MULTI-ISOTOPE STUDY OF THE COMPOUND ULTRA-REFRACTORY INCLUSION EFREMOVKA 101.1 SHEDS LIGHT ON COMPLEX CAI FORMATION PROCESSES. J. Aléon[1] , J. Marin-Carbonne[2], K. D. McKeegan[3] and A. El Goresy[4], [1]CSNSM, Univ. Paris Sud –CNRS/IN2P3, 91405 Orsay, France, jerome.aleon@csnsm.in2p3.fr, [2]IPGP, Univ. Paris Diderot - CNRS, 75005 Paris, France, [3]Earth, Planetary, and Space Sci, UCLA, Los Angeles CA, USA, [4]Bayerisches Geoinstitut, Univ. Bayreuth, 95440 Bayreuth, Germany.

Introduction: Efremovka 101.1 (E101.1) is a peculiar igneous melilite (mel)-rich CAI (compact type A, CTA) with multiple lithological units that were probably individual CAIs initially [1]. All lithological units are characterized by ultra-refractory (UR) Rare Earth Elements (REE) relative abundances, *i.e.* depleted in least volatile REEs [1]. We undertook a systematic isotopic study of E101.1 in order to use its peculiar chemical characteristics and compound nature to shed light on CAI formation processes in the hot innermost solar nebula. Oxygen, magnesium and limited silicon isotope analyses by ion microprobe have previously been reported [2-4]. Here we report the full correlated study of O, Mg and Si isotopes of E101.1 and we show how the combination of these isotopic systems in individual minerals and lithological units can be used to unravel its precursors and their thermal histories.

Experimental: O, Mg and Si isotopic analyses were conducted with the IMS 1270 ion microprobe at UCLA in several analytical sessions using appropriate analytical conditions and standards. 128 O isotope, 85 Mg isotope and 60 Si isotope analyses were acquired on all lithological units, including the host, the xenolithic sinuous pyroxene (px) fragments, spinel (sp) clusters in the host, specific regions nicknamed subinclusion 1 (sub1) [1], and areas 3 and 4 adjacent to this subinclusion and to the sinuous px fragments, as well as the Wark Lovering rim (WLR) and the forsterite (fo)-rich accretionary rim (AR). Minerals analyzed include notably mel, px, sp and fo. Complementary petrologic observations were done such as electron probe mapping of Mg in mel. All ion probe pits were examined individually by scanning electron microscopy. Analyses were paired (O with Mg, O with Si and Mg with Si) when ion probe pits were within ~ 20 µm from each other and hit the same mineral in the same region of the inclusion.

Results and discussion: Having been reported before, results specific to the O and Mg isotope systems will not be detailed here. The comparison between O isotopes in mel with its mineral chemistry reveals that mel at the contact with sp is more gehlenitic and ^{16}O-enriched. The Mg Kα map reveals in addition the presence of fingers of gehlenitic mel connecting most sp clusters to the rim of the inclusion. Furthermore, sp have δ^{25}Mg values between +2.6 and + 6.7‰ heavier than most surrounding mel which clusters around δ^{25}Mg ~ 0‰. Taken together these data suggest that sp clusters were once individual sp-rich CAIs that underwent partial melting and evaporation before being trapped and partially dissolved into the host CAI parental melt. Such a dissolution explains the ^{16}O-enrichment of mel at contact with sp, the fingers of gehlenitic mel, as well as the occurrence of anhedral sp with embayments and a reaction corona consisting of a sp+px symplectite.

The distribution of Mg and Si mass fractionation throughout the inclusion reveals that a large fraction of the E101.1 inclusion is characterized by δ^{25}Mg near 0‰ except in the sinuous px and at its vicinity, where negative δ^{25}Mg down to ~-6‰ are observed (sub 1). Intermediate low δ^{25}Mg values are found in the areas 3 and 4 connected to the rim. By contrast, heavy Si isotopic compositions are observed throughout the inclusion, with *F*Si between +4 and +9 ‰/AMU. Again, lower *F*Si values are found predominantly in the sinuous px (with *F*Si down to ~ -4‰) but also in areas 3 and 4 which have intermediate values.

Because the sinuous px is also enriched in ^{16}O compared to the surrounding mel, the isotopic compositions of areas 3 and 4 can be explained by the dissolution of the ^{16}O-rich sinuous px with light Mg and Si into a ^{16}O-poor parental host melt with near 0 δ^{25}Mg and heavy *F*Si values (Fig. 1). The very light Mg isotopic composition of mel in subinclusion 1 requires an additional component rich in light Mg but devoid of Si (Fig. 1a and c). Adding a fraction of sp with δ^{25}Mg down to -8‰ to the sinuous px is a possible explanation. Such light Mg isotopic compositions have already been observed in hibonite (hib) inclusions in CM chondrites and were attributed to kinetic isotopic fractionation during condensation of sp and hib precursors [5]. Mass balance calculations imply that, with the assumption of keeping solar Ca/Al ratios, the parental CMAS melt contained ~0.6 wt% MgO and ~ 9.8 wt% SiO_2. Such low concentrations are in line with the observed isotopic composition : strong evaporative loss of Si from a typical type A composition would have resulted in heavy *F*Si usually characteristic of FUN inclusions and the amount of MgO is so low that introduction of Mg with near 0 δ^{25}Mg either by direct condensation or by assimilation of condensate sp would easily overprint the large mass fractionation expected for Mg evaporation.

