Reprinted from "Field and Laboratory Investigations of Antarctic Meteorites Collected by United States Expeditions, 1985-1987. (eds. U.B. Marvin and G.J. MacPherson), *Smithsonian Contributions to Earth Sciences*, Number 30, 57-68, 1992.

7. Natural Thermoluminescence Levels and the Recovery Location of Antarctic Meteorites

(Received 1988 June 19, accepted in revised form 1989 March 18)

Fouad A. Hasan, Roberta Score, Benjamin M. Myers,
Hazel Sears, William A. Cassidy, and Derek W.G. Sears

In this article, the levels of natural thermoluminescence in 379 Antarctic meteorites are reported; 86 samples were from the 1985 collection at the Allan Hills site, 88 were collected in the Lewis Cliff region during the 1985–1986 season and 165 were collected at the Lewis Cliff sites during the 1986–1987 field season. An additional four samples came from the Allan Hills site in 1986, and 36 came from six other ice fields. The distributions of natural thermoluminescence data for the 1985 Allan Hills and 1986 Lewis Cliff collections are similar, with ks in the histograms at 32–63 krad with values ranging between <1 krad and 327 ± 3 krad. On the basis of a study of 23 meteorites of known ^{26}Al content, the natural TL data for these two collections seem consistent with the majority of the meteorites having terrestrial ages of 150,000 ± 100,000 years, while a smaller fraction fall in the 400,000 ± 200,000 year range. On the other hand, samples from the 1985 Lewis Cliff collections show a greater proportion of samples with natural thermoluminescence in the 5–20 krad range, consistent with the majority having ages in the order of 400,000 ± 200,000 years. The difference within the samples collected at Lewis Cliff is related to collection site, the meteorites collected at Meteorite Moraine having a peak at 50–63 krad, with relatively little spread in natural TL, while the meteorites collected on the Lewis Cliff Ice Tongue include a larger proportion with natural TL in the 5–20 krad range. There seems to be a trend in natural TL with location on the Lewis Cliff Ice Tongue, with natural TL levels tending to be higher in the northern part of the Tongue compared with the southern part, but it is not clear if this is an effect of concentration mechanism or a few major pairings. 14% of the 379 samples have low natural TL (<5 krad), which can be attributed to recent heating (close solar passage, shock, or atmospheric heating). Three meteorites have extremely high natural TL strongly suggestive of high radiation doses or low temperatures in space (these are ALH85033, LEW85448, and LEW86286), while a further 18 have natural TL values in excess of 100 krad and possibly experienced high extraterrestrial radiation doses or low temperatures.

Introduction

The mineralogical and petrographic surveys made on Antarctic meteorites as part of their initial description identify meteorites which are members of rare or previously unknown classes. However, they do not generally identify members of well-populated classes which have experienced unusual histories, such as particularly long or short terrestrial ages, unusual orbits, or other events resulting in anomalous thermal or radiation histories. To some degree, ^{26}Al measurements provide such information. Natural thermoluminescence (TL) measurements provide data which is complementary to the information available using cosmogenic isotopes and other techniques, and can help in the identification of meteorites with interesting and unusual histories. They can also provide an indication of relative terrestrial ages, and TL measurements can be useful in identifying fragments of a single meteorite (i.e., pairing). The natural thermoluminescence of meteorites was recently reviewed by Sears and Hasan (1986) and Sears (1988).

Thermoluminescence is a measure of the number of excited state electrons in a suitable crystalline lattice. In the chondritic meteorites the lattice is usually feldspar, but it can, on occasion, be various calcic minerals, forsterite, enstatite, quartz, or other trace constituents. The means of excitation is the passage of ionizing radiations, and natural thermoluminescence measurements have successfully been applied to radiation dosimetry and pottery dating for many years; in both cases the TL level is

---

Fouad A. Hasan, Benjamin M. Myers, Hazel Sears, and Derek W.G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701. Roberta Score, Planetary Materials Laboratory, Lockheed, NASA Johnson Space Center, Houston, Texas 77058. William A. Cassidy, artment of Geology and Planetary Sciences, University of sburgh, Pittsburgh, Pennsylvania 15260.

used to determine the absorbed dose. In meteorites, because of the larger dose rates and longer time scales involved, the number of excited electrons is determined by an equilibrium between the rate of excitation and de-excitation, the de-excitation being a thermally controlled process. Simple theoretical treatments yield the following relationship between natural TL level (k), dose rate (R) and temperature (T, in °K):

$$k = \frac{k_m}{1 + \frac{s}{aR} e^{\frac{-E}{kT}}}$$

where the other parameters are factors describing the TL process: s, the Arrhenius factor; k is Boltzmann's constant; E is the difference in energy of the excited state electrons and the conduction band; a is the rate constant for excitation of electrons; k_m is the maximum TL that can be induced (e.g., Sears, 1988). Any event in the history of a meteorite which involves a change in radiation dose and temperature will affect natural TL levels to some extent.

The calculated black-body temperature for a meteorite at 1 a.u. is 240 K (assuming plausible values for size and albedo) and dose rates are in the order of 1 rad/year. On earth, temperatures and dose rates are probably around 293 and 1 mrad/year, respectively. A relationship between natural TL and terrestrial age is therefore to be expected as the equilibrium TL level falls from its extraterrestrial value to its terrestrial value (Sears and Mills, 1974; Melcher, 1981a; McKeever, 1982). Thus, taking $s = 2 \times 10^{13}$/sec, E = 1.43 eV (McKeever, 1982), this simple treatment suggests that at temperatures observed in the central U.S. (say 15° C) natural TL levels decay by a factor of 20 in about 5×10^4 years, while at Antarctic temperatures (say −5° C) the TL fades by a factor of about 20 in 3×10^6 years. This relationship between natural TL and terrestrial age is borne out, to some degree quantitatively, by studies in which natural TL levels are compared with terrestrial ages determined by cosmogenic isotopes (Sears and Durrani, 1980; Hasan et al., 1987, see below). It is the case, however, that a small proportion of meteorites have low levels of natural TL which cannot be attributed to large terrestrial ages, and these must have experienced a recent heating event sufficient to lower their natural TL.

At a perihelion of 0.722 a.u. (the smallest perihelion observed for bright fireballs falling into the Prairie Network camera system), the black body temperature is 236° K. The Lost City meteorite had an orbit with a perihelion of 0.967 a.u., at which distance the black body temperature is 275° K. Substitution of these temperature values into the above equation shows that a factor of 100 difference in natural TL level could result from these differences in perihelion (McKeever and Sears, 1980; Melcher, 1981b).

Of course, there are other means by which the meteorite could have been heated, such as shock-heating. The temperatures involved do not have to be high, but it is necessary for the heating to have occurred sufficiently recently that the equilibrium has not had time to re-establish itself. This time period is unclear, but theoretical treatments seem to indicate time periods in the order of 10^5 years. Another major heating event is passage through the atmosphere, but the effects are limited the outermost centimeter or less (Vaz, 1971; Sears, 1975; Melcher, 1979). In addition, a factor of two variation in natural TL levels due to gradients in the cosmogenic dose rate throughout meteorites has been reported (Vaz, 1971; Sears, 1975; Lalou et al., 1970).

