Geochimica et Cosmochimica Acta Vol. 55, pp. 3831–3844
0016-7037/91/$3.00 + .00

Thermoluminescence constraints on the metamorphic, shock, and brecciation history of basaltic meteorites

J. DAVID BATCHELOR and DEREK W. G. SEARS
Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, USA

(*Received November* 30, 1990; *accepted in revised form September* 23, 1991)

Abstract—Induced thermoluminescence measurements have been performed on eighteen eucrites, thirteen howardites (plus seven splits from the Bholghati howardite), six diogenites, and fifteen mesosiderites in order to help clarify their metamorphic, shock, and brecciation history. The TL sensitivities of the basaltic meteorites reflect their bulk composition, and the effects of (1) igneous processes (diogenites and mesosiderites) and (2) the mixing of materials of different compositions (e.g., diogenitic and eucritic) during brecciation (howardites) can be observed. Two previously unclassified mesosiderites, LEW87006 and EET87500, are assigned to class A and B, respectively, on the basis of their TL sensitivities. The eucrites show a 15-fold range of TL sensitivities, which correlate with petrographic indicators of metamorphic intensity. We therefore describe a petrologic type scale based on TL and petrographic evidence, where the least metamorphosed eucrites are type 1 and most equilibrated are type 8. We see no evidence for two discrete metamorphic environments corresponding to the equilibrated and unequilibrated eucrites.

The temperature of the dominant TL peak observed for basaltic meteorites, and experiments in which four eucrites with diverse petrographic properties were annealed at various temperatures in the laboratory, suggests the metamorphic equilibration temperatures for most basaltic meteorites were ≤800°C. This estimate is generally consistent with palaeotemperatures determined from two-pyroxene, olivine-pyroxene, and oxygen isotope equilibria. Assuming this temperature was typical of conditions during metamorphism, then burial depths for type > 5 eucrites were >350 m and <50 m for type 2 eucrites. An important exception is LEW85303 (and three samples paired with it, LEW85300, 85302, and 88005) which has been shock-heated above 1000°C. Ibitira and LEW85305 have also been shocked but subsequently suffered low-temperature annealing (≤800°C). Since TL peak temperatures are related to the degree of disorder in the Al, Si chain in feldspar, the present data provide independent evidence for very slow cooling rates for mesosiderites and for the slower cooling rates for some cumulate eucrites relative to equilibrated non-cumulate eucrites.

INTRODUCTION

THE EUCRITES, howardites, diogenites, and mesosiderites are related groups of basaltic meteorites. They show textural and mineralogical similarities reflecting comparable or related igneous processes, share elemental and isotopic compositional trends, display many similar chronologic properties, and, most importantly, often co-exist in the same breccias (BOGARD and GARRISON, 1989; BUNCH, 1975; CLAYTON and MAYEDA, 1978; CLAYTON et al., 1976; DUKE and SILVER, 1967; MCCARTHY et al., 1972, 1973; STOLPER, 1977; TAYLOR et al., 1965). Recently, mesosiderites have been sorted into compositional groups A (feldspar > 24%) and B (feldspar < 21%), in which the silicates are somewhat analogous to howardites, and group C (feldspar 0–5%), in which the silicates may be said to be diogenitic (HEWINS, 1984, 1988).

Most of the basaltic meteorites show petrologic and radiometric evidence for complex metamorphic brecciation and shock histories. Monomict breccias are common, and there is a continuum of samples from polymict eucrites to howardites to polymict diogenites, with howardites containing >10% eucritic and <10% diogenitic material (DELANEY et al., 1983). Although to a first approximation howardites are breccias of eucritic and diogenitic material (LABOTKA and PAPIKE, 1980; MCCARTHY et al., 1972), other igneous components are present (e.g., BUNCH, 1975). Trace element data indicate the presence of chondritic material (CHOU et al., 1976; DESNOYERS and JEROME, 1977) and occasionally CM-like clasts are found (WILKENING, 1973). Howardites also frequently contain fused soils, glasses, charged-particle tracks, and solar-wind gases characteristic of a regolith history (LABOTKA and PAPIKE, 1980; MACDOUGALL et al., 1973; SUESS et al., 1964; WILKENING et al., 1971).

Radiometric evidence also suggests a complex history for these meteorites. Some clasts in Kapoeta, for instance, have concordant Rb-Sr and Ar-Ar ages around 4.55 Ga, consistent with crystallization within 30 Ma of formation and with the presence of decay products of extinct I-129 and Pu-244, while other recrystallized clasts have ages around 3.89 Ga (ROWE, 1970; DYMEK et al., 1976). The Rb-Sr internal isochron ages for metamorphosed eucrites are significantly lower than 4.55 Ga (BIRCK and ALLÉGRE, 1978). The Estherville mesosiderite has a 4.24 Ga Rb/Sr age for the whole-rock and 4.53 Ga for mesostasis-free separate (MURTHY et al., 1977). Ages < 4.5 Ga are usually interpreted in terms of thermal events such as metamorphism. TERA et al. (1987) argue that the Sm/Nd and Pb/Pb ages for cumulate eucrites are significantly younger than those of other eucrites (4.41–4.46 Ga compared with 4.53–4.54 Ga, JACOBSON and WASSERBURG, 1984; LUGMAIR et al., 1977; NYQUIST et al., 1985). While this observation has been questioned by NYQUIST et al. (1986), a 100 Ma time difference would be inconsistent with crystallization from the same magma unless the Sm-Nd ages refer to isotopic closure of the system, in which case these meteorites must have

Table 1. Samples, sources, catalog numbers, and induced thermoluminescence data or eucrites, diogenites, howardites, and mesosiderites.*

				Peak 1		Peak 2	
Meteorite[#]	Source/ Cat. #[+]	Descr[@]	Mass (mg)	Peak T (°C)	TL Sens. (Dhajala =1000)	Peak T (°C)	TL Sens. (Dhajala =1000)
Eucrites							
ALH85001,20	MWG	Cum	83	115±1.4	1600±110	--	--
ALH85001,19	MWG	Cum	106	117±7.5	989±162	--	--
ALHA76005,79	MWG	Eq	186	114±2.9	763±44	--	--
ALHA76005,78	MWG	Eq	158	123±8.1	712±143	--	--
ALHA77302,83	MWG	Eq	131	118±1.0	587±10	205±1.7	376±32
EET87542,8	MWG	Eq	172	105±3.6	986±102	207±3.6	468±61
EET87542,3	MWG	Eq	123	102±2.5	975±43	200±5.7	500±27
EET87548,2	MWG	Eq	100	108±3.5	712±29	196±1.5	505±10
EET87548,8	MWG	Eq	207	107±2.3	413±57	198±2.9	312±49
EETA79004,101	MWG	Eq	55	115±0.6	1060±60	--	--
EETA79004,102	MWG	Eq	171	140±8	685±150	--	--
Ibitira	UNMA7.12	Anom	36	110±2.3	178±41	198±3.6	127±19
Juvinas	MNHN40B	Eq	263	99±3.5	782±38	206±1	396±30
LEW85303,3	MWG	Eq	27	---	---	195±5	1330±150
LEW85303,86	MWG	Eq	200	---	---	209±15	554±83
LEW85305,2	MWG	Anom	73	111±4.5	215±22	197±4	215±22
LEW86001,16	MWG	Eq	160	112±1.5	876±44	193±6.1	644±30
LEW87004,7	MWG	Uneq	200	111±2.1	284±17	169±5.5	287±13
Moore County	USNM929	Cum	305	118±2.6	498±28	197±6.8	430±32
Nuevo Laredo	USNM1783	Eq	129	104±4.2	404±50	167±6.1	416±33
Pasamonte	USNM897	Uneq	148	110±4.6	226±24	167±2.6	170±21
Pasamonte	USNM897	Uneq	124	117±4	202±55	173±1.5	153±36
PCA82502,60	MWG	Uneq	221	105±4.9	245±35	188±3.5	328±14
PCA82502,59	MWG	Uneq	247	107±7	186±17	185±1.7	267±34
Serra de Mage	MNHN1606	Cum	303	102±2.6	3090±110	183±7.5	1850±50
Stannern	---	Eq	187	117±8.5	625±55	197±0.6	490±34
Diogenites							
ALHA77256,110	MWG		205	110±1.7	11±4	200±4.4	8±2
ALHA77256,109	MWG		154	136±5	5±5	195±5	7±7
ALHA84001,31	MWG		275	185±20	0.8±0.6	--	--
ALHA84001,32	MWG		88	110±5	0.5±0.5	200±5	0.5±0.5
EETA79002,83	MWG		86	--	3±1.5	--	--
EETA79002,84	MWG		250	185±25	0.6±0.29	--	--
Johnstown	AMNH2493		141	127±1	22±5	166±17	18±5
Shalka	BM33761		453	--	0.8±0.5	--	--
Tatahouine	MNHN1637		247	159±3.1	15±2	--	--
Howardites							
Bholghati,17	GSI		4.7	117±2.1	1300±30	220±2.1	1070±20
Bholghati,27	GSI		28	97±4.6	520±22	194±3.5	353±11
Bholghati,26	GSI		17	105±3.5	373±9	185±7.8	317±33
Bholghati,29	GSI		29	142±7.1	254±4.4	213±19	--
Bholghati,28	GSI		21	141±7	229±3.8	220±18	--
Bholghati,19	GSI		27	129±6.9	218±12	218±9.2	158±9
Bholghati,21	GSI		28	122±4.6	204±26	211±1	166±19
Binda	USNM4850		239	116±4.4	484±47	197±2.5	258±26
Bununu	USNM1571		216	117±1.2	182±28	197±5.8	129±20
Chaves	UTAD		800	118±3.1	68.8±5.3	203±1.0	51.4±6.7
EET83376,7	MWG		151	105±2.6	384±27	164±2.6	268±26
EET83376,8	MWG		187	116±4.4	340±29	165±3.6	308±18
EET87503,3	MWG		130	133±15	588±150	--	--
EET87503,14	MWG		153	105±2.9	195±14	--	--
EETA79006,61	MWG		207	112±2.5	412±23	169±5	418±76
EETA79006,60	MWG		123	107±3.2	354±12	168±0.6	311±19
Kapoeta	BM1946,141		190	115±4.2	453±78	189±1	373±67
Le Teilleul	MNHN711A		366	102±0.6	1030±60	192±1.5	588±30
LEW85313,35	MWG		152	108±3	227±19	194±2.3	158±12
LEW85313,3	MWG		105	103±3.6	130±3	196±8	86±12
LEW85441,2	MWG		81	106±1.5	540±40	198±2.1	410±8
Pavlovka	FM,ME1377		559	121±1.7	306±11	200±3	284±34
Petersburg	ASU334.2		190	101±3.1	487±94	199±2.6	282±55

