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The metamorphic history of eucrites and eucrite-related meteorites and the case for late metamorphism

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(Dedicated to the memory of Paul Pellas)

Abstract–We report induced thermoluminescence (TL) data for separates from three howardite, eucrite and diogenite (HED) meteorites and the Vaca Muerta mesosiderite. The results of thermal modeling of the surface of their parent body are also described. The TL sensitivities for matrix samples from the LEW 85300, 302 and 303 paired eucrites and the Bholghati howardite are lower than the TL sensitivities for the clasts, which is consistent with regolith working of the matrix in fairly mature regoliths. Within an isochemical series of HED meteorites, TL sensitivity reflects metamorphic intensity, but clast-to-clast variations in the TL sensitivities of the Vaca Muerta mesosiderite and clasts in the EET 87509, 513 and 531 paired howardite primarily reflect differences in mineralogy and petrology. Thermoluminescence peak temperatures indicate that all the components from the LEW 85300, 302 and 303 paired eucrites experienced a reheating event involving temperatures >800 °C, which is thought to have been due to impact heating, and therefore that the event was concurrent with or postdated brecciation. The Vaca Muerta clasts are essentially unmetamorphosed, but the induced TL data indicate that the remaining howardite, eucrite, dioenite and mesosiderite (HEDM) meteorites experienced metamorphism to a variety of intensities but involving temperatures <800 °C. Laboratory heating experiments show that temperatures >800 °C cause a change in TL peak temperature. Feldspars from a variety of terrestrial and extraterrestrial sources show this behavior, and x-ray diffraction and kinetic studies suggest that it is indirectly related to Al,Si disordering.

Cooling rates are not consistent with autometamorphism following the initial igneous event or with heating by subsequent eruptions of lava onto the surface of the HED parent body. Instead, our thermal models suggest that the metamorphism occurred within a regolith ejecta blanket of up to a few kilometers thick, with different levels of metamorphism corresponding to different thicknesses of blanket, between essentially 0 and ~2 km, rather than different burial depths in a regolith of uniform thickness. We argue that metamorphism occurred 3.9 Ga ago and was associated with the resetting of the Ar-Ar system for the HED meteorites.

INTRODUCTION

Howardites, eucrites, diogenites and mesosiderites (referred to here as the HEDM meteorites) are basalts or arguably basalt-related meteorites. The howardites and the eucrites probably originated on the asteroid Vesta, and there are suggestions of a possibly diogenitic region on Vesta (McCord *et al.*, 1970; Consolmagno and Drake, 1977; Binzel and Xu, 1993; Binzel, 1996). To date, no one has proposed Vesta as the mesosiderite parent body, although they do appear to be surface impact melt breccias from a basaltic parent body. Mineralogically, eucrites are ~3:7 mixtures of anorthitic plagioclase and pyroxene, the diogenites are essentially orthopyroxenites, and the mesosiderites are mixtures of eucritic silicates and metal (BVSP, 1981). The howardites are gas-rich regolith breccias of eucritic and diogenitic material (MacDougal *et al.*, 1973; Delaney *et al.*, 1983). Exsolution structures, compositional trends in the pyroxenes (Reid and Barnard, 1979; Takeda *et al.*, 1983) and induced thermoluminescence (TL) data (Batchelor and Sears, 1991a,b) suggest that eucrites and related meteorites have experienced significant levels of metamorphism on their parent bodies. In this respect, they differ from lunar samples that are similar in that many are also basalts from a relatively small airless planetary body (Symes *et al.*, 1995; Batchelor *et al.*, 1997). Eight petrologic types of eucrite have been defined on the basis of the compositional heterogeneity and exsolution structures in the pyroxenes and TL sensitivity. Identifying the timing and physical conditions under which metamorphism occurred, and the relative timing of their formation, metamorphism and brecciation, would provide important insights into the parent body and its history and is the main thrust of the present paper.

Takeda *et al.* (1983) made the important observation that the least metamorphosed eucrite samples were found as clasts in polymict breccias, while highly metamorphosed samples were found as monomict breccias or as individual grains. They inferred that brecciation postdated metamorphism. In part to test this idea, we have extended our earlier whole rock studies of the induced TL properties of HEDM meteorites to include a number of clasts and other separates from eucrite or eucrite-related meteorites. Preliminary reports of some of the present studies were given by Batchelor and Sears (1990, 1991c). We have used also the present data and literature estimates of metamorphic temperature and cooling rate, and calculations of the thermal history of the surface of the HEDM parent body, in an attempt to determine conditions and the physical setting of their metamorphism.

EXPERIMENTAL

Samples

Table 1 lists our samples, sample weights, brief descriptions and references to mineralogical and petrographic descriptions.

The Elephant Moraine 87509, 513 and 531 Paired Howardites–Our samples from this howardite were provided to us as part of two consortia,

TABLE 1. Samples used in this study with brief descriptions and references.

Sample	Mass (mg)	Description
The EET 87509, 513 and 531 Paired Howardites*		
EET 87509		
Clast Q,78	32	Pigeonite vitrophyre, B trend†
Clast E,91	30	Porphyritic eucrite with zoned pyroxene, B trend†
Split, 83	130	Matrix
Split, 88	103	Matrix
EET 87513		
Clast Y, 81	21	Recrystallized eucrite, B trend†
Clast E, 78	26	Eucrite, A trend†
Clast EE, 85	12	Recrystallized eucrite
Clast T, 80	9	Diogenite
Split, 96	104	Matrix
Split, 100	106	Matrix
Split, 91	111	Matrix
EET 87531		
Clast J, 81	114	Eucrite, partly recrystallized and partly zoned pyroxenes, B trend†
Clast P, 87	102	Unequilibrated eucrite, B trend†
Clast R, 91	39	Equilibrated eucrite, A trend†
Split, 96	112	Matrix
Split, 101	132	Matrix
The Bholghati Howardite‡		
Split, 17	5	Large eucrite clast
Split, 27	21	Eucrite clast
Split, 26	29	Eucrite clast
Split, 29	28	Matrix
Split, 28	27	Matrix
Split, 19	28	Matrix
Split, 21	17	Matrix

Sample	Mass (mg)	Description
The LEW 85300, 302 and 303 Paired Eucrite§		
LEW 85300		
Clast 9	400	Clast
Clast 71	227	Clast
Split, 9	400	Matrix
Split, 27	270	Matrix
LEW 85302		Clast
Clast 12	320	Clast
Clast 35	258	Clast
Clast 35	258	Glass
Split, 12	320	Matrix
Split, 31	259	Matrix
Split, 36	249	Matrix
LEW 85303		Clast
Clast 36	495	Clast
Clast 87	251	Clast
Split, 36	495	Matrix
Split, 88	263	Matrix
The Vaca Meurta Mesosiderite#		
Clast 11	109	Polygenic basalt
Clast 12	111	Cumulate gabbro
Clast 13	127	Monogenic basalt, quench texture
Clast 14	105	Polygenic basalt
Clast 15	90	Polygenic basalt
Clast 16	194	Monogenic basalt
Clast 17	131	Cumulate gabbro
Clast 18	139	Cumulate gabbro
Clast 19	282	Polygenic basalt
Clast 20	243	Cumulate gabbro
Clast 21	160	Cumulate gabbro

*Buchanan *et al.* (1990).
†Igneous geochemical trends A and B as described by Buchanan and Reid (1991).
‡Reid *et al.* (1990).
§Kozul and Hewins (1988a,b).
#Rubin and Mittlefehldt (1992).

one led by J. C. Laul and dealing with EET 87509 and EET 87531 and another led jointly by J. C. Laul and D. Mittlefehldt dealing with EET 87513. The pairing is disputed, however, and Mittlefehldt and Lindstrom (1991) suggest that EET 87513, which is 35% diogenite, is a separate meteorite from the others that consist of ~15% diogenite. Buchanan *et al.* (1990) and Buchanan and Reid (1991) briefly summarize the mineralogical and petrographic properties of these samples. We received seven matrix samples and ten highly diverse clasts.

