Northwest Africa 5401 CV chondrite: Not oxidized, not reduced, maybe in between?

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Introduction: Variations in oxidizing vs. reducing conditions in the early solar system are recorded by the CV chondrites. Nickel-poor compositions of troilite and relatively abundant Fe,Ni-rich metal are indicators of reducing conditions in a reduced subgroup (CV3red), whereas Ni-rich sulfide and a paucity of Fe,Ni-rich metal grains are indicators of oxidizing conditions in two oxidized subgroups (CV3oxA similar to Allende and CV3oxB similar to Bali) [1-3]. Raman analyses of temperature-sensitive carbon-rich matter have helped to show that the CV3red subgroup was metamorphosed at lower temperatures than the oxidized subgroups [2,4,5]. However, most CV chondrites appear to fall within one of the three subgroups—samples representing intermediate metamorphic temperatures and red-ox conditions are rare.

In this project, we present petrologic data and Raman spectroscopy analyses to argue that the meteorite Northwest Africa 5401 (NWA 5401) represents an intermediate stage in metamorphic temperature and oxidation, between the CV3red and CV3oxA subgroups. The presence of an intermediate suggests that the CV3red and CV3oxA subgroups represent stages along a continuum of temperature-oxidation conditions, and favors the interpretation that CV chondrites come from a single parent body that experienced a range of metamorphic conditions (cf. [3]).

Samples and Methods: Two polished thin sections and several chips were prepared from a slab of NWA 5401. One of the thin sections contains a texturally distinct clast (similar to dark inclusions reported from other CV chondrites, e.g. [6]) within the main host lithology of NWA 5401. The other thin section includes a coarse-grained Ca-Al-rich inclusion (CAI). The thin sections were imaged using petrographic microscopes, a Hitachi S-3400N scanning electron microscope (SEM) and JEOL JXA 8900 electron probe microanalyzer (EPMA) at Waseda University. Quantitative elemental analyses of minerals were collected by EPMA using a 15 kV, 20 nA, ~1-µm spot electron beam and well-characterized standards. Modes of chondrite components (chondrules, matrix, amoeboid olivine aggregates (AOAs), CAIs) were collecting by manually counting on a grid overlying elemental maps of the two thin sections.

Raman spectra were collected at the Waseda Physical Properties Measurement Center using a laser excitation wavelength of 532 nm and a spot size of ~3-4 µm focused by a 50x objective lens. The power at the sample surface was ~2.4 mW, the acquisition time was 10 seconds, and spectra were acquired in the range of 500-2200 cm^{-1}. Spectral fitting was conducted using a Lorentzian profile for the D-band, BWF profile for the G-band in the region of 900-1900 cm^{-1}. Model spectra with poor fits to data ($R^2 < 0.97$) were excluded. The D- and G-bands (abbreviated for defect and graphite, respectively) are attributed to molecular vibrations in carbon-rich matter; the full width at half maximum of the D-band (FWHM-D) decreases and peak intensity ratio of I_D/I_G increases with thermal maturity [4].

Results and Discussion: Large chondrules typical of CV chondrites are evident in the host lithology of NWA 5401 (Fig. 1). The clast lithology has much smaller chondrules and a higher matrix/inclusions* ratio (*inclusions used here to represent high-T components of chondrites including chondrules, CAIs and AOAs; see [7]). The NWA 5401 host has matrix/inclusions ~ 0.7-0.8, whereas the clast has matrix/inclusions ~ 3.8. Corresponding values determined by [7] are as follows: ~1.3 for Allende and Tibooburra (CV3oxA); 0.8 and 1.2 for Bali and Mokoia, respectively (CV3oxB); 0.6 and 0.4 for Vigarano and Leoville, respectively (CV3red, though Vigarano is a breccia with some CV3ox affinities). Bonal et al. (2020, ref. [2]) do not use the same matrix/inclusions parameter, but do report matrix mode percentages, with averages ($\pm 1\sigma$) of 48.9 (±5.6) for CVoxA, 52.3 (±8.5) for CVoxB and 35.1 (±7.2) for CVred. The matrix abundance of ~ 45 mode% of the NWA 5401 host lithology appears typical for the oxidized CV subgroups, but somewhat high for CVred.

The extent of alteration in the coarse-grained CAI (labelled SC-9) in one thin section of NWA 5401 also appears intermediate between observations reported from reduced and oxidized CV chondrites. Coarse-grained CAIs in Allende typically have alkali-FeO-rich minerals near CAI rims and grossular-rich veins extending into CAI interiors [8], whereas coarse-grained CAIs from CVred lack the grossular-rich veins and have only minor abundances of alkali-rich secondary minerals near CAI rims. In contrast, NWA 5401 CAI SC-9 has a widespread domain of alkali-rich minerals near its rim, but lacks the grossular-rich veins typical of Allende CAIs.

