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METAMORPHISM OF CO AND CO-LIKE CHONDRITES AND COMPARISONS WITH TYPE 3 ORDINARY CHONDRITES

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Abstract: In order to explore their metamorphic history, thermoluminescence data have been obtained for 10 CO or CO-related chondrites from the Antarctic. Six have TL properties indicating low to intermediate levels of metamorphism, while Lewis Cliff 85332 and three paired meteorites from MacAlpine Hills (87300, 87301 and 88107) have unusual TL properties similar to those of the very primitive Colony and Allan Hills A77307 CO-related chondrites. Cathodoluminescence photomosaics of nine well-studied CO chondrites are also presented and compared with similar data for the type 3 ordinary chondrites in which CL properties vary systematically with metamorphism. It is concluded that the CO chondrites, like the ordinary chondrites, form a metamorphic sequence and may be subdivided in an analogous manner using TL, CL and other petrographic and compositional data. Definitions for CO chondrites of the petrologic types 3.0–3.9 are proposed. However, it is stressed that the thermal history of the CO and ordinary chondrites is quite different, the range of equilibration for the CO chondrites is similar to the ordinary chondrites, but the former have not experienced temperatures above those experienced by type 3.5 ordinary chondrites (probably around 600°C). Presumably the CO chondrites spent longer times at lower temperatures. A CL photomosaic of Murchison is also presented, which has two features in common with the type 3.0–3.1 CO and ordinary chondrites; type I chondrules whose mesostases produce yellow CL (due to an unidentified but highly metamorphism-sensitive phase) and fine-grained matrix with red CL due to forsterite. Haloes of matrix material around chondrules and other objects in Murchison are thought to be due to aqueous destruction of those objects, and Fe-zoning in olivines in chondrules with broad haloes is also throught to be due to aqueous processes.

1. Introduction

The CO chondrites are similar to type 3 ordinary chondrites in several respects. They are both chondritic in bulk composition, with non-volatile elemental abundances generally within about 30% of the CI values. Thus the two groups are mineralogically very similar, consisting of olivine, pyroxene, plagioclase, metal and sulfide. Like the ordinary chondrites the CO chondrites appear to constitute a metamorphic sequence (MCSWEEN, 1977; KECK and SEARS, 1987; SCOTT and JONES, 1990). However, they also differ from ordinary chondrites in several respects. They are isotopically different (CLAYTON *et al.*, 1976; CLAYTON and MAYEDA, 1984), element ratios show small but significant differences (ANDERS *et al.*, 1976; KALLEMEYN and WASSON, 1981), they contain refractory amoeboid inclusions, and their chondrules are smaller (MCSWEEN, 1977; RUBIN, 1989). Unlike type 3 ordinary chondrites, CO chondrites often contain primary calcic feldspar (VAN SCHMUS, 1969), presumably associated with the refractory inclusions.

VAN SCHMUS (1969) also pointed out that olivine composition and heterogeneity varied considerably within the CO chondrite class, and MCSWEEN (1977) used this and other evidence to argue that the CO chondrites form a metamorphic sequence. He separated them into type I (least metamorphosed), type II and type III. Along the type I-type III sequence, olivines and pyroxenes increase in FeO and become less heterogeneous compositionally, kamacite increases in Ni and Co and decreases in Cr textures become blurred, chondrule mesostases become turbid, and rare gases decrease in abundance. KECK and SEARS (1987) also found that the thermoluminescence (TL) sensitivity of the 120°C peak increased by a factor of 100 with increasing metamorphism, while the TL sensitivity of a second TL peak at 230°C was not metamorphism-dependent. They suggested that the first peak was caused by feldspar formed by devitrification of chondrule glass, a situation analogous to that of type 3 ordinary chondrites (GUIMON *et al.*, 1985, 1988), while the 230°C peak was due to primary (*i. e.* non-metamorphic) feldspar, perhaps associated with refractory inclusions. Most recently, SCOTT and JONES (1990) have used mineral and phase compositions, and the TL sensitivity of the 120°C peak, to sort the CO chondrites into petrographic types 3.0–3.7, analogous to the type 3 ordinary chondrites (SEARS *et al.*, 1980). However, there is also a danger that real and important differences in the thermal history of the two classes will be neglected (KECK and SEARS, 1987).

Cathodoluminescence (CL) petrography has also proved very effective in visually assessing the mineralogical and petrological changes occurring along the metamorphic series of ordinary chondrites because CL responds to the same, or very similar, mineralogical changes that give TL its very strong metamorphism-dependence (DEHART *et al.*, 1987; SEARS *et al.*, 1989). CL studies are also useful in determining the widescale distribution of grains that are too small to analyze easily. Recent compilations of CL data for terrestrial rocks (MARSHALL, 1988) and meteorites (STEELE, 1989a), and detailed studies of the CL of unequilibrated chondrites (STEELE, 1986, 1989a; DEHART and SEARS, 1985; DEHART *et al.*, 1987, 1988, 1990), provide a useful basis for interpreting trends in the CL properties of primitive meteorites.

There is not unanimous agreement as to whether the petrologic types of the chondrite classes represent closed-system parent-body metamorphism, or whether equilibration was determined by pre-accretionary nebula processes (REID and FREDRIKSSON, 1967; FREDRIKSSON, 1983; DODD, 1969). Correlations between the abundance of amoeboid olivine inclusions, chondrule size and petrologic type, indicate some role for pre-accretionary processes in the history of CO chondrites (RUBIN *et al.*, 1985; RUBIN, 1989). Similarly, it is not entirely clear whether some compositional profiles in chondrule olivines reflect significant interaction with the nebula gas prior to accretion, or were due to metamorphic equilibration (PECK and WOOD, 1987; HUA *et al.*, 1988; HEWINS, 1989; KURAT, 1988; HOUSLEY and CIRLIN, 1983; SCOTT and JONES, 1990), or even aqueous processes (KERRIDGE, 1972). The usefulness of the petrologic types is not dependent on these conclusions, but our new data bear on some of these points.

Some authors have argued that Colony and Allan Hills A (ALHA)77307 are not normal CO chondrites, but members of other classes, or intermediate to existing classes (BISWAS *et al.*, 1981; SEARS and ROSS, 1983; KALLEMEYN and WASSON, 1981). These two meteorites have extremely low TL sensitivities, suggesting that they are especially primitive. The TL curves for Colony and ALHA77307 contain an additional peak at 350°C, reminiscent of curves produced by Allende CAI (SEARS and MILLS, 1974; GUIMON and SEARS, 1986). Other authors have argued that they are particularly primitive members of the CO chondrite class, and that this class is more varied in its properties than previously realized (SCOTT *et al.*, 1981; RUBIN *et al.*, 1985; KECK and SEARS, 1987). Lewis Cliff (LEW)85332, and three meteorites from MacAlpine Hills (MAC87300, 87301 and MAC88107), are primitive carbonaceous chondrites that resemble Colony and ALHA77307 in their TL properties (SEARS *et al.*, 1990). MASON (1987) suggested that LEW85332 was a CO chondrite, while RUBIN and KALLEMEYN (1990) have concluded that it is a unique carbonaceous chondrite. The MacAlpine Hills meteorites are CM chondrites, two of which, MAC87300 and MAC87301, were paired by MASON (1988, 1989). Induced TL and other data suggest that all three MacAlpine Hills meteorites are paired (SEARS and SEARS, 1990). These MacAlpine samples, and LEW85332, have very similar TL properties to Colony and ALHA77307 and unlike 17 other CM chondrites (SEARS *et al.*, 1991).

In the present paper, we report new induced TL data for 10 Antarctic meteorites, six normal CO chondrites (ALH82101, ALH85003, Yamato (Y)-82094, Y-791717, Y-81020 and Y-82050) and the four new samples whose induced TL properties resemble those of Colony and ALHA77307, and we present CL photomosaics of the Murchison CM chondrite and of nine representative CO chondrites. We are particularly interested in the degree of similarity in the metamorphic history of the CO3 and type 3 ordinary chondrite classes, in the development of a quantitative means of metamorphic subdivision of the CO chondrites and in the significance of the apparently anomalous primitive CO and related chondrites.