Many of these factors appear to have been involved in determining the natural thermoluminescence levels in 23 Antarctic meteorites of known ^{26}Al activity discussed by Hasan et al. (1987). In Figure 7-1 the earlier data have been replotted using our current methods of natural TL data reduction (see below) and normalizing the ^{26}Al activity to Si, the major target for ^{26}Al production. (These changes result in a slightly improved correlation coefficient, 0.69 compared to 0.62 in the paper by Hasan et al. (1987). While 17 meteorites lie on or near a regression line, six plot well below the line and have presumably suffered recent heating. Two of the six are shock-blackened L6 chondrites (RKPA79001 and RKPA80202, which may be paired), and the heat associated with the shock event may have lowered their natural TL. Two others, which also are paired, have rather high ^{26}Al activities; this situation is analogous to that for Malakal which is known to have experienced an unusual thermal and radiation history (Cressy and Rancitelli, 1974; Melcher, 1981a,b). These matters were discussed by Hasan et al. (1987). Based on our interpretations of Figure 7-1, we may assume that natural values of significantly less than ~5 krad imply recent heating, while values greater than this seem to be reflecting differences in history analogous to those responsible for the ^{26}Al range, predominantly differences in terrestrial age (and, on occasion, low cosmic ray exposure age). We can get some feel, albeit very approximate, of the terrestrial ages involved from a compilation of terrestrial ages by Nishiizumi (1984); five of the meteorites in the natural TL-^{26}Al "cluster," between 30–80 krad and 250–350 dpm/kg Si, have a mean terrestrial age of 150,000 ± 100,000 years, while six meteorites in the "cluster" corresponding to 10–30 krad and 150–250 dpm/kg Si have a mean terrestrial age 400,000 ± 200,000 years. These individuals and their terrestrial ages are listed in table 2 of Hasan et al. (1987). ALHA78008 has an unusual radiation history. Its low ^{26}Al activity (and presumably its low natural thermoluminescence relative to other meteorites involved in the regression line) reflects low cosmic ray exposure, rather than simply a particularly large terrestrial age (Nishiizumi et al., 1979).

In the present paper, we report natural TL data for 379 Antarctic meteorite fragments, we present histograms for most of them (separated into various find sites), and we discuss some possible interpretations of these data.

Experimental Procedures

Our data are listed in Table 7-1. Most of the data were gathered by Fouad Hasan, while data for 27 samples were

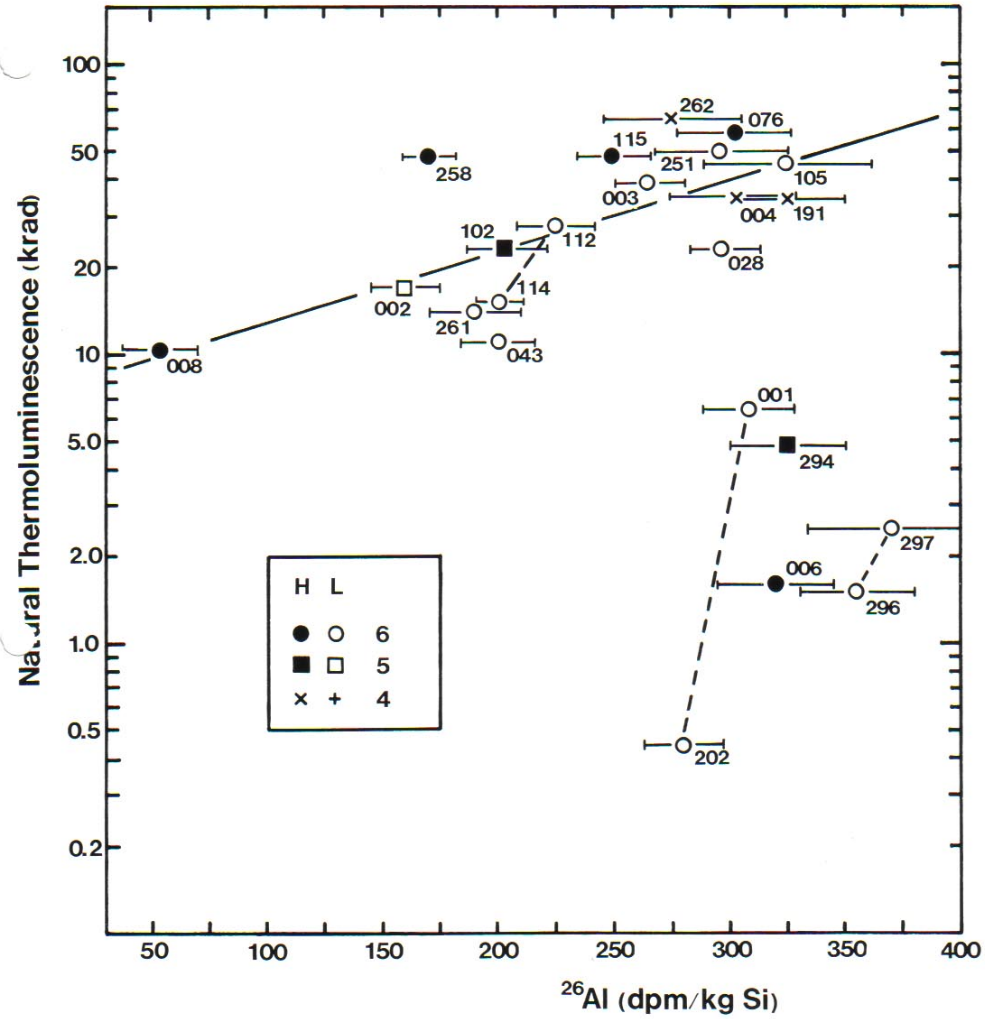

FIGURE 7-1.—Plot of natural thermoluminescence against ^{26}Al activity for 23 Antarctic meteorites. (The samples are from collections made between 1976 and 1981 at Allan Hills, Meteorite Hills, and Reckling Peak and may be identified from table 2 in Hasan et al., 1987.) The data are from Hasan et al. (1987), and references therein, but the TL data have been converted to doses using the method of Hasan et al. (1989) and the Al-26 activities have been calculated relative to Si assuming 17.2% Si for H chondrites and 18.9% Si for L chondrites. The solid line is a regression line through 17 meteorites and has the equation Log(Natural TL) = 0.00250 ^{26}Al + 0.8610, and correlation coefficient 0.69. The broken lines connect samples for which there is evidence for pairing (Scott, 1984).

TABLE 7-1.—Natural thermoluminescence data for Antarctic meteorites. These data supersede previous TL data (October 1987, April 1988, and February 1989 data sets). The quoted uncertainties are the standard deviations shown by replicate measurement of a single aliquot.