Table 1. (Continued)

Meteorite#	Source/ Cat. #+	Descr@	Mass (mg)	Peak 1 Peak T (°C)	Peak 1 TL Sens. (Dhajala =1000)	Peak 2 Peak T (°C)	Peak 2 TL Sens. (Dhajala =1000)
Mesosiderites							
ALHA77219,58	MWG	1B	340	119±2.2	37±1	--	--
ALHA77219,59	MWG	1B	210	112±1.2	27±2	--	--
Clover Spring	USNM1633	2A	88	123±1.5	280±81	--	--
Crab Orchard	FM,ME187	1A	811	108±1.7	265±35	--	--
EET87500,11	MWG	--	227	131±5	22.3±1.7	--	--
Estherville	MNHN769	3-4A	267	103±6	431±58	--	--
Estherville	MNHN1661	3-4A	207	104±5	206±20	--	--
Hainholz	NMVJ2895	4A	232	121±2.1	71±4.7	--	--
LEW87006,8	MWG	--	174	108±1.7	400±31	--	--
Lowicz	AMNH3775	3A	411	126±8.5	439±62	--	--
Lowicz A	AMNH3775	3A	51	116±1.5	92±5	--	--
Mincy	AMNH887	3B	113	114±7.6	76.3±10.1	184±1.5	66±6.4
Morristown	FM,ME1280	3A	180	114±4.5	79.9±5.9	183±7	55.2±6.3
Patwar	ASU634.1	1A	204	112±7.4	172±23	--	--
Pinnaroo	USNM2312	4B	668	114±1.5	46±3	--	--
QUE86900,27	MWG	1A	239	83±10	52.5±2.7	--	--
QUE86900,3	MWG	1A	413	103±3.5	50±7	--	--
RKPA79015,16	USNM	2C	216	106±7.6	3.3±1.4	--	--
RKPA79015,17	USNM	2C	229	126±13	2±1	--	--
Vaca Muerta	MNHN3116	1A	184	108±1.7	271±16	--	--
Vaca Muerta	MNHN1010	1A	233	108±2	42±3	--	--

* Uncertainties are one sigma values for triplicate measurements of a homogenized 150-500 mg mass.

Split numbers appear after a comma, where applicable.

+ MNHN, Museum National d'Historie Naturelle (Dr. Paul Pellas); MWG, Meteorite Working Group of NASA/NSF; USNM, National Museum of Natural History (Smithsonian Institution, Dr. Roy Clarke); AMNH, American Museum of Natural History (Dr. Martin Prinz); BM, British Museum (Natural History, Dr. Robert Hutchison); GSI, Geological Survey of India (via Dr. J. C. Laul; the numbers after the comma are JSC curatorial split numbers); ASU, Arizona State University (Dr. Carleton Moore); FM, Field Museum of Natural History (Dr. Edward Olsen); NMV, Naturhistorisches Museum, Vienna (Dr. Gero Kurat); UNM, University of New Mexico (Dr. Ed Scott); UTAD, Universidade de Tras-os-Montes e Alto Douro (J. Fernando Monteiro).

@ Anom, anomalous; Cum, cumulate; Eq, equilibrated; Uneq, unequilibrated; 1-4, petrographic type (subgroup) according to Powell (1969) and Floran (1978); A-C, chemical class according to Hewins (1985).

$ ALHA76005 is polymict, but our two splits both appear to be equilibrated.

experienced very slow cooling and burial depths of > 100 km (TERA et al., 1987). The calculated depth is strongly dependent on the assumed thermal diffusivity, and WARREN et al. (1989) calculate burial depths of about 10 km for the cumulate eucrites. They also point out that a similar situation exists for lunar cumulates.

Metamorphism of the basaltic meteorites is often noted in the pyroxenes. The present TL data show that it is equally evident in feldspar properties. Some eucrites (e.g., Pasamonte) contain pyroxene with igneous zoning, while others (e.g., Moore County, Binda) contain pyroxene which is not zoned but contains exsolution lamellae of augite (DUKE and SILVER, 1967). Thus, REID and BARNARD (1979) introduced the concept of 'equilibrated' and 'unequilibrated' eucrites, on the basis of pyroxene petrology, and TAKEDA et al. (1983) have suggested that the eucrites form a metamorphic sequence analogous to that of the ordinary chondrites for which the 'petrologic types' were devised. The howardites experienced post-brecciation metamorphism to varying degrees; glass beads in Yurtuk and Frankfort are completely devitrified, for instance, while in Malvern and Pavlovka they are not (LABOTKA and PAPIKE, 1980). The mesosiderites have been similarly sorted into types 1–3 on the basis of textural evidence for recrystallization (FLORAN, 1978; POWELL, 1971), while mesosiderites of type 4 show a magmatic texture indicating shock melting.

The thermal history of the basaltic meteorites is therefore complicated but of considerable significance in understanding their present nature. We have found that induced thermoluminescence (TL) studies can provide new insights into the thermal histories of a variety of meteorite classes (HASAN et al., 1986; KECK and SEARS, 1987; SEARS et al., 1980, 1989) and brecciation in gas-rich regolith breccias (HAQ et al., 1989), and we concluded that such a study of the basaltic meteorites would be useful. In past work, we have found that TL can provide some indication of metamorphic temperatures, as well as relative metamorphic intensities, which, of course, provide some indication of burial depths. Preliminary descriptions of our studies were presented by BATCHELOR and SEARS (1989a, 1990a). We have now determined the TL properties of whole-rock samples of eighteen eucrites, thirteen howardites, six diogenites, fifteen mesosiderites, and seven splits from the Bholghati howardite (REID and BUCHANAN, 1989). As an aid to interpreting these data, we have also performed measurements on mineral separates and samples of four eucrites annealed to various temperatures in the laboratory. Our study confirms the existence of metamorphic sequences in eucrites and mesosiderites, and the unique thermal history of LEW85303 (and the meteorites paired with it). Also, it provides a new indication of metamorphic and shock temperatures.

SAMPLES AND ANALYTICAL METHODS

The samples, their sources, classes, and simple descriptions (cumulate, unequilibrated, equilibrated, etc.) are given in Table 1. In general, we included only monomict eucrites, although there is always some uncertainty since all these meteorites are brecciated. We asked curators to provide us with two splits of different naked-eye lithology, where possible, in order to test for heterogeneity. Two previously unclassified mesosiderites, LEW87006 and EET87500, are assigned below to groups A and B, respectively. After inspection under a low-powered binocular microscope, 150–500 mg homogenized samples were prepared by hand-crushing in an agate or stainless steel mortar, with any metal removed by a hand-magnet. Three 4 mg aliquants were placed in shallow copper pans, their natural TL drained by brief heating to 500°C, and their induced TL properties measured after exposure to an ~20 grey beta dose from a 15.1 TBq ^{90}Sr source. After a 5 min delay (to standardize decay of very unstable low-temperature components), each sample was heated at 7.5°C/s in a Daybreak Nuclear and Medical Systems TL apparatus fitted with blue bandpass and IR filters (Corning 7-59 and 4-69). Similar aliquants of Dhajala, an H3.8 ordinary chondrite, were run at the beginning and end of each day as a normalization-standard and instrument-check. The TL data were digitally recorded, smoothed using a 5-point moving average, and the TL peak heights and temperatures were determined by inspection. TL peak height data were normalized to the value of Dhajala for that day, which showed a long-term fluctuation of ≤10%. Data for the three aliquants were averaged, the uncertainty quoted in our data tables is their standard deviation.

In order to identify the mineral(s) responsible for the TL in these meteorites, measurements were made on mineral separates. Five feldspar grains, five pyroxene grains, and six glossy black, opaque grains of chromite/ilmenite were separated from Serra de Mage. A Cambridge Stereoscan 600 SEM fitted with a Kevex 3201-600 Si(Li) EDX detector was used to identify grains. We were unable to find silica in Serra de Mage; but since quartz is known to be an efficient TL phosphor in many systems (MCKEEVER, 1985), several SiO_2 grains (with fan-like shapes suggestive of tridymite) were removed from the coarse-grained unequilibrated eucrite, LEW87004. The grains were separated by acetone/bromoform flotation (2.48 g/cc) using the SEM/EDS and hand-picking from the SEM stub. The TL glow curves of representative separates are shown in Fig. 1. Feldspar is obviously the major phosphor. In fact, the level of TL detected in the other separates is so low and the curve shapes so similar to that of the feldspar separate, that we suspect the TL signal from the other grains is due to feldspar contamination.

RESULTS

The TL data for the bulk samples are listed in Table 1.

Peak Temperatures

Most of the samples showed two peaks in their TL glow curves, a 'low' temperature peak at 113 ± 11°C and a 'high' temperature peak at 192 ± 15°C (Fig. 2). The presence, and often dominance, of the low peak is one of the most noteworthy properties of the basaltic meteorites. For the eucrites, the low-peak dominates in the glow curves of two of the three cumulates and of eight of the nine equilibrated eucrites. For the remaining eucrites, with one major exception, the peaks are generally of comparable intensity. The major exception is LEW85303 (and the samples paired with it, LEW85300, LEW85302 and LEW88005) which shows a single wide high-form peak. In addition, Ibitira shows a third small peak at 354 ± 5°C. Fig. 3 shows representative TL glow curves for eucrites.

Diogenite peak temperatures are uncertain because their TL signals are weak, but they lie within the same range as those of the eucrites. The howardite curves usually show high- and low-temperature peaks, with the low-temperature peak dominant. EET87503 shows only a low-temperature peak. The range of low-form peak temperatures of howardite splits is as large as that shown by the other achondrites, except possibly the diogenites. Except for Morristown and Mincy, the mesosiderites show only a low-form peak.

