**GEOLOGICAL CONTEXT OF ORDINARY CHONDRITE IMPACT MELT NWA 4150.**
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**Introduction:** Chondritic impact melts provide information about the collisional histories of their parent asteroids. The connection of radioisotopic ages with petrological constraints for these impact events were previously used to reconstruct the evolution of the HED, H, L, and LL chondrite parent asteroids [1-4]. Northwest Africa (NWA) 4150, a 436 g meteorite was classified as a H/L6 melt rock. It was assigned weathering grade of W0/1, and its olivine and low-Ca pyroxene have average compositions of $Fa_{24.1}$ and $Fs_{19.9}$, respectively [5]. We explore the petrology of NWA 4150 with the aim of revealing additional details about the collisional evolution of the inner solar system.

**Results:** *General Petrography:* Our thin section of NWA 4150 has maximum sample dimensions of 12.3 x 5.8 mm and an area of 48.4 $mm^2$ (Fig. 1). It is dominated by light-colored lithic fragments that are embedded in an aphanitic, dark interstitial matrix. Twenty-seven chondrules, most of which are fragments, were identified: 12 radial pyroxene (RP), 4 barred olivine (BO), 3 microcrystalline pyroxene (MP), 2 porphyritic olivine (PO), 3 porphyritic pyroxene (PP), and 3 porphyritic olivine pyroxene (POP) chondrules (Fig. 1). Their longest dimensions average 0.67 mm, which is similar to the mean diameter of 0.7 mm for L-chondrite chondrules [6]. However, these chondrules only account for 13% of the thin section area of NWA 4150 in contrast to typical chondrule abundances of 60-80 vol.% in ordinary chondrites [6]. Some chondrules have a mesostasis that crystallized ~10 µm-size laths of pyroxene in isotropic glass. This suggests a quenched melt or reheating unrelated to endogenous thermal metamorphism on its parent asteroid. In addition, microcrystalline chondrule fragments are present, and, together with the generally excellent state of preservation of most chondrules, make the assignment of petrological type 6 for NWA 4150 questionable [7].

*Shock Petrography:* The aphanitic matrix is an impact melt that crystallized olivine and zoned low-Ca pyroxene as ~5 µm crystals. Locally, euhedral and compositionally zoned olivine and pyroxene crystals grew from the melt to sizes of tens of µm. The assemblage is complemented by abundant rounded metal and sulfide particles that are typically <1 µm, but also comprise up to ~500 µm metal-sulfide aggregates. Moreover, rare, anhedral ~5-25 µm apatite and merrillite crystals occur in the crystallized impact melt.