Specimen number	Natural TL (krad at 250° C)
ALH85016	40 ± 3
ALH85017	3.6 ± 0.6
ALH85018	33.9 ± 0.6
ALH85020	39 ± 2
ALH85023	55 ± 1
ALH85026	36 ± 2
ALH85027	67 ± 4
ALH85028	18 ± 1
ALH85029	28.2 ± 0.9
ALH85030	29 ± 1
ALH85031	0.9 ± 0.4
ALH85033	258 ± 3
ALH85034	40 ± 3
ALH85035	6.0 ± 0.1
ALH85037	6.2 ± 0.4
ALH85038	27.2 ± 0.3
ALH85039	26.6 ± 0.3
ALH85040	40.5 ± 0.2
ALH85041	17.8 ± 0.6
ALH85042	48 ± 1
ALH85043	107 ± 11
ALH85044	20.2 ± 0.3
ALH85045	63 ± 2
ALH85048	15.1 ± 0.4
ALH85052	2.1 ± 0.5
ALH85054	7.7 ± 0.6
ALH85056	2.5 ± 0.1
ALH85059	50 ± 4
ALH85062	59 ± 6
ALH85063	9.0 ± 0.2
ALH85065	35.4 ± 0.3
ALH85066	77 ± 2
ALH85070	104 ± 2
ALH85071	5.3 ± 0.1
ALH85073	74.2 ± 0.8
ALH85075	45.9 ± 0.7
ALH85076	16.9 ± 0.4
ALH85077	8.3 ± 0.2
ALH85079	92 ± 1
ALH85080	57 ± 5
ALH85082	14.7 ± 0.4
ALH85083	52 ± 5
ALH85084	45 ± 2
ALH85086	54 ± 4
ALH85087	34 ± 2
ALH85090	80 ± 4
ALH85091	24 ± 2
ALH85094	96 ± 2
ALH85097	93 ± 2
ALH85098	5.6 ± 0.2
ALH85100	57 ± 2
ALH85102	1.7 ± 0.2
ALH85103	58 ± 1
ALH85104	0.56 ± 0.09
ALH85105	60 ± 1
ALH85107	19.1 ± 0.6
ALH85108	2 ± 1
ALH85110	148 ± 2
ALH85112	48.0 ± 0.5
ALH85114	8.92 ± 0.07
ALH85115	10 ± 1
ALH85118	38.0 ± 0.3
ALH85119	- -
ALH85120	10.1 ± 0.1
ALH85122	1.9 ± 0.4
ALH85123	74 ± 2
ALH85124	6.9 ± 0.3
ALH85125	10.1 ± 0.1
ALH85127	1.5 ± 0.2
ALH85128	4.3 ± 0.1
ALH85129	36 ± 2
ALH85131	32.2 ± 0.5
ALH85132	13 ± 1
ALH85133	57 ± 4
ALH85135	43.6 ± 0.5
ALH85136	20 ± 1
ALH85137	2.0 ± 0.3
ALH85141	21.5 ± 0.4
ALH85142	26.2 ± 0.2
ALH85143	5.7 ± 0.1
ALH85144	96 ± 2
ALH85146	59 ± 2
ALH85151	155 ± 2
ALH85152	88 ± 2
ALH85155	104 ± 17
ALH85156	8.8 ± 0.2
ALH86600	25.4 ± 0.5
ALH86601	4 ± 0.4
ALH86602	10.0 ± 0.2
ALH86603	80 ± 2
BOW85800	43 ± 3
DOM85501	4.0 ± 0.5
DOM85502	34 ± 2
DOM85503	36.3 ± 0.8
DOM85504	52 ± 1
DOM85505	14.6 ± 0.3
DOM85506	56 ± 1
DOM85508	20.6 ± 0.7
DOM85509	54.1 ± 0.7
DOM85510	63 ± 2
EET86800	2.7 ± 0.1
EET86801	7.7 ± 0.1
EET86802	29 ± 1
GEO85700	9.9 ± 0.2
GEO85701	72 ± 2
GRO85203	110 ± 4
GRO85204	43 ± 2
GRO85205	25.8 ± 0.3
GRO85207	77.3 ± 0.4
GRO85208	71.8 ± 0.2
GRO85209	18 ± 6
GRO85210	23.2 ± 0.3
GRO85211	39 ± 1
GRO85212	74 ± 1
GRO85213	105 ± 1
GRO85214	74 ± 2
GRO85215	0.80 ± 0.04
GRO85216	12.5 ± 0.1
GRO85218	5.6 ± 0.2
LEW85301	0.41 ± 0.03
LEW85303	31 ± 2
LEW85305	0.036 ± 0.005
LEW85306	- -
LEW85313	4.4 ± 0.04
LEW85314	35.8 ± 0.5
LEW85315	22.5 ± 0.6
LEW85316	52 ± 2
LEW85317	35.8 ± 0.2
LEW85318	12.2 ± 0.1
LEW85319	7.3 ± 0.1
LEW85321	41.8 ± 0.8
LEW85322	41 ± 1
LEW85323	6.6 ± 0.1
LEW85324	32 ± 3
LEW85325	20 ± 1
LEW85327	0.37 ± 0.05
LEW85329	26 ± 1
LEW85330	12.4 ± [illegible]
LEW85331	47 ± 2
LEW85333	52 ± 2
LEW85334	26.2 ± 0.5
LEW85335	6.9 ± 0.1
LEW85336	82 ± 4
LEW85337	10.2 ± 0.4
LEW85338	25.6 ± 0.6
LEW85340	27.1 ± 0.8
LEW85341	14 ± 1
LEW85343	40 ± 1
LEW85345	43 ± 3
LEW85346	50 ± 5
LEW85347	52 ± 5
LEW85348	19.5 ± 0.6
LEW85350	10.0 ± 0.2
LEW85351	6.4 ± 0.2
LEW85352	6.6 ± 0.3
LEW85353	0.5 ± 0.2
LEW85354	1.9 ± 0.4
LEW85356	14 ± 1
LEW85357	6.4 ± 0.2
LEW85359	24 ± 1
LEW85360	0.16 ± 0.01
LEW85362	8.0 ± 0.3
LEW85368	0.32 ± 0.02
LEW85371	24 ± 3
LEW85373	20 ± 3
LEW85379	14.4 ± 0.3
LEW85380	6.9 ± 0.1
LEW85381	7.8 ± [illegible]
LEW85383	34 ± [illegible]

TABLE 7-1.—Continued.

