PETROGRAPHIC, CHEMICAL AND SPECTROSCOPIC DATA ON THERMALLY METAMORPHOSED CARBONACEOUS CHONDRITES. E. K. Tonui[1] (etonui@ems.jsc.nasa.gov), M. E. Zolensky[1], T. Hiroi[2], M.-S. Wang[3] and M. E. Lipschutz[3] [1]NASA Johnson Space Center, Mail Code ST, Houston, Texas, 77058, USA, [2]Department of Geological Sciences, Brown University, Providence, Rhode Island 02912, USA, [3]Department of Chemistry, Purdue University, West Lafayette, Indiana 47907-1393, USA.

Introduction: Thermal metamorphism is one of the most intriguing post accretionary processes in carbonaceous chondrites. The source, timing and duration of heating is relatively unknown. We present the first comprehensive description of these events in 11 new and 5 previously studied carbonaceous chondrites (Table 1). The levels of heating have been checked against peak temperatures suggested by Radiochemical Neutron Activation Analysis (RNAA) of 15 thermally mobile trace elements [1]. Spectral reflectance data in the UV, visible and near IR [2] reveals the level of dehydration of secondary hydrous minerals, which can then be used to determine possible relationships to primitive asteroids notably C-, G-, B- and F- asteroids.

Petrography and trace element chemistry: *CI chondrites*: Both Y-82162 and Y-86029 exhibit extensive aqueous alteration and similar distribution of secondary minerals. Y-86029 contains unusual textures, which include evidence of shock in olivine, unusually large periclase clasts and presence of carbonate globules with cores of magnetite and ankerite rims [3]. Carbonates in Y-82162 occur as isolated grains of breunnerite, dolomite, calcite and ankerite. Thermal metamorphism is apparent in partial dehydration of matrix phyllosilicates, occurrence of periclase (through heating of Mg-Fe carbonate) and Ca-Fe-Mn carbonates within carbonate globules in Y-86029. Higher abundance of fine-grained and drusy elongate crystals of magnetite in both meteorites is consistent with heating of sulfides but this could also be due to higher oxygen fugacity instead. Trace element data when compared with that of heated Murchison, suggests peak temperatures of 600-700 ºC for Y-82162 and 500-600 ºC for Y-86029 (Table 1).

CM chondrites: The bulk of these meteorites have type 2 affinities. They exhibit a wide range of aqueous alteration and heating characteristics. Y-793321, Y-82054, A-881655, PCA-91008, WIS-91600 and B-7904 were partially aqueously altered as evidenced by well-preserved nature of chondrules and coarse-grained matrix silicates and presence of Fe-rich phyllosilicates. Y-86720 and Y-86789 were completely altered by aqueous fluids [4] hence their CM1 affinities. Y-793321 is the only CM2 that contains coarse-grained carbonate grains. Finer grained colloform carbonate masses are present within Y-86789 and Y-86720. Sub-rounded to irregular CAI's are present in all. Partial or complete recrystallisation of matrix phyllosilicates provides evidence of possible heating. This is apparent in all but Y-793321. Absence of tochilinite provides additional evidence as tochilinite is known to decompose to troilite at ~245 ºC [5]. Tochilinite is also absent from CMs that experienced high fO2. Tochilinite is abundant in Y-793321, sparse in Y-82054 and absent in others. Late-stage oxidation is apparent in replacement of sulfides by magnetite in Y-82054, A-881655, EET 90043 and PCA-91008. There is no evidence of this in the other meteorites despite abundance of sulfides. Textural evidence of heating is obvious in B-7904, PCA-91008 and EET 90043 in blurring and/or integration of chondrules with matrix and homogenisation of the entire rock. The CM1's experienced extensive heating, which resulted in complete recrystallisation of serpentine to olivine [6,7].

The levels of heating suggested by chemical data are consistent with petrographic observations. Despite presence of a few heated clasts and incompletely recrystallised serpentine in Y-793321 [3], no unambiquous evidence for heating is evident chemically. Y-82054, A-881655 and WIS-91600 show loss of Cd suggesting mild heating (~500 ºC). Data for PCA-91008 corresponds to the 500-600 ºC Murchison sample (i.e. loss of Cs→Bi). EET-90043 and B-7904 show loss of Cs→Zn consistent with ~600 ºC i.e. high to severe heating. Y-86789 and Y-86720 exhibit loss of Cs→Tl corresponding to severe heating (~700 ºC).

CO Chondrites: LEW85332 is a unique type 3 carbonaceous chondrite that resembles CI and CR chondrites [8]. Petrological characteristics resemble CO chondrites i.e. it consists of small chondrules, Fe-Ni metal, sulfides (mostly troilite) and matrix. It is a unique meteorite that shows no clear evidence of alteration of chondrules or silicate aggregates, while matrix consists of fine-grained partially recrystallised phyllosilicates [3,8]. This implies that formation of hydrous phases and heating occurred prior to final accretion in the parent asteroid. ALH85003 has similar mineralogical distribution although its chondrule mesostasis shows alteration to Fe-rich phyllosilicates. Fe-Ni metal grains are relatively fresh. Both meteorites show loss of Cd (Cs→Tl) suggesting mild heating (~500 ºC).

