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Metamorphism of eucrite meteorites studied quantitatively using induced thermoluminescence

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EUCRITE meteorites[1] are especially important in studies of the early Solar System because they are the simplest and most ancient products of a process that was widespread in the inner Solar System[2,3]: basaltic volcanism. They are also the meteorites for which there is least doubt of an asteroidal origin[4,5]. After volcanism the eucrites experienced a period of metamorphism[6], either inside the asteroid as it cooled from igneous temperatures[7] or on the surface of the asteroid as a result of impact heating[8]. Induced thermoluminescence studies provide a new and quantitative means of determining relative metamorphic intensities for these meteorites. Using this technique, we show that the eucrites constitute a continuous metamorphic series and not, as commonly assumed, two groups of metamorphosed and non-metamorphosed meteorites[9]. These studies are the first application of the induced thermoluminescence technique to igneous rocks and we suggest that the method may well have application to other basalts.

We suspected that induced thermoluminescence (TL) might be useful in investigating metamorphism of eucrites because a variety of studies have shown TL to be of great value in understanding metamorphism of chondritic meteorites[10,11]. Chondrites, however, are essentially 'cosmic sediments', in which the feldspar—the mineral responsible for the TL—is almost entirely metamorphic in origin[12]. In eucrites, the feldspar is igneous in origin, but many of the meteorites are surface breccias and impact reworking may have converted some of the feldspathic material to glass[13]. Metamorphism, depending on its timing relative to brecciation and the relative intensities of the two processes, might well have caused recrystallization of the feldspar[14]. If this is the case, metamorphism can be monitored rather precisely using induced TL of the feldspar.

Interior chips of mass ~160 mg were taken from 18 eucrites, duplicate chips being taken where possible. These were homogenized by hand-crushing in an agate mortar, and three 4-mg aliquots were placed in shallow copper pans and drained of their natural TL by brief heating to 500 °C. The TL induced by a 15-TBq ^{90}Sr β-particle source was then measured by heating at 7.5 °C s^{-1} in TL apparatus equipped with blue and infrared bandpass filters (Corning 7-59 and 4-69; ref. 15). Data for three aliquots were averaged. The H3.8 ordinary chondrite Dhajala was used as a normalization standard and instrument check.

The intensity of the TL at maximum light production (referred to as TL sensitivity) is plotted in Fig. 1 for each eucrite, ranked in descending order on a logarithmic scale. Duplicate data for different chips from a single eucrite are connected by tie-lines. Reid and Barnard divided the eucrites into 'equilibrated' and 'unequilibrated' groups, suggesting that the former were metamorphosed whereas the latter were not[9]. More recently, Takeda *et al.*[16] sorted the eucrites and several clasts separated from eucrites into six 'types' according to metamorphism, but their scheme has not been widely adopted. Both these authors, and several others, have used chemical zoning and exsolution in the pyroxenes to assess metamorphism in these meteorites. In the little-metamorphosed eucrites, igneous zoning is present, but for the more metamorphosed eucrites it is absent and exsolution of augite has occurred. The criteria used by Takeda *et al.* for their six types are listed in Table 1. We find that the TL sensitivities of the eucrites are spread uniformly over a 17-fold range. There is no indication that the eucrites formed in two discrete environments, corresponding to the equilibrated and unequilibrated categories of Reid and Barnard, but rather, as suggested by Takeda *et al.*, that they formed in a single environment that permitted a range of metamorphic conditions.

If we subdivide our TL range into intervals based on five divisions per decade on a log scale (as indicated in Fig. 1), we find agreement with Takeda *et al.*'s types in four out of the five cases for which comparison is possible. (Unfortunately, most of Takeda *et al.*'s samples are not readily available in the United States.) We can therefore propose a scheme based on TL sensitivity and pyroxene characteristics for metamorphic subdivision, in which eight types are required to cover the observed range (Table 1). For samples for which duplicates were available, type assignments are based on mean TL sensitivity values. Type assignments for duplicates never differ by more than two, and typically fall within the same type or differ by only one. Some of these differences may be caused by mineralogical

