EVIDENCE FOR WIDESPREAD POST-HYDRATION HEATING OF THE CM CARBONACEOUS CHONDRITES. M. R. Lee[1], B. E. Cohen[1,2], D. F. Mark[2], A. Boyce[2] [1]School of Geographical and Earth Sciences, University of Glasgow, G12 8QQ, U.K. (Martin.Lee@Glasgow.ac.uk). [2]Scottish Universities Environmental Research Centre (SUERC), Rankine Avenue, East Kilbride G75 0QF, U.K.

Introduction: The CM carbonaceous chondrites have all been aqueously altered, and a proportion of them have also been heated after hydration, resulting in the dehydroxylation and recrystallization of phyllosilicates. The CMs are therefore conventionally divided into 'unheated' and 'heated', and with regards to the heated category a range of peak metamorphic temperatures have been identified [1].

A few of the ostensibly unheated CMs, including Murchison, have yielded bulk $^{40}Ar/^{39}Ar$ ages [2] that are much younger than the age of aqueous alteration, as defined by ^{53}Mn–^{53}Cr dating of carbonates [3]. One interpretation of these unexpectedly young $^{40}Ar/^{39}Ar$ ages is that they reflect degassing of radiogenic argon in response to late-stage heating [2,4]. Thus many or all of the CMs may have been heated after aqueous alteration, but just to very different peak temperatures (i.e., there may be a continuum of degrees of heating rather than the binary 'unheated' and 'heated' divisions).

Here we have sought to test this idea by undertaking new measurements of the hydrogen and argon isotopic compositions of CMs, some 'unheated', others 'heated'. Specifically, we ask how widespread degassing of radiogenic argon is among the CMs by dating a meteorite that has a very different degree of aqueous alteration to Murchison, which can therefore reasonably be assumed to have come from a different parent body or different part of the same body. We also ask whether the hydrogen isotopic system can be used to explore the effects of post-hydration heating. Results of this work will provide a framework for exploring the thermal histories of these meteorites more broadly.

Materials and methods: The $^{40}Ar/^{39}Ar$ work used SCO 06043, which has been highly aqueously altered (petrologic type 1.1–1.2) and classified as 'unheated' by [5]. The sample was irradiated for 65 hours at Oregon State University and argon data were acquired at SUERC on a MAP-215 mass spectrometer. The data were corrected for cosmogenic argon contribution using the procedures of [6]. Hydrogen isotope work used bulk samples of nine CMs (Table 1). The degree of aqueous alteration (i.e., petrologic type) and heating categorisation for all meteorites apart for EET 96029 is from [5]. EET 96029 has been unusually mildly aqueously altered (classified as CM2.7 by [7]), then heated to ~400–600 °C [7]. Water was evolved from 32–80 mg aliquots via pyrolysis in temperature steps of 100, 200, 300, 400, 500, 700, and 1100 °C [±5 °C]). The water released was reduced to hydrogen via exposure to chromium powder at 850 °C. Hydrogen isotopes were measured using a VGI Optima mass spectrometer at SUERC.

Results: Preliminary results from incremental-heating of SCO 06043 do not yield a plateau, with ages for individual steps being outside 2-sigma uncertainty (Fig.1). Nevertheless, with the exception of the initial step (representing <4.5% of the ^{39}Ar released), all steps yielded ages of 3.2 Ga or younger. These results indicate SCO 06043 underwent sufficient heating to reset the K-Ar system at some point after 3.2 Ga.

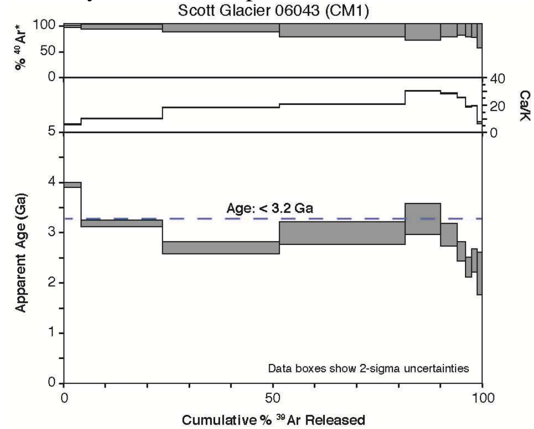

Fig. 1. $^{40}Ar/^{39}Ar$ data from SCO 06043.

The stepwise pyrolysis data are listed in Table 1. For brevity, results are aggregated into the <500 °C and >500 °C steps, and the bulk rock (i.e., all steps). In all of the 'unheated' CMs apart for Cold Bokkeveld the 400 °C step evolved the largest amount of water. The <300–500 °C steps had a negative δD, and higher temperature steps a positive δD. With regards to the heated CMs, EET 96029 evolved most water in the 200 °C step, and MET 01075 in the 700 °C step. Water evolved from Cold Bokkeveld and MET 01075 over all steps had a negative δD.

