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The natural thermoluminescence of meteorites 7. Ordinary chondrites from the Elephant Moraine region, Antarctica

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We report natural and induced thermoluminescence (TL) measurements for meteorites from the Elephant Moraine region (76°17′S, 157°20′E) of Antarctica. We use our data to identify fragmented meteorites (i.e., "pairings"); our dataset of 107 samples represents at most 73 separate meteorite falls. Pairing groups are generally confined to single icefields, or to adjacent icefields, but a small proportion cross widely separated icefields in the region, suggesting that the fields can be considered as a single unit. Meteorites from this region have high natural TL levels, which indicates that they have small terrestrial surface exposure ages (<12,500 years). There do not appear to be significant differences in natural TL levels (and hence surface exposure ages) between individual blue icefields in the region. The proportion of reheated meteorites from the Elephant Moraine region is similar to that of other Antarctic sites and modern falls, consistent with the uniformity of the meteoritic flux in this regard. An unusual subset of H-chondrites, with high induced TL peak temperatures, is absent among the data for meteorites collected in the Elephant Moraine region, which stresses their similarity to modern falls. We suggest that the Elephant Moraine icefields formed through shallow ablation of the ice. Unlike the Allan Hills sites to the south, lateral transport is probably less important relative to the infall of meteorites in concentrating meteorites on these icefields.

Introduction

The Antarctic continent has proved to be a prolific source of meteorites. Over the past decade Japanese, American, and European expeditions have collected over 14,000 meteorite fragments on the blue icefields of Antarctica [*Cassidy et al.*, 1992]. The contribution of this immense collection in the discovery of new meteorite types (such as meteorites from the Moon [*Yanai and Kojima*, 1991]) and new samples of very rare types [e.g., *Wasson*, 1991] has been immense. However, the majority of recovered fragments are of the most common types of meteorites, namely the ordinary chondrites. These are also of great significance since they provide a unique opportunity to study the nature of the meteorite flux to Earth over the last million years [*Benoit and Sears*, 1993*a*] and to study the formation mechanisms of the blue icefields on which they are found. We have previously reported thermoluminescence (TL) data for ordinary chondrite collections from the Lewis Cliff and the Allan Hills regions [*Benoit et al.*, 1992, 1993*a*) and now discuss data for meteorites collected in the Elephant Moraine region (76°17′S, 157°20′E) by the 1986/1987 and 1987/1988 expeditions. We also report TL data for meteorites from the icefields at nearby Reckling Moraine.

The Elephant Moraine region is located approximately 80 km northwest of the Allan Hills and the associated Allan Hills Main Icefield (Figure 1). As is the case for the Allan Hills region, there are multiple meteorite-bearing blue icefields in the Elephant Moraine region. These bear the names of Meteorite Moraine (proper), Meteorite City, Upper Meteorite City, Texas Bowl, and the Northern Icefields. In order to avoid confusion, we will distinguish between the Elephant Moraine Icefield and the Elephant Moraine region which includes all these individual icefields. As shown in Figure 1, the Elephant Moraine Icefield and the Northern Icefields are physically separated from the other three icefields by distances of approximately 10 and 30 km, respectively. Meteorite City, Upper Meteorite City, and Texas Bowl are contiguous (inset, Figure 1). With the exception of the Northern Icefields, the icefields surround the actual Elephant Moraine, which is a deposit of glacially derived clasts and fine-grained sediment [*Faure and Taylor*, 1985, *Faure and Harwood*, 1990] which includes some black calcite boulders which may have been derived from subglacial hotsprings [*Faure et al.*, 1988]. Unlike the Allan Hills Main Icefield, there are no mountains exposed above the ice sheet in the Elephant Moraine region. The icefields of the Elephant Moraine region have proved to be a rich source of meteorite finds, with approximately 1500 meteorite fragments collected to date and more noted during scouting missions [*Cassidy et al.*, 1983; G.R. Huss, personal communication, 1992].

Reckling Moraine (76°15′S, 158°40′E) is located east of the Elephant Moraine region and is about 15 km west of Reckling Peak. Black calcite clasts are absent in the moraine [*Faure et al.*, 1987], suggesting that the Reckling Moraine and the Elephant Moraine are not directly related. Mapping of major dust bands in the ice at Reckling Moraine suggests that the ice has been folded. Only a very small number of meteorite fragments (<100) have been collected near Reckling Moraine over the past decade.

We report on thermoluminescence measurements on 107 meteorite samples from the Elephant Moraine region and eight samples from the Reckling Moraine region, which are all the meteorites suitable for these measurements collected during the 1986/1987 and 1987/1988 expeditions.

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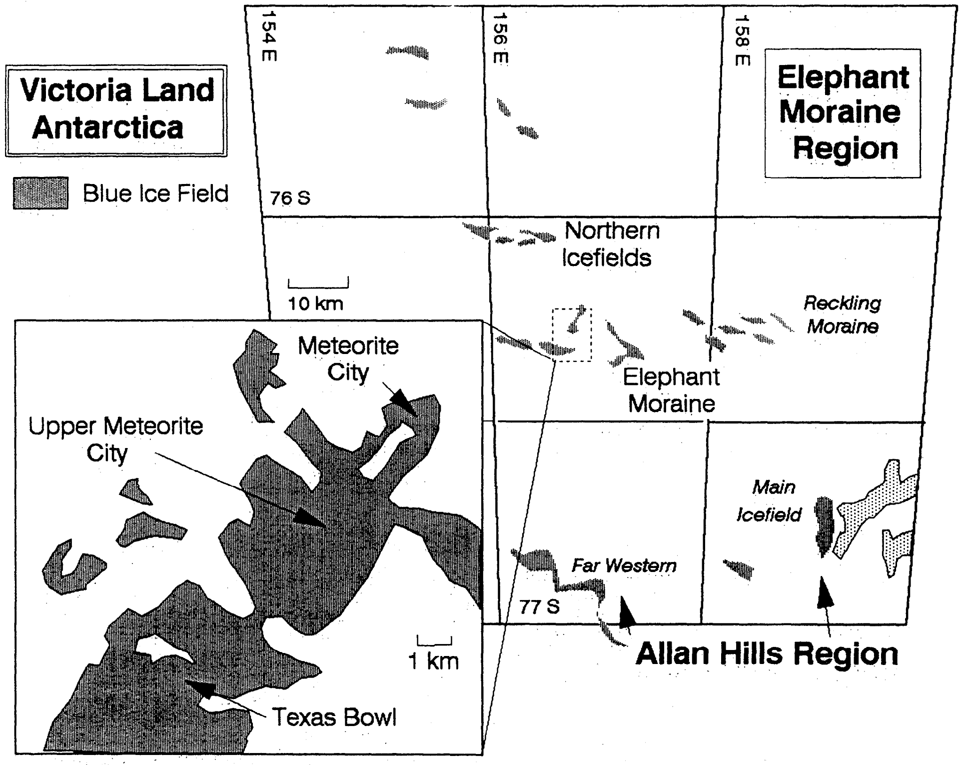

Fig. 1. Location sketch map for the Elephant Moraine region. Blue icefields, on some of which meteorites are exposed, are shown by dotted regions. The Far Western and Main icefields, both of which have proven rich sources of meteorites, are considered part of the Allan Hills region. Reckling Moraine, which has been the source of a few meteorites, is not considered part of the Elephant Moraine region for the purposes of this paper. The insert map shows the geographic relationships of some of the icefields associated with the Elephant Moraine.