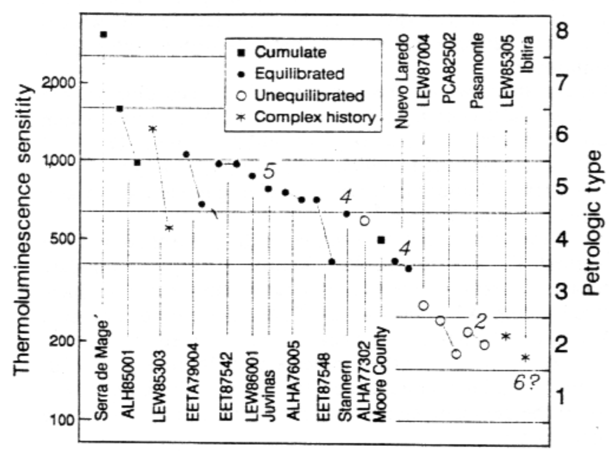

FIG. 1 Thermoluminescence (TL) sensitivity and petrologic type of 18 eucrites. The H3.8 ordinary chondrite Dhajala corresponds to a sensitivity of 1,000. Duplicate chips are connected by tie-lines. Reid and Barnard's[9] 'equilibrated' and 'unequilibrated' categories are indicated by symbols[2,18,30,31], and the types assigned by Takeda *et al.*[16] on the basis of pyroxene characteristics are indicated by the numbers over the symbols. There is agreement between the present classification and those assigned by Takeda *et al.*[16], and the division between the unequilibrated and equilibrated categories lies between petrologic types 3 and 4. TL sensitivity is determined primarily by the metamorphism experienced by the meteorites; the data indicate that the eucrites form a continuous metamorphic series. The eucrites LEW85303, LEW85305 and Ibitira have had unusual histories, involving intense shock, which has almost certainly affected their TL data.

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TABLE 1 Metamorphic classification of eucritic meteorites

Petrologic type	Thermoluminescence sensitivity (Dhajala = 1,000)	Pyroxene characteristics*	Meteorites
1	<160	Extensive Mg-Fe zoning trend in pyroxene and Fe-rich augite.	Y-75011†, clasts in Y-74450† and Y75015†
2	160–250	Fe-rich pyroxene not seen, Mg–Fe–Ca trend preserved.	Pasamonte‡, Ibitira, PCA82502, LEW85305, clasts in Y-74159†
3	250–400	Mg–Fe zoning mostly disappeared, Fe–Ca trend from core to rim preserved.	LEW87004, Y-790226†
4	400–630	Trend from host to exsolved augite dominant, original Fe–Ca trend can be recognized.	Stannern‡, Nuevo Laredo‡, Millbillillie†, Moore Co., EET87548, ALHA77302
5	630–1,000	All zoning has disappeared, exsolution trend dominant.	Juvinas‡, Haraiya†, Sioux Co.†, LEW85303, EETA79004, EET87542, LEW86001, ALHA76005
6	1,000–1,600	Partial to complete inversion of pigeonite to orthopyroxene.	ALH85001
7	1,600–2,500	Partial to complete inversion of pigeonite to orthopyroxene.	—
8	>2,500	Partial to complete inversion of pigeonite to orthopyroxene.	Serra de Magé

* Descriptions of types 1–5 from Takeda *et al.*[16].
† Assignments from Takeda *et al.*[16].
‡ Assignments based on the present TL data and Takeda *et al.*'s petrographic descriptions.
Other assignments based on TL sensitivity.
Ibitira is an unusual eucrite which Takeda *et al.* "tentatively" identified as type 6.

heterogeneity in these coarse-grained rocks, but especially interesting is the possibility of differences in metamorphism experienced by different clasts within a meteorite. This would suggest that brecciation post-dated metamorphism, and was found to be the case for the related howardite meteorites[17]. The present data, however, indicate that, despite these small variations, petrologic types may be assigned to the whole-rock by both petrographic and TL methods with a high degree of confidence.

The specimen whose assignment differs according to the schemes of Takeda *et al.* and the present work is Ibitira, which the previous authors "tentatively" assigned to type 6. This, and presumably LEW85305 to which it is petrographically similar[18], have experienced unusual histories involving intense shock and subsequent metamorphism[19].

Two of the three cumulate eucrites in the present study have the highest TL sensitivities. The thermal history of cumulate eucrites is especially interesting because they seem to have relatively young radiometric ages[20–26], and there is considerable debate as to whether this is because they formed in separate magma bodies or because they cooled especially slowly[20,23]. Our data support the latter conclusion because the high TL sensitivity of two of the cumulate eucrites suggests particularly prolonged metamorphism.

