COMPLEX BEHAVIOR OF FLUID-MOBILE ELEMENTS IN A LITHIC INCLUSION FROM THE NORTHWEST AFRICA NWA 2364 CV3$_{OxA}$ CHONDRITE: EVIDENCE FOR EXTENSIVE FLUID-ROCK INTERACTION AND METASOMATISM ON THE CV3 CHONDRITE PARENT BODY

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Introduction: The CV3 chondrites are divided into two distinct subgroups, oxidized and reduced. Both subgroups contain primitive solar system material such as Calcium-Aluminum-Inclusions (CAIs), chondrules, and matrix [1]. The two subgroups record significant evidence of secondary alteration, suggesting a complex alteration history on the CV3 chondrite parent body [2-4]. One important constituent found in both subgroups of these chondrites are dark inclusions (DIs). Dark inclusions have been classified into four types (A, B, A/B, and C) that share similar early solar system materials as their host chondrites. However, DIs are finer-grained, and show distinct evidence of more extensive alteration than their host chondrites [2-4]. Studying these DIs and their host meteorites can provide information and further insights into the complex processing that occurred on the CV3 chondrite parent body, as well as the relative timing of that alteration.

The goal of this investigation is to examine the elemental composition of a large lithic inclusion (LI) in the NWA 2364 CV3 chondrite in order to understand the behavior of fluid-mobile elements. Using these data, we can explore the complex alteration history of NWA 2364 and make a comparison to other DIs in CV3 chondrite Allende-like chondrites.

Methods: Full thin section BSE and X-ray map mosaics of NWA 2364 and its LI were obtained using a FEI Quanta 3D Field Emission Gun SEM. In addition, broad-beam EPMA analyses (50µm beam size) were collected of mineral phases within the matrix material of the host and LI utilizing a JEOL 8200 Superprobe electron microprobe via WDS spectrometry. In order to obtain compositions of the fine-grained matrix material the data points were collected using the Probe for EPMA software, "shotgun" selection, which enables collection of a randomized set of analytical points.

Results: X-ray mapping of the entire thin section of NWA 2364 revealed unique relationships in the behavior of many elements, specifically the fluid-mobile elements.

Lithic Inclusion: X-ray mapping shows that the LI is depleted in S, Na, and K-bearing phases. Figure 1 is an elemental X-ray map of the distribution of Mg, Ca, and S in the lithic inclusion. The map shows that there are no detectable S-bearing phases within the entire clast, either within chondrules or matrix. Sulfides are, however, present in the host chondrite. The modal abundance of sulfide content in the LI is approximately 0.01 vol%. This value is significantly lower the average CV chondrite sulfide abundance of 2.2 vol % [1]. Similarly, X-ray maps show that no Na- or K-bearing phases are present anywhere in the lithic inclusion.

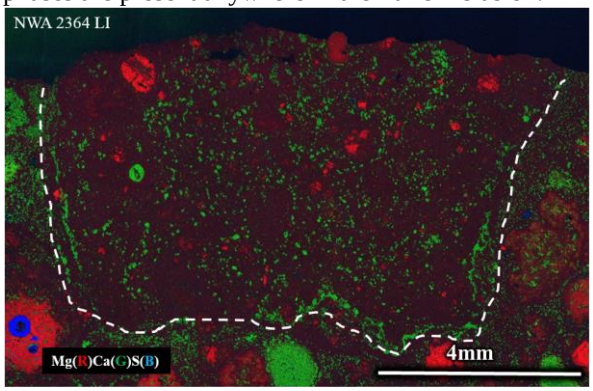

Figure 1: Composite Mg(R)Ca(G)S(B) X-ray map of NWA 2364 and its LI (outlined in white).

Figure 2a shows the LI bulk matrix composition compared with the bulk matrix compositions of two Allende dark inclusions [4], both normalized to CI chondritic values [5]. The overall abundance patterns for the LI and the Allende dark inclusions are remarkably similar for most elements, with some notable exceptions. The patterns are all characterized by depletions in the moderately volatile elements, Cr, Mn, Na, and K. Notably, the LI matrix is highly depleted in S compared to both CI chondrite abundances and the Allende dark inclusions. The LI is also more depleted in Ni compared with the two Allende dark inclusions. The refractory elements Ti and Mg have CI abundances, whereas Al is enriched to a comparable degree to the Allende dark inclusions. However, unlike the Allende dark inclusions, Ca and Al are strongly fractionated with a depletion in Ca (0.2 x CI). Figure 2b shows the LI matrix composition plotted normalized to bulk CV elemental abundances [6]. The LI matrix is depleted in Na, K, Ni, S, Ti, and Ca in comparison to the bulk CV abundances. The LI matrix is slightly more enriched in P than the CV abundances and the refractory elements Mg and Al are similar to the CV abundances.

