METAMORPHISM OF ORDINARY CHONDRITES AT THE TYPE-3/TYPE-4 BOUNDARY.

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Introduction: Probably the major process to have affected the ordinary chondrites since their formation is parent body metamorphism [1]. The original material for the ordinary chondrites consisted of heterogeneous minerals, traces of water and carbon, a fine-grained matrix that "cemented" the components together, diverse components with sharp outlines, including glassy chondrules [2]. Metamorphism homogenized the minerals, recrystallizated the matrix and crystallized the glass, removed volatiles, and blurred outlines. Because different meteorites have experienced different degrees of metamorphism, it has proved helpful to subdivide the meteorites into petrographic types [3]. Among the ordinary chondrites, type 3 specimens (unequilibrated chondrites) and type 5 and 6 specimens (equilibrated chondrites) have been well studied. The intermediate types, from high type-3 through the type 4/5 boundary, have been relatively little studied.

We are therefore undertaking a multidisciplinary study of ordinary chondrites that range from about type 3.7 through those classified as type 4/5, using electron microprobe data to monitor mineral heterogeneity and compositions, and induced thermoluminescence (TL) data to monitor the crystallization of glass and development of feldspar. Our objective is to improve our understanding of metamorphic process on meteorite parent bodies over the critical temperature range where the last primary minerals such as pyroxene finally equilibrate, and secondary metamorphic minerals such as coarse feldspar, chromite, and orthopyroxene develop. We report here on the first 11 samples from our study,

Experimental: Mineral compositions were determined by electron microprobe analysis at the USGS and at UCLA using standard procedures and appropriate standards and data-reduction methods. Thermoluminescence measurements were made at the University of Arkansas using a suitably modified Daybreak Nuclear and Medical Inc. instrument. Duplicate chips ≥50 mg were obtained, each chip representing a different lithology when present. After inspection under a binocular microscope, samples were gently crushed, the magnetic material removed with a hand magnet wrapped in lens tissue, and gently crushed again to produce a powder that flowed without clumping (~200 μm grains). Four-milligram aliquots were then placed in the TL rig for heating to 500^{o}C for the removal of any natural TL signal. The powders were then placed in a 200 mCi ^{90}Sr beta cell for three minutes, allowed to decay for five minutes (to remove unstable TL), and placed in the TL rig and heated to 500^{o}C at 7.5^{o}C/s for determination of induced TL. The temperature corresponding to the maximum TL signal (peak temperature) and the half-width-at-full-maximum of the TL peak (peak width) were measured. Dhajala was used as a standard and TL sensitivities reported here are Dhajala-normalized intensities.

Table 1. Induced TL data for eleven type 3 and type 4 ordinary chondrites*

Meteorite	Class	TL sensitivity (Dhajala=1)	Peak T (^{o}C)	Peak width (^{o}C)
Albareto	LL4	1.25±0.14	na	na
Bovedy #1	L4	0.025±0.009	191±16	155±16
Bovedy #2	"	0.028±0.005	182±9	151±8
Bo Xian	LL4	1.55±0.12	na	na
Cali #1	L/LL4	0.77±0.12	181±5	143±5
Cali #2″	"	1.56±0.07	180±7	145±2
Dhofar 658	L4/5	0.31±0.02	196±12	136±5
GRA 95215,8	H4	0.27±0.02	na	na
GRO 95541,7	H4	0.46±0.05	na	na
GRO 95541,8	"	0.73±0.03	211±3	144±4
Julesburg	L3.7	0.17±0.02	207±8	142±3
NWA 752	LL4/5	1.65±0.34	198±15	147±3
NWA 1974	LL4/5	0.76±0.04	190±5	133±3
WIS 91618,16	LL4	1.09±0.09	185±5	156±3
WIS 91618,17	"	0.93±0.09	203±8	149±3

* Uncertainties refer to 1σ determined from triplicate measurement of the same aliquot. Na means that data are not yet available. Types based only on TL sensitivity, see text for discussion of Bovedy.

Results: Our results are listed in Table 1. The TL sensitivity values range from 0.025 to 1.65, with all but Bovedy in the range appropriate for upper type 3 (3.7-3.8) through type 4 [4]. The Bovedy value is in the type 3.3 chondrite interval. Peak temperatures and peak widths are tightly clustered in the in upper part of the 3.5-3.9 field (Fig. 1).

Discussion: The TL data are essentially as expected on the basis of published properties for these meteorites, most especially their olivine and pyroxene heterogeneity. The one type 3 chondrite, Julesburg, has lower TL than all of the type 4s except Bovedy (Fig. 2), and also has the most heterogeneous olivine. The low TL value for Bovedy is significant and inconsistent with its type-4 classification. Bovedy is a well-known breccia, and contains igneous clasts that could easily have lower TL than the host [5]; it may be that both our chips came from such clasts, or even from type 3 clasts within the breccia, whereas our thin section clearly showed a type 4 lithology. We exclude Bovedy from the remainder of the discussion. Within type 4, there is no relationship between TL and olivine heterogeneity, although the range of PMD-Fa is very low and differences may not be significant.

