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Chemical and physical studies of type 3 chondrites—VIII: Thermoluminescence and metamorphism in the CO chondrites

BRADLY D. KECK* and DEREK W. G. SEARS
Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, U.S.A.

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Abstract—The thermoluminescence properties of nine CO chondrites have been measured. With the exception of Colony and Allan Hills A77307 (ALHA 77307), whose maximum induced TL emission is at approximately 350°C, CO chondrites exhibit two TL peaks, one at 124 ± 7°C (130°C peak) and one at 252 ± 7°C (250°C peak). The 130°C peak shows a 100-fold range in TL sensitivity (0.99 ± 0.21 for Isna to 0.010 ± 0.004 for Colony), and correlates with various metamorphism-related phenomena, such as silicate heterogeneity, metal composition and McSween's metamorphic subtypes. The peak at 250°C does not show these correlations and, Colony excepted, varies little throughout the class (0.3 to 0.07, Colony 0.018 ± 0.004). Mineral separation experiments, and a series of annealing experiments on Isna, suggest that the TL properties for CO chondrites reflect the presence of feldspar in two forms, (1) a form produced during metamorphism, and analogous to the dominant form of feldspar in type 3 ordinary chondrites, and (2) a primary, metamorphism-independent form, perhaps associated with the amoeboid inclusions. If this interpretation is correct, then the CO chondrites have not experienced temperatures above the order/disorder temperature for feldspar (500–600°C) and they cooled more slowly than comparable (*i.e.* type <3.5) type 3 ordinary chondrites. Colony and ALHA 77307 have atypical TL properties, including very low TL sensitivity, suggesting that phosphors other than feldspar are important. They have apparently experienced less metamorphism than the others, and may have also been aqueously altered.

INTRODUCTION

OF ALL THE CHONDRITE classes, the carbonaceous chondrites most closely resemble the sun in composition. Some 33 are known, most of them have been well-studied (MCSWEEN, 1979). They are subdivided into CI, CM, CV and CO chondrites, primarily on the basis of bulk composition (VAN SCHMUS and HAYES, 1974; KALLEMEYN and WASSON, 1981). In VAN SCHMUS and WOOD's (1967) scheme of petrologic types, CI are all type 1, CM are all type 2 and CV and CO are primarily type 3. Although Van Schmus and Wood had metamorphism in mind when they developed their scheme (1 least metamorphosed, 6 most heavily metamorphosed), it is now clear that types 1 and 2 have been heavily altered by aqueous processes (DUFRESNE and ANDERS, 1962; BUNCH and KERRIDGE, 1979; MCSWEEN, 1979) and that type 3 chondrites most closely resemble the solid material that agglomerated in the primordial solar nebula.

In many respects, the CO chondrites resemble the type 3 ordinary chondrites. The major mineralogy is similar, and compositional and textural variations suggest that the CO chondrites have experienced a range of metamorphic intensities; MCSWEEN (1977) has suggested subdivision into types I, II and III on the basis of metamorphism experienced (I being least metamorphosed). The major silicate phases are olivines and low-Ca pyroxenes, whose heterogeneity decreases and FeO content increases (from Fa_{12} to Fa_{34} and Fs_3 to Fs_{11}) with increasing metamorphism. The metal phases are kamacite and taenite and the Co content of the kamacite increases, and the Cr content decreases, with metamorphism. Particularly important for our present purposes, the abundance of primary igneous glass in the chondrules decreases and the abundance of feldspar increases with increasing metamorphism (MCSWEEN, 1977, page 483, and pers. commun.).

There are a few ways in which the CO3 chondrites differ from the type 3 ordinary chondrites; they have a much finer texture, consisting of a great many small chondrites and inclusions packed in a dark matrix, and they have a much lower proportion of matrix to chondrules. They also contain significant quantities of amoeboid inclusions consisting of refractory minerals (diopside, spinel, and anorthite) and olivine (MCSWEEN, 1979).

Thermoluminescence (TL) has proved of great value in providing new insights into the metamorphic history of the type 3 ordinary chondrites (SEARS *et al.*, 1980; GUIMON *et al.*, 1985) and of chondrules from them (SEARS *et al.*, 1984; KECK *et al.*, 1986). This is apparently because metamorphism caused the crystallization of feldspar in chondrule glass, and feldspar is the dominant TL phosphor in all but a few (type <3.2) of the chondrites (GUIMON *et al.*, 1986). Furthermore the TL emission characteristics, in particular the temperature at which TL emission is at a maximum (the "peak temperature") and the range of temperatures over which TL is emitted (the "peak width" or full width at half maximum, FWHM), depends on the degree of order in the Al, Si of the feldspar chain. The low-temperature, ordered, phase has TL peaks of 120–160°C and widths of 80–120°C, while annealed terrestrial and

* *Present address:* University of Missouri, Research Reactor Facility, Columbia, MO 65211.

meteorite samples have TL peaks at 180–220°C and widths of 140–180°C (GUIMON *et al.*, 1985). These changes appear to be related to disordering of the initially ordered phase. Thus type 3.2–3.5 ordinary chondrites have not been above the order/disorder transformation temperature, while type >3.5 underwent most of their feldspar crystallization above that temperature. About 80% of the chondrules in Dhajala contain high-form feldspar, while the remainder have glow curves typical of low-form (KECK *et al.*, 1986).

