DEHYDROXYLATION AND PEAK TEMPERATURE OF MATRIX IN CM AND RELATED CARBONACEOUS CHONDRITES. M. A. Velbel[1,2] and M. E. Zolensky[3], [1]Michigan State University, Department of Earth and Environmental Sciences, East Lansing, MI, USA 48824-1115 (velbel@msu.edu), [2]Smithsonian Institution, National Museum of Natural History, Division of Meteorites, Department of Mineral Sciences, [3]ARES, NASA Johnson Space Center, Houston, TX 77058 USA (michael.e.zolensky@nasa.gov).

Introduction: The target bodies of current asteroid sample-return missions (Hayabusa2, OSIRIS-REx) are carbonaceous near-Earth asteroids (NEAs) Ryugu and Bennu, chosen for the abundance and scientific importance of the volatiles they contain [1-3]. Volatile-rich constituents of interest include hydrated crystalline silicates (phyllosilicates), amorphous silicates, and associated organic compounds hosted by such volatile-rich phases [4,5]. All spectroscopic matches (with varying degrees of success) between mission-target asteroids and meteorites are with members of carbonaceous chondrite groups that contain H-hosting phyllosilicates and elevated abundances of reduced (organic) C compounds associated with the phyllosilicates, suggesting surface materials related to CM2, CM1, and CI chondrites, or anomalous C chondrites [1,3,6]. Spectroscopic matches between mission-target asteroids (Ryugu and Bennu) and specific carbonaceous chondrites include (1) "common" CM chondrites (*sensu* [7]; aqueously altered but not further heated, and rich in OH-bearing phyllosilicates, and thus the most aqueously altered meteorites available for study in terrestrial laboratories), (2) artificially heated CM and CI powder, and (3) naturally heated, both aqueously and thermally altered (dehydroxylated) ([8]; ATCC *sensu* [9,10]) CM and CM-like meteorites [6-8,11,12]. ATCC CM chondrites have mineral inventories and attributes that indicate they were dehydrated during heating to peak temperatures of 400 – 700 °C (~670 – 970 K), higher than peak temperatures experienced by typical CCs (e.g., [13-15]).

Spectral reflectance data in the ultraviolet (UV), visible, and near infrared (IR) for thermally metamorphosed carbonaceous chondrites (e.g., [15]) suggest that carbonaceous chondrite-like material that has been metamorphosed over the aforementioned range of temperatures now occurs at the surface of a number of C-, G-, B-, and F- asteroids [7,16,17], including Ryugu [11]. Consequently, it was expected that material depleted in H (OH) and other volatile elements and compounds (1) was encountered by sample-return missions to B- and C-type asteroids and (2) is present among the samples returned by these missions.

This project builds on existing knowledge (from meteorites) of thermal metamorphism and its effects, to develop a regimen of specific measurements for peak-temperature lithothermometry of mission-returned samples during preliminary and subsequent examination. The purposes of this presentation are to examine CM matrix dehydroxylation as a measure of thermally induced loss of volatiles from carbonaceous (CM) chondrite lithologies, from a compilation and synthesis of published data, in support of developing a corresponding peak-temperature lithothermometer for heating effects in CM lithologies.

CM matrix and its dehydroxylation: Different groups of carbonaceous chondrites differ in their modal abundances of matrix [4,18,19], and in the ranges of EPMA (anhydrous) analytical totals of their matrices [20-22], among other important factors. CM chondrites are dominated by serpentine-group minerals (e.g., 56-88% [23]), most of which is in matrix that constitutes 40-85 (but mainly 50-85) modal % of CMs [22,24,25]. A few CM chondrites, including Bells [21,26] and Belgica-7904 [27,21], contain appreciable saponite in various states of dehydration, or other non-serpentine-group minerals (talc, clinochlore), among their phyllosilicates.

A quantitative measurable compositional change known to result from thermal metamorphism of CM lithologies is variation in the shortfall of analytical matrix EPMA totals (EPMAΣ), that results from (1) matrix EPMA not analyzing the H and associated O in any phyllosilicate's OH group, as well as (2) microporosity and (3) microfractures produced due to grain-volume change during alteration and/or heating. CM chondrites that were altered by aqueous solutions to varying degrees have matrix EPMA analytical totals for matrix between 78-92 wt%, with a mid-range value of 85% [21], encompassing the ~83-89 wt % range of serpentine-group minerals, which contain OH [28]. Thermally metamorphosed CM2s ([8]; ATCCs *sensu* [9,10]) were subsequently naturally heated under open-system conditions in which dehydroxylated H and O were lost from the analyzed volume as H_2O. ATCCs contain evidence of heating to *maximum* temperatures of 400 – 700 °C (~670 – 970 K); the evidence including partially dehydrated matrices with EPMA analytical totals above ~91 wt % [21,15] (Table 1).

Dehydroxylation and peak temperature: It is suggested here [30] that the matrix EPMAΣ total (%) be used to quantify the degree of thermally driven loss of mineral (serpentine) OH. EPMAΣ varies between the upper part of the range of anhydrous analytical totals for serpentine (corresponding to an unheated CM chondrite that has experienced aqueous alteration in the common range for CMs), and 100%, corresponding to complete dehydration (dehydroxylation) of matrix phyllosilicates.

