MINERALOGY AND PETROLOGY OF CHONDRULES IN CARBONACEOUS CHONDRITE NWA 770.

S. J. Lawrence[1], A. N. Krot[1], E. R. D. Scott[1], T. E. Bunch[2], and K. Keil[1], [1]Hawai'i Institute of Geophysics and Planetology, SOEST, University of Hawai'i at Manoa, 1680 East-West Rd., Honolulu, HI 96822 , USA (slawrenc@hawaii.edu) [2]Department of Geology, Northern Arizona University, Flagstaff, AZ 86011, USA.

Introduction: The CH (ALH85085-like) chondrites are distinguished by the following characteristics: high abundance of Fe,Ni-metal (~20 vol %), small chondrule sizes (<50-80 μm), high abundance of cryptocrystalline chondrules, low abundance of Ca,Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs), the lack of fine-grained matrix rims around chondrules, CAIs and AOAs, and the presence of heavily hydrated matrix clasts [1]. These unusual characteristics prompted some workers to suggest that CH chondrites were not nebular products, but instead a product of asteroid collisions [2]. More recently, various workers concluded that chondrules, Fe,Ni-metal grains, CAIs, and AOAs in CHs are pristine, unaltered nebular products, and thus provide important new insights about high temperature processes in the solar nebula [3,4].

CH chondrites are part of the CR clan, which also includes the CR (Renazzo-like) and CB (Bencubbin-like) chondrites. The CR clan meteorites share some chemical and isotopic features, including: high abundance and broad compositional range of Fe,Ni-metal grains, large depletion in moderately volatile elements, bulk O-isotopic compositions, and large enrichment in $\delta^{15}N$ [5,6]. The chondritic components of the CH, CR, and CB chondrites, however, have distinct mineralogies, possibly due to different formation mechanisms. Despite their potential importance for understanding nebular processes, CH chondrites remain poorly characterized from a mineralogical and petrological standpoint. Only two CH chondrites, Acfer 182 and ALH85085, have been previously characterized in detail [7-10]. Here, we describe the mineralogy and petrology of chondrules in the recently discovered CH chondrite NWA 770.

Analytical Techniques: A polished thin section of NWA 770 was studied using optical microscopy, backscattered electron (BSE) imaging, X-ray elemental mapping, and electron probe microanalysis (EMPA). X-ray elemental maps in Mg, Ca, and Al Kα with resolutions of 1-10 μm/pixel were acquired using the five wavelength dispersive spectrometers (WDS) of the University of Hawaii's Cameca SX-50 microprobe. The elemental maps were combined using an RGB-color scheme and the ENVI software. Using these maps, chondrules with different textures and compositions were identified. BSE images of these chondrules were obtained with the JEOL JSM-5900LV scanning electron microscope. Electron probe analyses were performed with the Cameca SX-50 microprobe. Bulk compositions of chondrules were measured using a rastered ~15×20 μm beam. Matrix effects were corrected using PAP procedures.

Results: Chondrules in NWA 770 are petrographically diverse and based on their mineralogy, textures, and bulk chemistry can be divided into three major classes: (1) ferromagnesian chondrules, including skeletal olivine (SO), cryptocrystalline (CC), porphyritic olivine (PO), porphyritic olivine pyroxene (POP), and porphyritic pyroxene (PP) chondrules, (2) Al-rich chondrules, including Ca,Al-rich and Na,Al-rich chondrules, and (3) silica-rich chondrules (Table 1).

Ferromagnesian chondrules: The ferromagnesian chondrules can be divided into two categories: (1) small Fe,Ni-metal free SO and CC chondrules, and (2) larger metal-bearing chondrules with PO, POP, and PP textures.