2. Samples and Experimental Procedures

Table 1 lists the present induced TL samples. The procedures and apparatus for our induced TL measurements were recently described by SEARS *et al.* (1991). The samples we used for our CL studies and their sources are listed in Table 2. We used a Nuclide Corporation 'Luminoscope' attached to an Olympus optical microscope with an electron beam of 14 ± 1 keV and 7 ± 1 μA, a 35 mm Camera and Kodak VR400 film (C-40 development process), and exposures of 1.5–3.5 min. Each CL mosaic consists of 30–40 images.

3. Results

Induced TL data for the present samples are listed in Table 1. These data replace the preliminary data presented at the 15th Symposium on Antarctic Meteorites since

Table 1. Induced thermoluminescence data for CO and CO-like chondrites.[*1]

Meteorite[*2]	Source[*3]	TL sensitivity (Dhajala=1)			Peak temperature (°C)		
		Peak 1	Peak 2	Peak 3	Peak 1	Peak 2	Peak 3
ALH82101,12	MWG	0.33 ±0.095	0.07 ±0.01	—	138±21	268±26	—
ALH82101,13	MWG	0.2 ±0.1	0.041 ±0.009	—	134±18	270±26	—
ALH85003,2	MWG	0.28 ±0.08	0.05 ±0.02	—	118±11	266±25	—
ALH85003,18	MWG	0.15 ±0.07	0.031 ±0.008	—	117±11	267±25	—
Y-82094,95	NIPR	0.188 ±0.041	—	—	137±1	—	—
Y-791717,93	NIPR	0.072 ±0.006	0.019 ±0.02	—	120±3	232±2	—
Y-81020,25	NIPR	0.07 ±0.02	0.082 ±0.018	0.055 ±0.012	125±13	216±1	321±6
Y-82050,75	NIPR	0.054 ±0.008	0.019 ±0.02	—	116±8	231±7	—
LEW85332,13	MWG	0.0098 ±0.0005	0.017 ±0.002	0.016 ±0.001	120±11	258±25	412±40
LEW85332,2	MWG	0.0010 ±0.0008	0.019 ±0.004	0.018 ±0.005	119±11	240±25	395±36
MAC88107,3	MWG	0.02 ±0.01	0.07 ±0.04	0.07 ±0.04	125±13	202±3	392±10
MAC87301,3	MWG	0.03 ±0.02	0.07 ±0.03	0.07 ±0.03	125±13	210±11	300±10
MAC87300,3	MWG	0.012 ±0.003	0.031 ±0.002	0.032 ±0.005	125±13	212±7	311±7

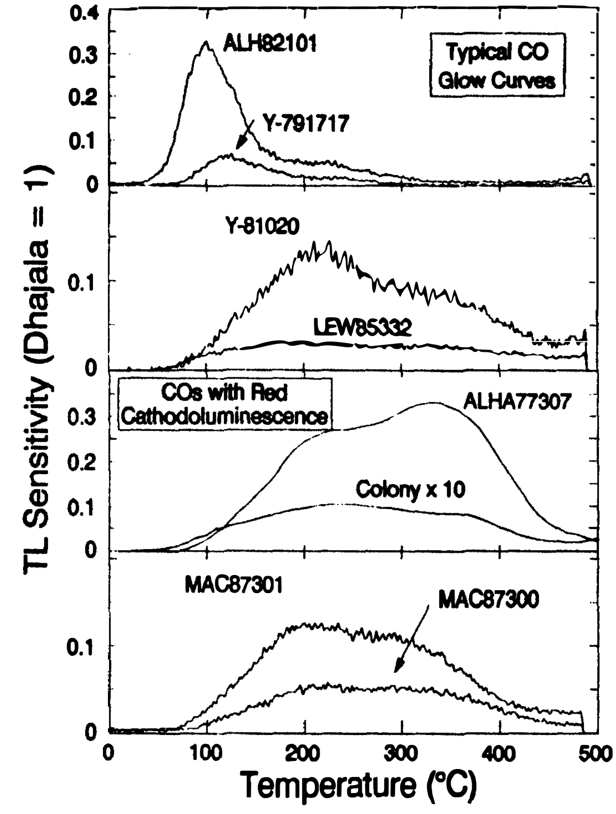
[*1] Uncertainties are 1 sigma on three splits from a single homogenized ~100 mg powder.
[*2] The number following the comma is the curational split number.
[*3] MWG, Meteorite Working Group of the US National Aeronautics and Space Administration and the National Science Foundation; NIPR, National Institute of Polar Research.

Table 2. Samples used for cathodoluminescence petrography, and their thin section numbers.

Meteorite	Source*	Section number	Figure number
ALHA77003	MWG	,7	5
ALHA77307	MWG	,25	6
Colony	UNM	826	6, 7c
Felix	USNM	235-1	5
Isna	UNM	825	4, 7a
Kainsaz	AMNH	4717-1	6
Lancé	UNM	824	5
Murchison	AMNH	4377-2	6, 7d, 7e
Ornans	USNM	1105-3	5, 7b
Warrenton	USNM	2486-2	4

* MWG, Meteorite Working Group of NASA/NSF; USNM, United States National Museum, Washington (Dr. R. S. CLARKE, JR.); UNM, University of New Mexico, Albuquerque (Dr. E. R. D. SCOTT); AMNH, American Museum of Natural History, New York (Dr. M. PRINZ).

Fig. 1. Representative glow curves for CO-like chondrites. Most CO chondrites contain two peaks, one at 120°C that is metamorphism-dependent and one at 230°C that is not. In most respects, Y-81020 behaves like normal CO chondrites, but it shows a weak peak is 350°C which becomes very important in the curves for the most primitive CO and CO-like chondrites. ALHA 77307 and Colony, whose properties are unusual but which are CO-related, have very low TL sensitivity and a TL peak at about 350°C. LEW85332 and three CM chondrites from MacAlpine Hills have curves resembling those of Colony and ALHA77307. The curves for ALHA77307 and Colony are from earlier work and have been smoothed, the others are from the present work. Further glow curves for normal CO chondrites were published by Keck *and* Sears *(1987).*



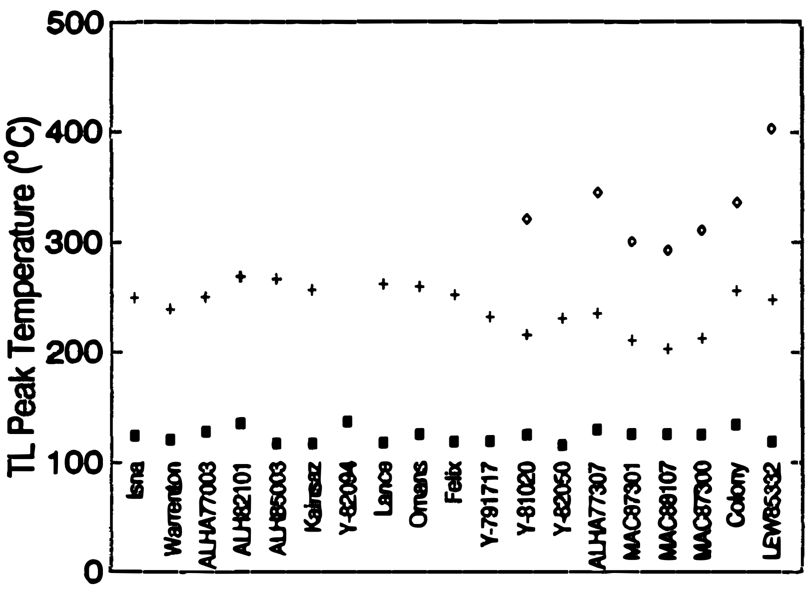


Fig. 2. Peak temperatures for induced thermoluminescence curves for CO and CO-like chondrites. The samples are listed in order of decreasing TL sensitivity. All the metamorphosed samples studied show peaks at about 120°C and at 200–230°C, while a few also show evidence for an additional peak at 300°C. Peak temperatures are of interest because, like TL sensitivities, they are related to the thermal history of the sample. As discussed in the text, the presence of the 120°C peak in all there samples, and laboratory heating experiments, demonstrate that CO chondrites were not heated above the order-disorder transformation temperature for feldspar (probably 500–600°C). Heating Isna for 100 h at 800°C caused the 120°C peak to move to around 220°C. Data from the present work and Keck *and* Sears *(1987).*

