THE CV CHONDRITES: METAMORPHISM, THERMAL HISTORY, AND THEIR RELATIONSHIP TO CK CHONDRITES.
P.H. Benoit, S.J.K. Symes, R.K. Guimon+, and D.W.G. Sears. Cosmochemistry group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, USA. +Present address: Natural Science Division, Missouri Baptist College, St. Louis, MO 63142 USA. Internet: COSMO@uafsysb.uark.edu

Virtually all classes of chondrite have experienced some level of metamorphism during their history, although in some cases (type 1 and 2 carbonaceous chondrites) this metamorphism involved considerable aqueous alteration. The CV chondrites are generally assigned to petrologic type 3. Among the type 3 ordinary chondrites there is broad diversity in levels of metamorphism, ranging from the little or unmetamorphosed Semarkona (LL3.0) to meteorites which verge on the "equilibrated" type 4 chondrites, such as Dhajala (H3.8). Luminescence techniques, notably induced thermoluminescence (TL) measurements, are very useful in examining this range of diversity among the ordinary chondrites, as well as the CO chondrites and some achondrite groups. In this paper we examine the levels of metamorphism of CV chondrites using luminescence techniques, including TL and cathodoluminescence (CL) and find that most CV chondrites exhibit fairly low degrees of metamorphism (type 3.3 and below). A few CV chondrites have experienced very low degrees of metamorphism, notably Axtell. We also discuss the effects of CAI, which are common in CV chondrites and which have luminescence properties which appear to reflect their pre-accretionary history, on the TL results of bulk samples of CV chondrites. Chondrules dominate the non-CAI luminescence signal in these meteorites. Two meteorites, Coolidge and Loongana 001, have been generally considered as more highly metamorphosed (type 4) CV chondrites but have also recently been considered as a separate chondrite "grouplet". Our present data generally support their position as metamorphosed CV chondrites. The CK chondrites, which share some compositional similarities with the CV chondrites, have significantly different TL properties; Ningqiang, variously classified as an anomalous CV or as a CK chondrite, has TL properties much more similar to CV chondrites. Based on TL and other data it appears that the thermal history of CV chondrites is quite different to that of ordinary chondrites.

Methods. Induced thermoluminescence measurements have been used to investigate the metamorphic history of ordinary chondrites [1], CO chondrites [2] and eucrites [3]. The TL measurements reported in this paper were obtained using the methods used for previous investigations. Two or more 150 mg chips from 16 meteorites (Table 1) were crushed to approximately 100 mesh, no particular attempt being made to avoid inclusions. Polished thin sections were used for CL observations of some of these meteorites, the apparatus and procedures being those used in our previous work [2,4]. Samples of individual CAI from Allende, including some density separates, were crushed and their induced TL measured using the techniques described for the other samples. This work is an extension of our ongoing investigation of carbonaceous chondrites [5].

Results. The induced TL glow curves of bulk CV chondrites are very similar to those of CO chondrites [2] in that they exhibit three peaks in the glow curve at ~120, ~240, and ~400 °C. However, not all peaks are present in all samples and their intensities vary considerably from sample to sample, although results for duplicate chips of individual meteorites are generally quite close. Based on the peaks present and their intensity, we can place most CV chondrites into three classes (Table 1), namely, an "Allende" group which exhibits peaks at 120 and 240 °C (with the 120°C peak being more intense), a "Kaba" group, which exhibits intense peaks at 240 and 400 °C and an "Arch" group, which exhibits a broad TL peak between 120 - 300 °C in the glow curve (and is thus more similar to the "Allende" group than the "Kaba" group). Coolidge and Loongana 001 are discussed separately below.

The induced TL glow curves of individual CAI from Allende are generally similar to those of bulk samples of Kaba group CV chondrites. A few CAI and lighter (<3.3 g/cm^3) density separates of some CAI have glow curves similar to those of the Allende group.

Cathodoluminescence observations of polished sections of selected CV chondrites indicate that (1) chondrules (specifically chondrule mesostasis) are the major center of luminescence in these meteorites although not all chondrules luminesce, and (2) some CAI in these sections exhibit a strong blue luminescence but most are completely non-luminescent. Matrix is generally non-luminescent. Those chondrules which exhibit luminescence generally have blue mesostasis, while phenocrysts are either non-luminescent or luminesce red.

Discussion. On the basis of our previous investigations of ordinary chondrites and on the CL images of CV chondrites, it is apparent that the major blue phosphors in CV chondrites are located in the mesostasis of certain chondrules, most probably as feldspathic microlites. Red luminescing grains occur as phenocrysts in chondrules and as small grains, the latter often concentrated in rims around luminescent chondrules; these, in analogy to CM chondrites, are probably low-Fe olivine grains [4]. It is also apparent from our CL images and from our TL data for CAI density-separates that melilite also luminesces strongly in the blue region of the spectra. These results are important because our TL measurements are largely restricted to blue luminescence. We expect our TL results to be determined by phases in chondrule mesostasis and by melilite in CAI. In our previous work [*i.e.*, 2] we have determined that the peak at 120°C in the glow curve is produced by ordered feldspar, while that at 240°C is produced by disordered feldspar and the peak at about 400°C, on the basis of the present TL results for CAI, is clearly associated with melilite.

