

Chemical and physical studies of type 3 chondrites XII: The metamorphic history of CV chondrites and their components

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Abstract—The induced thermoluminescence (TL) properties of 16 CV and CV-related chondrites, four CK chondrites and Renazzo (CR2) have been measured in order to investigate their metamorphic history. The petrographic, mineralogical and bulk compositional differences among the CV chondrites indicate that the TL sensitivity of the ~130 °C TL peak is reflecting the abundance of ordered feldspar, especially in chondrule mesostasis, which in turn reflects parent-body metamorphism. The TL properties of 18 samples of homogenized Allende powder heated at a variety of times and temperatures, and cathodoluminescence mosaics of Axtell and Coolidge, showed results consistent with this conclusion. Five refractory inclusions from Allende, and separates from those inclusions, were also examined and yielded trends reflecting variations in mineralogy indicative of high peak temperatures (either metamorphic or igneous) and fairly rapid cooling. The CK chondrites are unique among metamorphosed chondrites in showing no detectable induced TL, which is consistent with literature data that suggests very unusual feldspar in these meteorites. Using TL sensitivity and several mineral systems and allowing for the differences in the oxidized and reduced subgroups, the CV and CV-related meteorites can be divided into petrologic types analogous to those of the ordinary and CO type 3 chondrites. Axtell, Kaba, Leoville, Bali, Arch and ALHA81003 are type 3.0–3.1, while ALH84018, Efremovka, Grosnaja, Allende and Vigarano are type 3.2–3.3 and Coolidge and Loongana 001 are type 3.8. Mokoia is probably a breccia with regions ranging in petrologic type from 3.0 to 3.2. Renazzo often plots at the end of the reduced and oxidized CV chondrite trends, even when those trends diverge, suggesting that in many respects it resembles the unmetamorphosed precursors of the CV chondrites. The low-petrographic types and low-TL peak temperatures of all samples, including the CV3.8 chondrites, indicates metamorphism in the stability field of low feldspar (*i.e.*, <800 °C) and a metamorphic history similar to that of the CO chondrites but unlike that of the ordinary chondrites.

INTRODUCTION

Virtually all classes of chondrite have experienced some level of parent body metamorphism; although in the case of type 1 and 2 carbonaceous chondrites the metamorphism involved considerable aqueous alteration. Both the type 3 ordinary chondrites and the CO chondrites display mineralogical and petrographic evidence for metamorphic alteration that can be evaluated with a high degree of precision using induced thermoluminescence (TL) measurements, although the time-temperature histories of the ordinary and CO chondrites are quite different (Dodd *et al.*, 1967; McSween, 1977a; Keck and Sears, 1987; Scott and Jones, 1990; Sears *et al.*, 1991a,b). The present paper extends our studies of metamorphism of type 3 chondrites to the CV and the possibly related CK chondrites (Kallemeyn *et al.*, 1991).

Compositional equilibration between refractory inclusions and the ferromagnesian components, and variations in the homogenization of matrix olivines, suggests that the CV chondrites have suffered various levels of parent-body metamorphism (McSween, 1977b; Peck, 1984; Scott *et al.*, 1988). It has been proposed that metamorphism increased along the series Kaba, Mokoia, Vigarano, Grosnaja and Allende. Since the CV chondrites consist of both oxidized and reduced subgroups, a single metamorphic series is precluded although two parallel series are possible (McSween, 1977b). Recently, Weinbruch *et al.* (1993) estimated spinel-olivine equilibration temperatures for Allende ~625 °C and equilibration temperatures based on olivine profiles of ~325 °C. Guimon and Sears (1986) suggested <600 °C based on induced TL data. Of particular interest are the refractory inclusions (or, calcium- and aluminum-rich inclusions, CAIs) in CV chondrites, which exhibit a

number of properties that suggest a complex history (MacPherson *et al.*, 1988). It has been argued that some Allende inclusions were metamorphosed prior to emplacement in the meteorites (Meeker *et al.*, 1983), although MacPherson *et al.* (1988) argue that the features in question are igneous in origin.

Here we report induced TL measurements for 16 CV and CV-related chondrites and Renazzo, a CR chondrite, and five of the refractory inclusions and their mineral separates from the Meeker *et al.* (1983) study of Allende. We also prepared cathodoluminescence (CL) images of polished sections of selected CV chondrites. We heated samples of homogenized Allende powder for 1–100 h at 500–1000 °C (Guimon and Sears, 1986), since such experiments have proved essential in understanding the TL data of other classes.

EXPERIMENTAL

Samples

The samples we studied are listed in Tables 1 and 2. They consist of both reduced and oxidized CV chondrites, as defined by McSween (1977b). Coolidge and Loongana 001 have been described as a new "grouplet" related to CV chondrites by Kallemeyn and Rubin (1995), who argued that these two meteorites had different volatile element abundances and could not have been formed by closed-system metamorphism of the other CV chondrites. Since the CV chondrites are highly heterogeneous, and small in number, we think that such a conclusion may be premature. In most respects, these meteorites have the properties expected of meteorites closely resembling the CV chondrites prior to metamorphism. Nianqiang was described as an anomalous CV chondrite by Kallemeyn and Wasson (1982) and as an anomalous CK chondrite by Kallemeyn *et al.* (1991). The CV and CK chondrites have very similar properties; the most distinctive to date is that the CV chondrites have measurable TL sensitivities, while the CK chondrites do not. In this respect, Nianqiang is more closely related to the CV chondrites. However, we stress that these are subtle nuances in classification, and the matter of whether it is better to stress similarities

TABLE 1. Induced TL data for CV chondrites, Renazzo and Ningqiang.

Meteorite	Source /cat.# [‡]	Class ⁺	TL sensitivities* [†]			TL Peak		
			~130 °C	~250 °C	~350 °C	~130 °C	~250 °C	~350 °C
ALHA 81003	MWG/21 22	CV(?)	0.020 ± 0.006	0.003 ± 0.001	–	132 ± 5	250 ± 5	–
			0.0049 ± 0.0002	0.0010 ± 0.0003	–	123 ± 2	250 ± 5	–
ALH 84028	MWG/77	CV(?)	0.05 ± 0.03	0.02 ± 0.01	0.01 ± 0.01	143 ± 5	235 ± 20	350 ± 5
			0.034 ± 0.008	0.016 ± 0.004	0.004 ± 0.002	130 ± 4	250 ± 5	350 ± 5
ALH 85006	MWG/16	CV(?)	0.025 ± 0.004	0.092 ± 0.009	0.14 ± 0.02	128 ± 2	231 ± 13	331 ± 5
			0.034 ± 0.002	0.06 ± 0.02	0.04 ± 0.03	134 ± 8	196 ± 16	321 ± 12
Allende	USNM	CV(O)	0.044 ± 0.005	0.012 ± 0.001	0.0013 ± 0.0001	127 ± 5	240 ± 8	350 ± 5
Arch b	MPI	CV(R)	0.015 ± 0.002	0.003 ± 0.001	0.002 ± 0.0002	140 ± 4	250 ± 5	350 ± 5
			0.014 ± 0.001	0.015 ± 0.003	0.013 ± 0.002	141 ± 13	190 ± 8	350 ± 5
Axtell	UC	CV	0.0028 ± 0.0003 [§]	–	–	129 ± 9	–	–
Bali	NMW	CV(O)	0.030 ± 0.011	0.11 ± 0.06	0.15 ± 0.11	130 ± 4	239 ± 10	329 ± 9
			0.039 ± 0.008	0.15 ± 0.07	0.29 ± 0.11	130 ± 5	226 ± 9	353 ± 5
Coolidge	CMS397.2x	CV(R)	1.3 ± 0.05	0.34 ± 0.02	0.079 ± 0.001	148 ± 6	241 ± 6	350 ± 5
Efremovka	USNM2348	CV(R)	0.034 ± 0.003	0.051 ± 0.003	0.018 ± 0.003	127 ± 2	236 ± 7	340 ± 5
			0.034 ± 0.002	0.032 ± 0.01	0.022 ± 0.007	146 ± 5	250 ± 5	340 ± 5
Grosnaja	NMW	CV(O)	0.015 ± 0.001	0.011 ± 0.004	0.016 ± 0.01	132 ± 8	250 ± 5	341 ± 6
			0.010 ± 0.001	0.009 ± 0.002	0.005 ± 0.001	134 ± 9	230 ± 14	350 ± 5
Leoville	USNM3537	CV(R)	–	0.94 ± 0.26	0.89 ± 0.26	–	224 ± 7	290 ± 6
			–	2.8 ± 0.2	1.33 ± 0.21	–	232 ± 14	400 ± 5
Loongana 001	MPI	CV(R)	0.31 ± 0.04	–	–	143 ± 1	–	–
			0.52 ± 0.03 [§]	–	–	143 ± 4	–	–
Kaba	BM33969a	CV(O)	0.073 ± 0.015	0.62 ± 0.19	1.00 ± 0.28	128 ± 2	246 ± 12	344 ± 8
			0.22 ± 0.20	0.84 ± 0.11	1.15 ± 0.13	147 ± 5	230 ± 8	324 ± 8
Mokoia	BM1910,72	CV(O)	0.049 ± 0.005	0.018 ± 0.001	0.0029 ± 0.0001	128 ± 1	246 ± 6	350 ± 5
			0.01 ± 0.001	0.005 ± 0.001	0.002 ± 0.001	129 ± 3	250 ± 5	320 ± 5
Ningqiang	CAS	CK-An	0.19 ± 0.06	1.26 ± 0.14	2.31 ± 0.18	130 ± 5	227 ± 9	342 ± 8
			0.02 ± 0.005	0.09 ± 0.03	0.16 ± 0.06	130 ± 7	236 ± 12	336 ± 9
Renazzo	NMW	CR	0.0049 ± 0.001	0.002 ± 0.001	0.0008 ± 0.0001	130 ± 5	250 ± 5	350 ± 5
			0.015 ± 0.002	0.04 ± 0.03	0.013 ± 0.002	129 ± 5	221 ± 2	350 ± 5
Vigarano	USNM477	CV(R)	0.069 ± 0.004	0.06 ± 0.01	0.042 ± 0.014	137 ± 4	246 ± 5	338 ± 2
			0.049 ± 0.002	0.047 ± 0.006	0.048 ± 0.005	128 ± 3	242 ± 17	340 ± 5