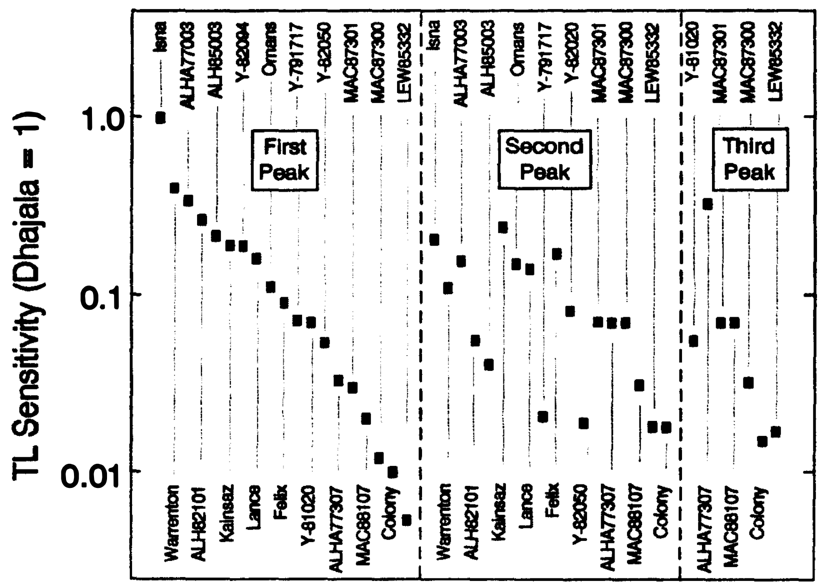


Fig. 3. Thermoluminescence sensitivities for the three peaks in CO and other chondrites. KECK *and* SEARS *(1987) showed that the 'first peak' (at about 120°C) was metamorphism-dependent while the 'second peak' is not. The 'third peak' is only present in the samples with especially low TL sensitivity. Data from the present work and* KECK *and* SEARS *(1987). In the few instances where an observable peak at 120°C was missing, the TL sensitivity plotted is that at 120°C.*

they include further measurements and more thorough data reduction. Figure 1 reproduces some representative glow curves and Figs. 2 and 3 compare TL peak temperatures and TL sensitivities, respectively. Most of the present samples, like those of KECK and SEARS (1987), display two TL peaks, namely the metamorphism-dependent peak at 120°C, the metamorphism-independent peak at 230°C. The first peak varies in intensity over a factor of 100, while the second peak generally remains within a factor of 3 of 0.1 (normalized to the Dhajala H3.8 ordinary chondrite). Like Colony and ALHA77307, LEW85332, Y-81020 and the three MacAlpine Hills meteorites display a third peak at 300–350°C. Again the peak is rather erratic in appearance and intensity and, with the exception of Y-81020, it is only apparent in samples of very low TL sensitivity. The Yamato CO chondrites Y-791717, Y-81020 and Y-81050 have TL sensitivities comparable with Felix; Y-791717 and Y-81050 have especially similar TL data. ALH82101, ALH85003 and Y-82094 have TL data comparable to those of Ornans.

Our CL photomosaics appear in Figs. 4–7. The CO chondrites of MCSWEEN's type III (Isna and Warrenton, Fig. 4) are comparable in their CL properties to ordinary chondrites of type 3.7–3.8 (*e. g.* Hedjaz and Dhajala, Fig. 6 in SEARS *et al.*, 1989). These meteorites consist primarily of numerous small grains, chondrules and chondrule fragments, all with blue CL, in a matrix with little or no CL. Figure 7a shows a typical matrix region in Isna. The numerous small chondrules have mesostases which are usually bright blue or bluish/white, and only a few chondrules or grains have red or orange CL.

The CO chondrites of MCSWEEN's type II (Felix, Ornans, Lance and ALHA77003,

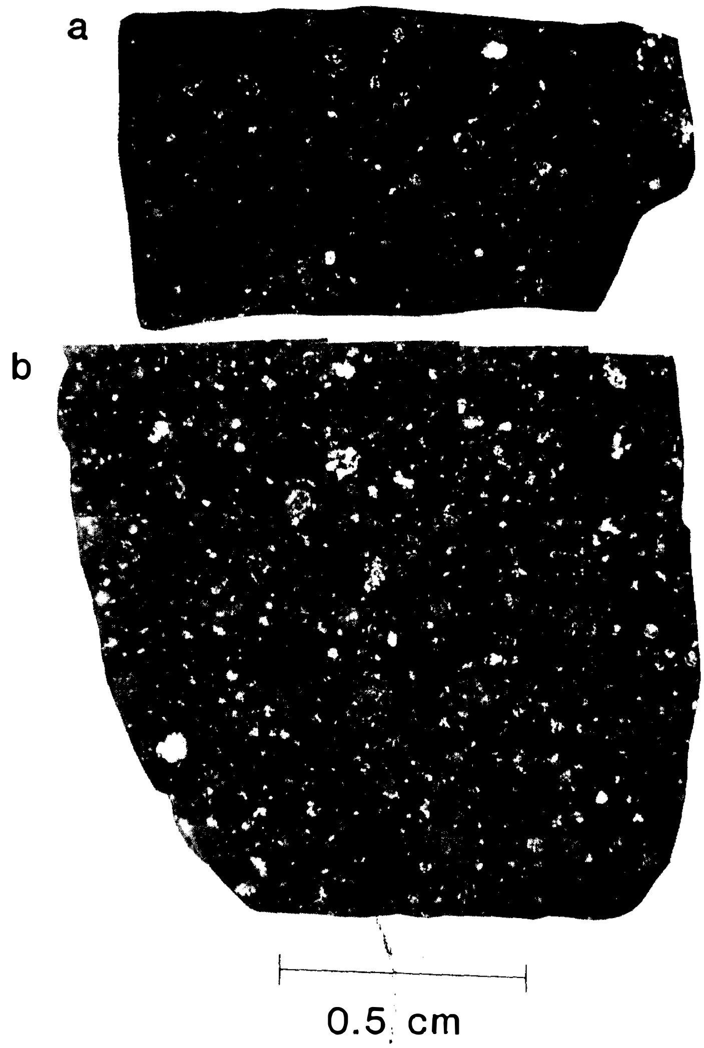


Fig. 4. *Cathodoluminescence photomosaics for two chondrites of* McSWEEN *type III (Most metamorphosed), Isna (a) and Warrenton (b). The CL properties of these samples resemble those of the ordinary chondrites Hedjaz (3.7) and Dhajala (3.8). On the basis of TL sensitivity and other data (Table 4), they have been assigned to types 3.7 and 3.6, respectively, in the present study. The photomosaics in Figs. 4–5 are to the same scale.*

Fig. 5) resemble the ordinary chondrites Chainpur (3.4) and ALHA77214 (3.4) in their CL properties (Fig. 5 in SEARS *et al.*, 1989). Lance, Felix, ALHA77003 and Ornans have matrices which are largely non-cathodoluminescent, but contain (1) scattered, isolated grains with red CL (presumably olivine and pyroxene with low FeO content), (2) somewhat larger matrix 'grains' (probably grain aggregates) with blue CL which grade into AOI or CAI, and (3) chondrules whose mesostases have blue or bluish/white CL and whose grains have either blue CL, red CL or are non-luminescent. A chondrule surrounded by typical matrix in Ornans is shown in Fig. 7b. Enstatite shows red and blue CL in enstatite chondrites, (LEITCH and SMITH, 1982; McKINLEY *et al.*, 1984), however blue luminescing pyroxenes are rare or absent in our samples.

