Introduction: Among all the carbonaceous chondrite groups, the CV3s have proved to be one of the most enigmatic, recording a diverse array of primary and secondary processes. The recognition of two distinct subgroups of CV3 chondrites, oxidized (CV3ox) and reduced (CV3red) [1], has led to a debate regarding the processing of chondritic materials within the solar nebula and on asteroidal parent bodies [2-4]. In particular, the presence of distinct fine-grained lithic inclusions, so called dark inclusions (DIs) in other CV3 chondrites has provided further complex samples that likely originate from the CV3 parent body [3-6]. Although DIs, like their host chondrites, consist of chondrules, CAIs and fine-grained matrix, they are typically much finer-grained and exhibit a wide range of degrees of secondary alteration. Most DIs appear to be more extensively modified than their host chondrites [2-6]. Studying these DIs and their host meteorites provides essential information into the complex processing that occurred on the CV3 chondrite parent body.

Although DIs have been recognized in both CV3ox and CV3red chondrites [2-6], studies of DIs in the oxidized group have focused almost entirely on Allende (CV3oxA subgroup). We recently described a cm-sized lithic inclusion (LI) in the NWA 2364 CV3oxA chondrite that shows significant evidence of secondary alteration and metasomatism [7,8]. In this study, we have used trace element analyses by LA-ICP-MS and synchrotron-based XANES of Cr, Ti and V valences to understand the complex alteration of the LI more fully. Our main objective is to evaluate the possible role of fluids in the alteration history of the LI.

Methods: Laser-ablation ICP-MS was carried out using a New Wave Research UP213 ultraviolet laser coupled to a Thermo Finnigan Element 2 magnetic sector, single collector ICP-MS at the Department of Geology, University of Maryland. Analyses were collected from representative regions of different chondritic components (e.g. fine-grained rims and matrix, chondrule olivines, altered chondrule mesostasis, etc.) in a polished block of the LI. A laser beam diameter between 55 and 100 µm was used depending on the size of the analysis target. Valences of V, Ti, and Cr were determined by X-ray absorption near-edge structure (XANES) spectroscopy. XANES spectra were collected using the GSECARS X-ray microprobe in fluorescence mode, with a 1 µm X-ray beam. Valences of Ti were determined following the methods of [8] and represent averages for the analytical volumes, with precisions based on spectral fitting uncertainties. The valence of V was determined using Fe-free glass standards with Cr3+ or Cr2+ [9]. The valence of V was calibrated following [10]. For each analysis spot, spectra were collected at three or four different orientations and merged to minimize orientation effects.

Results: Trace element data. The matrix of the LI is highly porous and consists dominantly of platy ferroan olivines [7]. Fine-grained rims (FGRs) on chondrules are still recognizable, but consist of finer-grained but morphologically similar olivines to matrix. CI-normalized element abundance patterns for matrix and FGRs (Fig. 1) show that the refractory elements ranging from Zr through the REE to Lu are essentially flat with abundances that range from 1 to 3 x CI. The exceptions are Sr, Ba, W, and U, which show enrichments up to 10 x CI for U and 6-7 x CI for W, Sr, and Ba. All of these elements, especially Sr and Ba, are known to be contamination produced by terrestrial weathering [11]. Some analyses exhibit a slight enrichment in the ultrarefractory elements relative to the REEs.

In the LI, all the mesostasis glass in chondrules has been replaced by masses of platy ferroan olivine, a process that has resulted in complete loss of Ca from the interior of chondrules. Calcium is, however, abundant as porous aggregates of clinopyroxene (Di-Hd) in

![Figure 1](image324x107to532x250.png)

**Figure 1.** Representative element abundance patterns for different components in the NWA 2364 lithic inclusion, normalized to CI chondrites.
the matrix. Most of these aggregates are too small to analyze by LA-ICPMS, but we were able to obtain one analysis from a large aggregate. The aggregate has a highly unusual stepped REE abundance pattern (Fig.1) with flat LREE ~ 6-7 x CI, stepping down to abundances of ~ 3 x CI for the HREE. The ultrarefractory elements show highly variable behavior ranging from enrichments of 2-4 x CI (Zr, Sc, Th, U, Ta) to significant depletions (0.4 x CI for Hf).

