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The natural thermoluminescence of meteorites: III. Lunar and basaltic meteorites*

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Abstract—Natural thermoluminescence (TL) data have been obtained for the lunar meteorite MacAlpine Hills 88104/5 and for 65 eucrites, howardites, diogenites, and mesosiderites in order to investigate their recent thermal and radiation histories. All these meteorites have low levels of natural TL compared to chondrites, which is primarily because they display "anomalous fading" (i.e., fading by non-classical mechanisms). However, some have especially low natural TL (<5 krad at 250°C in the glow curve) which cannot be attributed to anomalous fading or thermal fading over especially large terrestrial ages, and which must reflect heating within the last 10^5–10^6 y. In some cases, this heating may have been associated with shock (e.g., LEW85303) or regolith processes (Kapoeta), but in most cases (Bununu, Lowicz, the diogenites ALHA77256, ALHA84001, EET79002, and maybe others) solar heating at perihelia <0.8 AU may be responsible for the low TL values. The fraction of basaltic meteorites thought to have had small perihelia (about 20%) is comparable to the fraction of chondrites with low natural TL and to the fraction of observed falls and fireballs with small perihelia. This may imply ejection from the asteroid belt via similar mechanisms. Assuming plausible values for cosmic ray dose rate, and that the natural TL of MAC88104/5 was totally drained by ejection from the moon, the parameters for TL decay determined in the present study suggest that the Moon-Earth transit times for MAC88104 and MAC88105 were 2,000 and 1,800 y, respectively, compared with 19,000 and 2,500 y for Y791197 and ALHA81005, respectively. Although they are clearly not paired, the possibility that MAC88104/5 and ALHA81005 were ejected from the moon by the same event should be considered, since diverse rock types are found in close proximity on the lunar surface. The natural TL data confirm most previous published pairings among basaltic meteorites and suggest others.

INTRODUCTION

THERE IS STRONG elemental and isotopic evidence that 11 Antarctic meteorites (8 considering pairing) originated on the Moon. Seven of them, ALHA81005, Y791197, Y82192 (paired with Y82193 and Y86032), and MAC88104 (paired with MAC88105), are probably samples of the lunar farside highlands; EET87521, Y793169, and Asuka-31 are samples from the lunar maria, while Y793274 is a mixture of mare and nonmare material (GRL, 1983; NIPR, 1986, 1987, 1990; WARREN and KALLEMEYN, 1989; DELANEY, 1989). The howardites, eucrites, and diogenites (which we will refer to as "basaltic meteorites" since they are either basalts or basalt-related) have suffered somewhat similar igneous, brecciation, regolith, and metamorphic histories to those of the lunar samples (e.g., BVSP, 1981). Mesosiderites have experienced similar igneous histories, and we will include them in this group, although their ubiquitous metal phase distinguishes them from the others. The basaltic meteorites differ from lunar samples, however, in the cosmochemically important Fe/Mn ratio (meteorites, 30; lunar samples, 80; LAUL and SCHMITT, 1973), oxygen isotopes (CLAYTON et al., 1976), and in their composition prior to igneous differentiation (MCSWEEN, 1989). Spectral reflectivity data, time-of-fall data, and geochemical modelling indicate a close relationship between basaltic meteorites and basaltic asteroids, some of which are still in Earth-approaching orbits (MCCORD et al., 1970; CONSOLMAGNO and DRAKE, 1977; CRUIKSHANK et al., 1991). Time-of-fall data have been used to argue that, unlike chondrites, basaltic meteorites originated in the inner fringes of the asteroid belt, although this has been questioned (WETHERILL, 1968, 1987; GREENBERG and NOLAN, 1990).

Lunar samples and basaltic meteorites are the result of igneous differentiation approximately 4.5 Ga ago (BVSP, 1981), and subsequently both suffered major gas loss, 3.9 Ga ago for the lunar meteorites (EUGSTER, 1989) and 3.0–4.4 Ga ago for the basaltic meteorites (BOGARD and GARRISON, 1989). They are also usually brecciated, often with a wide variety of components. The cosmic ray exposure for the meteorites occurred in 4π geometry for 4–40 Ma, although a few have larger cosmic ray exposure ages (AYLMER et al., 1988). In contrast, except for Y82192 and samples paired with it, lunar meteorites received significant exposure on the lunar surface in 2π geometry for 460–910 Ma (EUGSTER, 1989). $4\ \pi$ irradiation for these lunar meteorites would have occurred during Moon-Earth transit and appears to have lasted <0.5 Ma. Yamato 82192 and its pairs had little exposure on the lunar surface but a 5–11 Ma exposure in space (EUGSTER, 1989). Most lunar meteorites, and many basaltic meteorites, were found in Antarctica and have terrestrial ages ranging from 0.08 Ma (Y82192 and its pairs) to 0.1–0.43 Ma (MAC88104/5; EUGSTER, 1989; NISHIIZUMI et al., 1989; 1991; EUGSTER et al., 1991; VOGT et al., 1991).

The natural thermoluminescence level of a meteorite is determined by competition between build-up, during exposure to ionizing radiations, and decay due to thermal or so-called anomalous processes. In principle, natural TL measurements can provide information on cosmic ray exposure, orbit and terrestrial age (e.g., SEARS and HASAN, 1986).

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* This paper is part of a consortium study of the largest lunar meteorite MAC88104/5.

Thermal decay is the major mode of TL decay in ordinary chondrites. It can be described by an Arrhenius equation. Lifetimes for the TL at 250°C in the glow curve are comparable to the terrestrial ages of Antarctic meteorites, while the lifetime of the TL at 400°C in the glow curve is $>10^8$ *years* (MCKEEVER, 1980). The main thermoluminescent carrier in the basaltic meteorites is Ca-rich feldspar, and similar feldspars in terrestrial igneous rocks often display "anomalous fading." *Anomalous fading is a loss of natural TL which occurs at room temperature on the timescale of weeks, even at the highest glow curve temperatures* (GARLICK and ROBINSON, 1972; WINTLE, 1973; HASAN et al., 1986; MCKEEVER, 1985). Natural TL properties should be distinguished from induced TL properties, which are a reflection of the amount and nature of the mineral phases producing the thermoluminescence. The induced properties are therefore of value in studying metamorphism, shock, and brecciation. BATCHELOR and SEARS (1991a,b) recently reported detailed studies of the induced TL properties of basaltic meteorites, and SEARS et al. (1989) recently reviewed induced TL studies of other meteorite classes.

The mechanism for anomalous fading is unknown, but the rate usually follows a power-law function (VISOCEKAS, 1985; TEMPLER, 1986). Although 'anomalous' and 'thermal' fading are very different processes, readily distinguishable by kinetic studies in the laboratory, their relative importance in determining present natural TL levels requires careful experimental work. Lunar and basaltic meteorites show anomalous fading (SUTTON and CROZAZ, 1983; SUTTON, 1986a,b; HASAN et al., 1986), but Sutton argued that this was not sufficient to account for the low natural TL of ALHA81005, Y791197, and Y82192. He suggested that they had suffered recent reheating; ALHA81005 and Y791197 by shock-heating at the time of lunar ejection followed by a very short Moon-Earth transit time (2.5 and 19 Ka, respectively) and Y82192 by close passage to the sun due to a small perihelion. In the present paper, we report natural TL data for the lunar meteorites, MAC88104 and MAC88105, and for 65 basaltic meteorites. We also present detailed studies of the anomalous fading of the two lunar meteorites and five other meteorites. We discuss the implications of the data for understanding the thermal and radiation history of these meteorites and their orbital history and origins.

EXPERIMENTAL

The samples and our natural TL data are given in Tables 1–3. We have separately listed data for non-Antarctic meteorites (Table 1), Antarctic meteorites for which we have attempted to remove paired samples (Table 2), and paired meteorites (Table 3). The tables include 'means' and 'selected' values. These are normally averages with errors compounded in the normal way, but one or two data were rejected because of large uncertainties, and in a few cases the calculated uncertainty on an individual value was thought to be unreasonably small. Since data reduction involves taking the ratio of two experimentally determined values (HASAN et al., 1989), an upper limit in the denominator will result in a *lower* limit for the quotient and therefore a lower limit for the natural TL value quoted in Tables 1–3. This only occurs with the high temperature TL of samples of very low TL sensitivity. Throughout this paper, we have used the abbreviations for Antarctic meteorite names used in the *Antarctic Meteorite Newsletter*. We use the krad unit instead of the SI-approved Gray because its use is established in the meteorite literature.

Table 1. Natural thermoluminescence data for basaltic meteorites not recovered in the Antarctic[*+].

