A CAI IN THE IVUNA CI1 CHONDRITE. D. Frank[1], M. Zolensky[2], J. Martinez[1], T. Mikouchi[3], K. Ohsumi[4], K. Hagiya[5], W. Satake[3], L. Le[1], D. Ross[1], A. Peslier[1]. [1]ESCG/NASA Johnson Space Center, Houston, TX, 77058 USA, (david.r.frank@nasa.gov); [2]ARES/NASA Johnson Space Center, Houston, TX 77058 USA; [3]University of Tokyo, Hongo, Bunkyo-Ku, Tokyo 113, Japan; [4]JASRI, Sayo-cho, Hyogo 679-5198, Japan; [5]Graduate School of Life Science, University of Hyogo, Hyogo 678-1297, Japan.

Introduction: We have recently discovered the first well-preserved calcium aluminum-rich inclusion (CAI) in a CI1 chondrite (Ivuna). Previously, all CI1 chondrites were thought to be devoid of preserved CAI and chondrules due to the near total aqueous alteration to which their parent body (bodies) have been subjected. The CAI is roughly spherical, but with a slight teardrop geometry and a maximum diameter of 170 microns (fig. 1). It lacks any Wark-Lovering Rim. Incipient aqueous alteration, and probably shock, have rendered large portions of the CAI poorly crystalline. It is extremely fine-grained, with only a few grains exceeding 10 microns. We have performed electron microprobe analyses (EPMA), FEG-SEM imaging and element mapping, as well as electron back-scattered diffraction (EBSD) and synchrotron X-ray diffraction (SXRD) in order to determine the fundamental characterstics of this apparently unique object.

Mineralogy:

Melilite. By far the most abundant phase, the pervasive melilite is similar in composition and texture to that found in type A CAIs [1]. Both EBSD mapping and SXRD were unable to obtain good diffraction patterns from the majority of the melilite grains, probably due to shock. We did obtain well-defined diffraction patterns from one single melilite crystal measuring ~10 microns across. The composition within this crystal is concentrically zoned with an Al-rich core and more Mg-rich rim, consistent with an igneous origin. 18 other EPMA analyses of stoichiometric melilite show that it falls within a fairly narrow compositional range (Ak_{14-31} with trace Ak_{32-36}). The slightly more Mg-rich grains of this range (Ak_{25-36}) typically characterize the less common "compact" Type A (CTA) CAI [1,2]. The melilite encloses the other phases listed below.

Spinel. Nearly pure spinel ($MgAl_2O_4$) occurs throughout the CAI, within melilite, but is preferentially clustered in one corner of the CAI. Although most spinels are too small to permit reliable probe measurements, we obtained one good measurement of a 10 micron grain containing 1.22 wt.% TiO_2, 0.25 wt.% V_2O_3, and 1.14 wt.% CaO. The latter is most likely associated with an extremely fine-grained, Ca-rich phase enclosed within the spinel.

Grossmanite. Clinopyroxene classified as grossmanite (under the recently approved nomenclature by [3]) occurs as irregularly shaped grains throughout the CAI interior. The Ti content of grossmanite reaches up to 20.8 wt.% TiO_2, higher than in previously described material [3]. Some grossmanite contains up to 1.1 wt.% V_2O_3 and 0.29 wt.% Sc_2O_3.We successfully obtained both EBSD and SXRD patterns for one single grossmanite crystal ~20 microns across (fig 2). This grain (and probably others) show a rim that is depleted in Al and enriched in Ti with respect to its core with a 1:1 corellation. This implies depletion in the $CaAl_2SiO_6$ (kushiroite) component and enrichment in the $CaTi^{3+}AlSiO_6$ (grossmanite) component in the rim and suggests a decrease in the O-fugacity of the formation environment during the final stage of crystallization. This is unlike the zoned or rimmed grossmanite composition profiles found in other chondrite varieties. In CV3 CAI, clinopyroxene rims show enrichment in the diopside component and depletion in the grossmanite component [2,4]. In CH CAI, the kushiroite component is replaced by diopside [5].

Minor Phases. Due to the fine-grained nature of the CAI we cannot obtain good EPMA measurements for some phases. However, by performing background subtraction, we noted what appears to be a minor amount of nearly pure anorthite and hibonite enclosed within the melilite, the latter associated with spinel.

Metal and Fremdlinge. Sub-micron and micron-sized metal alloys can be seen sprinkled sparsely throughout the CAI. The largest of these metal grains reaches ~3 microns. Some appear to be nearly pure Fe/Ni/Co metal grains while others resemble the exotic "fremdlinge" only found in the CV3 oxidized subgroup [1]. These grains contain abundant P and/or S and an enrichment in Pt-group metals (Pt, Ir, Os, Re, Ru, Rh). The Fe/Ni ratios of the measured inclusions vary wildly (0.35-71.90 atomic % ratio). These compositions imply condensation in an oxidizing environment.

Aqueous Alteration: The CAI has been heavily altered. Aqueous alteration has occured along the edge of the CAI, within the accrectionary rim, and in veins that project from the rim inward towards the core. These zones are dominated by a generally submicron assemblage of phases and will require TEM characterization. However, within the accretionary rim, we have identified a local high concentration of embayed crystals >5 microns of olivine (Fa_{2-17}), low-Ca pyroxene (Fs_{2-10}), pyrrhotite, and magnetite, all floating within phyllosilicates. One may speculate that the object we see today is the core of a much larger

CAI that has largely been altered into the surrounding phyllosilicate matrix. However, we note the unlikelihood of such an event resulting in a spheroidal end product. Therefore, we propose that the CAI may actually be close in size and shape to the pre-altered object. In addition, we find olivine only within the accretionary rim and not in the interior, altered veins. This evidence suggests that the olivine and pyroxenes present in the rim are remnants of the CI precursor lithology.