Altered mesostasis regions in a type IA and a type IIA chondrule have variable REE abundances, from ~0.6 to 3 x CI (e.g. Fig. 1). Although the patterns are generally flat, there is a considerable variability from one REE to another. Type IA chondrule mesostasis with the highest REE abundances have negative Eu anomalies and in one case has slightly lower LREE than HREE. In each pattern, the ultrarefractory elements show quite variable and distinct abundance patterns, generally slightly elevated relative to the REE.

Cr, Ti, and V valences. Type IA chondrules in both NWA 2364 host and LI contain forsterite phenocrysts with FeO-rich rim overgrowths. We measured the valences of Cr, Ti, and V in both the cores and Fe-rich overgrowths in the NWA 2364 host and LI. In both host and LI, Cr in the Fe-rich overgrowths is oxidized with an average valence of ~2.95. The cores, however, are more variable, especially in the host. In the LI, the cores have generally less oxidized Cr (~2.85), but can vary between 2.74 and 2.92. The host chondrule forsterite cores are typically more reduced (2.7 to 2.8), but some grains have values that are comparable to the Fe-rich olivine rims. The Ti valence data for the LI show that both the Fe-rich rims and forsteritic cores are fully oxidized with valences within error of 4. The only exceptions are two olivine cores in the LI, which contain somewhat less oxidized Ti (valence ~ 3.7). In the host chondrules, Ti in the Fe-rich rims and Mg-rich cores are all highly oxidized with from the lowest valence being 3.84. None of the measured olivine cores contain more reduced Ti. Vanadium valence data show more scatter than for Cr and Ti (due at least in part to low signal to noise) but generally show similar behavior to Cr, with Fe-rich rims having V valences of 2.8 to 3.2 and some cores having less oxidized values. Vanadium in the host NWA 2364 olivine is much more variable and complex with a total range in V valence from cores and rims of ~ 2.2 to 3.1. There are no obvious systematic differences between the cores and rims.

Discussion: We have previously argued that the LI in NWA 2364 has undergone extensive interaction with an aqueous fluid during metasomatic alteration that has significantly modified the mineralogy and bulk composition of the inclusion. Our LA-ICPMS analysis provide additional constraints on whether this hypothes is viable. Here we focus on the behavior of REE. The matrix and FGRs have flat REE patterns that are up to 3 x CI. This enrichment is consistent with redistribution of REE during fluid-rock interaction [12]. Our analyses of heavily altered mesostasis are variable, have REE abundances <3 x CI. These values are very low compared with literature values for mesostasis glass in chondrules from ordinary and carbonaceous chondrites, which are usually 10 x CI [13,14]. This observation provides strong evidence that REE, along with Ca were mobilized and lost from chondrules. One mesostasis analysis shows a depletion in the LREE relative to the HREEs, a feature which could be indicative of the higher solubility of LREE in aqueous fluids. Further, the abundance pattern for a Ca-rich pyroxene aggregate in the LI matrix has exactly the complementary REE pattern, with elevated LREE compared to HREE. This pattern is also highly unusual for a Ca-rich pyroxene, which should preferentially take up HREE to LREE, implying that a LREE-enriched fluid would be required to cause this unusual pattern.

Finally, the valence states of Cr, Ti, and V in Type IA olivines demonstrate that these elements have undergone oxidation during the secondary alteration event. Nevertheless, the cores of some phenocrysts retain evidence of their more reduced precursor compositions, which, in the case of the LI, are close to the values found in the most pristine CO3 chondrites [15]. However, of significant interest is the fact that the response of these elements to oxidation is clearly distinct between the LI and the host, providing further support for our contention that the LI has undergone fluid-rock interactions, metasomatizing the LI on the CV parent body before emplacement into the NWA 2364 host.

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