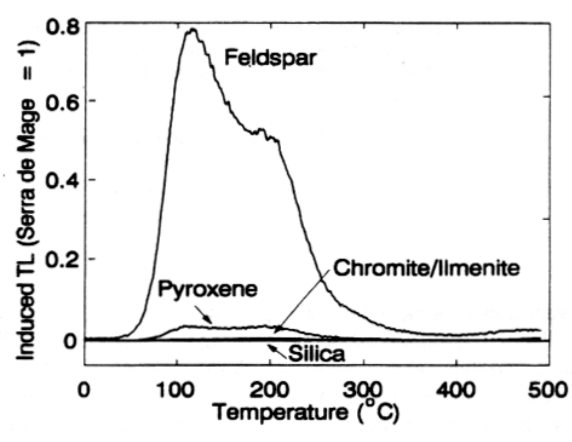

FIG. 1. Induced thermoluminescence glow curves for mineral grains separated from the Serra de Mage eucrite, except silica which was removed from LEW87004, normalized to the TL sensitivity of the whole-rock Serra de Mage. Minerals were separated by flotation and hand-picking, and identified by SEM/EDX. The TL signal from the bulk sample is produced almost entirely by feldspar. The shape of the curves and the weakness of the signals from the other separates suggests that their TL signal is from incomplete feldspar removal.

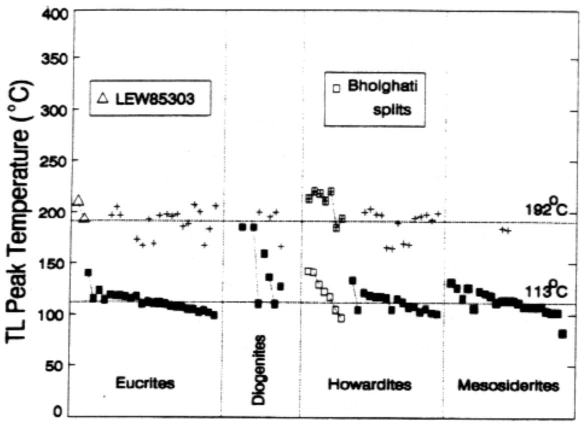

FIG. 2. Plot showing the temperatures of the TL peaks in the glow curves of basaltic meteorites. The lowest temperature peak to appear (usually around 115°C) is shown as filled squares (open squares in the case of the Bholghati splits), and the higher temperature peak (which usually appears at around 195°C) is shown as crosses. With few exceptions, the peak at 115°C is very strong and often dominates the glow curve. The 195°C peak may be comparable in strength to the first peak in some unequilibrated eucrites, but in the eucrites generally it is much weaker. LEW85303 (and LEW85300, LEW85302 and LEW88005, which are paired with LEW85303; MASON, 1986; SEARS and SEARS, 1990) is notable for having a very strong broad peak at around 200°C. The diogenites have very low TL sensitivities and it is often difficult to assign meaningful peak temperatures. The mesosiderites are noteworthy for the virtual absence of a peak at around 195°C.

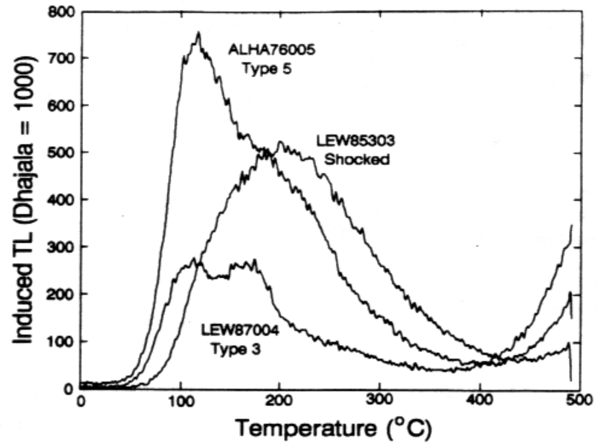

FIG. 3. Induced thermoluminescence glow curves for an equilibrated eucrite, an unequilibrated eucrite, and the unusual LEW85303. Equilibrated eucrites have a strong peak at 115°C, while unequilibrated eucrites have an additional peak at around 195°C and have lower overall TL sensitivities which is at least comparable in intensity to the 115°C peak (see previous figure). The unusual LEW85303 eucrite has a broad peak at around 200°C.

Annealing Experiments

Annealing experiments were performed on a cumulate, an equilibrated and an unequilibrated eucrite, and the unusual shocked eucrite LEW85303. Homogenized powders weighing about 20 mg were sealed in quartz vials which had been filled, flushed, and evacuated three times with N_2, and then annealed for 96 h in Lindberg 55035 tube furnaces. Annealing below 700°C did not affect the TL peak temperatures, but annealing at 800, 900, and 1000°C caused the 113°C peak to shift to higher temperatures, reaching 160–220°C after annealing at 1000°C (Fig. 4). In contrast, the TL curves for LEW85303 were not significantly affected by annealing at any temperature up to 1000°C. The implications of these data are discussed below, but clearly the TL peak temperatures of the whole-rock samples are related to their thermal histories.

TL sensitivities

All the basaltic meteorites have low TL sensitivities relative to Dhajala (Fig. 5). Among the eucrites, two cumulates (Serra de Mage and ALH85001) have the highest values. Among the noncumulate eucrites, we see a continuous sequence of decreasing TL sensitivity with unequilibrated samples at the low end. The vesicular lava Ibitira and LEW85305 show the lowest values.

Diogenite TL sensitivities are very low, 0.01–0.001 times that of Dhajala. The howardites generally have TL sensitivities slightly below those of the eucrites, Chaves having the lowest value while a eucritic clast from Bholghati has the highest. Matrix samples from Bholghati have sensitivities comparable to the lowest howardite values. The mesosiderites show a wide range of TL sensitivities, which decrease along the A-B-C series. Four out of the five mesosiderites with the lowest TL sensitivities are from the Antarctic, and weathering may be lowering their values by causing the grains to darken (SEARS, 1980; SEARS et al., 1982). The lowest TL sensitivity

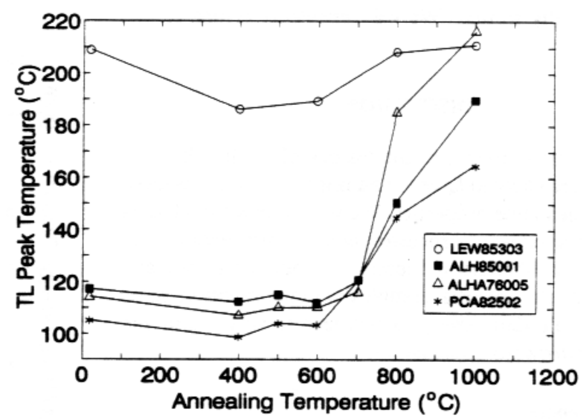

FIG. 4. Plots of the temperature of the dominant TL peak for four eucrite samples, annealed in an inert atmosphere for 96 h, as a function of annealing temperature. ALH85001 and PCA82502 are cumulate and unequilibrated eucrites, respectively, while our ALHA76005 samples are equilibrated material from a polymict eucrite. Their peak temperatures are stable until annealing at 700°C and above, when they increase from 100–120°C to 160–220°C after annealing at 1000°C. The relatively high peak temperature for LEW85303 is not significantly altered by the annealing treatment. This suggests that meteorites for which the 115°C peak dominates have not been heated >800°C since the last crystallization of their feldspar, while LEW85303 has been heated to >1000°C. Studies of GUIMON et al. (1985) and HARTMETZ and SEARS (1987) indicate that such variations in TL peak temperature are associated with the degree of structural order in the feldspar.

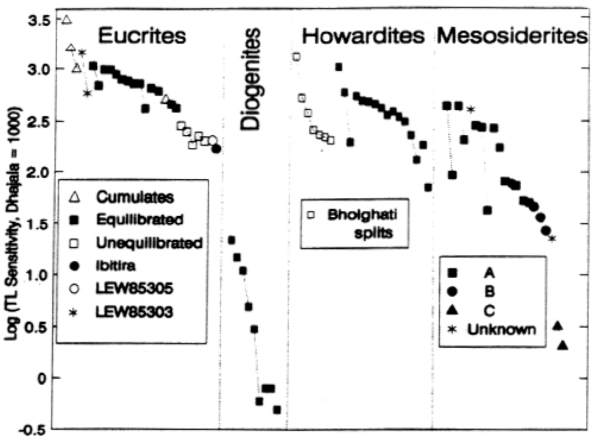

FIG. 5. Thermoluminescence sensitivity values at the low peak for the basaltic meteorites, normalized to Dhajala = 1000. The symbols are explained in the key that accompanies each class. The low TL sensitivity of the diogenites, and the relationship between mesosiderite class A, B, and C and TL sensitivity, reflects variations in feldspar abundance.

value for any mesosiderite is that of the unusual diogenitic mesosiderite RKPA79015.

For most of our samples, duplicate chips were obtained from the museums. Considering the coarse-grained textures and the brecciation of these meteorites, the agreement between splits is remarkable (Table 1), even for ALHA76005, which is polymict and was accidentally included in this study. The agreement between splits is partly because the sample masses are generally quite high, but also because host and clasts are usually similar. We will repeatedly return to this point.

DISCUSSION

There are many events in the history of the basaltic meteorites that are likely to have left an imprint on their induced thermoluminescence properties. We will discuss the TL data in terms of the relevant processes: igneous processes (which resulted in class differences), brecciation, metamorphism, and shock. Despite the potential complexity of the situation, some trends in the TL data emerge which lead to very useful and fairly straightforward conclusions.

Class Differences

Probably the two most striking trends in our TL sensitivity data are the low TL sensitivity of the basaltic meteorites compared with the chondrites (typically 1.0–0.001 times Dhajala) and the especially low TL sensitivity of the diogenites and diogenitic (class C) mesosiderite.

The lower TL sensitivity of these meteorites (compared to the chondrites) despite their higher feldspar content, is due to the composition of the plagioclase. Chondritic plagioclase is typically An_{10} (VAN SCHMUS and RIBBE, 1968), while feldspar in basaltic meteorites is An_{85-95} (DUKE and SILVER, 1967). BATCHELOR and SEARS (1989b) and AKBER and PRESCOTT (1987) have shown that calcic plagioclase has a TL sensitivity 0.01 times that of albite. There is no indication that the small variation in plagioclase compositions within the basaltic meteorites is affecting TL data. For example, cumulate eucrites contain more calcic plagioclase than equilibrated eucrites, while their TL sensitivities are generally higher. Similarly, cathodoluminescence images suggest that zoning will not affect whole-rock TL data, since the zoning in the CL is minor compared to the major differences in total CL level between equilibrated and unequilibrated eucrites. The zoning does suggest that trace element variations may play some part in determining TL sensitivities within the eucrite class. For example, the Fe content of the feldspars, which may depend on metamorphism, would affect TL sensitivity.