The Bholghati Howardite–Our Bholghati samples were provided to us as part of a consortium study led by J. C. Laul (Laul, 1989). Mineralogical and petrographic properties were described by Reid *et al.* (1990). One of the seven samples we received was part of a large eucritic clast widely distributed to consortium members, two were samples of light colored eucritic clasts and four were matrix samples.

The Lewis Cliff 85300, 302 and 303 Paired Eucrite–Our samples from this unusual eucrite were provided as part of a consortium organized by R. Hewins. Mineralogical and petrographic properties were described by Kozul and Hewins (1988a,b), and the eucrite is unusual in having experienced a major shock event that had a profound effect on its induced TL properties (Batchelor and Sears, 1991b). We were provided with seven matrix samples and six clast samples. We also separated a piece of glass from one of the clasts.

The Vaca Muerta Mesosiderite–Our samples of Vaca Muerta were also provided as part of a consortium study led by Dave Mittlefehldt. They were described by Rubin and Mittlefehldt (1992). We received six samples of basaltic clasts and five samples of gabbroic clasts.

Procedures

After examination under a low-powered microscope and removal of adhering matrix where necessary, the samples were lightly ground to ~100 mesh. Aliquants of 4 mg were placed in a Cu pan, heated to 500 °C to remove preexisting natural TL and then given a dose of ~20 Gy using a 250 mCi ^{90}Sr source. The induced TL of each sample was measured three times using modified Daybreak Nuclear and Medical apparatus. Corning 7-59 and 4-69 filters were used to minimize interference from black body radiation. Samples of the Dhajala type 3 ordinary chondrite were run at the beginning and end of each day to act as a normalization standard and monitor stability of the apparatus. The maximum induced TL intensity and the peak temperature were measured. The quoted uncertainties are standard deviations for the three measurements, compounded with the uncertainties for the standard in the case of TL sensitivity.

RESULTS

Our data are summarized in Table 2 and Fig. 1. The Elephant Moraine howardite samples also show peaks at relatively high temperatures (160–213 °C); but with few exceptions, the peak at 104–137 °C is slightly stronger and is plotted in Fig. 1a. The TL sensitivities show an extremely large range (6–970) with most lying in the range 48–970. The whole rock samples plot near the upper end of the range. The two outlying clasts are the recrystallized eucrite clast EE and the diogenite clast from EET 87513. Most of the remaining clasts have similar TL properties to the matrix samples, although the matrix samples have more uniform TL sensitivity.

The seven Bholghati samples have dominant peaks with temperatures of 97–142 °C high TL sensitivities (204–1300, Fig. 1b) and slightly weaker peaks at 185–220 °C (not shown in the figure). Ma-

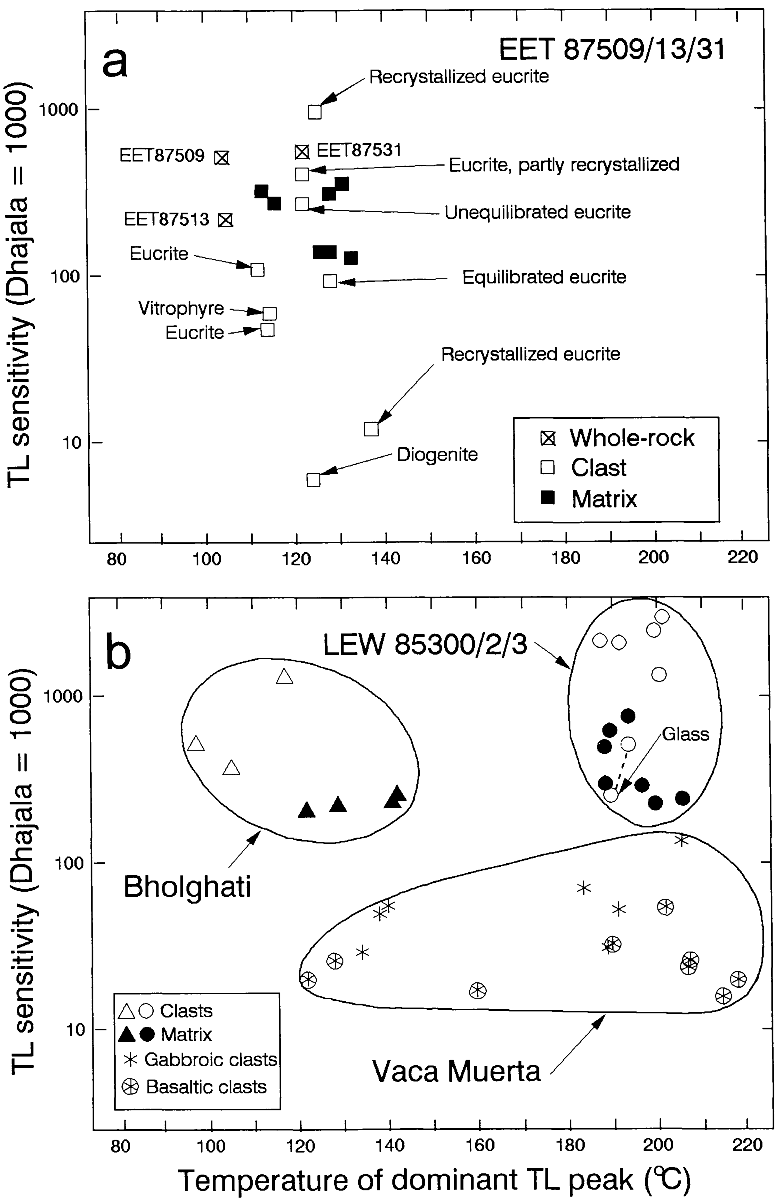


FIG. 1. The TL sensitivity against TL peak temperature for the dominant peak (or the low-temperature peak when both peaks are of approximately equal intensity) for (a) the paired howardites EET 87509, 87513 and 87531 and (b) the paired eucrites LEW 85300, 85302 and 85303, the howardite Bholgati and the Vaca Meurta mesosiderite. For Bholgati and the LEW 85300 group eucrites, clasts have higher TL sensitivity than matrix, and a glass sample and its associated clast, by up to an order of magnitude. Vaca Muerta samples have weak peaks with a range of peak temperatures. Basaltic clasts have slightly lower TL sensitivity than gabbroic clasts. Matrix and bulk samples of the EET 87509, 87513 and 87531 howardites tend to cluster fairly closely but the clasts have highly varied TL sensitivity that is consistent with their great mineralogical diversity. The lowest TL sensitivities are displayed by a recrystallized eucrite clast and a diogenitic clast.

trix samples are well discriminated from clast samples, having lower TL sensitivities and higher peak temperatures.

The clast and matrix separates from the LEW 85300 eucrite group have TL peak temperatures of 189–206 °C and high TL sensitivities (225 to 2490 where Dhajala = 1000), with the matrix samples having discretely lower TL sensitivity than the clast samples (Fig. 1b). An exception is clast 35 and its glass fragment, both of which had TL sensitivities comparable to the matrix samples. Some of the matrix samples also showed minor peaks at 123–136 °C, but with relatively low TL sensitivities (181–243) that are not plotted on Fig. 1b.

The Vaca Muerta clasts have relatively low TL sensitivities (usually <100) with peaks at 181–219 °C and 122–160 °C of comparable TL sensitivity, although in about half the cases the position of the lower temperature peak is poorly defined. There is a slight tendency for the basaltic clasts to have lower TL sensitivities than the gabbroic clasts. Several of the Vaca Muerta samples also displayed a sharp TL peak at 120–136 °C that mineral separations of related meteorites have shown to be due to quartz (Batchelor and Sears, 1991b). These peaks are not plotted in Fig. 1b but are listed in a footnote to Table 2.

DISCUSSION

Thermoluminescence Sensitivity of Eucrite and Eucrite-related Meteorites

The TL sensitivity of whole-rock eucrites is related to their metamorphic history (Fig. 2; Batchelor and Sears, 1991a,c). Cumulate eucrites tend to have higher TL sensitivities than equilibrated eucrites, which, in turn, have higher TL sensitivities than unequilibrated eucrites. The TL sensitivities of bulk eucrite samples can be used to make quantitative petrographic type assignments that generally conform to the Takeda *et al.* (1983) types based on pyroxene composition and texture. The major exception is the highly anomalous eucrite, Ibitira, which is type 6 according to pyroxene properties and type 2 according to TL sensitivity (Batchelor and Sears, 1991b; Batchelor *et al.*, 1997). It is a vesicular lava and, as this disagreement in assigned type indicates, should be compared with the other eucrites only with caution. The petrographic type assignments for eucrites shown in Fig. 2 constitute the largest data base available to date and should be of considerable help in locating samples for detailed petrographic study.