We suspect that the increase in TL sensitivity in response to parent-body metamorphism is due to the increase in the degree of crystallinity of the feldspar. Cathodoluminescence petrography shows that the feldspars in the Juvinas type 5 eucrite are brighter and more uniform in their luminescence than those in the Pasamonte type 2 eucrite. Processes on the surface of the parent body probably cause some of the feldspar to be converted to glass, and metamorphism reverses this process. We cannot, however, rule out other mechanisms involving trace elements or more subtle structural changes. In the case of the related howardite class, we have observed changes in TL sensitivity that correlate with bulk aluminium content[32]. The howardites, however, are breccias of Al-poor diogenite and Al-rich eucrite material, whereas the eucrites in the present study are, to a good approximation, breccias of one type of material.

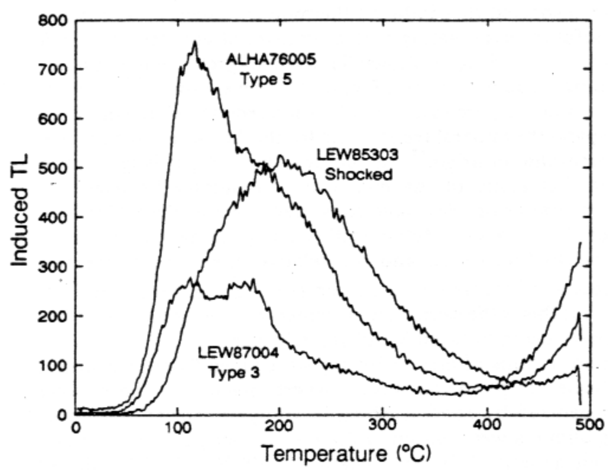

FIG. 2 Induced thermoluminescence glow curves for an equilibrated eucrite (ALHA76005, type 5), an unequilibrated eucrite (LEW87004, type 3), and the unusual shocked eucrite LEW85303. The Dhajala chondrite corresponds to 1,000. Equilibrated eucrites have a strong peak at about 110 °C and a weaker peak at about 190 °C, and unequilibrated eucrites have a stronger peak at 190 °C. The unusual eucrite LEW85303 has a broad peak at around 200 °C. A TL peak at about 110 °C reflects metamorphism below 800 °C, and the single peak at 200 °C reflects heating to temperatures >1,000 °C.

Additional information on the metamorphic conditions experienced by the eucrites is provided by the temperature at which the TL light production reaches a maximum. Figure 2 shows the TL 'glow curves' (light production as a function of temperature as the sample is heated) for two representative eucrites (ALHA76005 and LEW87004) and a very unusual eucrite (LEW85303). The glow curves consist of two peaks, at 113 ± 11 °C and 192 ± 15 °C. These two peaks are thought to be indirectly related to ordered and disordered feldspar respectively[10]. LEW85303 was the only meteorite in the present study that showed no sign of a 113 °C peak. Annealing of four eucrites (a cumulate, an equilibrated eucrite, an unequilibrated eucrite and LEW85303) in an inert atmosphere for 100 h showed that at or just below 800 °C, the 113 °C peak moves to 160–200 °C, consistent with the idea that ordering of the feldspar crystal lattice affects peak temperature. As all eucrites in this study except LEW85303 had a dominant peak at 113 °C, or had two peaks of comparable heights, we conclude that most eucrites cooled slowly below 800 °C, but that LEW85303 has been heated to >1,000 °C. Ar–Ar data for LEW85303 also show evidence of a major degassing event at about 1 Gyr (ref. 27), and there is petrographic evidence that this meteorite has experienced a shock event[28,29].

Our results indicate that induced thermoluminescence studies may have much wider application than previously realized. The technique has been of considerable value in understanding metamorphism in chondrites, but these are very unusual materials in which the feldspar has a novel origin and history. The eucrites, on the other hand, are igneous rocks not unlike terrestrial and lunar basalts. The successful application of induced TL to studies of the the thermal histories of the eucrites suggests that the technique may be applied usefully to a wide variety of basalt types for which dry, low-level metamorphism has occurred, and preliminary work on terrestrial[32] and lunar[33] samples is encouraging. □

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