The low TL sensitivity of the diogenites and the diogenitic mesosiderites is almost certainly due to their extremely low abundances of feldspar. For example, Johnstown contains 0.7% plagioclase, while PRINZ et al. (1982) found no plagioclase in RKPA79015 and CLARKE and MASON (1982) found only 'a little' plagioclase (An_{86-94}) in RKPA80258, which is paired with RKPA79015. Variations in feldspar abundance are almost certainly the cause of the variations in the TL sensitivity of the mesosiderites of class A, B, and C (Fig. 6). TL sensitivities are typically 320, 50, 3 (Dhajala = 1000), while modal plagioclase is 33, 6–18, traces, for classes A, B, and C, respectively (HEWINS, 1985, see previously). The broadly similar TL sensitivities of eucrites, howardites, and the silicate fraction of class A mesosiderites are consistent with their similar model abundances of feldspar. On the basis of TL sensitivities, we are able to classify two previously unclassified mesosiderites: LEW87006 is class A and EET87500 is class B.

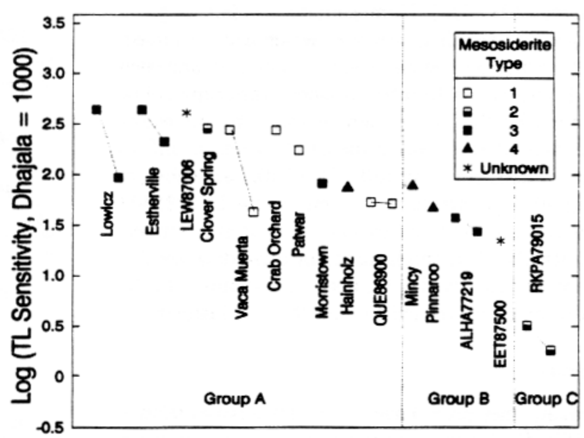

FIG. 6. Thermoluminescence sensitivities for mesosiderites, normalized to Dhajala = 1000. The three chemical classes (A, B, and C) defined by HEWINS (1985) are shown in separate boxes and their different TL values reflect different feldspar contents. The petrographic types 1–4 (FLORAN, 1978; POWELL, 1969) are indicated in the key. Within the isochemical class A, with the exception of Morristown, types 1–3 show TL sensitivities which increase with type (as feldspar is produced by devitrification of glasses), while Hainholz (type 4) has low TL sensitivity because feldspathic material has been partially melted. Two previously unclassified mesosiderites (LEW87006 and EET87500) have been assigned classes on the basis of the present TL data.

Brecciation

Brecciation, or processes associated with brecciation, can affect TL data in two ways: (1) Mixing components of different TL sensitivities, for example eucritic and diogenitic material, would produce a range of TL sensitivities depending on the proportions of the end-members. (2) The fusion or sintering of the feldspathic component during regolith working would lower the TL sensitivity by an amount dependent on the proportion of feldspar affected. This was found to be the major process governing TL sensitivities of the matrix of chondrite regolith breccias (HAQ et al., 1989). Both processes occur, but their relative importance is not always clear. MCCARTHY et al. (1972) observed that howardite compositions plot on a eucrite-diogenite mixing line, while the formation of glasses has often been petrographically observed (e.g., LABOTKA and PAPIKE, 1980; TAKEDA et al., 1983).

Petrographic and bulk chemical data suggest that mixing of material is the major factor determining the TL sensitivities of the howardites in the present study. Data for seven splits from the Bholghati howardite are indicated in Fig. 7, with the nature of the splits indicated. Four matrix samples have rather uniform TL sensitivity which is a factor of six lower than a eucritic clast, while two 'light clasts' have intermediate values. The matrix presumably has lower TL sensitivity because of mixing of low TL components and vitrification of the feldspathic material (BATCHELOR and SEARS, 1990b). Comparison of Bholghati matrix data with whole-rock and matrix data from other howardites indicates Bholghati probably has a whole-rock value comparable to EETA79006. LEW85313, a polymict howardite situated near the lower limit of the TL sensitivity range, is notable for its abundant diogenitic clasts (BUCHANAN et al., 1990; DELANEY, 1989). Literature data for the aluminum content of seven of the present howardites are indicated in Fig. 8. There is a factor of about ten increase in TL sensitivity for a factor of two increase in Al content, suggesting that it is the amount of eucritic material that determines TL sensitivity.

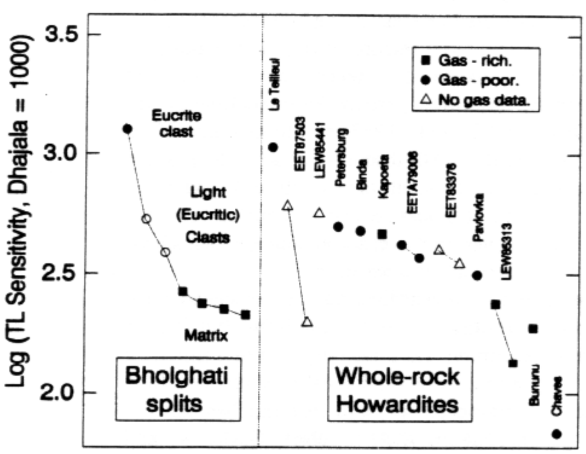

FIG. 7. Thermoluminescence sensitivity of the howardites. Matrix samples from Bholghati have TL sensitivities a factor of about seven lower than that of a eucritic clast, while two 'light' clasts have intermediate values. Unlike chondrite regolith breccias, regolith exposure, as reflected in the abundance of trapped solar gases (SCHULTZ and KRUSE, 1989), does not appear to be important in determining the TL sensitivity of the howardite whole-rock samples. Neither does post-brecciation metamorphism, since Pavlovka and Bununu have very different post-metamorphic brecciation histories (LABOTKA and PAPIKE, 1980).

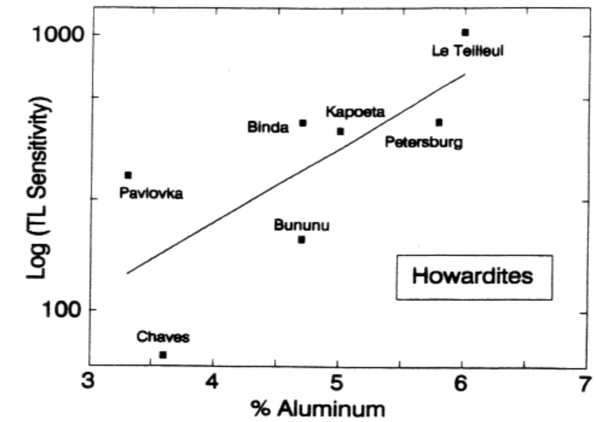

FIG. 8. The TL sensitivity of the howardite whole-rock samples appears to be governed primarily by the proportion of eucritic to diogenitic material, as reflected in the aluminum content (data from MASON, 1967; MCCARTHY et al., 1972; UREY and CRAIG, 1953).

Regolith processing is probably not a major factor in determining the TL sensitivities of the present howardite samples, since there is no relationship between TL sensitivity and solar-gas content; Kapoeta and Bununu are gas-rich, while EET79006, Le Teilleul, Pavlovka, and Petersburg are not (SCHULTZ and KRUSE, 1989).

Brecciation has also affected eucrites, diogenites, and mesosiderites and must be responsible for some of the scatter in our data. However, most of our eucrites are monomict, and clasts have the same composition as the hosts, so that brecciation has relatively little influence on our data for these classes.

Metamorphism of Basaltic Meteorites and Petrologic Classification of Eucrites

Metamorphism has apparently played a major part in determining the TL sensitivities of the eucrites. Juvinas and Pasamonte are among the most studied eucrites; Juvinas is highly equilibrated and Pasamonte is one of the most unequilibrated (REID and BARNARD, 1979; TAKEDA et al., 1983). Juvinas has the higher TL sensitivity by a factor of almost four, well outside the uncertainties on the data which are ≤10%. Mineralogical data for the other eucrites are scarce, but like Juvinas and Nuevo Laredo, EET87548, EET79004, and LEW85303 contain augite exsolution lamellae and are clearly equilibrated eucrites (MASON, 1986, 1989; SCORE et al., 1981). EET87542 and LEW86001 contain a broader range of Ca than normally observed in unequilibrated eucrites (Wo > 35), and augite is mentioned in the description of the former (MASON, 1987, 1989), so we assume these are equilibrated also. ALHA76005 tested our ability to make an equilibrated/unequilibrated assignment. ALHA76005 pyroxenes have a rather restricted range of Wo contents (OLSEN et al., 1978), but REID and LE ROEX (1984) have paired it with ALHA78132 which contains augite exsolution lamellae

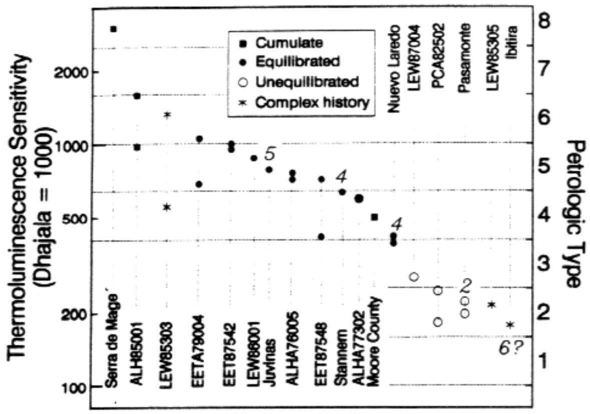

FIG. 9. TL sensitivities for eighteen eucrites with the individual meteorites identified. The sensitivities show a continuous variation over a range of roughly an order of magnitude. LEW85303, LEW85305 and Ibitira have complicated histories, as discussed in the text, and have been given unique symbols. Two of the three cumulate eucrites have especially high TL sensitivities. Petrologic types based on TL sensitivity are indicated on the right-hand axis; types assigned by TAKEDA et al. (1983) on the basis of pyroxene characteristics are indicated by the values placed near the respective data points.