In the case of a fairly straightforward isochemical series like the eucrites, feldspar is the only producer of TL (to an excellent approximation), and as "equilibration" or "metamorphism" drives Fe out of the feldspar its TL intensity increases. This is because Fe is a quencher. Thermoluminescence can therefore monitor this process as surely as an electron microprobe can measure pyroxene composition or the human eye can see augite lamellae with a microscope. However, TL measurements have slightly better precision than the former, since they are bulk measurements, and are slightly less subjective than the latter where poorly formed lamellae may be difficult to identify. However, one obviously uses all the data available to assign a petrographic type to a given meteorite. As we shall see, in comparing data for eucrite-related meteorites of different classes, or clast and matrix samples from breccias, allowance must be made for differences in mineralogy and composition. As with any technique, sufficient samples must be taken to ensure that the sample measured is representative.

Clast-to-clast Variation in Thermoluminescence Sensitivity and Some Implications

The TL sensitivities of matrix samples of Bholghati, LEW 85300, 85302 and 85303, and the glass and associated clast material

TABLE 2. Data for clasts and other separates from eucrite and eucrite-related meteorites.*

Sample	T_p (°C)	TL sensitivity Dhajala = 1000	T_p (°C)	TL sensitivity Dhajala = 1000
The EET 87509, 513 and 531 Paired Howardites				
EET 87509				
Bulk	104 ± 5	520 ± 98	160 ± 2	450 ± 98
Clast Q,78	115 ± 4	60 ± 6	169 ± 5	85 ± 9
Clast E,91	114 ± 4	48 ± 6	172 ± 5	40 ± 5
Matrix 83	113 ± 3	326 ± 41	165 ± 5	254 ± 49
Matrix 88	116 ± 4	274 ± 31	164 ± 2	229 ± 29
EET 87513				
Bulk	105 ± 4	220 ± 38	180 ± 5	200 ± 42
Clast Y, 81	125 ± 4	970 ± 87	–	–
Clast E, 78	112 ± 5	110 ± 30	–	–
Clast EE, 85	137 ± 5	12 ± 2	213 ± 6	16 ± 2
Clast T, 80	124 ± 5	6 ± 2	180 ± 6	6 ± 2
Matrix, 96	126 ± 8	140 ± 20	199 ± 8	110 ± 20
Matrix, 100	128 ± 4	140 ± 10	208 ± 5	110 ± 10
Matrix, 91	133 ± 4	130 ± 40	208 ± 1	130 ± 10
EET 87531				
Bulk	122 ± 4	560 ± 110	164 ± 7	610 ± 120
Clast J, 81	122 ± 5	412 ± 49	183 ± 6	315 ± 32
Clast P, 87	122 ± 4	275 ± 14	180 ± 5	226 ± 13
Clast R, 91	128 ± 2	94 ± 10	182 ± 3	96 ± 8
Matrix, 96	131 ± 6	360 ± 19	180 ± 2	304 ± 22
Matrix, 101	128 ± 2	314 ± 19	177 ± 4	301 ± 25
The Bholghati Howardite				
Clast, 17	117 ± 2	1300 ± 30	220 ± 2	1070 ± 20
Clast, 27	97 ± 5	520 ± 22	194 ± 4	353 ± 11
Clast, 26	105 ± 4	373 ± 9	185 ± 8	317 ± 33
Matrix, 29	142 ± 7	254 ± 4	213 ± 19	–
Matrix, 28	141 ± 7	229 ± 4	220 ± 18	–
Matrix, 19	129 ± 7	218 ± 12	218 ± 9	158 ± 9
Matrix, 21	122 ± 5	204 ± 26	211 ± 1	166 ± 19

Sample	T_p (°C)	TL sensitivity Dhajala = 1000	T_p (°C)	TL sensitivity Dhajala = 1000
The LEW 85300, 302 and 303 Paired Eucrite				
LEW 85300				
Clast 9	–	–	200 ± 5	2490 ± 410
Clast 71	–	–	202 ± 5	3030 ± 490
Matrix 9	–	–	190 ± 5	620 ± 67
Matrix 27	123 ± 6	243 ± 35	189 ± 5	300 ± 34
LEW 85302				
Clast 12	–	–	201 ± 6	1350 ± 300
Clast 35	–	–	194 ± 5	523 ± 51
Clast 35 glass	–	–	190 ± 5	259 ± 26
Matrix 12	–	–	189 ± 3	495 ± 83
Matrix 31	131 ± 8	236 ± 15	197 ± 11	288 ± 19
Matrix 36	–	–	194 ± 2	750 ± 73
LEW 85303				
Clast 36	–	–	188 ± 3	2180 ± 270
Clast 87	–	–	192 ± 1	2110 ± 350
Matrix 36	128 ± 4	204 ± 57	206 ± 2	241 ± 66
Matrix 88	136 ± 7	181 ± 17	200 ± 4	225 ± 24
The Vaca Meurta Mesosiderite†				
Clast 11	128 ± 10	26 ± 2	205 ± 6	24 ± 4
Clast 12	–	~69	181 ± 6	69 ± 7
Clast 13	–	~53	201 ± 8	53 ± 9
Clast 14	160 ± 4	17 ± 1	214 ± 2	15 ± 1
Clast 15	122 ± 8	20 ± 1	219 ± 8	19 ± 1
Clast 16	–	31 ± 4	205 ± 9	31 ± 4
Clast 17	–	143 ± 5	200 ± 5	169 ± 15
Clast 18	140 ± 9	55 ± 7	189 ± 5	70 ± 4
Clast 19	–	~24	210 ± 5	24 ± 3
Clast 20	134 ± 6	29 ± 2	188 ± 2	35 ± 4
Clast 21	138 ± 6	49 ± 4	191 ± 6	63 ± 6

*"T_p" refers to peak temperature and "TL sensitivity" refers to Dhajala-normalized TL sensitivity. The stated uncertainties are 1σ variations on triplicate measurements on the same aliquant of homogenized powder.
†The glow curves of mesosiderites normally showed an additional peak thought to be caused by silica. The peak temperatures and their TL sensitivities were as follows: clast 11, 120 ± 3, 44 ± 9; clast 12, 132 ± 5,130 ± 20; clast 13, 124 ± 5,61 ± 13; clast 14, 124 ± 4,28 ± 2; clast 15, none; clast 16, 124 ± 5,36 ± 5; clast 17, 123 ± 13,–; clast 18, 142 ± 5,98 ± 16; clast 19, 124 ± 1,36 ± 4; clast 20, 136 ± 5,33 ± 2; clast 21, none.

of LEW 85300, are about a factor of 5–10 lower than the corresponding clast samples. We suggest that this is because the matrix material is composed of comminuted clast material, and the process of comminution, which involves localized shock-heating, lowers TL sensitivity. In the case of the gas-rich ordinary chondrites, Haq *et al.* (1989) were able to use the ratio of the TL sensitivity of matrix to clast as a measure of regolith maturity. Applying this parameter to Bholghati would indicate that its matrix is as mature as the most gas-rich ordinary chondrites. This parameter may not be applicable to the LEW 85300 meteorites since they are not regolith breccias.

Two bulk samples of Vaca Muerta were found by Batchelor and Sears (1991b) to have TL sensitivities of 271 ± 16 and 42 ± 3 (Dhajala = 1000). Thus, the present values for clasts are, with one exception, comparable to the lower whole-rock value and somewhat lower than the howardite and eucrite clast values (Fig. 1). The low TL sensitivities of the clasts reflects the abundance of feldspar and the lack of metamorphism experienced by the clasts, while the lower TL sensitivities of the basaltic clasts compared with the gabbroic clasts is surely a reflection of the more anorthitic feldspar of basalt (Reid *et al.*, 1990; Rubin and Mittlefehldt, 1992).