METHODS

The technique and apparatus used for our TL measurements have been described in detail elsewhere [*Sears*, 1988; *Benoit et al.*, 1992]. For the purposes of the present work, we stress that only data for ordinary chondrites are used; unlike achondrites, the equilibrated ordinary chondrites do not show "anomalous fading" [*Sears et al.*, 1991]. Sample processing was limited to light crushing; no acid treatments or mineral separation procedures, such as those typically used in archeological TL dating [*Aitken*, 1985], were needed because because the only significant radiation source is galactic cosmic rays which results in a very high TL intensity in these samples, and the dominance of a single TL phosphor, namely, sodic feldspar.

Only meteorites with find weights of more than ~20 g were sampled for this study and, even then, only if it was possible to obtain a sample greater than 0.6 cm from any potential fusion crust. The TL of a thin layer on the outside of a meteorite is drained by the passage of the meteorite through the Earth's atmosphere [*Sears*, 1988]; our sampling procedure was designed to avoid this layer. This procedure has the added advantage of filtering out the smallest meteorites, which may have been transported by storm winds in the Antarctic [*Huss*, 1990]. Such transport considerably complicates interpretation of data for the geographic distribution of meteorites. The degree of terrestrial weathering undergone by the samples was not important for purposes of natural TL interpretation. Unlike induced TL data, natural TL data are internally normalized and are thus unaffected by terrestrial weathering [*Benoit et al.*, 1991*a*]. In the present work we report our data using kilorads (krad) to allow easy comparison with existing literature data, but conversion to the SI unit is trivial (1 krad = 10 gray).

RESULTS

The natural TL data for meteorites from Elephant Moraine and Reckling Moraine are given in Table 1. The induced TL data, including TL maximum intensity (sensitivity) relative to homogenized bulk Dhajala meteorite (H3.8) and peak temperature and peak width, are given in Table 2. The natural TL data for the Elephant Moraine meteorites, separated into individual icefields, and for the much smaller number of Reckling Moraine meteorites are shown in Figure 2. Figure 3 shows the the natural TL data for non-Antarctic falls [*Benoit et al.*, 1991*b*] and, for comparison, data for the Allan Hills and Lewis Cliff regions [*Benoit et al.*, 1992, 1993*a*]. The induced TL sensitivity data for all the Elephant Moraine meteorites are shown in Figure 4, where the data for the individual icefields and for non-Antarctic modern falls are also shown. Figure 5 shows TL sensitivity data for meteorite finds from the Texas Bowl Icefield and a combined plot for the other Elephant Moraine region icefields and also data for other Antarctic icefields, including the Allan Hills Far Western and Main fields [*Benoit et al.*, 1993*a*] and the Lewis Cliff Lower and Upper ice tongues [*Benoit et al.*, 1992].

DISCUSSION

The natural TL levels of meteorites are controlled by a number of factors, most notably by the terrestrial history of the meteorites and their thermal history in space [*Sears*, 1988]. Our discussion therefore concentrates on the

TABLE 1. Natural Thermoluminescence Levels for Meteorites From the Elephant Moraine Region and From the Reckling Moraine Icefield (RKP and RKPA) of Antarctica

Sample*		Natural TL, krad	Location+	Sample*		Natural TL(krad)	Location+
86800	L6	2.7	TB	87594	L6	28.4	TB
86801	L6	7.7	TB	87596	L6	9.5	TB
86802	H4	29	TB	87601	L6	11.8	TB
87502	L6	19.3	TB	87603	L6	12.1	TB
87533	L6	34.9	MC	87607	L6	42.8	TB
87534	L5	70	UMC	87613	L6	12.2	TB
87535	L6	17	TB	87615	L6	0.8	MC
87536	L6	0.54	UMC	87616	L6	12.9	TB
87537	H5	57	EM	87622	L6	22.1	TB
87538	L6	37.2	UMC	87623	L6	15.4	TB
87539	H5	11.8	NIP	87626	L6	7.9	TB
87540	L6	44.6	EM	87635	L6	8.7	TB
87541	L6	6.6	NIP	87639	L6	20.3	TB
87543	H6	1.5	UMC	87644	L6	27	TB
87544	LL4	69.	MC	87652	L6	9.9	TB
87545	H5	26.2	UMC	87655	L6	66	UMC
87546	H6	82	UMC	87660	L6	11.3	TB
87547	H6	2.8	NIP	87661	L6	20.7	UMC
87549	L6	86.9	MC	87744	L6	103	UMC
87550	H5	29	UMC	87754	H5	0.92	TB
87551	H5	25.8	NIP	87755	H5	98	NIP
87552	H6	85	NIP	87756	L6	17.9	TB
87553	H4	16.2	MC	87758	L6	25.6	UMC
87554	L6	90	TB	87759	L6	53	UMC
87555	L6	44	MC	87768	L6	58	EM
87556	L6	8.6	TB	87774	L5	18	EM
87557	L4	35.3	NIP	87788	L6	14.6	TB
87558	L5	0.78	EM	87789	L6	9.6	TB
87559	L6	67	TB	87790	H5	3.2	MC
87560	L6	10	MC	87794	L6	15.2	EM
87561	L6	11.2	EM	87796	L6	33.5	TB
87562	H6	40.2	MC	87798	H5	8.7	TB
87563	H6	77.4	MC	87804	L6	33	TB
87564	L4	31.6	MC	87805	H3	6.4	MC
87565	H6	5.1	EM	87807	L6	20.6	MC
87566	L6	59	MC	87817	L6	19.3	TB
87567	L6	15.4	UMC	87818	L6	135	UMC
87568	L6	8.9	TB	87820	H6	44.3	TB
87569	L6	23.8	TB	87821	H5	81	MC
87570	L5	22	EM	87822	H5	15.2	NIP
87571	H5	29	MC	87827	L6	21.1	MC
87572	L6	2	UMC	87829	L6	10.9	TB
87573	L4	53.1	TB	87830	L6	12.7	TB
87574	L6	33.3	MC	87840	H5	65.4	EM
87575	H6	18.3	NIP	87843	L6	47.7	UMC
87576	H5	58.2	EM	87851	LL5	78	NIP
87577	H5	51.6	TB	87855	L6	10.5	TB
87578	L6	25.5	UMC	87857	L6	23	TB
87579	H5	17.9	UMC	87858	L6	8.9	TB
87580	L6	32	TB	RKPA79001	L6	6.5	
87581	H5	69	MC	RKPA80202	L6	0.5	
87582	L4	1.7	MC	RKP 86700	L3	9	
87583	L6	2.4	NIP	RKP 86701	H5	37.8	
87584	L6	9.5	UMC	RKP 86702	L6	12	
87586	L6	21.6	TB	RKP 86703	H6	10.2	
87587	L6	8.4	TB	RKP 86704	LL6	38	
87589	L6	7.6	TB	RKP 86705	H5	13.7	
87592	H6	48.3	MC				

