ISOTOPIC AND TRACE ELEMENT CHARACTERISTICS OF AN UNUSUAL REFRACTORY INCLUSION FROM ESSEBI; E. Deloule1,2, A. K. Kennedy1,3, I. D. Hutcheon1 and A. El Goresy4, 1Div. Geol. Planet. Sci., Caltech; 2CRPG-CNRS, Vandoeuvre, France; 3Curtin Univ. of Technology, Perth, Australia; 4Max Planck Institut für Kernphysik, Heidelberg, Germany.

The isotopic and chemical properties of Ca-Al-rich inclusions (CAI) provide important clues to the early solar nebula environment. While the abundances of refractory major and trace elements are similar to those expected for high temperature condensates, the variety of textural, chemical and isotopic signatures indicate most CAI experienced complex, multi-stage histories involving repeated episodes of condensation, evaporation and metamorphism. Evidence of multiple processes is especially apparent in an unusual refractory inclusion from Essebi (URIE) described by El Goresy et al. [1]. The melilit (mel)-rich core of URIE contains polygonal framboids of spinel (sp) and hibonite (hb) or sp and fassaite (fas) and is surrounded by a rim sequence consisting of five layers (Table 3 in [1]). In contrast to rims on Allende CAI [2], the mineralogy of the URIE rim layers becomes increasingly refractory from the core outwards, ending in a layer of spinel-Al2O3 solid solution + Sc-rich fassaite. The chemical and mineralogical features of URIE are inconsistent with crystallization from a homogeneous melt and El Goresy et al. [1] proposed a multi-step history involving condensation of sp + hb and aggregation into framboids, capture of framboids by a refractory silicate melt droplet, condensation of rim layers and alteration of mel to calcite and feldspathoid. The PANURGE ion probe was used to investigate the isotopic and trace element characteristics of URIE to develop a more complete picture of the multiple processes leading to formation and metamorphism.

Trace elements were measured on a previously unstudied fragment (URIE-3). The mineralogy is similar to URIE-2 [1] with two important differences: (1) hb is much more abundant, occurring as aggregates of bladed crystals surrounded by feldspathoid + calcite and (2) an unidentified, hydrous silicate (phase X; approximately CaAl2SiO6 * 3 H2O) occurs as a large, 60x60 µm crystal within a framboid and as small isolated crystals within melilit. The REE data from URIE (Figs. 1 and 2) display six prominent characteristics: 1) REE abundances are highly variable, even within a single phase, with CI-normalized La abundances of 35 to 100 in pv, 20 to 120 in hb, 40 to 60 in mel, 12 to 45 in fas and ~2 in phase X; 2) Mel, pv and hb exhibit flat REE patterns; 3) Fas and phase X exhibit mildly HREE-enriched patterns with CI-normalized Er/La ratios of 1.5 to 2; 4) Negative Eu anomalies are found in ~70% of the analyses and the absence of an Eu anomaly is always accompanied by lower total REE; 5) Hb is a possible host phase for Ba with abundances of up to 150 x CI; 6) REE abundances in rim phases are uniformly lower than in interior phases and no evidence for a Sc-rich, ultra-refractory component was found. The relatively flat REE patterns and similar REE abundances for co-existing phases in URIE contrast sharply with the complementary REE patterns characteristic of mel, pv and fas in Allende Type A CAI [3] and are inconsistent with equilibrium partitioning of REE during crystallization from a homogeneous melt. The REE patterns in URIE pv are similar to those of pv in Type A CAI, but abundances are ~3 to 10x lower. Overall, the distribution of REE supports the suggestion that URIE is an aggregate of condensates.

Mg and Ca isotopes were measured in URIE-3 and in URIE-2. Mel, hb, sp and phase X from the core are uniformly enriched in the heavier Mg isotopes, F_Mg = 8.2±1.5 %/amu. In contrast, rim phases have isotopically lighter Mg; hb in rim layer C has F_Mg = 0.2±1.3 %/amu, while spinel in layer D has F_Mg = 3.1±1.0 %/amu. Excess 26Mg* was detected in all mel and hb with 27Al/24Mg > 10 and data from hb, sp and mel define a linear array with slope 26Mg*/27Al = (4.7±0.4) x 10^-5 (Fig. 3). Both interior hb and rim hb lie along a single array, despite different F_Mg. Within the measurement precision of 5 to 8 % (2σ), no Ca isotope anomalies were found in URIE mel or hb. Isotopically normal Ca in URIE fits the pattern reported by Ireland for Murchison PLAC hibonites [4]; large Ca isotope anomalies are generally absent when 26Al is present. Excess 26Mg* is also present in phase X. In contrast to data from hb, sp and mel, δ26Mg is not correlated with the Al/Mg ratio; δ26Mg = 7.0±2.1 % for all
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analyses of phase X with $^{27}\text{Al}^{24}\text{Mg}$ ranging from 10 to 365 (Fig. 4). The D/H ratio of the water in phase X was determined with PANURGE. The instrumental mass fractionation factor was calculated from analyses of amphibole glasses and minerals (see Watson et al., this volume). Three analyses gave consistent $\delta_{\text{DSMOW}}$ of 920 ± 180 %. This large deuterium enrichment indicates that phase X is not a terrestrial weathering product and suggests that the growth of secondary phases in URIE may have accompanied the production of hydrous matrix phases on the Essebi parent body.

The new isotope and trace element data allow us to refine the model for the formation of URIE outlined in [1]. The uniform $F_{\text{Mg}}$ of sp and mel in the core indicates either formation of sp-framboids and the silicate precursor melt from a common reservoir enriched in the heavier Mg isotopes or an initial cooling rate of URIE sufficiently slow to allow Mg isotopic re-equilibration of initially isotopically disparate phases. Redistribution of REE did not occur due to much lower diffusion rates of REE. The differences in $F_{\text{Mg}}$ and REE patterns between core and rim require condensation of hb and sp to form rim layers from distinct reservoirs; condensation must have occurred within $-2 \times 10^5$ y of the "solidification" of the core to preserve the $^{26}\text{Mg}^{+27}\text{Al}$ correlation (Fig. 3). The hydrous alteration and redistribution of Mg isotopes in phase X occurred much later, following the decay of $^{26}\text{Al}$. Division Contribution 5236(800). References: [1] El Goresy A., Palme H., Yabuki H., Herrwerth I. and Ramdohr P. (1984) GCA 48, 2283; [2] Wark D.A. and Lovering J.F. (1982) GCA 46, 2595; [3] Kennedy A.K., Hutcheon I.D. and Wasserburg G. J. (1991) LPSC XXII, 709; [4] Ireland T.R. (1990) GCA 54, 3219.

Fig. 1. REE abundances in URIE hb and pv. P#2 has a pattern identical to P#1 but with $-3x$ higher REE.

Fig. 3. $^{26}\text{Al}^{26}\text{Mg}$ evolution diagram for URIE.

Fig. 4. $^{26}\text{Al}^{26}\text{Mg}$ evolution diagram for URIE phase X.