Meteorite[@]	Natural TL	
	krad at 250°C	krad at 400°C
Howardites		
Binda	11+-2	26+-9
Bununu	0.19+-0.01	8+-1
Chaves	7+-1	29+-2
Kapoeta	5.2+-0.4	21+-4
Le Teilleul	8.5+-1	39+-20
Pavlovka	9+-3	42+-49
Petersburg	11+-5	36+-9
Eucrites		
Ibitira	2.6+-0.7	70+-15
Juvinas	12.6+-0.7	57+-44
Moore County	1.3+-0.3	86+-16
Nuevo Laredo	8+-1	23+-1
Pasamonte #1	1.0+-0.1	28+-3
#2	1.44+-0.07	33+-3
sample mean	1.2+-0.1	31+-2
Serra de Mage	8+-1	>99
Diogenites		
Johnstown	27+-11	124+-55
Shalka	<0.7	---
Tathouine	4+-2	57+-17
Mesosiderites		
Clover Springs	0.08+-0.02	11+-4
Crab Orchard	3.0+-0.2	22+-3
Estherville 1161	3.7+-0.7	51+-1
769	2.6+-0.4	43+-16
sample mean	3.2+-0.5	47+-11
Hainholz	0.6+-0.3	>7
Lowicz	0.3+-0.3	2.3+-0.4
	0.14+-0.04	4.4+-0.7
sample mean	0.2+-0.2	3+-1
Mincy	1.4+-0.8	>7
Morristown	0.7+-0.3	>7
Patwar	9+-1	55+-7
Pinaroo	4.2+-0.2	29+-7
Vaca Muerta 3116	3.3+-0.7	34+-9
1010	9+-1	>11
sample mean	6+-3	34+-9

[*] Uncertainties refer to standard deviations of triplicate measurements. All data were measured in the induced TL laboratory.

[+] See Batchelor and Sears (1991b) for sources and catalog numbers.

[@] Finds underlined.

Much of the data reported here was obtained as part of the natural TL survey currently being performed for all suitable Antarctic meteorites. After examining these data, we decided to obtain further samples, and to reduce natural TL data for samples obtained for induced TL projects (BATCHELOR and SEARS, 1990; 1991a,b). The survey and non-survey samples were therefore analyzed in two different laboratories using slightly different procedures, and the laboratory responsible for each piece of data is indicated in Tables 1–3.

Table 2. Natural thermoluminescence data for basaltic and lunar meteorites recovered in the Antarctic*.

Meteorite	Mass (g)	Natural TL krad @ 250°C	Natural TL krad @ 400°C	Notes$^+$
Howardites				
EETA79006,60	716.4	4.1+-0.4	25+-0.5	
61		4.8+-0.7	39+-11	
sample mean		4.5+-0.5	25+-0.5	
EET83376,7	79.3	4.4+-0.4	22+-2	
8		5.1+-0.2	23+-3	
sample mean		4.8+-0.3	23+-2	
EET87503 group	---	6.1+-0.8	24+-5	2
EET87512,10	181.6	16+-1	46.8+-0.2	1
LEW85313 group	---	6+-1	11+-1	2
Eucites				
ALHA76005 group	---	7+-1	20+-2	2
ALHA85001,19	212.3	0.09+-0.01	3+-1	
20		0.10+-0.02	1.9+-0.7	
sample mean		0.10+-0.01	2.0+-0.9	
EET79004,101	390.3	18+-3	34+-8	
102		10.2+-3.7	---	
EET87532,3	193.5	2.8+-0.6	18+-4	1
EET87542,3	608.6	0.3+-0.1	9+-4	1
3		0.4+-0.1	9+-1	
8		0.32+-0.01	12+-1	
sample mean		0.4+-0.1	11+-1	
EET87548,2	560.2	2.3+-0.5	3.1+-0.9	1
2		3+-1	8.5+-0.3	
8		1.4+-0.1	4+-1	
sample mean		2+-1	6+-2	
HOW88401,4	1622.7	6.9+-1.3	21+-5	1
LEW85303 group	---	24+-1	39+-4	2
LEW85305,2	40.8	.036+-.005	---	1
2		0.06+-0.03	4+-1	
sample mean		0.04+-0.02	4+-1	
LEW85353,2	24.5	0.5+_0.2	---	1
LEW86001,4	290.6	28+-4	---	1
16		13+-1	18+-3	
sample mean		20+-7	18+-3	
LEW86002,2	32.6	13+-3	---	1
LEW87004,3	208.4	4.3+-0.4	19.5+-0.6	1
7		7.0+-0.7	28+-1	
sample mean		5.6+-0.6	24+-3	
PCA82502,59	890.4	7+-1	41+-6	
60		4.8+-0.7	36+-12	
sample mean		6+-1	38+-6	
Diogenites				
ALHA77256,109	676.2	2+-2	3+-1	
110		0.6+-0.1	2.2+-0.7	
sample mean		0.6+-0.1	3+-1	
ALHA84001,32	1930.9	1.3+-0.1	4+-3	
EETA79002,83	2843.0	4+-2	14+-5	
LEW88008,2	17.9	6.4+-0.4	---	1
Mesosiderites				
ALHA77219,58	637.1	7+-1	18+-1	
59		8+-3	18+-3	
sample mean		8+-2	18+-2	
LEW87006,3	269.5	10+-1	31+-3	1
8		9+-1	25+-3	
sample mean		9.5+-0.5	28+-2	
EET87500 group	---	0.20+-0.04	9+-1	2
MAC88102,3	754.3	1.1+-0.3	21+-8	1
RKPA79015,16	10022.0	<1	3+-1	
17		<0.7	>1	
sample mean		<0.7	3+-1	
QUE86900,3	1532.3	16+-7		1
3		13+-2	>32	
sample mean		15+-5		
Lunar Meteorites				
MAC88104 group	---	2.5+-0.3	7.1+-0.2	2
ALHA81005	18.9	~0.75	~13	3
Y791197	52.4	~1.7	~81	3
Y82192	36.67	~0.5	~5	3

* Uncertainties are standard deviations of triplicate measurements.

\+ Notes:

1. Data gathered by the natural TL survey laboratory.
2. See Table 3 for details.
3. Data from Sutton and Crozaz (1983), Sutton (1986a,b). Data read from glow curves.

Survey samples were hand carried from JSC, to avoid inadvertent heating or exposure to radiation, and then handled only in red light to avoid optical bleaching of the TL (HOYT et al., 1972; HASAN et al., 1987). Samples of ≥250 mg were obtained >0.6 cm from any potential fusion crust to avoid heat-alteration (SEARS, 1975), and 50–100 mg of interior material was taken. This was gently ground, the magnetic material removed with a hand-magnet, and the powder gently ground again until it just passed through a 100 mesh sieve. Three 4 mg aliquots of powder were then placed in shallow Cu pans and their TL measured in Daybreak Nuclear and Medical TL apparatus, modified by (1) placing metering valves in the gas and vacuum lines, (2) placing silica gel capsules in the photomultiplier tube (PMT) housing, (3) putting a shutter on the PMT housing (so that the high-voltage supply to the PMT is left on over 3–6 month periods), (4) gathering the data on a Texas Instruments personal computer using a custom-made interface and software, and (5) placing a 4 mm Cu aperture between the sample and PMT window. Disposable cellulose sheets, with flat absorption throughout the visible range and with a transmittance of 0.90 ± 0.01, were placed between the aperture and the PMT to prevent weathering and other products from degrading the PMT window. After measuring the natural TL for the three aliquots, the samples were exposed to a 250 mCi Sr-90 source for 2–5 min and the induced TL measured. The natural TL data were then reduced using the methods described by HASAN et al. (1989). Curves of natural TL as a function of glow curve temperature (termed 'equivalent dose' curves by MELCHER, 1981a,b and SUTTON and CROZAZ, 1983) were produced by dividing, in 1°C temperature intervals, the glow curve for the 'as-received' sample by the glow curve for the sample irradiated in the laboratory, and multiplying the ratio by the dose administered. We will also discuss the natural TL values at specific glow curve temperatures, 250 and 400°C, and we will refer to these as natural TL(250) and natural TL(400).

The non-survey samples were treated in the same way as the survey samples, except that they were sent through the US mail and they were not handled in red light. It should be expected that the natural TL data obtained for these samples would be of somewhat lower quality than the survey data and in general this is borne out by the experimental uncertainties. On the other hand, the samples were taken from large well-documented meteorites and were stored with the survey samples. Comparison of data for eleven meteorites

Table 3. Natural thermoluminescence data for paired and supposedly paired meteorites.