* All samples bear the designation EET unless otherwise specified.
\+ Ice field on which a given sample was found. EM, Elephant Moraine (proper); MC, Meteorite City; NIP, Northern Ice Patch; TB, Texas Bowl; UMC, Upper Meteorite City.

evaluation of these factors for Elephant Moraine meteorites. We begin by examining the question of "pairing," i.e., the potential biases in our database caused by most of our samples being fragments of larger meteorites, the fragmentation occurring either while on Earth or during their atmospheric passage. Having used the results of this examination to remove redundant samples from the database, we discuss the natural and induced TL of the Elephant Moraine region meteorites in the general context of average TL terrestrial ages and exposure to Antarctic surface processes (i.e., weathering). We then discuss meteorites which have very low natural TL levels because

TABLE 2. Induced Thermoluminescence Data for Meteorites From the Elephant Moraine Region of Antarctica

Sample*	TL Sensitivity+ (Dhajala=1)	Peak Temperature, °C	Peak Width, °C
86800	0.7 ±0.1	184± 8	163±13
86801	0.63±0.09	183± 3	168± 8
86802	0.31±0.04	171± 3	148± 1
87502	2.8 ±0.2	178± 6	
87533	1.8±0.2	166± 2	127± 2
87534	1.34±0.09	190± 2	149± 4
87535	4.0 ±0.3	172± 4	138± 2
87536	0.27±0.03	150±11	220±16
87538	0.92±0.07	162± 1	130± 4
87539	1.11±0.05	161± 2	132± 5
87540	0.50±0.03	160± 4	126± 3
87541	0.98±0.05	181± 3	152± 2
87543	2.6 ±0.3	167± 2	125± 2
87544	1.4 ±0.1	163± 2	137± 6
87545	1.5±0.3	176± 5	138± 3
87546	0.51±0.01	193± 5	127± 3
87547	2.6±0.6	172± 4	138± 3
87549	3.2±0.2	186± 4	140±10
87550	4.9±0.5	159± 4	130± 3
87551	0.97±0.09	164± 8	123± 3
87552	1.1 ±0.2	167± 1	124± 2
87553	1.2 ±0.1	174± 6	142± 4
87554	1.6±0.2	169± 3	
87555	1.18±0.06	183± 3	137± 2
87556	1.6 ±0.1	183± 2	141± 2
87557	5.5± 0.4	168± 5	125± 4
87558	0.31±0.02	168± 6	170± 3
87559	3.4± 0.3	180± 2	138± 2
87560	1.3±0.1	137± 6	163± 3
87561	1.5±0.1	135± 4	161± 2
87562	3.4±0.3	170±12	125± 2
87563	2.9±0.3	185± 2	151± 2
87564	0.75±0.07	162± 2	126± 3
87565	1.2±0.2	176± 2	160±10
87566	3.4±0.3	170± 3	131± 3
87567	1.3±0.2	175± 1	127± 4
87568	2.2±0.3	171± 4	127± 2
87569	2.1±0.1	170± 5	131± 3
87570	2.0±0.3	180±10	
87571	0.75±0.04	186± 2	136± 1
87572	0.53±0.05	182± 3	148± 4
87573	2.4±0.1	169± 1	129± 4
87575	2.0±0.1	175± 4	129± 2
87576	0.75±0.08	185± 2	140± 3
87577	3.05±0.01	191± 4	134± 4
87578	2.4±0.5	167± 1	131± 5
87579	0.27±0.03	194± 4	168± 2
87580	2.4±0.09	161± 2	131± 3
87581	0.55±0.05	197± 1	
87582	0.9±0.04	184± 6	157± 5
87583	0.06±0.01	170±10	170±12
87584	1.0±0.1	162± 4	128± 4
87586	2.6±0.2	164± 4	130± 2
87587	1.6±0.1	166± 3	132± 1
87589	0.84±0.07	156± 1	132± 2
87592	2.6±0.1	185± 6	139± 4
87594	3.2±0.2	166± 3	135± 1
87596	2.8±0.6	165± 6	129± 2
87601	3.1±0.3	165± 4	133± 4
87603	3.9±0.2	166± 5	130± 4
87607	2.28±0.01	163± 2	131± 1
87613	2.6±0.3	163± 8	128± 2
87615	4.2±0.3	173± 1	128± 5
87616	2.8±0.4	166± 7	134± 9
87622	4.1±0.3	165± 4	128± 5
87623	4.0±0.3	161± 4	129± 3
87626	6± 1	166± 6	130± 1
87635	2.9±0.4	166± 4	133± 2
87639	4.8±0.2	167± 1	131± 2
87644	4.8±0.6	167± 4	136± 3
87652	6.2±0.7	169± 5	123± 9
87655	13± 2	167± 3	127± 3
87660	10± 1	171± 7	122± 4
87661	3.4±0.4	174± 6	134± 5
87744	4.1±0.2	187± 3	
87754	1.04±0.09	176± 5	129± 2
87755	4.2±0.8	184± 3	145± 9
87756	2.0±0.3	168± 2	134± 2
87758	2.5±0.4	172± 1	128± 2
87759	2.8±0.5	171± 3	134± 5
87768	2.3±0.3	189± 5	163± 7
87774	1.8±0.3	181± 7	150± 2
87788	5± 2	173± 1	126± 4
87789	2.8±0.4	168± 4	130± 3
87790	2.6±0.4	183± 5	136± 1
87794	1.5±0.2	160± 7	145± 2
87796	2.3±0.1	166± 2	132± 2
87798	4.5±0.9	169± 4	123± 2
87804	2.6±0.2	161± 5	132± 2
87805	0.57±0.04	150± 9	
87807	1.96±0.07	175± 2	155± 5
87817	1.2±0.1	172± 5	127± 3
87818	3.0±0.2	192± 2	
87820	0.85±0.09	184± 2	132± 2
87821	0.55±0.05	179± 4	138± 6
87822	1.9±0.5	186± 3	
87827	1.1±0.1	173± 3	135± 9
87829	0.32±0.06	169± 3	131± 1
87830	3.4± 0.6	166± 2	127± 2
87840	0.84±0.05	192± 5	142± 6
87843	3.3±0.2	176± 1	136± 5
87851	5.5±0.5	179± 3	131± 2
87855	2.9±0.7	180±10	136± 5
87857	1.8±0.5	170± 4	128± 2
87858	1.4±0.2	164± 2	135± 2

*All samples bear the designation EET.
+Maximum intenstity (sensitivity) of the induced TL signal relative to that of the Dhajala (H3.8) meteorite.

they were reheated prior to Earth impact, probably by virtue of small perihelia orbits, and we also discuss induced TL peak temperature and width data for H chondrites which have implications for the long-term evolution of the meteorite flux. Finally, we discuss the implications of our data for the histories of the blue icefields on which the meteorites were found.

