# WHY IS THE DEGREE OF AQUEOUS ALTERATION VARIABLE?

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**Introduction:** Minerals containing water form inside of asteroids during aqueous alteration. We have quantified the range in degrees of aqueous alteration for carbonaceous chondrites from all groups [1]. Here we focus on the CM chondrite Paris and selected CM falls. We aim to answer the question: *why did aqueous alteration inside of the CM parent body asteroid(s) vary?*

*Our approach:* The fraction of hydrated silicates to anhydrous silicates (PSF) measures the degree of aqueous alteration [1]. The key parameter controlling hydration reactions is water/rock ratio. Water/rock ratios have only been inferred to date, e.g., from O-isotope compositions [2] and O-stoichiometry [1]. Paris preserves large volumes of primary matrix in the form of amorphous Fe-(Mg)-silicate [3], quantifying its abundance allows us to place an upper limit on the fraction of ice accreted in CM matrix. From bulk modal mineralogy and component (chondrule vs. matrix) abundances, we reconstruct the initial $H_2O$ contents of CMs to reveal the cause of variable hydration.

**Samples and methods:** Using Position Sensitive Detector X-ray Diffraction (PSD-XRD) and pattern fitting [1], we determine the first bulk modal data for Paris. Here we report on the abundances of crystalline anhydrous silicates (olivine+pyroxene), phyllosilicates (cronstedtite+MgFe-serpentine) and X-ray amorphous Fe-(Mg)-silicate. The petrography of Paris has been described and the proportions of chondrules and matrix in the sample are known [3]. Results for Paris are compared to CM fall samples with constrained chondrule/matrix proportions [4]: Murchison, Murray, Mighei, Nogoya and Cold Bokkeveld. Modal data are for 100-200 mg aliquots and are reported in vol.%.

**Results:** For two aliquots of Paris the silicate mineralogy is comprised of olivine (19-26%), pyroxene (16-19%), phyllosilicate (38-40%) and X-ray amorphous Fe-(Mg)-silicate (9-12%). Paris is the first CM in which PSD-XRD has detected large volumes of amorphous Fe-(Mg)-silicate. Phyllosilicate in Paris is well-crystalline (cronstedtite) and yields sharp peaks in diffraction patterns. Diffuse *hkl* reflections from disordered/extremely fine grained material (MgFe-serpentine), which dominate PSD-XRD patterns of more altered CMs, are largely absent in diffraction patterns for Paris. The PSF for Paris is 0.54-0.56 and ranges from 0.76-0.82 for the other CMs reported here. On 1.0-3.0 classification schemes [1,5], Paris is a petrographic sub-type 2.0 - the least altered CM chondrite so far (on the 2-3 classification scheme of [6], Paris is a 2.9/3.0; despite being $\approx$ 50% hydrous).

**Discussion:** Amorphous Fe-(Mg)-silicates are rapidly hydrated and converted to phyllosilicates in reactions with $H_2O$. Therefore, the determined abundances of amorphous Fe-(Mg)-silicates in Paris should be considered a minimum estimate of the initial abundance. Petrographic studies of Paris indicate that amorphous Fe-(Mg)-silicate is located in matrix and that 47% of the meteorite is matrix [3]. A bulk abundance of 12% amorphous silicate, located entirely in matrix, corresponds to a 25% matrix proportion of amorphous Fe-(Mg)-silicate. This constrains the maximum initial ice/$H_2O$ content in the matrix of Paris to 75%, corresponding to an initial maximum bulk $H_2O$ fraction of 0.35. Using this estimate of the matrix ice fraction in Paris as proxy for matrix in the other studied CMs, we can can reconstruct maximum initial bulk $H_2O$ contents in these samples from their matrix/chondrule proportions [4]. For all samples, calculated maximum bulk initial mass fractions of $H_2O$ range from 0.35 to 0.63 and correlate with the PSF/degree of aqueous alteration [1] and measured H/OH abundances [5]. This indicates that the chondrule/matrix ratio is primary and that the proportion of matrix controls the water/rock ratio and the degree of alteration - the inverse of the original suggestion [7] that matrix abundance is a product of the degree of alteration.

Greater volumes of phyllosilicate formed in samples with greater initial $H_2O$ contents. Extended duration of fluid supply drove recrystallization of phyllosilicates in the most hydrated samples, increasing Mg/Si ratios [7,8] as Fe from phyllosilicate was lost to fluid, forming Fe,Ni-sulfides+FeOH [1]. S (bulk and matrix) and Na/Si (bulk) abundances [9] decrease as the PSF increases, otherwise aqueous alteration appears to have been isochemical. The abundance of cronstedtite in Paris is ~15% lower than a typical CM2 (e.g., Murchison) $\approx$ the volume of amorphous Fe-(Mg)-silicate that the sample preserves. With an initial bulk mass $H_2O$ fraction of 0.35, fluid in Paris was likely exhausted hydrating amorphous Fe-(Mg)-silicate to form cronstedtite. For CMs with larger initial fractions of $H_2O$ (0.43-0.63), hydration reactions progressed further. As $H_2O$ was consumed, the rock fraction came to dominate reactions, this yielded excess nucleation sites, inhibiting crystal growth (even with higher effective water/rock ratios in matrix, cronstedtite formation is inhibited at $H_2O$ fractions <0.5 [10]). Subsequently, disordered/extremely fine grained phyllosilicates (MgFe-serpentine±saponite) became the dominant late-stage alteration products.

**Conclusion:** The accreted fraction of matrix can explain variations in the degree of aqueous alteration. Prolonged, large-scale, fluid flow or dynamic transport of chondrules and matrix inside asteroids are not required.

**References:** [1] Howard K. T. et al. (2015) *GCA* 149: 206-222. [2] Clayton R. N. & Mayeda T. K. (1999) *GCA* 63: 2089-2104. [3] Hewins R. H. et al. (2014). *GCA* 124: 190-222. [4] McSween H. Y. (1979) *GCA* 43: 1761-1770. [5] Alexander C. M. O'D et al. (2013) *GCA* 123: 244-260. [6] Rubin A. E. et al. (2007) *GCA* 71: 2361-2382. [7] McSween H. Y. (1987) *LPS 18*: 631. [8] Browning L. et al. (1996) *GCA* 60: 2621-2633. [9] Zolensky M. E. et al. (1993) *GCA* 57: 3123-3148. [10] Dyl K. et al. (2006) *LPS 37,* Abstract #2060.