The howardites EET 87509, 87513 and 87531 show a wide spread in TL sensitivity, but the whole-rock and the matrix samples have reasonably similar values suggesting that these splits are fairly well mixed and homogeneous. The wide spread in the TL sensitivity of the clasts is mainly a reflection of the petrographic and mineralogical diversity of these clasts. The lowest TL sensitivities are those of a vitrophyre and a diogenitic clast, while a recrystallized and a partly recrystallized clast have the highest TL sensitivity. Another recrystallized eucritic clast and unequilibrated eucrite clast have unexpectedly low TL sensitivities, but these are particularly small samples (12 mg and 39 mg, respectively) and their data might not be reliable.

Clast-to-clast Variation in Thermoluminescence Peak Temperatures and Metamorphic Temperatures

Most noteworthy in the present TL data is that despite the complexities behind TL sensitivities, peak temperatures show a very consistent pattern of low peak temperatures in material from Bholghati and EET 87509, 87509 and 87509, and high peak temperatures for the eucrite LEW 85300, 85302 and 85303. The peak temperatures for the mesosiderite clasts show a wide spread, but some of this might be attributable to poor peak resolution for these low-intensity peaks. Whole-rock samples also display two peaks with the lower temperature peak being the dominant one in all except

LEW 85300, 85302 and 85303 (Fig. 3) and the mesosiderites, which typically display a high-temperature peak of comparable sensitivity to the low-temperature peak.

Previous work demonstrates that TL peak temperatures are related to the thermal history of the samples (Pasternak, 1978; Guimon *et al.*, 1984, 1985; Hartmetz and Sears, 1987a,b; Hartmetz, unpubl. data; Batchelor and Sears, 1991a,b; Batchelor *et al.*, 1997). The data are summarized in Fig. 4. Equilibrated, unequilibrated and cumulate eucrites whose TL peak is naturally at ~110 °C, after sealing in an inert atmosphere and heating >700 °C, display peaks at 160–220 °C; whereas, the shocked eucrite LEW 85303 whose TL peak is naturally at 192 °C shows no significant change after laboratory heating. This behavior is observed in a wide variety of feldspar and feldspar-bearing samples including terrestrial feldspars from pegmatites (Hartmetz and Sears, 1987a,b; Hartmetz, unpubl. data), Apollo 16 soils that are essentially comminuted and regolith-worked igneous materials (Batchelor *et al.*, 1997), and ordinary chondrites in which the feldspar is metamorphically produced from glasses in mafic rocks (Guimon *et al.*, 1985). In bulk samples of type 3 ordinary chondrites, low TL peak temperatures are generally displayed by petrologic types ≤3.5 (Fig. 4e), while high-temperature TL peaks are displayed by types >3.5. The position of the TL peak is, therefore, a fundamental property of feldspar and essentially independent of apparently major differences in formation and trace-element composition.

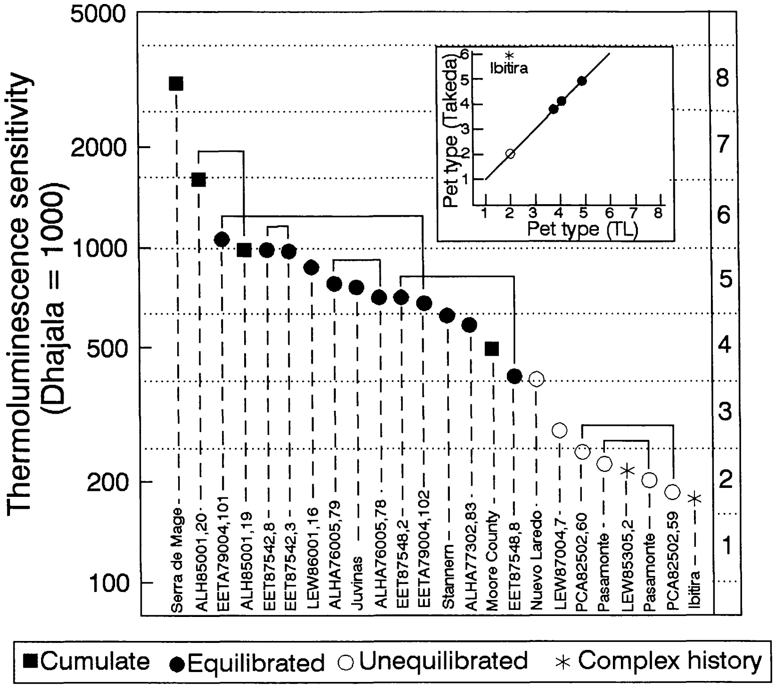


FIG. 2. Induced TL sensitivities for whole-rock samples of equilibrated, unequilibrated and cumulate eucrites and two unusual eucritic lavas, Ibitira and LEW 85305. The unequilibrated eucrites and lavas have lower TL sensitivity than the equilibrated eucrites and the cumulates. The inset compares petrographic type assigned by TL sensitivity according to the scale on the right with assignments by Takeda *et al.* (1983) based on pyroxene properties. Except for the anomalous Ibitira, the types assigned on the basis of TL and pyroxene data show excellent agreement.

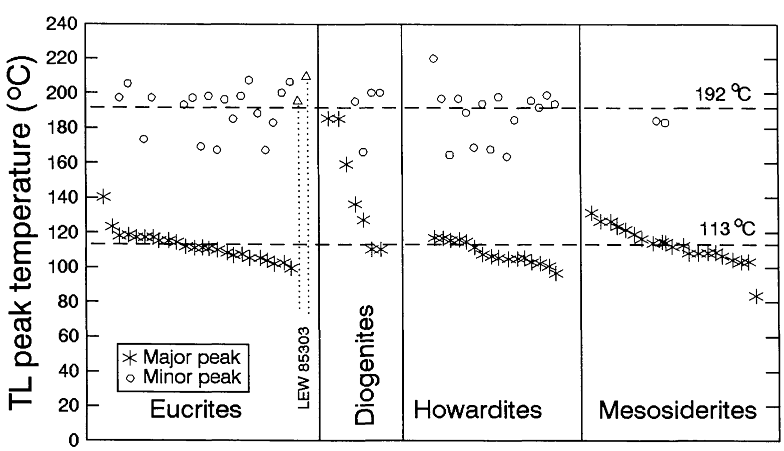


FIG. 3. Induced TL peak temperatures for whole-rock samples of eucrites, diogenites, howardites and mesosiderites. Major peaks are shown as stars, minor peaks as open circles. Lewis Cliff 85303 shows only a broad high-temperature peak, but most eucrite-related meteorites show two peaks, the major peak normally being at ~113 °C.

The broad high-temperature TL peak of the eucrite LEW 85300 and its many pairings is very similar to that of normal eucrites heated >1000 °C (Fig. 4), which suggests that LEW 85300 has been severely shock-heated. This conclusion also was borne out by petrographic observations (Hewins, 1990).

Pasternak (1978) suggested that TL peak position is related to the degree of disorder in the Al,Si chain of feldspar. Figure 5 indicates that increases in the TL peak temperature are associated in a nonlinear way with an increase in the $\Delta 2\theta$ parameter, which suggests that it is related to structural disordering (Hartmetz and Sears, 1987a). The $\Delta 2\theta$ parameter, the difference in the 2θ angles for the 131 and $1\bar{3}1$ reflections, is well suited to measuring the degree of disorder in sodic feldspars but fails with increasingly calcic feldspars as $\Delta 2\theta$ tends towards zero. Nevertheless, plagioclases of all compositions can be disordered, and the increase in peak temperature upon heating is displayed by even the most anorthitic samples (Fig. 5). However, the nature of the relationship is unclear. It is probably complex, and therefore it is not surprising that Fig. 5 is nonlinear. The activation energy for the TL change is 10–20 kcal/mol (Guimon *et al.*, 1985) compared with ~70 kcal/mol for disordering (McKie and McConnell, 1963, reported a value of 74.3 ± 1.4 kcal/mol). Pasternak (1978) suggested that the TL change was due to defect formation that preceded disordering.