Meteorite	Mass	Natural TL		Notes
	(g)	krad @ 250°C	krad @ 400°C	
Howardites				
EET87503,3	1734.5	6.1+-0.8	24+-5	
EET87509,4	583.9	3.55+-0.05	19+-2	1
91		4.8+-0.4	19+-9	
78		4.8+-0.4	15+-3	
88		4.4+-0.7	25+-2	
sample mean		4.4+-0.3	17+-6	
EET87510,2	250.3	7.9+-0.3	31+-5	1
EET87513,2	394.5	5+-1	18+-5	1
78		5.8+-0.2	22+-1	
91		5.2+-0.7	9+-2	
96		9.6+-0.7	10+-2	
100		9+-2	10+-2	
sample mean		7+-1	13+-6	
EET87518,3	349.6	2.5+-0.5	12+-2	1
EET87528,5	40.5	5.1+-0.8	21+-4	1
EET87531,3	527.2	2.5+-0.1	13+-1	1
91		1.5+-0.1	13+-2	
96		3.6+-0.2	11+-14	
101		3.2+-0.1	10+-2	
87		2.6+-0.4	---	
sample mean		2.7+-0.3	11+-2	
pair group mean		*5+-2*	*19+-7*	*2*
LEW85313,3	191.2	5+-1	12+-1	1
3		5+-1	12+-3	
35		7+-1	10+-2	
sample mean		6+-1	11+-2	
LEW85441,2	10.9	0.60+-0.01	---	1
2		0.15+-0.02	6.3+-0.7	
sample mean		0.4+-0.2	6.3+-0.7	
pair group mean		*6+-1*	*11+-2*	*3*
Eucrites				
LEW85303,3	408.0	13+-1	24+-2	1
LEW88005,2	253.9	23+-2	34+-5	1
pair group mean		*18+-5*	*29+-4*	4
ALHA76005,78	1425.0	6+-2	20+-5	
79		7.4+-0.4	24+-3	
sample mean		7+-1	22+-4	
ALHA77302,83	235.5	7.7+-0.7	18+-1	
pair group mean		*7+-1*	*20+-2*	*5*
Mesosiderites				
EET87500,3	8132.0	0.18+-0.05	8+-2	1
EET87501,3	4403.0	0.21+-0.04	9.7+-0.6	1
pair group mean		*0.20+-0.04*	*9+-1*	*6*
Lunar Meteorites				
MAC88104,2	61.2	2.4+-0.3	7.1+-0.2	1
MAC88105,4	662.5	2.9+-0.3	6.4+-2.2	1
pair group mean		*2.5+-0.2*	*7.1+-0.2*	*7*

* **Uncertainties are standard deviations of triplicate measurements.**

\+ **Notes:**

1. **Data produced in the natural TL survey laboratory**
2. **Mason (1988b),(Myers et al., 1989)**
3. **Mason (1988a)**
4. **Score et al. (1986), Sears and Sears (see Myers et al., 1990)**
5. **Scott (1989)**
6. **Mason (1988b)**
7. **Lindstrom (1989a)**

measured independently through the two laboratories suggests that the non-survey data are probably quite reliable. Only two meteorites show >2 sigma difference between the two samples (LEW86001 and LEW87004), and such differences may reflect large cosmogenic gradients.

Anomalous fading studies were made by irradiating 4 mg aliquots of seven samples listed in Table 4 in the Sr-90 beta cell three times. The induced TL was then measured with a 5 min delay after the first and third irradiation. After the second irradiation the samples were allowed to stand in red light in an air-conditioned laboratory for 1 h, 12 h, 24 h, 48 h, 15 d, and 28 d. Provided the TL induced by the first and third irradiation agreed within ±5%, the induced TL remaining after the storage period was divided by an average of the TL induced by the other two irradiations. This ratio provides a measure of the amount of fading occurring over the period in question as a function of glow curve temperature.

RESULTS

Figure 1 shows natural TL as a function of glow curve temperature for a number of basaltic and lunar meteorites and three ordinary chondrites. Two of the ordinary chondrites have fairly typical natural TL data but have very different terrestrial ages according to NISHIIZUMI (1984; ALHA78076, 130 ± 70 ka; ALHA78043, 490 ± 90 ka), and the factor of about 5 difference in the natural TL (250) is consistent with this. At all glow curve temperatures these two ordinary chondrites have higher natural TL than the other samples in Fig. 1 except Y791197, which levels off at a value around 50 krad (SUTTON, 1986a, and pers. comm.). Malakal is representative of a few ordinary chondrites which have experienced considerable draining of their natural TL at all glow temperatures (MELCHER, 1981a). This might reflect a small perihelion orbit, but it is also possible that the heating was due to a recent shock heating event; the meteorite has an unusual history involving shock (MELCHER, 1981a; HASAN et al., 1986).

The lunar meteorites, MAC88104 and MAC88105, have the highest natural TL (250) values (2.5 ± 0.2 krad) yet observed for lunar meteorites (approximately 0.5–1.7 krad according to the data of SUTTON and CROZAZ (1983) and SUTTON (1986a,b), and the values for the two MAC meteorites are identical within limits. MAC88104/5 have high temperature natural TL similar to that of ALHA81005 (SUTTON and CROZAZ, 1983) which is appreciably higher than 82192 and appreciably lower than Y791197 (SUTTON, 1986a,b). The basaltic meteorites in Fig. 1 have similar curves to those of the lunar meteorite ALHA81005, showing sig-

Table 4. Data on the anomalous fading of the TL of meteorites[*].

Meteorite[+#] [class]	Glow Curve Temp[$] (°C)	Fractional TL remaining after given time [@]					
		1h	12h	24h	48h	15d	28d
Bruderheim [L5]	250	0.91+-0.06	0.97+-0.06	0.92+-0.03	0.95+-0.06	0.85+-0.04	0.87+-0.01
	400	0.92+-0.04	0.98+-0.06	1.00+-0.08	0.98+-0.08	0.88+-0.04	0.97+-0.08
Kapoeta [howardite]	250	0.88+-0.07	0.83+-0.05	0.64+-0.12	0.63+-0.12	0.44+-0.01	0.43+-0.07
	400	0.89+-0.07	0.83+-0.04	0.68+-0.09	0.60+-0.01	0.46+-0.02	0.42+-0.08
LEW85303 [shkd. euc]	250	0.92+-0.04	0.80+-0.03	0.72+-0.07	0.77+-0.08	0.53+-0.05	0.49+-0.02
	400	0.90+-0.03	0.79+-0.03	0.73+-0.08	0.71+-0.04	0.54+-0.06	0.50+-0.07
MAC88104 [lunar]	250	0.89+-0.09	0.76+-0.08	0.69+-0.09	0.62+-0.08	0.45+-0.08	0.42+-0.08
	400	0.98+-0.01	0.94+-0.03	0.82+-0.03	0.80+-0.05	0.71+-0.07	0.57+-0.05
MAC88105 [lunar]	250	0.83+-0.06	0.83+-0.12	0.74+-0.05	0.61+-0.03	0.39+-0.07	0.32+-0.05
	400	0.86+-0.06	0.89+-0.10	0.92+-0.06	0.85+-0.04	0.72+-0.04	0.56+-0.01
PCA82502 [eucrite]	250	0.89+-0.01	0.79+-0.10	0.68+-0.16	0.64+-0.04	0.56+-0.09	0.55+-0.05
	400	0.89+-0.02	0.78+-0.04	0.80+-0.06	0.66+-0.05	0.69+-0.02	0.75+-0.04
Serra de Mage [cum. euc.]	250	0.97+-0.04	0.65+-0.07	0.66+-0.13	0.60+-0.02	0.38+-0.03	0.37+-0.03
	400	0.97+-0.03	0.70+-0.04	0.73+-0.17	0.66+-0.04	0.59+-0.03	0.58+-0.01

[*] Uncertainties are one sigma based on triplicate measurements.

[+] Sources and catalog numbers (if applicable) are as follows: Bruderheim, University of Arkansas, Fayetteville, AR; LEW85303, PCA82502, MAC88104/5, Meteorite Working Group of NASA/NSF; Serra de Mage, Smithsonian Institution, Washington, DC; Kapoeta, British Museum, London.

[#] Shkd euc., shocked eucrite; cum. euc., cumulate eucrite.

[$] The glow curve temperature to which the data apply. The 400°C data are actually the values of the plateau.

nificantly lower natural TL values than most chondrites at all glow curve temperatures.

Figure 2a shows histograms for the natural TL(250) levels for the present basaltic meteorite samples, compared with those for ordinary chondrites. In general, basaltic and lunar meteorites have lower natural TL values than the chondrites. All but a few of the basaltic meteorites have natural TL(250) <30 krad, while only 40% of the chondrites have values this low. In fact, there is an indication of a mode in the natural TL(250) data at around 10 krad for the basaltic meteorites. The distribution for Antarctic and non-Antarctic meteorites is very similar but with a slight, yet significant, tendency for the Antarctic meteorites to be skewed to lower values.

