**Introduction:** Calcium, Aluminum-rich Inclusions (CAIs) were the first formed solids in our Solar System [1], with mineral assemblages reflecting the first phases predicted to condense out of a hot nebular gas of Solar composition [2]. Geochemical, textural and crystallographic information in CAIs can be used to constrain the temperature, pressure, and composition (e.g., oxygen fugacity) of the gaseous reservoir(s) from which they formed, as well as any secondary (nebular and parent body) processes they underwent. Coordinated geochemical and textural analyses provide information on nebular conditions (i.e., astrophysical environments and dynamics of nebular gas reservoirs) in which these CAIs formed. In order to better understand the evolution of nebular reservoirs at the time of CAI formation, we analyzed a Type A, B and C CAI using Electron Probe Micro-Analyzer (EPMA) and Electron BackScatter Diffraction (EBSD) at NASA Johnson Space Center (JSC).

**Samples and Analytical Methods:** Our samples were selected because of their diverse attributes, including grain size, texture and mineralogy (Figure 1). Leoville (CV3r) Senita is a ~2 x 1 mm, fine-grained Type A CAI with spinel, melilite, hibonite and perovskite (Fig. 1a.). Allende EK5-1-1 (cm-sized) is coarser-grained, characteristic of an igneous Type B1 CAI [3], containing > 50% melilite—some of which exhibits zoning (Fig. 1b.). Also present is anorthite, Al, Ti-rich pyroxene, spinel, minor perovskite and alteration phases including metal-rich sulfides, sodalite and nepheline. Allende (CV3cm) EK5-3B is a fine-grained, ~6 x 1.5 mm CAI, consisting mainly of spinel, diopside, anorthite (in order of decreasing abundance) and minor perovskite (Fig. 1c.). Alteration phases (e.g., nepheline, sodalite, Fe-rich pyroxene) are also present in EK5-3B.

At NASA JSC, a JEOL JXA 8530F Hyperprobe EPMA with a 15 kV beam energy and 30 nA beam current was used to determine chemical compositions. Wavelength dispersive spectroscopy (WDS) spot-analyses were performed on individual phases. Energy dispersive spectroscopy (EDS) maps were created, also using EPMA. Quantitative chemical analyses were extracted from individual EDS map frames and averaged for each CAI to determine bulk composition. Valence state for Ti in pyroxene, used to determine oxygen fugacity, was calculated by applying a Ti-V overlap correction to the EPMA data and then determining its structural formula. The resulting cation deficiency (indicating the presence of Ti3+) is divided by total Ti to quantify Ti3+, similar to [4].

An Oxford Symmetry EBSD detector on a JEOL JSM 7600F scanning electron microscope at NASA JSC was used to quantify crystallographic orientation relationships (CORs) of the samples in order to determine crystallization sequences and genetic relationships among grains. A 20 kV beam energy and 9 nA current was used to collect rastered maps with step sizes ranging from 0.1 to 0.25 μm.

**Results:** Leoville Senita has a bulk composition that resembles a Type A CAI. Senita has ÅK-poor (~ÅK0) melilite with grain sizes ranging from 10-50 μm. Spinel is Mg end-member that varies from 1-100 μm in size. Senita contains hibonite-rich areas enclosed by perovskite and spinel grains. Perovskite exists as 10-20 μm-sized grains and hibonite is upwards of 50-100 μm in this CAI. Grain orientations in Senita have a random distribution and exhibit triple junctions. Hibonite exhibits twin lamellae. Individual spinel grains bear evidence of crystal-plastic strain (Figure 2). The spinel grains

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*Figure 1.* MgCaAl (RGB) false-color electron backscatter maps taken with EPMA. a.) Leoville Senita (Type A) b.) Allende EK5-1-1 (Type B) c.) Allende EK5-3B (Type C).

*Figure 2.* [left] Inverse pole figure (IPF) map of spinel grains from Senita, where gradual color transitions represent intragrain crystal-plastic strain resulting from a post-crystallization deformation event. [right] IPF key, indicating which of spinel’s axes in the IPF map are pointed towards the EBSD camera.
show a maximum grain orientation spread up to 7° and major slip along [100] crystallographic plane.

**Allende EK5-1-1** has a bulk composition that is fairly representative of a Type B1 CAI. This inclusion has a poikilitic texture in which melilite contains anorthite, pyroxene and spinel as chadacrysts. Melilite is zoned in EK5-1-1, with the strongest zonation occurring across its mantle. WDS analyses range from ÅkS in the core to ÅkS in the rim.