* – = peak not present.

† Dhajala = 1.

‡ MWG, Meteorite Working Group of the NASA/NSF/SI; USNM, United States National Museum, Smithsonian Institution (Glenn MacPherson); MPI, Max-Planck-Institut für Chemie (Frank Wlotzka); NMW, Naturhistorisches Museum, Wien (Gero Kurat); CMS, Center for Meteorite Studies (Carleton Moore); BM, Natural History Museum, London (Robert Hutchison); CAS, Chinese Academy of Sciences (Ouyang Ziguan); UC, University of Chicago (Steve Simon).

+ (O) and (R) refer to the oxidized and reduced subgroups of McSween (1977b).

§ After acid washing to remove weathering products (Benoit *et al.*, 1991).

TABLE 2. Samples details for five refractory inclusions from the Allende CV chondrite.

Sample	Description*	Mass (mg)	Reference
Egg 3	3.3 sinks	1.2	Meeker <i>et al.</i> (1983)
	Hand-picked melilite	2.4	
	Two chunks mantle	3.3	
Egg 4	Interior grains	4.1	Meeker <i>et al.</i> (1983)
	Int grains + matrix	2.5	
Egg 6	3.3 sinks	2.1	Meeker <i>et al.</i> (1983),
	3.0 floats	3	Meeker (1995a)
	One chunk, mantle + int	28.9	
Big Al	Interior	15	Papanastassiou <i>et al.</i> (1984)
	Rim	5.7	
Pink Angel	Rim	2	Armstrong and Wasserburg (1981)

* Density separates are indicated by the relevant density (in g cm⁻³) and whether the separate "floats" or "sinks."

or differences in classifying these small classes of meteorites, is debatable. For our present purposes, the matter is academic. Just as we have found that the H6 and LL3.0 chondrites can be placed on the same plots for comparing TL data with metamorphically-driven mineralogical and petrographic properties, we are confident that placing these meteorites on the same plots is not going to obscure real or create artificial trends. In fact, in some cases the trends would be strengthened, but not altered, if the CO chondrites were added to some of the present figures. Renazzo is a CR chondrite that was included for comparison and for reasons that will become apparent. We do not mean to imply that we consider it a CV or CV-related chondrite. We also measured the induced TL of four CK chondrites: ALH85002 (type 4), EET87507 (type 5), LEW86258 (type 4) and Karoonda (type 4).

The CAIs and their separates in the present study were splits of samples from the Meeker *et al.* (1983) study. Brief descriptions and references are included in Table 2 and the Appendix.

Whole-rock TL Measurements

The thermoluminescence of duplicate splits was measured using the methods of Sears *et al.* (1991a). The TL apparatus is equipped with Corning filters 7-59 and 4-69, which restrict the measurement to blue wavelengths. About 130–200 mg of each split was crushed, and the powder homogenized prior to measurement.

Cathodoluminescence Petrography

Mosaics of the CL of 1 × 1 cm polished sections of Axtell and Coolidge were obtained with a real magnification of 50× using a Nuclide

Corporation (now MAAS) "Luminoscope." We used a 14 ± 1 keV, 7 ± 1 μ A, a 1.0×0.7 cm electron beam, and recorded the images using Kodacolor 400 film, the C-40 development process, and exposures of 5 min for Axtell and 1 min for Coolidge.

Heating Experiments

The methods of Guimon *et al.* (1985a) were used to anneal 20-mg splits of homogenized Allende powder obtained from fragment NMNH 3636 (Sears and Mills, 1974). The times, temperatures and the data obtained are listed in Table 3.

Refractory Inclusions

The 11 samples of five refractory inclusions were crushed and their induced TL measured in the normal way (Sears *et al.*, 1991a). Inclusion EGG-4 had to be cleaned of mounting resin by mechanical abrasion under a microscope and washed in methylene chloride and acetone.

RESULTS

Glow Curve Shapes For Natural Samples

The glow curves (plots of light produced as a function of temperature) for bulk CV chondrites (Fig. 1) resemble those of the CO chondrites (Keck and Sears, 1987). Most samples produce curves with three peaks (Fig. 2), although there is considerable variability in their relative intensities. Coolidge and Loongana 001 are exceptional in that they display one very intense peak. The meteorites can be divided into a group consisting of Allende, Vigarano, Efremovka, Mokoia and ALH84028, with a TL peak at ~ 130 °C and a weaker peak at 220 °C; a group consisting of Kaba, Leoville, Bali, and ALH85006 with approximately equal peaks at 240 and 350 °C; and Coolidge and Loongana 001 with a single

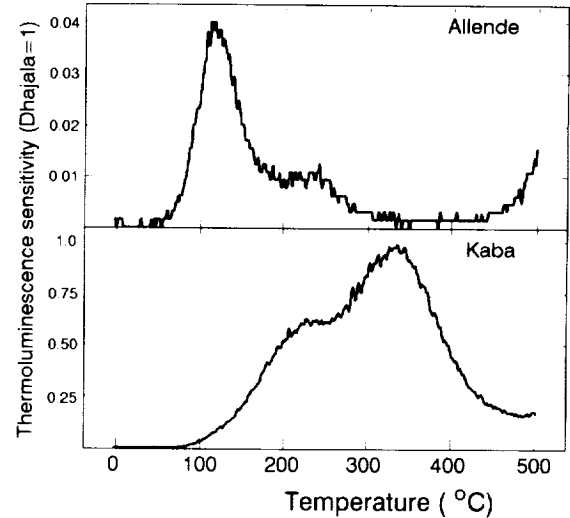


FIG. 1. Representative glow curves (plots of TL produced as a function of temperature of sample) for whole-rock CV chondrite samples. Allende, Vigarano, Efremovka, Mokoia and ALH84028 have fairly similar curves with a TL peak at ~ 130 °C and a weaker peak at 220 °C; Kaba, Leoville, Bali and ALH85006 have curves with approximately equal peaks at 240 and 350 °C; and Coolidge and Loongana 001 have glow curves with a single strong peak at ~ 130 °C. The curves of Arch, Axtell and Grosnaja display only a broad range of TL between 120 and 300 °C and most closely resemble Allende. Renazzo generally resembled the glow curves of Arch and occasionally those of Kaba.