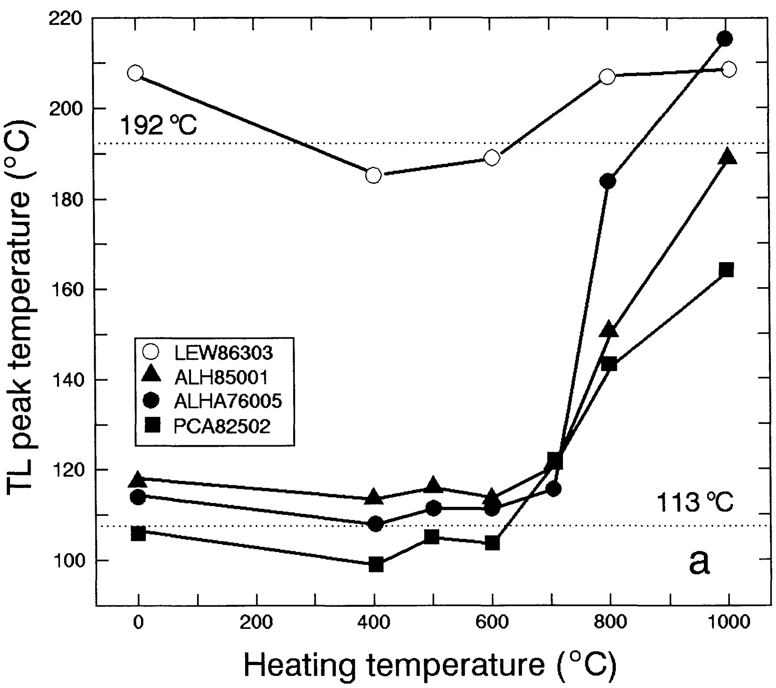
Taken at the simplest empirical level of interpretation, the TL data suggest that most eucrites experienced metamorphism at temperatures <800 °C. The major exception are the paired LEW 85300 meteorites. All the components of this shock-heated eucrite suffered heating to >1000 °C, and the heating event must have been concurrent with or postdated the brecciation. The low TL sensitivity and lack of a low-temperature peak reflects an absence of a metamorphic episode following formation of the breccia. Rubin and Mittlefehldt (1992) argued that clast 13 of Vaca Muerta was an impact melt that crystallized near the surface.

When applying data from laboratory measurements to real rocks, there is always the question of kinetics. Although a change occurred at 800 °C in the laboratory, it might occur at lower temperatures when geological time scales are available. This might be the case in fact. If disordering is the mechanism for peak temperature change, then eucritic feldspars should be disordered at ~700 °C, which would still be reasonably consistent with estimates from mineral pairs. For this reason, we quote <800 °C in Table 2, rather than 800 °C.

Table 3 summarizes present and literature data on equilibration temperatures and cooling rates for HED meteorites. The two-pyroxene thermometer and the spinel-orthopyroxene thermometers have been applied most frequently to HED meteorites, but there are occasional references to other systems such as olivine-pyroxene and the cloudiness of the phases. Based on comparison with other thermometers, in particular O isotope systematics, we suspect that the Ishii *et al.* (1976) results are systematically high by ~100–200 °C (Batchelor and Sears, 1991b). The especially high values obtained by Mukherjei and Viswanath (1987) for the essentially unmetamorphosed diogenites presumably reflect premetamorphic (igneous) thermal events. Cumulate eucrites have the highest equilibration temperatures, but these are probably crystallization temperatures (Takeda *et al.*, 1994; Yamaguchi *et al.*, 1995).

The history of the HEDM meteorites is also constrained by their cooling rates, the most reliable estimates being those based on the size and composition of the augite exsolution lamellae (Table 3). These show a large range but generally indicate rather fast cooling, 100 to 4.8 × 104 °C/Ma. Six cumulate eucrites have cooling rates of 100–500 °C/Ma (Miyamoto and Takeda, 1977, 1994b), while noncumulate eucrites have cooling rates 2–3 orders of magnitude faster (4×10^3–3×10^5 °C/Ma). The metal phase of the mesosiderites yield cooling rates that are slower by 2–3 orders of magnitude (~0.1 °C/Ma). There are many discussions of the extraordinarily slow mesosiderite cooling rates in the literature (*e.g.*, Powell, 1969, 1971).

Of course, cooling rate and metamorphic temperature place important constraints on the physical history of the meteorites. We argue that a consideration of even the most simple thermal models for the HEDM meteorites essentially precludes the notion that metamorphism occurred during initial igneous events but that it was associated with the impact heating that reset the Ar-Ar ages 4.0–3.4 Ga ago (Bogard, 1995). This is the topic of the next section of our discussion.



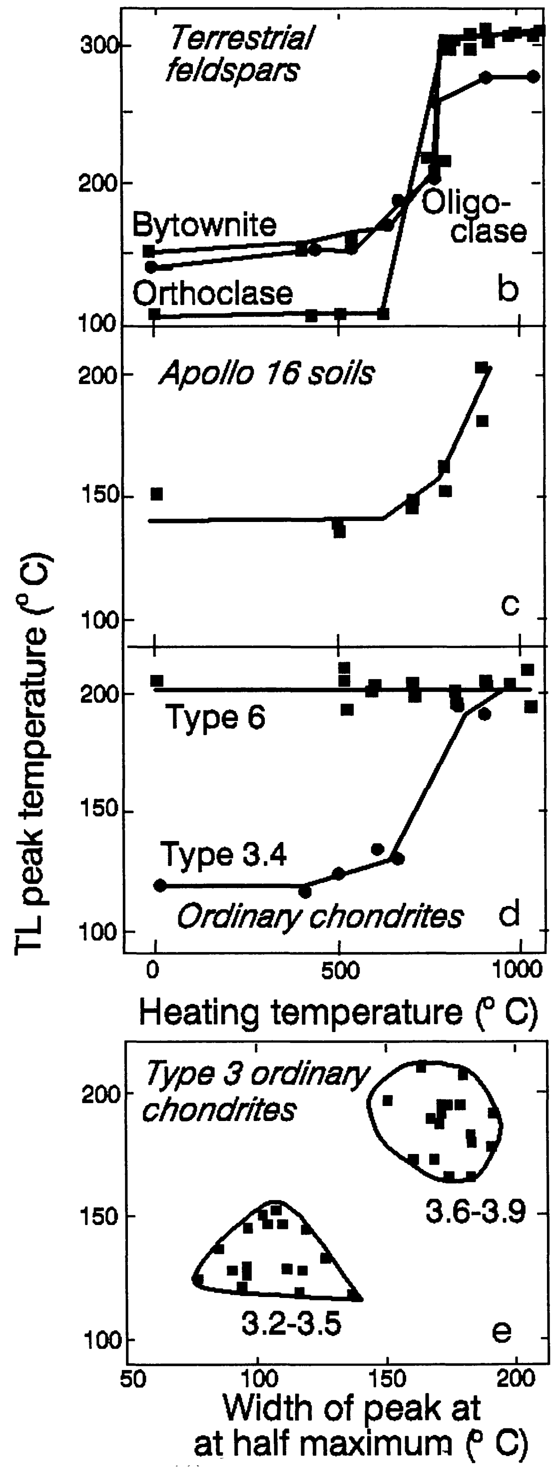


FIG. 4. (a) Induced TL data for whole-rock samples of four eucrites heated in an inert atmosphere in the laboratory for 100 h at the temperatures indicated on the horizontal axis. Eucrites that originally had low-temperature peaks had those peaks moved to higher temperatures after heating at ~700 °C; whereas, heating had no effect on the samples whose TL peak was originally at high temperatures. Note that the eucrites are a cumulate (ALH 85001), an equilibrated eucrite (ALHA76005), an unequilibrated eucrite (PCA 82502), and the atypical shocked eucrite (LEW 85303). (b) Similar data for terrestrial feldspars (Hartmetz and Sears, 1987a; Hartmetz, unpubl. data), (c) Apollo 16 soils (Batchelor *et al.*, 1997), and (d) ordinary chondrites (Guimon *et al.*, 1985). (e) Thermoluminescence peak temperature *vs.* peak width for type 3 ordinary chondrites of petrologic type 3.2–3.5 and 3.6–3.9 (Sears *et al.*, 1991).