imen nber	Natural TL (krad at 250° C)	Specimen number	Natural TL (krad at 250° C)	Specimen number	Natural TL (krad at 250° C)
LEW85384	48 ± 0.5	LEW86035	96.0 ± 0.2	LEW86199	27.6 ± 0.2
LEW85385	8.2 ± 0.1	LEW86037	79 ± 1	LEW86203	16 ± 3
LEW85386	0.090 ± 0.004	LEW86039	5 ± 2	LEW86204	9.7 ± 0.1
LEW85398	14 ± 1	LEW86040	139 ± 5	LEW86206	96 ± 1
LEW85402	31.0 ± 0.9	LEW86041	2.34 ± 0.08	LEW86207	8 ± 1
LEW85403	18.2 ± 0.4	LEW86043	24.8 ± 0.3	LEW86211	6 ± 1
LEW85404	35 ± 1	LEW86044	21.9 ± 0.9	LEW86213	13 ± 2
LEW85405	5.9 ± 0.2	LEW86047	32.2 ± 0.8	LEW86215	9.0 ± 0.9
LEW85406	22 ± 0.4	LEW86050	136 ± 14	LEW86225	42.5 ± 0.7
LEW85413	7.9 ± 0.2	LEW86053	52 ± 5	LEW86226	64 ± 2
LEW85418	10.1 ± 0.2	LEW86055	37.1 ± 0.5	LEW86228	55.8 ± 0.9
LEW85420	96 ± 4	LEW86056	11 ± 0.6	LEW86232	62 ± 4
LEW85423	31.8 ± 0.2	LEW86057	77 ± 6	LEW86238	59 ± 9
LEW85426	6.5 ± 0.1	LEW86060	1.4 ± 0.07	LEW86241	20 ± 1
LEW85427	77 ± 4	LEW86070	58 ± 1	LEW86249	17 ± 1
LEW85428	13.6 ± 0.4	LEW86072	60.5 ± 0.6	LEW86250	45 ± 2
LEW85429	54 ± 1	LEW86073	47 ± 4	LEW86251	55.8 ± 0.7
LEW85433	93 ± 1	LEW86074	47 ± 1	LEW86252	155 ± 19
LEW85441	0.60 ± 0.01	LEW86076	42.7 ± 0.9	LEW86255	60.7 ± 0.6
LEW85443	46 ± 1	LEW86077	101 ± 6	LEW86258	4 ± 2
LEW85445	25.4 ± 0.5	LEW86078	107 ± 4	LEW86266	24.2 ± 0.6
LEW85446	48 ± 1	LEW86079	66.7 ± 0.4	LEW86268	16 ± 1
LEW85448	206 ± 5	LEW86081	93 ± 1	LEW86273	31 ± 1
LEW85449	6.2 ± 0.4	LEW86083	36 ± 2	LEW86282	89 ± 0.2
LEW85450	3.2 ± 0.6	LEW86084	29 ± 1	LEW86286	327 ± 3
LEW85451	0.88 ± 0.02	LEW86085	19 ± 1	LEW86295	5.7 ± 0.3
LEW85454	1.76 ± 0.01	LEW86086	93 ± 2	LEW86302	1.7 ± 0.1
LEW85455	3.4 ± 0.3	LEW86088	54.9 ± 0.4	LEW86305	33 ± 1
85456	62.5 ± 0.6	LEW86089	4.7 ± 0.3	LEW86311	53 ± 1
LEW85457	1.63 ± 0.03	LEW86090	6.9 ± 0.1	LEW86312	19.5 ± 0.1
LEW85458	33 ± 0.06	LEW86091	12.7 ± 0.1	LEW86314	74 ± 2
LEW85459	1.7 ± 0.1	LEW86096	76 ± 1	LEW86317	68 ± 2
LEW85460	11.24 ± 0.5	LEW86098	2.9 ± 0.1	LEW86327	19.6 ± 0.1
LEW85461	77 ± 2	LEW86099	9.7 ± 0.4	LEW86337	53 ± 2
LEW85463	1.5 ± 0.1	LEW86101	6 ± 1	LEW86340	96 ± 8
LEW85464	12.5 ± 0.3	LEW86104	27.2 ± 0.2	LEW86344	19.4 ± 0.7
LEW85465	5.3 ± 0.2	LEW86107	40 ± 2	LEW86349	84 ± 2
LEW85472	24.2 ± 0.7	LEW86110	53.2 ± 0.5	LEW86350	3 ± 1
LEW86001	28 ± 4	LEW86111	59 ± 28	LEW86352	20.4 ± 0.1
LEW86002	13 ± 3	LEW86115	52.5 ± 0.7	LEW86354	25.0 ± 0.3
LEW86011	157 ± 1	LEW86118	3.6 ± 0.65	LEW86360	57 ± 1
LEW86012	50.8 ± 0.9	LEW86119	1.7 ± 0.08	LEW86364	29.7 ± 0.3
LEW86013	93 ± 2	LEW86120	22.9 ± 0.9	LEW86366	44 ± 1
LEW86014	93 ± 2	LEW86123	21 ± 3	LEW86367	8 ± 2
LEW86015	122 ± 6	LEW86134	- -	LEW86368	96 ± 4
LEW86016	8.2 ± 0.3	LEW86135	88 ± 4	LEW86371	28.4 ± 0.8
LEW86017	17 ± 1	LEW86138	196 ± 22	LEW86376	9.9 ± 0.6
LEW86018	- -	LEW86152	107 ± 2	LEW86380	45 ± 9
LEW86019	114.8 ± 0.7	LEW86160	10.2 ± 0.2	LEW86382	3.76 ± 0.07
LEW86020	37.0 ± 0.2	LEW86161	69 ± 2	LEW86385	50 ± 1
LEW86021	36 ± 2	LEW86163	10 ± 3	LEW86388	67 ± 2
LEW86022	- -	LEW86164	13.1 ± 0.5	LEW86393	21.7 ± 0.4
LEW86023	32 ± 3	LEW86165	50.6 ± 0.7	LEW86395	22.5 ± 0.1
LEW86024	21.9 ± 0.1	LEW86166	2.3 ± 0.2	LEW86396	2.6 ± 0.2
LEW86025	0.9 ± 0.1	LEW86168	96 ± 2	LEW86397	25.9 ± 0.3
LEW86026	64 ± 2	LEW86174	93 ± 4	LEW86407	16.5 ± 0.1
LEW86028	38 ± 2	LEW86181	16 ± 1	LEW86418	0.85 ± 0.07
LEW86030	75. ± 0.6	LEW86183	22.3 ± 0.6	LEW86438	88 ± 2
86031	127 ± 2	LEW86186	17.9 ± 0.3	LEW86442	28.7 ± 0.6
LEW86033	62 ± 2	LEW86195	16.0 ± 0.5	LEW86451	52 ± 2

TABLE 7-1.—Continued.