The natural TL(400) data (Fig. 2b) also shows a weak mode at around 25 krad with a slightly greater proportion of non-Antarctic meteorites above this value than Antarctic meteorites. This slight difference in the natural TL(400) data is not due to weathering, because any potential effect is eliminated from the final value quoted by the data reduction (HASAN et al., 1989; BENOIT et al., 1991a). Most probably it is a terrestrial age effect, since anomalous fading will cause high-temperature TL to fade in a time-dependent way. Ordinary chondrites have much higher natural TL(400) than basaltic meteorites. The 23 ordinary chondrites of HASAN et al. (1989) give 45 ± 5 krad (HASAN et al., 1989).

The results of our measurements of anomalous fading are plotted in Fig. 3. Decay of TL at 250 and 400°C in the glow curve is presented, with the data for ALHA81005 from SUTTON and CROZAZ (1983) for comparison. The fading at 250°C in the glow curve is to be expected, since at this glow curve temperature some thermal fading is expected. However, all the basaltic samples showed considerable anomalous fading at 400°C; typically, the TL decayed 50–60% after 28 days. In contrast, the Bruderheim L chondrite showed no fading at high glow curve temperatures. These results agree with those of MCKEEVER and DURRANI (1982) and HASAN et al. (1986). Our data are consistent with the anomalous fading following a power-law function, and the coefficients a and b in the expression (TL remaining) = $a(\text{time})^{-b}$ are given in Table 5. LEW85303 and Kapoeta are especially noteworthy, since the fading we observed for these samples did not appear temperature-dependent; the fading at 400°C in the glow curve was comparable with that at 250°C in the glow curves of the other basaltic meteorite samples.

DISCUSSION

Since a large fraction of the present samples are Antarctic meteorites, before we can make statistical comparisons with the chondrites it is necessary to discuss pairing. We will then

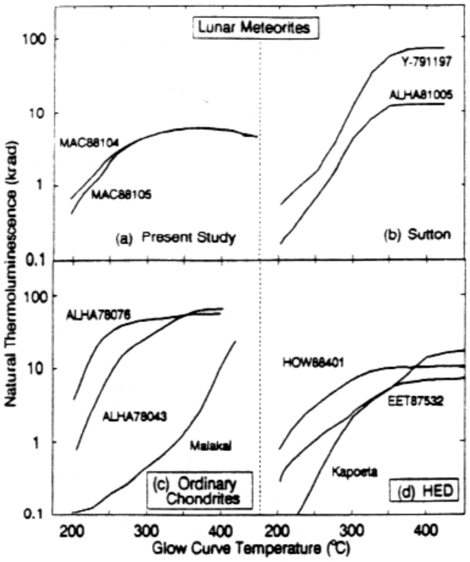

FIG. 1. Natural TL as a function of glow curve temperature for (a) the present lunar meteorites, (b) previous lunar meteorites (SUTTON and CROZAZ, 1983; SUTTON, 1986a,b), (c) three ordinary chondrites, (d) the HOW88401 and EET87532 eucrites and the Kapoeta howardite. Two of the ordinary chondrites in Fig. 1c were chosen because of their very different terrestrial ages (ALHA78076, 130 ± 70 ka; ALHA78043, 490 ± 90 ka; NISHIIZUMI, 1984), while Malakal is an example of a recently reheated chondrite (MELCHER, 1981a).

discuss the terrestrial age systematics of the natural TL of basaltic meteorites and their low natural TL compared to chondrites. Finally, we will discuss the lunar meteorites.

Pairing

MASON (1988b) suggested that many of the howardites in the present study were paired on the basis of petrographic and hand-specimen descriptions. While the TL data for these meteorites display some scatter which reflects their weak TL signals and TL curve shapes, only EET87512 (Table 2) is significantly outside the range shown by the others in the EET87503 pairing group (Table 3). The unusual clast observed in this meteorite by MASON (1988b) would not explain these TL data, and we suggest that EET87512 is not paired with the others. EET87528 was not paired with the EET howardites by MASON (1988b), but its TL data fall well within the range of the others. In fact, there is a suggestion that the large EET87503 howardite pairing group may actually represent two discrete falls; one containing EET87503, EET87509, EET87510, EET87513, and EET87528 with natural TL(250) of 5–7 krad, and another consisting of EET87518 and EET87531 with natural TL(250) around 2.5 krad.

LEW85313 and LEW85441 are howardites that are paired by MASON (1988a), but their natural TL(250) differs by a factor of 10. Their natural TL(400) differs by 40% and their TL sensitivities differ by a factor of three. LEW85441 is an extremely small sample (10.9 g) so that the natural TL(250) may be low due to heating during atmospheric passage, but the 400°C data and induced TL data are not subject to this

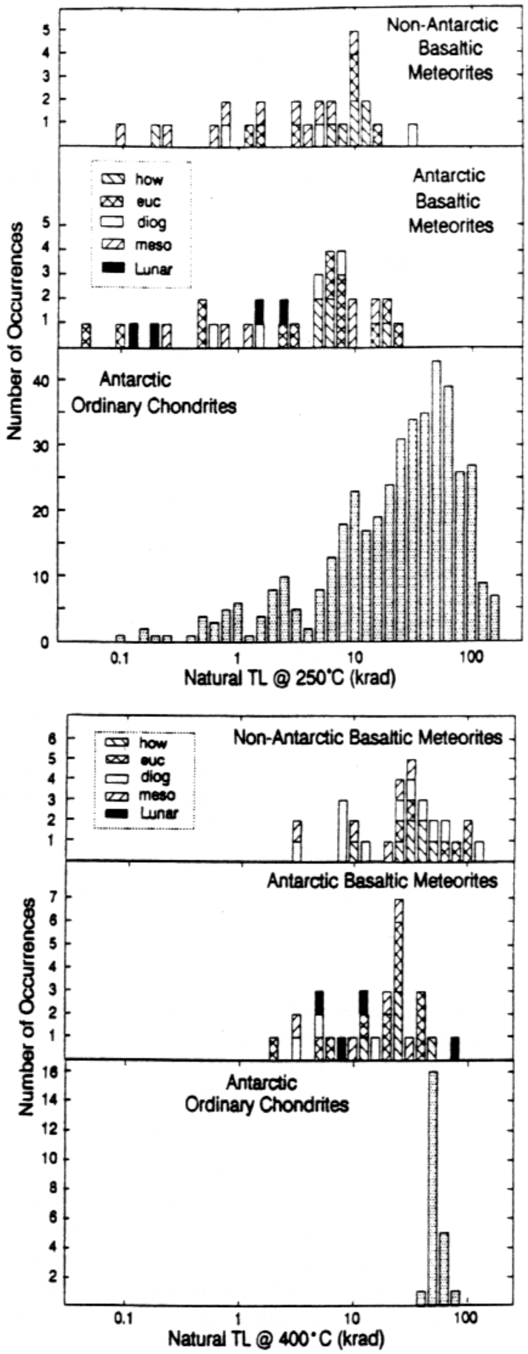

FIG. 2. Histograms of natural TL values for basaltic (howardites, eucrites, diogenites, and mesosiderites) and lunar meteorites, and ordinary chondrites, measured at (a) 250°C in the glow curve, (b) 400°C in the glow curve. 250°C is the glow curve temperature at which the natural TL is most sensitive to the range of radiation and temperature experienced by most meteorites. The natural TL at a glow curve temperature of 400°C is very stable to normal thermal decay, but the basaltic and lunar meteorites have undergone anomalous fading. The achondrite data are from the present work, while the data for ALHA81005, Y82192, and Y791197 are from SUTTON and CROZAZ (1983), SUTTON (1986a,b) and S. R. SUTTON (pers. comm.), respectively. The 250°C chondrite data are from HASAN et al. (1992), the 400°C data are unpublished data from this laboratory. Data for paired basaltic meteorites have been averaged.

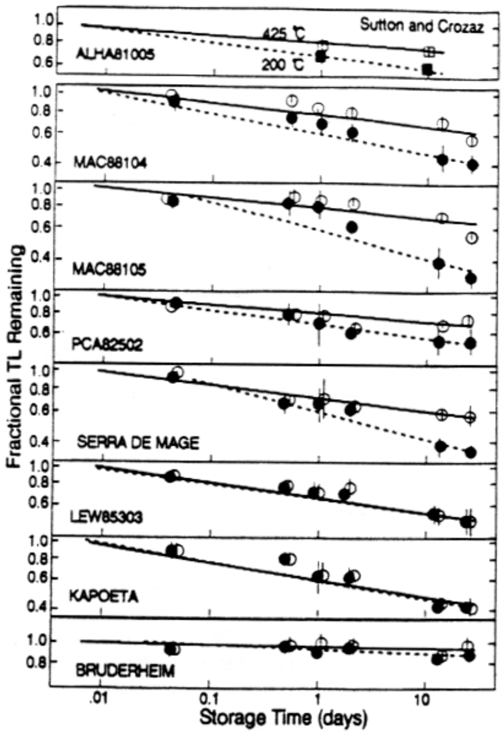

FIG. 3. Plots of the TL remaining as a function of storage time for the seven samples listed in Table 4 and ALHA81005 (from SUTTON and CROZAZ, 1983). The lines are regression lines through the data, broken lines, and filled symbols representing the decay at 250°C and the solid lines and open symbols representing the decay at 400°C.

uncertainty. We therefore suggest caution in the pairing of these two samples.