Nickel concentrations in sulfides were among the first observations that led [9] to distinguish oxidized CVs (with high-Ni sulfides) from reduced CVs (with low Ni-sulfides); the variations in Ni abundances in sulfides are verified by [3] (Fig. 2). Sulfides in NWA 5401 host lithology are near-endmember troilite with minimal Ni (Fig. 2).

Raman analyses show that the FWHM-D and I_D/I_G parameters of NWA 5401 fit most closely with previously compiled analyses from the CVoxB subgroup, though there is some overlap with CVred (Fig. 3).

In summary, the NWA 5401 host lithology appears similar to the CVoxB and CVred groups in Raman parameters, to the CVred group in sulfide composition, but exhibits greater alteration in a coarse-grained CAI than is typical of CVred CAIs. The matrix/inclusions ratio of NWA 5401 host is above that of most CVred chondrites and comparable to matrix/inclusions of some oxidized CVs. NWA 5401 may represent an intermediate metamorphic history between low-T metamorphism of CVred and higher-T metamorphism typical of oxidized CVs.

References: [1] Weisberg et al. (2006) in Lauretta D.S. & McSween H.Y. (editors) MESS II, p. 19-52. [2] Bonal L. et al. (2020) GCA 276: 363-383. [3] Gattacceca J. et al. (2020) EPSL 547: 116467 (9 pages). [4] Bonal L. et al. (2006) GCA 71: 1849-1863. [5] Bonal L. et al. (2016) GCA 189: 312-337. [6] Buchanan P.C. (1997) GCA 61: 1733-1743. [7] Ebel D.S. et al. (2016) GCA 172: 322-356. [8] Fagan T.J. et al. (2007) MAPS 42: 1221-1240. [9] McSween H.Y. (1977) GCA 41: 1777-1790.

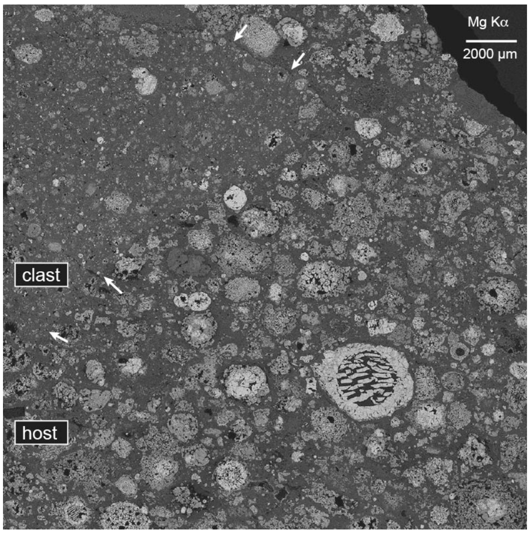

Fig. 1. Mg Ka map of NWA 5401 host and clast lithologies. Arrows highlight boundary.

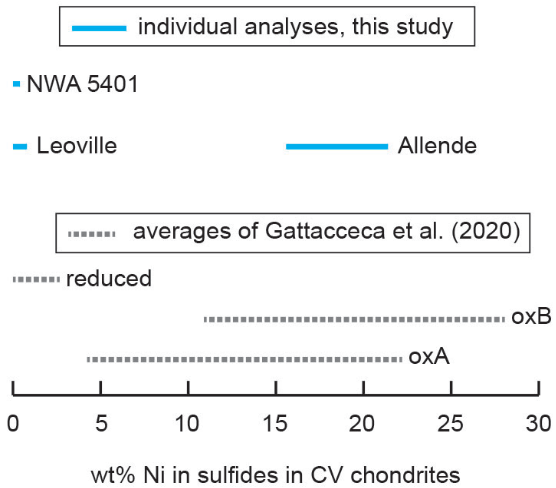

Fig. 2. Nickel concentrations in sulfides in CV chondrites. Ranges of values in the CV subgroups show averages from individual meteorites reported by Gattacceca et al. (2020) and ranges of individual analyses collected for this study.

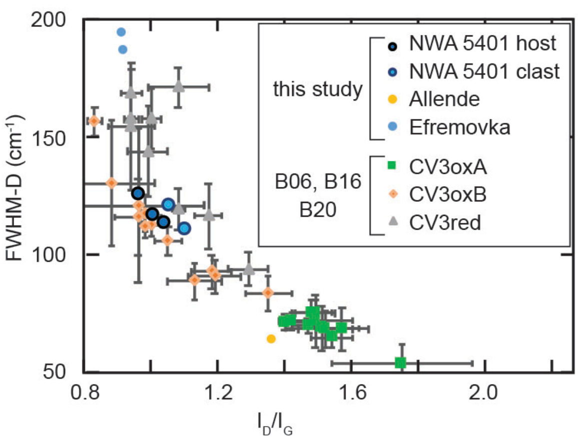

Fig. 3. Raman parameters collected in this study and reported by Bonal et al. (2006; 2016; 2020).