SO chondrules are composed of olivine (Fa_3), Al-rich (9-17 wt% Al_2O_3) low-Ca pyroxene ($Fs_{1.4-2.8}Wo_{0.5-3.4}$), Al-rich (9-13 wt% Al_2O_3) high-Ca ($Fs_{1-3}Wo_{37-45}$) pyroxene, and anorthitic mesostasis. CC chondrules are usually Mg-rich (mg# > 96) and have an olivine-pyroxene normative composition. Both chondrule types are depleted in moderately volatile elements, are metal-free, and display a wide range (0.001-4×CI) of abundances of refractory lithophile elements (Ca, Al, Ti) with SO chondrules enriched in these elements compared to CC chondrules.

Porphyritic chondrules are composed of olivine ($Fa_{1.4}$), low-Ca pyroxene ($Fs_{2.1}Wo_{2.2}$), Fe,Ni-metal nodules, and alkali-bearing (~1-2 wt% Na_2O) glassy or microcrystalline mesostasis. No sulfides have been observed. Most PO and POP chondrules have olivine-rich cores and pyroxene-rich shells; silica-rich igneous rims surround some of the chondrules.

Aluminum-rich chondrules: Two kinds of Al-rich chondrules were identified: Ca,Al-rich and Na,Al-rich.

The Ca,Al-rich chondrules are characterized by a spherical shape and the presence of abundant Al-diopside. These chondrules can be further subdivided into spinel-bearing and spinel-free. The spinel-bearing chondrules consist of Al-diopside, coarse euhedral or subhedral grains of spinel, and minor forsteritic olivine; glassy mesostasis is either absent or very minor. The spinel-free chondrules contain phenocrysts of Al-diopside enclosing skeletal crystals of forsteritic olivine and interstitial mesostasis composed of low-Ca pyroxene intergrown with forsteritic olivine. The Al-diopside chondrules have high Al_2O_3 (7.6-21.8 wt%) and TiO_2 (0.7-2.8 wt%), very low Cr_2O_3 (<0.15 wt%)

and MnO (<0.08 wt%). Al-diopside grains show large variations in Al_2O_3 contents. The spinel is poor in FeO (<0.4 wt%) and TiO_2 (<0.3 wt%), but contains up to 0.8 wt% of Cr_2O_3. Low-Ca pyroxene is very rich in Al_2O_3 (12-13 wt%) and contains no detectable Cr_2O_3 and MnO. Olivine is nearly pure forsterite ($Fa_{0.7}$) and poor in minor elements.

The Na,Al-rich chondrules contain coarse-grained, chemically-zoned pyroxenes composed of a low-Ca pyroxene or pigeonite core and an augite rim, and abundant (> 50 vol%) alkali-rich (~6-9 wt% Na_2O, ~0.1-0.7 wt% K_2O), glassy mesostasis.

Silica-rich chondrules: The silica-rich chondrules are composed of silica (quartz and/or cristobalite) and a glassy, pyroxene-normative phase.

Discussion: Chondrules in CR chondrites are predominantly magnesian and Fe,Ni-metal-rich; they typically have porphyritic textures and are often surrounded by silica-rich igneous rims. Chondrules in CB chondrites are magnesium-rich and Fe,Ni-metal-free; they have exclusively CC and SO textures. The diverse array of chondrules in NWA 770 includes chondrules that are similar to both the CR and the CB chondrule populations, suggesting that the CH chondrites are genetically related to the CR and CB chondrites and accreted well-mixed populations of the CR- and CB-like chondrules.