In analogy to the unequilibrated ordinary chondrites [1], we suggest that the intensity of the feldspar peaks in bulk samples of CV chondrites can be used as a guide to the degree of metamorphism. These phosphors are largely concentrated in chondrule mesostasis and thus variations in chondrule abundance as well as feldspar growth as a result of metamorphism must be considered; the CV chondrites exhibit a range of chondrule abundances between 30 to 80%, a very large range compared to other chondrites [6]. Studies of mineral chemistry heterogeneity [6,7] suggest that there is a range of metamorphism among the CV chondrites. One result of these studies is that Grosnaja and Vigarano have experienced similar degrees of metamorphism; if we use this result to "calibrate" the effect of varying chondrule abundance on TL intensity among the CV chondrites, we can assign metamorphic rankings to our samples. The relative ranking in this system is determined by the intensity of the 120°C TL peak, taking into account varying chondrule abundance between samples, and the absolute numerical ranking is based on those used for CO chondrites [2]. We find that (a) the CV chondrites do exhibit a range of metamorphism but, (b) the observed range encompassing most CV's is much smaller (3.0 - 3.3) than that observed in either the ordinary or CO chondrites. Axtell is apparently the least metamorphosed meteorite in the current database [8].

The CK chondrites are similar to CV chondrites in terms of their elemental abundance patterns [9]; all CK are of type 4 or higher and, although mineral and bulk chemistry data argue otherwise, it might be asked whether CK are merely metamorphosed CV chondrites. We measured the induced TL of four CK chondrites (ALHA 85002, EET 87507, LEW 86258, and Karoonda) and found that, in contrast to CV chondrites, none showed appreciable TL at any temperature in their glow curves. Thus, the TL data support the separation between these two classes. Ningqiang, which has been classified both as an "anomalous" CV [10] and as a CK chondrite [9], is clearly not part of the latter group based on its intense induced TL signal.

It has also been argued [11] that Coolidge and Loongana 001 should be placed in a separate "grouplet" rather than being considered metamorphosed CV chondrites. Our present data suggest that these meteorites have TL and CL properties appropriate for being metamorphosed CV chondrites of type 3.8 or higher. We observe that while chondrules in most CV chondrites are generally group A3 or B1-B2, which also occur in ordinary chondrites of types <3.5 [12], chondrules in Coolidge are all of group A5 or B3, similar to those observed in the more highly equilibrated ordinary chondrites such as Dhajala.

In light of the comparison between CV and ordinary chondrites in the previous paragraph, we wish to stress that metamorphism involves more than just exposure to high temperatures, but also includes heating/cooling duration. We agree, based on the low abundance of disordered feldspar in our samples relative to ordered feldspar as evidenced by the intensity of the 240 and 120°C induced TL peaks, that CV chondrites (including Coolidge and Loongana 001) have not been heated to high temperatures equivalent to those experienced by ordinary chondrites of types >3.6 (*e.g.*, Dhajala). We suggest, however, that, although metamorphosed at lower temperatures, the CV chondrites may well have been subjected to metamorphism longer than ordinary chondrites, thus allowing the production of high type CV's.

TABLE 1. CV chondrites analyzed in this study, groups based on induced TL glow curve shape and apparent metamorphic grade.

Sample	Grouping*	Petrologic type
ALH 81003	A	3.0
ALH 84028	A	3.2
ALH 85006	K	3.0
Allende	A	3.2
Arch b	Ar	3.0
Axtell	Ar	3.0
Bali	K	3.0
Coolidge	C	3.8
Efremovka	Ar	3.2
Grosnaja	Ar	3.3
Kaba	K	3.0
Leoville	K	3.0
Loongana 001	C	3.8
Mokoia	A	3.2
Vigarano	Ar	3.3

* A = Allende; K = Kaba; Ar = Arch; C = Coolidge; Anom = Anomalous

Acknowledgements. We wish to thank the suppliers of the samples used in this study, notably Glenn MacPherson, Frank Wlotzka, Gero Kurat, Carleton Moore, Robert Hutchison, Ouyang Ziyuan, Steve Simon, and the Meteorite Working Group of NASA. This study funded by NASA grant NAGW 3519.

[1] Sears D.W.G. *et al.* (1991) *Proc. Lunar Planet. Sci.* **21**, 493-512. [2] Sears D.W.G. *et al.* (1991) *Proc. NIPR Symp. Ant. Meteor.* **4**, 1745-1805. [3] Batchelor J.D. and Sears D.W.G. (1991) *Geochim. Cosmochim. Acta* **55**, 3831-3844. [4] Sears D.W.G. *et al.* (1993) *Meteoritics* **28**, 669-675. [5] Symes S.J.K. *et al.* (1993) *Meteoritics* **28**, 446-447. [6] McSween H.Y. (1977) *Geochim. Cosmochim. Acta* **41**, 1777-1790. [7] Peck J.A. (1984) *Lunar Planet. Sci.* **15**, 635-636. [8] Simon *et al.* (1995) *Meteoritics* (in press). [9] Kallemeyn G.W. *et al.* (1991) *Geochim. Cosmochim. Acta* **55**, 881-892. [10] Rubin A.E. *et al.* (1988) *Meteoritics* **23**, 13-23. [11] Kallemeyn G.W. and Rubin A.E. (1995) *Meteoritics* (in press).