The eucrites LEW85303 and LEW88005 have similar natural TL data and highly unusual and identical induced TL data (BATCHELOR and SEARS, 1991a,b), confirming the pairing suggestion of LINDSTROM (1989b). An error in our earlier published value for LEW85303 has been corrected in Table 3 (MYERS et al., 1990). The present data are also consistent with the pairing of ALHA76005 and ALHA77302, as suggested by SCOTT (1989). The mesosiderites EET87500 and EET87501 have identical natural TL data, which confirm earlier pairing suggestions (MASON, 1988b), as do the lunar meteorites MAC88104 and MAC88105 (LINDSTROM, 1989a). On the basis of the natural TL data reported here, and with the induced TL and other data gathered in the course of this work (hand-specimen appearance, ease of sample preparation, nature of color changes during TL measurement), we also suspect that the howardite EETA79006 and EET83376 are paired although there does not appear to be any prior suggestion of this.

Natural TL and Terrestrial Ages

In the Antarctic, dose rates are lower and temperatures higher than in space, and the natural TL equilibrium level is much lower on Earth than in space. This process has been discussed at some length by several authors (MELCHER, 1981b; MCKEEVER, 1985), and theoretical models are in reasonable agreement with empirical data. Indeed, the 'correlation' between natural TL(250) and ^{14}C terrestrial age for US Prairie State meteorites has improved as the ^{14}C data have improved (SEARS and DURRANI, 1980; BENOIT et al., 1991b). The effect of anomalous fading on these decay systematics has not been considered, but the present data permit some insights into this.

We may expect anomalous fading to have three effects, and all are borne out by the data. (1) The rate of decay of the natural TL will be much greater at all temperatures in the glow curve than in the absence of this fading. This is confirmed by the present data, since basaltic meteorites are systematically lower than chondrites in their natural TL at both 250°C (Fig. 2a) and 400°C (Fig. 2b). (2) Since the natural TL level at the time of entering the atmosphere will be much lower, the changes in natural TL level due to thermal fading on earth will be smaller and more difficult to detect. The natural TL data for basaltic meteorites do scatter more

Table 5. The values of *a* and *b* in the expression $I = at^{(-b)}$, where I is the fraction of thermoluminscence remaining at time t (years), determined from the data in Fig. 3 and Table 5 and the method of least squares.

Meteorite	Glow curve temperature (°C) 250		400	
	a	*b*	*a*	*b*
ALHA81005*	0.49	0.062	0.66	0.036
Bruderheim	0.85+-0.48	0.01+-0.01	0.95+-1.0	0.01+-0.01
Kapoeta	0.32+-0.03	0.12+-0.02	0.32+-0.02	0.12+-0.02
LEW85303	0.40+-0.04	0.10+-0.02	0.41+-0.03	0.09+-0.01
MAC88104	0.32+-0.02	0.12+-0.01	0.52+-0.07	0.08+-0.02
MAC88105	0.25+-0.04	0.16+-0.03	0.57+-0.15	0.06+-0.02
PCA82502	0.44+-0.02	0.08+-0.01	0.63+-0.13	0.03+-0.01
Serra de Mage	0.25+-0.01	0.15+-0.01	0.46+-0.04	0.08+-0.01

* Data from Sutton and Crozaz (1983) for 200 and 425°C in the glow curve.

than for chondrites, especially at 400°C. (3) Unlike chondrites, anomalous fading will cause basaltic meteorites to display a relationship between the natural TL at 400°C in the glow curve and terrestrial age.

We attempted to see if there was a relationship between natural TL and terrestrial age using the present data, although it is difficult because not only does anomalous fading weaken the TL signals, but cosmogenic terrestrial ages are often poorly known, particularly for MAC88104/5. The data are plotted in Figs. 4a and 4b. Despite greater scatter, it is possible to see certain similarities between these figures and analogous plots for chondrites. For chondrites, there are 'two groups'; one in which natural TL decays with terrestrial age in a manner consistent with theoretical calculations, and one in which natural TL levels are too low to be accounted for by any combination of terrestrial age and storage temperature (SEARS and MILLS, 1974; MELCHER, 1981a,b; MCKEEVER and SEARS, 1980; HASAN et al., 1987). Those with abnormally low natural TL have apparently suffered a recent heating event and have not had time to return to their equilibrium values.

From Fig. 4, it would seem that Y791197, EETA79006, EET79004, PCA82502, Ibitira, Tatahouine, Johnstown, Moore County, Pavlovka, Estherville, Petersburg, Le Teilleul, and Juvinas are analogous to the chondrite groups in which natural TL values can be understood in terms of a 'normal' history in which terrestrial age is a factor in determining natural TL. On the other hand, ALHA84001, ALHA77256, ALHA81005, Bununu, and Lowicz have values which are analogous to those chondrites which have been reheated. Patwar, Kapoeta, Pasamonte, Chaves, ALHA76005, EETA79002, and ALHA77219 plot near the 'hinge' of the two groups and their situation is less certain. The distribution of data for 250°C and 400°C is very similar, consistent with expectation (3) above. The natural TL(250) for Antarctic samples with terrestrial ages >200,000 y and for non-Antarctic samples with terrestrial ages >100 y is about 5 krad, [30 krad for natural TL(400)], so apparently values below these indicate heated meteorites. Below we will discuss individual cases and independent evidence for heating. Considering that the cosmogenic terrestrial age determinations are in such poor agreement (they range from 100,000 to 400,000 y, VOGT et al., 1991; EUGSTER et al., 1991; NISHIIZUMI et al., 1991), MAC88104/5 can be viewed as plotting at the lower limit of the terrestrial age trend, or at the upper limit of those samples thought to have been reheated. We return to this sample below.

There is an interesting difference in the natural TL (250) levels of Antarctic and non-Antarctic mesosiderites (Tables 1 and 2). The Antarctic mesosiderites generally have higher natural TL (250) but lower natural TL (400), relative to the non-Antarctic ones. This is consistent with the non-Antarctic meteorites being stored at higher temperatures and suffering higher rates of decay in the low temperature region of the glow curve. On the other hand, Antarctic meteorites have much higher terrestrial ages and, therefore, lower TL values in the high temperature region. Among the meteorites of Table 1, only the non-Antarctic mesosiderites exhibit this relationship to their Antarctic analogues since non-Antarctic mesosiderites are predominately finds and thermal decay in

