**SPINEL-BEARING, AL-RICH CHRONDRULES IN THE UNEQUILIBRATED ORDINARY CHONDRITE NWA7402.**
D. K. Ross[1,2,3], J. I. Simon1[1] and M.J. Cato[1,4], [1]Center for Isotope Cosmochemistry and Geochronology at ARES, NASA-Johnson Space Center, 2101 NASA Parkway, Houston Tx, 77058, [2]Jacobs-JETS, 2224 Bay Area Blvd., Houston Tx, 77058. Daniel.Ross@nasa.gov, [3]University of Texas at El Paso, CASSMAR. [4]Geosciences and Natural Reasources Dept., Western Carolina University, 331 Stillwell Building, Cullowhee, NC, 2872.

**Introduction:** Several Al-rich chondrules (ARCs) have been discovered in the unequilibrated ordinary chondrite NWA7402. Two of these three ARCs are spinel-bearing. Here we have characterized these unusual chondrules with respect to their mineralogy and bulk compositions. These objects will be targets for future O and Mg isotope analysis. NWA7402 is clearly unequilibrated, with wide ranges of olivine compositions in chondrules ($Fo_{99}$-$Fo_{70}$, excluding rims). Chromium-oxide contents in olivine, and Raman organic spectral parameters support the classification of this meteorite as petrologic type 3.1 [1]. NWA7402 is similar to, and could be paired with NWA5717, in that they both possess light and dark lithologies.

**Analytical Methods:** Chemical maps and quantitative chemical data were obtained using the JEOL 8530F electron probe at NASA-Johnson Space Center. X-ray data for chemical mapping were acquired with a SDD-EDS system from Thermoelectron. Hyperspectral mapping data were acquired and processed with Thermoelectron NSS software. Elemental maps were combined into tri-color images using ImageJ software. Quantitative chemical data on the bulk chemical composition of ARCs were obtained by averaging numerous broad-beam WDS analyses (10 μm defocused beam).

**Mineralogy and Mineral Compositions:** All three chondrules are olivine-bearing, and lack low Ca pyroxene. Olivine in these chondrules is ultramagnesian, ~$Fo_{99}$. In chondrule 1 (see Fig. 1), olivine occurs as phenocrysts. In chondrules 2 and 3 (in Figs. 2 and 3 respectively), olivine is skeletal, and perhaps grew during quenching. Two of the ARCs are spinel-bearing, and the spinel is essentially end-member $MgAl_2O_4$. In all three chondrules, CPX is ultra-aluminous, with ~ 15-20 wt. % $Al_2O_3$. CPX in these samples is not rich in $TiO_2$, with generally < 2 wt. % $TiO_2$. Plagioclase is not a phenocryst phase in any of the chondrules discussed here. No melilite was observed in these ARCs.

**Chondrule Bulk Compositions:** Bulk compositions of these ARCs (see Table 1) are rich in silica (~40-45 wt %) and magnesia (~15-35 wt %) and poor in CaO (~8-15 %) and alumina (~13-20 %) relative to CAIs. They are, however, significantly enriched in $Al_2O_3$ and CaO relative to 'normal' chondrules. The compositions of these ARCs are plotted on the phase diagram $Mg_2SiO_4$-$Ca_2SiO_4$-$Al_2O_3$, and compared with the compositions of various types of CAIs, previously described ARCs, as well as 'normal chondrules'. Al-rich chondrules from NWA7402 have compositions similar to previously studied ARCs, and one has a composition that matches the location of Type C CAIs. NWA7402 ARCs are offset toward higher $Al_2O_3$ and $Ca_2SiO_4$ relative to 'normal chondrules' on the phase diagram. Their compositions are clearly transitional between 'normal chondrules' and Type C CAIs. This observation prompts the question of the origin of Al-rich chondrules. Models for their origins include melting of CAI + chondrule mixtures, and evaporation of Mg and Si from 'normal' chondrules [2,4].