CV3 Chondrites: These include EET96010 and ALH81003. EET 96010 consists of relict chondrules, CAI's, sulfides (mainly pyrrhotite) and matrix. It is extensively aqueously altered as evidenced by discrete phyllosilicate 'balls' in chondrules and fine grained matrix. Embayed sulfide clusters within matrix appear to be products of late stage aqueous alteration and sulfidization. Petrographic evidence of heating is obvious in fusion of chondrules with matrix and presence of fine grained completely recrystallised olivine. When compared with data for Allende sample, EET 96010 shows loss of Cs→Ag making it the most severely heated carbonaceous chondrite to date (~900 ºC). ALH81003 differs from EET96010 in that it consists of low-Ca-rich pyroxene-rich chondrules and fayalitic olivine-rich matrix. These chondrules show evidence of Fe-alkali-halogen metasomatic alteration to nepheline and sodalite. Mesostasis of chondrules have been replaced by ferroan olivine and phyllosilicates; some of the forsteritic olivine phenocrysts have fayalitic rims. The matrix is composed of subhedral or tabular fayalitic olivine and rarely phyllosilicates. Heating in ALH85003 is apparent in the high degree of homogeneity of matrix olivine. Other indicators of heating in CV3 chondrites include dehydration of dark inclusions and variation in contents of presolar grains and noble gas signatures [9].

Table 1: Mobile trace element data of thermally metamorphosed carbonaceous chondrites compared with data for heated Murchison [x±σ- mean and standard deviation; ¶this study; §previous studies]

Meteorite	Type	x±σ	Elements (No.)	Ref.†
Y-86029	CI¶	1.20±0.19	Cs→Zn (5)	4
Y-793321	CM2¶	0.51±0.08	Cs→Tl (9)	2
Y-82054	CM2¶	0.59±0.08	Cs→Tl (8)	5
WIS91600	CM2¶	0.58±0.09	Cs→Tl (8)	5
PCA91008	CM2¶	0.46±0.13	Cs→Bi (7)	3
EET90043	CM2¶	0.39±0.08	Cs→Tl (8)	5
LEW85332	CO3¶	0.26±0.04	Cs→Tl (8)	2
ALH85003	CO3¶	0.23±0.04	Cs→Tl (8)	3
EET96010	CV3¶	0.42±0.07	Cs→Ag (3)	5
ALH81003	CV3¶	0.29±0.09	Cs→Tl (8)	3
EET96026	C4/C5¶	0.15±0.13	Cs→Tl (9)	5
Y-82162	CI§	1.36±0.18	Cs→Zn (5)	1
A-881655	CM2§	0.39±0.17	Cs→Tl (8)	3
B-7904	CM§	0.57±0.08	Cs→Zn (5)	1
Y-86789	CM1§	0.65±0.16	Cs→Te (4)	1
Y-86720	CM1§	0.69±0.08	Cs→Te (4)	3

†References: (1) Paul & Lipschutz (1989, 1990); (2) Xiao & Lipschutz (1992); (3) Wang & Lipschutz (1998); (4) Tonui *et al.*, (2001); (5) Tonui *et al.*, (this study).

Loss of Cd is apparent in ALH81003 suggesting mild heating (~500 ºC).

C4/C5 Chondrite: EET 96026 consists of relict porphyritic olivine-low Ca-pyroxene chondrules and matrix of fine grained to subangular olivine grains (5-20 µm), pentlandite and magnetite. The chondrules are fairly discernible. The olivines within matrix have homogenous compositions (σFa/(mean Fa) x 100 <3, hence the type 4-5 affinities. Olivine-rich matrix aggregates with fayalitic rims similar to those in CV3 chondrites are also present. The matrix exhibits intense 'silicate darkening' as commonly observed in CK chondrites [10]. The homogeneity of matrix and fairly discernible chondrules indicates some degree of recrystallization. Zn, Bi and Tl values are somewhat low but this may be due to heating or high condensation temperatures.

Spectroscopy: Heating results in weakening of the 0.7 µm band and UV and 3 µm absorption strengths. Preliminary data shows that among CM chondrites (Fig. 1), appreciable dehydration is apparent in Y-793321, Y-82054 and WIS91600 based on both UV and 3 µm features. EET90043 shows intermediate degree of dehydration, while PCA91008 still show both strong UV and dehydration, suggesting weakest dehydration. EET96010 has strong dehydration and UV features, while ALH81003 exhibits moderate dehydration and strong UV absorption. LEW85332 exhibits strong UV absorption and 3 µm band. EET96026 shows moderate dehydration, strong UV absorption and clear mafic silicate features. None of these samples show 0.7 µm band. Strong UV and 3 µm can be due to terrestrial weathering. We are examining these data to determine precise dehydration temperatures and relationships with primitive asteroids.

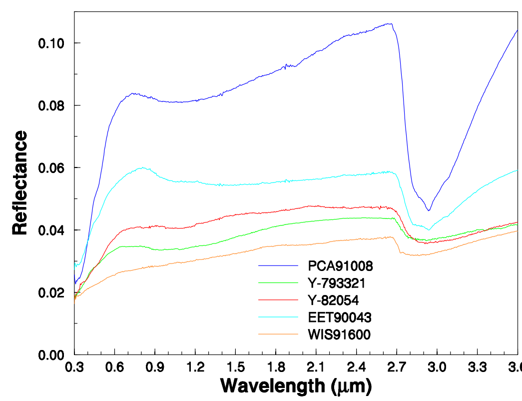

Fig. 1: Reflectance spectra of 5 thermally metamorphosed CM chondrites

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