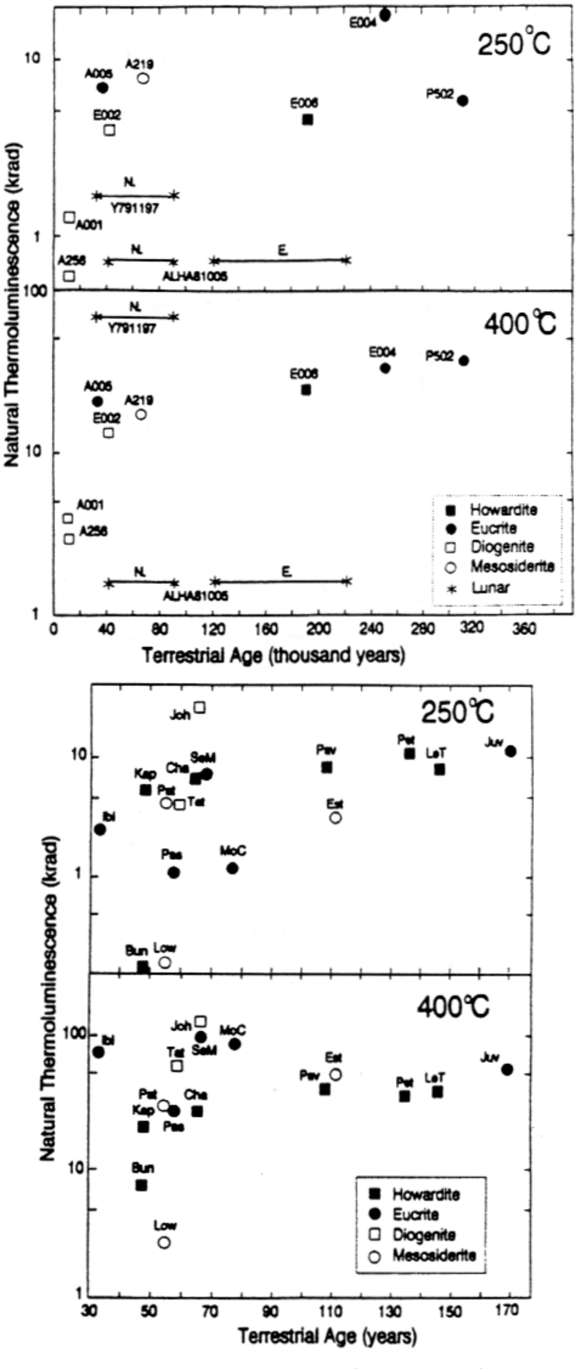

FIG. 4. Natural thermoluminescence for (a) Antarctic lunar and basaltic meteorites and (b) non-Antarctic basaltic meteorites as a function of terrestrial age (NISHIIZUMI et al., 1989; GRAHAM et al., 1985). The cosmogenic data for lunar meteorites are from NISHIIZUMI et al. (1988; N) and EUGSTER (1989; E). Data for MAC88104/5 are not plotted because of the lack of agreement in the isotopic data, EUGSTER et al., (1991); NISHIIZUMI et al., (1991); and VOGT et al., (1991). Abbreviations: A001, ALHA84001; A005, ALHA76005; A219, ALHA77219; A256, ALHA77256; Bun, Bununu; Cha, Chaves; E002, EETA79002; E004, EETA79004; E006, EETA79006; Est, Estherville; Ibi, Ibitira; Joh, Johnstown; Juv, Juvinas; Kap, Kapoeta; LeT, Le Teilleul; Low, Lowicz; MoC, Moore County; P502, PCA82502; Pas, Pasamonte; Pat, Patwar; Pav, Pavlovka; Pet, Petersburg; Tat, Tatahouine.

the low temperature region is significant over long time spans in temperate climates.

Basaltic and Lunar Meteorites Compared with Chondrites

It is clear that both basaltic and lunar meteorites display significantly lower natural TL levels than chondrites. The point of interest is whether this can be attributed entirely to anomalous fading, or whether these meteorites have suffered a recent thermal event as suggested for lunar meteorites (SUTTON and CROZAZ, 1983; SUTTON, 1986a,b). To evaluate the importance of anomalous fading it is necessary to make an extrapolation from the laboratory data to times on the order of cosmic ray exposure ages, 10^6–10^7 years (AYLMER et al., 1988). If we do this using a power-law expression, we obtain the curves in Fig. 5a. It is difficult to make a fully quantitative comparison between the curves determined by extrapolation using the decay parameters in Table 5 because we do not know original natural TL levels. For the sake of comparison we may assume typical chondrite values. We then obtain a suite of curves for a variety of times whose relative positions are accurate but whose vertical placement on the plot is somewhat arbitrary. These basaltic samples show decay of factors of approximately 5 to 10 due to anomalous fading when extrapolated to 10^7 y. The MacAlpine Hills samples are noteworthy because, assuming chondritic starting values, anomalous fading will not alone explain their low natural TL.

Equally important is the degree to which the extrapolated curves match the shape of the observed curves, which is easier to evaluate if we normalize to the high temperature natural TL. This also removes uncertainty over starting levels (Fig. 5b). Thermal fading of the low temperature TL may have occurred during the anomalous fading experiment. An idea of the scale of this effect can be assessed from the data for Bruderheim, where the lack of any fading at high glow curve temperatures indicates the lack of anomalous fading. When extrapolated to $\leq 10^7$ year, the natural TL as a function of glow-curve temperature is flat at glow curve temperatures above 250°C, while below this temperature the curve drops rapidly with decreasing glow curve temperature (Fig. 6). (It should be stressed that this is an attempt to distinguish the two modes of TL decay. It is not a definition of the two modes of decay, which were defined in the Introduction.) Apparently, the effects of thermal decay during the experiment are limited to temperatures <250°C.

Within the uncertainties of our experimental methods we may conclude that the natural TL of Serra de Mage, for instance, whose natural TL(250) is 8 ± 1 krad, is entirely due to anomalous fading, while the natural TL of PCA82502 and Kapoeta (6 ± 1 and 5.2 ± 0.4 krad at 250°C, respectively) seem to require some thermal draining in addition to the anomalous fading. LEW85303 [natural TL(250) 13 ± 1 krad] has unique TL properties that are discussed further below. The two lunar meteorites MAC88104/5 are equivocal. Their natural TL (250; 2.5 ± 0.3 krad) may be explicable in terms of (1) anomalous fading, if cosmic ray exposure times of 10^7 year are feasible, (2) an extremely long terrestrial age, >0.3 Ma judging from Fig. 4a or $\gg 10^7$ years judging from Fig. 5a, or (3) heating to temperatures >500°C to drain natural TL throughout the glow curve and then falling to earth before the natural TL had time to reaccumulate.

Shock Reheating

The markedly different anomalous fading characteristics of Kapoeta and LEW85303 compared to the other samples are interesting but, perhaps, not too surprising. Laboratory heating of basaltic meteorites causes the TL peak to move to higher temperature (BATCHELOR and SEARS, 1990, 1991a,b), and higher temperature peaks are known to have different anomalous fading properties (HASAN et al., 1986; SEARS et al., 1989). Kapoeta is regolith breccia with a great variety of clasts in a matrix which has a complex history involving heating (FREDRIKSSON and KEIL, 1963; ASHWORTH and BARBER, 1976; BISCHOFF et al., 1983). The TL properties of the whole-rock will be a composite of the properties of the diverse material present (HAQ et al., 1989).

Regardless of the cause of its unusual anomalous fading properties, the conclusion that Kapoeta has been reheated recently is not without interest, since there is some uncertainty over the timing of regolith activity. PELLAS (1972) argued that regolith activity occurred early in solar system history because several regolith breccias contain shocked and melted clasts with ages close to 4.5 Ga. On the other hand, SCHULTZ and SIGNER (1977) pointed out clast-to-clast differences in the activity of short-lived cosmogenic nuclides and argued that this indicated that the regolith was still 'active' immediately prior to fall. It might be that at least some of the regolith activity of Kapoeta occurred within the last million years or so and that the associated shock heating resulted in drainage of natural thermoluminescence, especially at low glow curve temperatures.

LEW85303 (and the meteorites paired with it) was found to be unique among the 64 basaltic meteorites in showing induced TL evidence for heating >1000°C (BATCHELOR and SEARS, 1990, 1991a,b), and petrographic and isotopic evidence for an unusual and major shock event (KOZUL and HEWINS, 1988a,b), perhaps <1 Ga ago (BOGARD and GARRISON, 1989). It seems likely that the unusual TL properties of LEW85303 reflect partial disordering of the feldspar structure, which HASAN et al. (1986) argued would lessen the extent of anomalous fading. The shape of the natural TL vs. glow curve temperature plot for this meteorite (Fig. 5) would suggest that it has been heated within the last million years or so, perhaps associated with the shock event suffered by this unusual meteorite.

We have also examined the noble gas data of SCHULTZ and KRUSE (1989) for evidence of low ^{3}He/^{21}Ne ratios for the basaltic meteorites that would be consistent with shock heating and the diffusive loss of ^{3}He from the low natural TL samples (Fig. 7). In fact, ^{3}He/^{21}Ne is strongly depth-dependent, so it is the displacement of the sample from the ^{3}He/^{21}Ne vs. ^{22}Ne/^{21}Ne correlation line that is really significant (SCHULTZ et al., 1991). The line indicated in Fig. 7 applies to chondrites, but a similar line should exist for basaltic meteorites. However, the plot of ^{3}He/^{21}Ne vs. ^{22}Ne/^{21}Ne for basaltic meteorites produces a shotgun pattern with no indication of a trend, so that depth effects cannot be allowed for in this way. Taken at face value, there is no correlation