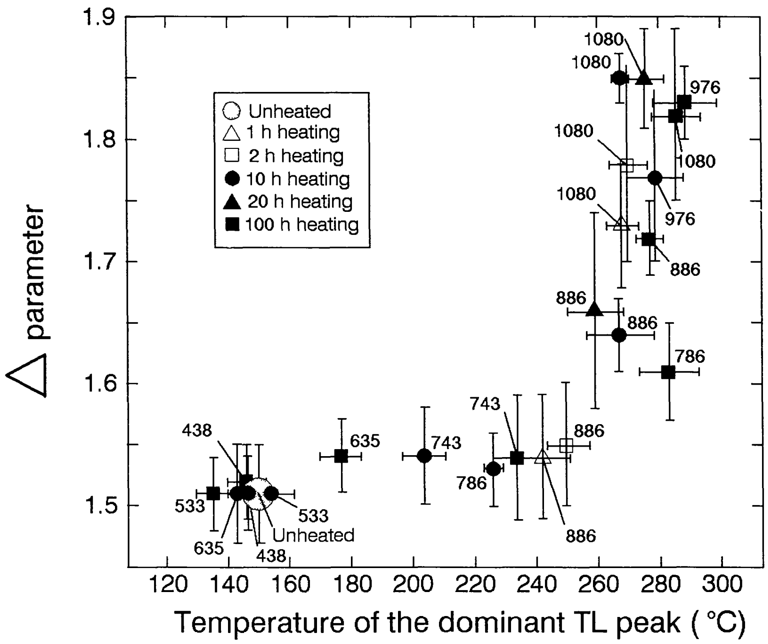


FIG. 5. Increases in peak temperature upon heating compared with the $\Delta 2\theta$ parameter, which is a measurement of the degree of structural disordering in a terrestrial oligoclase (Smith, 1974). The numbers alongside the data points refer to heating temperatures in degrees celsius. Parameter $\Delta 2\theta$ increases from ~1.5 to 2.0 as the structural order of the feldspar changes from being ordered to disordered. We suggest that the change in the TL peak temperature is associated with disordering; however, the activation energy for the TL changes is considerably less than that required for disordering, so the effect must be indirect. Pasternak (1978) suggested that the TL was reflecting defect production that preceded structural disordering.

Metamorphism of Howardite, Eucrite, Diogenite and Mesosiderite Meteorites

The eucrite parent body is assumed to have a eucritic crust that was global in extent with cumulate eucrites at the bottom of the crust and a diogenitic upper mantle (Miyamoto and Takeda, 1994a,b). Cooling rates following the igneous event (0.001 to 100 °C/h), as determined from texture (Walker *et al.*, 1978), were many orders of magnitude faster than those calculated from subsolidus reactions for metamorphic cooling. The metamorphism experienced by the HED meteorites did not therefore occur automatically during initial cooling following igneous differentiation (Miyamoto *et al.*, 1985; Yamaguchi *et al.*, 1995; Takeda *et al.*, 1994). A method of slowing down the rate of cooling following igneous differentiation is required. Either the lavas became insulated immediately after their initial formation, perhaps by subsequent lava flows or by the growing crust as partial melts percolated to the surface (Yamaguchi *et al.*, 1995). Insulation by subsequent lavas can confidently be eliminated because it requires 100–1000 flows per year and an unreasonable rate of overturn of material in the upper mantle (Yamaguchi *et al.*, 1995, and see below). Insulation by growing crust may run into similar mass balance difficulties. It also seems difficult to reconcile with the 4.50 Ga age of Ibitira (Bogard and Garrison, 1995). At the cooling rates indicated by the pyroxenes, the Ar system would not remain open for the 50 Ma required by its age.

Additional possible scenarios for HED metamorphism involve burial under impact deposits, either during forma-

TABLE 3. Metamorphic temperatures and cooling rates of eucrite and eucrite-related meteorites.

Method	Samples	Metamorphic temperature (°C)	References
Induced TL	**All classes**	**<800**	**Present work**
Texture	Kapoeta clasts	500–1000	Bunch (1975)
Two pyroxene	Mt.Padbury	972, 930	Ishii *et al.* (1976)
Two pyroxene	Binda	>1110, 970	Ishii *et al.* (1976)
Two pyroxene	Yamato (e)	1004, 913, 960	Ishii *et al.* (1976)
Clouding in pyroxene and plagioclase	4 eucrites	~900	Harlow and Klimentis (1980)
Olivine-pyroxene	ALHA80102	750 ± 20	Treiman and Drake (1985)
Spinel-orthopyroxene	Johnstown	687–886	Mukherjei and Viswanath (1987)
Spinel-orthopyroxene	Y75032	687–886	Mukherjei and Viswanath (1987)
Spinel-orthopyroxene*	*Unequil. diogenites*	*1512–1941*	Mukherjei and Viswanath (1987)
Two pyroxene/spinel-orthopyroxene	Diogenites	650–850	Mittlefehldt (1994)
Two pyroxene	4 cumulate eucrites	750–1000	Yamaguchi *et al.* (1995)

Method	Samples	Cooling rate (°C/Ma)	References
Composition and size of taenite fields	9 mesosiderites	0.1	Powell (1969)
Composition and thickness of augite lamellae	Moama	100	Miyamoto and Takeda (1977)
Composition and thickness of augite lamellae	Moore County	100	Miyamoto and Takeda (1977)
Composition and thickness of augite lamellae	Mount Padbury	4.8×10^4	Miyamoto and Takeda (1977)
Composition and thickness of augite lamellae	Juvinas	4×10^3–3×10^5	Takeda *et al.* (1983)
Composition and thickness of augite lamellae	Pasamonte	2×10^5	Miyamoto *et al.* (1985)
Composition and thickness of augite lamellae	Moore County	$160 / 3 \times 10^4$†	Miyamoto and Takeda (1994b)
Composition and thickness of augite lamellae	Medanitos	300	Miyamoto and Takeda (1994b)
Composition and thickness of augite lamellae	Serra de Magé	180	Miyamoto and Takeda (1994b)
Composition and thickness of augite lamellae	Yamato 79439	500	Miyamoto and Takeda (1994b)

*These values for unequilibrated diogenites probably refer to equilibration during igneous processes rather than metamorphism.
†Two heating and cooling episodes.

tion of the lavas (Nyquist *et al.*, 1986; Takeda and Graham, 1991; Takeda *et al.*, 1994; Miyamoto and Takeda, 1994a) or during the period of intense bombardment 3.9 to 3.5 Ga ago shared by all HEDM meteorites and lunar samples (Bogard, 1995; Bogard and Garrison, 1995). We seriously doubt that regolith formation would have been fast enough for insulation of freshly formed lavas to be significant and suggest that metamorphism 3.9–3.5 Ga ago should be considered the most viable option. The arguement of Keil *et al.* (1997) that impact heating is insufficient for eucrite metamorphism assumes uniform distribution of heat throughout the target, and it assumes a hard consolidated target rather than a regolith or otherwise friable target. Clearly, considerable localized heating is associated with impact, since impact melts are found in and around craters and Ar was degassed from the eucrites by thermal diffusion at the time of impact. Temperatures for Ar diffusion are comparable with metamorphic temperature estimates for eucrites (Table 2).

Recent theoretical treatments (Housen 1992; Asphaug and Nolan, 1992; Asphaug and Melosh, 1993), and satellite observations of Gaspra, Ida and Phobos (Carr *et al.*, 1994), suggest that there are substantial impact-produced regoliths on even small asteroids. One can also expect ejecta blankets on asteroids, whether they formed 4.5 Ga or 3.5 Ga ago, to reach considerable depths. It has been argued that cooling in a regolith-like ejecta blanket can be rejected because impact deposits cool fast and impact melts are scarce in HED meteorites (Yamaguchi *et al.*, 1995). Certainly, rapid cooling may well explain the lack of metamorphic alteration displayed by lunar samples, which also contain abundant glass and crystallized melts (Batchelor *et al.*, 1997). However, caution is necessary in applying lunar observations to much smaller bodies like asteroids where large impacts and thick ejecta blankets could result in very slow cooling rates and little or no glass. Melosh (1989) points out that the breccias under a 15 km crater take ~100 000 years to cool to ambient temperatures assuming that the target had the thermal properties of solid rock. Impact into a regolith or poorly consolidated debris not only results in much larger quantities of glass than impact into solid rock (*e.g.*, ~50 vol% melt compared with a few volume percent for a 60 GPa impact; Schaal *et al.*, 1979), but the lower thermal diffusivity would increase cooling times to 10^6–10^7 years. With cooling rates of this order, we would not expect to find glasses, quench textures or recognizable melts in the HED meteorites. Of course, it has been argued that mesosiderites are impact melts.