In view of the mineralogical similarity of the CO and type 3 ordinary chondrites, and their potentially similar metamorphic history which caused glass devitrification in both types of meteorites, we have undertaken a study of the TL properties of the CO chondrite class in the hope that the technique may contribute to a quantitative understanding of the metamorphic history of this class.

EXPERIMENTAL

The meteorites, their sources and other details are given in Table 1. Allan Hills A77307 (ALHA 77307) and Colony were included here because the abundance of non-volatile, usually major, elements suggests that both meteorites are strongly CO-related, if not normal CO chondrites (KALLEMEYN and WASSON, 1982; SEARS and ROSS, 1983; RUBIN *et al.*, 1985). However, they have a number of unusual properties which has made their classification controversial (BISWAS *et al.*, 1981; SCOTT *et al.*, 1981; RUBIN *et al.*, 1985). The TL properties of these meteorites are also unusual, but in some respects can be considered an extension of the properties of the other CO chondrites to lower levels of metamorphism.

For TL measurement, two representative chips were coarsely ground, the magnetic material removed with a hand-magnet, and then ground again so as to pass through a 100-mesh sieve. TL apparatus manufactured by Daybreak Nuclear and Medical was modified by the addition of metering valves on the nitrogen and vacuum lines, silica gel capsules placed in the photomultiplier tube housing, a 4 mm Cu aperture and an EMI shutter placed between sample and photomultiplier. The high voltage to the photomultiplier tube is therefore interrupted only to replace the silica gel, typically once every 3–4 months, and this operation is performed in red light. Other important features of the apparatus are standard; a chromel-alumel thermocouple, EMI 9635 photomultiplier tube, and photon-counting electronics.

Samples weighing 4 mg were placed in a Cu pan, their natural TL drained by momentary heating to 500°C in the TL apparatus, and then exposed to a ^{90}Sr beta source until the adsorbed dose was about 25 krad. The samples were then placed in the TL apparatus again, the chamber evacuated to 100 μm, and filled with high-purity nitrogen which was allowed to pass through the apparatus during the measurement. Linear heating rates of 7.5°C/s were normally used, however some of the present data were obtained at 2.5°C/s in an attempt to improve peak resolution. Before and after a day's measurements, a sample of the Dhajala meteorite was run to check constancy in the apparatus and to act as a normalization standard for inter-laboratory comparison. At least three aliquants from each sample were measured, 3–5 curves being obtained each time. The values quoted are means, with uncertainties expressed as the standard deviations of replicate curves. In the case of TL sensitivity, the uncertainties have been compounded with those of Dhajala.

Mineral separations were performed to identify the TL phosphors in Isna, one of the samples with particularly high TL. The sample was ground, the magnetic material removed and the 100–200 mesh fraction collected. The density gradient method was used, with water as the light component and Clerici solution as the heavy component (MULLER, 1977); thus minerals with densities of 1.0–4.0 were collected. After settling overnight, six fractions were tapped off, filtered and washed in distilled water and acetone. The errors quoted for the TL data for the separates in Table 2 include the uncertainty for the mass determination.

Annealing experiments were performed in the manner described by GUIMON *et al.* (1985). 20 mg aliquants of non-magnetic powder were sealed in an inert atmosphere in quartz vials and annealed in a wire-wound tube furnace at 800°C for 200, 400 and 600 h.

Table 1. TL sensitivities and peak positions for the CO chondrites.*

Meteorite†	Source+	Cat. no.	TL sensitivity (Dhajala=1) 130°C peak	250°C peak	350°C peak	Peak Position (°C) ~130	~250	~350
Isna #1	CGM	---	1.3 ±0.2	0.25±0.03	---	127±18	253± 9	---
Isna #2	CGM	---	0.69±0.11	0.16±0.02	---	124± 6	247± 4	---
Warrenton	P	81d	0.40±0.07	0.11±0.02	---	121± 4	239± 4	---
77003, 12	MWG	12	0.35±0.06	0.2 ±0.02	---	132± 8	263± 7	---
77003, 55	MWG	55	0.33±0.06	0.11±0.03	---	124± 4	237± 6	---
Ornans #1	MHN	A581	0.093±0.014	0.13±0.03	---	122± 6	256± 6	---
Ornans #2	MHN	A581	0.13±0.03	0.14±0.085	---	130± 4	264± 4	---
Lance #1	MHN	27	0.16±0.03	0.16±0.03	---	115± 6	259± 6	---
Lance #2	MHN	27	0.16±0.03	0.14±0.03	---	120± 6	265± 6	---
Felix #1	SI	235	0.072±0.011	0.086±0.03	---	115± 6	245± 6	---
Felix #2	SI	235	0.11±0.02	0.13±0.02	---	122± 5	259± 7	---
77307 #1	MWG	27	0.036±0.007	---	0.44±0.06	130± 7	233± 7	334± 8
77307 #2	MWG	27	0.030±0.006	0.071±0.008	0.214±0.03	130± 9	237± 8	355± 9
Kainsaz #1	Me	2654	0.24±0.03	0.26±0.03	---	116± 6	250± 8	---
Kainsaz #2	Me	2755	0.14±0.02	0.22±0.04	---	120± 6	263± 7	---
Colony	JW	---	0.010±0.004	0.018±0.004	0.015±0.006	135± 7	257± 8	337±14

* Errors quoted are 1 sigma errors for each measurement.