(SCORE et al., 1981). Apparently, ALHA76005 is polymict, consisting of both equilibrated and unequilibrated clasts. Like Pasamonte, LEW87004 and PCA82502 contain a restricted range of Wo (<35) and a wide and, in the case of PCA82502, a 'fairly continuous' range of pyroxene compositions. In LEW87004, the range of pyroxene compositions is more consistent with igneous zoning than exsolution, and we assume these are both unequilibrated eucrites.

Figure 9 shows the range of TL sensitivities observed in the present study, coded according to whether the meteorite is equilibrated, unequilibrated, or a cumulate. The unusual specimens LEW85303, LEW85305, and Ibitira, which have been given unique symbols, appear to have had an unusual thermal history involving shock heating and are discussed below. Our sample of ALHA76005 plots with the equilibrated eucrites and is presumably predominently equilibrated material. The samples show a continuous spread in TL sensitivity, which covers a ~15-fold range, and there is no indication of a hiatus between the unequilibrated and the equilibrated eucrites as noted by REID and BARNARD (1979). Apparently, the eucrites experienced metamorphism in a single continuously varying environment. TAKEDA et al. (1978, 1983) have made essentially the same suggestion. On the basis of pyroxene properties these authors proposed subdivision of the eucrites into six types, and they stressed that these types were analogous to the petrologic types in widespread use with chondrites. We can also use our TL sensitivity data to subdivide the eucrites according to the experienced metamorphism. On the right-hand axis of Fig. 9 we have indicated petrologic types produced by a five-fold division of each decade interval on a logarithmic scale. This mode of division is fairly arbitrary, but its virtue is that our nomenclature is the same as that of TAKEDA et al. (1983). With these divisions, we have agreement in four out of the five cases in which direct comparison between our types and those of TAKEDA et al. (1983) is possible. Five divisions per decade requires eight types to completely cover the range of data observed, with the cumulate Serra de Mage being type 8.

Ibitira was 'tentatively' assigned to type 6 by TAKEDA et al. (1983), but we find that it is type 2, a discrepancy probably related to the unusual history of this eucrite (see later). Moore County plots so far from the other cumulates, which is somewhat surprising since its petrography is so similar (N. Z. BOCTOR, pers. comm.). This may reflect sample heterogeneity of these particularly coarse-grained rocks but deserves further study since our sample mass was quite large. Table 2 is a summary of the TL and petrographic properties of the eight petrologic types for eucrites.

The least equilibrated eucrites have values very similar to those of the Bholghati matrix and low-TL howardites, suggesting that there is a TL sensitivity value for basaltic meteorites typical of parent body surfaces and the associated brecciation processes and that these values may be enhanced by metamorphism or the addition of metamorphosed material. The lunar meteorites MAC87104/MAC87105 also have TL sensitivities just below those of the eucrites (SEARS et al., 1990).

The mechanism for the relationship between TL sensitivity and metamorphism within the eucrites is not yet fully understood. The analogous relationship in ordinary chondrites has been attributed to the devitrification of feldspathic glass in chondrule mesostases (GUIMON et al., 1985; DEHART et al., 1991), but this explanation is less likely for the eucrites. Although glass has been noted in eucrites (DUKE and SILVER, 1967; OLSEN et al., 1978), it is only present in small quantities and not present at all in some eucrites (i.e., the cumulates). Most importantly, cathodoluminescence mosaics of Pasamonte and Juvinas show that the brightening occurs within intact feldspar crystals (BATCHELOR, 1991). The CL intensity is zoned within individual crystals, being brighter at the core. In some cases core and outer regions have different angles of extinction. This suggests that the intensity may be controlled by minor element variations, perhaps Fe quenching or Mn activation. DUKE and SILVER (1967) mentioned, and HARLOW and KLIMENTIDIS (1980) discussed at some length, the clouding of plagioclase as a result of exsolution during metamorphic equilibration. It is possible that a quenching element such as Fe is being sequestered in exsolved grains which allows the feldspar to increase in luminescence.

While it is clear that howardites have experienced post-brecciation metamorphism, it seems doubtful that it is as important in determining TL sensitivity as the amount of eucrite material present. Pavlovka has experienced very little post-brecciation metamorphism, and Bununu has suffered considerable post-brecciation metamorphism (LABOTKA and PAPIKE, 1980). Yet their relative TL sensitivities are within a factor of ~1.7. Metamorphic recrystallization has also been important among the mesosiderites. However, these meteorites are extremely brecciated and coarsely heterogeneous, and the number of factors affecting TL sensitivity is high. In addition to metamorphism there is chemical composition (the A, B, C classes of Hewins, 1988, described previously) and weathering. The meteorites with the lowest TL sensitiv-

Table 2. Metamorphic Classification of Eucritic Meteorites

Pet Type	TL sensivity (Dhajala=1000)	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, LEW85305, PCA82502, 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 - 1000	All zoning has disappeared, exsolution trend dominant.	*Juvinas*, Haraiya, Sioux Co., LEW85303, EETA79004, EET87542, LEW86001, ALHA76005
6	1000 - 1600	Partial to complete inversion of pigeonite to orthopyroxene.	ALH85001
7	1600 - 2500	Partial to complete inversion of pigeonite to orthopyroxene.	---
8	>2500	Partial to complete inversion of pigeonite to orthopyroxene.	Serra de Mage

* Descriptions of types 1-5 from Takeda et al. (1983).
+ Assignments from Takeda et al. (1983) in italics. Assignments based on the present TL data and Takeda et al. petrographic descriptions in italics. Other assignments are based entirely on TL sensitivity.

ities in both class A and B are Antarctic meteorites, and weathering may be responsible for the low values. Despite this, there is a slight suggestion of a trend of increasing TL sensitivity with increasing type 1–3 among the class A mesosiderites (Fig. 6). Morristown is the only sample that is inconsistent with a relationship between type and TL sensitivity. The Hainholz type 4 mesosiderite should have low TL sensitivity because partial melting has destroyed some of the feldspar.

Conditions of Metamorphism

The data in Figs. 2 and 4 suggest that the basaltic meteorites, as the whole-rocks we now observe, have not been heated above 800°C since the feldspar now present in the meteorite crystallized. LEW85303 and the meteorites paired with it are the only exceptions. Terrestrial feldspars in the low (ordered) form have peak temperatures around 100–120°C (BATCHELOR and SEARS, 1989b), while feldspars which are largely in the disordered form have peak temperatures around 200°C (e.g., equilibrated chondrites, VAN SCHMUS and RIBBE, 1968). A detailed study of induced TL peak temperature and ordering as determined by XRD for terrestrial feldspars has been performed by HARTMETZ and SEARS (1987), who found that annealing caused peak temperatures to increase from around 100°C to ≥200°C and was associated with disordering. The detailed relationship between TL sensitivity and disordering is very complicated (e.g., see GUIMON et al., 1985, 1987), but it seems clear that peak temperature and disordering are related. We therefore conclude that, with the exception of LEW85303, all the basaltic meteorites we have examined contain a large proportion of feldspar in the ordered form, as evidenced from the presence of the low-temperature peak.

There is surprisingly little data on the structural state of the feldspar and the thermal histories of eucrites. GAME (1957) argued for a variety of thermal histories for individual grains from Juvinas using optical data for annealed plagioclases, while DUKE (1963) found no XRD evidence for differences in thermal history among the non-cumulate eucrites although he could discriminate between cumulate and non-cumulate eucrites. Most recently, STEELE and SMITH (1976) suggested that the feldspar in Ibitira was in the ordered state. Our present results are entirely consistent with this earlier work, although the induced TL data are apparently better suited to detecting small differences in the structural state of the feldspar than optical and XRD methods.

The thermal histories suggested by the TL peak temperatures are consistent with the petrographic properties of the samples, given the uncertainties in the methods and their different closure temperatures. Based on three-pyroxene thermometry, ISHII et al. (1976) report equilibration temperatures (with uncertainties of around 100°C) of around 1000°C for BINDA and YAMATO 7308 and 930°–972°C for Mount Padbury. However, a comparison of the ISHII et al. (1976) data for chondrites with that of literature data (KRETZ, 1963; McCallum in DODD, 1981; SAXENA, 1976; BUNCH and OLSEN, 1974) suggests that their values are probably too high by 10–15%. Additionally, it is difficult to determine reliable data because of the fineness of the exsolved augite laths. TREIMAN and DRAKE (1985) used recent thermodynamic data for a rare olivine-pyroxene association to determine a closure temperature of 750 ± 20°C for the matrix of the ALHA80102 polymict eucrite, assuming the equilibrium. The exsolution products ('cloudiness') in some eucrite pyroxenes appear to have formed at about 900°C (HARLOW and KLIMENTIDIS, 1980).

Equilibration temperatures determined from oxygen isotopes are shown in Table 3. Five out of seven eucrites and the Yurtuk howardite have equilibration temperatures of 560–975°C, with Pasamonte and Stannern having values of 1108 and 1322°C. The value for the unequilibrated Pasamonte might reflect equilibration following the igneous processes and lack of subsequent equilibration during the any mild metamorphic episode. This might also be the explanation for Stannern, despite the pyroxenes having lost their igneous zoning (BVSP, 1981, p. 225), although TAKEDA et al. (1983) dispute this. CLAYTON et al. (1991) have pointed out oxygen isotopes are slower to equilibrate than Fe and Mg in mafic minerals.

Table 3. Equilibration temperatures for basaltic meteorites calculated from oxygen isotope data for feldspar-pyroxene pairs.

Meteorite	Ref.*	Temp. (°C)
Eucrites		
Ibitira	2	975
Ibitira	2	938
Juvinas	1	560
Juvinas	2	771
Juvinas	2	874
Moore Co.	1	601
Nuevo Laredo	1	855
Pasamonte	1	1108
Serra de Mage	1	771
Stannern	1	1322
Howardite		
Yurtuk	2	819
Mesosiderites		
Crab Orchard	1	1680
Crab Orchard	2	1274
Estherville	2	1144

* References for oxygen isotope data are (1) Taylor et al. (1965), (2) Clayton et al. (1976). The relationship:

$$1000\ln\left(\frac{1 + d_{An}/1000}{1 + d_{Di}/1000}\right) = -0.76\times10^{6}T^{-2}$$

(Chiba et al., 1989) was used to calculate equilibration temperatures. Two sigma uncertainties for the calculated temperatures are probably about ±200°C.