Discussion: The apparent age of SCO 06043 significantly postdates aqueous alteration of the CMs (4.563 Ga [3]) and is so consistent with the loss of radiogenic ^{40}Ar. The age is similar to Murchison (3.24 ± 0.12 Ga, [2]), thus suggesting that both meteorites have been degassed, and that that the process(es) responsible affected different parent body regions, including those that had been mildly aqueously altered (as represented by Murchison) and highly aqueously altered (sampled by SCO 06043). As the CMs that have been heated to thermal metamorphic temperatures also yield young $^{40}Ar/^{39}Ar$ ages (~1.21–2.08 Ga, [8]), the process responsible for disturbing the argon isotope system may be common to both 'unheated' and heated CMs. One proposed mechanism is that the CMs were radiative heated during perihelion, either relatively recently, leading to partial degassing of ^{40}Ar, or much earlier (i.e., at ~3 Ga) resulting in complete resetting of the argon chronometer. Numerical models show that radiative heating is most effective in those meteorites that have come from small meteoroids with low perihelia distances [9]. It is highly unlikely that both Murchison and SCO 06043 were heated to the same extent within the same small meteoroid. Thus, for radiative heating to have been responsible for degassing of both CMs, they would need to have come from two different meteoroids that had shared similar orbital histories. Shock is another mechanism that has been proposed to explain heating [5]. Impacts are stochastic events whose effects are notoriously spatially variable, but would need to have affected at least two CMs and to a similar extent. Nonetheless, both Murchison and SCO 06043 have good petrographic evidence for deformation by low intensity impacts [10], and so with regards to these two CMs at least, shock remains a viable mechanism for post-hydration heating and degassing.

Table 1. Stepwise pyrolysis data.

CM meteorite (petrologic type)[5]	H_2O (wt. %) / δD (‰)		
	< 500 °C steps	>500 °C steps	Bulk rock
'Unheated'			
LEW 85311 (1.9)	5.6 / 3	1.3 / 80	6.9 / 83
DOM 08013 (1.8)	5.9 / -8	1.0 / 66	6.9 / 58
MCY 05230 (1.8)	5.4 / -54	2.3 / 36	7.6 / -16
DNG 06004 (1.8)	5.5 / -21	2.8 / 21	8.3 / 0
QUE 97990 (1.7)	5.5 / -21	2.0 / 37	7.5 / 16
LAP 02239 (1.1)	6.3 / -66	2.2 / 23	8.5 / -43
Cold Bokk. (1.3)	5.7 / -52	5.3 / -51	11.0 / -103
'Heated'			
MET 01075 (1.5)	1.8 / -40	6.2 / -160	8.1 / -200
EET 96029	3.5 / -30	1.4 / 8	4.9 / -21

Post-hydration heating of the CMs can also be recognized and explored through its effect on the abundance and δD value of water/hydroxyls. The principal carriers of hydrogen in the CMs are phyllosilicates (deuterium-poor) and organic matter (deuterium-rich) [5]. Stepwise pyrolysis results show that MET 10175 and EET 96029 are clearly differentiated in the <500 °C steps (Fig. 2), thus indicating that they have been heated to ~500 °C. This result is consistent with the petrological and mineralogical properties of EET 96029 [7]. The heated CMs have a much narrower range in δD values than the 'unheated' meteorites, which probably means that most of the water liberated at <500 °C is an absorbed terrestrial component. [5] also noted that the heated CMs have a narrow range of δD values. Data from the >500 °C steps show that the unheated and heated CMs plot together on a line of increasing δD with decreasing amounts of evolved water (Fig. 2). The low water/high-δD component is likely from organic matter, whereas the high water/low δD component is less easy to identify. This component of water must come from a thermally stable and deuterium-poor carrier, which especially abundant in MET 10175 – this meteorite evolved 0.6 wt. % H_2O with a δD value of -243 ‰ in the 1100 °C step.

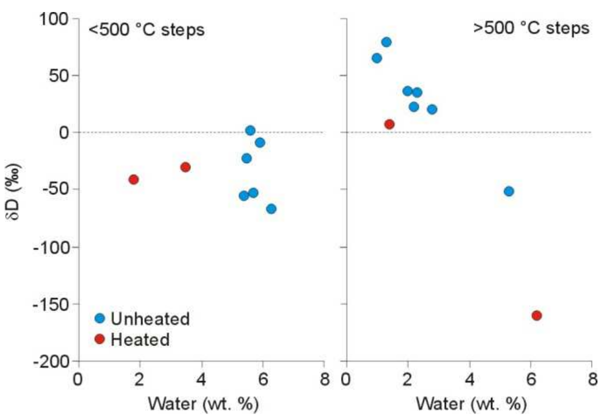

Fig. 2. Stepwise pyrolysis results.

Conclusions: The $^{40}Ar/^{39}Ar$ ages of 'unheated' CMs are consistent with the idea that many of these meteorites have undergone post-hydration heating. Stepped pyrolysis data show that the 'unheated' and heated CMs can be distinguished clearly at low temperatures, but the technique is insufficiently sensitive to test the concept of a continuum of heating. Other chemical/isotopic or mineralogical tools will be needed to further test the idea that the 'unheated' CMs have been mildly thermally processed, and to quantify the temperatures that they experienced.

References: [1] Nakamura T. (2005) *J. Min. Petrol. Sci., 100,* 260–272. [2] Turrin B. et al. (2014) *LPS, 45,* 2485. [3] Fujiya W. et al. (2012) *Nat. Comms, 3,* 627. [4] Mazor E. et al. (1970) *GCA, 34,* 781–824. [5] Alexander C. M. O'D. et al. (2013) *GCA, 123,* 244–260. [6] Cassata, W. S. et al. (2016) *GCA, 187,* 279–293 [7] Lee M.R. et al. (2016) *GCA, 187,* 237–259. [8] Nakamura T. et al. (2015) *MetSoc 78,* 5147. [9] Chaumard N. et al. (2012) *Icarus, 220,* 65–73. [10] Lindgren P. et al. (2015) *GCA, 148,* 159–178.

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