TRACING THE EARLIEST STAGES OF HYDROTHERMAL ALTERATION ON PRIMITIVE ASTEROIDS. E. Mason[1,2], A. J. King[2], H. Bates[2,3], P. F. Schofield[2], K. L. Donaldson Hanna[3], N. E. Bowles[3] and S. S. Russell[2] [1]Department of Earth Science & Engineering, Imperial College, London, UK, [2]Department of Earth Science, Natural History Museum, London, UK, [3]Atmospheric, Oceanic & Planetary Physics, University of Oxford, Oxford, UK. E-mail: a.king@nhm.ac.uk

Introduction: The original mineralogy of many primitive asteroids was overprinted by the effects of low temperature (<100°C) aqueous alteration. During this process anhydrous silicates, sulphides and metal react with fluids to produce secondary mineral assemblages of Fe- and Mg-rich phyllosilicates, oxides and carbonates [1, 2]. Samples of these asteroids are available for study in the form of CM carbonaceous chondrite meteorites. The majority of CM chondrites experienced moderate alteration (~70 vol% phyllosilicates, CM2.4 on the Rubin et al. [3] scale), while some are almost completely hydrated rocks (>80 vol% phyllosilicates, CM2.0). However, there are only a handful of CM chondrites that record the earliest stages (CM >2.6) of aqueous alteration.

Currently the least altered CM chondrites are Paris (CM2.9–2.7), EET 96029 (CM2.7), QUE 97990 (CM2.6) and Y-791198 (CM2.4). They retain unaltered amorphous silicates and metal in the matrix, glassy mesostasis in chondrules, and gehlenite-bearing calcium- and aluminium-rich inclusions (CAIs) [3–6]. These "pristine" CM chondrites therefore provide an opportunity to investigate the initial mineralogy of primitive asteroids and constrain the nature of the first aqueous reactions.

Recent petrological observations of four meteorites recovered from the LaPaz Icefield in Antarctica (LAP 04514, LAP 04527, LAP 04565 and LAP 02333) suggest that they are amongst the least altered CM chondrites [7, 8]. There is also evidence that these meteorites experienced thermal metamorphism after hydration. Here, we have characterized the bulk properties (modal mineralogy, hydrogen abundance and spectral features) of these CM chondrites in order to assess the extent of aqueous and thermal alteration and examine their relationship to primitive asteroids.

Experimental: We studied ~200 mg interior, fusion crust free chips of LAP 04514, LAP 04796 (paired with LAP 04527), LAP 04565 and LAP 02333.

PSD-XRD. Each chip was powdered and modal mineral abundances were obtained using position-sensitive-detector X-ray diffraction (PSD-XRD) at the Natural History Musuem (NHM). The meteorites were analysed for 16 hours and mineral standards for 30 minutes. Phase quantification involved a profile-stripping method for which the uncertainties have been shown to be <5 vol% [e.g. 2].

TGA. For each meteorite we analysed three ~10 mg aliquots using a TA Instruments SDT Q600 thermogravimetric analysis (TGA) instrument at the NHM. The samples were loaded into a alumina crucible and mass loss was recorded whilst heating (10°C min^{-1}) them under an N_2 flow from 25 – 1000°C.

IR Spectroscopy. Infrared (IR) diffuse reflectance spectra of the powders were acquired using a Bruker Vertex 70v FTIR spectrometer within the Planetary Spectroscopy Facility at the University of Oxford. Samples were packed into a stainless steel cup and spectra were collected from ~1.6 – 100 µm under vacuum (2hPa). Spectral measurements of a brushed gold sample were used for calibration.

Results: The bulk mineralogy of LAP 04514, LAP 04796 and LAP 04565 is similar and includes Fe- and Mg-rich phyllosilicates (68–72 vol%), olivine (11–15 vol%), enstatite (10–17 vol%), magnetite (~2 vol%), Fe-sulphides (~1 vol%) and carbonates (~1 vol%). LAP 02333 contains a higher proportion of Fe- and Mg-rich phyllosilicates (79 vol%) and less olivine (7 vol%), plus enstatite (10 vol%), magnetite (2 vol%), Fe-sulphides (1 vol%) and carbonates (1 vol%). Minor phases (<1 vol%) include tochilinite in LAP 04796, LAP 04565 and LAP 02333, and metal in LAP 04796 and LAP 04565. TGA mass loss from 300–800°C is caused by the dehydration and dehyroxylation of the phyllosilicates and can be used to estimate hydrogen abundances in CM chondrites [9, 10]. From the TGA we determine hydrogen abundances of 0.8 ± 0.04 wt% for LAP 04514, 0.9 ± 0.1 wt% for LAP 04796, 0.9 ± 0.01 wt% for LAP 04565, and 1.0 ± 0.05 wt% for LAP 02333. In the IR spectra all four samples show a broad feature from ~2.7 to ~3.5 µm that is attributed to -OH/H_2O bonds. We are unable to discriminate between adsorbed terrestrial H_2O, and -OH/H_2O within the phyllosilicates, however qualitatively the depth of the 3 µm feature is smallest in LAP 04514 and largest in LAP 02333 (Fig. 1). For each sample we observe a reflectance minimum near ~9 µm (Christiansen feature) and maximum near ~12 µm (transparency feature) consistent with the presence of both phyllosilicates and anhydrous silicates.

