TEMPERATURES OF CARBONATE FORMATION IN CM CARBONACEOUS CHONDRITES: NEW CONSTRAINTS FROM CLUMPED ISOTOPE THERMOMETRY.

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Introduction and aims: CM carbonaceous chondrites provide valuable insights into the early thermal and fluid processing of their C-complex asteroid parent bodies. Carbonate minerals are a volumetrically minor product of aqueous alteration yet can be particularly instructive about parent body evolution. Their oxygen isotopic compositions are a rich source of information on: (i) the provenance of fluids and the degree to which they have interacted with primary anhydrous silicates (from $\delta^{17}O$, $\delta^{18}O$ and $\Delta^{17}O$) [1–3]; (ii) the temperature (*T*) of the aqueous solutions, which can be determined using clumped isotope thermometry [4] or the isotopic fractionation between mineral pairs [5]. Here we report the first results of a comprehensive oxygen and clumped isotopic study of carbonates in a suite of CMs that have undergone different degrees of aqueous alteration. We report the *T*s of calcite and dolomite mineral phases using clumped isotope thermometry, and $\Delta^{17}O$ values of the same carbonates that can provide information on interaction of the precipitating solutions with the host rock. In addition to providing new insights into the evolution of CM parent body(ies), these results are relevant to understanding water/rock interaction within asteroids, including interpreting samples from the B-class asteroid Bennu that may have carbonates from large-scale hydrothermal systems [6].

Samples and methods: Our study is unique in that the same CO_2 aliquots of gas derived from acid digestion were used for both clumped isotopes and for triple oxygen isotopic measurements. Three meteorites were analysed that span a range of degrees of alteration, but none have evidence for post-hydration heating: Murchison (CM2.5), Cold Bokkeveld (CM2.2), and Allan Hills (ALH) 83100 (CM2.1). The petrography of these samples including the abundance and mineralogy of the carbonates was determined by SEM prior to clumped isotope and triple oxygen analyses. In preparation for acid digestion, rock chips were crushed to the <60 mm fraction to limit potential problems from carbonate grains being enclosed in other minerals, and to fully homogenize the mineral components. CO_2 was obtained by phosphoric acid digestion, separated from other gaseous products and measured on a ThermoFisher 253 IRMS for 2 hours in dual inlet mode for the abundances of ions formed at masses 44 to 48. Remaining gas was recaptured in a breakseal tube and later introduced in a ThermoFisher Ultra high-resolution mass spectrometer to measure $^{18}O/^{16}O$ and $^{17}O/^{16}O$ ratios of the CO_2 aliquots on the O fragment formed by the breakup of CO_2 in the ion source (similar to the method of [7]). Measurement time was 4–16 hours depending on sample size. For meteorites containing both calcite and dolomite, separate aliquots were digested at 25 and 90 °C to extract CO_2 from only calcite or from all carbonate phases, respectively. We recognise that these bulk analyses will average the isotopic compositions of multiple generations of the same mineral (e.g., Types 1 and 2 calcite if present; [1]).

Results: There are considerable differences between meteorites in both *T* and $\Delta^{17}O$. Murchison calcite: *T* 20–25 °C, $\Delta^{17}O$ -0.9 to -1.1 ‰; Cold Bokkeveld calcite. *T* 27–39 °C, $\Delta^{17}O$ -1.5 to -1.7 ‰. ALH 83100 calcite: *T* 53 °C, $\Delta^{17}O$ -1.9 ‰. ALH 83100 dolomite. *T* 124.4 °C, $\Delta^{17}O$ -2.6 ‰. Typical standard errors are: *T* = 5–10 °C, $\Delta^{17}O$ = 0.1 ‰. Our results are in good agreement with *T*s derived from previous clumped isotope measurements of Murchison (20–34 °C) and Cold Bokkeveld (26–71 °C) [4], and the *T* of dolomite in ALH 83100 as determined using the dolomite/magnetite oxygen isotope fractionation (125 ±60 °C) [5].

Discussion and conclusions: Some of the findings and implications of our results are: (i) Calcite in the more highly aqueously altered meteorites grew at higher *T*, thus implying that the overall degree of alteration of the CMs was determined by *T*; (ii) The good correspondence between *T* and $\Delta^{17}O$ shows that the hotter fluids had interacted more with ^{17}O-depleted anhydrous silicates in the host rock; (iii) Dolomite in ALH 83100 grew after its calcite and from fluids that were considerably hotter and isotopically more evolved. These conclusions will be be tested by further analysis of the CMs LaPaz Icefield (LAP) 031166, Lonewold Nunataks (LON) 94101 and Scott Glacier (SCO) 06043.

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