

DEGREE OF AQUEOUS ALTERATION IN CM2 PARIS AND THE PETROGRAPHY OF ITS REFRACTORY AND AMOEBOID OLIVINE INCLUSIONS. Alan E. Rubin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90095-1567, USA (aerubin@ucla.edu).

Introduction: A widely used aqueous-alteration scale for CM chondrites [1] ranges from subtype 2.0 (highly altered rocks, equivalent to CM1, e.g., MET 01070) to 2.6 (moderately altered rocks, e.g., QUE 97990). Petrologic changes occurring during alteration from subtype 2.6 to 2.0 include complete alteration of mafic silicate grains, a decrease in metallic Fe-Ni from ~1 to ≤ 0.02 vol.%, a decrease in the abundance of coarse clumps of PCP (“poorly characterized phases” identified as cronstedtite-tochilinite intergrowths [2,3]) from 15-40 to 2-5 vol.%, a decrease in “FeO”/SiO₂ in PCP from 2.0-3.3 to 1.0-1.7 (wherein “FeO” includes FeO in phyllosilicates and Fe²⁺ in sulfide calculated as FeO), a decrease in S/SiO₂ in PCP from 0.18-0.35 to 0.05-0.09, a change in sulfide mineralogy from pyrrhotite plus pentlandite to pentlandite plus intermediate sulfide (i.e., grains with Ni/(Fe+Ni) between 0.10 and 0.40), and a change in carbonate mineralogy from Ca carbonate alone to Ca carbonate associated with more-complex carbonates containing Ca, Mg, Mn and Fe.

Degree of Aqueous Alteration: Examination of the Paris chondrite allows the extrapolation of these classificatory criteria to subtype 2.7. Such rocks should contain altered chondrule mesostases, abundant matrix phyllosilicates, 1-2 vol.% metallic Fe-Ni, unaltered mafic silicate grains, ~5-25(?) vol.% PCP clumps with “FeO”/SiO₂ of 4.0-6.0 and S/SiO₂ of 0.40-0.60, sulfide consisting of pyrrhotite and pentlandite, and Ca carbonate being the only carbonate phase.

Hypothetical CM3.0 chondrites should contain somewhat more metallic Fe-Ni (probably 2-5 vol.%), no PCP, unaltered chondrule mesostases (some containing clear isotropic glass), little Ca carbonate and pentlandite, and only minor matrix phyllosilicates. Because significant changes occur during the early stages of parent-body aqueous alteration [1], the distinguishing textural and compositional characteristics of subtype 2.9 and 2.8 CM chondrites cannot be determined before examining actual samples.

Paris is the first CM2.7 chondrite. It contains well-defined chondrules, unaltered mafic silicate grains, 1.2 vol.% metallic Fe-Ni (3217 points; 100-mm² area), Ca carbonate as the sole carbonate phase, sulfide consisting exclusively of pyrrhotite and pentlandite, and 12±3 vol.% PCP with “FeO”/SiO₂ = 5.6 and S/SiO₂ = 0.54. As in the CM2.0-2.6 chondrites, the matrix of Paris is rich in phyllosilicates and its chondrule mesostases have been altered to phyllosilicate.

CAIs: X-ray mapping of a 9×12-mm portion of a thin section of Paris revealed the presence of 37 CAIs, ranging in size from 30 to 450 μm. These CAIs are very similar to those in CM2.6 QUE 97990 [4]: e.g., the mean size of the QUE 97990 CAIs is 130±90 μm (n=40), whereas that of the Paris CAIs is 130±80 μm (n=37); hibonite-bearing inclusions are the least abundant variety in both meteorites; and the mineral chemistry of the CAIs in both meteorites is similar. Nevertheless, CAIs appear to be more abundant in QUE 97990 (1.8 vol.%) than in Paris (0.76 vol.); in addition, QUE 97990 contains ~50 largely intact refractory inclusions/cm², whereas Paris contains ~25.

The combined set of 77 CAIs in Paris and QUE 97990 (the two least-altered CM chondrites known) includes 27% spinel-pyroxene inclusions (mostly intact objects), 20% spinel inclusions (typically, distended fragments), 13% spinel-pyroxene-olivine inclusions (mainly intact), 27% pyroxene inclusions (mainly intact), 8% pyroxene-olivine inclusions (both intact objects and fragments), and 5% hibonite-bearing inclusions (mainly intact).