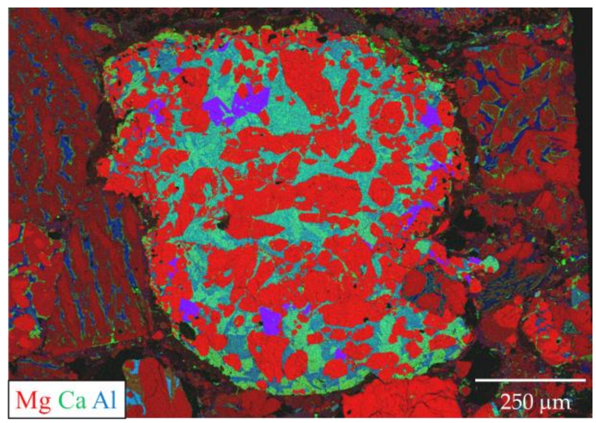


**Figure 1.** Chemical map of spinel-bearing, Al-rich chondrule. Olivine is red, spinel is purple, CPX is green, and glassy, quench crystallized matrix is green-blue. This chondrule is labeled Chond 1 in table 1.

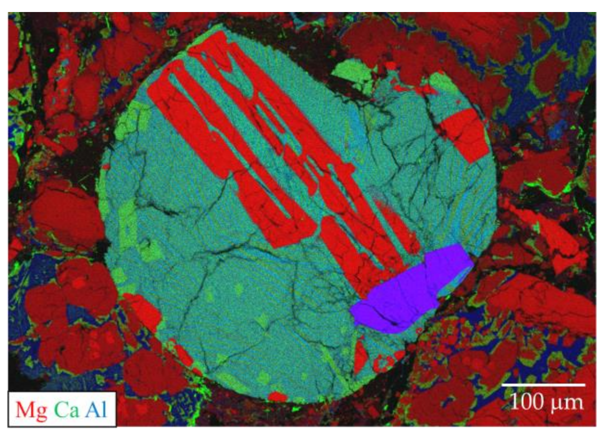


**Figure 2.** Combined x-ray maps of spinel-bearing ARC. Spinel is purple, olivine is red, CPX is green, and glassy, fine-grained CPX-rich matrix is blue-green. This chondrule is labeled Chond 2 in table 1.

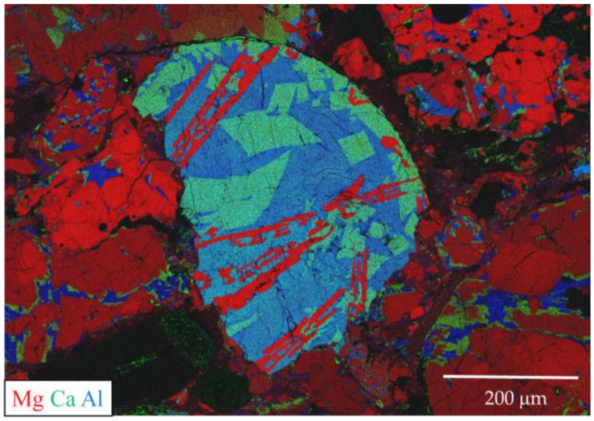


**Figure 3.** This chondrule is a broken fragment of a larger chondrule. Note that this chondrule has no exposed spinel. Olivine is red, aluminous CPX is green, and glassy, partly crystallized matrix is blue. Bulk chemical data for this chondrule is labeled Chond 3 in table 1.