The oxygen isotope equilibration temperatures for the mesosiderites are higher than the <800°C value inferred from the TL data, even allowing for the probable 2 sigma uncertainty in the oxygen palaeotemperatures of ±200°C (CLAYTON and MAYEDA, 1989). The cooling rates of mesosiderites determined from central Ni-dimension relationships in the taenite are around 0.1 K/Ma (POWELL, 1969), and the metal in mesosiderites must also have continued to equilibrate down to about 400°C. The extremely slow metallographic cooling rates have been well discussed (POWELL, 1971; WOOD, 1985), especially in view of the rapid cooling following the igneous event suggested by the co-existence of silicate and metal. Most authors assume that the rapid post-igneous cooling was followed by insulation by a thick dusty regolith. On the other hand, fission-track data for the mesosiderites are inconsistent with the very slow metallographic cooling rates (CROZAZ and TASKER, 1981). The lack of a 200°C TL peak, and our interpretation of TL peak temperatures cited earlier, would be consistent with a very slow cooling in the stability field of low-temperature feldspar compared to the eucrites. To this extent, the TL data and metallographic data indicate that mesosiderites suffered prolonged annealing at low temperatures. Unfortunately, like the CROZAZ and TASKER (1981) fission-track data, the induced TL data do not allow quantitative cooling rate estimates. It is possible that the high oxygen isotope temperatures of the mesosiderites reflect the high-temperature rapid cooling phase and not any subsequent prolonged low-temperature annealing.

It is also of interest to examine the data for the cumulate eucrites, in which a very slow post-igneous cooling rate has been suggested (approximately 6 K/Ma, 1600 to 1000°C in 100 Ma; TERA et al., 1987; WARREN et al., 1989). One of the cumulate eucrites in our study (ALH85001) has similar TL properties to the mesosiderites, i.e., no detectable peak at 200°C, which would be consistent with very slow cooling at temperatures < 800°C. Particularly high TL sensitivities of two of the three cumulates might also be an indication of prolonged metamorphism. However, our data are equivocal in that both Serra de Mage and Moore County have young crystallization ages (LUGMAIR et al., 1977; TERA et al., 1987), yet they differ by a factor of six in TL sensitivity. Their primary igneous textures are evidence that the cumulate eucrites did not suffer retrograde metamorphism, yet their TL data indicates that the feldspar in the cumulates is similar to that of the most equilibrated eucrites. Presumably, their slow cooling rates permitted considerable autometamorphism, so their TL sensitivities may reflect cooling rates rather than duration of (essentially isothermal) metamorphism.

Calculations based on the homogenization of eucrite pyroxenes at 1000°C and a regolith thermal model led MIYAMOTO et al. (1985) to suggest burial depths for equilibrated eucrites of 150 m and <50 m for the unequilibrated eucrites. Using the same model, our value of <800°C for the equilibration temperature yields >350 m depths. The value for unequilibrated eucrites is unchanged. This result is consistent with other data assuming that the basaltic meteorite parent body was a large differentiated asteroid. HOUSEN et al. (1979) developed a numerical model for regolith formation and found that large (≫10 km) strong asteroids (internal strength comparable to basalt) could produce regolith a few kilometers in depth, while this was not true of small <10 km objects of comparable strength. Weak 1–10 km asteroids, consisting predominantly of regolith-like material, could also maintain regoliths, but only a few meters in depth. CRUIKSHANK et al. (1990) argue that three basaltic earth-approaching asteroids may be crustal fragments of the same Vesta-like object and the parent bodies of the basaltic meteorites. Their arguments were based on compositional and time-of-fall data, and these asteroids currently have diameters of 1.2, 1.0, and 3.4 km.

The metamorphism experienced by the basaltic meteorites could have resulted from large-scale bombardment at 3.6–3.7 Ga and the generation of a deep regolith and regolith metamorphism (BOGARD and GARRISON, 1989). In this case, the depths of the regoliths are particularly noteworthy. Alternatively, if the metamorphism occurred earlier, for example autometamorphism following the igneous event recorded by the crystallization ages, then the 3.5–3.7 Ga event did not produce temperatures greater than 800°C. On the basis of data from separated clasts in howardites (BATCHELOR and SEARS, 1990b), we think the former possibility is more likely. Stepwise heating experiments indicate that temperatures of the order of 800°C are required for Ar-loss in the laboratory (see HAQ et al., 1988 for a discussion), but longer duration heating in an asteroid regolith would bring this number down. For example, assuming a thermal diffusivity of 0.004, similar activation energies for loss of Ar from the present meteorites and shergottites, and a burial depth of >350 m, temperatures of <400°C are required to drive off 95% of the Ar (Fig. 3 of BOGARD et al., 1979).

Shock and Related Processes

Our annealing experiments show that the unusual peak temperature for LEW85303 is most readily interpreted as being due to heating to ≥1000°C. This heating must have been subsequent to the metamorphism that caused exsolution and raised the TL sensitivity above the presumed precursor values seen in the unequilibrated eucrites. Ibitira and LEW85305 show lower TL sensitivities than would be expected from the metamorphic history suggested by petrographic data, and these values might also reflect a history involving intense shock. Experiments with terrestrial feldspars and chondritic meteorites show that shock at pressures >27 GPa can cause a 10- to 100-fold decrease in TL sensitivity; the most likely mechanisms for this decrease involve the conversion of feldspar to maskelynite and/or glass (HARTMETZ et al., 1986; SEARS et al., 1984). However, from the TL peak temperatures for Ibitira and LEW85305 we infer equilibration <800°C (and the probable presence of ordered feldspar).

From the unaltered texture of the pyroxene, but mosaicism and X-ray diffraction evidence for partial ordering of the plagioclase, STEELE and SMITH (1976) have shown that Ibitira has been shocked to about 30 GPa and subsequently annealed. The similarity in mineral compositions and texture between Ibitira and LEW85305 was mentioned by MASON (1986), and DELANEY (1987) infers a somewhat similar history for LEW85305 to that of Ibitira from the presence of SiO_2-rich veins and homogeneous plagioclase. Plagioclase is notoriously resistant to metamorphic homogenization, but the laboratory experiments of OSTERTAG and STOEFFLER (1982) have shown that shocked feldspar readily recrystallizes, and presumably homogenizes, upon subsequent annealing. LEW85303 also has petrographic evidence of intense shock (minerals heavily cracked, augite lamellae 'flexed and faulted', plagioclase with patchy extinction, some masekelynite), but with heterogeneous plagioclase (HEWINS, 1990; R. HEWINS, pers. comm.; KOZUL and HEWINS, 1988a, 1988b, 1989). The petrographic data are therefore consistent with the TL data in indicating a post-crystallization history involving metamorphism and shock for LEW85303, but without the post-shock annealing of Ibitira and LEW85305.

The existence of carbonaceous clasts in LEW85303 is especially significant in view of its shock history. It is not clear at present whether these clasts are hydrated. Hydrated material clearly could not have withstood temperatures as high as 1000°C, and one would have to assume that brecciation post-dated the shock-heating event. Isotopic data also indicate a history of multiple disturbances for LEW85302 (which is paired with LEW85303), probably at 3.5 and 1 AE ago (BOGARD and GARRISON, 1989; NYQUIST et al., 1990).

In summary, Ibitira, LEW85303, and LEW85305 are three eucrites that appear to have experienced intense post-metamorphic shock events, but LEW85303 differs from the others in that post-shock annealing was not significant. The high TL sensitivity of LEW85303, relative to that of Ibitira and LEW85305, suggests that it also experienced much lower peak shock-pressures.

CONCLUSIONS

The different bulk compositions of basaltic meteorites, which reflect igneous and brecciation processes, are responsible for large-scale variations in TL sensitivity. Thus it has been possible to classify two previously unclassified mesosiderites, LEW87006 and EET87500, as class A and B, respectively. There is no indication that regolith maturity as determined from solar gas content or that post-brecciation metamorphism is important in determining the TL sensitivity of the howardites. Rather, mixing of eucritic and diogenite material is the major factor. However, the eucrites have a continuous range of TL sensitivities which probably reflects the enhancement in the TL sensitivity of feldspar during metamorphism, perhaps by the loss of Fe and formation of exsolution products. Petrologic-type assignments for the eucrites based on TL data and petrographic evidence are suggested. There is a slight suggestion of TL sensitivity varying systematically with metamorphism in the class A mesosiderites.

The TL data provide evidence that metamorphic equilibration temperatures for feldspar in basaltic meteorites after igneous processing were ≤800°C. This is consistent with palaeotemperature estimates based on elemental and oxygen isotope exchange between mineral pairs. Assuming that this temperature was typical of metamorphic conditions, the thermal model of MIYAMOTO et al. (1985) suggests a burial depth of >350 m for the equilibrated eucrites compared to <50 m for the unequilibrated eucrites. Metamorphism may have resulted either from the major Ar degassing event 3.6–3.7 Ga ago, or because that event did not involve temperatures above 800°C. The first possibility seems more likely. Peak shape considerations lead us to argue that the mesosiderites and the cumulate eucrites cooled particularly slowly, consistent with metallographic and radiogenic data, respectively.

An exceptional meteorite is LEW85303 (and the meteorites paired with it: LEW85300, LEW85302, and LEW88005) which has been heated to >1000°C. Petrographic and radiogenic data suggest that this heating event may have been shock-related. Ibitira and LEW85305 have also been shocked but have subsequently been annealed below 800°C.

Acknowledgments—We gratefully acknowledge the donors of the meteorites listed in Table 1 for supplying the samples for study, N. Z. Boctor, A. Reid, and J. S. Delaney for very helpful reviews, R. Hewins and L. Nyquist for discussions, and Ted Beeler, Ben Myers, Hazel Sears, Joyce Roth, Monty Steele, and Raye Stucker for technical assistance. This work is supported by NASA grant NAG 9-81.

Editorial handling: R. A. Schmitt

REFERENCES

AKBER R. A. and PRESCOTT J. R. (1987) Thermoluminescence dating: Can we date all types of feldspar? In *Archaeometry: Further Australian Studies* (eds. W. R. AMBROSE and J. M. J. MUMERY), p. 177. Austral. Nat. Univ.

