**EVIDENCE FOR PERVASIVE METAMORPHISM ON THE CR CHONDRITE PARENT BODY FROM HIGHLY EQUILIBRATED CR6 CHONDRITES NORTHWEST AFRICA 2994 AND NORTHWEST AFRICA 3100.**

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Among the two dozen or so known unpaired CR chondrite specimens, virtually all have been assigned as petrologic type 2; one example (GRO 95577) is of petrologic type 1. Two other meteorites lacking chondrules (Tafassasset, LEW 88763) have chemical affinities to CR chondrites [1], as do igneous achondrites NWA 011 and pairings [2, 3]. Here we describe two Northwest African specimens that represent rare examples of highly equilibrated (and chemically modified) CR6 chondrites, and which add to the evidence for a relatively large-sized CR parent body capable of significant and perhaps prolonged internal heating [3].

**Northwest Africa 2994:** This large (4756 gram) stone recovered in Algeria in 2007 is superbly fresh and partly covered in black fusion crust (Figure 1). The

**Figure 1:** Whole NWA 2994 stone. Note the overall khaki-green color and patches of fresh fusion crust.

grainsize is mostly in the range 0.1-1.6 mm, and textures range from subequigranular to porphyroblastic to poikiloblastic (see Figure 2). Scarce, highly modified relict chondrules are present Figures 2b, 3a). The rock consists of 45% olivine ($Fa_{37.3}$, FeO/MnO = 81-88), 42% orthopyroxene ($Fs_{29.5}Wo_{3.1}$, FeO/MnO = 53-58), 3% augite ($Fs_{12.1}Wo_{45.7}$), 3% plagioclase ($An_{53.3}Or_{0.8}$, FeO = 0.38 wt %), 3% troilite, 2% chromite (*cr#* = 71, $TiO_2$ = 1.91 wt.%), 2% metal (kamacite and taenite) and rare merrillite. The elevated FeO/MnO ratios in the mafic silicates and the relatively calcic plagioclase are features we have previously recognized as hallmarks of carbonaceous metachondrites [3, 4]. The relatively high sulfide content also is noteworthy.

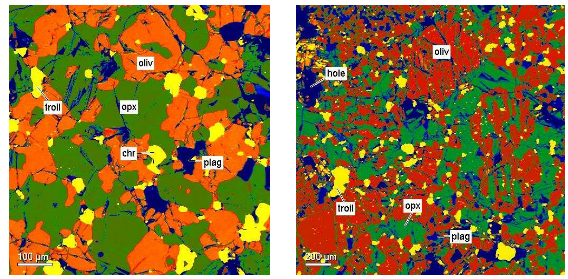


**Figure 2:** BSE images of typical texture (left) and two diffuse, recrystallized chondrules (right) in NWA 2994.

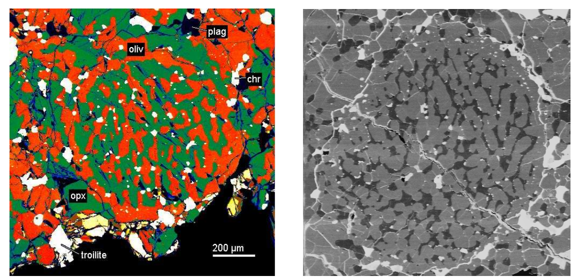


**Figure 3:** Chondrules in NWA 2994 and NWA 3100.

**Northwest Africa 3100 and Tafassasset:** NWA 3100 is an extremely fine grained 136 gram stone [3] with a inequigranular metamorphic texture (Figure 4); however, two small chondrules were found in one of two thin sections (Figure 3b). We also confirmed that Tafassasset has a recrystallized poikiloblastic texture (Figure 5), although we found no recognizable chondrules [cf. 5]. Progressive higher grade metamorphism of NWA 2994 could readily produce such textures.

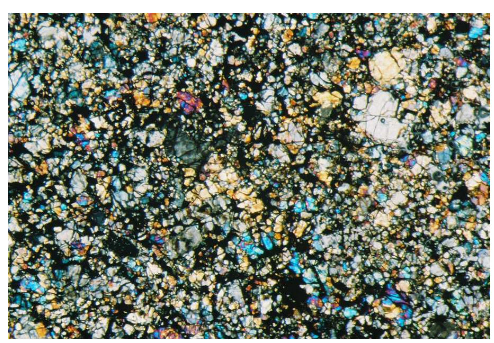

**Figure 4:** XPL image of NWA 3100 (4.5 mm wide).

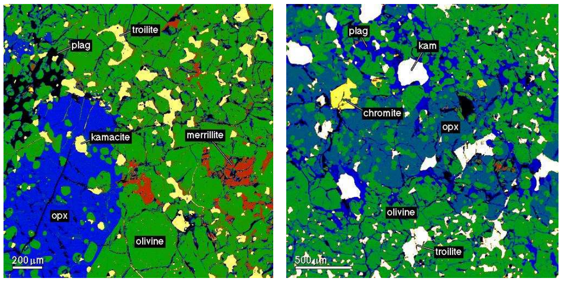


**Figure 5:** BSE images of Tafassasset showing poikiloblastic textures. Note also abundant sulfides.

**Oxygen Isotopes:** Data for CR2 chondrite NWA 801 and igneous achondrite NWA 2400 were reported previously [3]. New results for other acid-washed samples analyzed by laser fluorination are (all in per mil):

| | $\delta^{17}O$ | $\delta^{18}O$ | $\Delta^{17}O$ |
|---|---|---|---|
| NWA 2994 | -0.007 | 3.351 | -1.769 |
| | +0.078 | 3.355 | -1.687 |
| NWA 3100 | -1.227 | 1.101 | -1.806 |
| Tafassasset | -0.458 | 2.063 | -1.543 |
| | -0.548 | 2.057 | -1.630 |