† 77003 and 77307 should be preceded by 'Allan Hills A'.

+ MWG, Meteorite Working Group of NASA/NSF; SI, National Museum of Natural History (Smithsonian Institution) (R.S. Clarke); CGM, Cairo Geological Museum (R.A. Eissa); Me, Field Museum of Natural History, Chicago (E. Olsen); MHN, Museum National D'Historie Naturelle, Paris (P. Pellas); P, Peabody Museum, Yale University (K. Turekian); JW, Jim Wescott, Sedona, Arizona.

Table 2. TL sensitivities and masses for the mineral separates (from a 20 mg sample) and bulk powder (prepared in the same manner as the mineral separates) from the Isna meteorite.*

Fraction Number†	Mass (mg)	TL Sens. (Bulk Isna=1)
1	0.2 ± 0.1	0.098 ± 0.002
2	0.5 ± 0.1	0.178 ± 0.006
3	12.1 ± 0.1	2.66 ± 0.067
4	5.9 ± 0.1	3.48 ± 0.189
5	1.4 ± 0.1	0.834 ± 0.025
6	0.8 ± 0.1	0.552 ± 0.038
Bulk	1.2 ± 0.1	1.0 ± 0.08

* Uncertainties are one sigma on 3 measurements of a single sample.

† 1-6 refers to fractions of decreasing density in density range 4.2-1.0 g/cm^3.

RESULTS

The TL data for the CO chondrites are listed in Table 1. The data from the SEARS and ROSS (1983) study have been averaged in with the present data after correction for a systematic error in the temperature calibration and differences in heating rate. The glow curves usually exhibited two peaks, one at about 130°C and the other at about 250°C (Fig. 1). The two peaks varied considerably in relative intensity (Fig. 2), the ratio of the 130 to the 250°C peak varied from 5.2 for Isna to about 1.0 for Felix and virtually zero for Colony and ALHA 77307. However, the positions of these two peaks, when present, were remarkably constant from meteorite to meteorite (Fig. 3); the mean peak temperatures and standard deviations for all samples are 124 ± 7°C and 252 ± 7°C. ALHA 77307 and Colony have unusual glow curves, essentially because of a relatively strong additional peak at 342 ± 10°C (Fig. 1). The cathodoluminescence properties of these meteorites show clearly that this additional peak is due to different phosphors becoming important, which may either reflect the little-metamorphosed nature of these meteorites or the influence of aqueous alteration (see below).

Thermoluminescence sensitivities show a 100-fold range throughout the class (Fig. 4), varying from a Dhajala-normalized value of 0.99 ± 0.21 in Isna to 0.01 ± 0.004 in Colony. This compares with the 10^3-fold range in the type 3 ordinary chondrites. The 250°C peak shows very little variation except for Colony which is about an order of magnitude lower than the others.

The mineral separation data are listed in Table 2 and the mass-normalized TL sensitivities for each fraction are plotted in Fig. 5. The small mass of fraction 1 (the densest fraction) results in error bars too large

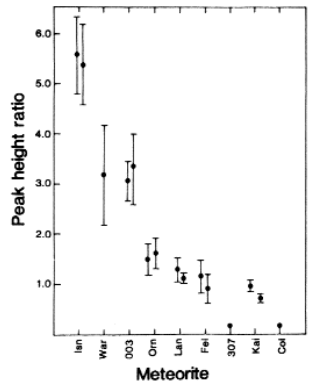

FIG. 2. Ratio of the intensity of the 130°C peak to that of the 250°C peak. Meteorites are identifield by the first three letters or last three numbers of their names (see Table 1). The variation in the ratio is determined primarily by changes in the intensity of the 130°C peak.

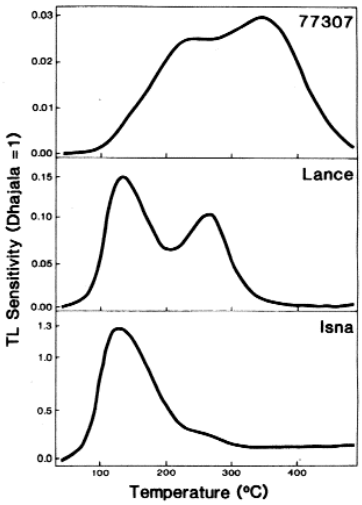

FIG. 1. Representative glow curves (TL against temperature) for the CO chondrites. Warrenton and Allan Hills A77003 (ALHA 77003) have curves similar to Isna's, with a strong 130°C peak; Ornans, Felix and Kainsaz have curves similar to that of Lance with strong peaks at 130 and 250°C; and, Colony has a glow curve similar to that of Allan Hills A77307 (ALHA 77307) with a dominant peak at about 350°C.