The SO and CC chondrules in CH chondrites are very similar to those in CB chondrites, suggesting a similar formation mechanism. The lack of relict grains and igneous rims associated with these chondrules suggests that it was probably a single-stage formation mechanism: either direct gas-liquid condensation from an elevated temperature nebular region that had already undergone evaporation, or prolonged heating of the gas-solid condensates above their liquidus temperatures, destroying all solid nuclei [11]. In contrast, Type I PO, POP, and PP chondrules in NWA 770 must have resulted from incomplete melting of solid precursors. Since the silica-rich bulk compositions of the silica-rich and the pyroxene-rich chondrules cannot be produced by equilibrium condensation from a gas of solar composition, a large degree of Si/Mg fractionation prior to or during the chondrule formation process is required [12]. The silica-rich rims in NWA 770 suggest a high temperature formation, involving either gas-solid condensation of silica-rich materials onto chondrules followed by subsequent melting [13] or direct SiO gas condensation into chondrule melts [14]. This is similar to the two-step process for silica-rich chondrule formation postulated by [15]: (1) fractional condensation of forsterite, enstatite, and SiO_2-rich phases in the solar nebula (which would form the CC/SO chondrules) followed by (2) reheating of the SiO_2-rich components to high temperatures (>1968 K).

References: [1] Greshake et al. (2002) *MAPS, 37*, 281. [2] Wasson J. T. and Kallemeyn G. W. (1990), *EPSL, 91*, 19. [3] Meibom et al. (1999) *JGR, 104*, 22053. [4] Krot et al. (2000) *LPS, XXXI,* #1481. [5] Weisberg et al., *Proc. NIPR SAM, 8,* 11. [6] Krot et al. (2002) *MAPS, 37*, 1451. [7] Scott E. R. D. (1988) *EPSL, 91*, 1. [8] Weisberg et al. (1988) *EPSL, 91*, 19. [9] Grossman et al. (1988), *EPSL, 91*, 33. [10] Bischoff et al. (1993) *GCA, 57*, 2631. [11] Krot et al. (2001) *Science, 291*, 1776-1779 [12] Ebel D. and Grossman L. (2000) *GCA, 64*, 339. [13] Krot et al. (2003) *LPS, XXXIV*, # 1451. [14] Tissandier et al. (2002) *MAPS, 37*, 1377. [15] Hezel et al. (2002), *MAPS, 37*, A63.

Table 1. Representative bulk compositions of chondrules in NWA 770.

type	SO	CC	PO	POP	POP	PP
chd#	#4-1	#3-15	#4-2	#4-8	#1-12	#2-21
SiO_2	48.6	54.8	44.9	41.3	45.3	51.7
TiO_2	0.33	0.06	0.26	0.17	0.16	0.92
Al_2O_3	8.1	1.0	6.5	5.4	3.6	8.3
Cr_2O_3	0.50	0.70	0.35	0.51	0.43	0.50
FeO	2.7	0.29	2.8	10.0	1.8	5.8
MnO	<0.08	<0.08	0.11	0.20	0.10	0.15
MgO	33.5	42.1	40.8	39.4	46.0	21.3
CaO	6.1	0.90	3.8	2.9	2.1	10.9
Na_2O	<0.06	<0.06	0.61	0.10	0.48	0.34
K_2O	<0.04	<0.04	0.04	0.03	0.10	<0.04

type	Ca,Al	Ca,Al	Na,Al	Na,Al	Sil
chd#	#3-31	#2-28	#2-X	#3-32	#4-53
SiO_2	7.7	49.4	54.3	59.0	58.6
TiO_2	3.3	0.90	0.33	0.45	0.11
Al_2O_3	60.5	19.6	9.1	16.0	1.6
Cr_2O_3	<0.06	0.72	0.37	0.34	0.71
FeO	1.1	3.4	13.2	2.9	6.1
MnO	<0.08	0.13	0.32	0.09	31.6
MgO	0.24	9.8	12.0	7.4	0.07
CaO	27.0	16.0	6.4	6.7	1.2
Na_2O	<0.06	0.06	3.87	6.48	<0.06
K_2O	<0.04	<0.04	0.19	0.53	<0.04

Key: SO = skeletal olivine; CC = cryptocrystalline; PO = porphyritic olivine; POP = porphyritic olivine-pyroxene; PP = porphyritic pyroxene; Ca,Al = Ca,Al--rich; Na,Al = Na,Al-rich; Sil = silica-rich.