this O isotopic dichotomy is still not understood. To understand how CAIs recorded this range of variations it is crucial to correlate the O isotopic compositions with the physical conditions of the early solar system. However the respective roles of (1) fluctuations in the ambiant gas during igneous crystalization [1], (2) secondary solid state diffusion following exchange with the nebular gas [2], and (3) exchange with a fluid in an asteroidal context are still unclear.

We report the results of a coupled petrogramphy and in situ O and Mg isotopic study of two compact Type A (CTA) CAIs. Our goal is to try to link the O isotope variations to the CAI thermal history. O and Mg isotopes were measured by IMS 1270 using the UCLA and CRPG national facility ion probes. X-ray maps and individual WDS chemical analyses were obtained using SX100 and SX5 electron probes at the CAMPARIS facility in Paris. Isotopic analyses were performed in conventional multi-collection conditions for both O and Mg isotopes with a lateral resolution of 10-20 μm and 30-40 μm, respectively.

Samples: E101,3 is a ~1 mm by ~2 mm fragment of an elongated inclusion extracted from the Efremovka reduced CV3 chondrite, (courtesy of A. El Goresy). N-MNHN-14 (hereafter N14) is a smaller inclusion ~1 mm in diameter from the NWA 4767 CV3 chondrite (from the National Museum of Natural History in Paris). Both inclusions are largely dominated by gehlenitic mellite (mel) (Åk < 35 mol%) and contain spinel (sp) and minor interstitial Al-rich pyroxene (px) and perovskite (pv). A Wark-Lovering rim (WLR) is present around both inclusions.

Results: E101,3. Mel composition varies between Åk_{27} and Åk_{32}. X-ray mapping (Fig. 1) indicates that mel crystals become smaller and more aluminous toward the rim of the CAI. Mel crystals are systematically reversedly zoned with more magnesian cores.

The O isotopic composition of E101,3 varies between $^{16}$O-rich in sp and pv to $^{16}$O-poor in px. Mel is $^{16}$O-poor as well and shows slight variations in $^{16}$O content. Fe-bearing sp in the WLR has intermediate $^{16}$O-excesses.

Mg isotopes in the interior of E101,3 show a uniformly heavy Mg isotopic composition with an average $\delta^{25}$Mg ~6.3‰ including sp and mel. No variations are seen with location in the inclusion apart from the region with coexisting mel and px where $\delta^{25}$Mg reaches +9‰. In the WLR lighter $\delta^{25}$Mg values are observed in sp, from 0.8‰ to 3.1‰. Al/Mg systematics yield an isochron with an initial $^{26}$Al/$^{27}$Al ratio ~ 5.2 × 10^{-5}.

N14. Mel composition varies between Åk_{3} and Åk_{35}. The Mg X-ray map (Fig. 1) shows co-existence of several distinct regions with different crystal sizes, different Åk content and different types of zoning including normal, reverse and oscillatory zoning. Most regions appear limited by ribbons of tiny spinels. A very Al-rich core with sharp boundaries is observed.

O isotopes in N14 have already been reported [3]. Sp is classically $^{18}$O-rich. Mel in the mantle has an average $\delta^{18}$O ~ -2‰ except near the WLR where it becomes progressively $^{18}$O-enriched (Fig. 2). In the Al-rich core mel has an average $\Delta^{17}$O ~ -6‰.

Heavy Mg isotopic compositions are observed in the inclusion with $\delta^{25}$Mg up to ~6.8‰ but a zoning is observed with lighter $\delta^{25}$Mg values within 75 μm of the WLR (0‰ < $\delta^{25}$Mg < 4‰). Sp in the rim has light isotopic compositions with average $\delta^{25}$Mg ~1.1‰. In the heavy portion of the mantle and in the core parallel trends of increasing $\delta^{25}$Mg with decreasing Mg content are observed (Fig. 2). Al/Mg systematics yield an isochron with an initial $^{26}$Al/$^{27}$Al ratio ~ 5.0 × 10^{-5}. No statistically significant differences are observed between edge, mantle, or core mel.

Discussion and conclusions: Interior E101,3. The combination of X-ray mapping O and Mg isotopic analyses indicates that E101,3 probably crystallized from a molten droplet as commonly found for CTA [4]. Interstitial px in the core is the last phase that crystallized in agreement with stability fields of CAI minerals, textural observations and Mg isotope fractionation indicating protracted evaporation. Mel crystal sizes and chemistry suggest crystallization starting from the edge of the inclusion. Because O-self-diffusion is sluggish in px, it faithfully records the composition of the melt from which it crystallized, itself rapidly equilibrated with the ambiant gas. The px $^{16}$O-poor composition thus indicates that the O isotopic composition of the gas evolved from $^{16}$O-rich to $^{16}$O-poor during crystallization. The systematic reverse zoning of mellite can be attributed to progressive evaporation of the residual melt during crystallization.
Compound N14. Petrography, O and Mg isotopes are consistent with N14 being a compound inclusion with at least an Al-rich core and less Al-rich mantle [3]. Both mantle and core underwent similar degrees of Mg loss associated with reverse zoning of melilite. The sharp contact and the lack of O isotopic equilibration between core and mantle are in favor of limited partial melting of precursors already having isotopic histories consistent with that of E101,3, notably a $^{16}$O-depletion in mel before aggregation. They also favor Mg loss during sublimation. Spinel ribbons may constitute the relicts of former WLR around smaller CTA units. Such an interpretation agrees with the suggestion that Fluffy Type A CAIs may represent aggregates of small CTA [5] and that N14 is a somewhat intermediate inclusion.

Edges and rims. Whereas the CAI interiors appear depleted in $^{16}$O and have heavy Mg isotopic composition, the WLR are enriched in $^{16}$O and light Mg as already observed in CTA CAIs [6-9]. Mel in contact with the WLR tends to be enriched in Al, $^{16}$O and light Mg, although these characteristics may not be systematically observed together, which has also been seen in Type A CAIs and Type B1 CAI mantles [6-11]. We suggest that this zoning is a by-product of WLR formation. O and Mg isotopes suggest that solid state diffusion is not a viable mechanism for the isotopic variations, rather infiltration of a peripheral refractory melt, possibly produced by flash melting [12, 13] and enriched in a WLR sp isotopic component may produce the expected trend (Fig 3.).

Age of the $^{16}$O-poor reservoir. Both inclusions have O isotope systematics consistent with isotopic exchange during aggregation / partial melting / crystallization and have Al/Mg systematics consistent with crystallization within the first 100,000 years of the solar system. Therefore parent-body alteration is not the major driver of $^{16}$O depletion in the interior of igneous CAIs and both $^{16}$O-poor and $^{16}$O-rich gases existed in the region of CAI formation when solar system formation started. The $^{16}$O depletion must thus have been inherited from the interstellar medium or was created by a rapid chemical reaction in the inner disk.


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Fig. 1. False color Mg X-ray maps of CAIs E101,3 and N14 with inverted color scheme. Mg-rich phases (mtx, px) are black, Mg-free phases (pv) are white and geh content in melilite increases from dark purple to bright yellow.

Fig 2. O and Mg isotope in N14 mel. Green : mantle mel, circled in red near the CAI edges. Blue : core mel.

Fig 3. O and Mg isotopes in N14 with diffusion and mixing trends. Green square: range of composition in the vicinity of the WLR.