TABLE 3. Thermoluminescence data for samples of the Allende meteorite heated at the temperatures and for the times indicated.*

Heating Temp Time	~ 130 °C peak		~ 250 °C peak		~ 350 °C peak	
	TL. sens [†]	Peak T (°C)	TL. sens [†]	Peak T (°C)	TL. sens [†]	Peak T (°C)
500 °C						
10 h	1.75 ± 0.33	122 ± 4	—	—	—	346 ± 12
100 h	2.18 ± 0.48	122 ± 6	—	—	4.4 ± 1.0	290 ± 20
600 °C						
10 h	1.00 ± 0.08	132 ± 6	—	—	5.5 ± 0.6	224 ± 6
100 h	1.48 ± 0.20	122 ± 6	—	—	3.5 ± 0.5	336 ± 8
700 °C						
1 h	1.83 ± 0.20	130 ± 10	—	—	3.0 ± 0.9	328 ± 6
2 h	3.43 ± 0.38	126 ± 4	2.17 ± 0.17	236 ± 6	—	—
10 h	3.65 ± 0.73	118 ± 4	1.73 ± 0.33	264 ± 4	—	—
20 h	2.83 ± 0.82	116 ± 6	1.60 ± 0.37	258 ± 12	5.8 ± 2.2	412 ± 12
100 h	3.9 ± 2.5	122 ± 2	9.33 ± 1.87	256 ± 6	—	—
800 °C						
10 h	2.60 ± 0.28	114 ± 4	1.77 ± 0.47	228 ± 16	—	—
100 h	2.2 ± 1.2	118 ± 4	1.87 ± 0.33	254 ± 12	4.5 ± 1.0	434 ± 12
900 °C						
1 h	—	—	1.12 ± 0.67	186 ± 6	2.0 ± 5.2	450 ± 10
2 h	—	—	1.00 ± 0.43	176 ± 8	—	—
10 h	—	—	0.93 ± 0.43	215 ± 12	2.2 ± 1.1	374 ± 28
20 h	—	—	0.70 ± 0.10	194 ± 8	—	—
100 h	—	—	0.43 ± 0.03	194 ± 10	—	—
1000 °C						
10 h	—	—	1.60 ± 0.20	174 ± 12	—	—
100 h	—	—	1.00 ± 0.03	170 ± 2	—	—

* Uncertainties are standard deviations calculated from triplicate measurements.

† Relative to unheated powder = 1.0

strong peak at ~ 130 °C. Arch, Axtell and Grosnaja, display only a broad range of TL between 120 and 300 °C and most closely resemble the Allende group. Agreement between duplicate splits is usually very good, with only the Arch group showing serious heterogeneity where the minerals responsible for the individual peaks in Arch group are present in small but heterogeneous amounts. Renazzo generally resembled Arch but occasionally produced curves like those of Kaba. The glow curves of Allende, Coolidge and Kaba groups approximately resemble those of the Lance, Isna and ALHA77307 CO chondrites, respectively.

The Allende CAIs and their separates show a similar range of glow curves to those of the CV chondrites (Fig. 3). They all have TL peaks at ~ 250 °C, and many have intense peaks at 300–350 °C. The Pink Angel rim and a few other samples have a strong peak at ~ 130 °C with little or no TL at high temperatures.

Glow Curve Shapes For Heated Samples

Figure 4 compares the peak temperatures observed for the Allende samples after heating. The ~ 130 °C peak is present in the samples heated at low temperatures, but after 900 °C for 2 h, it appears to have been replaced with a peak at 200 °C. The ~ 220 °C peak is absent or rare in the 500 and 600 °C samples but is present in samples heated at 700 or 800 °C. It also disappears at ~ 900 °C. Peaks at 350 and 450 °C are occasionally present.

TL Sensitivity Variations

The TL sensitivity data are summarized in Table 1 and Fig. 5. The TL sensitivity at 120 °C for CV chondrites covers a similar range to that of CO chondrites (a little over

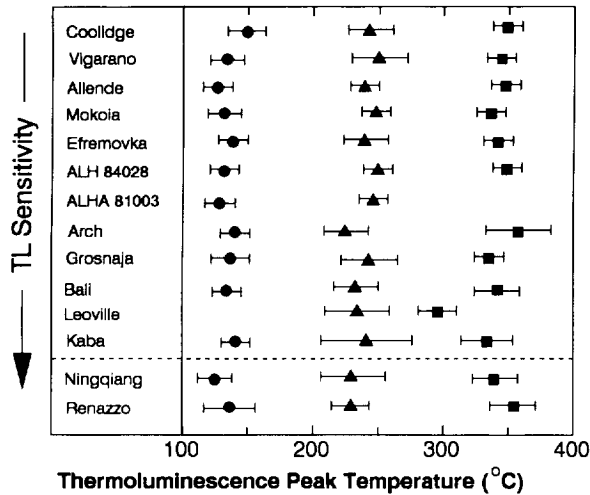


FIG. 2. Plots comparing the peak temperatures for CV chondrites, the Renazzo CR chondrite and the unusual CV chondrite, Ningqiang. Peaks thought to be due to low-feldspar (~130 °C), high-feldspar (~240 °C) and melilite (~350 °C) are present in most of the samples, although relative intensities vary greatly.

two orders of magnitude) and slightly less than the type 3 ordinary chondrites. The range shown by the higher temperature peaks is also very large (nearly three orders of magnitude for the ~220 °C peak and about two orders of magnitude for the 350 °C peak) and larger than observed for the other chondrite groups. We did not attempt to measure the TL sensitivities of CAIs or the CAI separates because of the small sample number and size (Table 3). We found that none of our CK chondrites exhibited detectable induced thermoluminescence.

Luminescence Petrography

The CV chondrites have little or very weak CL. The matrix is nonluminescent, and the CAIs in our Axtell section were generally nonluminescent. The CAIs in Coolidge produced blue CL, although they were few in number. Five of the 30 chondrules in our Axtell

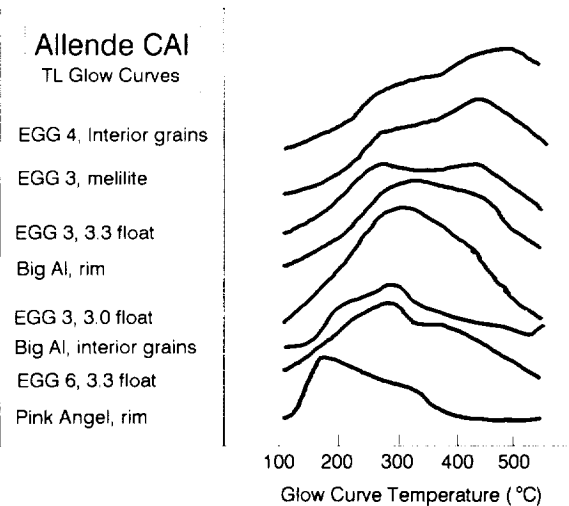


FIG. 3. Glow curves for five refractory inclusions from Allende and separates from them. The values 3.0 and 3.3 refer to the densities (g cm^{-3}) of the liquids used for separations. The temperature of the dominant TL peak moves to higher temperatures as the dominant mineral moves from being low-feldspar to high-feldspar to melilite.

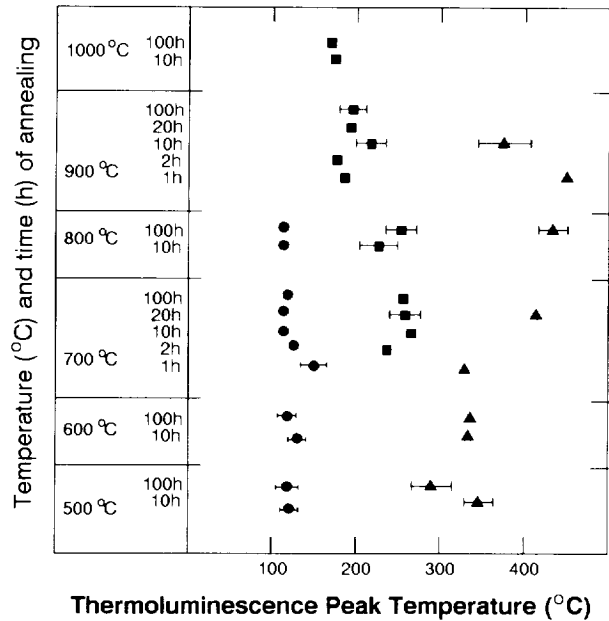


FIG. 4. Plot comparing the peak temperatures for 18 samples of homogenized Allende powder heated at the times and temperatures indicated. Each data point is the mean of three aliquots. The peak at ~130 °C disappears and merges with the 240 °C peak to produce an apparent peak at ~200 °C, as low-feldspar is converted to high-feldspar. (Unlike some samples of Allende, especially CAIs, the samples used for our heating experiments did not display the 240 °C peak prior to heating.)

section have mesostasis with bright blue CL, phenocrysts with red CL and rims of fine-grained material with red CL and are group A3 chondrules, while the remainder had non-luminescent mesostasis and phenocrysts characteristic of group B1 or B2 chondrules (DeHart *et al.*, 1992). In contrast, most chondrules in Coolidge were group A5 (mesostases with blue CL and nonluminescent phenocrysts), while a few appeared to be group B3 (mesostases with weak blue CL) (DeHart *et al.*, 1992). The fine-grained rim material in Axtell closely resembles the material that rims many chondrules in the Murchison CM chondrite (Sears *et al.*, 1993), while Coolidge chondrules did not have these fine-grained red CL rims.