The CO chondrites of McSWEEN's type I (Colony and ALHA77307, Fig. 6) have

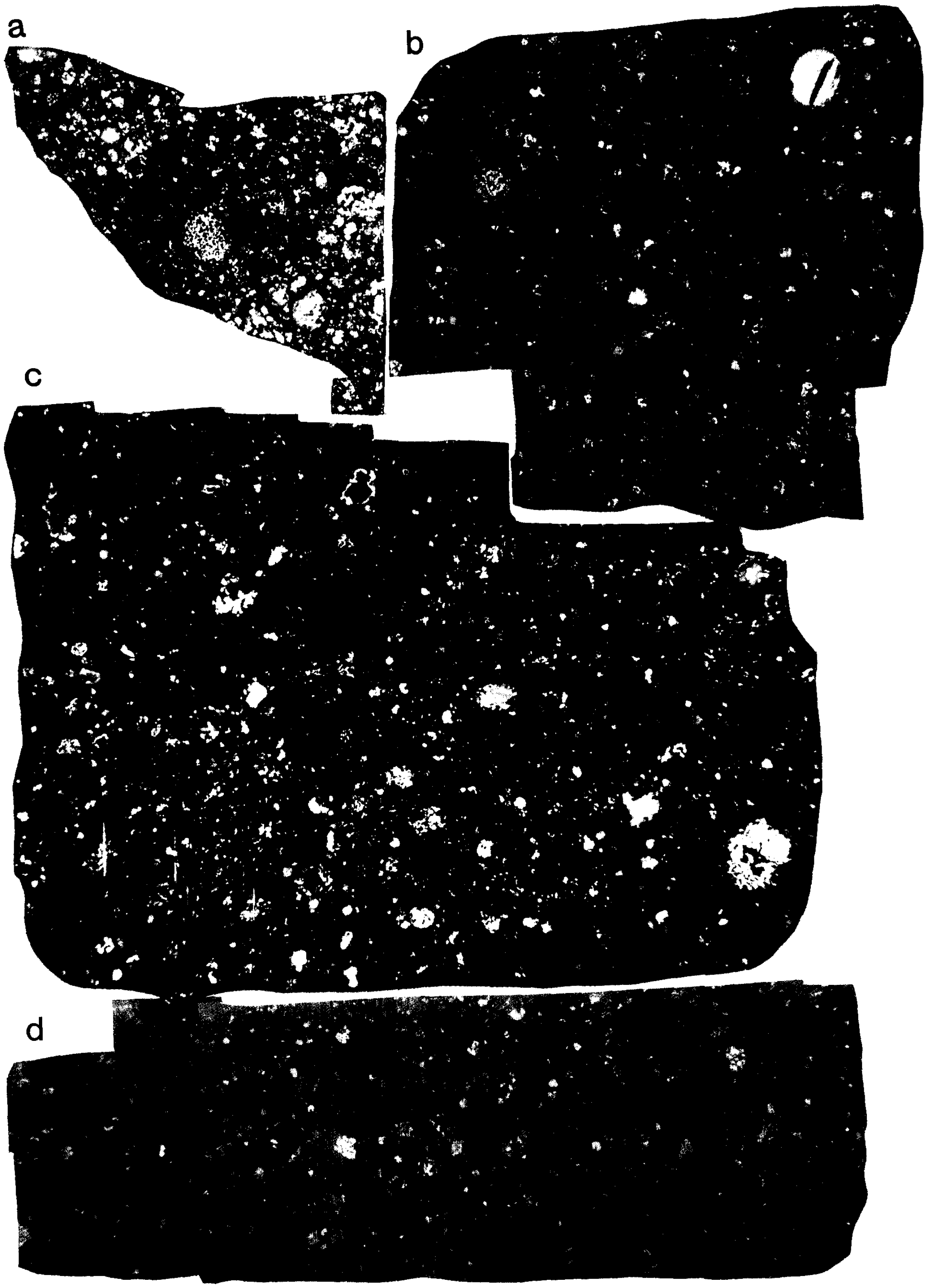


Fig. 5. Cathodoluminescence photomosaics for four CO chondrites of McSWEEM *(1977) type II (intermediate levels of metamorphism): (a) ALHA77003, (b) Lancé, (c) Ornans and (d) Felix. To a reasonable approximation, these meteorites resemble the ordinary chondrites ALHA77214 (3.4) and Chainpur (3.4) in their CL properties. On the basis of TL sensitivity and other data (Table 4), these meteorites have all been assigned to type 3.4 in the present paper.*

Fig. 6. Cathodoluminescence photomosaics for (a) Colony, (b) ALHA77307, (c) Kainsaz, and (d) Murchison. The CO chondrites have been assigned to type I in the McSWEEN scheme (McSWEEN, 1977; SCOTT et al., 1981; RUBIN et al., 1985), Murchison is a CM2 chondrite. All these meteorites are noteworthy for the abundance of red phosphors and occasional yellow chondrule mesostases, which are also present in Semarkona (3.0) and, in trace amounts, in Krymka (3.1) and Bishunpur (3.1). On the basis of TL sensitivity and other data (Table 4), Kainsaz, ALHA77307 and Colony have been assigned to types 3.2, 3.1 and 3.0, respectively, in the present study. The photomosaic of Murchison also shows the red CL of forsterite in chondrule olivines, very fine matrix grains and as fine grains in the 'haloes' around chondrules and other objects. The regions of yellow CL appear to be remnants or fragments of type I chondrules similar to those in Semarkona. Images a, b, c and d are to the same scale, the horizontal distance across images c and d is 1.9 cm.

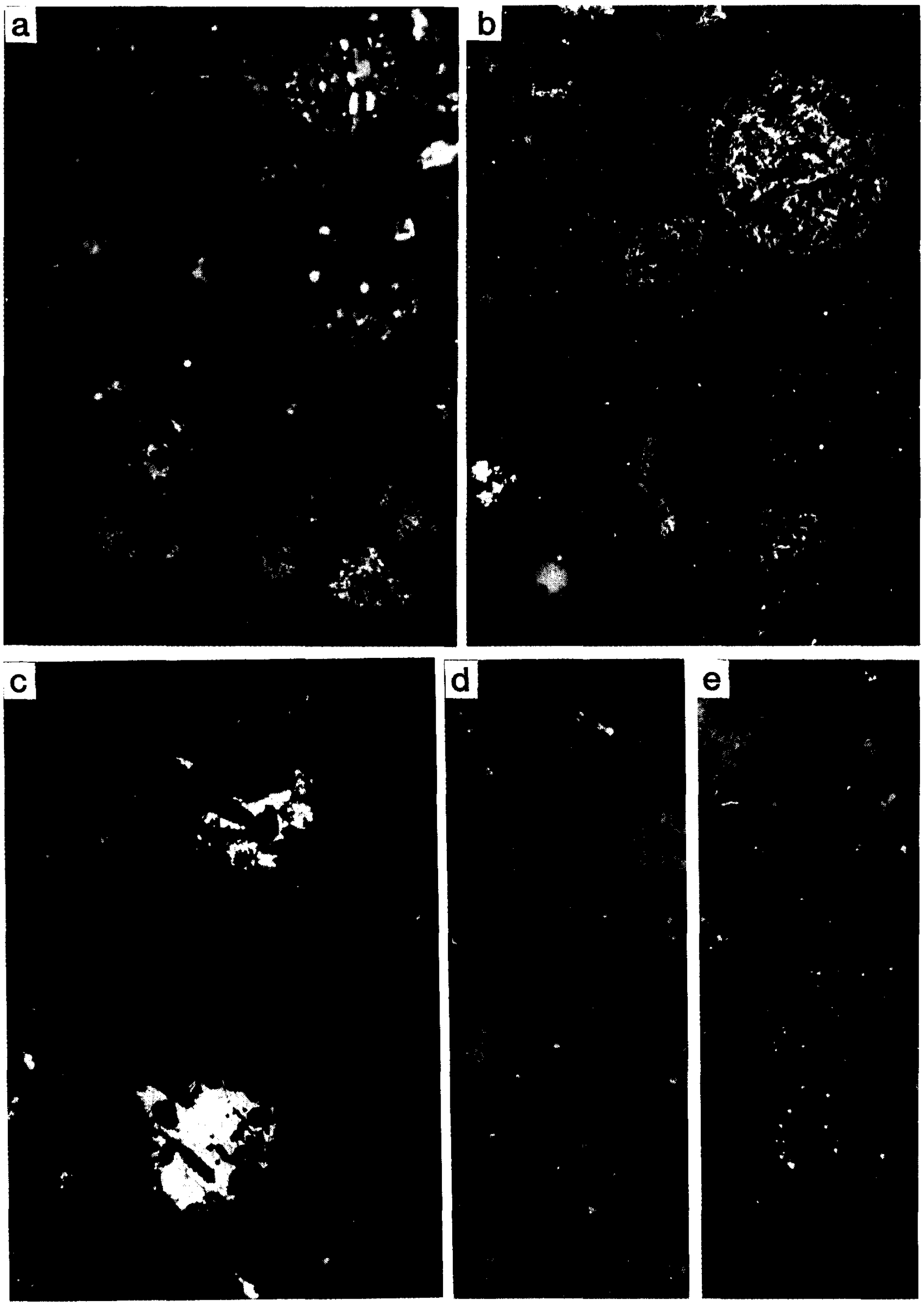


Fig. 7. *Details from cathodoluminescence photomosaics in Figs. 4–6 (vertical distance is 0.36 mm). Figures 7a and 7b show chondrules and typical matrix regions in the Isna (3.7) and Ornans (3.4) CO chondrites, respectively. Figure 7c is a region in Colony showing both the ubiquitous red CL of the matrix and a region of yellow CL similar to that of Semarkona type I chondrules. Figures 7d and 7e are details from the Murchison mosaic showing two chondrules and their 'haloes' of fine-grained material, and some surrounding matrix. All chondrules with luminescent olivines (e) have broad rims and often the outer regions of the central olivine grains show a dull red luminescence. In contrast, the rims on the nonluminescent objects (d) are much thinner.*

CL properties comparable to type 3.0–3.1 ordinary chondrites (Semarkona, Bishunpur and Krymka, Fig. 4 in SEARS *et al.*, 1989), especially Semarkona (type 3.0). Colony and ALHA77307 have abundant red CL matrices and grains, with inclusions and chondrules which are either non-luminescent or whose mesostasis luminesces white (probably over-exposed blue) or yellow (Fig. 7c). Kainsaz is also MCSWEEN type I, but has CL properties intermediate to those of the other type I and the type II CO chondrites, tending towards the latter (Fig. 6).