Specimen number	Natural TL (krad at 250° C)	Specimen number	Natural TL (krad at 250° C)	Specimen number	Natural TL (krad at 250° C)
LEW86463	30 ± 4	LEW86490	58.5 ± 0.2	LEW86544	18.9 ± 0.3
LEW86465	39.6 ± 0.7	LEW86499	13.5 ± 0.5	LEW86546	57 ± 2
LEW86466	47 ± 1	LEW86500	38 ± 1	LEW86549	52 ± 4
LEW86470	21.3 ± 0.4	LEW86503	28.4 ± 0.3	QUE86900	16 ± 7
LEW86471	5 ± 0.6	LEW86514	63.0 ± 0.8	RKP86700	9 ± 1
LEW86472	42.7 ± 0.3	LEW86515	54 ± 1	RKP86701	37.8 ± 0.8
LEW86473	87.1 ± 0.2	LEW86522	0.9 ± 0.2	RKP86702	12 ± 1
LEW86479	80 ± 10	LEW86525	7.3 ± 0.1	RKP86703	10.2 ± 0.4
LEW86485	28 ± 0.9	LEW86528	27 ± 0.3	RKP86704	38 ± 2
LEW86489	30.0 ± 0.9	LEW86534	14.4 ± 0.4	RKP86705	13.7 ± 0.4

gathered by Roberta Score. Over the eighteen month period during which the data were gathered, which is also the first eighteen months of the project, our techniques and procedures were constantly improved and, therefore, the data vary in quality. The procedures are essentially those described by Hasan et al. (1987), but improvements concerned primarily the criteria for the selection of samples and subsequent storage conditions. Initially, samples were taken randomly. Later, an attempt was made to take samples at least 1 cm from any obvious fusion crust. Most recently, sampling was restricted to those meteorites in which it was possible to take samples at least 1 cm away from all existing surfaces. This restricts the measurements to samples >20g. Samples in the present data base were sent from JSC to the TL laboratory at Arkansas through the United States mail. In the future, samples will be hand-carried to avoid the danger of accidental heating in transit.

We also have developed a means of standardizing our reporting procedure, so that a single datum for each meteorite is reported. The natural TL signal must be normalized to remove the major effects of meteorite-to-meteorite differences in TL sensitivity due to sample heterogeneity, shock, and metamorphism. There are two commonly used means of doing this, and the relative advantages and disadvantages of each were discussed by McKeever and Sears (1980). Here we use a composite method described by Hasan et al. (1989). It is important to note that (1) these new data replace *both* measures of natural TL in earlier versions of our data (*Antarctic Meteoric Newsletter*, 11(1), 11(2)); and (2) the uncertainties quoted refer only to the standard deviation shown by replicate measurements of a single powder and not to total accuracy, which would require measurements on several separate chips of meteorite. We quote natural TL values observed at 250° C, since this appears to be the optimum temperature: low enough to be sensitive to the events of interest and yet high enough to avoid the most trivial heating (Melcher, 1981a,b; Hasan et al., 1987, 1989).

Results and Discussion

Histograms of natural TL values for the present samples from the Allan Hills and Lewis Cliff regions are shown in Figure 7-2. The histograms have been labeled to identify individual meteorites in the belief that in this form the data will be most helpful, especially with regard to identifying paired meteorites. Unfortunately, most of the samples are unclassified at the present time, and there is little other information relevant to pairing.

The distribution in natural thermoluminescence for the 1986 samples from Lewis Cliff resembles that for the Allan Hills 1985 samples, but the Lewis Cliff 1985 samples seem to show a distribution that favors lower values (Hasan and Sears, 1988). The distribution of natural TL data for the Allan Hills 1985 meteorites shows a peak in the 32–63 krad intervals, consistent with the cluster in Figure 7-1 showing a mean terrestrial age of 150,000 ± 100,000 years. Seventy-five per cent of the samples fall in the range 5–100 krad, while three show values exceeding 125 krad, and one (ALH85033) is particularly noteworthy at 258 ± 3 krad. The other highs are 148 ± 2 krad (ALH85110) and 155 ± 2 krad (ALH85151). Such values seem high even for observed falls, and may indicate meteorites which have experienced high radiation doses or unusually low storage temperatures in space. The distribution tails more slowly toward lower values. Thirteen samples (i.e., 15% of all the ALH85 meteorites) register below the 5 krad level we would associate with heated samples, affected by small perihelia, recent shock heating, or atmospheric heating. There are some minor peaks in the histogram (e.g., those at 5.0–6.3 krad and 1.6–2.5 krad) which might indicate that some of the individuals in these peaks are paired. Of the five meteorites in the 5.0–6.3 krad range, three (ALH85071, 85098, and 85143) are H5 chondrites and are possibly paired. The other two are an H6 chondrite (ALH85037) and an LL6 chondrite (ALH85035). The group in the 1.6–2.5 krad range are two H5 chondrites (ALH85102, 85122), which may be paired, two H6 chondrites (ALH85052, 85108), which also may be paired, and one LL6 chondrite (ALH85137).

The 1985 collection from the Lewis Cliff site does not seem to show any tendency to an overall "preferred" value. Instead, values are fairly uniformly spread between 7.3 and 63 krad, although there is an indication that the distribution is bimodal with a hiatus in the 16 to 20 krad interval. The 20–63 krad range corresponds to the "cluster" in Figure 7-1 with 150,000 ± [illegible]0,000 year terrestrial ages, while the 5–16 krad range corresponds, approximately, to the "cluster" in Figure 7-1 with 400,000 ± 200,000 year terrestrial ages. There is only one Lewis Cliff sample with natural TL greater than 100 krad, namely LEW85448 (206 ± 5 krad), whereas six samples in the Allan Hills 1985 data set had values this high. Eighteen samples, making up 17% of the Lewis Cliff 1985 collection, have natural TL less than 5 krad and have presumably suffered some form of recent heating.

The shape of the histogram for the LEW86 samples resembles that of the ALH85 samples, but with a more pronounced peak at 50–63 krad. Seventy per cent of the samples have values between 13 and 100 krad, which is very similar to the group in Figure 7-1 that has a mean terrestrial age of 150,000 ± 100,000 years. There are also minor peaks at 79–100, 25–32, 7.9–10 krad, which may not be significant. High values are relatively common in the LEW86 data, 12 meteorites (7.2%) having values over 100 krad with LEW86286 at a remarkable 327 ± 3 krad, suggestive of high radiation doses or low temperatures in space. Eighteen meteorites (11% of the LEW86 samples) have values below 5 krad, suggestive of recent heating.

The difference in the distribution of natural TL data between the 1985 and 1986 collections at Lewis Cliff is related to find location. Histograms of the natural TL in samples collected on the Lewis Cliff icefields are shown in Figure 7-3. The meteorites have been separated into those found at Meteorite Moraine and those found on the Ice Tongue (Figure 7-4, 7-5), and the latter have also been subdivided according to latitude (Figure 7-4). The northernmost tip of the Tongue has not yet been systematically searched, so the lack of meteorites in the latitude intervals numbered 8–10 in Figure 7-3 is not significant. Nevertheless, it is clear that the distribution of meteorites over the region is not random, but that meteorites tend to cluster along the western edge of the Tongue. The latitude intervals are not equal, but were chosen to separate meteorites found on the Upper Ice Tongue from those found on the Lower Ice Tongue; these regions are separated by a steep step in the ice surface.