DISCUSSION

We are primarily interested in the metamorphic history of the CV chondrites, but in order to clarify TL production by this class we will first examine the CAIs. These are well-characterized mineral assemblages and separates and, together with the heating and CL results, help to establish the identity and nature of the major TL phosphors in this class. We will then be in a position to discuss implications of the bulk-sample TL data for metamorphism in the CV chondrites and to assign petrographic types to these meteorites. We will then return to CAIs in order to discuss possible metamorphic effects in the inclusions, and we will discuss CK chondrites.

Thermoluminescent Minerals in CV Chondrites

The glow curves in Fig. 3 and the petrographic descriptions of the CAIs in the Appendix suggest mineralogical controls on the TL of the CV class. The interior of EGG 4, the mantle and a dense mineral separate of EGG 3 and coarse-grained melilite rim from

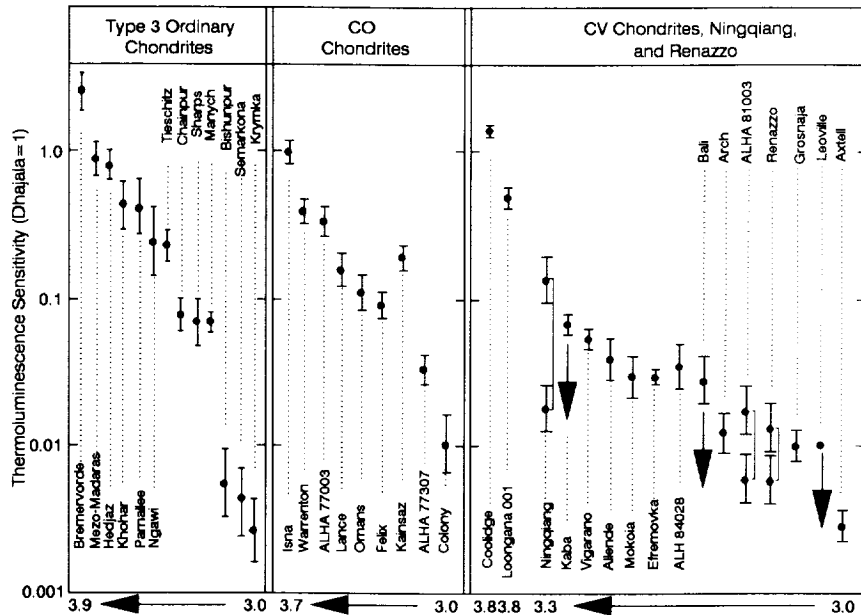


Fig. 5. Plot comparing TL sensitivities of type 3 ordinary, CO and CV chondrites. The ranges for ordinary, CO and CV chondrites are fairly similar, but CV chondrites show a hiatus between Ningqiang and Loongana 001.

Big Al have glow curves consisting of peaks at ~ 400 and ~ 250 °C, often with the higher peak more intense, suggesting that this glow-curve shape is characteristic of melilite. The ~ 130 °C peak observed in most bulk samples of CV chondrites is lacking in these samples. In contrast, low-density plagioclase-rich fractions of EGG 3 and EGG 6 have peaks ~ 130 and ~ 250 °C, although their relative intensity varies, and there is no evidence for a high-temperature peak. Interior samples of Big Al and rim samples of Pink Angel exhibit glow curves similar to those of the low-density separates. In fact, the glow curves of the low-density separates, as well as Big Al interior grains and Pink Angel rim material, resemble those of achondrites, in which we have shown by mineral separations that the primary TL phosphor is plagioclase (Batchelor and Sears, 1991).

We suspect that the peak observed at ~ 250 °C is due to feldspar and that its presence in both low- and high-density separates indicates incomplete separation of feldspar and melilite in the high-density separates. Feldspar is frequently enclosed in melilite in these CAIs. Other common phases in these meteorites, including olivine and pyroxene, probably exhibit little or no luminescence since they tend to be Fe-rich (Batchelor and Sears, 1991; McSween, 1979). The only major exception is the red luminescent grains that we expect to be forsterite in the rims of certain Axtell chondrules.

Metamorphic Series Among the CV Chondrites?

Most of the CV chondrites, especially those of the Allende and Arch groups, have glow curves that resemble those of the feldspar-dominated light fractions of CAIs. Members of the Kaba group, however, exhibit glow curves similar to melilite-rich CAI samples. Notably, although all the CAI samples in Fig. 3 came from Allende, the characteristic 400 °C TL peak is very low in intensity in our bulk-Allende samples. Apparently, melilite, while important in many CAIs, is a relatively rare constituent in Allende. The reproducibility of our Allende measurements argues against heterogeneity being the sole cause of variations in the meteorite-to-meteorite TL properties. However, it suggests that there are real

variations in the ratio of feldspar to melilite as one would expect if melilite was primary and much of the feldspar was secondary. In this case, the Allende, Arch and Kaba groups may represent different metamorphic grades of CV chondrite.

Figure 6 shows induced TL for CV chondrites vs. the heterogeneity of the olivine (the standard deviation of the FeO). The samples can be divided into three groups, those with heterogeneous olivine compositions ($\sigma(\text{Fa}) = 20\text{--}200\%$) and TL sensitivities for the ~ 130 °C peak $< \sim 0.02$, those with somewhat less heterogeneous olivine compositions ($\sigma(\text{Fa}) = 20\text{--}120\%$) and TL sensitivities for the ~ 130 °C peak of 0.02–0.06 and the Coolidge group with homogeneous olivine and TL sensitivity near 1.0. This behavior is similar to that observed for the type 3 ordinary and CO chondrites and suggests that the TL sensitivity increases as olivine compositions homogenize. By contrast, the TL sensitivity of the 240 °C and 350–400 °C peaks (not shown) display no correlations with olivine heterogeneity. The olivine data in Fig. 6 were taken from

McSween (1977b) and probably refer mainly to chondrule olivines. Peck (1984) analyzed matrix olivine and also found varying degrees of homogenization, which she interpreted in terms of homogenization during metamorphism. She suggested the series Kaba \ll Mokoia $<$ Vigarano / Grosnaja / Allende (see Scott *et al.*, 1988), which is somewhat different to the series we propose here. Our CL

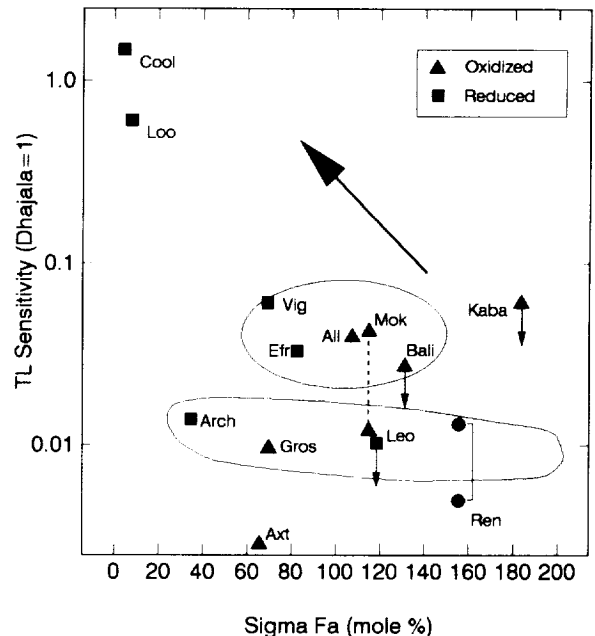


Fig. 6. The TL sensitivity vs. standard deviation of the Fa in the olivine of CV chondrites for the ~ 130 °C glow-curve peak. (Olivine data from McSween, 1977b). The proposed metamorphic trend is indicated by the large arrow. The balloons are discussed in the text. McSween's (1977b) oxidized and reduced subgroups are indicated by different symbols. Splits from a single meteorite, where they differ outside uncertainty limits, are connected by tie-lines. Upper limits on the TL data are indicated with small arrows.