The CM chondrite Murchison also contains a great abundance of red CL phosphors (Fig. 6d). The largest objects show red CL are chondrule olivine grains, which WOOD (1967), STEELE (1986) and others have shown to be forsteritic. We have confirmed this for the present sample using an energy-dispersive X-ray spectrometer (EDX) on a Cambridge S600 Scanning Electron Microscope. Several of the olivines show zoning in their CL, with the outer portions of the grains having little or no CL. The luminescent chondrules are surrounded by rings of fine-grained material, with thicknesses approximately 30% of the chondrule radius (Fig. 7e). Several distinct non-luminescent objects (presumably chondrules) have a similar surrounding ring of material, but its thickness is only about 10% of the object's radius (Fig. 7d). Significantly the rims of fine-grained material uniformly surround all objects, whether circular or irregular, and there are no instances of rims which fractured with their host chondrules. The rims clearly formed *in situ*. These rings of material were described as 'haloes' by BUNCH and CHANG (1980) who found them to consist of phyllosilicates and to be carbon rich. EDX analysis shows them to be compositionally similar to the fine-grained inter-chondrule matrix. The boundaries between the chondrule and the ring are seldom sharp. The fine luminescent grains grow in coarseness and number from the inner to the outer edge of the rim. In contrast, the outer limits of the rim material are quite sharp. The matrix is a mixture of very fine-grained material, some with red CL some with no CL, and some with regions of both bright and dull red CL. There are also many small chondrules, or chondrule fragments, with yellow mesostases enclosing red grains, similar to the type I chondrules in the Semarkona ordinary chondrite (DEHART *et al.*, 1987).

4. Discussion

4.1. Primitive CO-like chondrites

On plots of TL sensitivity against olivine composition and olivine heterogeneity (Fig. 8), TL sensitivity against matrix composition (Fig. 9) and TL sensitivity against metal composition (KECK and SEARS, 1987), Colony, ALHA77307, LEW85332, and the MacAlpine Hills samples appear to be less-metamorphosed versions of the well-established CO chondrites.

The new cathodoluminescence results show two striking similarities between Colony, ALHA77307, Murchison and Semarkona. (1) The type I chondrules in all these meteorites display yellow CL in their mesostasis and (2) their matrices produce strong red CL. Semarkona is unique among the type 3 ordinary chondrites in the extent to which it displays these phenomena, only traces of both types of CL appear in higher types although type I chondrules and fine-grained opaque matrix are common

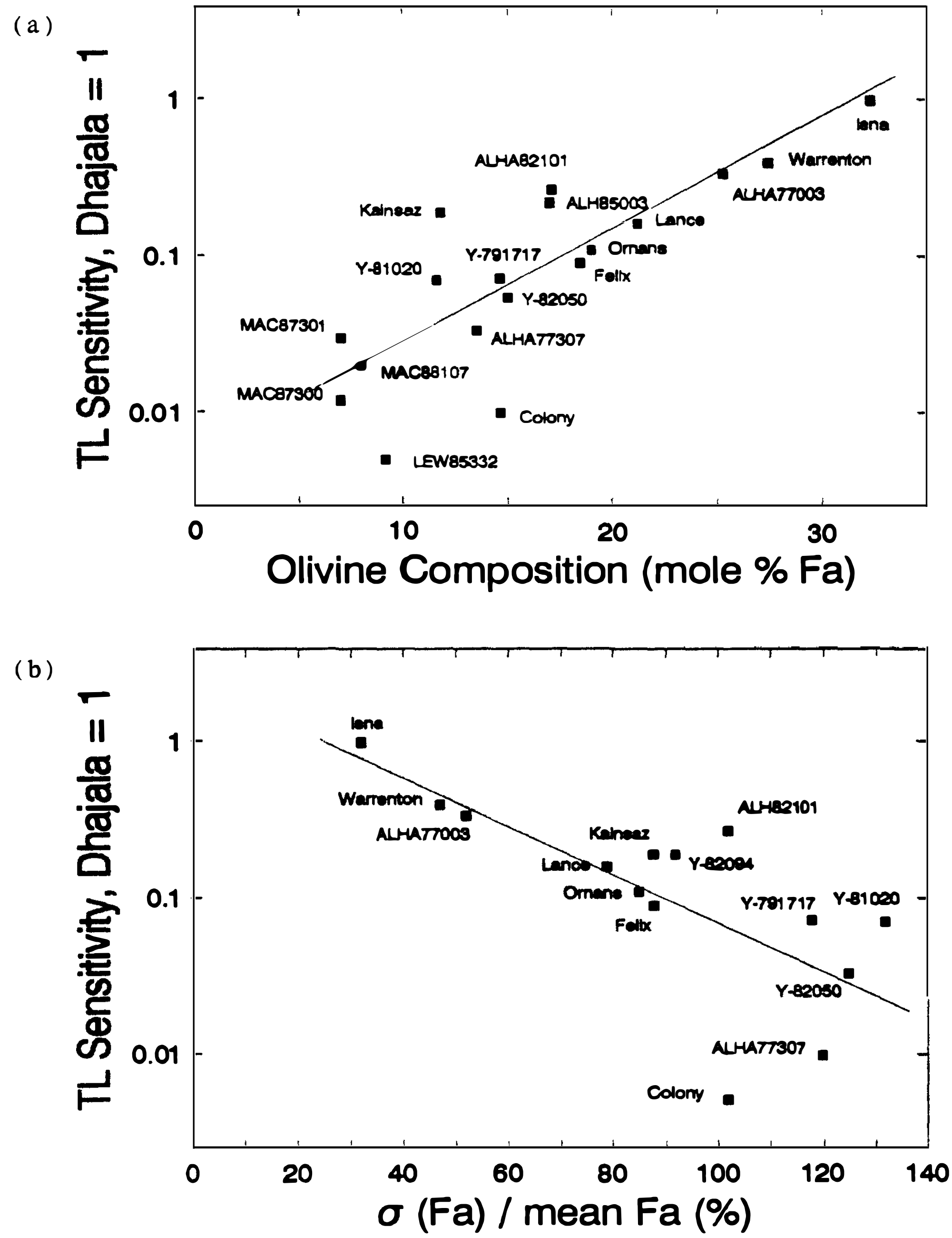


Fig. 8. Thermoluminescence sensitivity of the 120°C peak against (a) olivine composition (mol% Fa), (b) the heterogeneity of the olivine composition (standard deviation/mean, see SCOTT, 1984; SEARS and WEEKS, 1983). As TL sensitivity increases, the olivine becomes richer in iron and less heterogeneous. (Data from SCOTT and JONES, 1990, and references therein; YANAI and KOJIMA, 1987; GRAHAM and YANAI, 1986; MASON, 1988, 1989; K. YANAI, personal communication).

to the other type 3 ordinary chondrites (HUSS *et al.*, 1981; NAGAHARA, 1984; SCOTT and TAYLOR, 1983). The phosphor responsible for the yellow CL (a calcic pyroxene?) was formed during chondrule formation and is unstable to even the mildest levels of metamorphism (DEHART *et al.*, 1990). We have not yet identified the phosphor

