

**THE AMPHIBOLE-PHLOGOPITE R-CHONDRITE LAP 04840: HOT HYDRATION BY HEAVY H<sub>2</sub>O.** A. H. Treiman<sup>1</sup>, C. M. O'D. Alexander<sup>2</sup>, E. J. Essene<sup>3</sup>, and M. C. McCanta<sup>1,4</sup>. <sup>1</sup>Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058 <treiman@lpi.usra.edu>. <sup>2</sup>DTM, Carnegie Institution, 5241 Broad Branch Rd., Washington DC. 20015. <sup>3</sup>Dept. Geological Sciences, Univ. Michigan, Ann Arbor, MI 48109. <sup>4</sup>Geology Dept., Pomona College, 609 College Ave., Claremont CA 91711.

**Introduction:** The R chondrite meteorite LAP 04840 contains abundant amphibole and biotite – water-bearing minerals not previously reported in a chondrite. The amphibole and biotite are nearly pure hydroxyl species. Minerals in LAP have homogeneous mineral compositions, and mineral equilibria suggest equilibration at ~650°C, P(H<sub>2</sub>O) between 100 and 700 bars, and  $f(O_2) \approx QFM$ . Hydrogen in the amphibole is so heavy,  $\delta D \sim +3660\%$ , as to be inconsistent with most H reservoirs except that macromolecular carbon in chondrites. LAP's water could possibly derive from oxidation of such macromolecular carbon, mixed by impact into LAP's parent asteroid.

**The Meteorite:** LAP 04840 is an R chondrite by oxidation state and oxygen isotopes [1], and contains chondrules in a fine-grained granulitic-textured matrix [2,3]. Minerals are of constant compositions: olivine (Fo<sub>62</sub>), opx (En<sub>60</sub>Wo<sub>01</sub>), plagioclase (Ab<sub>90</sub>Or<sub>03</sub>), magnetite (Mt<sub>63</sub>Chr<sub>28</sub>Sp<sub>05</sub>Usp<sub>04</sub>), hornblende amphibole (K<sub>0.04</sub>Na<sub>0.33</sub>)(Ca<sub>1.52</sub>Na<sub>0.48</sub>)(Mg<sub>3.60</sub>Fe<sub>1.27</sub>Mn<sub>0.01</sub>Ti<sub>0.04</sub>Cr<sub>0.08</sub>)(Si<sub>6.95</sub>Al<sub>1.02</sub>Fe<sub>0.03</sub>)O<sub>22</sub>(OH<sub>1.93</sub>F<sub>0.04</sub>Cl<sub>0.01</sub>O<sub>0.02</sub>), phlogopite mica, apatite, pyrrhotite & pentlandite [2,4,5]. Amphibole and biotite are widely distributed; in chondrules, they are most abundant among euhedral olivine and opx crystals (Fig. 1; i.e., what would have been mesostasis).

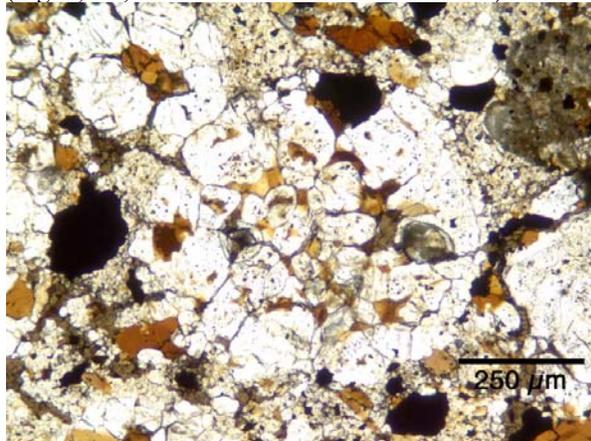


Figure 1. A porphyritic olivine chondrule in LAP, plane polarized light. Most clear grains are olivine; amphibole and biotite are brown; magnetite and sulfide are black. Note amphibole and biotite among olivine subhedra in the chondrule. See [4].