Most of the hibonite-bearing inclusions also contain spinel; e.g., Paris inclusion #16 contains hibonite, spinel and diopside. The diopside in inclusion #16 is somewhat poorer in Al₂O₃ than the average diopside from other Paris CAIs (2.5 vs. 3.7 wt.%). This is probably due to the preferential partitioning of Al into hibonite. (Hibonite in inclusion #16 contains 81.5 wt.% Al₂O₃.)

Absence of Melilite: None of the CAIs in QUE 97990 or Paris contains melilite, but the vast majority of these CAIs contain appreciable phyllosilicate. In many cases, phyllosilicate could have replaced primary melilite during parent-body aqueous alteration. Although melilite is abundant in refractory inclusions from unaltered carbonaceous chondrites [e.g., 5-8], it is highly susceptible to alteration [9]. For example, in CO3 chondrites that have experienced moderate hydrothermal alteration (e.g., CO3.5 Lancé), melilite was replaced by feldspathoids, diopside and sulfide [8]. In Fluffy Type-A inclusions in CV3 Allende, most grains of primary melilite were replaced by fine-grained secondary phases including anorthite, nepheline, grossular and sodalite [10].

The paucity of melilite in CAIs from CM2.0-2.7 chondrites is probably due to parent-body alteration [4], not to peculiar conditions in the solar nebula [e.g.,

5, 11-13]. If any CM2.9-3.0 chondrites are eventually recovered, it seems likely that they will contain abundant melilite-bearing CAIs.

Compound Objects: Two pyroxene inclusions from Paris (#26 and #45) are compound CAI-chondrule objects rich in phyllosilicate. Inclusion #26 (350×540 μm) encloses a 165×270-μm low-FeO porphyritic-pyroxene (Type IB) chondrule (Fs1.7Wo2.3) containing ~15-vol.% rounded 2-24-μm metallic Fe-Ni blebs; the chondrule is partially surrounded by a 14-μm-thick Ca-pyroxene rim (Fs1.5Wo31.8). Inclusion #45 (220×290 μm) comprises a fine-grained 50-60-μm-thick symmetric rim around a 115×160-μm low-FeO porphyritic pyroxene-olivine (Type IAB) chondrule (Fs1.1Wo0.95; Fa0.92) containing ~5-vol.% rounded 2-13-μm metallic Fe-Ni blebs.

Compound chondrule-CAI objects that have been reported previously in carbonaceous chondrites include CAIs enclosing chondrules [14] and chondrules enclosing CAIs [15]. The dearth of compound chondrule-CAI objects strongly suggests that chondrules and CAIs formed separately [e.g., 16], consistent with their apparent difference in formation age [17-19] and distinct bulk chemical [20,21] and O-isotopic [22] compositions.

Nevertheless, the fact that some compound chondrule-CAI objects exist indicates that transient heating events occurred in the solar nebula after chondrules and CAIs were admixed, i.e., during the epoch of chondrule formation. Analogous to the case for enveloping compound chondrules, Paris inclusion #45 and its congeners may have formed after solidified ferromagnesian chondrules were incorporated into porous CAI-fragment-laden dustballs that were heated insufficiently to remelt the enclosed chondrules.

Aluminum-rich chondrules [23], plagioclase-rich chondrules [24] and the refractory-lithophile-rich chemical component inferred within normal ferromagnesian chondrules [25-27] may have resulted from compound chondrule-CAI objects in which the CAI fragment was largely to completely melted during one or more chondrule heating events [24].

AOIs: The x-ray-mapped region of Paris includes four 240-640-μm amoeboid olivine inclusions (AOIs) averaging 400±180 μm. This is somewhat larger than the mean AOI size of 225 μm previously estimated for CM chondrites [28]. Although the number density of AOIs in Paris is only ~4/cm², these relatively large objects constitute 0.65 vol.% of the whole rock, not much lower than that of Paris CAIs (0.76 vol.%).