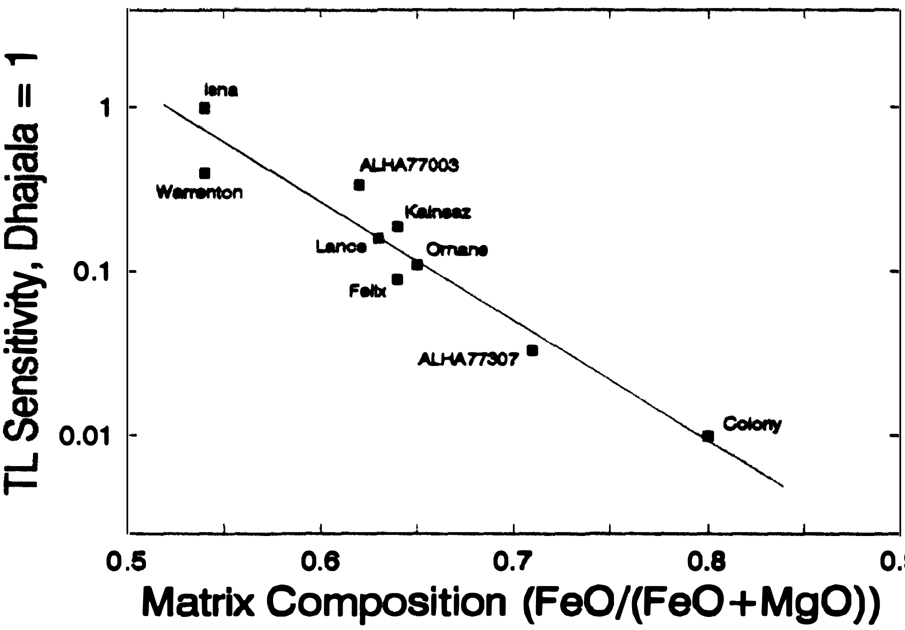


Fig. 9. Thermoluminescence sensitivity of the 120°C peak against FeO/(FeO+MgO) of the matrix. The increase in TL sensitivity is associated with a decrease in the iron content of the matrix. The FeO/(FeO+MgO) of the matrix of Colony may have been increased by weathering. (Data from SCOTT *and* JONES*, 1990, and references therein).*

responsible for the yellow CL. The yellow mesostasis has anorthite composition, and terrestrial and eucritic calcic plagioclases have yellow CL, but it may also be an extremely fine-grained calcic pyroxene (*e.g.* Tschermak's molecule) in intimate association with silica (DEHART *et al.*, 1990).

The red matrix grains are almost certainly forsterite. Apparently, this mineral is a ubiquitous component of the fine grain matrix of primitive meteorites. A few especially large red CL matrix grains in Semarkona were analyzed by DEHART (1989) who found them to be forsterite. NAGAHARA (1984) found that most of the olivine in the matrix of Semarkona was quite forsteritic (Fo_{100-72}), unlike that of other type 3 ordinary chondrites where it could be very fayalitic (HUSS *et al.*, 1981). Similarly, BREARLEY (1990) reported forsteritic olivine in the matrix of ALHA77307, as well as fayalitic olivine (Fa_{40-50}) and amorphous material, but CHRISTOPHE MICHEL-LEVY (1969) and KELLER and BUSECK (1990) found that matrix olivines in other CO chondrites were generally very fayalitic (Fa_{32-60}). In Murchison, forsteritic olivine is common as large chondrule grains and as fine intergrowths with phyllosilicates (WOOD, 1967; FUCHS *et al.*, 1973; BUNCH and CHANG, 1980). The large red CL grains in chondrules in CM, CO and type 3 ordinary chondrites are known to be olivine with very low FeO contents (STEELE, 1986, 1989a, b; DEHART *et al.*, 1990). There are no electron microprobe data for the very fine red CL grains in the Murchison matrix and haloes in the present study, although we have analyzed the large chondrule grains, but (1) their identical color, and (2) that, like the chondrule olivines, they display regions of both bright and dull red CL, suggests that they are also forsterite of varying FeO contents. Phyllosilicates are the other ubiquitous matrix component in CM chondrites, and thses are also present in Semarkona (HUTCHISON *et al.*, 1987) and some CO chondrites (KELLER and BUSECK, 1990). However, WEBER *et al.* (1967) found that 85% of 136 serpenting grains from 33 sources displayed blue-green CL, which was suppressed by Fe. The intimate association of forsterite with FeO-rich materials, and its rapid destruction during mild metamorphism, would also explain why the red CL matrix is found only in the most primitive meteorites.

Regardless of their detailed mineralogical explanation, the presence of yellow CL mesostases and red CL matrix in Colony, ALHA77307, Murchison and Semarkona is very significant because it underscores their unmetamorphosed nature and the similarity of these three types of early solar system material.

In addition to induced TL properties, CL data, olivine composition and heterogeneity, matrix and metal compositions, the primitive chondrites share several other properties. They all contain evidence for varying degrees of aqueous alteration (MCSWEEN, 1979; TOMEOKA and BUSECK, 1985; TOMEOKA *et al.*, 1989; HUTCHISON *et al.*, 1987), they are relatively rich in volatile elements (ANDERS *et al.*, 1976; KALLEMEYN and WASSON, 1981), they often contain carbides and Ni-bearing sulfides. The type I chondrules in all these meteorites seem to have formed in very similar environments and in a similar fashion. They also have certain isotopic similarities. The anhydrous phases from CM, CO, CV chondrites plot on the same slope 1 line on the oxygen isotope plot (CLAYTON and MAYEDA, 1984); components from the type 3 ordinary chondrite ALHA76004 (3.2) plot along another line whose slope is close to 1 (MAYEDA *et al.*, 1980). They also contain unusually high D/H ratios (KOLODNY *et al.*, 1980), and Murchison and Semarkona both contain evidence for SiC of interstellar origin (MING and ANDERS, 1988; HUSS and LEWIS, 1989). We conclude that although relatively subtle differences exist (*e.g.* chondrule size distributions, zoning in olivine, olivine composition histograms), some of which may have become exaggerated by differing amounts of aqueous alteration and metamorphism on the parent bodies, these primitive meteorites formed in a very similar nebular (*i. e.* pre-parent body) environment.

4.2. *Haloes and olivine Fe-zoning in Murchison*

We suggest that the haloes in Murchison are aqueous alteration features, and that they reflect the outline of the chondrules prior to attack. Our conclusion is based on (1) the sharp outline of the outer surface and the ragged inner surface of the halo, (2) the dependence of the thickness of the rim on chondrule composition as evidenced by CL properties, and (3) the presence of some sort of rim material on all objects regardless of size and shape, *i. e.* there are no chondrule fragments with only the original surfaces covered in rim material. We argue that glass of calcic plagioclase composition containing microlites of forsterite would produce fine-grained forsterite dispersed in phyllosilicates upon aqueous alteration, as well as some of the phyllosilicate-olivine associations described by FUCHS *et al.* (1973). This process is well-documented on the 100 μm-scale by Fig. 1 in TOMEOKA *et al.* (1989).

It is interesting to note that Murchison is one of the least altered CM chondrites, being 64 vol% matrix with an FeO/(FeO+MgO) of 0.70, compared with >80 vol% and 0.5–0.7 for the most altered CM chondrites (*e. g.* Nogoya and Bells) (MCSWEEN, 1979, 1987). Upon further alteration one might expect forsterite to disappear completely. The abundant red CL matrix might therefore not only be a characteristic of unmetamorphosed chondrites, but also a feature of those least-affected by aqueous processes. It is an indicator of those important few meteorites which most closely resemble their pre-parent body state.

There is also a suggestion that the amount of aqueous alteration suffered by the CO chondrites decreases with metamorphism (see below), but it is not clear whether this represents a real trend in the amount of aqueous activity or progressive erasure of the effects of aqueous alteration during metamorphism.

FeO-rich outer zones occur in forsteritic olivine in CV and CO chondrites, where they are thought to reflect equilibration during metamorphism (HOUSLEY and CIRLIN, 1983; HOUSLEY, 1986; SCOTT and JONES, 1990) or reactions between the olivine and nebula gases (PECK and WOOD, 1987; HUA *et al.*, 1988; WEINBRUCH *et al.*, 1990). STEELE (1986) suggested that they reflect a change in oxygen fugacity during the crystallization of the olivine (either from the liquid or gaseous state). The present data suggest an additional possibility, that they were also produced during aqueous alteration. KERRIDGE (1972) made a similar suggestion during his study of FeO-rich regions in chondrule olivines in the Warrenton CO chondrite.

