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

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(Received 1994 December 8; accepted in revised form 1995 August 14)

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 ALHAR1003 are type 3.0-3.1, while ALH84018, Efremovka, Grosnaja, Allende and Vigaran 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 type 3 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 (Kalllemeyn 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, Vigaran, 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 Kalllemeyn 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 Kalllemeyn and Wasson (1982) and as an anomalous CK chondrite by Kalllemeyn 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.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Source</th>
<th>Class</th>
<th>TL sensitivities*</th>
<th>TL Peak</th>
<th>TL peak temperatures*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>~130 °C</td>
<td>~250 °C</td>
<td>~350 °C</td>
<td>~130 °C</td>
</tr>
<tr>
<td>AllHA 81003</td>
<td>MWG/21</td>
<td>CV(?)</td>
<td>0.020 ± 0.006</td>
<td>0.003 ± 0.001</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV(?)</td>
<td>0.0049 ± 0.002</td>
<td>0.0010 ± 0.0003</td>
<td>–</td>
</tr>
<tr>
<td>ALH 84028</td>
<td>MWG/77</td>
<td>CV(?)</td>
<td>0.05 ± 0.03</td>
<td>0.02 ± 0.01</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>ALH 85006</td>
<td>MWG/16</td>
<td>CV(?)</td>
<td>0.034 ± 0.008</td>
<td>0.016 ± 0.004</td>
<td>0.004 ± 0.002</td>
</tr>
<tr>
<td>Allende</td>
<td>USNM</td>
<td>CV(O)</td>
<td>0.044 ± 0.005</td>
<td>0.012 ± 0.001</td>
<td>0.0013 ± 0.0001</td>
</tr>
<tr>
<td>Arch b</td>
<td>MPI</td>
<td>CV(R)</td>
<td>0.015 ± 0.002</td>
<td>0.003 ± 0.001</td>
<td>0.002 ± 0.0002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV(R)</td>
<td>0.014 ± 0.001</td>
<td>0.015 ± 0.003</td>
<td>0.013 ± 0.002</td>
</tr>
<tr>
<td>Axtell</td>
<td>UC</td>
<td>CV</td>
<td>0.0028 ± 0.0003</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Bali</td>
<td>NMW</td>
<td>CV(O)</td>
<td>0.030 ± 0.011</td>
<td>0.11 ± 0.06</td>
<td>0.15 ± 0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV(O)</td>
<td>0.039 ± 0.008</td>
<td>0.15 ± 0.07</td>
<td>0.29 ± 0.11</td>
</tr>
<tr>
<td>Coolidge</td>
<td>CMS397.2x</td>
<td>CV(R)</td>
<td>1.3 ± 0.05</td>
<td>0.34 ± 0.02</td>
<td>0.079 ± 0.001</td>
</tr>
<tr>
<td>Efremovka</td>
<td>USNM2348</td>
<td>CV(O)</td>
<td>0.034 ± 0.003</td>
<td>0.051 ± 0.003</td>
<td>0.018 ± 0.003</td>
</tr>
<tr>
<td>Groenaja</td>
<td>NMW</td>
<td>CV(O)</td>
<td>0.034 ± 0.002</td>
<td>0.032 ± 0.01</td>
<td>0.022 ± 0.007</td>
</tr>
<tr>
<td>Leoville</td>
<td>USNM3537</td>
<td>CV(R)</td>
<td>0.015 ± 0.001</td>
<td>0.011 ± 0.004</td>
<td>0.016 ± 0.01</td>
</tr>
<tr>
<td>Loongana 001</td>
<td>MPI</td>
<td>CV(R)</td>
<td>0.31 ± 0.01</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV(R)</td>
<td>0.52 ± 0.03</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Kaba</td>
<td>BM33969a</td>
<td>CV(O)</td>
<td>0.073 ± 0.015</td>
<td>0.62 ± 0.19</td>
<td>1.00 ± 0.28</td>
</tr>
<tr>
<td>Mokoia</td>
<td>BM1910,72</td>
<td>CV(O)</td>
<td>0.22 ± 0.20</td>
<td>0.84 ± 0.11</td>
<td>1.15 ± 0.13</td>
</tr>
<tr>
<td>Ningqiang</td>
<td>CAS</td>
<td>CK-An</td>
<td>0.01 ± 0.001</td>
<td>0.005 ± 0.001</td>
<td>0.002 ± 0.001</td>
</tr>
<tr>
<td>Renazzo</td>
<td>NMW</td>
<td>CR</td>
<td>0.0049 ± 0.001</td>
<td>0.002 ± 0.002</td>
<td>0.0008 ± 0.0001</td>
</tr>
<tr>
<td>Vigarano</td>
<td>USNM477</td>
<td>CV(R)</td>
<td>0.015 ± 0.002</td>
<td>0.04 ± 0.03</td>
<td>0.013 ± 0.002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV(R)</td>
<td>0.049 ± 0.002</td>
<td>0.06 ± 0.01</td>
<td>0.042 ± 0.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV(R)</td>
<td>0.049 ± 0.002</td>
<td>0.047 ± 0.006</td>
<td>0.048 ± 0.005</td>
</tr>
</tbody>
</table>

* = 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); IM, 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.