The Paris AOIs contain abundant 5-110-μm-size grains of forsterite (Fa0.34) enclosing minor 3-70-μm-size wormy patches containing diopside (Fs0.85

Wo50.2, averaging 5.9 wt.% Al₂O₃) and accessory Al-rich diopside (Fs0.75Wo50.7, averaging 11.6 wt.% Al₂O₃). Interior portions of the AOIs are porous and rimmed by relatively coarse forsterite.

The Paris AOIs texturally resemble those in CV and CK chondrites [28-30]. The AOIs may all have formed in the solar nebula via transient heating of precursors consisting of porous forsteritic rims surrounding fine-grained rimless diopside-rich CAIs [28].

References: [1] Rubin A. E. et al. (2007) *Geochim. Cosmochim. Acta*, 71, 2361-2382. [2] Zolensky M. E. (1984) *Meteoritics*, 19, 346-347. [3] Tomeoka K. and Buseck P. R. *Geochim. Cosmochim. Acta*, 49, 2149-2163. [4] Rubin A. E. (2007) *Meteoritics & Planet. Sci.*, 42, 1711-1726. [5] Weber D. (1995) *Meteoritics*, 30, 595-596. [6] Weber D. and Bischoff A. (1997) *Chemie der Erde*, 57, 1-24. [7] Kojima T. et al. (1995) *Proc. NIPR Symp. Antarct. Meteorites*, 8, 79-96. [8] Russell S. S. et al. (1998) *Geochim. Cosmochim. Acta*, 62, 689-714. [9] Nomura K. and Miyamoto M. (1998) *Geochim. Cosmochim. Acta*, 62, 3575-3588. [10] MacPherson G. J. and Grossman L. (1984) *Geochim. Cosmochim. Acta*, 48, 29-46. [11] MacPherson G. J. and Davis A. M. (1994) *Geochim. Cosmochim. Acta*, 58, 5599-5625. [12] Wood J. A. (2004) *Geochim. Cosmochim. Acta*, 68, 4007-4021. [13] Petaev M. I. et al. (2005) *Lunar Planet. Sci. XXXVI*, abstract #1238. [14] Itoh S. and Yurimoto H. (2003) *Nature*, 423, 728-731. [15] Misawa K. and Fujita T. (1994) *Nature*, 368, 723-726. [16] Krot A. N. et al. (2002) *Geochim. Cosmochim. Acta*, 68, 2167-2184. [17] MacPherson G. J. et al. (1995) *Meteoritics*, 30, 365-386. [18] Kita N. T. et al. (2000) *Geochim. Cosmochim. Acta*, 64, 3913-3922. [19] Amelin Y. et al. (2002) *Science*, 294, 1678-1683. [20] Jones R. H. et al. (2005) in *Chondrites and the Protoplanetary Disk*, pp. 251-285, (ed. Krot A. N. et al.), Astronomical Society of the Pacific, San Francisco. [21] Grossman L. et al. (2008) *Geochim. Cosmochim. Acta*, 72, 3001-3021. [22] Yurimoto Y. et al. (2008) in *Reviews in Mineralogy and Geochemistry*, 68, 141-186, (ed. MacPherson G. J.). [23] Krot A. N. and Keil K. (2002) *Meteorit. Planet. Sci.*, 37, 91-111. [24] Krot A. N. et al. (2002) *Meteorit. Planet. Sci.*, 37, 155-182. [25] Grossman J. N. and Wasson J. T. (1983) *Geochim. Cosmochim. Acta*, 47, 759-771. [26] Misawa K. and Nakamura N. (1996) in *Chondrules and the Protoplanetary Disk*, pp. 99-105, (ed. Hewins R. H. et al.), Cambridge University Press, Cambridge. [27] Grossman J. N. et al. (1985) *Geochim. Cosmochim. Acta*, 49, 1781-1795. [28] Rubin A. E. (2013) *Meteoritics & Planet. Sci.*, 48, 432-441. [29] Grossman L. and Steele I. M. (1976) *Geochim. Cosmochim. Acta*, 40, 149-155. [30] Kornacki A. and Wood J. A. (1984) *Proc. Lunar Planet. Sci. Conf.*, 14th, B573-B587.