Discussion: *Degree of Aqueous Alteration*. Fig. 2 shows how the abundance of phyllosilicate increases with degree of aqueous alteration in CM chondrites. Assuming that the starting mineralogy was similar, the phyllosilicate fraction (PSF) (total phyllosilicate abundance / (total anhydrous silicate + total phyllosilicate abundance)) can be used to infer the degree of hydration [1] and defines an alteration sequence of LAP 04514 = LAP 04796 = LAP 04565 < LAP 02333. The phyllosilicate abundance of LAP 02333 measured by [1] is lower than our value but still indicates that it is the most altered of these meteorites. LAP 02333 also contains more hydrogen and has the largest 3 µm feature. The alteration sequence is in agreement with matrix oxide totals, although not the abundance of amorphous silicates reported by [7, 8]. On the petrologic scale of [1], LAP 02333 is classified as a sub-type 1.4, whereas LAP 04796, LAP 04515 and LAP 04565 are sub-type 1.6, comparable with other weakly altered CM chondrites [3–6].

Thermal Metamorphism. Based on the Cr_2O_3 content of fayalitic olivines and the presence of fine-grained olivine and coarse Fe-sulphides in the matrix, [7, 8] suggested that LAP 02333 may have experienced thermal metamorphism. However, at the bulk scale we find no evidence for phyllosilicate dehydration and volatile loss in LAP 02333; this is also the case for LAP 04796 and LAP 04565.

LAP 04514 contains the lowest hydrogen abundance and has the smallest 3 µm feature. While this could be consistent with it being the least aqueously altered of these meteorites, its petrologic sub-type is the same as LAP 04796 and LAP 04565. We therefore argue that LAP 04514 has suffered mild thermal metamorphism. Previous studies have shown the Fe-rich phyllosilicates dehydrate at lower temperatures (300–450°C) than the more Mg-rich phyllosilicates (450–800°C) [10]. Fig. 3 shows that the mass loss for LAP 04514 between 300–450°C was lower than in most CM chondrites, suggesting partial dehydration of the Fe-rich phyllosilicates. The absence of tochilinite, which breaks down at temperatures >120°C, is further evidence for thermal metamorphim of LAP 04514.

Conclusions: Bulk modal mineralogy, hydrogen abundances and IR spectral features indicate that LAP 04514, LAP 04796 and LAP 04565 are amongst the least altered CM chondrites. Observations of these meteorites at the grainscale can provide insights into the accreted mineralogy of the CM parent body and the initial conditions of aqueous alteration [7, 8]. LAP 04514 experienced thermal metamorphism at 300–450°C, probably due to impacts and/or solar radiation, and may be a good anlogue for the types of materials that will be encountered on the surface of asteroids targeted by OSIRIS-REx and Hayabusa2 [10, 11].

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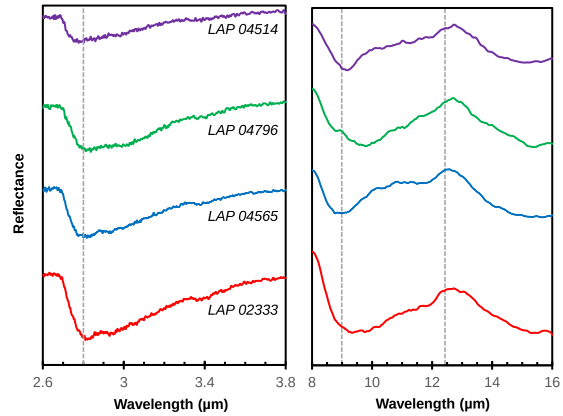

Figure 1. *IR reflectance spectra normalized to unity at 2.3 µm and 8 µm and offset for clarity.*

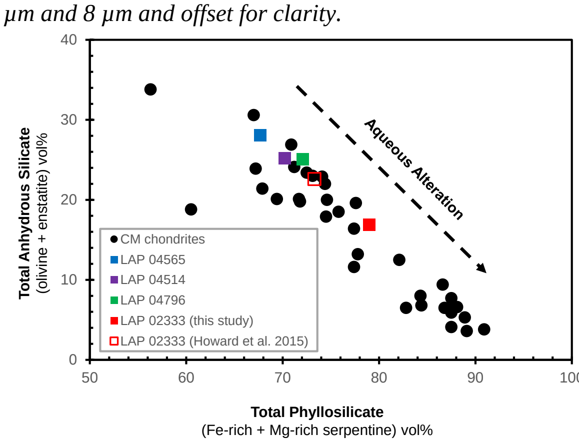

Figure 2. *The abundance of phyllosilicates and anhydrous silicates in CM chondrites (data from [1, 2]).*

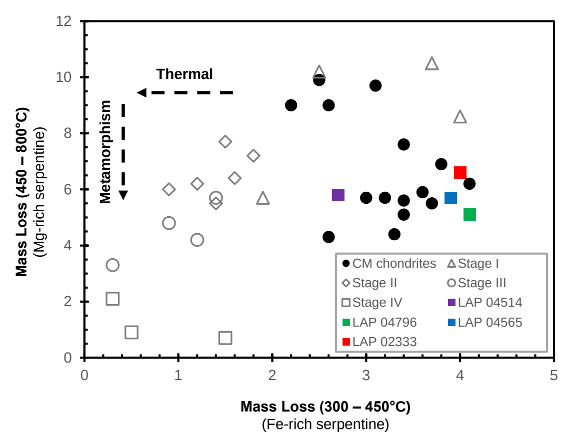

Figure 3. *TGA mass loss in unheated and heated (Stage I to IV after [11]) CM chondrites [9].*