Variable Burial Depths During the Metamorphism of Howardite, Eucrite, Diogenite and Mesosiderite Meteorites

If the heat was deposited into regolith by one or many impact events, while the bottom and top of the layer were maintained at a temperature of essentially zero, then one can readily determine the combinations of burial depth and regolith depth that produce the observed cooling rates (Carslaw and Jaeger, 1959; Miyamoto *et al.*, 1985; Batchelor and Sears, 1991b). The relevant expression is:

$$T = 0.5T_0\left\{2\,\mathrm{erf}\left[\frac{x}{2(Kt)^{1/2}}\right] - \mathrm{erf}\left[\frac{(x-d)}{2(Kt)^{1/2}}\right] - \mathrm{erf}\left[\frac{(x+d)}{2(Kt)^{1/2}}\right]\right\} \qquad \text{Eq. (1)}$$

where T is the temperature at time t at depth x in an ejecta blanket of depth d, T_0 is the initial temperature at the end of the impact(s) which we take to be 800 °C (see above), and K is thermal diffusivity (10^{-5} cm^2 s^{-1}, the value used by Miyamoto *et al.*, 1985, which was the value for Apollo 16 lunar fines reported by Cremer and Hsia, 1974). The bottom of the regolith cools more slowly than the top, and the temperature profiles at the bottom of the regoliths are also slightly more complicated. Most important is the similarity of the profile shape for a large range of regolith thickness so that the rate at which the regolith cools is determined more by its thickness than the burial depth of a sample (Fig. 6).

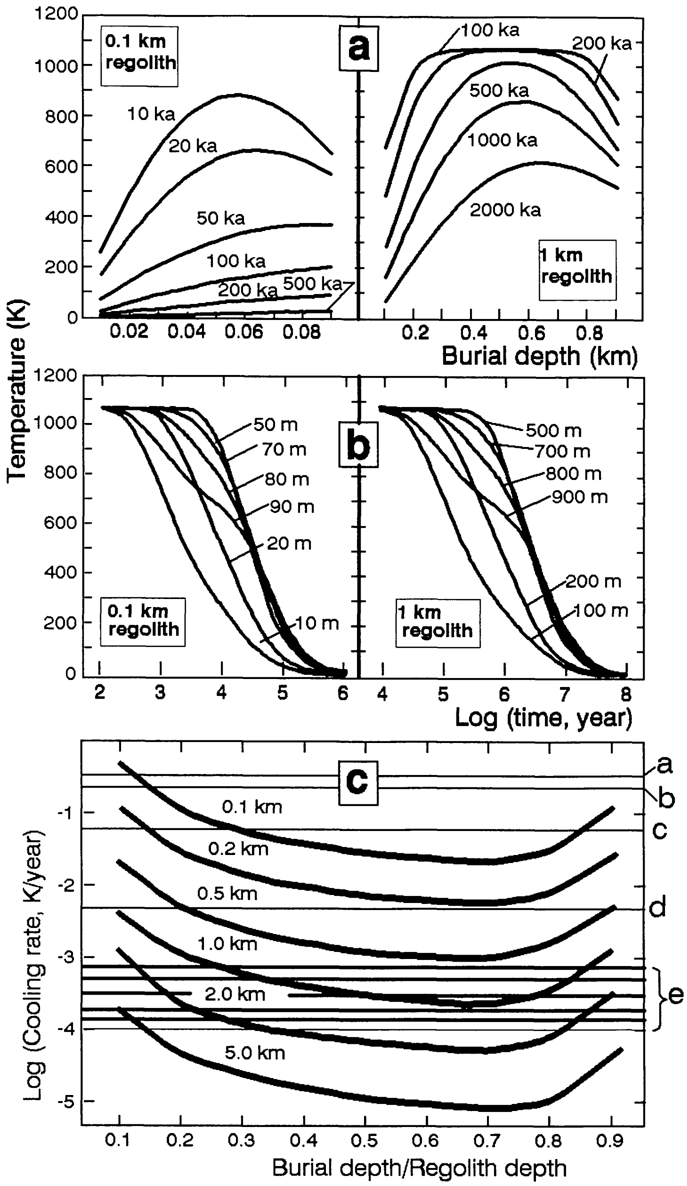


FIG. 6. (a) Depth profiles for the temperature of 0.1 km and 1 km deep regoliths for the times indicated. The curves have been calculated using the equations given in the text that assume that the top and bottom surfaces of the regolith are held at zero and that the regolith is allowed to cool after being heated to 800 °C. The thermal diffusivity of the Apollo 16 soil is assumed. Time scales for cooling from 800 °C to 30 °C increase from 50 ka for a 0.1 km regolith to 2 Ma for a 1 km regolith. (b) Temperature *vs.* time profiles for the regoliths shown in Fig. 6a. The regolith cools more rapidly at the surface and bottom than in the central portions, and slightly different profiles are displayed near the surface and at depth. (c) Cooling rates estimated from Fig. 6b as a function of fractional burial depth. The total thicknesses of the regoliths are indicated. The cooling rate varies relatively little with depth in a given regolith, and more than a factor of 200 variation in cooling rate requires burial in a regolith at different depth. Experimentally measured cooling rates are indicated by the horizontal lines: a, Juvinas upper limit (0.02 K/year); b, Pasamonte (0.2 K/year); c, Mount Padbury (0.048 K/year); d, Juvinas lower limit (0.004 K/year); e, six cumulate eucrites (0.0001–0.0006 K/year).

The cumulate eucrites, with cooling rates of ~10^{-4} °C/year, probably cooled in a regolith ~2 km deep at fractional depths anywhere between 0.3 and 0.8, while Pasamonte's cooling rate (0.2 °C/year) is so fast that the meteorite must have cooled near the surface of a very thin (essentially nonexistent) regolith. The silicates in the Mount Padbury mesosiderite also have a fast cooling rate that is consistent with burial of 25 m in a 0.1 km regolith. The large range in cooling rates determined for Juvinas suggest that it is a breccia of material that cooled at various depths in regoliths varying between 0.1 and 0.2 km total thickness. The greatest uncertainty in the thermal model concerns the choice of thermal diffusivity. These depth and thickness estimates depend on the assumed thermal diffusivity, and our present value corresponds to a highly unconsolidated regolith. But while higher values for diffusivity result in greater burial depths and thicker regoliths, they do not significantly change the shape of the thermal profiles. Thus within this general scenario, the HEDM meteorites came from regoliths of various thicknesses between essentially 0 and 2 km rather than being buried to various extents in a single regolith or in regoliths of similar thicknesses (Fig. 7).

These calculations also enable us to evaluate the idea that metamorphism occurred by heating of the samples by the flow of lavas over them (Fig. 8). Lava flows on Earth are up to 10–30 m thick (Easton, 1987). Figure 8a shows the results of applying Eq. (1) with a thermal diffusivity appropriate to lava (4×10^{-3} cm²/s) and an initial temperature of 1820 K. Cooling times for the peripheries of the flows are on the order of days, and even the center of the flows cools on the time scale of weeks to months rather than years. The thickness of the lava sheets required to produce the observed cooling rates for HED meteorites are on the order of many kilometers. In fact, the cumulate eucrites would require lava flows of 20–50 km thickness, meaning that 1000–2500 flows of ~20 m thickness would need to reach the same region of the surface within a year or so.