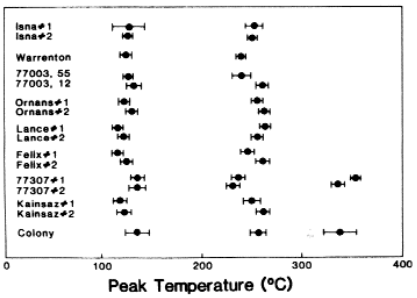

FIG. 3. Plot showing the positions of peaks and inflections in the glow curves of CO chondrites. Uncertainties refer to the standard deviations shown by 3–5 replicate measurements on 3 aliquants. All samples have peaks or inflections at 130 and 250°C, but only Colony and ALHA 77307 have peaks at 350°C.

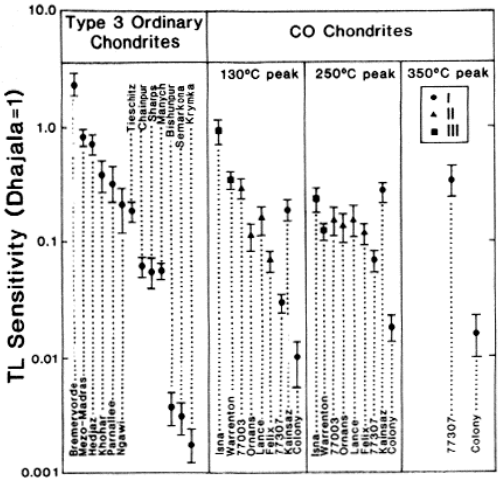

FIG. 4. The TL sensitivities of CO chondrites compared with those of type 3 ordinary chondrites. One sigma errors. The range of TL sensitivity for type 3 ordinary chondrites is almost 10 times that of the CO chondrites. The TL sensitivity of the 130°C peak vary over 2 orders of magnitude, while the TL sensitivity of the 250°C shows less than a factor of 4 variation, Colony excepted. Also indicated are McSween's petrologic subtypes I, II and III, where I refers to the least metamorphosed type.

for meaningful use of the data, but the other relatively dense fractions (numbers 2 and 3), which contain the bulk of the mass, have significantly lower TL sensitivity than the three less-dense fractions. Therefore, although the separation we achieved is rather poor, it does serve to show that the phosphor is located in the light fractions which contain the smaller fraction of the mass. We are concerned that none of the separates had a mass-normalized TL sensitivity $\gg 1.0$. This probably reflects the considerable heterogeneity of the meteorite; it is unlikely that it indicates missing high-TL sensitivity material since the total mass of the separates is the same, within experimental uncertainties, as the original mass. More clearly, the separation data provided no evidence that the phosphor responsible for the 130°C

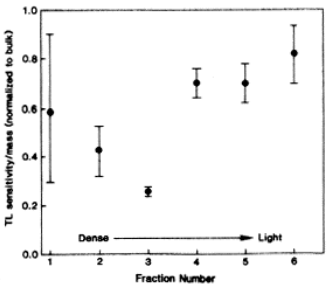

FIG. 5. The TL sensitivity per unit mass (normalized to the same quantity for the bulk meteorite) for fractions of Isna taken from a density gradient column. The TL phosphor is apparently located in the lower density fractions.

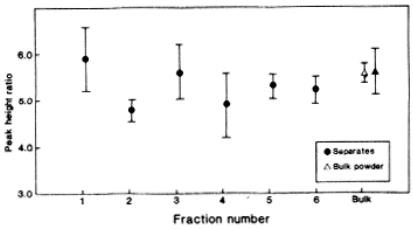

FIG. 6. Ratio of the height of the 130°C peak to that of the 250°C peak for each separate taken from the density gradient column. The open triangle refers to an unseparated sample, otherwise prepared in the same manner as the separates, and the triangle refers to bulk powder measured in the usual way. All fractions have a ratio identical to the unseparated powder, indicating that the procedure did not separate the phosphors responsible for the two peaks. Either the same mineral is responsible for both peaks, or the minerals responsible for each peak have similar densities. The data in Fig. 7, and other data, suggest that feldspar is responsible for both peaks.

peak differs from that responsible for the 250°C peak, as all separates have a ratio of the 130°C peak to that of the 250°C identical to the bulk powder within experimental uncertainty (Fig. 6). Even if mass had been lost in the separation, or if very poor separation had been achieved, one would expect some change in the peak height ratio were the two peaks due to entirely different minerals.

The results of the annealing experiment are shown in Table 3 and plotted in Fig. 7. The TL sensitivity decreased by nearly an order of magnitude, from 0.99 ± 0.24 to 0.11 ± 0.02, after annealing at 800°C for 600 h, while the peak temperature increased from 127 ± 6°C to 192 ± 29°C and the peak width increased from 90 ± 8 to 213 ± 28°C.