Meteorite "Pairing" and Relationships Between Icefields

Most modern falls break into multiple fragments prior to striking the ground, and, although the average number of fragments is usually between 1 and 10, on rare occasions meteorites are observed to disintegrate into hundreds of fragments during their fall [see *Graham et al.*, 1985; *Halliday et al.*, 1989; *Scott*, 1989]. Weathering and stress during burial in the ice cause further fragmentation of Antarctic meteorites and our samples are generally from sites where dozens to hundreds of individual samples were present. Most of the samples are equilibrated ordinary chondrites and thus difficult to distinguish from each other using routine petrologic observations. Thermoluminescence is well suited to recognizing fragments of a single meteorite fall, especially in conjuction with other data since the range of TL observed

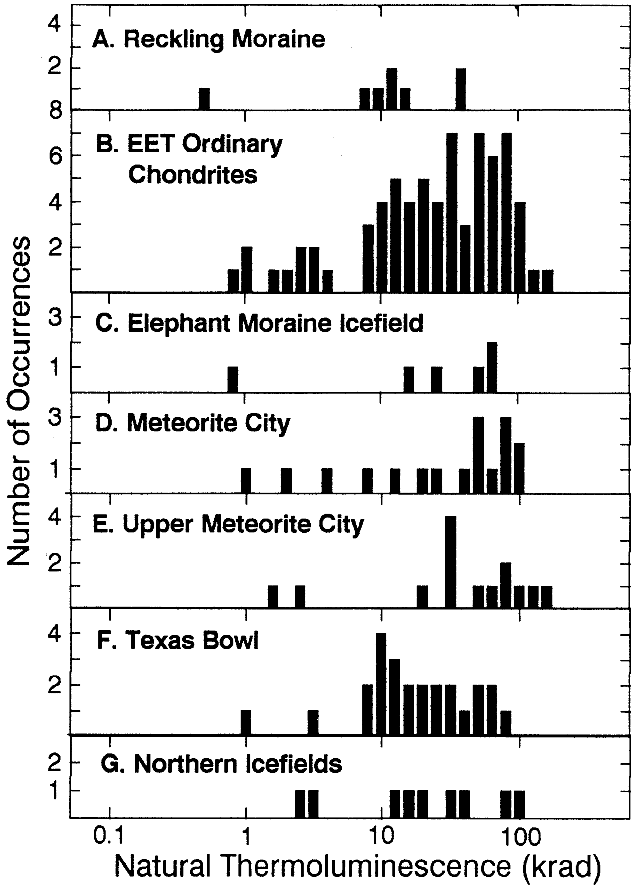

Fig. 2. Natural TL data for meteorites from (*a*) Reckling Moraine and (*b*) the Elephant Moraine region. The meteorites from the Elephant Moraine region show a broad range of natural TL levels, concentrated between 10 and 100 krad. Data for individual icefields (*c-g*) show that the meteorites from most fields have high TL levels (>30 krad). Only the Texas Bowl Icefield (*f*) has a large number of samples with low TL levels. In general, these data indicate that the meteorites from the Elephant Moraine region have small TL terrestrial ages.

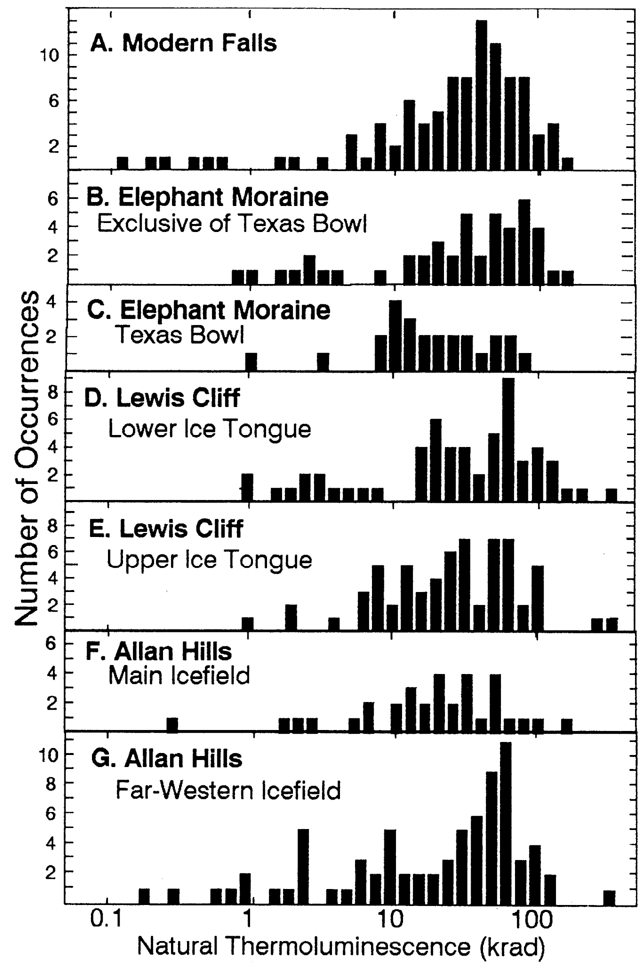

Fig. 3. Natural TL data for (*a*) modern falls and meteorites from (*b*, *c*) the Elephant Moraine region and (*d-g*) other Antarctic blue icefields. All sites show similar ranges of natural TL but have different proportions of meteorites with low TL levels (10-20 krad). The Upper Ice Tongue at Lewis Cliff and the Main field at Allan Hills have a large proportion of meteorites with low TL levels and hence large TL terrestrial ages. The Far Western field at Allan Hills and Lower Ice Tongue at Lewis Cliff have a large proportion of meteorites with high TL levels and hence small TL terrestrial ages. The Elephant Moraine distribution exclusive of Texas Bowl is most similar to the latter two fields. The Texas Bowl distribution appears to be most similar to the former fields.

is several orders of magnitude greater than that which can be observed for the fragmentation of a single fall. Our criteria for "pairing" include natural and induced TL levels, petrologic classifications, cosmogenic nuclide concentrations (where available) and field observations [*Benoit et al.*, 1992].