observations indicate that the luminescence of CV3 chondrites is not concentrated in the CAIs but in chondrule mesostases, and unlike CO and ordinary chondrites, CV3 chondrites show considerable variability in modal chondrule abundance, 30 to 65% (McSween, 1977b; Huss *et al.*, 1981; King and King, 1978, 1979; Grossman *et al.*, 1988). In Fig. 7, we therefore plot the TL sensitivity of the ~ 130 °C peak normalized to the modal abundance of Type I chondrules vs. the standard deviation of the Fa. The line is marginally improved, but Arch, Axtell and Grosnaja still plot off the line by amounts exceeding analytical uncertainties. We, therefore, do not continue to normalize the TL sensitivity data.

The low-TL sensitivity of most of these samples and their heterogeneity make these measurements difficult, but weathering and shock could also complicate the picture. Grosnaja and Arch are shock stage 3, but then so are many meteorites plotting close to the trend line, which suggests that shock is not creating the scatter. Weathering causes a decrease in TL sensitivity by up to an order of magnitude, which can be removed, at least for Antarctic meteorites, by acid-washing (Benoit *et al.*, 1991). However, there is no evidence that Arch, Axtell and Grosnaja are especially weathered, and the TL sensitivity seems much too low for this to be a reasonable explanation. Acid washing of Loongana 001 increased its TL sensitivity by only a factor of two or less (Table 1), suggesting that the small difference between Loongana 001 and Coolidge might be due to weathering but not the low TL values of Arch, Axtell and Grosnaja. With samples that are this heterogeneous, it is clearly necessary to look at data for as many mineral systems as possible.

During metamorphism, the chondrules (like the refractory inclusions) acquired Fe from the matrix (McSween, 1977b) so that TL sensitivity of the ~ 130 °C peak and the mean Fa content of the olivines in reduced and oxidized CV chondrites display positive

trends (Fig. 8). On the basis of Fe-Mg-Ca,Al plots, McSween (1977b) ranked the reduced CV chondrites in order of increasing metamorphism experienced as Efremovka, Leoville < Vigarano, Arch < Coolidge, and for the oxidized CV chondrites the series was Grosnaja, Bali, Kaba, Mokoia < Allende. These series are similar to those expected on the basis of the data shown in Fig. 8 except that we would place Efremovka with Vigarano and Arch with Leoville.

Metal and sulfide compositions are also sensitive indicators of thermal history and are compared with TL sensitivity in Fig. 9. The Ni content of the metal and sulfide of the oxidized subgroup of CV chondrites increases with TL sensitivity, with Kaba and Bali having the lowest Ni content; for the reduced subgroup, the Ni content of the metal and sulfide is essentially independent of TL sensitivity. This suggests that metamorphism caused the oxidation of Fe in the oxidized subgroup but had little effect on the Fe in the reduced subgroup. Significantly, Renazzo plots at the origin of these two trends, indicating that it might represent the starting material for both series. Wood (1967) noted that heating Renazzo in the laboratory caused the Ni in the metal to increase and suggested that Ni was migrating from the matrix to the metal grains.

In the ordinary chondrite groups, the concentration of volatiles decreases with increasing TL sensitivity (Sears *et al.*, 1991a). The data for CV chondrites is not as clear cut (Fig. 10). We expect C to behave as a volatile because of the thermodynamic stability and volatility of CH_4 and CO, and the concentration of C decreases with increasing TL sensitivity (Fig. 10b), with the meteorites with the lowest TL sensitivity generally having fairly high C/Si ratios. Vigarano, which our TL analysis suggests is relatively metamorphosed, has a fairly high C/Si ratio. The water data are inconclusive or even contradictory (Fig. 10a) showing little trend as a function of TL sensitivity. Although Coolidge may have a higher water content due to terrestrial weathering, we observe that Kaba,

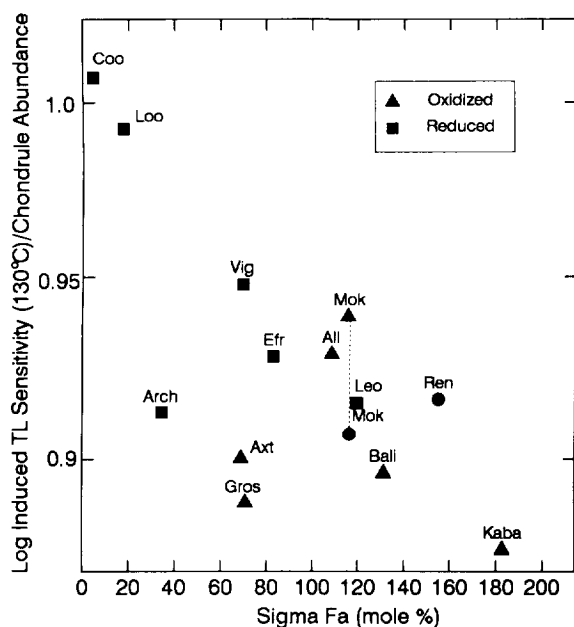


FIG. 7. The TL sensitivity of the ~ 130 °C peak normalized to modal abundance of chondrules in CV chondrites vs. the standard deviation of Fa in the olivine. Modal data from McSween (1977b), Rubin *et al.* (1988) and Kallemeyn and Rubin (1995). Chondrule abundance data are not available for all CV chondrites (especially Antarctic finds) and, thus, not all CV chondrites in the present study are plotted.

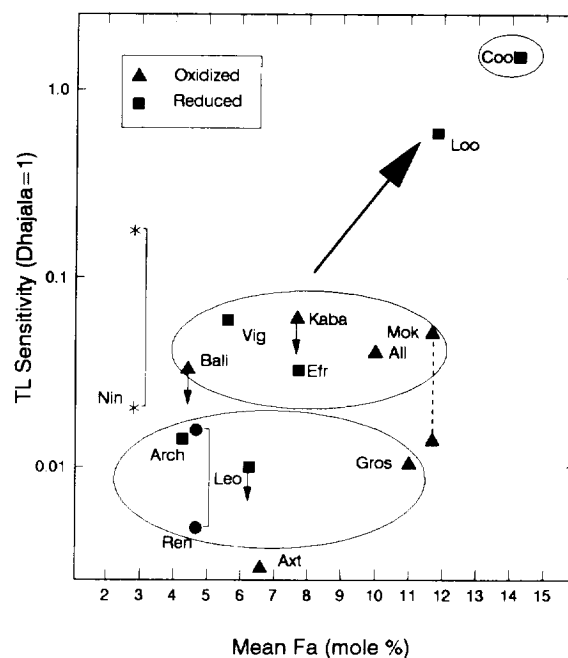


FIG. 8. Plot of TL sensitivity of the ~ 130 °C peak vs. composition of the olivine in CV chondrites. The balloons, arrows, tie-lines and symbols are as in Fig. 6. Olivine composition data from McSween (1977b), Simon *et al.* (1995) and Kallemeyn and Rubin (1995).