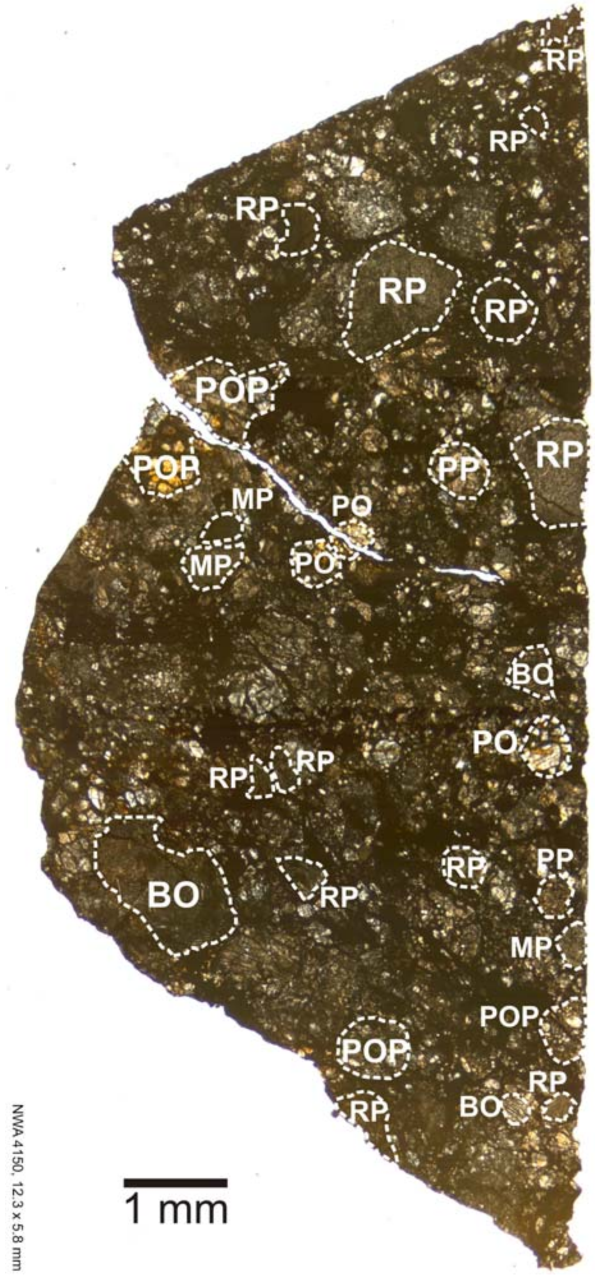


*Figure 1. Plane-polarized light mosaic of NWA 4150. Dark domains are mostly melt, metal and sulfide. Chondrule fragments are outlined by white, striped lines: BO-barred olivine, MP-microcrystalline pyroxene, PO-porphyritic olivine, POP-porphyritic olivine pyroxene, PP-porphyritic pyroxene, RP-radial pyroxene.*

Feldspathic domains are present in the impact melt, but their small size of ~5 µm prohibited quantification of their compositions. Larger, >10 µm feldspathic domains in chondrule fragments sometimes show recrystallization features with intergrowths of pyroxene laths. No maskelynite was recognized optically, but chondrule fragments display all stages of shock metamorphism, including strong, undulous extinction, planar fractures, intense mosaicism, and brown coloration of olivine. Pyroxene frequently shows mechanical twinning and planar fractures.

*Modal Composition:* Point counting of 2053 points under reflected light yield an abundance of 4.6 vol.% metal, 6.3 vol% sulfide, 84.4 vol% silicates, 3.7 vol% limonite, 0.5 vol% spinel and 0.5 vol% voids. The metal abundance is a good match to the mean metal abundance in L-chondrites of 5 vol% [6]. Eighty-one vol% of silicates occur as lithic clasts, such as chondrules, while 19 vol% are constituents of a dark, aphanitic impact melt. This is a minimum amount of melt, because a significant proportion of the sulphide and metal in NWA 4150 also belongs to this impact melt. Frequently, such metal-troilite aggregates are at least in part oxidized.

*Microprobe Data:* Olivine ($Fa_{22-25}$, n=88) compositions fall in the typical range of L-chondrites [6]. No statistically significant difference between olivine in lithic clasts and that crystallized from the impact melt is apparent. Low-Ca pyroxene in lithic clasts exhibits compositions of $Fs_{19-21}$ (n=25), which is within the typical range of $Fs_{19-22}$ for L-chondrites. Low-Ca pyroxene in the melt is very variable in composition ($En_{77-90}$ $Fs_{9-21}$ $Wo_{0.6-4.6}$; n=32), reflecting an unequilibrated nature as zoned crystals that rapidly grew from the impact melt. High-Ca pyroxene (three diopsides, $En_{47-48}$ $Fs_{7-8}$ $Wo_{44-46}$, and three pigeonites, $En_{74-79}$ $Fs_{11-16}$ $Wo_{9-11}$) is rare, but is associated with crystallized chondrule glass in BO and RP chondrules. Feldspar exhibits compositions similar to those in equilibrated ordinary chondrites ($Ab_{80-86}$ $An_{10-16}$ $Or_{4-6}$, n=11) [6]. However, most analyses indicate variable compositions of a feldspathic mesostasis that is associated with chondrules and impact melt. Troilite has an average Ni content of 0.19 wt% (n=9), which suggests rapid quenching [8]. It is associated with Fe-Ni metal that is P-undersaturated (avg. P=0.07 wt.%). The dominant metal phase is martensite with an average Ni concentration of 13.7 wt% and a range of 7.58 to 26.04 wt% Ni (n=182). Kamacite is a minor metal phase, which crystallized 2 to 20 µm wide rims around metal particles. Co concentrations between 0.7 and 0.9 wt% (n=14) in the kamacite are typical for L-chondrites [9]. One metal analysis with 45 wt% Ni and 6.12 wt% S could have captured a thin tetrataenite domain.