The peak in the histogram for the Lewis Cliff 1986 samples (50–63 krad), which is absent in the distribution for the 1985 Lewis Cliff samples, is due, in large part, to the meteorites from Meteorite Moraine. On the basis of the appearance of hand-specimens, considerable pairing among the Meteorite Moraine samples was suspected, and the spread in TL data is less for this site than the others. However, only 25 of our 67 Meteorite Moraine meteorites have yet been classified (10 are H5, 9 are L6, 4 are H6, 1 is LL6, and 1 is L4), while 10 of the 13 in the 50–63 krad peak are unclassified; the other three are L4, L6, and LL6.

Most of the 13% of the samples with natural TL levels below 5 krad were found on the upper part of the tongue (latitude intervals 1–5). Furthermore, there may be a weak tendency for the histograms to be skewing to higher TL values as one proceeds from the upper part of the Tongue to the lower part (i.e., proceeds north); intervals 3, 4, and 5, for instance, have about half of the samples with TL >5 krad in the range 5–20 krad, while the intervals 6 and 7 have the bulk of their samples in the range 16–100 krad. It is possible that a few major pairings are responsible for this spatial distribution. However, it is also possible that systematic variations in terrestrial age (and therefore natural TL) with location on the ice could result from the mechanisms by which the meteorites were accumulated (e.g., Bull and Lipschutz, 1982; Annexstad, 1986; Drewry, 1986). It will be necessary to make a careful study of potential pairing before seriously examining the possibility of a spatial variation in natural TL levels at this field. It will also help to have data for samples from the remainder of the ice field. The northern tip of the Lewis Cliff Ice Tongue is the prime site for the 1988–1989 field season.

Data for 36 samples collected at other sites, and a further 4 samples collected in the Allan Hills region in 1986, are listed in Table 7-1 but are too few for meaningful discussion of possible trends. Four of the samples have natural TL values less than 5 krad, and two have values in excess of 100 krad (these are listed below). Three of the 5 samples collected at Reckling Peak in the 1986–1987 season have values in the 7.9–16 krad range, while the "preferred values" among samples collected at Grosvenor Mountains and the Dominion Range during the 1985–1986 season, based on these very limited data, are in the 50–125 krad range.

Conclusions

Data for the first eighteen months of systematic measurement of natural thermoluminescence levels in Antarctic meteorites identify several meteorites with unusual histories, allow some crude sorting of meteorites by terrestrial age, and provide data which will be useful in the recognition of paired meteorites. There is evidence in the data that the patterns of natural TL levels vary with find site, which could have implications for concentration mechanisms.

Based on a comparison with Figure 7-1, and the known terrestrial ages for the samples in the plot determined from cosmogenic isotopes, the majority of samples in Allan Hills 1985 and Lewis Cliff 1986 collections have terrestrial ages in range 150,000 ± 100,000 years, with most of the remainder in the order of 400,000 ± 200,000 years. For the Lewis Cliff 1985 collection, the majority of the meteorites have natural TL values suggestive of terrestrial ages in the range 400,000 ± 200,000 years, with a smaller fraction in the 150,000 ± 100,000 year range.

Fourteen percent of the 379 Antarctic meteorites in the present study have natural TL values suggestive of recent heating (small perihelion orbits, shock heating, or heating during atmospheric passage). These are as follows:

ALH85; 017, 031, 052, 056, 102, 104, 107, 112, 115, 119, 127, 128, 137,

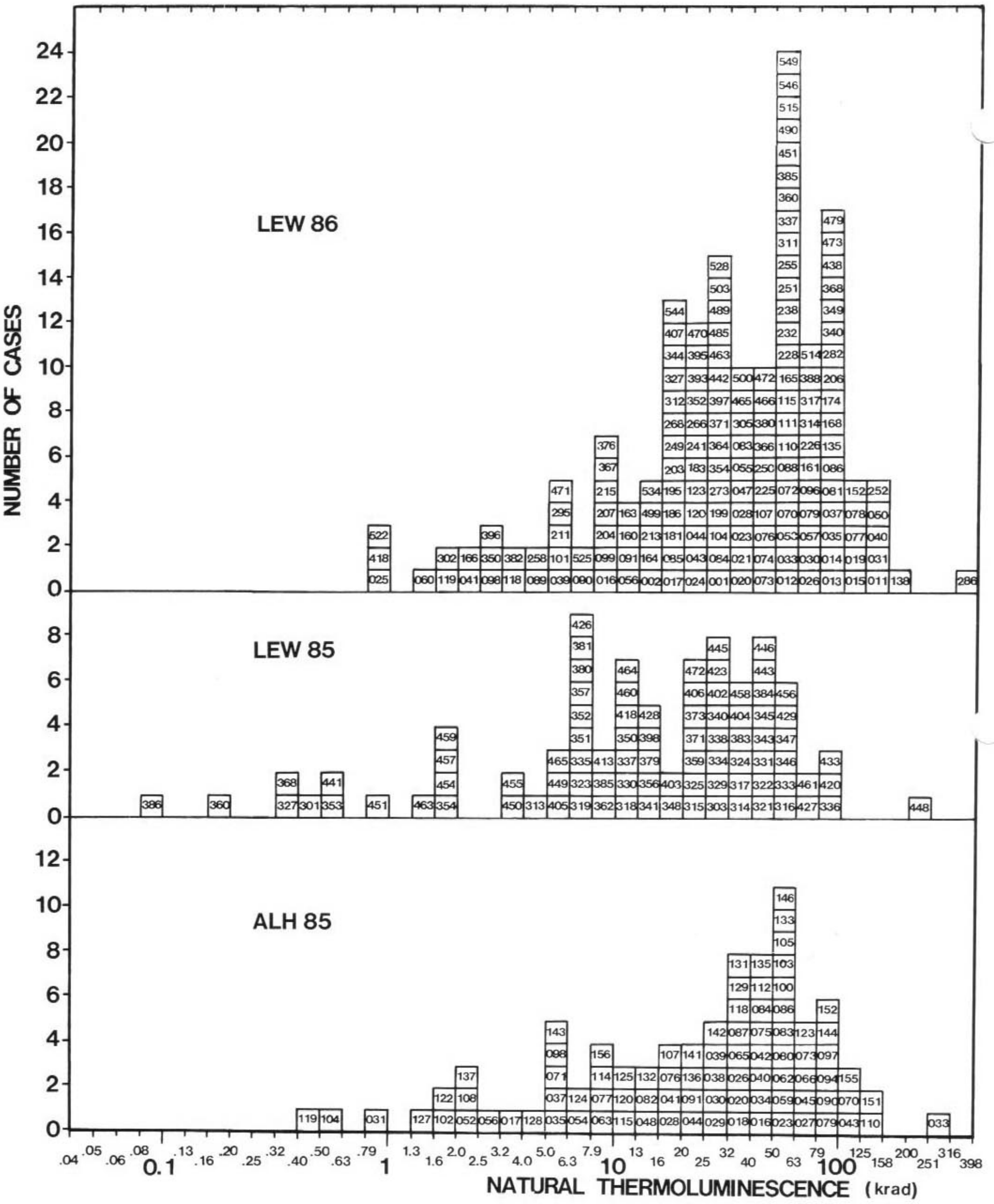

FIGURE 7-2.—Histograms of natural TL values in 86 meteorites from the 1985 collection at the Allan Hills, 86 meteorites collected from the Lewis Cliff region in 1985–1986 and 162 meteorites collected in the Lewis Cliff region in 1986–1987. Two samples from the LEW85 collection (LEW85305 and 85306), and three from LEW86 (LEW86022, 86018, and 86134) collections, plot off the graph to lower values.

