Ca/Al variations in CV3 dark inclusions: Evidence for pre-accretion aqueous and thermal processing. Y.S. Goreva and T.J. McCoy, Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119 USA (gorevay@si.edu)

Introduction: Dark inclusions (DI) are fine-grained lithic clasts ranging from 1 mm to a few cm. They have been reported in numerous carbonaceous chondrites, but are the most prevalent in CV3 chondrites. Despite a close mineralogical and textural relationship with the host meteorite, they are considerably different from the host, and their origin is still subject of a debate. Two major models have been proposed: nebular and asteroidal. According to the nebular model, DIs are nebular condensates that experienced high-T metasomatic reaction with highly oxidized nebular gas [e.g. 9]. In the asteroidal model, DIs are fragments of CV-like materials that experienced various degrees of hydrous alteration either before or after incorporation into asteroidal parent body [e.g. 10]. Furthermore, several authors have argued that dark inclusions might represent an extreme end-member in the alteration-dehydration sequence observed in CV chondrites, although alternative interpretations (e.g., CM origin) are also suggested [1, 2]. Based on similar O-isotopic composition and observed elevated Ca/Al ratio (Ca/Al>2), Goodrich et al. [3] argued that CV3 dark inclusions provided an attractive possibility for ureilite precursors, as superchondritic Ca/Al ratio is required by a single stage melting model for ureilites. This hypothesis, in part, motivated us to look into possible causes of such variation. Here we present a petrographic study of an Allende DI that exhibits a wide Ca/Al range, and discuss possible causes of such variation.

Results: Dark inclusion HC3 from Allende USNM 3509 is an angular cluster approximately 1x1.5 cm. It is similar to Allende matrix, void of chondrules and CAIs, and consists primarily of olivine clusters embedded in fine-grained platy Fe-rich olivine, minor high- and low-Ca pyroxene, Fe sulfides, Fe-Ni metal and nepheline and can be classified as a Type B dark inclusion [4]. However, close examination of BSE images revealed distinct banded texture, characterized by zones of finer- and coarser-grained material. Figure 1 illustrates the sharp boundary between such bands. The lower right corner of the image is predominantly platy fayalitic Ol with minor nepheline and rare sulfides and metals. The upper left corner is an area with larger platy Ol matrix, abundant low- and high-Ca pyroxenes, sulfides, Fe-Ni metal and nepheline.

An X-ray map of the inclusion revealed compositional variation between fine and coarse-grained bands. Banded texture defined by high- and low-Ca regions. Low-Ca bands consist of fayalitic Ol with very minor nepheline. High-Ca regions include abundant, often heavily altered, pyroxenes, sulfides, metal and other very minor phases (Fig. 1) Semi-quantitative bulk EDX analysis (FEI NOVA NanoSEM 600 scanning electron microscope at the Smithsonian Institution) of high-Ca regions exhibit Ca/Al close to 3, while low-Ca bands are sub-chondritic.

A summary of available CI-normalized Ca/Al ratios in CV DIs is presented in Figure 3. Dark inclusions exhibit Ca/Al ratios ranging from subchondritic to superchondritic. Although most of the data is for Allende DIs, few bulk DI analyses are available for reduced CV3. There appears to be no apparent correlation of Ca/Al with the degree of hydration among CV3 chondrites. The highest Ca/Al ratio of 4.3 is from the DI studied by [5] and that DI is likely type B. Sub-chondritic Ca/Al values are also from type B - Allende AF, one of the best studied inclusions [6] has a Ca/Al ratio of 0.7. Vigaran and Leoville DIs appear to be super chondritic, although given the variation in reported Ca/Al bulk composition of Allende inclusions, these data might be sample-biased. Average bulk Ca/Al composition of low- and high-Ca regions in HC3 calculated in this study, 0.4 and 2.8 respectively fall close to extreme values reported in literature. The average bulk Ca/Al value of the inclusion is close to chondritic.

Discussion: Ca redistribution within this dark inclusion seems to occur on a fairly small scale prior to incorporation into Allende. Although similar process
Late-stage mobilization and re-distribution of Ca in Allende DIs was described by [10]. These authors argued that Ca was in-situ leached out from dark inclusion and deposited into Ca, Fe-rich rims around DI and/or in the surrounding Allende matrix. In the inclusion HC3 we see prominent Ca redistribution within the inclusion itself. While Ca/Al ratio in Allende matrix is close to chondritic value, Ca/Al ratios of fine- and coarse grained bands within inclusion complement each other. While some late-stage redeposition of Ca from HC3 into the Allende matrix is possible, it is more probable that remobilization of Ca occurred during hydrous alteration on the asteroidal parent body, prior to incorporation of dark inclusion material into Allende. The apparent high Ca/Al ratio reported by [5] and others is most likely to be the result of the preferential sampling of a high-Ca region.

It is possible that dark inclusions sampled regions on the parent asteroid which experienced more extensive aqueous alteration than other regions. Perhaps they even represent aqueous conduits along which fluid percolated through. The sharp boundary and angular appearance of the bands within dark inclusion suggest that the banded texture occurred during metamorphic, rather than metasomatic event. Higher temperature metamorphism is also supported by a lack of correlation between Ca/Al enriched/depleted regions with the distribution of more volatile S and Na. The same metamorphic process is likely responsible for dehydrating of the products of hydrous alteration.

We conclude that inclusion HC3 experienced extensive aqueous alteration that was followed by high temperature metamorphism prior to incorporation into Allende.