**Metamorphism:** Physical and chemical conditions during LAP's equilibration can be constrained by metamorphic mineral equilibria (Fig. 2). The T and partial pressure of water during equilibration are restricted by the absence of anthophyllite and the pres-

ence of phlogopite + feldspar, Figure 1. Equilibrium locations are calculated with THERMOCALC [6], and its accessory for calculating activities (at T) of the components tremolite, phlogopite, forsterite, and enstatite from LAP mineral analyses [4,5]. The reaction {1} Anth+Fo=En+H<sub>2</sub>O marks the lower T stability limit of En, and is a lower T limit for LAP because it does not contain anthophyllite. To locate this reaction, we used a fictive anthophyllite composition, constrained to have been in Fe/Mg equilibrium with LAP's olivine, using natural olivine-anthophyllite pairs [7]. The reaction {2} Trem+Fo=En+Di+H<sub>2</sub>O marks the upper T stability of amphibole, but LAP does not contain calcic clinopyroxene. To use this latter reaction, fictive augite compositions were calculated (at each T) in Mg/Fe equilibrium with the opx [8], with Ca content constrained by the augite-pigeonite solvus [9]. The reaction {3} Phl+En=Fo+San+H<sub>2</sub>O is more restrictive than {2} (Fig. 1). In locating that reaction, the activity of sanidine component in the plagioclase was calculated (at T) from the parameterization of [10], with results nearly identical to that of [11]. LAP's critical mineral assemblage, En + Phl, is stable in a thin wedge in P(H<sub>2</sub>O)-T space (Fig. 2).

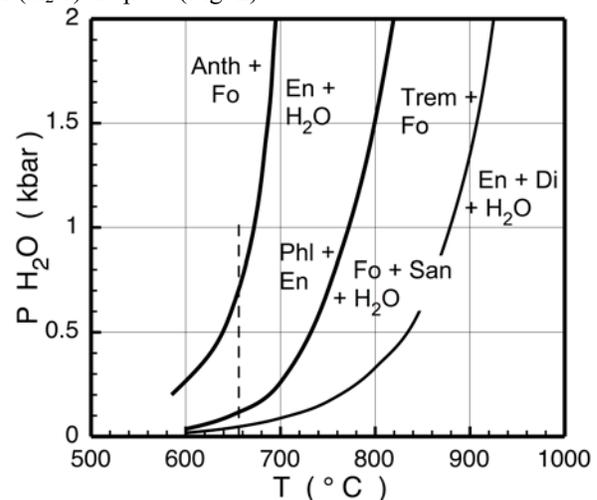


Figure 2. Limiting equilibria for mineral assemblage and compositions in LAP (see text). Its equilibration is constrained most tightly by the assemblage phlogopite + opx (Phl+En). Dashed line, T=655°C, is result from amphib-plag thermometer [12].

Equilibration T is poorly constrained by these equilibria, but is consistent with T≈655°C calculated from the plagioclase-amphibole {Ca+Al ↔ Na+Si} equilibrium [12]. Thermometers using Fe-Mg ex-

change among magnetite, olivine and pyroxene give  $T \approx 1000^\circ\text{C}$  [13] or  $T < 400^\circ\text{C}$  [14,15], which must reflect resetting of the magnetite composition. For  $T \approx 655^\circ\text{C}$ ,  $P(\text{H}_2\text{O})$  is restricted to  $\sim 100$ -700 bars. The oxidation state was high, near QFM, based on the ferric iron content of the amphibole, biotite, and magnetite [4,5] and the absence of metal. The QUILF calibration [13] gives  $f(\text{O}_2) \sim \text{QFM}+0.75$  at  $650^\circ\text{C}$  (although magnetite was likely reset).

**Hydrogen and Water:** The D/H ratios of hydrogen in LAP amphibole and biotite were measured at the DTM, Carnegie Inst. Washington with their IMS-6f ion microprobe, using terrestrial amphiboles and biotites as standards. Instrumental mass fractionations were  $-190\text{‰}$  for amphibole and  $-90\text{‰}$  for biotite. Amphibole in LAP has  $\delta\text{D} = +3660 \pm 75\text{‰}$ . Biotite has  $\delta\text{D} = +2930 \pm 100\text{‰}$ , but also contains abundant C (up to 1.5%), which suggests significant contamination (perhaps by epoxy,  $\delta\text{D} = -420\text{‰}$ , or polishing compound). The very high  $\delta\text{D}$  value for LAP hydrogen is unlike nearly all known hydrogen reservoirs [16].

**Constraints on Origin:** LAP presents many conundrums -- was its parent body dry (as are other R chondrites), at what temperature and pressure (and depth) did water enter the rock, how did the water get in, and where did the water originate?

First, it seems likely that LAP was originally dry because its relict chondrules are texturally identical to typical chondrules elsewhere. It seems unlikely that the matrix among chondrules was hydrous, because biotite and amphibole are not concentrated there (Fig. 1).