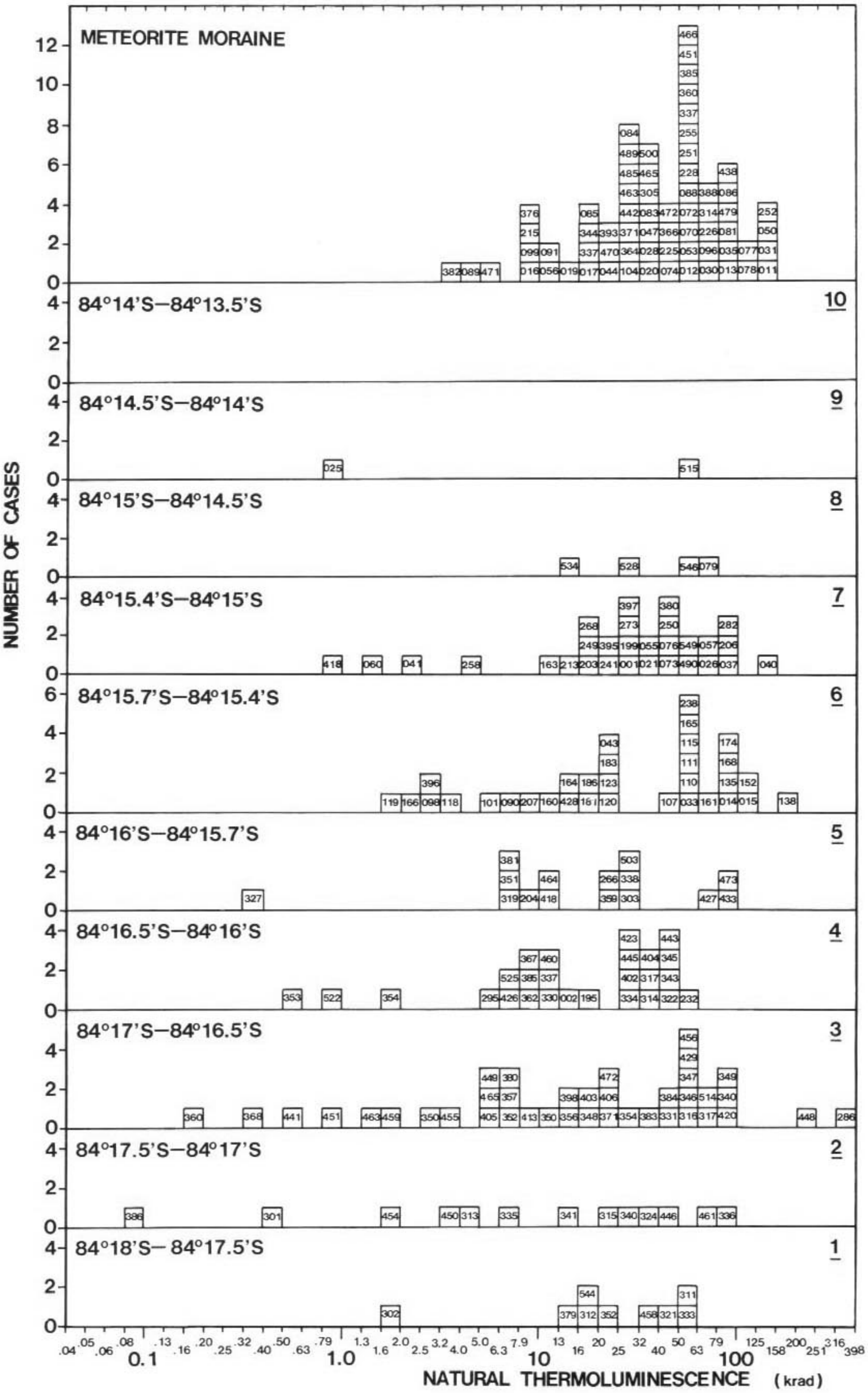

FIGURE 7-3.—Histograms of natural TL values for meteorites collected in the Lewis Cliff region of the Antarctic in the 1985–1986 and 1986–1987 field seasons. Samples from Meteorite Moraine and from the Lewis Cliff Ice Tongue have been plotted separately, the latter being subdivided into 10 regions according to latitude; the sites are located in Figure 7-4. The five samples plotting off the graphs to the left are distributed over the regions as follows: region 2, LEW85305; region 3, LEW85306; region 6, LEW86134; region 10, LEW86022; Meteorite Moraine, LEW86018.

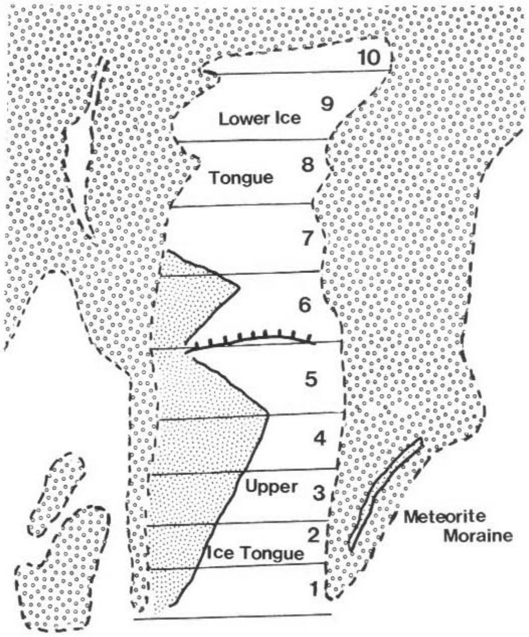

FIGURE 7-4.—Sketch map showing the locations of the regions referred to in Figure 7-3. North is to the top of the figure, the Tongue is approximately 2.3 km wide. The shading refers to moraine and snow (circles) and regions of the highest meteorite densities (dots). Regions 8–10 were searched in the 1988–1989 field season and data are not yet available.

LEW85; 301, 305, 306, 313, 327, 353, 354, 360, 368, 386, 441, 450, 451, 454, 455, 457, 459, 463,

LEW86; 018, 022, 025, 041, 060, 089, 098, 118, 119, 134, 166, 258, 302, 350, 382, 396, 418, 522,

DOM85501, EET86800, GRO85215, ALH86601.