Discussion: There is a plethora of evidence that indicates DIs have interacted with aqueous fluids, indicated by the redistribution of elements, secondary min-

eral phases, textural features, and isotopic compositions [2-4]. In general, the NWA 2364 LI has similar features to other dark inclusions, especially those from Allende, but the LI has several unique features that suggest a more extensive alteration history. The oxygen isotopic composition of the LI [7] is closer to Leoville DIs [2], with a clear heavy isotope enrichment that displaces it from the CCAM line. Veins that cross cut chondrule phenocrysts in the LI [8] are unlike the sulfide and Ca-rich pyroxene veins found cross cutting entire DI sections in Allende [3]. DIs in Allende show depletions in Na and K that are similar to those in the NWA LI, but a significant difference is the much higher depletion in S and, surprisingly, the absence of Na- and K-bearing phases. These features are distinct from Allende DIs where Na, K, and S-bearing phases, such as nepheline, sodalite, and pyrrhotite are within chondrules and matrix [2-4].

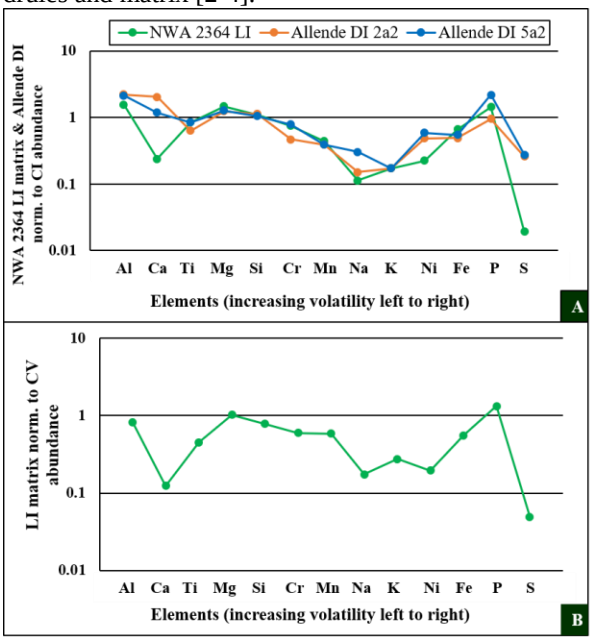

Figure 2: (A) CI normalized abundance plot of the bulk matrix composition of the NWA 2364 LI and the average bulk matrix composition of Allende dark inclusions. CI chondrite values from [5]. Average Allende DI matrix values from [4]. (B) CV normalized abundance plot of the bulk matrix composition of NWA 2364 LI and the average bulk CV chondrite values. CV chondrite values from [6].

Calcium is apparently significantly depleted in the matrix of the NWA LI. However, our previous studies show that Ca is no longer present in chondrules, due to complete alteration of chondrule mesostasis glass, but instead occurs within the Ca-rich pyroxene aggregates found within the matrix of the LI (Fig.1). Therefore, the apparent depletion in Ca is probably not real and attributable to the fact that Ca is concentrated in these Ca-rich pyroxene aggregates that were under sampled by the broad beam matrix analyses.

Cosmochemically, K, Na, S, and Ca behave differently, but all four are soluble in aqueous fluids. Hence, any changes in their relative abundances can provide important indicators of mobilization and transport via a fluid. Collectively, our observations are consistent with extensive fluid-rock interaction that has significantly modified the mineralogy and bulk composition of the inclusion. However, the behavior of these four elements is distinct. The depletions in Na and K and the absence of Na- and K-bearing phases demonstrate that these alkali elements have been completed mobilized by aqueous fluids and lost from the inclusion. In addition, and unlike other DIs in, for example, Allende, S-bearing phases has been completely dissolved by fluids and S has also been entirely lost from the NWA 2364 LI, a phenomenon that has not been recognized previously in other DIs. In contrast, Ca has been extensively redistributed from chondrules (and CAIs), but has re-precipitated as Ca-rich aggregates within the matrix, rather than being mobilized and leached from the LI.

The complete absence of Na-, K-, and S-bearing phases within the DI demonstrate that this LI has had its bulk mineralogy and chemistry modified more extensively than any DI studied to date in any other CV3 chondrite. These observations, coupled with our isotopic, petrographic, and mineralogic observations of NWA 2364 [7-9] show that the LI has undergone intensive fluid-rock interactions, that metasomatized the LI on the CV parent body before emplacement into the NWA 2364 host. The lithic inclusion has undergone complex processing involving interaction with an aqueous fluid that altered the primary mineralogy and mobilized fluid-soluble elements, probably during a thermal metamorphic event that ultimately resulted in loss of the fluid. After this processing the LI was emplaced into the NWA 2364 host chondrite.

Bulk trace element analyses of the LI are in progress and will provide additional constraints on the fluid-rock interactions the LI experienced.

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