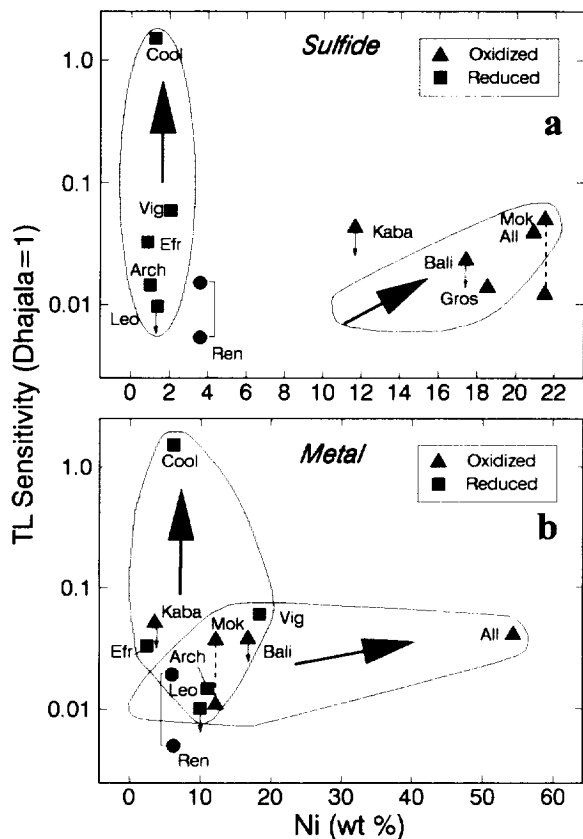


FIG. 9. The TL sensitivity of the ~ 130 °C peak vs. (a) the Ni content of the sulfide and (b) the Ni content of the metal. With increasing TL sensitivity, and therefore metamorphism, the Ni content of the metal and sulfide of the oxidized subgroup increases; while for the reduced subgroup, it is either constant or may decrease slightly. Renazzo appears to plot at the origin of the two trends. (Sulfide and metal compositions were read from the plots of McSween, 1977b). The large arrows indicate possible metamorphic trends. The symbols, tie-lines and small arrows are as in Fig. 6.

Bali and Leoville all have low water contents. The apparently more metamorphosed Allende, Vigarano and Grosnaja exhibit a wide range of water contents. Data for the inert gases scatter widely with only the slightest, if any, indication of a negative correlation (Fig. 11).

Petrographic Types for CV Chondrites

We suggest that variations in TL sensitivity and mineral properties are consistent with oxidized and reduced CV chondrites forming two metamorphic series. As for the ordinary and CO chondrites, it seems that meaningful petrographic types can be assigned to CV chondrites. This will help to distinguish between nebular and parent-body processes and compare metamorphism on different parent bodies. There is no *a priori* reason to suppose the "calibration" between TL sensitivity and metamorphism is the same for all chondrites classes, but in practice, these differences seem relatively minor. The type definitions we propose for CV chondrites are listed in Table 4. The TL sensitivity ranges are those previously proposed for CO chondrites; other parameters are determined from trend lines drawn through the data in Figs. 6–8. Table 5 shows the results obtained by assigning petrographic types

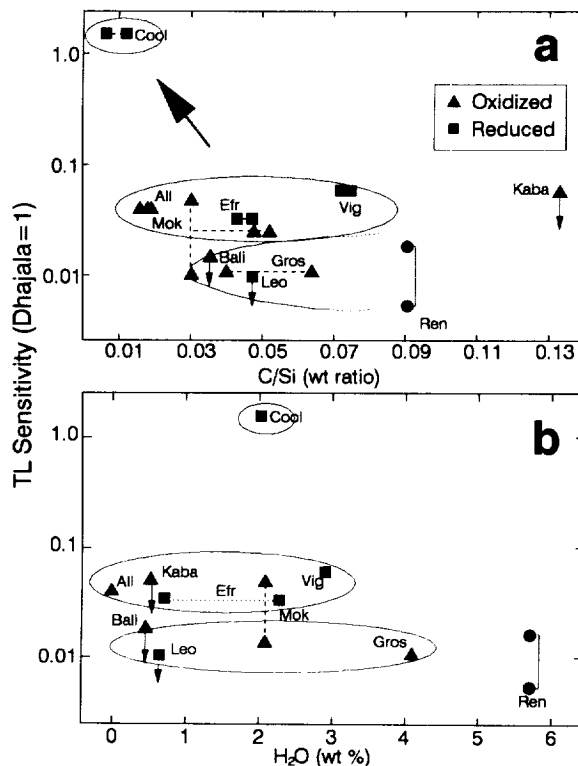


FIG. 10. The TL sensitivity of the ~ 130 °C peak vs. (a) C-Si ratio and (b) H₂O content for CV chondrites and Renazzo. With increasing TL sensitivity, and therefore metamorphism, the C and H₂O content of the samples decreases. The balloons, arrows, tie-lines and symbols are as in Fig. 6. (Carbon and H₂O data from Wiik, 1969, and Jarosewich, 1990).

on the basis of each parameter independently and our recommended petrographic type for each meteorite. The scatter in Figs. 6–8 manifests itself as scatter in the assigned types, but when presented this way outlying data can be recognized easily. With the exception of Coolidge and Loongana 001, which are type 3.8, all the samples are of low petrographic type (*i.e.*, <3.3). Axtell, Leoville and Arch (and possibly Kaba and Bali) are types 3.0–3.1, and Allende, Grosnaja, Mokoia, Efremovka and Vigarano are types 3.2–3.3.

Metamorphic History of CV Chondrites Compared with Other Classes

The most notable aspect of the metamorphic history of the CV chondrites is how little metamorphism they have suffered compared with the CO and ordinary chondrites. Only Coolidge and Loongana 001 are above type 3.3, while most ordinary chondrites and about half of the CO chondrites are type >3.3. This could imply small parent bodies or late accretion (Grimm and McSween, 1993), or it might be a sampling artifact. In this connection, the relationship between oxidized CV chondrites and the CK chondrites is especially interesting.

Despite the problem of representative sampling of small classes, it seems clear that there are major differences in time-temperature history during metamorphism of the various classes (Fig. 12). Although there are several CO chondrites that, like Coolidge and Loongana 001, are of type >3.5, the feldspar in these samples is apparently in the low form. Thus, they have a predominant ~ 130 °C peak in their glow curves. In contrast, ordinary chondrites of type

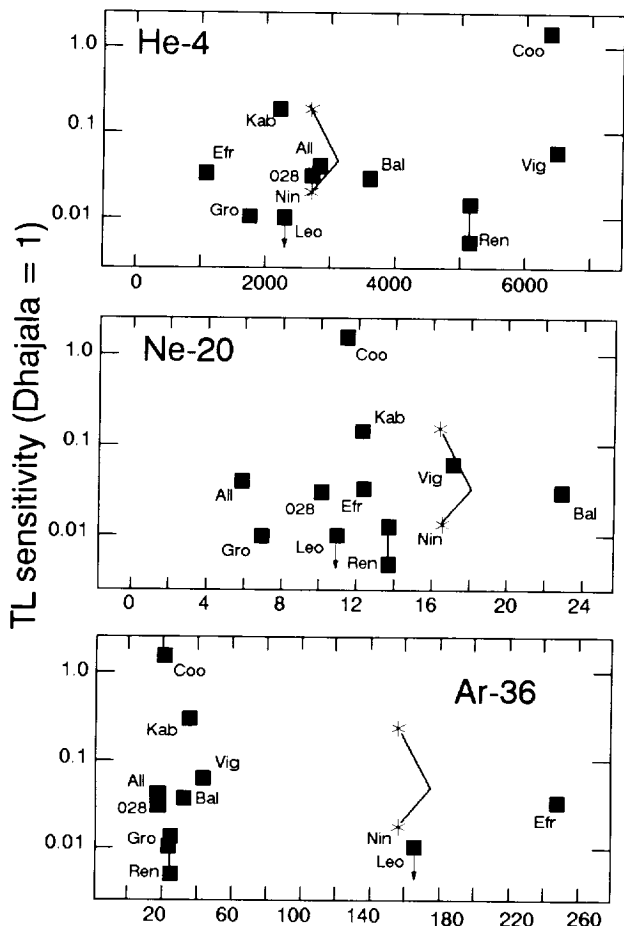


FIG. 11. The TL sensitivity for the ~130 °C peak vs. inert-gas content for CV chondrites. In general, these plots show no obvious correlations, but an exception might be the content of the heaviest of the three, which may decrease with increasing TL sensitivity and therefore metamorphism. Gas loss might explain the lack of a correlation by He and Ne. (Inert-gas data from Schultz and Kruse, 1989).