Comparison to Wild 2: Wild 2 contains fragmental chondrules and CAI [6,7]. Of all primitive chondrite types, both olivine and sulfide compositions in the CI chondrites appear to be the most mineralogically similar to those in Wild 2 [8]. The presence of a CI CAI provides a new means to compare the two materials. Because of its highly variable composition, the grossmanite found in both materials (as well as other CAI) provides a logical means to compare their mineralogy. We performed TEM/EDXS analysis of grains from 5 particles extracted from the CAI in Wild 2 track 25. The Wild 2 grossmanite compositions largely resemble those in CV3 CAI and appear to be different than those in the Ivuna CAI. Results are summarized in figure 3.

Summary/Conclusions: The Ivuna CAI resembles a highly altered CTA in terms of its basic mineralogy. In particular, its small size, spherical shape, and fine-grained texture resemble the melilite-rich CAIs found in CH chondrites. However, the Ivuna CAI is apparently unique in 3 respects: it is the only known CAI in a CI1, its grossmanite compositions are Mg-depleted with respect to other CAI and have Ti^{3+} enriched rims, and it may be the only CAI outside of the CV3 oxidized subgroup to harbor fremdlinge.

The CAI has a complex history. We conclude that it underwent formation in both oxidizing and reducing environments, a period of partial melting, shock, and ultimately aqueous alteration. It is possible that what remains is not completely representative of the initial object. However, what does remain can provide new insight into the CI precursor mineralogy.

References:

[1] MacPherson G. J. (2005) *Meteorites, Comets and Planets*, 201-245. [2] Simon S. B. et al. (1999) *GCA, 63*, 1233-1248. [3] Ma C. and Rossman G. (2009) *American Mineral.*, *94*, 1491–1494. [4] Brearly A. J. and Jones R. H. (1998) *Rev. Mineral., 36*, 3-01-3-398. [5] Krot A. N. *MAPS, 37*, 1451-1490. [6] Zolensky M. et al. (2006) *Science, 314*, 1735-1740. [7] Nakamura T. (2008) *Science, 321*, 1664-1667. [8] Zolensky M. et al. *MAPS, 43*, 261-272.

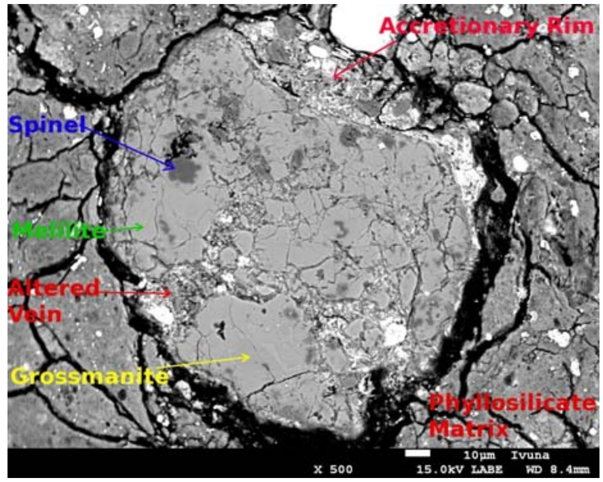

Figure 1: BSE image of the Ivuna CAI with major phases and features. White pyrrhotite crystals among the aqueous alteration products delineate the CAI.

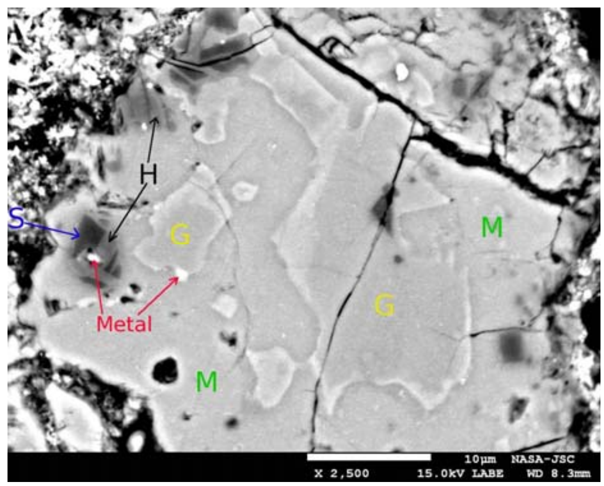

Figure 2: BSE image of melilite (M) enclosing metal, spinel (S), hibonite (H), and well-crystalline grossmanite (G).

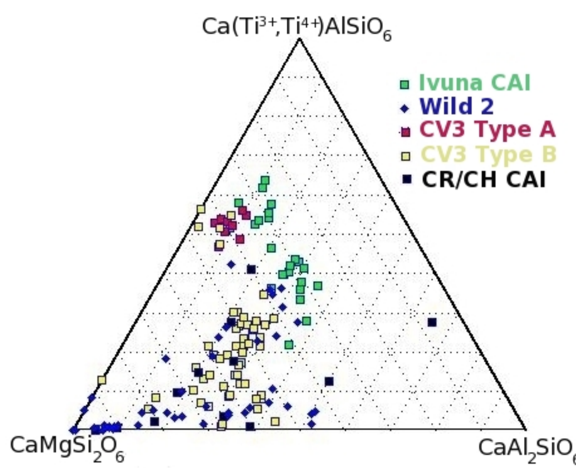

Figure 3: CAI Clinopyroxene compositons from Wild 2 Track 25 and different C-chondrites. Diagram represents occupation of the M1 crystallographic site by Mg, Al, and Ti.