The origin of the very negative δ^{25}Mg and *F*Si values is not clear but kinetic fractionation during condensation owing to rapidly dropping temperature is a possible solution [5,6]. In this case it seems possible that such conditions could yield UR-REE patterns by bypassing the condensation of the least refractory REE for instance by rapid transport from the regions of highest temperature into a region where REEs are already in a solid phase. Such a scenario highlights the connection of E101.1 precursors with hib CAIs in CM chondrites, which can have UR-REE patterns and low δ^{25}Mg.

Fo in the AR has the slightly negative or near 0 δ^{25}Mg and *F*Si expected for equilibrium condensation, and the WLR exhibits near 0 δ^{25}Mg in both px and sp (with one exception at ~ +3‰) but its *F*Si spans the full range between the AR and the host melt. Because Mg is more volatile than Si and because UR-REE patterns have been found in the rim, this suggests that the rim could have formed by condensation of Mg ± Si into a melt with REE content and Si isotopic composition characteristics of the host interior. This would agree with the nanoscale petrography of WLRs [7].

To conclude, the muti-isotope study of E101.1 provides evidence that this peculiar CAI formed by coagulation of several different proto-CAIs, at least two of which (the main host and the sinuous px xenolith) being UR-CAIs and one of which (the main host) having experienced a thermal history similar to that of FUN CAIs. Contributions of small melt fractions from the main host to the WLR and possibly the Ca-Al component of the AR explains their UR-REE signature.

The mixing evidence between sp clusters and the main host on one hand and between the sinuous px xenolith and the main host on the other hand implies that the main host silicate component had achieved a ^{16}O-poor composition early in its history before accretion and assimilation of these components. As a result the O isotope change from solar to planetary in the solar system occurred most likely during or before the main phase of CAI growth, that is during the first 10^5 years of the solar system although the disturbed Mg isotope systematics of E101.1 does not allow a clear dating [3]. If this conclusion were to be confirmed this would probably rule out the self-shielding-in-the-outer-disk model for the origin of the solar sytem O isotope dichotomy.

References: [1] El Goresy A.et al. (2002) *GCA 66*, 1459. [2] Aléon J. et al. (2010) *MAPS 45*, A7. [3] Aléon J. et al. (2011) *MAPS 46*, A8. [4] Marin-Carbonne J. et al. (2011) *MAPS 46*, A147. [5] Liu M.-C. et al. (2012) *EPSL 327-328*, 75. [6] Richter F. M. (2004) *GCA 68*, 4971. [7] Toppani A. et al. (2006) *LPS 37*, Abstract #2030. [8] Davis A.M. and Richter F. M. (2005*) in Meteorites, comets and planets*, Treatise on Geochemistry vol 1 (Holland H. D. and Turekian K.K. eds), 407.

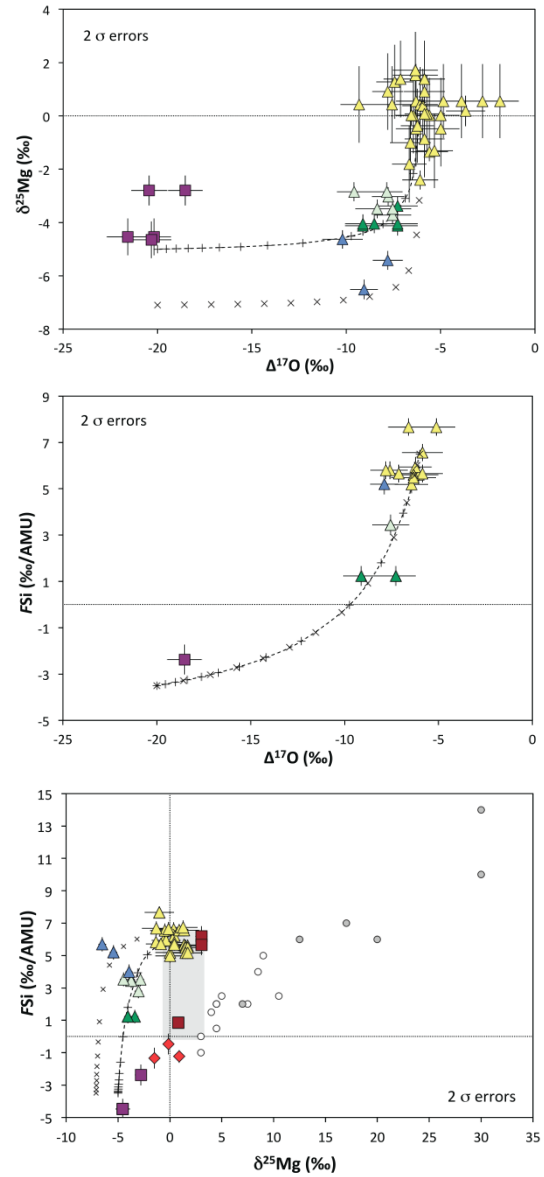

Fig 1: O-Mg-Si isotope diagrams, with calculated mixtures between between the sinuous px and a single parental CMAS melt (dashed line). Crosses indicate mixing with an additional sp component with light δ^{25}Mg. Last panel : normal and FUN CAIs [8] are shown for comparison (circles) and the grey box shows the full range of WLR composition. Triangles : mel, squares : px, diamonds: fo. Yellow: host, green: areas 3 and 4, blue: sub 1, purple: sinuous px, brown: WLR, red: AR.