4.3. Metamorphism in CO3 and type 3 ordinary chondrites, a comparison

Mineralogical and chemical similarities have been discussed by MCSWEEN (1977), KECK and SEARS (1987) and SCOTT and JONES (1990) and were summarized above. Some of these well-known mineralogical changes, and some changes which are either little-known or previously unknown, are very readily apparent in CL imagery.

The CL of type 3.0 ordinary chondrites consists of the yellow CL from the mesostasis of magnesian chondrules, red CL from low-Fe olivines and pyroxenes in chondrules and matrix, and blue CL from chondrule mesostases with plagioclase-normative compositions. Chondrules whose mesostases produce yellow CL are type I of MCSWEEN (1977) and SCOTT and TAYLOR (1983). Additionally, a significant number of chondrules contain quartz-normative mesostases which are non-luminescent. With increasing metamorphism, this diversity in color disappears, to be replaced by the ubiquitous blue CL of sodic plagioclase as calcic chondrule mesostases 'equilibrate' towards oligoclase, and magnesian silicates become relatively Fe-rich and therefore non-luminescent (DEHART *et al.*, 1988, 1990; STEELE, 1986, 1989a, b). The CL "quenching" properties of Fe have been well-documented.

The importance of phosphors with red CL and yellow CL in the meteorites at the bottom of the series, the very early disappearance of yellow phosphors and the more gradual disappearance of red matrix phosphors, and the increase in abundance of chondrule mesostases with blue CL with increasing metamorphism, are common to both CO and type 3 ordinary chondrites. Some of these CL properties reflect well-known mineralogical changes (devitrification of chondrule glass), others reflect changes either previously unknown (the metastable phase in type I chondrule mesostases) or not documented as convincingly (*e.g.*, the importance of matrix forsterite in low types and its subsequent destruction). Most of these mineralogical changes reflect equilibration between components of diverse origin and therefore indicate that the CO chondrites form a metamorphic series analogous to the ordinary chondrites.

Several authors have argued against the idea that the chondrites experienced closed system post-accretion metamorphism, suggesting, instead, that the equilibration observed occurred during chondrule cooling or otherwise during the dispersed nebula phase and prior to final accretion (*e. g.* FREDRIKSSON, 1983). Certain chondrule properties probably do reflect processes occurring during chondrule formation and subsequent cooling. For example, major element loss and FeO reduction probably accompanied the formation of type I chondrules, but not other chondrule types (LU *et al.*, 1990). Many mineralogical changes which accompanied metamorphism appear to have occurred *in situ* (*e. g.* metal growth, WOOD 1967) or involved components of diverse origin (*e. g.* matrix-chondrule reactions), suggesting, but not proving, that metamorphism was post-accretional. Probably the best argument for post-accretional metamorphism is that metamorphism lasted longer than the nebula (SCOTT and JONES, 1990), but even this argument is model-dependent. The recognition of a metamorphic sequence does not, of course, imply any particular mechanism for producing that sequence.

It is important to stress, however, that there are very important quantitative differences in the metamorphic history of the CO and type 3 ordinary chondrites. Compositional trends in the metal indicate metamorphic temperatures below 400°C for CO chondrites (MCSWEEN, 1977; KECK and SEARS, 1987). Figure 2 shows that all metamorphosed CO chondrites have a strong peak at around 120°C. KECK and SEARS (1987) showed that annealing samples of CO chondrite above 800°C caused this peak to shift to higher temperatures, comparable to those observed for the type $\geq$3.5 ordinary chondrites. This property of the induced TL curve has been observed in all samples in which feldspar is the dominant phosphor and probably reflects the disordering of the feldspar structure. The upper limit for metamorphism for CO chondrites is probably therefore 500–600°C, the order-disorder transformation temperature for sodic feldspar. Most recently, JONES and RUBIE (1990) showed that the compositional profiles in olivines of metamorphosed CO chondrites could be modeled by the appropriate choice of diffusion coefficients and physical conditions. Their calculations yielded peak metamorphic temperatures of 470–490°C for ALHA77307 and 510–520°C for Isna. By contrast, palaeotemperatures for ordinary chondrites, based on a variety of methods, are approximately $\leq$400°C for type 3.0–3.1, 400–500°C for type 3.2–3.5, 600–700°C for type 3.6–3.8 (see SEARS *et al.*, 1991 for a summary of recent data). Since CO chondrites did not experience temperatures as high as type $\geq$3.5 ordinary chondrites, and yet have TL sensitivity and other properties equivalent to higher types, we assume that the CO chondrites spent longer times at lower temperatures than the ordinary chondrites. Our data do not permit us to discuss the relative durations of metamorphism in a more quantitative way.

4.4. Petrologic subtypes for CO3 chondrites

The arguments for subdivision of CO3 chondrites were made by SCOTT and JONES (1990). We accept those arguments, subject to the important caveats above, and propose the type definitions in Table 3. These are based on correlations with TL sensitivity (Figs. 8, 9 and updated versions of those in KECK and SEARS, 1987). The major difference between this scheme and that used for ordinary chondrites is

Table 3. Definition of petrographic types for CO chondrites.

Type	TL sens (120°C) (Dhajala=1)	Fa (mol%)	σ(Fa)/Fa (%)	Matrix $\frac{FeO}{FeO+MgO}$	Ni	Kamacite (wt%) Co	Cr	C (wt%)	Ne-20 10–8 cc/g
3.0	<0.017	<11.0	>126	>0.77	<4.4	<0.2	>0.5	>0.65	>19
3.1	.017– .03	11.0–13.5	112–126	.73–.77	4.4–4.6	0.2–0.4	0.47–0.50	>0.65	>19
3.2	.03 – .054	13.5–16.0	102–112	.70–.73	4.6–4.8	0.4–0.6	0.34–0.47	0.55–0.65	16–19
3.3	.054– .10	16.0–18.5	90–102	.67–.70	4.8–5.0	0.6–0.8	0.26–0.34	0.45–0.55	13–26
3.4	.10 – .17	18.5–21.0	78–90	.63–.67	5.0–5.2	0.8–1.0	0.18–0.26	0.35–0.45	10–13
3.5	.17 – .30	21.0–24.0	64–78	.60–.63	5.2–5.4	1.0–1.2	0.10–0.18	0.25–0.35	7–10
3.6	.30 – .54	24.0–27.5	46–64	.57–.60	5.4–5.7	1.2–1.4	<0.10	0.15–0.25	4–7
3.7	.54 –1.0	27.5–31.0	28–46	.53–.57	5.7–6.0	1.4–1.6	<0.10	<0.15	< 4
3.8	1.0 –1.7	31.0–35.0	8–28	< .53	6.0–6.4	1.6–1.8	<0.10	<0.15	< 4
3.9	>1.7	>35.0	< 8	< .53	6.4–6.7	1.8–2.0	<0.10	<0.15	< 4

Table 4. Petrographic types assigned on the basis of the parameters in Table 3, previous assignments and the recommended value.

Meteorite	TL sens	CL	Oliv Fa	σ(Fa)/Fa	Mx Fe#	Kamacite Ni	Kamacite Co	Kamacite Cr	C wt%	Ne-20	McSween	Scott-Jones	Recom.
Colony	3.0	3.0–3.1	3.2	3.2	3.2	3.2	3.2	3.1	3.2	—	I	3.0	3.0
LEW85332	3.0		3.0	3.2	—	3.1	3.5	—	—	—	—	—	3.0
MAC88300	3.0		3.0		—	—	—	—	—	—	—	—	3.0
MAC88107	3.1		3.0		—	—	—	—	—	—	—	—	3.1
MAC87301	3.2		3.0		—	—	—	—		—	—	—	3.1
ALHA77307	3.2	3.0–3.1	3.2	3.0	3.2	3.2	3.0	3.1	≤3.1	≤3.1	I	3.0	3.1
Kainsaz	3.5	~3.2	3.1	3.4	3.4	3.1	3.3	3.2	3.2	3.3	I	3.1	3.2
Y-82050	3.3		3.2	3.0	—	—	—	—	—	—	—	—	3.3
Y-791717	3.3		3.2	3.1	—	—	—	—	—	—	—	—	3.3
Y-81020	3.3		3.3	3.0	—	—	—	—	—	—	—	—	3.3
Felix	3.3	~3.4	3.3	3.4	3.5	3.5	3.6	3.5	32.	3.2	II	3.2	3.4
ALH82101	3.5		3.4	3.3	—	—	—	—	≤3.7	3.5	—	3.3	3.4
Ornans	3.4	~3.4	3.4	3.4	3.4	—	—	—	3.5	3.6	II	3.3	3.4
Lancé	3.4	~3.4	3.5	3.4	3.4	3.5	3.5	3.5	3.5	≤3.7	II	3.4	3.4
ALHA77003	—	~3.4	3.5	3.4	3.1	3.3	3.7	3.3	—	—	—	3.4	3.4
ALH85003	3.5		3.3		—	—	—	—	—	—	—	—	3.5
Y-82094	3.5		X. X	3.3	—	—	—	—	—	—	—	—	3.5
Warrenton	3.6	3.7–3.8	3.6	3.6	<3.7	3.8	3.7	<3.5	3.5	3.5	III	3.6	3.6
Isna	3.8	3.7–3.8	3.8	3.7	<3.7	3.6	—	3.6	≤3.7	<3.7	III	3.7	3.7