Table 3 lists the pairings which result from applying these criteria to our Elephant Moraine samples. For the sake of completeness we include three groups of achondrites described by *Sears et al.* [1991]. We have identified 23 groups with two to six members each, involving 65 samples. Twenty of these groups (54 samples) are composed of ordinary chondrites. Therefore, not counting the achondrite groups, there is a maximum of 73 actual meteorite falls in our 107 samples from the Elephant Moraine region. This is a deliberately conservative estimate because it is less misleading to omit a paired sample than to accidentally include one.

One of the criteria we have used in previous pairing studies of Antarctic meteorites [*Benoit et al.*, 1992, 1993*a*] is the distance between members of a potential pairing group. We had observed that pairing groups generally covered less than 3 km at the Lewis Cliff site and somewhat greater at the Allan Hills site. The howardite pairing group EET87503 [*Mason*, 1988; *Sears et al.*, 1991] was spread over both the Elephant Moraine and Texas Bowl icefields, although the two icefields are not physically contigious and 10 km apart (Figure 1). Therefore we have assumed that paired meteorites can be dispersed up to 10 km at this site. We have identified a number of other pairing groups which span several icefields (Table 4), although about half of the recognized pairing groups are confined to a single icefield (Texas Bowl), including eight L6 groups. A further quarter of the pairing groups cover the contiguous Texas Bowl, Meteorite City, and Upper Meteorite City icefields, suggesting that these fields are related to each other fairly closely. The remainder are dispersed evenly over the Northern Icefields and the Texas Bowl-Meteorite City-Upper Meteorite City fields and the Elephant Moraine field and the three contiguous fields. The only cross-field pairing association not seen in the collection is the Elephant Moraine and Northern Icefields association. These fields are also the furthest apart among those in the region.

We have removed the paired samples from further discussion and we use averaged data for each pairing group in our figures. This does not generally have significant effect on

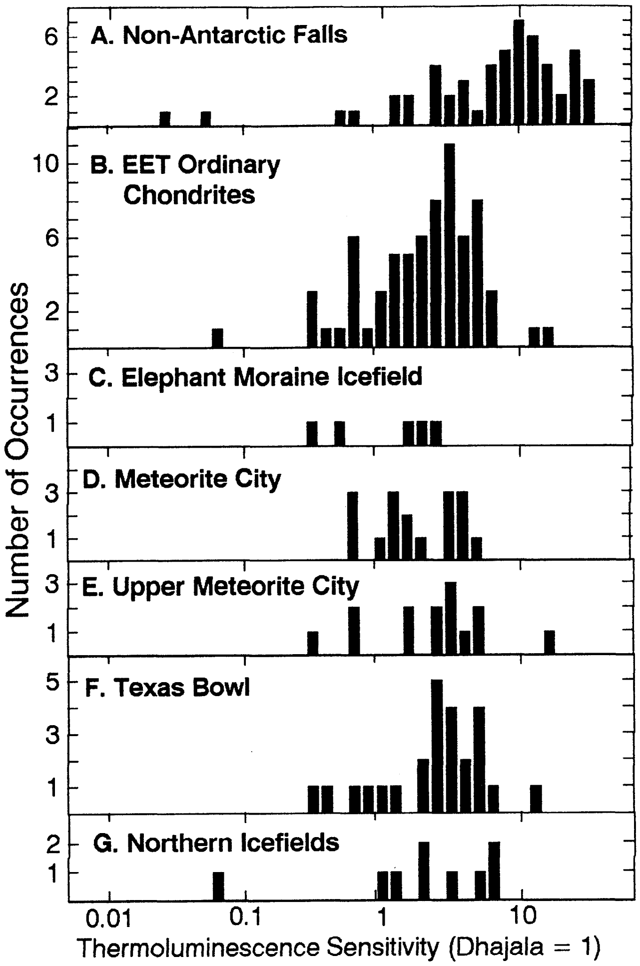

Fig. 4. Induced TL sensitivity (relative to homogenized Dhajala meteorite) for (*a*) non-Antarctic modern falls, (*b*) ordinary chondrites from the Elephant Moraine region, and (*c-g*) meteorites from the Elephant Moraine region differentiated by icefield. The meteorites from the Elephant Moraine region have significantly lower TL sensitivities relative to modern falls, which reflects their higher degree of terrestrial weathering. The meteorites from the Elephant Moraine Icefield appear to have slightly smaller TL sensitivities than those from the other fields, suggesting they have been somewhat more weathered.

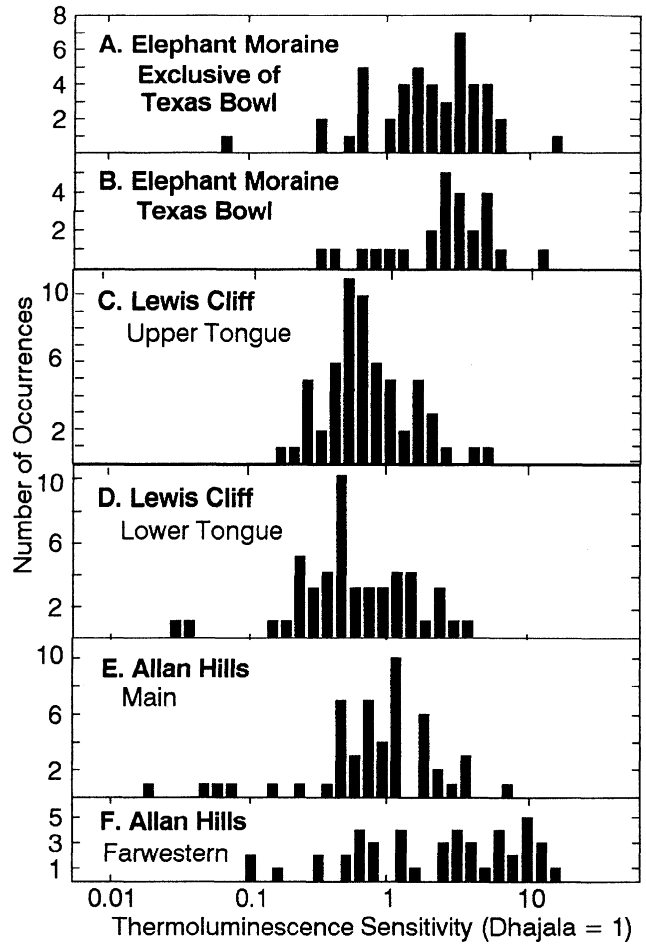

Fig. 5. Induced TL sensitivity data for meteorites from the Elephant Moraine region and other Antarctic icefields. In comparision to meteorites from other icefields, the meteorites from the Elephant Moraine region (*a*, *b*) have significantly higher TL sensitivities. Only the Farwestern Icefield at Allan Hills has a significant number of meteorites with equal or greater sensitivity, but this field also shows the greatest range. These data suggest that meteorites from the Elephant Moraine region are less weathered than most Antarctic meteorites.

our observations, besides reducing the total number of samples. An exception is the large number of samples from the Texas Bowl Icefield (Figure 6). Most of these belong to a few L6 pairing groups (EET87601, 87587, and 87626) which have natural TL levels between 8 and 13 krad. It is likely that these three groups are actually part of a single meteorite and differences in TL sensitivities which precluded pairing the three groups may simply reflect slight differences in weathering. Using meteorite mass distribution curves, *Huss* [1991] suggested that there was a major L6 shower in the Elephant Moraine meteorite collection. He also suggested that this shower must have been relatively recent in order for the mass effects to still be apparent, but as we will discuss next, the natural TL data suggest a rather large terrestrial age.