BVSP (1981) *Basaltic Volcanism Study Project*. Lunar and Planetary Institute.

BATCHELOR J. D. (1991) Cathodoluminescence of equilibrated and unequilibrated eucrites and the discovery of multiple silica populations. *Lunar Planet. Sci. XXII*, 61–62.

BATCHELOR J. D. and SEARS D. W. G. (1989a) Metamorphism, brecciation and shock of the eucrite association meteorites: A study by thermoluminescence techniques. *Meteoritics* **24**, 250.

BATCHELOR J. D. and SEARS D. W. G. (1989b) Thermoluminescence of plagioclase feldspars and implications for meteorite studies. *Lunar Planet. Sci. XX*, 52–53.

BATCHELOR J. D. and SEARS D. W. G. (1990a) The metamorphic, shock and brecciation history of eucrite association meteorites. *Lunar Planet. Sci. XXI*, 54–55.

BATCHELOR J. D. and SEARS D. W. G. (1990b) Metamorphism on the HED parent body. Presented at the 53rd Ann. Mtg. Meteor. Soc., Perth, 17–21 September 1990.

BIRCK J. L. and ALLÈGRE C. J. (1978) Chronology and secondary history of the parent body of basaltic achondrites studied by the ^{87}Rb-^{87}Sr method. *Earth Planet. Sci. Lett.* **39**, 37–51.

BOGARD D. D. and GARRISON D. H. (1989) ^{39}Ar-^{40}Ar ages of eucrites: Did the HED parent body experience a long period of thermal events due to major impacts? *Lunar Planet. Sci. XX*, 90–91.

BOGARD D. D., HUSAIN L., and NYQUIST L. E. (1979) ^{40}Ar-^{39}Ar age for the Shergotty achondrite and implications for its post-shock thermal history. *Geochim. Cosmochim. Acta* **43**, 1047–1055.

BUCHANAN P. C., REID A. M., and SCHWARZ C. (1990) Clast populations in three Antarctic achondrites. *Lunar Planet. Sci. XXI*, 141–142.

BUNCH T. E. (1975) Petrography and petrology of basaltic achondrite polymict breccias (howardites). *Proc. 6th Lunar Sci. Conf.*, pp. 469–492.

BUNCH T. E. and OLSEN E. (1974) Restudy of pyroxene-pyroxene equilibration temperatures for ordinary chondrite meteorites. *Contrib. Mineral. Petrol.* **43**, 83–90.

CHIBA H., CHACKO T., CLAYTON R. N., and GOLDSMITH J. R. (1989) Oxygen isotope fractionations involving diopside, forsterite, magnetite, and calcite: Application to geothermometry. *Geochim. Cosmochim. Acta*, **53**, 2985–2995.

CHOU C-L., BOYNTON W. V., RILD R. W., KIMBERLIN J., and WASSON J. T. (1976) Trace element evidence regarding a chondritic component in howardite meteorites. *Proc. 7th Lunar Sci. Conf.*, 3501–3518.

CLARKE R. S. and MASON B. (1982) A new metal-rich mesosiderite from Antarctica, RKPA79015. *Mem. NIPR, Spec. Issue 25*, 78–85.

CLAYTON R. N. and MAYEDA T. K. (1978) Genetic relations between iron and stony-iron meteorites. *Earth Planet. Sci. Lett.* **40**, 168–174.

CLAYTON R. N. and MAYEDA T. K. (1989) Oxygen isotopic composition of LEW86010. *Meteoritics* **24**, 259.

CLAYTON R. N., ONUMA N., and MAYEDA T. K. (1976) A classification of meteorites based on oxygen isotopes. *Earth Planet. Sci. Lett.* **30**, 10–18.

CLAYTON R. N., MAYEDA T. K., GOSWAMI J. N., and OLSEN E. J. (1991) Oxygen isotope studies of ordinary chondrites. *Geochim. Cosmochim. Acta* **55**, 2317–2337.

CROZAZ G. and TASKER D. R. (1981) Thermal history of mesosiderites revisited. *Geochim. Cosmochim. Acta* **45**, 2037–2046.

CRUIKSHANK D. P., THOLEN D. J., HARTMANN W. K., BELL J. F., and BROWN R. H. (1990) Three basaltic earth-crossing asteroids and the course of the basaltic meteorites. *Icarus* **89**, 1–13.

DEHART J. M., LOFGREN G. E., and SEARS D. W. G. (1991) Chemical and physical studies of chondrites—X: Cathodoluminescence studies of metamorphism and nebular processes in type 3 ordinary chondrites. *Geochim. Cosmochim. Acta* (submitted).

DELANEY J. S. (1987) The Lewis Cliff 85305 eucrite, and shock effects in eucrites. *Meteoritics* **22**, 365–366.

DELANEY J. S. (1989) The relationship between the Lewis Cliff basaltic achondrites (1985, 1986 and 1987 series) and other polymict achondrites. *Lunar Planet. Sci. XX*, 236–237.

DELANEY J. S., TAKEDA H., PRINZ M., NEHRU C. E., and HARLOW G. E. (1983) The nomenclature of polymict basaltic achondrites. *Meteoritics* **18**, 103–111.

DESNOYERS C. and JEROME D. Y. (1977) The Malvern howardite: A petrological and chemical discussion. *Geochim. Cosmochim. Acta* **41**, 81–86.

DODD R. T. (1981) *Meteorites*. Cambridge Univ. Press.

DUKE M. B. (1963) Petrology of the basaltic achondrite meteorites. Ph.D. thesis, California Institute of Technology, California.

DUKE M. B. and SILVER L. T. (1967) Petrology of eucrites, howardites, and mesosiderites. *Geochim. Cosmochim. Acta* **31**, 1637–1665.

DYMEK R. G., ALBEE A. L., CHODOS A. A., and WASSERBURG G. J. (1976) Petrography of isotopically dated clasts in Kapoeta howardite and petrologic constraints and the evolution of its parent body. *Geochim. Cosmochim. Acta* **40**, 1115–1130.

FLORAN R. J. (1978) Silicate petrography, classification, and the origin of the mesosiderites: Review and new observations. *Proc. 9th Lunar Planet. Sci. Conf.*, 1053–1081.

GAME P. M. (1957) Plagioclases from the Juvinas meteorite and from allivalite from the Isle of Rhum. *Mineral. Mag.* **31**, 656–671.

GUIMON R. K., KECK B. D., WEEKS K. S., DEHART J., and SEARS D. W. G. (1985) Chemical and physical studies of type 3 chondrites—IV: Annealing studies of a type 3.4 ordinary chondrite and the metamorphic history of meteorites. *Geochim. Cosmochim. Acta* **49**, 1515–1524.

GUIMON R. K., LOFGREN G. E., and SEARS D. W. G. (1987) Chemical and physical studies of type 3 chondrites IX: Thermoluminescence and hydrothermal annealing experiments and their relationship to metamorphism and aqueous alteration in type <3.3 ordinary chondrites. *Geochim. Cosmochim. Acta* **52**, 119–127.

HAQ M., HASAN F. A., and SEARS D. W. G. (1988) Thermoluminescence and the shock and reheating history of meteorites—IV: The induced TL properties of type 4–6 ordinary chondrites. *Geochim. Cosmochim. Acta* **52**, 1679–1689.

HAQ M., HASAN F. A., SEARS D. W. G., MOORE C. B., and LEWIS C. F. (1989) Thermoluminescence and the origin of the dark matrix of Fayetteville and similar meteorites. *Geochim. Cosmochim. Acta* **53**, 1435–1440.

HARLOW G. E. and KLIMENTIDIS R. (1980) Clouding of pyroxene and plagioclase in eucrites: Implications for post-crystallization processing. *Proc. 11th Lunar Planet. Sci. Conf.*, 1131–1143.

HARTMETZ C. P. and SEARS D. W. G. (1987) Thermoluminescence and X-ray diffraction studies of annealed oligoclase. *Lunar Planet. Sci. XVIII*, 397–398.

HARTMETZ C., OSTERTAG R., and SEARS D. W. G. (1986) A thermoluminescence study of experimentally shock-loaded oligoclase and bytownite. *Proc. 17th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **91**, E263–274.

HASAN F. A., HAQ M., and SEARS D. W. G. (1986) Thermoluminescence and the shock and reheating history of meteorites—III: The shergottites. *Geochim. Cosmochim. Acta* **50**, 1031–1038.

HEWINS R. H. (1984) The case for a melt matrix in the plagioclase-Poik mesosiderites. *Proc. 15th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **89**, C289–297.

HEWINS R. H. (1985) Petrologic data for Antarctic mesosiderites. *Lunar Planet. Sci. XVI*, 343–344.

HEWINS R. H. (1988) Petrology and pairing of mesosiderites from Victoria Land, Antarctica. *Meteoritics* **23**, 123–129, 385.

HEWINS R. H. (1990) Geologic history of LEW85300, 85302, and 85303 polymict eucrites. *Lunar Planet. Sci. XXI*, 509–510.

HOUSEN K. R., WILKENING L. L., CHAPMAN C. R., and GREENBERG R. (1979) Asteroidal regoliths. *Icarus* **39**, 317–351.

ISHII T., MIYAMOTO M., and TAKEDA H. (1976) Pyroxene geothermometry and crystallization, subsolidus equilibration temperatures of lunar and achondritic pyroxenes. *Lunar Planet. Sci. VII*, pp. 409–410. Lunar and Planetary Institute.

JACOBSON S. B. and WASSERBURG G. J. (1984) Sm-Nd isotopic evolution of chondrites and achondrites, II. *Earth Planet. Sci. Lett.* **67**, 137–150.

KECK B. D. and SEARS D. W. G. (1987) Chemical and physical studies of type 3 chondrites, VIII: The CO chondrites. *Geochim. Cosmochim. Acta* **51**, 3013–3022.

KOZUL J. and HEWINS R. H. (1988a) LEW85300, 02, 03 polymict eucrite consortium—I: Petrology of igneous clasts. *Lunar Planet. Sci. XIX*, 645–646.

KOZUL J. and HEWINS R. H. (1988b) Polymict eucrite consortium—II: Breccia clasts, CM inclusion, glassy matrix and assembly history. *Lunar Planet. Sci. XIX*, 647–648.