Second, it seems likely that LAP was hydrated while hot. Had it been hydrated cold, its original olivine and pyroxene would have been altered to serpentine, chlorite, smectite, etc (e.g., [17]). It seems unlikely that metamorphism of such a rock would recreate its original chondrule textures and euhedral olivine and pyroxene with any fidelity (e.g., [18]). So, it seems most reasonable that LAP was hydrated while at conditions where its olivine and opx were stable.

Third, mineral textures constrain the mechanism of hydration. Amphibole and biotite are not distributed randomly -- they are rare in fine-grained rims around chondrules common in chondrules where mesostasis would have been (Fig. 1); the latter may suggest formation by the reverse of reaction {2}. In some spots biotite appears to replace olivine, which may suggest the reverse of reaction {3}. Further, formation of biotite and amphibole does not appear to have disrupted the textures of chondrules, suggesting that hydration was isovolumetric. If so, it was not isochemical, and bulk chemistry should show significant deviations from normal chondrite compositions.

Third, the source of the water is tightly constrained by its extraordinarily high  $\delta\text{D}$  value -- much larger than the Earth, average carbonaceous chondrites, or comets. The most reasonable known source is macromolecular carbons (e.g. kerogens) in chondrites [20,21], which are interpreted as arising in the interstellar medium.

**Scenarios for Origin:** Data in hand do not provide a unique history for the formation of LAP 04840. Two general scenarios are possible: water generated in the parent asteroid, and water delivered from outside.

Enodogenic scenarios would have D-rich organics, source of the D-rich water, accreting with the R-chondrite matrix. As the parent body heated up from the center outwards, the organics would have oxidized to  $\text{H}_2\text{O}$ ,  $\text{CO}/\text{CO}_2$  etc, which would diffuse towards space.  $\text{CO}$  and  $\text{CO}_2$  might escape entirely, but  $\text{H}_2\text{O}$  would react with metal and silicates to form a zone of hydrated chondrite, i.e. LAP 04840.

Exogenic scenarios would have the D-rich carbonaceous matter entering the LAP parent body after accretion. If a dry, hot R-chondrite parent body collided with a H-rich asteroid or comet, both might be disrupted and re-accrete together, retaining both heat [19] and hydrogen. The more volatile H-bearing species (with lower  $\delta\text{D}$  [16]) would be lost to space. The remaining organics would oxidize in the R-chondrite host (as above) to  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , which would then react to form amphibole and biotite (as above).

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**References:** [1] Satterwhite C. & Righter K. (2006) *Antarctic Meteorite Newsletter*. [2] McCanta M. et al. (2006) *Meteor. Planet. Sci.*, 41, A118. [3] Treiman A. H. et al. (2006) *EOS* 87(52), Abstract V42A02. [4] McCanta M. et al. (2006) *This Volume*. [5] Dyar M. D. et al. (2006) *This Volume*. [6] Powell R. et al. (1988) *J. Metam. Geol.* 16, 577-588. [7] Frost R. (1975) *J. Petrol.* 16, 272-313. [8] Johnson C. & Essene E. (1982) *Contrib. Mineral. Petrol.* 81, 240-251. [9] Lindsley D. & Andersen D. (1983) *J. Geophys. Res.* 88, A887-A906. [10] Holland T. & Powell R. (2003) *Contrib. Mineral. Petrol.* 145, 492-510. [11] Elkins J. & Grove T. (1990) *Am. Mineral.* 75, 544-559. [12] Holland T. & Blundy J. (1994) *Contrib. Mineral. Petrol.* 116, 433-47. [13] Andersen D. et al. (1993) *Computers Geosciences* 19, 1333-1350. [14] Liermann H. & Ganguly J. (2003) *Contrib. Mineral. Petrol.* 145, 217-227. [15] Ballhaus et al. (1991) *Contrib. Mineral. Petrol.* 107, 27-40. [16] Robert F. et al. (2000) *Space Sci. Rev.* 92, 201-224. [17] e.g., p 191ff of Brearley A. & Jones R. (1998) *Rev. Mineral.* 36. [18] Nakamura T. (2005) *J. Min. Pet. Sci.*, 100, 260-272. [19] Grimm, R. (1985) *J. Geophys. Res.*, 90, 2022-2028. [20] Deloule E. and Robert F. (1995) *Geochim. Cosmochim. Acta* 59, 4695-4706. [21] Nakamura-Messenger K. et al. (2006) *Science* 314, 1439-1442.