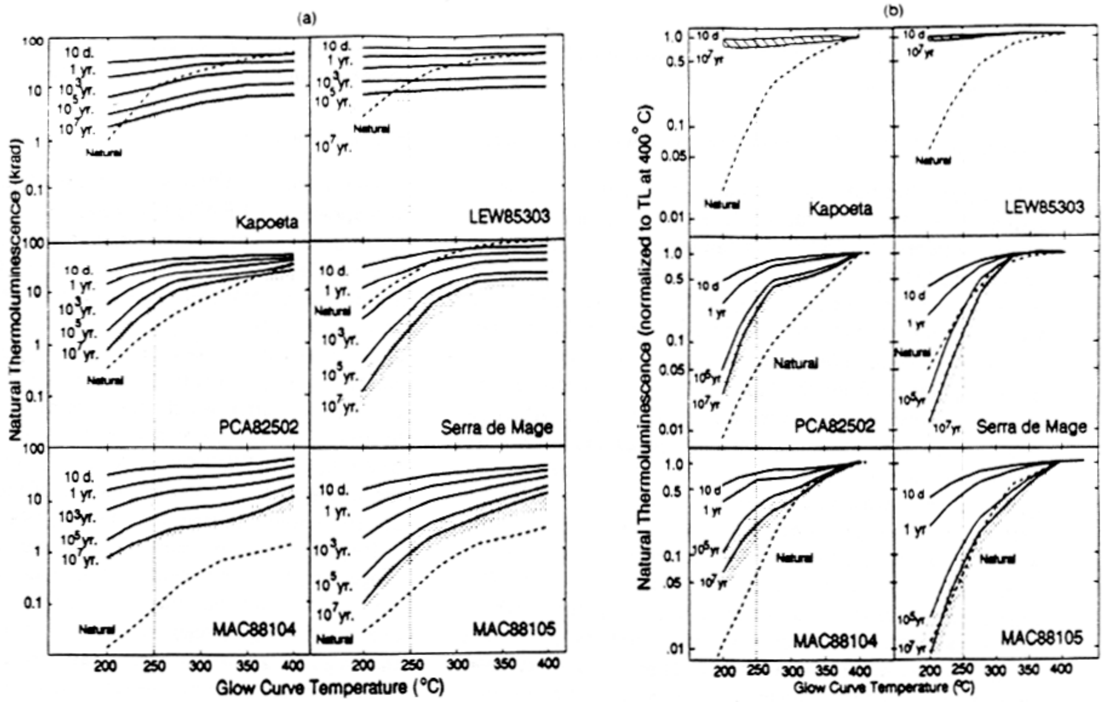

FIG. 5. Versions of Fig. 1 obtained by extrapolation of laboratory data for anomalous fading (Table 5). (a) The solid lines are the curves calculated for the indicated decay times, where typical chondrite starting values are assumed and the broken lines are those observed for the natural TL of the original meteorite. (b) The same curves as in Fig. 5a but normalized to the high temperature portion of the curve to emphasize changes in curve shape. Uncertainties in the calculation due to the uncertainties in the input parameters are indicated on the 10^7-year curve by the stippled region.

between natural TL and ^{3}He/^{21}Ne that would suggest that the low natural TL values are due to shock heating.

Orbits and the Origin of Basaltic Meteorites

DRAKE (1979) argued that the basaltic meteorites originated on Vesta, but others have argued that the eucrite parent body must have fragmented in order to have produced the observed variety of basaltic and related meteorites observed (WASSON and WETHERILL, 1979; CRUIKSHANK et al., 1991). The best spectrophotometric evidence for differentiated asteroids is in the Flora region of the inner asteroid belt. If the ratio of afternoon to morning (PM/AM) falls for basaltic meteorites is 0.50 ± 0.14 compared with 0.66 ± 0.04 for chondrites as suggested by WETHERILL (1987), then this would be consistent with an origin for the basaltic meteorites in the inner regions of the asteroid belt. The mass-flux is also consistent with an inner-belt origin for the basaltic meteorites (WETHERILL and CHAPMAN, 1988; WETHERILL, 1987). If the low natural TL of the basaltic meteorite classes as a whole is associated with perihelia <0.8 AU, chondrites and achondrites should show different distributions in natural TL data, since their PM/AM ratio is governed by orbit.

SIMONENKO (1975) determined orbital elements for 45 meteorites and found perihelia ranging from <0.65 to about 1.0 AU, most were 0.85–1.0 AU. In a study of 27 of these, natural TL levels were found to drop two orders of magnitude as the perihelion decreased from 1 to 0.7 AU, and that the data were broadly consistent with the theoretical treatments of MCKEEVER (1985). The theoretical curve natural TL as a function of perihelion sharply changes slope at 5 krad and 0.8 AU, so that TL levels <5 krad indicate very small perihelia. Albedo and variations in dose rate due to shielding also affect the natural TL data, but to a much smaller extent than the orbit and would not produce the total range of natural TL observed here. A factor of 100 change in dose rate causes a factor of four change in natural TL, and a factor of 3 change in albedo causes a factor of two change in natural TL. By comparison, we are concerned with a factor of 1000 range in natural TL. The matter is discussed in some depth by BENOIT et al. (1991a,b). A detailed study of the sort performed by MCKEEVER (1985) for ordinary chondrites has not been performed for basaltic meteorites, although we expect the results to be broadly similar. SUTTON and CROZAZ (1983) found that lunar meteorite natural TL is more stable in regards to thermal fading than ordinary chondrite TL.

In the absence of our anomalous fading data, it would be possible to argue that the displacement of the natural TL data to lower values indicates a much greater proportion of small perihelia among the orbits of the basaltic meteorites than among the chondrites. This might be consistent with the different time-of-fall distribution for chondrites and achondrites described by WETHERILL (1968; 1987). However, we suspect that basaltic meteorites as a whole have lower natural TL because the class displays anomalous fading, and we do not believe that small perihelia are the norm for basaltic meteorites.

There are independent arguments for this conclusion. Three basaltic asteroids on orbits with perihelia of 1.07, 1.04, and 1.23 AU have recently been discovered, and it has been suggested that these may be typical of the parent objects for the basaltic meteorites (Cruikshank et al., 1991). Wetherill (pers. comm.) has pointed out that the earth-impact efficiency of Amor asteroids is small, but this would be consistent with the low fall rate of basaltic meteorites compared with the other classes. In addition, values of 4–6 for the ^{3}He/^{21}Ne ratio are typical for unheated chondrites (e.g., Graf et al., 1990), and 42 eucrites, 19 howardites and 13 diogenites have ^{3}He/^{21}Ne values of 5.8 ± 1.7, 5.4 ± 2.2, and 4.4 ± 1.1, respectively (Schultz and Kruse, 1989). The similarity of these values to the chondrite value is striking and is presumably because the targets for these elements are lithophile elements and similar in relative abundance in both classes. The data do not suggest systematically greater loss of the lighter He from the basaltic meteorites due to the higher temperatures associated with smaller perihelia.

It should be stressed that although small perihelia are not the norm for basaltic meteorites, small perihelia probably do exist in about the same proportion as for chondrites. Based on our natural TL vs. terrestrial age plots, we suggest that 5 out of 24 basaltic meteorites have been heated, compared with 7 out of 39 for ordinary chondrites (McKeever and Sears, 1980; Benoit and Sears, 1991). Considering the small statistics, these numbers are in good agreement with the orbital data of Simonenko (1975), who found that 8 out of 43 ordinary chondrites had perihelia of <0.8 AU. Estimates based on fireballs are in reasonable agreement with the data of Simonenko (Wetherill, 1985). Assuming that the distribution of natural TL levels is primarily governed by the distribution of orbits, we see no difference between basaltic meteorites and chondrites in this respect and no reason to invoke different orbital distributions.

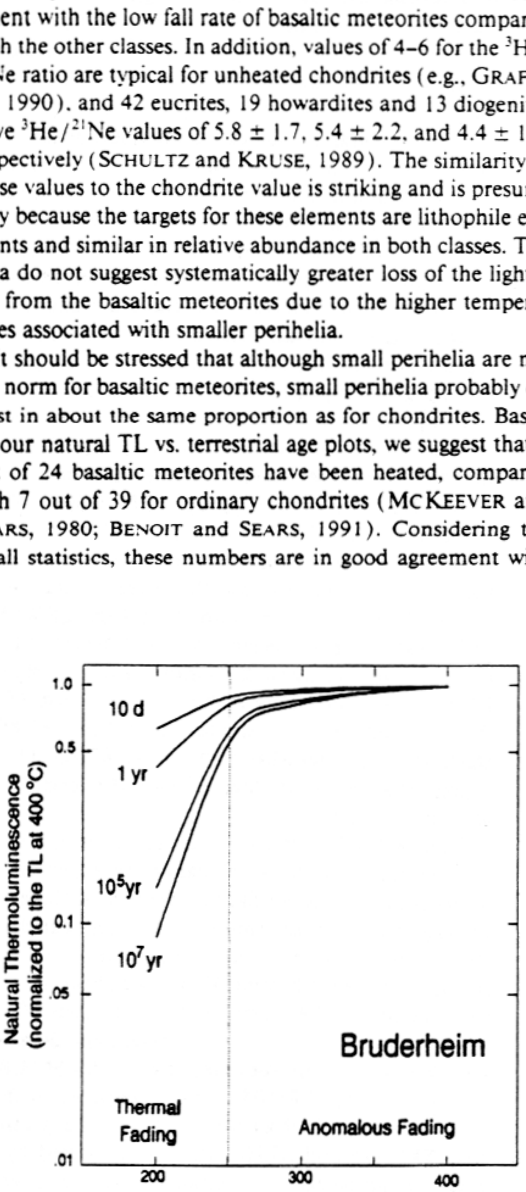

FIG. 6. A calculated version of Fig. 1 for the ordinary chondrite Bruderheim determined from the fading observed in the laboratory. Bruderheim does not show anomalous fading, but did, like all the samples, display some thermal decay during the measurements. The above diagram indicates that the effect of thermal decay on the calculated curves in excess of the experimental uncertainty occurs only at glow curve temperatures <250°C.