DISCUSSION

Thermoluminescence and metamorphism

We are primarily interested in a possible relationship between the TL properties of the CO chondrites and their metamorphic history. McSween's metamorphic subtypes are indicated on Fig. 4 (assignments from MCSWEEN, 1977; SCOTT *et al.*, 1981; RUBIN *et al.*, 1985). For the 130°C peak, type III tend to lie at the top end of the range with type I at the bottom and type

Table 3. TL sensitivities, peak temperatures, and peak widths for Isna annealed at 800°C for the times indicated.*

Annealing Time (h)	TL Sens. (Dhajala=1)	Peak Temp. (°C)	Peak Width (°C)
Unannealed	0.99 ± 0.24	127 ± 6	90 ± 8
200	0.27 ± 0.04	111 ± 2	109 ±18
	0.24 ± 0.03	161 ± 2	213 ±23
400	0.29 ± 0.03	158 ± 4	140 ± 6
600	0.13 ± 0.02	186 ±26	239 ±20
	0.08 ± 0.01	198 ±13	188 ±20

* Uncertainties are 1 sigma for triplicate measurements of a single sample.

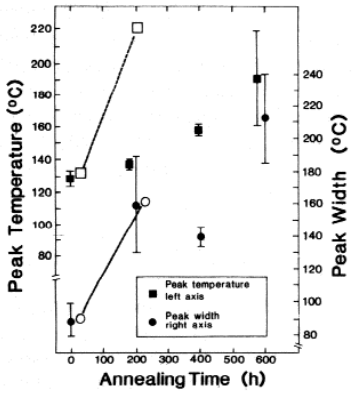

FIG. 7. The results of an annealing experiment performed on Isna. The temperature of the TL peak (left axis) and the width of the TL peak (right axis) are plotted against the time for which the sample was heated at 800°C. Also shown (larger, open symbols) are data for the ALHA 77011 type 3.4 ordinary chondrites before and after annealing at 900°C for 200 h (GUIMON *et al.*, 1985).

II being intermediate. An exception is Kainsaz, which has a TL sensitivity comparable with three type II chondrites. The 250°C peak probably does not show this trend, meteorites of all metamorphic subtypes, except Colony, having comparable TL sensitivity. The

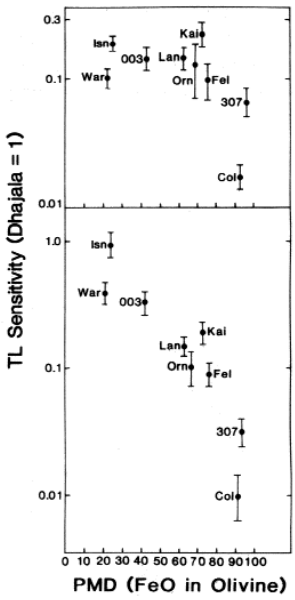

FIG. 8. TL sensitivity against silicate heterogeneity expressed as the percent mean deviation for the Fa in the olivine. (This is related to standard deviation in the way discussed by SCOTT, 1984, and SEARS and WEEKS, 1983.) The 130°C peak decreases in sensitivity as silicate heterogeneity increases, while the 250°C peak is independent of silicate heterogeneity. The TL sensitivity of the 250°C peak for Colony is about a factor of ten lower than the others.

weak suggestion of a trend that may be present in the 250°C peak probably reflects overlap with the 130°C peak. The 350°C peak correlates with metamorphism in as much as it is only present in two type I chondrites.

With a few exceptions, the individual metamorphism-sensitive properties show the trends predicted by the trends between TL sensitivity and McSween's subtypes. Olivine heterogeneity increases steadily with decreasing TL sensitivity for 130°C peak, but the 250°C peak is unrelated to this parameter (Fig. 8). We have considered the effect of the amoeboid inclusion abundance on these trends, since it is known that refractory inclusions in carbonaceous chondrites show significant levels of TL (SEARS and MILLS, 1974). In Fig. 9 we plot TL sensitivity for each peak against amoeboid inclusion abundance. The 130°C peak shows a weak positive correlation, while the 250°C shows little, if any, evidence for a correlation. Apparently, at least some of the variation in the intensity of the 130°C peak could be attributed to phosphors in the inclusions; however, the variation in the amount of inclusions is not alone adequate to explain the full 100-fold range in TL sensitivity for the class. When the amoeboid-inclusion-normalized TL sensitivity is plotted against silicate heterogeneity (Fig. 10), the trend shown by the 130°C peak is still present; in fact there is a very small increase in the correlation coefficient (−0.91 without, and −0.93 with, the normalization). The indirect relationship between metamorphism and amoeboid inclusion abundance was observed by RUBIN *et al.* (1985), who suggested possible mechanisms for achieving such a relationship.