TL Terrestrial Ages: A Preliminary Consideration

Natural TL levels of meteorites decay from their initially high levels in space to lower equilibrium levels appropriate to terrestrial conditions in a time- and temperature-dependent fashion; thus natural TL (at 250°C in the glow curve) is essentially fully drained within 50,000 years at typical non-Antarctic sites (~20°C average temperature) but will not adjust fully in less than a million years at Antarctic sites (~0°C average temperature) [*McKeever*, 1982; *Benoit et al.*, 1993*b*]. Thus the TL level of an Antarctic meteorite reflects both its terrestrial age and thermal history.

Modern falls, with terrestrial ages of essentially zero, show an approximately lognormal distribution of natural TL values with a mode of about 40 krad and a tail to lower values (Figure 3). This distribution is caused largely by thermal history in space, or more specifically by the orbital histories of the meteorites [*Benoit et al.*, 1991*b*]. If all the meteorites collected on an icefield fell at the same time, their TL distribution would become more compact and shift to lower natural TL values over time by an amount that can be readily calculated (Figure 7; see also *McKeever* [1982]). It would then be a simple matter to use the difference between the geometric means (or the mode) of the modern falls and the Antarctic meteorites and an estimate of the average annual temperature at the site obtained using climate records in order to calculate typical terrestrial ages for the meteorites of

TABLE 3. Paired Meteorite Specimens From the Icefields in the Elephant Moraine Region, Antarctica

Meteorite*	Class	Natural TL, krad	Icefield+	Meteorite*	Class	Natural TL, krad	Icefield+
87503	HOW	6.1	TB				
87509	HOW	3.6	EM	87569	L6	24	TB
87510	HOW	7.9	EM	87586	L6	22	TB
87513	HOW	5	TB	87661	L6	21	UMC
87518	HOW	2.5	EM	87807	L6	21	MC
87531	HOW	2.5	EM	87857	L6	23	TB
87537	H5	57	EM	87587	L6	8.4	TB
87576	H5	58	EM	87858	L6	8.9	TB
				87589	L6	7.6	TB
87550	H5	29	UMC				
87571	H5	29	MC	87594	L6	28	TB
				87644	L6	27	TB
87581	H5	69	MC				
87840	H5	65	EM	87596	L6	9.5	TB
				87635	L6	8.7	TB
87557	L4	35	NIP	87789	L6	9.6	TB
87564	L4	32	MC				
				87601	L6	12	TB
87570	L5	22	EM	87603	L6	12	TB
87774	L5	18	EM	87613	L6	12	TB
				87616	L6	13	TB
87502	L6	19	TB	87830	L6	13	TB
87535	L6	17	TB	87855	L6	11	TB
87567	L6	15	UMC				
				87622	L6	22	TB
87530	L6	37	UMC	87639	L6	20	TB
87533	L6	35	MC				
87574	L6	33	MC	87626	L6	7.9	TB
87580	L6	32	TB	87652	L6	9.9	TB
87536	L6	0.5	UMC	87756	L6	18	TB
87583	L6	2.4	NIP	87817	L6	19	TB
87541	L6	6.6	NIP	87796	L6	34	TB
87556	L6	8.6	TB	87804	L6	33	TB
87568	L6	8.9	TB				
87584	L6	9.5	UMC	87500	MES	0.18	NIP
				87501	MES	0.21	NIP
87549	L6	87	MC				
87554	L6	90	TB	87511	URE	1.5	MC
				87517	URE	1	MC
87560	L6	10	MC	87523	URE	0.8	MC
87561	L6	11	EM				

Criteria for pairing are described in text. Pairing groups are referred to by the lowest numbered member of the group.
*All samples bear the designation EET.
+ EM, Elephant Moraine; MC, Meteorite City; NIP, Northern Icefields; TC, Texas Bowl; UMC, Upper Meteorite City.

TABLE 4. Geographic Distribution of Members of Pairing Groups

	Percentage of All Pairing Groups
SINGLE ICEFIELD	52
INTERFIELD GROUPS	
Elephant Moraine (EM)-(MC-UMC-TB) fields	13
MC-UMC-TB fields	22
NIP-(MC-UMC-TB) fields	13
NIP-EM	0
Total	100

Abbreviations for icefield names are from Table 1.

a given site. Since meteorites continue to fall on the site, however, the histograms will be quite broad (Figure 7*d*).

Another point to keep in mind is that a meteorite exposed on the surface of the ice will be considerably warmer than one buried deep in the ice and its TL will decay faster. Therefore, an "age" estimated from TL for an Antarctic meteorite is essentially a terrestrial surface exposure age which must by less than or equal to the true terrestrial age. Precise terrestrial ages for Antarctic meteorites are not known of course, but may be estimated with fairly large uncertainties from radiogenic cosmogenic nuclide abundances [*Nishiizumi et al.*, 1989]. The similarity or otherwise of the TL age and the terrestrial age depends on the length of time the meteorite spends buried relative to its time on the surface. For the meteorites collected on a given icefield, it depends on the nature of the local meteorite concentration mechanism.

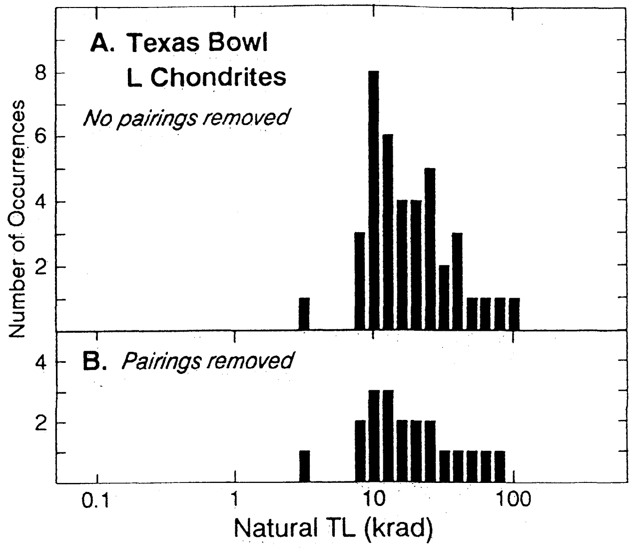

Fig. 6. Natural TL data for meteorites from the Texas Bowl Icefield (*a*) before and (*b*) after considering the effects of meteorite fragmentation ("pairing"). Three pairing groups (EET87587, EET87601, and EET87626), composed of meteorites with low (10-13 krad) natural TL levels, dominate the Texas Bowl distribution. The low apparent average natural TL level for Texas Bowl meteorites is largely the result of these pairing groups.