Lunar Meteorites

The work on the natural TL of lunar meteorites of Sutton and Crozaz (1983) and Sutton (1986a,b) resulted in several significant conclusions concerning the history of lunar meteorites; for example, that ALHA81005 and Y791197 were shock-heated at the time of lunar ejection and suffered a short transit time, that Y82192 reached earth on a small perihelion orbit, and that the burial depth of Y791197 was on the order of meters. These results depend critically on the conclusion that the low natural TL levels of lunar meteorites are not due entirely to anomalous fading.

We have argued, on the basis of our own anomalous fading measurements and the plots of natural TL against terrestrial age, that meteorites whose natural TL(250) is ≤5 krad have probably suffered draining of their natural TL from the equilibrium levels dictated by build-up and thermal plus anomalous decay. We would agree with Sutton (Sutton and Crozaz, 1983; Sutton, 1986a,b), that ALHA81005, Y791197, and Y82192 have had their natural TL drained within the last 10^5–10^6 years, either by shock heating or small perihelion. The 10 Ma cosmic ray age for Y82192 precludes recent heating at the time of ejection from the Moon, but this constraint does not apply to the others which have cosmic ray exposure ages of <0.2 Ma (Nishiizumi et al., 1991; Vogt et al., 1991; Eugster, 1989). We suggest that the TL systematics for MAC88104/5 are similar to those of ALHA81005 and Y791197, that they suffered major reheating, and that their current levels of natural TL reflect build-up during Moon-Earth transit. Assuming (1) a minimum dose rate of 10 rad/year, (2) the experimentally determined anomalous fading parameters *a* and *b*, (3) that the level of the low and high temperature natural TL of ALHA81005 before shock-heating was equal to 10 krad, (4) that the shock-heating event was ejection from the Moon, then Sutton and Crozaz (1983) calculated a Moon-Earth transit time of 2.5 ka. This is an upper limit because the dose rate is a lower limit. The same procedure yields a Moon-Earth transit time of 19 ka years for Y791197 (Sutton, 1986a).

The low temperature natural TL values for MAC88104/5 are the highest yet obtained for any lunar meteorite and in terms of Fig. 4a are borderline between being low due to a large terrestrial age and low due to recent heating. Unfortunately, the terrestrial age information obtained from cosmogenic isotopes for these meteorites does not help us to understand the history of these meteorites. Vogt et al. (1991) found a terrestrial age of 0.10–0.19 Ma, Nishiizumi et al. (1991) suggested 0.25 Ma, while three fragments analyzed by Eugster et al. (1991) yielded values of 0.43 ± 0.07, 0.35 ± 0.06, and 0.30 Ma. However, our laboratory decay experiments are probably inconsistent with the low levels of natural

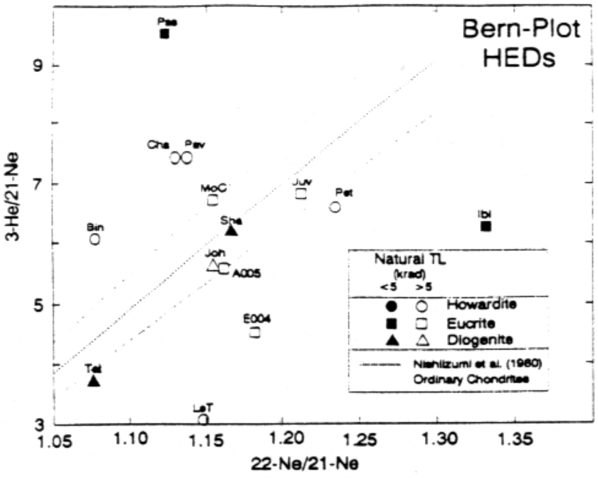

FIG. 7. Plot of $^3He/^{21}Ne$ vs. $^{22}Ne/^{21}Ne$ for basaltic meteorites. This is an attempt to identify reheated meteorites which should have $^3He/^{21}Ne$ ratios below that expected from their $^{21}Ne/^{22}Ne$. The broken lines are the trends (regression line ± 10%) observed for H chondrites due to variation with depth. Eucrites would presumably show similar shielding effects although the type of the curve might be different.

TL in the MacAlpine Hills lunar meteorites being entirely due to equilibrium processes. The decay rates observed are such that 10^6–10^7 y would be required to reproduce the low levels of natural TL observed, and cosmic ray exposure ages for these meteorites are $\ll 10^6$ years; NISHIIZUMI et al. (1991) and VOGT et al. (1991) report cosmic ray exposure ages of 50 ka and 40–110 ka, respectively. If we assume that the low natural TL levels of MAC88104/5 are due to recent heating and not to especially large terrestrial ages, then we obtain 2.0 and 1.8 ka for the Moon-Earth transit times of MAC88104 and MAC88105, respectively, using the methods and assumed dose-rate of Sutton, and the present anomalous fading parameters.

The Moon-Earth transit times determined for the MacAlpine Hills lunar meteorites are so close to that of ALHA81005 that it is worthwhile considering the likelihood that they were ejected from the same location by the same event. The terrestrial age of ALHA81005 seems well constrained below 20 ka, and it was probably buried at a shallower depth on the moon than MAC88104/5 (NISHIIZUMI et al., 1991; VOGT et al., 1991; EUGSTER et al., 1991; EUGSTER, 1989). ALHA81005 is a mature regolith, while MAC88104/5 is a highly immature regolith breccia (OSTERTAG et al., 1986; WARREN et al., 1990). Shock glasses and maskelynite are absent in ALHA81005, unlike MAC88104/5 (TAKEDA et al., 1991). Also, ALHA81005 shows a greater range of pyroxene compositions than MAC88104/5. On the basis of find-site, petrology and, probably, terrestrial age data, it is clear that ALHA81005 and the MacAlpine Hills lunar meteorites are not paired. However, it seems quite likely that a major impact of the sort required to eject the lunar meteorites would affect a wide area and that a variety of rock types from a variety of depths might be ejected.

CONCLUSIONS

Lunar and basaltic meteorites have low levels of natural TL, compared with ordinary chondrites, both at 250°C in the glow curve and at 400°C. Measurements of the kinetics of decay at room temperature in the laboratory show that 5 basaltic meteorites, MAC88104 and MAC88105 display the phenomenon of 'anomalous fading' which is often a property of terrestrial feldspars of igneous origin. Within the limits of the current measurements, it is possible that anomalous fading explains the low TL levels of most of these meteorites, but about 20% of the basaltic meteorites and the lunar meteorites have experienced recent heating events. In most instances these low natural TL values are the result of small perihelia orbits, and the fraction of basaltic meteorites with low natural TL is comparable to the fraction of ordinary chondrites with low natural TL and the fraction of chondrites with perihelia <0.8 AU. Following the arguments of WETHERILL (1987), this might suggest ejection from the asteroid belt via similar resonances. Some exceptions include the unusual shocked eucrite (LEW85303 and meteorites paired with it) and the regolith breccia (Kapoeta) which may have suffered a recent heating due to regolith working or shock heating.

The present TL data largely confirm earlier pairing suggestions. However, the present data would suggest that EET87528 may be paired with the other members of the major EET howardite group (EET87503, EET87509, EET87510, EET87513, EET87518, EET87531) and the group may actually consist of two separate meteorites. Contrary to earlier suggestions, the present data suggest that EET87512 is not paired with the others. LEW85313 and LEW85441 have appreciably different natural TL and may also not be paired. Our data confirm the pairing of the eucrites LEW85303 with LEW88005 and ALHA76005 with ALHA77302, the mesosiderites EET87500, EET87501, and the lunar meteorites MAC88104, MAC88105. The data also suggest that the howardites EETA79006 and EETA83376 are possibly paired.

Like the basaltic meteorites, the lunar meteorites also show low natural TL levels which cannot be explained purely in terms of the anomalous fading observed for these samples in the laboratory. These samples have been heated within the last 10^5–10^6 y, either by solar heating due to small perihelion passage or by shock heating. If the shock heating was ejection from the Moon, then reasonable assumptions of the cosmic ray dose rate, original natural TL levels, and decay constants yield Moon-Earth transit times of 2.0 ka for MAC88104 and 1.8 ka for MAC88105. This compares with 2.5 for ALHA81005 and 19 ka for Y791197. The possibility that MAC88104/5 and ALHA81005 were ejected by the same event should be borne in mind, though compositional and textural data on these meteorites clearly indicate that they are not paired.

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