KOZUL J. M. and HEWINS R. H. (1989) Fayalite-bearing eucrites and the origins of HED magmas. *Meteoritics* **24**, 289.

KRETZ R. (1963) Distribution of magnesium and iron between orthopyroxene and calcic pyroxene in natural mineral assemblages. *J. Geol.* **71**, 773–785.

LABOTKA T. C. and PAPIKE J. J. (1980) Howardites: Samples of the regolith of the eucrite parent-body: Petrology of Frankfort, Pavlovka, Yurtuk, Malvern and ALHA77302. *Proc. 11th Lunar Planet. Sci. Conf.*, 1103–1130.

LUGMAIR G. W., SCHEININ N. B., and CARLSON R. W. (1977) Sm-Nd systematics of the Serra de Mage eucrite. *Meteoritics* **12**, 300–301.

MACDOUGALL D., RAJAN R. S., and PRICE P. B. (1973) Gas-rich meteorites: Possible evidence for origin on a regolith. *Science* **183**, 73–74.

MASON B. (1967) The Bununu meteorite, and a discussion of the pyroxene-plagioclase achondrites. *Geochim. Cosmochim. Acta* **31**, 107–115.

MASON B. (1986) *Antarctic Meteorite Newsletter*, 9(3), 19–20.

MASON B. (1987) *Antarctic Meteorite Newsletter*, 10(2).

MASON B. (1989) *Antarctic Meteorite Newsletter*, 12(1), 14.

MCCARTHY T. S., AHRENS L. H., and ERLANK A. J. (1972) Further evidence in support of the mixing model for howardite origin. *Earth Planet. Sci. Lett.* **15**, 86–93.

MCCARTHY T. S., ERLANK A. J., and WILLIS J. P. (1973) On the origin of eucrites and diogenites. *Earth Planet. Sci. Lett.* **18**, 433–442.

MCKEEVER S. W. S. (1985) *Thermoluminescence of Solids*. Cambridge Univ. Press.

MIYAMOTO M., DUKE M. B., and MCKAY D. S. (1985) Chemical zoning and homogenization of Pasamonte-type pyroxene and their bearing on thermal metamorphism of a howardite parent body. *Proc. 15th Lunar Planet. Sci. Conf; J. Geophys. Res.* **90**, C629–635.

MURTHY V. R., COSCIO M. R., and SABELIN T. (1977) Rubidium-strontium internal isochron and the initial strontium-87/strontium-86 ratio for the Estherville mesosiderite. *Proc. 8th Lunar Sci. Conf.*, 177–186.

NYQUIST L. E., BAUSAL B. M., SHIH C.-Y., WIESMANN H., WOODEN J. L., and TAKEDA H. (1985) Rb-Sr and Sm-Nd internal isochron ages of a subophitic basalt clast from the Y75011 eucrite (Abstr.). *NIPR Symp. Antarctic Meteor. 10th*, 155–157.

NYQUIST L. E., TAKEDA H., BANSAL B. M., SHIH C.-Y., WEISSMANN H., and WOODEN J. L. (1986) Rb-Sr, Sm-Nd isochron ages of a subophitic basalt clast and a matrix sample from the Y75011 eucrite. *J. Geophys. Res.* **91**, 8137–8150.

NYQUIST L. E., BOGARD D. D., BANSAL B. M., WIESMANN H., and SHIH C.-Y. (1990) Ar-Ar, Rb-Sr, Sm-Nd studies of eucritic clast LEW85300, 55. *Lunar Planet. Sci. XXI*, 903–904.

OLSEN E. J., NOONAN A., FREDRIKSSON K., JAROSEWICH E., and MORELAND G. (1978) Eleven new meteorites from Antarctica, 1976–77. *Meteoritics* **13**, 209–225.

OSTERTAG R. and STOEFFLER D. (1982) Thermal annealing of experimentally shocked feldspar crystals. *Proc. 13th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **87**, A457–A463.

POWELL B. N. (1969) Petrology and chemistry of mesosiderites—I. Textures and composition of nickel-iron. *Geochim. Cosmochim. Acta* **33**, 789–810.

POWELL B. N. (1971) Petrology and chemistry of mesosiderites—II. Silicate textures and compositions and metal-silicate relationships. *Geochim. Cosmochim. Acta* **35**, 5–34.

PRINZ M., NEHRU C. E., and DELANEY J. S. (1982) Reckling Peak A79015: An unusual mesosiderite. *Lunar Planet. Sci. XIII*, 631–632.

REID A. M. and BARNARD B. M. (1979) Unequilibrated and equilibrated eucrites. *Lunar Planet. Sci. X*, 1019–1022.

REID A. M. and BUCHANAN P. (1989) The Bholghati howardite: Petrography and mineral chemistry. *Lunar Planet. Sci. XX*, 892–893.

REID A. M. and LEROEX A. P. (1984) Compositions of 7 Allan Hills polymict eucrites and one diogenite. *Meteoritics* **19**, 299.

ROWE M. W. (1970) Evidence for decay of extinct ^{244}Pu and ^{129}I in the Kapoeta howardite. *Geochim. Cosmochim. Acta* **34**, 1019–1025.

SAXENA S. K. (1976) Two pyroxene geothermometer: A model with an approximate solution. *Amer. Mineral.* **61**, 643–652.

SCHULTZ L. and KRUSE H. (1989) Helium, neon, and argon in meteorites—A data compilation. *Meteoritics* **24**, 155–172.

SCORE R., SCHWARZ C. M., KING T. V. V., MASON B., BOGARD D. D., and GABEL E. M. (1981) Antarctic meteorite descriptions, 1976-1977-1978-1979. *Antarctic Meteorite Newsletter* **4**, i-144.

SEARS D. W. (1980) Thermoluminescence of meteorites: Relationship with their K-Ar age and their shock and reheating history. *Icarus* **44**, 190–206.

SEARS D. W. G. and SEARS H. (1990) National thermoluminescence data for Antarctic meteorites. *Antarctic Meteorite Newsletter* **13**, 26.

SEARS D. W. G., GROSSMAN J. N., MELCHER C. L., ROSS L. M., and MILLS A. A. (1980) Measuring the metamorphic history of unequilibrated ordinary chondrites. *Nature* **287**, 791–795.

SEARS D. W. G., GROSSMAN J. N., and MELCHER C. L. (1982) Chemical and physical studies of type 3 chondrites—I: Metamorphism-related studies of Antarctic and other type 3 ordinary chondrites. *Geochim. Cosmochim. Acta* **46**, 2471–2481.

SEARS D. W. G., ASHWORTH J. R., BEVAN A., and BROADBENT C. P. (1984) Studies of an artificially shock-loaded H group chondrite. *Geochim. Cosmochim. Acta* **48**, 343–360.

SEARS D. W. G., DEHART J. M., HASAN F. A., and LOFGREN G. E. (1989) Induced thermoluminescence and cathodoluminescence studies of meteorites: Relevance to structure and active sites in feldspar. In *Spectroscopic Characterization of Minerals and their Surfaces; Symposium Series 415* (eds. L. M. COYNE et al.), pp. 190–222. American Chemical Society.

SEARS D. W. G., SEARS H., and MYERS B. M. (1990) The natural

TL survey of the 1987/1988 Antarctic meteorite collections: Pairing, an unusual carbonaceous chondrite group and the lunar meteorites. *Lunar Planet. Sci. XXI*, 1121–1122.

STEELE I. M. and SMITH J. V. (1976) Mineralogy of the Ibitira eucrite and comparison with other eucrites and lunar samples. *Earth Planet. Sci. Lett.* **33**, 67–78.

STOLPER E. (1977) Experimental petrology of eucritic meteorites. *Geochim. Cosmochim. Acta* **41**, 587–611.

SUESS H. E., WAENKE H., and WLOTZKA F. (1964) On the origin of gas-rich meteorites. *Geochim. Cosmochim. Acta* **28**, 209–233.

TAKEDA H., MIYAMOTO M., DUKE M. B., and ISHII T. (1978) Crystallization of pyroxenes in lunar KREEP basalt 15386 and meteoritic basalts. *Proc. 9th Lunar Planet. Sci. Conf.*, 1157–1171.

TAKEDA H., MORI H., DELANEY J. S., PRINZ M., HARLOW G. E., and ISHII T. (1983) Mineralogical comparison of Antarctic and non-Antarctic HED (Howardites-Eucrites-Diogenites) achondrites. *Mem. NIPR, Spec. Issue 30*, 181–205.

TAYLOR H. P., DUKE M. B., SILVER L. T., and EPSTEIN S. (1965) Oxygen isotope studies of minerals in stony meteorites. *Geochim. Cosmochim. Acta* **29**, 489–512.

TERA F., CARLSON R. W. and BOCTOR N. Z. (1987) Just how old are cumulate eucrites? *Meteoritics* **22**, 513–514.

TREIMAN A. H. and DRAKE M. J. (1985) Basaltic volcanism on the eucrite parent body: Petrology and chemistry of the polymict eucrite ALHA80102. *Proc. 15th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **90**, C619–628.

UREY H. C. and CRAIG H. (1953) The composition of the stone meteorites and the origin of the meteorites. *Geochim. Cosmochim. Acta* **4**, 36–82.

VAN SCHMUS W. R. and RIBBE P. H. (1968) The composition and structural state of feldspar from chondritic meteorites. *Geochim. Cosmochim. Acta* **32**, 1327–1342.

WARREN P. H., HAACK H., and RASMUSSEN K. L. (1989) Effects of megaregolith insulation on Sm-Nd cooling ages of deep-crustal cumulates from the moon and large asteroids. *Lunar Planet. Sci. XX*, 1179–1180.

WILKENING L. L. (1973) Foreign inclusions in stony meteorites—I. Carbonaceous chondritic xenoliths in the Kapoeta howardite. *Geochim. Cosmochim. Acta* **37**, 1985–1989.

WILKENING L. L., LAL D., and REID A. M. (1971) The evolution of the Kapoeta howardite based on fossil track studies. *Earth Planet. Sci. Lett.* **10**, 334–340.

WOOD J. A. (1985) Meteoritic constraints on processes in the solar nebula. In *Protostars and Planets II* (eds. D. C. BLACK and M. S. MATTHEWS), pp. 687–702. Univ. Ariz. Press.