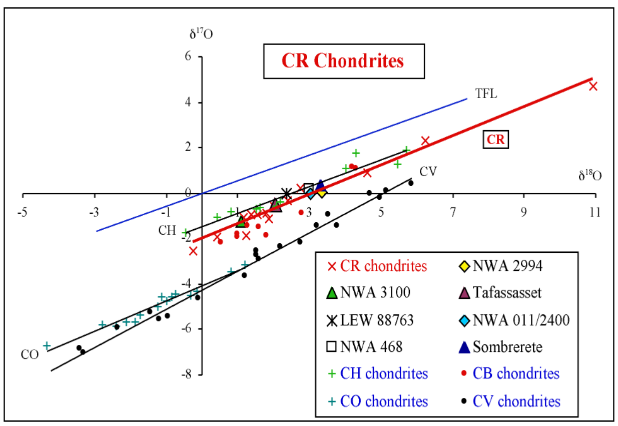


**Figure 6:** Oxygen isotope compositions of NWA 2994, NWA 3100, Tafassasset, LEW 88763, NWA 011 pairings, and two irons compared with analyzed CR chondrites. Data from [2, 3, 6 and this work].

**Bulk Compositions:** Analyses by XRF and INAA (see Table, Figure 7) show that NWA 2994 and NWA 3100 share compositional similarities with Tafassasset, LEW 88763, Renazzo and other CR2 chondrites [1]. Other data for NWA 3100 (courtesy of R. Korotev) show that the REE pattern is essentially chondritic, like that for LEW 88763 [1]. However, both NWA 2994 and Tafassasset are clearly fractionated relative to CR chondrites, implying that their metamorphism was not isochemical (perhaps caused by mobile hydrous fluids).

| | NWA 2994 | NWA 3100 | Renazzo[1] | Taf-Paris |
|---|---|---|---|---|
| $SiO_2$ | 39.07 | 34.99 | 33.82 | 33.42 |
| $TiO_2$ | 0.10 | 0.12 | 0.18 | 0.07 |
| $Cr_2O_3$ | 0.68 | 0.57 | 0.56 | 0.62 |
| $Al_2O_3$ | 1.14 | 2.27 | 2.36 | 1.62 |
| FeO | 32.25 | 30.63 | 32.07 | 36.97 |
| MnO | 0.29 | 0.29 | 0.25 | 0.28 |
| MgO | 24.69 | 23.34 | 23.76 | 24.02 |
| CaO | 0.93 | 1.99 | 1.78 | 1.54 |
| $P_2O_5$ | 0.15 | 0.16 | | 0.13 |
| SUM | 99.30 | 95.02 | 95.37 | 98.66 |

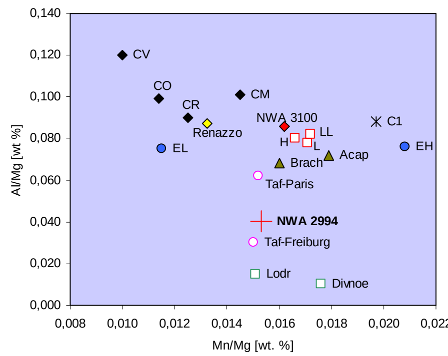


**Figure 7:** Moderately volatile Mn vs. refractory Al for NWA 2994, 3100, Tafassasset, and CR chondrites.

**Conclusions:** The discovery of NWA 2994 bolsters our hypothesis [3] regarding the extent and perhaps the duration of metamorphism on the CR parent body. Additional specimens (NWA 2976 and NWA 4587 [7]) paired with the plutonic igneous achondrites NWA 011 and NWA 2400 have since been recovered as well. Based on the oxygen isotopic affinities of all these specimens to CR chondrites, we conclude that the CR parent body must have been sufficiently large to have undergone substantial, non-isochemical internal metamorphism and partial melting (both perhaps fluid mediated), while also possessing a chondrite regolith.

**References:** [1] Mason B. and Wiik H. B. (1962) *Amer. Mus. Novitates* **2106**, 1-11; Kallemeyn G. W. et al. (1994) *Geochim. Cosmochim. Acta* **58**, 2873-2888; Swindle T. D. (1998) *Meteorit. Planet. Sci.* **33**, 31-48; Zipfel J. et al. (2002) *Meteorit. Planet. Sci.* **37**, A155 [2] Yamaguchi A. et al. (2002) *Science* **296**, 334-336; Floss C. et al. (2005) *Meteorit. Planet. Sci.* **40**, 343-360 [3] Bunch T. E. et al. (2005) *Lunar Planet. Sci.* **XXXVI**, #2308 [4] Irving A. J. et al. (2005) *Meteorit. Planet. Sci.* **40**, 5218 [5] Bourot-Denise M. et al. (2002) *Lunar Planet. Sci.* **XXXIII**, #1611; Nehru C. E. et al. (2003) *Lunar Planet. Sci.* **XXXIV**, #1370 [6] Clayton R. N. & Mayeda T. (1996) *Geochim. Cosmochim. Acta* **66**, 199-2016; Clayton R. N. & Mayeda T. (1999) *Geochim. Cosmochim. Acta* **69**, 2089-2104 [7] *Meteorit. Bulls.* **91** & **92**.

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