EK5-1-1 also contains compositionally zoned Al,Ti-rich pyroxene, with grains 100s of µm in size. Enrichments in Ti occur towards the core (as evidenced by WDS spot analysis and EDS mapping). Scandium and V display a similar trend as Ti, as expected given their similar chemical behaviors. Trivalent Ti exhibits an inverse trend, becoming enriched towards the rim of the pyroxene grains.

Anorthite grains in EK5-1-1 are ~100 µm in size. Spinel is Mg end-member with variable grain sizes from 1-100 µm. Allende EK5-1-1 contains secondary Fe,Ni-rich sulfides, unique to this inclusion relative to the other two studied. Allende EK5-1-1 exhibits epitaxial growth among its pyroxene, anorthite and melilite as demonstrated by preferred orientations within grains.

**Allende EK5-3B** most closely resembles a Type C (anorthite-rich, melilite poor) CAI in terms of its mineralogy and bulk composition, and has a fine-grained, lacy texture, also described in [5]. Pyroxene composition is close to end-member diopside and occurs as irregular shapes with variable thicknesses in the core (1-10 µm) of the inclusion versus the rim (10-20 µm). Plagioclase grains are An100 and ~10 µm wide, generally located between spinel and diopside. Perovskite occurs as ≤ 1 µm grains, often in association with spinel (generally 10-20 µm). Alteration phases rich in Fe, Na and Cl are distributed throughout the inclusion. Grains in EK5-3B exhibited random crystallographic orientations.

**Discussion:** Leoville Senita has no significant porosity based on totals from EDS mapping; they are ~100% in Senita, whereas they are ≤100% in EK5-3B. Triple junctions and deformation suggest annealing and solid-state recrystallization during a post-formation thermal event. Thus, while we observe no compositional zoning, it is unclear whether this CAI records primary condensation because of the possibility of re-equilibration. A possible explanation for transient heating lies in parent body metamorphism or shock resulting from the outward radial transport of grains that formed near the protosun [6]. Temperatures must have been maintained below spinel’s solidus at 1513 K [2].

**Allende EK5-1-1:** The coarse grain size and zoning within melilite and pyroxene suggest that EK5-1-1 crystallized from a melt. It has been shown that precursors to Type B1 CAIs may have undergone nebular shock, resulting in pressures of at least 10^4 bars (a minimum requirement for the formation of melilite mantles) and temperatures > 1790 K (the liquidus of AkS) that began to subside within hours [7]. Once the melilite mantle in EK5-1-1 crystallized below 1773 K, evaporative loss of Mg and Si would have occurred. As evidenced by the Mg-rich core of EK5-1-1, further Mg loss would not have occurred after the formation of the mantle. In order to preserve compositional zoning, temperatures could not have been maintained above 1273 K for more than 10^3 years [7].

The increase in Ti^3+ towards the rim of the pyroxene grain analyzed in EK5-1-1 suggests a change in the redox conditions towards a more reducing environment. It is possible that the Ti^3+ enrichment observed at the rim is due to the breakdown of a Ti,O-rich phase (e.g., perovskite) that became incorporated along the margins of pyroxene grains [3]. It would do well to analyze more pyroxene grains for Ti^3+ within this inclusion to further substantiate this hypothesis.

**EK5-3B** is thought to be a “layered” condensate, given its small grain size (5-20 µm in the interior and 20-50 µm towards the margin) and higher porosity. Random crystallographic orientations and lack of zoning implies that grains in EK5-3B were in equilibrium with the gas from which they formed. The mineralogical assemblage of this CAI suggests that it formed at the lowest temperatures of the three. EK5-3B bears evidence of evolving conditions during formation, given the mid-inclusion transition from a fine-grained, spinel-rich (lower-temperature phase) interior to a slightly coarser-grained and pyroxene-rich mantle. It would do well to look for phases which may have been replaced by thermal processing in the Solar nebula.

**Conclusion:** The inclusions presented in this study contain evidence of a rapidly changing nebular environment. We observe more phases with decreasing refractory compositions in our Type A, B and C CAIs, respectively. Leoville Senita provides evidence of a transient heating event occurring below 1700 K, while EK5-1-1 indicates a separate heating event with temperatures maintained above 1790 K. EK5-3B condensed from a cooler and likely more evolved nebular gas, and may have been transported to another gaseous reservoir. Trace element analysis could further address crystallization sequences and/or nonextant phases.

**References:**