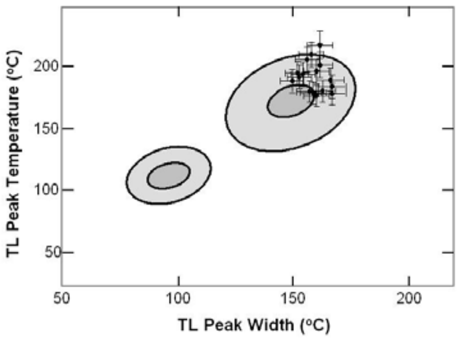

Fig. 1. Temperature-width data for the samples compared with the fields occupied by type 3.0-3.5 (lower field) and type 3.5-3.9 (upper field) ordinary chondrites [6]. The bulls-eyes refer to 1 sigma and 2 sigma fits to the data.

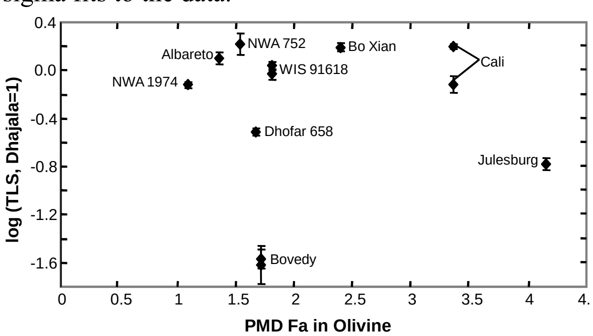

Fig. 2: The TL sensitivities of the present samples appear to be independent of olivine heterogeneity, although the spread on the olivine data is very small. The relatively low value of Bovedy and Julesburg are noted.

The range of pyroxene heterogeneity is much greater than that of olivine in the type 4 chondrites (Fig. 3), suggesting that it might be a better monitor of progressive metamorphism in these meteorites. There is a suggestion of a negative trend in TL sensitivity vs. pyroxene heterogeneity within type 4 (Fig. 3), with several chondrites near the type 4/5 boundary (e.g., Dhofar 658, NWA 1974) having somewhat lower TL, contrary to the known trend of increasing TL going from type 4 to types 5-6 [4]. More data are required before meaningful conclusions can be made.

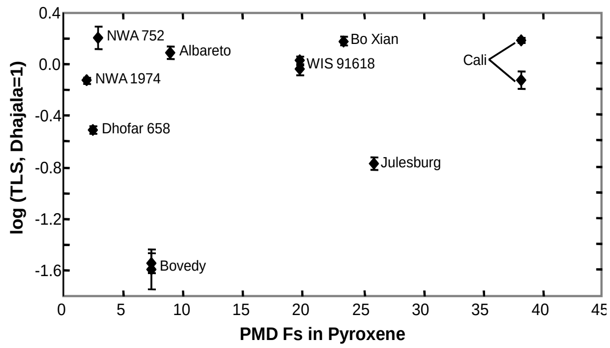

Fig. 3: The TL sensitivities of the present samples also appear to be independent of pyroxene heterogeneity, although pyroxene shows a large range of heterogeneities.

The tight clustering of the present data and their location on the peak temperature vs. peak width plot (Fig. 1) suggests that this plot may be capable of providing new information on the thermal history of these meteorites. The two fields on Fig. 1 refer to feldspar in the low-temperature (structurally ordered) form (lower field) and feldspar and in the high-temperature (structurally disordered) form, the transition temperature being ~500°C [6]. Precise placement in the upper field depends on the presence of minor amounts of low-T feldspar in meteorites in which the feldspar is predominantly in the high-T form. The relative proportion of these phases will depend on peak metamorphic temperatures and cooling rates. Thus the present suite of meteorites, mostly type 4 chondrites, as expected, must have experienced higher temperatures than most of the meteorites in the upper cluster (which range from type 3.9 to 3.5). These are issues we will explore as the database grows and we further integrate TL and mineralogical data.

Conclusions: The thermoluminescence properties of the meteorites studied here are all consistent with their literature classifications, the exception being Bovedy, for which we may have sampled anomalous material. We may be seeing trends in TL sensitivity and mineral heterogeneity, suggesting that metamorphic differences may be present in these essentially similar meteorites, and that fine structure may be present in the TL peak temperature - peak width plot that will provide new insights into the thermal history of ordinary chondrites. Further data will help resolve some of these issues.

References: [1] Huss et al. (2006) In *Meteorites and the Early Solar System* II, 567. [2] Dodd et al. (1967) *Geochim. Cosmochim. Acta* **31**, 921. [3] Van Schmus and Wood (1967) *Geochim. Cosmochim. Acta* **31**, 747. [4] Sears et al. (1980) *Nature* **287**, 791. [5] Rubin et al. (1981) *Geochim. Cosmochim. Acta* **45**, 2213. [6] Benoit et al. (2001) *American Mineralogist* **86**, 780.