Metal composition also shows the trends expected for metamorphic equilibration, assuming that the 130°C is metamorphism-related and the 250°C peak is not (Fig. 11). The Cr content of the kamacite decreases, with decreasing TL sensitivity, while the Ni and Co contents increase. These trends could reflect

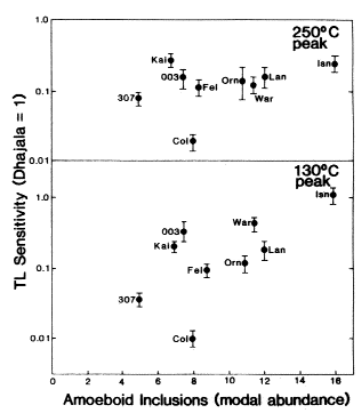

FIG. 9. TL sensitivity against the modal abundance of amoeboid inclusions in CO chondrites (MCSWEEN, 1977; RUBIN *et al.*, 1985). The 130°C peak shows a positive correlation, whereas the 250°C peak shows little, if any, correlation.

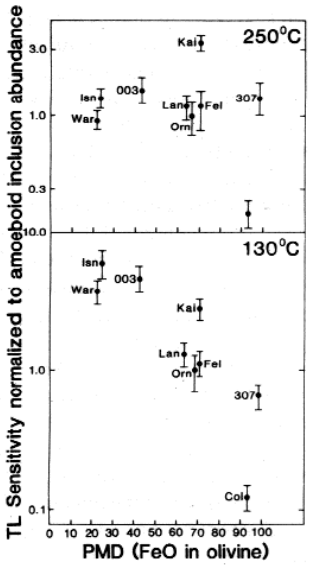

FIG. 10. TL sensitivity normalized to the abundance of amoeboid inclusions plotted against the heterogeneity of the silicates. The normalization was performed to remove any effect on the TL sensitivity of variations in the number of amoeboid inclusions. Correlation of the 130°C peak is still evident.

the removal of the more lithophile Cr and resultant enrichment in Fe and Ni. However if this were the only process affecting metal composition we would expect a constant Fe/Ni ratio for the kamacite and this is not observed. An additional process is probably the equilibration of kamacite and taenite, in which case the Ni content of the kamacite provides an independent indication of metamorphic temperature. The Ni-Fe phase diagram of MOREN and GOLDSTEIN (1978) predicts that kamacite equilibrating with taenite over a series of increasing temperatures, below 400°C, would have increasing Ni content. Above 400°C, the saturation level of Ni in the kamacite decreases with increasing temperature.

Thermoluminescence and bulk composition

Carbon and the inert gases show variations in abundance in ordinary chondrites which are related to petrologic type, although the physical processes behind this relationship are controversial (LARIMER and ANDERS, 1967; DODD, 1969; IKRAMUDDIN *et al.*, 1977). Several trends are displayed in the TL sensitivity *vs.* carbon and TL sensitivity *vs.* inert gas plot for CO chondrites, but again the 130°C peak is involved and not the 250°C peak. Figure 12 compares TL sensitivity with bulk carbon content, while Fig. 13 compares TL sensitivity with the inert gas data. Carbon abundance increases with decreasing TL sensitivity, as it does in the case of the ordinary chondrites. ^{20}Ne probably behaves like carbon, however, ^{36}Ar shows no correlation with the 130°C TL peak, while there may be a slight positive correlation between ^{36}Ar and the 250°C peak. Similarly, ^{132}Xe and TL sensitivity show no significant correlations. Data for the highly volatile elements, In and Tl, which show 10^3-fold variations in abundance with petrologic type in ordinary chondrites, are very meager and conclusions may be premature. On the basis of present data, they show no correlations with McSween's subtypes or with TL sensitivity.

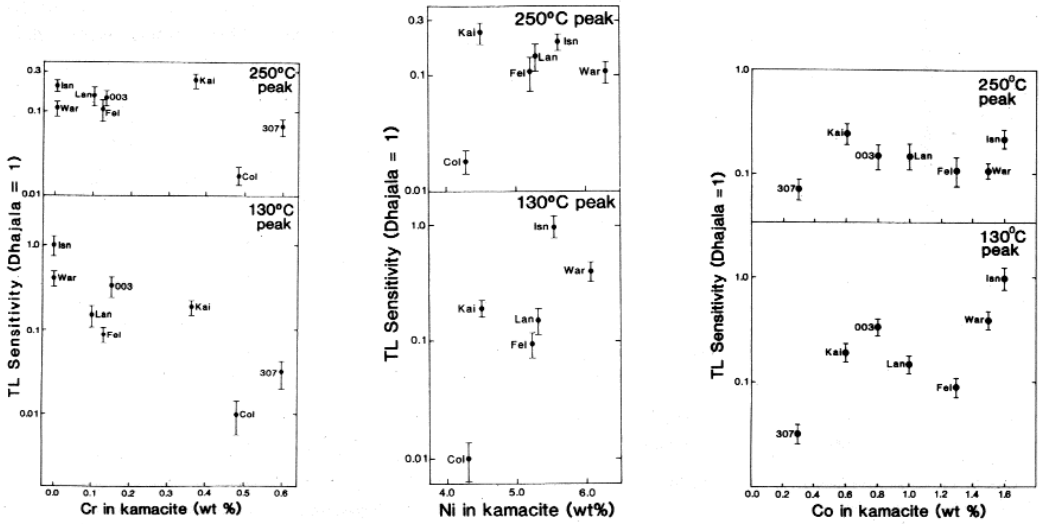

FIG. 11. TL sensitivity plotted against metal composition (MCSWEEN, 1977; RUBIN *et al.*, 1985). The 250°C peak shows no significant trends, but the 130°C peak shows the following: (a) Cr in the kamacite decreases with decreasing TL sensitivity; (b) Ni in the kamacite increases with increasing TL sensitivity; (c) Co in the kamacite behaves like Cr. The binary phase diagrams for Fe-Cr, Fe-Ni, and Fe-Co indicate that these trends could reflect equilibration at a range of temperatures increasing along the sequence Colony-Lance-Isna, but all below 400°C.