Table 1. Matrix EPMA total, MDI, and estimated T_{peak} of naturally heated CM and CI chondrites

Meteorite	Classification[1]	T_{peak} (°C)[2]	Matrix EPMAΣ total; wt%)[3]	T_{peak} est. from EPMAΣ (°C)[4]
Y-86789	CM2TIV	≥700 =↓	98.7	800
Y-86720	CM2TIV	=↑	96.54	800
Y-82162	CI1TII/III		96.6	700
Y-86029	CI1TIII	=↓	95.0	600
B-7904	CM2TIV	=↑ ≈600	91.5	*500*
PCA 91008	CM2TIII		97.3	700
A-881655	CM2TIII	=↓ ≈500	98.17	700
WIS 91600	CM2TII	=↑	94.4	*600*
Y-793321	CM2TII	≥400	91.8	400
Y-791198	CM2		88.3	300
Compiled	Unaltered CM	<400	84-88	<0

As arranged by [15], corrected and modified from [29]. Arrows point to adjacent listed samples identified as having equal peak temperatures of metamorphism. [1]From [15] unless otherwise credited. [2]From [15], estimated from similarity of labile-element depletion to Murchison experimentally heated to the indicated temperature. [3]From [21,15] and other sources. [4]To one significant figure, from [30]. *Italicized* T_{peak} values fall outside the range of the thermal metamorphic Stage [8] to which the meteorite was assigned by [15]. *All listed meteorites that fall outside are in the CM-like Belgica subgroup*. [31]

An equation for inferring T from EPMAΣ over the entire previously estimated range 400 °C < T_{peak} < 700 °C has been developed and will be reported soon [30]. Table 1 shows the published EPMA analytical totals for matrix [15,21], previous semi-quantitative estimates of peak temperature [15] (originally reported to the nearest hundred degrees Centigrade, one significant figure) determined using the thermal metamorphism scale of [8], and the estimates from our new equation (rounded to one significant figure). T_{peak} values estimated quantitatively using measured EPMAΣ totals and our dehydroxylation thermometer equation agree closely (when rounded to one significant figure) with previous estimates for most of these meteorites, except for the CY / CM-like Belgica subgroup.

References: [1] Wada K. et al. (2018) *Progr. Earth Plan. Sci., 5*:82. [2] Lauretta et al. (2015) *MAPS, 50*, 834–849. [3] Lauretta et al. (2017) *SpaceSciRev, 212*, 925-984. [4] Hutchison R. (2004) *Meteorites: A Petrologic, Chemical and Isotopic Synthesis*. [5] Grady M. M. (2000) *Catalog of Meteorites* 5th ed. [6] Clark B. E. et al. (2011) *Icarus, 216*, 462-475. [7] Hiroi T. et al. (1996) *MAPS, 31*, 321-327. [8] Nakamura T. (2005) *JMinPetSci, 100*, 260-272. [9] Cloutis et al. (2012) *Icarus, 220*, 586–617. [10] Cloutis et al. (2018) Ch. 4 in *Primitive Meteorites and Asteroids: Physical, Chemical and Spectroscopic Observations Paving the Way for Exploration*, Abreu N. M. (ed.) p. 273-343. [11] Kitazato et al. (2019) *Science, 364*, 272-275. [12] Hamilton et al. (2019). *Nature Astron. 3*, 332-340. [13] Tonui E. K. et al. (2002) *Antarct. Meteorit. Res., 15*, 38–58. [14] Tonui E. K. et al. (2003) *MAPS, 38*, 269–292. [15] Tonui E. K. et al. (2014) *GCA, 126*, 284-306. [16] Hiroi T. et al. (1993) *Science, 261*, 1016-1018. [17] Hiroi T. et al. (1994) *Proc. NIPR Symp. Antarct. Meteorites, 5*, 49-73. [18] Krot A. N. et al. (2005) *Treatise Geochem. Vol. 1*, 83-128. [19] Weisberg M. K. et al. (2006) *MESSII*, 19-52. [20] McSween H. Y. Jr. and Richardson S. M. (1977) *GCA, 41*, 1145-1161. [21] Zolensky M. E. et al. (1993) *GCA, 57*, 3123-3148. [22] Zolensky M. E. et al. (1997) *GCA, 61*, 5099-5115. [23] Howard K. T. et al. (2015) *GCA, 149*, 206–222. [24] McSween H. Y. Jr. (1979) *Rev. Geophys. Space Phys., 17*, 1059-1078. [25] Hewins R. H. et al. (2014) *GCA, 124*, 190–222. [26] Brearley A. J. (1995) *GCA, 59*, 2291-2317. [27] Akai J. (1992) *Proc. NIPR Symp. Antarct. Meteorites, 5*, 120-135. [28] Deer W. A. et al. (1962) *Rock Forming Minerals, vol. 3 Sheet Silicates*. [29] Zolensky M. E. et al. (2018) Ch. 2 in *Primitive Meteorites and Asteroids: Physical, Chemical and Spectroscopic Observations Paving the Way for Exploration*, Abreu N. M. (ed.) p. 59-204. [30] Velbel M. A. and Zolensky M. E. (in revision). [31] Choe et al. (2010) *MAPS, 45*, 531-554.