>3.5 contain predominantly high-feldspar. This means that either (1) feldspar production in CO, CV and CV-related chondrites of types 3.5–3.9 took place over a longer time span than in ordinary chondrites but at lower maximum temperatures, or (2) the CO, CV

TABLE 4. Petrographic type definitions for CV chondrites.*

Type	TL sens (Dhajala = 1)	Mean Fa (mol%)	σ Fa (%)	Ni in sulfide† (wt%)	C (wt%)	H ₂ O (wt%)
3.0	<0.017	<8.0	>110	<17	>1.05	>3.5
3.1	0.017–0.030	8.0–10.0	90–110	17–20	0.75–1.05	2.5–3.5
3.2	0.030–0.054	10.0–11.0	70–90	20–22	0.60–0.75	2.5–3.5
3.3	0.054–0.10	11.0–12.0	50–70	22–23	0.45–0.60	2.0–2.5
3.4	0.10–0.17	12.0–12.5	40–50	23–24	0.40–0.45	1.5–2.0
3.5	0.17–0.30	12.5–13.0	30–40	24–25	0.30–0.40	1.3–1.5
3.6	0.30–0.54	13.0–13.5	20–30	25–26	0.20–0.30	0.8–1.3
3.7	0.54–1.00	13.5–14.0	5–20	26–28	0.15–0.20	0.5–0.8
3.8	1.0–1.7	14.0–14.5	<5	>28	<0.15	<0.5
3.9	>1.7	>14.5	<5	>28	<0.15	<0.5

* Fa and Fs data from McSween (1977b); sulfide compositions from Wood (1967) and McSween (1977b); C and H₂O data from Wiik (1969) and Jarosewich (1990).

† Parameter applicable to oxidized subgroup of CV chondrites only.

TABLE 5. Assignment of petrographic types to CV chondrites.

	TL sens	Mean Fa	Fa	Ni in sulf*†	C	H ₂ O	Type†
ALHA 81003	3.0/3.5	–	–	–	–	–	3.0
ALH 84018	3.2	–	–	–	–	–	3.2
Allende	3.2	3.2	3.1	3.2	3.6	3.6	3.2
Arch	3.0	3.0	3.5	n.a.	–	–	3.0
Axtell	3.0	3.0	3.3	–	–	–	3.0
Bali	<3.2	3.0	3.0	3.1	3.3	3.6	3.0
Coolidge	3.8	3.8	3.8	n.a.	≥3.8	≥3.8	3.8
Efremovka	3.2	3.0	3.2	n.a.	3.1	3.6	3.2
Grosnaja	3.3	3.3	3.3	3.1	3.2	3.0	3.3
Kaba	<3.3	3.0	3.0	3.3	3.0	3.6	3.0
Leoville	3.0	3.0	3.0	n.a.	3.0	3.6	3.0
Loongana 001	>3.3	3.8	3.8	n.a.	–	–	3.8
Mokoia	3.2	3.3	3.0	3.3	3.1	3.2	3.2
Vigarano	3.3	3.0	3.3	n.a.	3.0	3.2	3.3

* n.a. = not applicable. This parameter is only applicable to the oxidized subgroup of CV chondrites; – = data not available.

† Recommended petrographic type.

and CV-related chondrites were metamorphosed at roughly the same maximum temperature as the ordinary chondrites but cooled through the high-low feldspar transition much more slowly than ordinary chondrites, allowing most of their feldspar to transform to the low state (Keck and Sears, 1987; Sears *et al.*, 1991b). The equilibration temperatures for Allende calculated by Weinbruch *et al.* (1993) are well below the high-low transformation temperature for feldspar, which is probably ~600 °C (Smith, 1972) but certainly <800 °C, the temperature at which the TL peak moves to higher temperatures after heating for 100h (Guimon *et al.*, 1985a).

The Low TL Sensitivity of CK Chondrites

The most perplexing property of the CK chondrites is that despite their high petrographic grade, they produce no detectable induced TL. Other type 4,5 chondrites typically have TL sensitivities 10⁵–10⁶× the detection limit. In fact, in view of the similarity of the

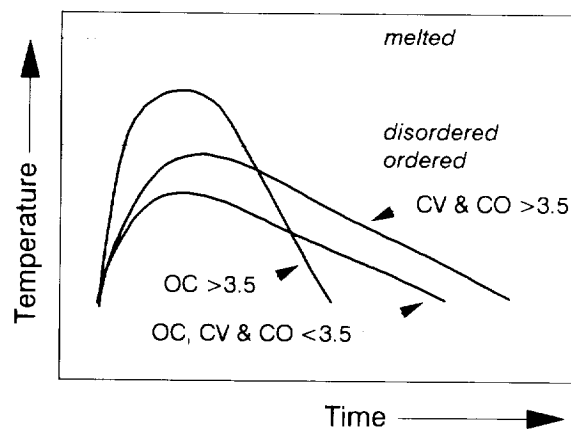


FIG. 12. Schematic temperature-time metamorphic histories for ordinary, CO and CV chondrites based on TL and other studies. The CV and CO chondrites of petrographic type ≤3.5 did not experience sufficient peak metamorphic temperatures to produce disordered feldspar, while ordinary, CV and CO chondrites of petrographic types >3.5 were metamorphosed to a higher degree but still below the order-disorder transformation temperature for feldspar. Ordinary chondrites of petrographic types >3.5 were heated to temperatures or for times that varied with petrographic type but above the order-disorder temperature. Ordinary chondrites are referred to as "OC" in the figure.

two classes (McSween, 1977b; Kallemeyn *et al.*, 1991), it might be suggested that the CK chondrites are simply highly metamorphosed equivalents of the CV chondrites. However, the TL data alone indicate that this is clearly not so.

The most straight-forward explanation for a meteorite to show little or no induced TL is the absence of crystalline feldspar. However, not only is this unlikely in view of their bulk compositions and metamorphic history, crystalline feldspar is petrographically observed (Geiger and Bischoff, 1991; Rubin, 1992; Keller, 1993). One of the characteristics of CK chondrites is their low chondrule content, 10 to 15 vol%, but this would decrease the TL sensitivity by only a factor of 2–3 and not by the 2–3 orders of magnitude below those of chondrites of comparable petrographic types. Shock-heating can lower TL sensitivities of terrestrial feldspars and meteorites by 1–2 orders of magnitude through the destruction of crystalline feldspar and shock-darkening of the sample (Hartmetz *et al.*, 1986; Haq *et al.*, 1988). Unusual shock and thermal histories for CK chondrites have been proposed by Kallemeyn *et al.* (1991) and Rubin (1992), although this interpretation appears unlikely (Keller, 1993). The CK chondrites show only modest petrographic indications of shock (shock stages S1–S3; Scott *et al.*, 1992), and there is certainly no indication that CK chondrites are more heavily shocked than CV chondrites. Nor is there any relationship between TL sensitivity and shock (Fig. 13).

A possible alternate explanation for lack of measurable induced TL in these meteorites is that the plagioclase contains Fe, which is quenching the TL production. We have argued that the relatively low TL sensitivity of lunar mare basalts and unequilibrated eucrites was due to Fe-quenching, (Batchelor and Sears, 1991). However, the TL sensitivity of CK chondrites seems even too low for Fe-

quenching, and mild levels of metamorphism should cause the Fe to diffuse out of the plagioclase. In short, we are unable to satisfactorily explain the lack of measurable TL of CK chondrites, but it surely indicates major differences in the feldspar of this and almost every other chondrite and achondrite class.

Metamorphic Series among the Allende Refractory Inclusions?

Meeker *et al.* (1983) suggested that five refractory inclusions in Allende, including Egg-3, Egg-4, and Egg-6 in the present study, constituted a metamorphic series. It was suggested that Egg-4 had experienced metamorphism throughout and that Egg-3 and Egg-6 contain altered mantles and pristine cores. Embayed pyroxene, the optical continuity of separated pyroxenes, lobate sutured grain boundaries and 120° triple junctions were thought to be evidence that pyroxene was converted to melilite by an *in situ* reaction with a Ca source during metamorphism on the parent body. Meeker *et al.* (1983) were unclear as to the source of the Ca, suggesting CaCO₃ or calcic pyroxenes as possibilities. Calcic feldspar might be another. Possible parent-body metamorphic effects on dark clasts in Allende have also been reported by Kojima and Tomeoka (1994). The Meeker *et al.* suggestion is not widely accepted, and the features they described are usually ascribed to preaccretionary igneous events (see MacPherson *et al.*, 1988; Meeker, 1995a).