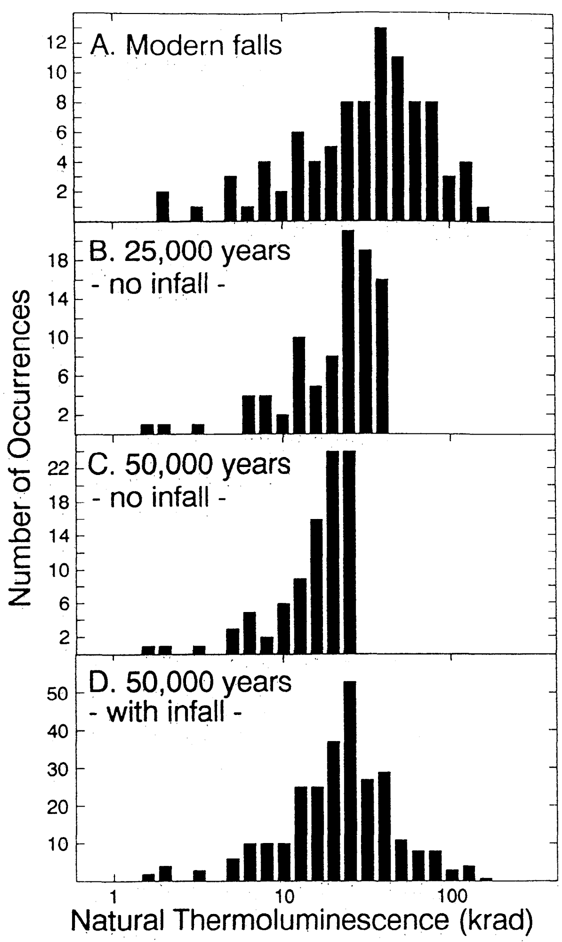

Fig. 7. The distribution of natural TL values for (*a*) modern falls and the effects of thermal decay (time) on this distribution. Shown are the resulting histograms after (*b*) 25,000 years and (*c*) 50,000 years at a storage temperature of 0°C, assuming all meteorites fell at the same time and no new falls were added. Also shown is (*d*) the distribution after 50,000 years at 0°C if new falls are added continuously.

TL Terrestrial Ages: Elephant Moraine Samples

The ordinary chondrites of the Elephant Moraine meteorite collection show a broad range of natural TL levels (10-100 krad, Figure 2*b*). Such a range is unusual among Antarctic sites which usually have distinct 30-80 krad peaks in their histograms (Figure 3). If we examine histograms for each icefield (Figures 2*c*-2*g*), however, it appears that the cumulative distribution is distorted by the data from the Texas Bowl Icefield (Figure 2*f*). The distributions for meteorites from Meteorite City and Upper Meteorite City are broad, but similar and tend towards high TL levels. The Texas Bowl meteorites, however, include a relatively large number with low TL levels (~15 krad) which may reflect the presence of unrecognized members of the L6 pairing groups which dominate this icefield. As for these groups (especially EET87601, 87587 and 87626), their natural TL levels seem to require either a relatively large terrestrial age or atypically low TL levels at the time of fall. If we assume that the meteorite (or meteorites) represented by these groups had an initial TL level of 40 krad (the mode of the modern falls, Figure 3*a*), then it would require about 110,000 years for their natural TL levels to decay to the observed level, assuming a temperature of 0°C.

The Reckling Moraine data (Figure 2*a*) are sparse but tend towards fairly low natural TL levels with a concentration of meteorites at about 10 krad. Using the same assumptions as used above, this would also suggest an approximate TL age of 110,000 years for these meteorites.

In comparison to meteorites recovered at other Antarctic blue icefields and elsewhere (Figure 3), the distribution of natural TL data for Elephant Moraine meteorites is most similar to that of the modern falls. The main difference between the two distributions is the "hump" at low TL values in the Elephant Moraine data caused by the Texas Bowl data (Figure 3*c*). If we exclude these data (Figure 3*b*), the Elephant Moraine distribution is similar to that of the modern falls and the meteorites from the Lower Ice Tongue at Lewis Cliff. We can show this quantitatively by determining the proportion of meteorites with low natural TL levels (5-20 krad, Table 5). About 15% of modern falls have such low levels of natural TL; a higher percentage is expected for Antarctic meteorite finds due to TL decay. We find that the modern falls, meteorites from the Lewis Cliff Lower Ice Tongue, and meteorites from Elephant Moraine (Texas Bowl samples excluded) have essentially the same percentage of meteorites with low TL levels. The other icefields have significantly higher percentages, ranging up to 30% for the Allan Hills Main Icefield. The Texas Bowl distribution has the highest percentage of meteorites with low TL levels in Table 5, but unlike the data for the other fields, we ascribe this to both the relatively small number of samples from this site (after the extensive pairing described above) and to suspected unrecognized pairings related to the L6 groups which were also discussed above. Given that the Elephant Moraine samples have a TL distribution very similar to modern falls, we should be able to obtain an estimate of how long such a similarity would be expected to last under Antarctic conditions. Using the same assumptions used above, the similarities of the low TL portion of the distribution should not last more than 12,500 years regardless of whether the system is considered as open or closed to meteorite infall (i.e., after this amount of time a sufficient number of meteorites will have "decayed" into the low TL category to create a significant difference, Table 5). This estimate is, of course, an upper limit. Not coincidentally,

TABLE 5. Percentages of Reheated Ordinary Chondrites (Natural TL < 5 krad), and Meteorites With Low (5-20 krad) and High (>60 krad) Natural TL Levels from the Icefields of the Elephant Moraine Region

Icefield	<5 krad	5-20 krad	>60 krad
Elephant Moraine Region			
Meteorite City	18% (3)	--	---
Texas Bowl	8% (2)	44% (11)	12% (3)
Upper Meteorite City	14% (2)	--	---
	13 (7)*		
Elephant Moraine Region exclusive of Texas Bowl	17% (8)	11% (5)	35% (14)
Allan Hills Region			
Main	12% (4)	30% (10)	12% (4)
Farwestern	22% (17)	21% (16)	27% (21)
Lewis Cliff Region			
Upper Ice Tongue	6% (4)	28% (18)	25% (16)
Lower Ice Tongue	15% (9)	12% (7)	37% (22)
Modern falls	12%	15%	24%
Calculated (no falls)			
after 12,500 years	12%	22%	8%
25,000 years	12%	34%	0%
50,000 years	12%	63%	0%
Calculated (with falls)			
after 12,500 years	12%	22%	14%
25,000 years	12%	29%	12%
50,000 years	12%	40%	8%
Modern Falls (adj)†	12%	10%	36%

Numbers in parentheses are actual number of meteorites in the category. Data for meteorites from other icefields and for modern falls are shown for comparison.