Data sources: This paper, KECK and SEARS (1987 and references therein), SCOTT and JONES (1990), YANAI and KOJIMA (1987), GRAHAM and YANAI (1986), RUBIN and KALLEMEYN (1990), and K. YANAI (personal communication).

FeO/(FeO+MgO) normalized to the same ratio for the whole-rock.

that the TL sensitivity intervals have been modified to allow for the effect of the 230°C peak. Our suggestions for ranges in olivine composition are not significantly different from those of SCOTT and JONES (1990), who also present ranges for olivines in type I and type II chondrules.

The assignments we obtain using each available parameter, the assignments of McSWEEN (1977) and SCOTT and JONES (1990) and our recommended assignments are listed in Table 4. Our recommendations take into account the reliability of each measurement and the recognition that certain parameters are stronger indicators over certain metamorphism intervals than others. The agreement between type assignments using different parameters, and with the suggestions of previous workers, is very good. Usually the assignments based on individual parameters are within about ± 0.1 of the final recommended value.

Three of the present Yamato samples are also of low petrographic type (3.3). The only petrologic data for these meteorites are the brief descriptions by YANAI and KOJIMA (1987) and GRAHAM and YANAI (1986), whose data are consistent with the above assignments; their olivine heterogeneity data may, in fact, suggest slightly lower types. YANAI and KOJIMA (1987) observed phyllosilicates in Y-82050, which might also consistent with a low petrographic type. The phyllosilicates in Lance (3.4) are especially well-documented (KERRIDGE, 1964; CHRISTOPHE MICHEL-LEVY, 1969; KURAT and KRACHER, 1980; KELLER and BUSECK, 1990) and they have been described in Ornans (3.4, KERRIDGE, 1964), Felix (3.4, VAN SCHMUS, 1969, described fibrous microcrystalline alteration products of olivine and pyroxene), and ALHA77307 (3.1, IKEDA, 1983). KELLER and BUSECK (1990) were not able to find phyllosilicates in the type 3.6 CO chondrite, Warrenton. Phyllosilicates may therefore be a feature of types <3.5. However, they were unable to locate phyllosilicates in Kainsaz, which has been assigned type 3.2 on the basis of CL and the other parameters.

The assignment of the three CM chondrites to type 3.1 is highly tentative as it is based only on TL characteristics and the mean olivine compositions. We make this suggestion to stress (1) the dissimilarity between these three paired CM chondrites and the other 17 CM chondrites for which we have TL data, and (2) the fact that these three samples appear to plot on the low end of the TL sensitivity—Fa trend of the CO and CO-like chondrites. It is probably also worth noting that many of the properties of the type 3.0–3.1 chondrites approach those of type 2 in the VAN SCHMUS and WOOD scheme (1967); in fact, HUTCHISON *et al.* (1987) mentioned that Semarkona, and possibly Bishunpur, might be regarded as type 2 since they have experienced aqueous alteration. The matter is not simply one of nomenclature, because it relates to the question of the similarity of parent body conditions for the various classes. The most reliable discriminator according to VAN SCHMUS and WOOD (1967) was that type 2 chondrites contain $>0.5\%$ Ni in their sulfide minerals and type 3 chondrites contain $<0.5\%$. Other parameters were that for type 2 taenite is minor or absent, the opaque matrix is abundant, bulk carbon is $>0.6\%$ and bulk water is $>4\%$. Table 5 gathers together the relevant data for the present meteorites. If we abandon Ni content of the sulfides as the main discriminator between types 2 and 3, and use matrix content as the main criterion (B. MASON, personal communication), then all of the present meteorites for which matrix data are available should probably be called

Table 5. Data relating to assignment to type 2 vs. type 3 for primitive chondrites.

V-W Criteria (1)	Colony (2)	LEW85332 (3)	ALHA77307 (4)	3.0–3.1 Ord Ch (5)
Ni in sulf. (>0.5% Ni)	Pure FeS no pent	0.72%	Pent present	>19 grains >0.5%
Taenite amt. (bulk Ni <20%)	Rare	None mentioned	Present	Present
Opaque mtx. (>50%)	29–35	Abundant fine-grained mtx	41	13.6–15.6
Bulk C (>0.6%)	0.55, 0.63	0.80	—	0.3–0.6
Bulk H20 (>4)	5.7	6.8	—	1.4–2.2
Other comments	No carbides/ magnetite	CI & CM clasts	Haxonite/ cohenite. Magnetite most abund opaque	

(1) VAN SCHMUS and WOOD (1967). The data in parentheses apply to type 2 chondrites.
(2) RUBIN *et al.* (1985).
(3) RUBIN and KALLEMEYN (1990).
(4) SCOTT *et al.* (1981), SCOTT and JONES (1990), JAROSEWICH (1990), GRADY *et al.* (1989).
(5) RAMBALDI and WASSON (1981), HUSS *et al.* (1981), JAROSEWICH (1990).

type 3. A detailed mineralogical and petrological study of MAC87300, MAC87301 and MAC88107 would be most interesting in this regard.

5. Conclusions

New TL data are presented for 10 CO and CO-related chondrites. Six of these appear to be fairly normal CO chondrites with low to intermediate levels of metamorphism, although Y-81020 display the 350°C peak, their induced TL properties resemble those in the study of KECK and SEARS (1987). The remaining four resemble the unusual Colony and ALHA77307 primitive chondrites in their TL properties.

Photomosaics of the cathodololuminescence of 9 CO chondrites are also presented. The data are consistent with other data in indicating that the CO and related chondrites form a metamorphic sequence analogous to that of the type 3 ordinary chondrites. Subdivision is appropriate to stress the major differences existing in the extent of metamorphic alteration within the CO chondrite class, and to provide a basis for the study of nebula and metamorphic processes. A scheme of subdivision, analogous to that used for type 3 ordinary chondrites is proposed. The petrographic types so assigned are listed in Table 4. It is stressed, however, that there are major differences in the metamorphic history of the two classes. The CO chondrites were metamorphosed at much lower temperatures, *i. e.* at temperatures below those experienced by type 3.5/3.6 ordinary chondrites, presumably for longer times.

We also present a photomosaic of the CL of the Murchison CM chondrite. This has two features (type I chondrules whose mesostases produce yellow CL and a ubiquitous very fine-grained red matrix) which are common to the type 3.0–3.1 CO and ordinary chondrites but which are extremely rare in the higher types. The yellow mesostasis is thought to be due to a mineral phase which is highly unstable against the mildest levels of metamorphism and the red matrix CL is due to forsterite. 'Haloes' around chondrules and other objects in Murchison are thought to be due to aqueous alteration of those objects, and Fe enrichments in the outer regions of olivines within the chondrules are also thought to be due to aqueous processes.

LEW85332, MAC87300, 87301, 88107, Colony and ALHA77307 are little-metamorphosed carbonaceous chondrites. They are all unusual, compared with other meteorites in their classes. Colony, ALHA77307 and LEW85332 are compositionally anomalous, but, following the arguments of RUBIN *et al.* (1985), Colony and ALHA77307 may be regarded as CO3.0 and CO3.1, respectively. LEW85332 is an unusual type 3.0 carbonaceous chondrite. MAC87300, 87301 and 88107 have unusual natural and induced TL properties, the latter resembling those of Colony, ALHA77307 and LEW85332. We tentatively suggest that they be regarded as CM3.1.

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