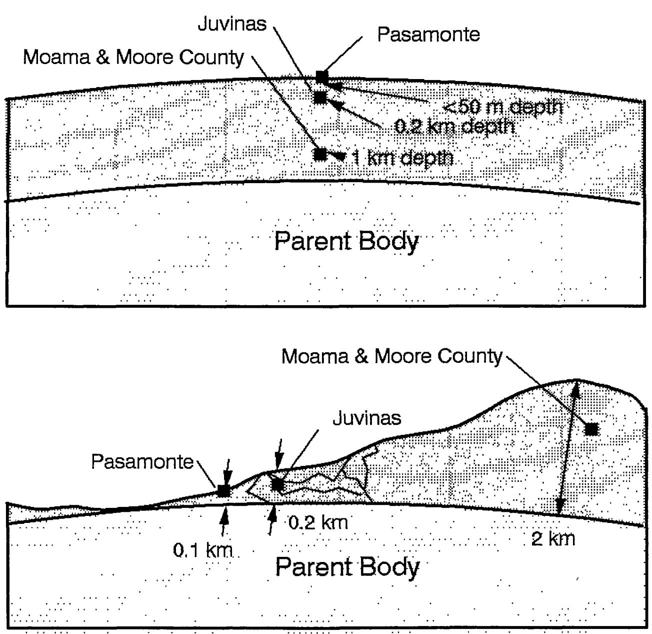


FIG. 7. Schematic diagram illustrating two views of the origin of eucrite and eucrite-related meteorites in the regolith of a parent body. The traditional view is that different cooling rates correspond to burial in a common regolith at different thicknesses (upper figure). We find this inconsistent with the calculations in Fig. 6 and suggest that the regolith on the parent body of the eucrite and eucrite-related parent body varied considerably in depth.

This depth is apparently reduced 3 to 8 km if one assumes spherical symmetry (Miyamoto and Takeda, 1994a,b), but still requires an unreasonably large number of flows.

Was Metamorphism of Howardite, Eucrite, Diogenite and Mesosiderite Meteorites Early or Late?

The lack of a correlation between petrologic type and metamorphic equilibration temperature (Yamaguchi *et al.*, 1995) and the lack of exsolution textures in Ibitira despite its 3.95 ± 0.05 Ga ^{39}Ar-^{40}Ar age (Takeda *et al.*, 1994) has suggested to some workers that the metamorphism experienced by the HED meteorites occurred at ~4.5 Ga rather than during the Ar degassing event. We do not find these arguments convincing because Ar degassing is more facile than sili-

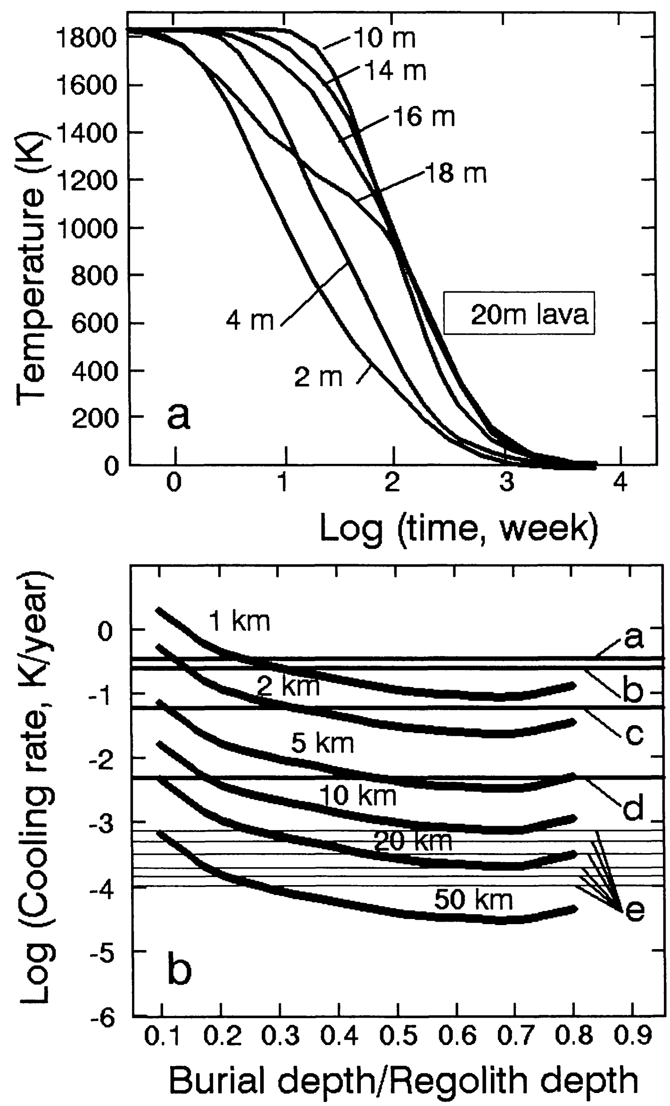


FIG. 8. Cooling histories of lava ejected onto the surface of the HED parent body calculated using the methods used for Fig. 6 but assuming a thermal diffusivity appropriate to lava (4×10^{-3} cm²/s) and an initial temperature of 1820 K. (a) Thermal profiles for a 20 m thick lava sheet; calculations for 10 and 30 m sheets yielded almost identical results. Cooling times for such lava sheets on the surface of the parent body are on the order of a few months. (b) Thicknesses of the lava layers that would be required to produce the observed cooling rates are indicated by the horizontal lines that are keyed as in Fig. 6c. To produce the cooling rates observed for the cumulate eucrites, the lava thickness would have to be 20–50 km.

cate equilibration (see Fig. 1 in Bogard, 1995) and because petrologic type is determined by both cooling rate and temperature. There are many instances of cooling rate and temperature being decoupled from petrologic type. For example, EL6 chondrites have very different cooling rates from EH chondrites of similar petrologic type (Zhang *et al.*, 1995) and CO3.8 chondrites that have lower metamorphic equilibration temperatures than H3.8 chondrites (Guimon *et al.*, 1995). On the other hand, the Ar degassing indicates that these meteorites were heated 3.9–3.5 Ga ago, and the present thermal calculations indicate that the process was capable of causing pyroxene exsolution and compositional homogenization. The data clearly indicate that there were a great variety of conditions, and the present calculations indicate that probably the major variable was the thickness of the regolith/ejecta blanket in which the samples cooled.

CONCLUSIONS

Our major conclusions are as follows: (1) the TL sensitivities for matrix samples from the LEW 85300, 302 and 303 paired eucrites and the Bholghati howardite are lower than the TL sensitivities for the clasts that are consistent with regolith working of the matrix in a fairly mature regolith. (2) Within an isochemical series of HED meteorites, TL sensitivity reflects metamorphic intensity, but clast-to-clast variations in the TL sensitivities of the Vaca Muerta mesosiderite and clasts from the EET 87509, 513 and 531 paired howardites reflect major mineralogy and petrology. (3) Thermoluminescence peak temperatures indicate that all the components from the LEW 85300, 302 and 303 paired eucrites experienced a reheating event, which is thought to have been due to impact heating, and therefore that the event was concurrent with or postdated brecciation. (4) Laboratory heating experiments show that at temperatures >800 °C, TL peak temperatures increase significantly. Thus, induced TL data for eucrites indicate that the HED meteorites, the Vaca Muerta and LEW 85300 group excepted, experienced metamorphism <800 °C. This is consistent with equilibration temperatures calculated from mineral pairs. (5) Feldspars from a variety of terrestrial and extraterrestrial sources show an increase in TL peak temperature after heating >800 °C TL. X-ray diffraction and kinetic studies suggest that it is indirectly related to Al,Si disordering. (6) Postmetamorphic cooling rates are inconsistent with the metamorphism occurring during cooling after the initial igneous event or with heating by subsequent eruption of lava onto the surface of the HED parent body. (7) Our thermal models are consistent with the metamorphism occurring within a regolith ejecta blanket up to a few kilometers thick, with different levels of metamorphism corresponding to different thicknesses of blanket rather than different burial depths. The ejecta blanket must have been highly variable in thickness, ranging from essentially nonexistent to ~2 km thick. We suggest that metamorphism occurred 3.9 Ga ago, at the time the Ar-Ar chronometers were reset, probably due to the inner-solar-system-wide terminal cataclysm.

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