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

* Density separates are indicated by the relevant density (in g cm⁻³) and whether the separate "floats" or "sinks."
Corporation (now MAAS) "luminoscope." We used a 14 ± 1 keV, 7 ± 1 μA, 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 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.

**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
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 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 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

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**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.

**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).
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 (σ(FeO) = 20–200%) and TL sensitivities for the ~130 °C peak < ~0.02, those with somewhat less heterogeneous olivine compositions (σ(FeO) = 20–120%) 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 << Mokoia < Vigarano / Grossnaja / Allende (see Scott et al., 1988), which is somewhat different to the series we propose here. Our CL
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 \(-130 \, ^{\circ}C\) 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 \(-130 \, ^{\circ}C\) 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,
1.0

0.1

0.01

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{The TL sensitivity of the $\sim 130$ °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 \textit{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 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 in 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 $\sim 130$ °C peak in their glow curves. In contrast, ordinary chondrites of type
The metamorphic history of CV chondrites and their components

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

![Graph](Image)

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).

<table>
<thead>
<tr>
<th>Type</th>
<th>TL sens (Dhajala = 1)</th>
<th>Mean Fa (mol%)</th>
<th>α Fa (%)</th>
<th>Ni in sulfide (wt%)</th>
<th>H2O (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>0.017–0.030</td>
<td>8.0–10.0</td>
<td>90–110</td>
<td>17–20</td>
<td>0.75–1.05</td>
</tr>
<tr>
<td>3.2</td>
<td>0.030–0.054</td>
<td>10.0–11.0</td>
<td>70–90</td>
<td>20–22</td>
<td>0.60–0.75</td>
</tr>
<tr>
<td>3.3</td>
<td>0.054–0.10</td>
<td>11.0–12.0</td>
<td>50–70</td>
<td>22–23</td>
<td>0.45–0.60</td>
</tr>
<tr>
<td>3.4</td>
<td>0.10–0.17</td>
<td>12.0–12.5</td>
<td>40–50</td>
<td>23–24</td>
<td>0.40–0.45</td>
</tr>
<tr>
<td>3.5</td>
<td>0.17–0.30</td>
<td>12.5–13.0</td>
<td>30–40</td>
<td>24–25</td>
<td>0.30–0.40</td>
</tr>
<tr>
<td>3.6</td>
<td>0.30–0.54</td>
<td>13.0–13.5</td>
<td>20–30</td>
<td>25–26</td>
<td>0.20–0.30</td>
</tr>
<tr>
<td>3.7</td>
<td>0.54–1.00</td>
<td>13.5–14.0</td>
<td>5–20</td>
<td>26–28</td>
<td>0.15–0.20</td>
</tr>
<tr>
<td>3.8</td>
<td>1.0–1.5</td>
<td>14.0–14.5</td>
<td>&lt;5</td>
<td>&gt;28</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>3.9</td>
<td>&gt;1.7</td>
<td>&gt;14.5</td>
<td>&lt;5</td>
<td>&gt;28</td>
<td>&lt;0.15</td>
</tr>
</tbody>
</table>

* 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.

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 10^3–10^6 times the detection limit. In fact, in view of the similarity of the

![Diagram](Image)

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 measureable 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 melilitite 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 this 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 melilitite. 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 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.](image-url)
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 in the study make the trend more difficult than previous studies of unmetamorphosed 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., Xietel) to type 3.8 (Coolidge and Loongana 001). Studies of the cathodoluminescence properties of Xietel 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 metasomate displaying strong high-temperature TL (~400 °C) and high-field splitting. 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 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 (Xietel, Bali, Kaba and Loovlie) are virtually unmantled (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 11l 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.

Acknowledgments: We wish to thank the suppliers of samples for this study, notably Glenn MacPherson (Smithsonian Institution, Washington, D.C.), Frank Witztka (Max-Planck-Institut für Chemie, Mainz), Gero Kunze (Naturhistorisches Museum, Wien), Carleton Moore (Center for Meteorite Studies, Arizona State University, Tempe), Robert Hutchinson (British Museum, London), Ouyang Ziyuan (Chinese Academy of Sciences), Steve Nam (University of Chicago), and the Meteorite Working Group of NASAN/Smithsonian Institution. We also appreciate helpful reviews from Alan Rubin and Greg Mecker. This research was funded by NASA grant NAGW 3519 and a visiting scientist grant from NSF to Kyle Guimon.

Editorial handling: M. J. Caffey

REFERENCES


APPENDIX

Descriptions of the Refractory Inclusions in this Study

Big Al is a 1.2 x 1.8 cm type B1 inclusion (Grossman, 1975) with a coarse-grained melilitic 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 melilitic with minor opaques and perovskite (Wark and Wasserburg, 1980; Wark and Lovering, 1980, 1982; Meeker et al., 1983). The melilitic 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 melilitic 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 melilitic, respectively.

EGG 4 is a cm-sized type A inclusion (Grossman, 1975) of 0.5–2 mm melilitic grains encasing 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 melilitic were interpreted by Meeker et 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 melilitic. 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 melt, 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 MASH 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.