Three meteorites have exceptionally high natural thermoluminescence values which suggest high radiation doses or low storage temperatures in space; these are ALH85033, LEW85448 and LEW86286. Meteorites with natural thermoluminescence values greater than 100 krad, and for which the possibility of exposure to high radiation doses or low temperatures should be borne in mind, are:

ALH85; 043, 070, 110, 151, 155,

LEW86; 011, 015, 019, 031, 040, 050, 077, 078, 138, 152, 252.

ACKNOWLEDGMENTS.—We are grateful to Rene Martinez, Cecilia Satterwhite, and Carol Schwarz for their help in various forms, the MWG for their cooperation, Ralph Harvey for his discussions, Steve McKeever and an anonymous reviewer for helpful reviews, Raye Stucker for help in manuscript preparation, and Ursula Marvin for her gracious editorial assistance. This work is supported by grants from the National Science Foundation and the National Aeronautics and Space Administration (DPP-8613998 and NAG 9-81/natural TL, respectively, to DWGS, and DPP-8314496, to WAC).

Literature Cited

Annexstad, J.O.
1986. Meteorite Concentration Mechanisms in Antarctica. *In* J.O. Annexstad, L. Schultz, and H. Wänke, editors, Workshop on Antarctic Meteorites. *LPI Technical Report,* 86-01, pages 23–25. Houston: The Lunar and Planetary Institute.

Antarctic Meteorite Newsletter, 11(1), February. 1988.

Antarctic Meteorite Newsletter, 11(2), August. 1988.

Bull, C., and M.E. Lipschutz
1982. Introduction. *In* C. Bull and M.E. Lipschutz, editors, Workshop on Antarctic Glaciology and Meteorites. *LPI Technical Report,* 82-03, pages 6–26. Houston: The Lunar and Planetary Institute.

Cressy, P.J., and L.A. Rancitelli
1974. The Unique Cosmic-ray History of the Malakal Chondrite. *Earth and Planetary Science Letters,* 22:275–283.

Drewry, D.J.
1986. Entrainment, Transport, and Concentration of Meteorites in Polar Ice Sheets. *In* J.O. Annexstad, L. Schultz, and H. Wänke, editors, Workshop on Antarctic Meteorites. *LPI Technical Report,* 86-01, pages 37–47. Houston: The Lunar and Planetary Institute.

Hasan, F.A., M. Haq, and D.W.G. Sears
1987. The Natural Thermoluminescence of Meteorites; I: Twenty-three Antarctic Meteorites of Known ^{26}Al Content. *Proceedings of the 17th Lunar and Planetary Science Conference, Journal of Geophysical Research,* 92:E703–E709.

Hasan, F.A., R. Score, and D.W.G. Sears
1989. The Natural Thermoluminescence Survey of Antarctic Meteorites; A Discussion of Methods for Reporting Natural TL Data. *Lunar and Planetary Science XX,* pages 383–384. Houston: The Lunar and Planetary Institute.

Hasan, F.A., and D.W.G. Sears
1988. Thermoluminescence Evidence for a Terrestrial Age Difference between Allan Hills and Lewis Cliff Meteorites. *Lunar and Planetary Science XIX,* pages 457–458. Houston: The Lunar and Planetary Institute.

Lalou, C., D. Nordemann, and J. Labyrie
1970. Etude Preliminaire de la Thermoluminescence de la Meteorite Saint Severin. *Compte Rendu Hebdomadaire des Séances de l'Académie des Sciences, Serie B (Sciences Physiques),* 270:2401–2404.

McKeever, S.W.S.
1982. Dating of Meteorite Falls Using Thermoluminescence: Application to Antarctic Meteorites. *Earth and Planetary Science Letters,* 58:419.

McKeever, S.W.S., and D.W.G. Sears
1980. Natural Thermoluminescence of Meteorites: A Pointer to Orbits? *Modern Geology,* 7:137–145.

Melcher, C.L.
1979. Kirin Meteorite: Temperature Gradient Produced during Atmospheric Passage. *Meteoritics,* 14:309–316.
1981a. Thermoluminescence of Meteorites and their Terrestrial Ages. *Geochimica et Cosmochimica Acta,* 45:615–626.
1981b. Thermoluminescence of Meteorites and their Orbits. *Earth and Planetary Science Letters,* 52:39–54.

Nishiizumi, K.
1984. Cosmic-ray Produced Nuclides in Victoria Land Meteorites. *I* [illegible]. Marvin and B. Mason, editors, Field and Laboratory Investigations

FIGURE 7-5.—Aerial photograph of the Lewis Cliff Ice Tongue looking northeast with the tongue in the foreground. Note the step in the tongue, which is highlighted by the snow infilling. Meteorite Moraine is on the center, extreme right of the photograph. (Photograph TMA999-044 of the United States Geological Survey).

of Meteorites from Victoria Land, Antarctica. *Smithsonian Contributions to the Earth Sciences*, 26:105–109.

Nishiizumi, K., J.R. Arnold, D. Elmore, R.D. Ferraro, H.E. Gove, R.C. Finkel, R.P. Beukens, K.H. Chang, and L.R. Kilius

1979. Measurements of ^{36}Cl in Antarctic Meteorites and Antarctic Ice Using a Van de Graff Accelerator. *Earth and Planetary Science Letters*, 45:285–292.

t, E.R.D.

84. Pairing of Meteorites Found in Victoria Land, Antarctica. *In* Proceedings of the Ninth Symposium on Antarctic Meteorites. *Memoirs of National Institute of Polar Research* (Japan), special issue, 35:102–125.

Sears, D.W.G.

1975. Thermoluminescence Studies and the Pre-atmospheric Shape and Mass of the Estacado Meteorite. *Earth and Planetary Science Letters*, 26:559–568.

1988. Thermoluminescence of Meteorites: Shedding Light on the Cosmos. *Nuclear Tracks and Radiation Measurement/International Journal* *of Radiation Applied Instrumentation*, part D, 14:5–17.

Sears, D.W.G., and S.A. Durrani

1980. Thermoluminescence and the Terrestrial Age of Meteorites: Some Recent Results. *Earth and Planetary Science Letters*, 46:159–166.

Sears, D.W.G., and F.A. Hasan

1986. Thermoluminescence and Antarctic Meteorites. *In* J.O. Annexstad, L. Schultz, and H. Wänke, editors, Workshop on Antarctic Meteorites. *LPI Technical Report*, 86-01, pages 83–100. Houston: The Lunar and Planetary Institute.

Sears, D.W.G., and A.A. Mills

1974. Thermoluminescence and the Terrestrial Age of Meteorites. *Meteoritics*, 9:47–67.

Vaz, J.E.

1971. Asymmetric Distribution of Thermoluminescence in the Ucera Meteorite. *Nature Physical Science*, 230:23–24.