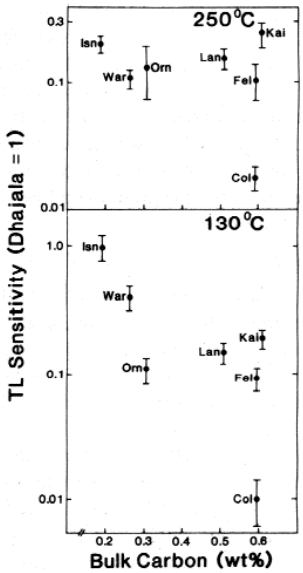

FIG. 12. TL sensitivity against carbon abundance (MCSWEEN, 1977; RUBIN *et al.*, 1985). The 130°C peak shows a negative correlation between the two parameters while the 250°C peak shows no correlation.

Causes of the TL sensitivity variations

The mechanism behind the variation in the intensity of the 130°C peak with metamorphism is most plausibly the same as that involved in the type 3 ordinary chondrites; and it is that which caused us to look for metamorphism-related TL sensitivity changes in CO chondrites: namely, the formation of feldspar by the crystallization of glass. MCSWEEN (1977) observed glass in certain CO chondrites, and photographs of the cathodoluminescence of Isna show that chondrule mesostasis is an important source of CL, and therefore very probably also an important source of TL (KECK and SEARS, 1986). The insensitivity of the 250°C peak to metamorphism implies the presence of the associated phosphor in its present form prior to metamorphism. The amoeboid inclusions are an obvious candidate for the carrier of the material for the 250°C peak, since they are known to be important carriers of TL phosphors and are present in the CO chondrites and virtually absent in the type 3 ordinary chondrites. The mineral separation data are consistent with the phosphor being feldspar, which should be in the lowest density fraction, and with the same mineral being responsible for both TL peaks.

More complicated explanations are possible: for example, that the TL is coming from a single mineral phase which has both a metamorphism sensitive and a metamorphism-insensitive peak. This behavior is not displayed by any important meteorite mineral, certainly not feldspar, although quartz has been known to behave this way (S. SUTTON, pers. commun.).

Thermal history of CO chondrites and petrologic type assignment

Our TL data have implications for our understanding of the thermal history of the CO chondrites. Also indicated on Fig. 7 are data for samples of the type 3.4 ordinary chondrites ALHA 77011, before and after annealing at 800°C. The ordinary chondrite showed a similar increase in peak temperature and width upon annealing, although apparently at a faster rate, which is associated with the onset of disordering (GUIMON *et al.*, 1985). On a plot of peak temperature against width (Fig. 14), the type >3.2 ordinary chondrites plot in two fields—a low cluster of type 3.2–3.5 and an upper cluster of type 3.6–3.9—which reflect meteorites whose feldspar is predominantly in the low or high forms. Isna moved from one field to the other as the order/disorder temperature was reached.

The 130°C peak of the CO chondrites is apparently due to feldspar in the low-temperature form and therefore the crystallization of the chondrule glass occurred predominantly below the order/disorder temperature. While this was also the case for ordinary chondrites of type <3.6 (GUIMON *et al.*, 1985), the TL sensitivity of type 3.5 ordinary chondrites is only ~0.2 (SEARS *et al.*, 1980). Presumably the CO chondrites, with TL

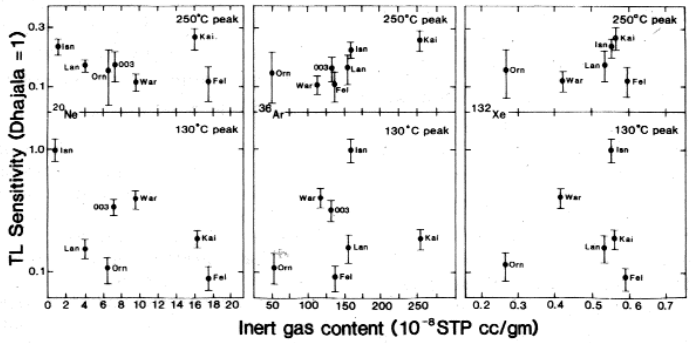

FIG. 13. TL sensitivity against inert gas abundances (SCHULTZ and KRUSE, 1983; MAZOR *et al.*, 1970). ^{20}Ne shows behavior similar to C, but ^{36}Ar and ^{132}Xe show no correlation.