*Metallographic Cooling:* Using the P-free phase diagram of [10], the Ni-diffusion coefficient of [11], and the method of [8], the metallographic cooling rate through the temperature interval of ~700 to 400 °C was determined for 6 lines through 4 metal particles that crystallized secondary kamacite. From these calculations, an average cooling rate on the order of 0.05 °C/a (1.06 x $10^{-9}$ °C/sec) is estimated.

**Discussion:** Pending oxygen isotope analytic evidence that is underway, it seems unlikely that NWA 4150 represents an intermediate H/L-chondrite as is currently suggested [5]. Most chemical data is consistent with a L-chondrite composition except some aberrant, compositionally- zoned low-Ca pyroxene, which crystallized from the impact melt. Thus, NWA 4150 appears to be a clast-rich L-chondrite impact melt rock. Surviving lithic clasts suggest it mainly formed from L3-L4 petrologic grade material [7]. Its metallographic cooling rate falls between the cooling rates of the L5 Farmington and L6 Wickenburg meteorites as determined by [8]. It is also similar to the cooling rate of the Cat Mountain L5 impact melt breccia [12]. However, metal particles in NWA 4150 have a striking morphological similarity to the metal particles in L6 Wickenburg [Fig. 1 in 8]. Following the diffusional heat loss considerations of these authors, a burial depth for Wickenburg, and, thus, for NWA 4150, on the order of 1 km corresponds to the metallographic cooling rate. Moreover, such deep burial suggests location in a thick breccia lens in a crater on the L-chondrite parent asteroid [4]. Assuming NWA 4150 was part of a thick breccia lens in a simple crater on the L-chondrite asteroid, scaling relationships [13] and observations of [14] on small asteroids imply a crater diameter on the order of 5 to 7 km. Interestingly, both Farmington and Wickenburg have Ar-Ar degassing ages of ~0.5 Ga [15], while Cat Mountain exhibits a distinctly different texture and age for a melting event at 0.88 Ga [12]. A K-Ar experiment is underway to test the chronological setting of the impact event that produced NWA 4150 and the circumstances of its delivery to Earth.

**References:** [1] Anders (1978), *NASA Conf. Pub. 2053*, 57-75. [2] Bogard (1995), *MAPS 30*, 244-268. [3] Swindle et al. (2009), *MAPS 44*, 747-762. [4] Wittmann et al. (2010), *JGR 115*, E07009. [5] Connolly et al. (2006) *MAPS 41*, 1383-1418. [6] Brearley & Jones (1998) *Rev. Min. 36*, 398 p. [7] Van Schmus & Wood (1967) *GCA 31*, 747-765. [8] Smith & Goldstein (1977), *GCA 41*, 1061-1072. [9] Rubin (1990) *GCA 54*, 1217-1232. [10] Yang et al. (1996), *J. Phase Equilibria 17*, 522–531. [11] Hopfe & Goldstein (2001), *MAPS 36*, 135-154. [12] Kring et al. (1996), *JGR 101*, 29353-29371. [13] Grieve (1987), *Ann. Rev. Earth Planet. Sci. 15*, 245-270. [14] Sullivan et al. (1996), *Icarus 120*, 119-139. [15] Bogard (1980), *GCA 44*, 1667-1682.