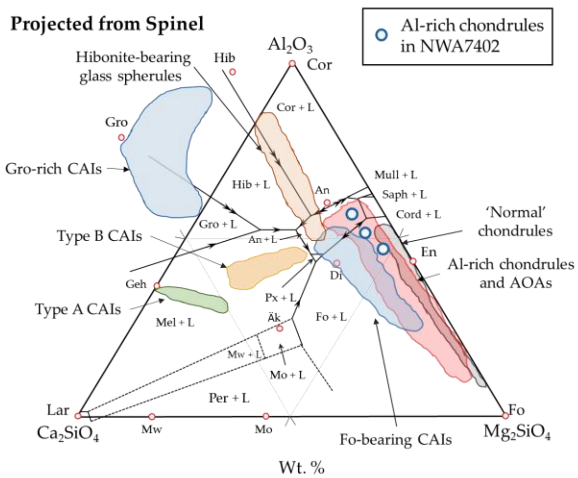


**Figure 4.** Compositions of ARCs projected from spinel into the plane $Mg_2SiO_4$-$Ca_2SiO_4$-$Al_2O_3$, in the quaternary CMAS (CaO-MgO-$Al_2O_3$-$SiO_2$). Details of the plotting procedure are in [2]. Data for various CAI and chondrule types are from [2-4] and references therein. All phase fields on this diagram also crystallize spinel, in addition to the phases noted. Type C CAIs in this compositional space occupy the phase region labeled An + L.

**Discussion:** Bulk compositions of ARCs are transitional between those of CAIs and ferromagnesian chondrules, particularly in terms of their $Al_2O_3$ and CaO compositions. Likewise, they have mineralogical features that are transitional, with end member spinel, and ultra-aluminous diospside being present in Al-rich chondrules and in CAIs. Some features of ARCs are more like ferromagnesian chondrules – they are olivine-bearing quenched melt droplets, with silica abundances like ferromagnesian chondrules. Potential scenarios for the formation of Al-rich chondrules [2,4,5] are: (1) they represent melted hybrids of Type C CAI and chondrule mixtures, or (2) they result from evaporation of MgO and $SiO_2$ from ferromagnesian chondrules, thus enriching the residual chondrule in CaO and $Al_2O_3$. Oxygen isotope studies of Al-rich chondrules [5] show that they have isotopic compositions that are transitional between CAIs and ferromagnesian chondrules, although they are closer to chondrules. Such oxygen isotope compositions are not those expected from kinetic mass dependent fraction effects expected during evaporation in low pressure ($<10^{-5}$ bar) nebular environments. Although the evaporation could take place in "chondrule-forming" environment(s) at higher gas pressures, which would preclude significant heavy isotope enrichment [6], a mixing process is a simpler explanation. The latter origin is supported by the existence of hybrid CAI-chondrule objects, with CAI material engulfed in chondrules, and CAIs with incorporated chondrules, suggesting that hybrid objects were the starting material for the formation of the Al-rich chondrules.

**Table 1: Compositions of chondrules**

| | Chond 1 | Chond 2 | Chond 3 |
|---|---|---|---|
| $SiO_2$ | 40.48 | 41.50 | 44.46 |
| MgO | 34.45 | 22.73 | 15.32 |
| $Na_2O$ | 1.15 | 0.43 | 2.17 |
| $Al_2O_3$ | 13.11 | 19.55 | 17.47 |
| S | 0.04 | 0.03 | 0.07 |
| $K_2O$ | 0.05 | 0.02 | 0.06 |
| CaO | 8.35 | 12.22 | 15.45 |
| $P_2O_5$ | 0.03 | 0.01 | 0.01 |
| $TiO_2$ | 0.50 | 0.65 | 0.95 |
| $Cr_2O_3$ | 0.16 | 0.13 | 0.19 |
| FeO | 0.90 | 2.46 | 4.18 |
| MnO | 0.02 | 0.02 | 0.05 |
| Total | 99.21 | 99.75 | 100.39 |

Notes on Table 1. These bulk compositions were obtained by broad-beam analysis, with > 150 probe spots obtained on each chondrule. FeO contents in these chondrules is elevated due to the presence of cross-cutting, Fe-rich veins that reflect terrestrial alteration.

**References:** [1] Jilly-Rehak C.E., et al. *Chemie der Erde*, *76*, 111-116. [2] MacPherson G.J. and Huss G.R. (2005) *GCA*, *69*, 3099–3127. [3] MacPherson G.J. et al. (2005) 225-250 *in Chondrites and the Protoplanetary Disk*. [4] Russell, S.S. et al. (1996) 317-350 *in Chondrites and the Protoplanetary Disk*. [5] Wang, Y. et al. (2016) *Met. Planet. Sci.*, 51, 116- 137. [6] Davis A.M. et al. (1990) Nature, 347, 655-658.