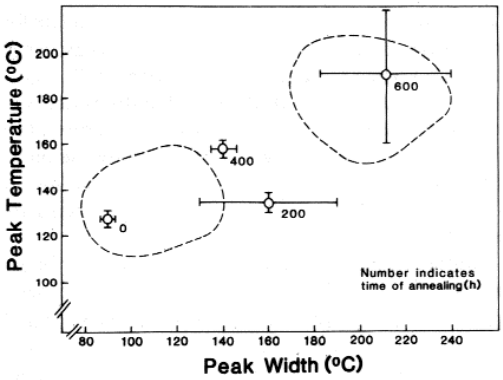

FIG. 14. TL Peak temperature against peak width for samples of Isna annealed at 800°C for the time indicated by each data point (h). The fields indicated by broken lines refer to the fields occupied by type 3.2–3.5 (lower left) and by type 3.5 and 3.9 (upper right). The Isna data start in the lower field and after annealing move to the upper field. GUIMON *et al.* (1985) have identified the lower field with low-temperature feldspar and the upper field with feldspar showing the onset of disordering. The behavior is qualitatively very similar to that of a type 3.4 similarly annealed (see Fig. 7).

sensitivities as high as 1.0 ± 0.2 (Isna), cooled more slowly than the ordinary chondrites and experienced greater crystallization of the glass at temperatures below the order/disorder transformation temperature. The TL "peak" in ordinary chondrites is known to be a composite of several discrete peaks, some identified with the high-form and some with the low; the TL properties of bulk samples reflect the relative proportions of both forms (KECK *et al.*, 1986). Two discrete peaks, such as observed for the CO chondrites, are not observed for the ordinary chondrites, presumably since both high and low forms are compositionally identical and both formed by divitrification of the same starting material. For the CO chondrites, the high form is compositionally different to the low form and primary in the origin.

Cooling rate estimates (for the temperature interval 400–500°C) based on Ni profiles in several type 3 ordinary and CO chondrites of the taenite, were determined by WOOD (1967). The calculations make many assumptions, the most significant being that all the kamacite and taenite grains measured are at thermodynamic equilibrium in these primitive meteorites. Not surprisingly, Krymka and Bishunpur (both type 3.1) completely fail to yield coherent composition-dimension plots. Mezo Madaras and Tieschitz (type 3.2 and 3.6, respectively) have cooling rates of ~1°C/Ma, while the CO chondrites Felix and Lance yield cooling rates of 0.3°C/Ma and 0.1–1.0°C/Ma, respectively. The type 3.4 ordinary chondrite Chainpur yields a value of 0.2°C/Ma. Although meagre, and subject to uncertainty over the extent of equilibrium, these data are consistent with the conclusions based on the present TL data that CO chondrites cooled more slowly than ordinary chondrites that have experienced comparable temperatures (*i.e.* type 3.2–3.5).

It would be convenient if the CO chondrites could be included in the 3.0–3.9 scheme used for ordinary chondrites. However, since the cooling history of the two classes are different it is unclear how this can be achieved in an unambiguous way. For example, on the basis of TL sensitivity Isna would be assigned to type 3.8, which implies temperature above the order/disorder temperature, but the presence of low-temperature feldspar in Isna precludes this.

AQUEOUS ALTERATION IN COLONY?

The low values for the TL of both the 130°C and 250°C peaks for Colony, and the unusual glow curves for both Colony (and ALHA 77307), suggest some special process has been involved. The low values for the 130°C peak are most readily interpreted as a result of the low levels of metamorphism experienced, but the low value of the 250°C in Colony cannot be interpreted this way as the peak is metamorphism-insensitive. If our interpretation is correct, and the 250°C peak is due to primary feldspar, then its low value in Colony reflects destruction by some means. The cathodoluminescence properties of Colony are very different to the other CO chondrites, the meteorite consisting of essentially only red phosphors while the others consist mainly of blue phosphors located in the chondrule mesostasis and amoeboid inclusions (KECK and SEARS, 1986). The abundant amoeboid inclusions in Colony have apparently been altered so as to convert the major CL from blue to red. Aqueous alteration seems a plausible mechanism, since the CL of Colony resembles that of Bishunpur whose TL properties may well reflect this process (GUIMON *et al.*, 1986). Colony is highly weathered, and has certainly experienced terrestrial aqueous alteration; however, traces of red CL can be seen in the matrix of Lance, an unweathered fall, while ALHA 77003, with a similar weathering history to that of ALHA 77307, shows only very minor traces of matrix with red CL. It seems at least plausible that the aqueous alteration is extraterrestrial. Although effects due to aqueous alteration are well documented for the CI and CM chondrites, petrographic observations of such a process in CV and CO chondrites are sparse. BUNCH and CHANG (1979) described possible aqueous alteration effects in the Allende meteorite, and KERRIDGE (1972) has described Fe-rich regions in porphyritic olivine chondrules which may be due to fluid transport of iron in the Warrenton CO chondrite. Such regions are common in metamorphosed CO chondrites (E. SCOTT, pers. commun.).

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