We agree with Meeker *et al.* (1983) that their proposal carries the implication that metamorphism must have occurred prior to emplacement in the meteorite. Not only is the degree of alteration from one inclusion to another more than one would expect for *in situ* metamorphism, but petrographic type and the TL sensitivity at high glow-curve temperatures would show a positive correlation, as feldspar is converted to melilite. This is not observed. In addition, the 200 °C glow-curve peak displayed by the CAIs is more intense than the ~130 °C peak (Fig. 1b), suggesting that the CAIs in feldspar is predominantly in the high form. The CAIs apparently cooled rapidly from temperatures >800 °C and the meteorite-wide metamorphism was clearly not sufficiently intense to cause the feldspar to revert to the low form. Our data do not permit us to choose between the metamorphic and igneous theories for the production of these trends. They are consistent with both.

The fairly intense ~130 °C TL peak, relative to the 200 °C peak (Fig. 1b), shown by the Pink Angel rim is noteworthy and suggests a history quite unlike that of most CAIs. Almost certainly this history involved low temperatures and/or a slow cooling history (MacPherson *et al.*, 1981; Brigham *et al.*, 1986; see MacPherson *et al.*, 1988), consistent with the presence of low-feldspar and relative paucity of high-feldspar. The hydrothermal heating experiments of Guimon *et al.* (1985b) make it seem unlikely that secondary alteration is responsible for the production of this feldspar since aqueous alteration preferentially destroys low-feldspar and does not result in its formation. It is also unlikely that chondrule mesostasis, which drives the TL trends of our bulk samples, is responsible for the production of the ~130 °C peak in this CAI. Another possibility is that the Pink Angel inclusion, the only fine-grained CAI in our study (Armstrong and Wasserburg, 1981), either did not experience the high temperatures necessary to produce high feldspar in the first place or, if it did, cooled sufficiently slowly to enable complete conversion to the low form. The small grain size and the presence of alkali- and halogen-rich phases suggest formation at much lower temperatures than typical coarse-grained CAIs or perhaps, as suggested by Chen and Wasserburg (1981), as part of a multistage evolution quite different from that of coarse-grained CAIs.

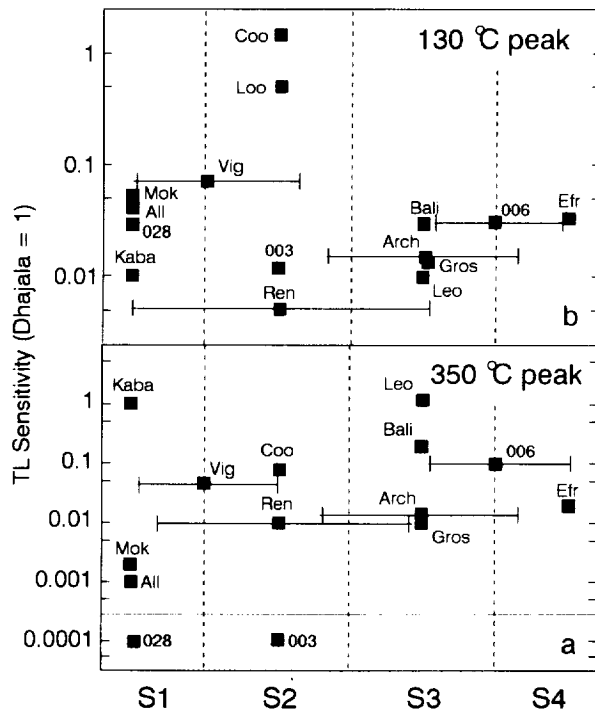


FIG. 13. The TL sensitivity of various TL peaks as a function of shock stage for CV chondrites. We plot shock stage against (a) intensity of the ~350 °C induced TL peak and (b) intensity of the ~130 °C peak. Shock stage data are from Scott *et al.* (1992). Stippled region marks limits of detection.

SUMMARY AND CONCLUSIONS

We have explored the metamorphic history of CV chondrites using their induced thermoluminescence properties. The greater heterogeneity and generally low levels of metamorphism involved made the study more difficult than previous studies of unequilibrium ordinary chondrites or even the CO chondrites, but we can observe trends in TL sensitivity and mineral composition that appear to reflect parent-body metamorphism. We propose petrologic types ranging from type 3.0 (e.g., Axtell) to type 3.8 (Coolidge and Loongana 001). Studies of the cathodoluminescence properties of Axtell and Coolidge are consistent with our interpretations. We also have studied the TL properties of a suite of individual CAIs, which display TL trends consistent with known mineralogical variations and with melilite displaying strong high-temperature TL (~400 °C) and high-feldspar contributing TL at ~230 °C. These data are consistent with either an igneous origin or with metamorphism prior to emplacement in the meteorite, but they clearly are not consistent with *in situ* metamorphism. The CK chondrites have no detectable induced TL, which make them unique among metamorphosed chondrites and is a further indication of their unusual feldspar. On the basis of its TL properties, we argue that Ningqiang is more closely related to CV than to CK chondrites.

The CV chondrites are unlike CO chondrites and ordinary chondrites in their generally low degree of metamorphism. Among the samples analyzed in this study, only Coolidge and Loongana 001 exhibit a petrologic type >3.3 and a relatively large number of CV chondrites (Axtell, Bali, Kaba and Leoville) are virtually unmetamorphosed (type 3.0). Thus, like the low petrologic types of other chondrite classes, the CV chondrites provide opportunities for studying premetamorphic processes in the Solar System without the postaccretionary aqueous alteration that characterizes other classes of carbonaceous chondrites. Like the CO chondrites, the CV chondrites, including the two type 3.8 chondrites, have TL properties indicative of low-temperature metamorphism. There are, thus, important differences in the thermal history of the various chondrite classes, even for individual meteorites with the same petrographic type.

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APPENDIX

Descriptions of the Refractory Inclusions in This Study

Big Al is a 1.2 × 1.8 cm type B1 inclusion (Grossman, 1975) with a coarse-grained melilite mantle (Papanastassiou *et al.*, 1984, 1987). We were provided with samples of both the mantle and the interior of this inclusion.

EGG 3 is a large type B inclusion (Grossman, 1975) of Ti-rich fassaite, anorthite, spinel and melilite with minor opaques and perovskite (Wark and Wasserburg, 1980; Wark and Lovering, 1980, 1982; Meeker *et al.*, 1983). The melilite is in a 0.1–2 mm mantle and is essentially absent from the interior. Spinel becomes small and anhedral or disappearing towards the rim. We obtained samples of pure melilite and two density separates, <3.0 gm/cm³ and 3.0–3.3 gm/cm³. We presume these mineral separates consist primarily of plagioclase, and plagioclase and melilite, respectively.

EGG 4 is a cm-sized type A inclusion (Grossman, 1975) of 0.5–2 mm melilite grains enclosing small (<100 μm) grains of spinel, Ti-rich fassaite, perovskite and minor opaques (Meeker *et al.*, 1983; Teshima and Wasserburg, 1985). "Kink band-like features," lobate sutured grain boundaries and 120° triple points displayed by the melilite were interpreted by Meeker *et al.* (1983) as evidence for intensive metamorphism. The present sample consisted of interior grains.

al. (1983) as evidence for intensive metamorphism. The present sample consisted of interior grains.

EGG 6 is a 2 cm diameter inclusion that consists of a core of pyroxene, plagioclase and spinel surrounded by mantle of melilite. It also contains "spinel-free islands" that have caused considerable discussion (Meeker, 1995b). As in *EGG 3*, the spinels become small, anhedral or disappear towards the rim of the inclusion. Unlike *EGG 3*, this inclusion contains assemblages of V-Fe-Ni-S phases in a single 250-μm inclusion (Meeker *et al.*, 1983; Teshima and Wasserburg, 1985). Our sample from *EGG 6* consisted of a 3.3 gm/cm³ float, consisting primarily of plagioclase.

Pink Angel is a 2-cm diameter inclusion that is representative of a class of fine-grained Allende inclusions rich in Mg and Al (referred to as MASHI inclusions) and contain phases rich in Na and halogens (Armstrong and Wasserburg, 1981; Villa *et al.*, 1981). The interior of this inclusions consists of a porous aggregate of spinel cemented by dense patches of sodalite and associated grossular. The rim of this inclusion is a compact assemblage of spinel and fine-grained anorthite and diopside. We were supplied with samples of the rim of this inclusion.