EARLY IMPACT EVENTS ON ORDINARY-CHONDRITE PARENT ASTEROIDS: INSIGHTS FROM NORTHWEST AFRICA (NWA) 11004, A TYPE-7 BRECCIA.

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Introduction: Early in Solar-System history, the impact flux was high in the asteroid belt. This was also the period when asteroids may have been heated to metamorphic temperatures by the decay of ^{26}Al. Asteroidal meteorites likely experienced complex interactions involving radiogenic thermal metamorphism and collisional heating. Here, we combine the results of U–Pb dating of Ca-phosphate with petrographic and geochemical studies of a type-7 OC breccia, Northwest Africa (NWA) 11004, to provide insights into the complex petrogenetic processes of the early Solar System.

Classification: NWA 11004 was classified in the Meteoritical Bulletin as an L7 chondrite, but our data show that it is either LL7 or L/LL7. Although olivine ($Fa_{25.4\pm0.3}$; n=17) and orthopyroxene (opx) ($Fs_{21.2\pm0.1}$; n=21) compositions are in the L range, the mean O-isotopic (δ^{17}O=3.77‰; δ^{18}O=5.39‰), kamacite (3.2–4.2 wt.% Co; 4.6–5.3 wt.% Ni) and taenite (0.6–1.8 wt.% Co) compositions are well within the LL range. The high opx CaO content (~1.8 wt.%), paucity of chondrules, and large plagioclase grains (50–500 μm) are consistent with petrologic type 7.

Petrography: NWA 11004 is a medium-grained, partly brecciated, highly recrystallized rock. A few recrystallized patches could be relict porphyritic chondrules. The opx grains are very large (typically 3–5 mm) and exhibit undulose to weak mosaic extinction; they have poikilitic or poikiloblastic textures and enclose smaller (~100–500 μm) olivine grains with sharp optical extinction (Fig. 1a). A few coarse olivine grains outside the large opx grains are penetrated by ~100-μm-wide recrystallized impact-melt veins (Fig. 1b). NWA 11004 has low modal abundances of plagioclase (~5.0 vol.%), troilite (~0.6 vol.%) and, possibly, metallic Fe-Ni (~1.8 vol.%) relative to mean LL chondrites (~10 vol.%, 5 vol.% and 2 vol.%, respectively [1]). Some coarse troilite grains are polycrystalline with ~20-μm-wide domains (Fig. 1c). There are opaque assemblages consisting of small, irregular troilite grains within metallic Fe-Ni (Fig. 1d). A few silicate-rich veinlets containing tiny angular grains of metallic Fe-Ni also occur. Ca-phosphate grains (50–300 μm) are anhedral to subhedral; they commonly are associated with metallic Fe–Ni, troilite and plagioclase.

Trace element chemistry: Compared to typical equilibrated ordinary chondrites, the silicates in NWA 11004 have similar REE patterns, but lower REE contents (Fig. 2a-d). Ca-phosphate grains in NWA 11004 show negative slopes (with HREE depletions) and pronounced negative Eu anomalies (Fig. 2e-f). The calculated bulk REE abundances in NWA 11004 (based on individual mineral REE concentrations and modal abundances) are much lower than in typical LL chondrites.

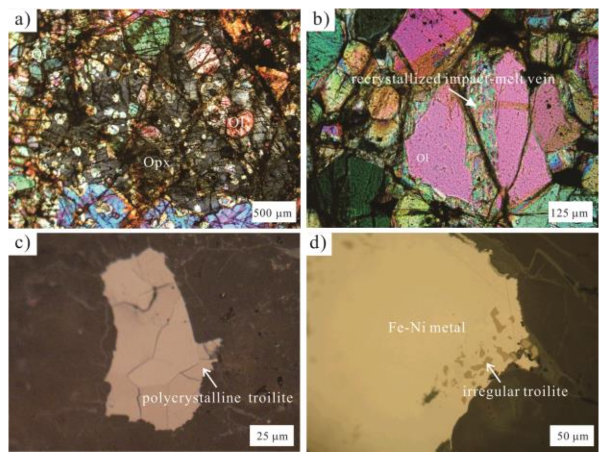

Figure 1. (a) Poikilitic opx enclosing olivine. (b) Olivine penetrated by a recrystallized impact-melt vein. (c) Polycrystalline troilite grain. (d) Irregular troilite grains within metallic Fe-Ni.

Ca-phosphate ages: Fifteen analyses were conducted on eight Ca-phosphate grains in NWA 11004. With the assumption that all the common Pb was introduced from primordial Pb, the intercept age is 4544±37 Ma (MSWD=0.52) in a Tera-Wasserburg diagram; the weighted average ^{207}Pb/^{206}Pb age (corrected) is 4546±34 Ma (MSWD=0.51; Fig. 3). This latter value is considered the best estimate of the sample age.

Two-pyroxene thermometry: The two-pyroxene thermometer [2] yields an equilibration temperature of ~1060°C.

Metallographic cooling rate: The metallographic cooling rate, evaluated by measuring the central Ni concentrations of taenite grains and distances to the nearest grain boundary [3], shows that NWA 11004 cooled at a rate of ~0.5–4°C/Ma at ~500°C (Fig. 4).

Petrogenesis: We examined thin sections of 75 L6 and LL6 chondrites and found no poikilitic pyroxene grains with sizes >1.5 mm. However, large poikilitic pyroxene grains occur in some acapulcoites (e.g., Northwest Africa 2627) [4], suggesting that the large poikilitic opx grains in NWA 11004 formed from extreme recrystallization (equivalent to type 7) or from minor-to-moderate melting. The occurrence of a few impact-melt veins within relict olivine grains and the possible presence of some relict chondrules indicate that NWA 11004 was partly melted, consistent with its equilibrium temperature of ~1060°C. This impact melting event is also responsible for (a) the loss of some plagioclase and troilite (and probably some metallic Fe-Ni) and (b) the low REE contents of silicate and Ca-phosphate grains that crystallized from the residual melt. If NWA 11004 is an LL chondrite, its low Fa and Fs values suggest it suffered moderate reduction at this time.

The coarse opx grains in NWA 11004 exhibit undulose to weak mosaicism extinction, corresponding to shock stage S2-S4 [5] and pointing to a second, late-stage shock event that occurred after the opx formed. This second shock event also produced polycrystalline troilite (S4–S5) [6], small irregular troilite grains within metallic Fe–Ni (S3–S6) [7] and veinlets with tiny metallic Fe-Ni grains (≥S3) [8]. The second shock event thus corresponded roughly to shock stage S4. However, the sharp optical extinction of the olivine grains (S1) indicates a period of post-shock annealing.

Diffusion calculations show it would take ~3–9 times longer for olivine grains (r=200 μm) to reach equilibrium than Ca-phosphate grains (r=75 μm) (diffusion coefficients from [9,10]) at 500–900°C. Because the olivine was annealed (as indicated by sharp optical extinction), the Ca-phosphate must also have been annealed. Thus, the Ca-phosphate $^{207}Pb/^{206}Pb$ age of 4546 Ma dates the second shock event.

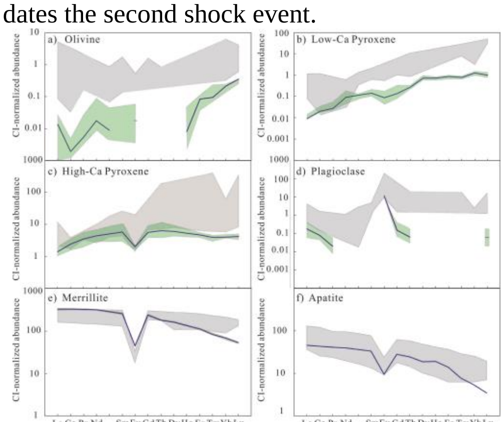

Figure 2. REE patterns of silicates and Ca-phosphates. The gray-shaded areas represent mineral REE patterns from typical equilibrated ordinary chondrites [11-14]; the green-shaded areas represent mineral REE ranges of NWA 11004; blue solid lines represent the average.

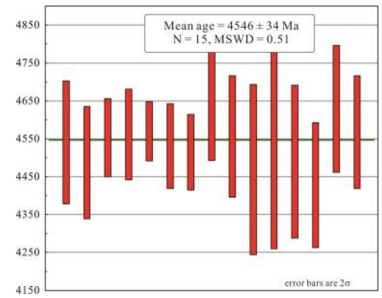

Figure 3. Weighted avg Ca-phosphate $^{207}Pb/^{206}Pb$ age.

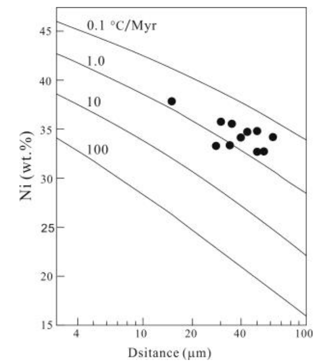

Figure 4. Metallographic cooling rate of NWA 11004.

Formation setting: Because diffusion in metallic Fe-Ni is relatively rapid, the metallographic cooling rate (~0.5–4°C/Ma at ~500°C) applies to the second shock-heating event and indicates that the rock was buried deep within its parent body. This depth can be estimated by making assumptions about the physical and thermal conditions on the parent asteroid and the thermal diffusivity of the crust [15]. If we assume a thermal diffusivity of 10^{-4} cm^2/s (comparable to that of the lunar regolith), we find that NWA 11004 was at a depth of 7–10 km. If the parent asteroid were porous, impacts could have caused the pores to collapse beneath the resultant crater, significantly heating local material. Rocks at this site would cool slowly.

References: [1] Hutchison R. *Meteorites*, Cambridge Univ. Press, 506 pp. [2] Kretz R. (1997) *GCA*, *46*, 411–421. [3] Willis J. and Goldstein J.I. (1981) *LPS XII*, 1135–1143. [4] Keil K. and McCoy T.J. (2018) *Chemie der Erde*, *78*, 153–203. [5] Rubin A.E. et al. (1997) *GCA*, *61*, 847–858. [6] Schmitt R.T. et al. (1993) *Meteoritics*, *28*, 431-432. [7] Rubin A.E. (1994) *Meteoritics*, *29*, 93-98. [8] Stöffler D. et al. (1991) *GCA*, *55*, 3845–3867. [9] Cherniak D.J. et al. (1991) *GCA*, *55*, 1663–1673. [10] Chakraborty S. (2010) *Rev. Mineral. Geochem.*, *72*, 603–639. [11] Allen R. and Mason B. (1973) *GCA*, *37*, 1435-1456. [12] Curtis D. B. and Schmitt R.A. (1979) *GCA*, *43*, 1091-1103. [13] Ward D. et al. (2017) *AM*, *102*, 1865-1880. [14] Crozaz G. et al. (1989) *EPSL*, *93*, 157-169. [15] Rubin A.E. et al. (1981) *GCA*, *45*, 2213–2228.