*Percentage for these three fields combined, considering all pairing within and among these fields (Tables 3 and 4).

†Distribution adjusted upward by 10% to account for possible shielding corrections for comparison with Antarctic meteorites.

uranium-series dating of dust bands within the ice at the Lewis Cliff Lower Ice Tongue suggests ages on the order of 20,000 years and low concentrations of radiogenic cosmogenic nuclides (^{36}Cl, ^{26}Al [*Nishiizumi*, 1987; *Nishiizumi et al.*, 1989]) indicate that the meteorites from the Main Icefield at Allan Hills have the broadest range of terrestrial ages observed to date.

One important comparison is that of data for the Elephant Moraine and the Far Western Icefield (Figure 3g), which, although officially part of the Allan Hills region (Figure 1), lies about equidistant from the Allan Hills Main Icefield (to the east) and Elephant Moraine (to the north). Despite broad similarities (Figure 3), data for the Farwestern site and the Elephant Moraine sites differ slightly in detail (Table 5), in that the Farwestern distribution has a greater abundance of meteorites with low TL levels. This suggests that the Elephant Moraine meteorites include a greater number of meteorites with smaller TL ages than those from the Far Western Icefield in the Allan Hills region.

Meteorites With High TL Levels

The high TL of some samples is relatively straightforward to interpret because there is no mechanism to boost the TL level of a meteorite to high TL levels in the natural terrestrial environment. The occurrence of high TL in an Antarctic meteorite find can thus be interpreted in only one way, namely, as indicative of a short terrestrial surface exposure age.

In Table 5 we give the percentage of meteorites with natural TL levels greater than 60 krad at the Elephant Moraine Icefields, Lewis Cliff and Allan Hills icefields, and in modern falls. We also give the percentages expected using the modern fall distribution subjected to decay at 0°C for the two models discussed above for various lengths of time. The percentage of meteorites with high TL levels from Texas Bowl is considerably less than that of modern falls, but the significance of this observation is limited by the small number of samples and the pairing problems discussed above. The percentage of meteorites with high TL levels from the Elephant Moraine icefields exclusive of Texas Bowl is higher than that observed in modern falls. If we look at the percentages of meteorites with high TL levels at other Antarctic icefields (also given in Table 5) we see that this is also the case at the Lower Ice Tongue at Lewis Cliff and that the Upper Ice Tongue and the Farwestern icefields have percentages very similar to modern falls. Only the Allan Hills Main Icefield has a percentage of meteorites with high TL levels which is considerably lower than that of modern falls. In fact, the data for the Main Icefield compare very well with the calculated distribution after 25,000 years with continual infall but has a higher percentage of meteorites with high TL than a calculated distribution with a terrestrial age greater than 12,500 years with no infall.

The high percentage of meteorites with high TL (and hence low TL ages) at the Elephant Moraine icefields and at the Lower Ice Tongue at Lewis Cliff is perplexing in that there is no reasonable natural terrestrial mechanism to boost

TL levels in the way observed; even exposure to uranium-rich meltwater, as has been suggested for certain meteorites from the Meteorite Valley Icefield of Frontier Mountain [*Delisle et al.*, 1989; *Cassidy et al.*, 1992], would not suffice. The preferential concentration of high TL meteorites is also difficult to explain in terms ice and wind movement. One must therefore suggest that the modern falls natural TL data is unlike that of the original TL distribution for Antarctic meteorites. Such a difference would result from an evolution of average perihelion near 1 AU to a perihelion closer to 0.95 AU between the fall of the Antarctic meteorites and the modern falls. This is unlikely in light of our knowledge of celestial mechanics [*Wetherill*, 1987]. More reasonably, the explanation lies in the smaller size of Antarctic meteorites during irradiation. The average mass of an Antarctic meteorite is about 100 times smaller than that of modern falls [*Harvey and Cassidy*, 1989; *Cassidy*, 1990; *Huss*, 1991]. There are many factors which contribute to the difference in average mass between the two groups of meteorites, not least of which is the greater efficiency of meteorite collection and preservation on the Antarctic ice sheet. Natural TL shows small but calculable and measureable depth-dependence which must be allowed for before comparison. Our calculations indicate that TL levels should be about 10% higher in meteorites about 100 times less in mass, other factors being equal. We have therefore increased the natural TL values for modern falls by 10% (Table 5). This causes a slight decrease in the percentage of meteorites with low TL values which strengthens the conclusion of the previous section by improving the similarity of the Antarctic and non-Antarctic data. The proportion of high TL meteorites in this distribution is, however, considerably greater than that in the modern falls distribution (35% versus 24%) and is, in fact, very similar to the EET distribution.

In summary, EET meteorites resemble non-Antarctic meteorites in their TL distribution once shielding corrections are made and at least one third have TL terrestrial ages <12,500 years.

Weathering

Among other factors, induced TL sensitivity is affected by the degree of weathering exhibited by a meteorite [*Benoit et al.*, 1991*a*]. In general weathering lowers TL sensitivity by increasing albedo [*Sears and McKeever*, 1980]. As expected, meteorites from the Elephant Moraine region have lower TL sensitivities than non-Antarctic falls (Figures 4*a* and 4*b*), and meteorites from the Elephant Moraine Icefield (Figure 4*c*) appear more weathered than meteorites from other sites in the region which are approximately comparable with each other. In comparison to other Antarctic sites, the Elephant Moraine region meteorites tend to have rather high TL sensitivities so that, except for a few meteorites from the Far Western site, Elephant Moraine meteorites appear less weathered than those from the other sites.

Meteorites From Low Perihelion Orbits

In addition to being drained by the relatively high temperatures and low cosmic radiation environment while on Earth, meteorites can have their natural TL reduced while still in space by being reheated. There are several ways this might occur the most likely being shock heating following a collision and by close passage to the Sun (small perihelion). Approximately 12% of modern falls have natural TL levels <5 krad and have been reheated in this fashion [*Benoit and Sears*, 1993*b*]. The estimated number of meteoroid orbits with small perihelia estimated from visual observations of meteorite radiants and fireball trajectories is close to 15% [*Wetherill and Chapman*, 1988; *Benoit et al.*, 1991*b*], and ~15% of the meteorites from the individual icefields in the Lewis Cliff and Allan Hills regions [*Benoit et al.*, 1992, 1993*a*] also have TL levels <5 krad. This suggests that the orbital characteristics of meteorites falling to Earth have been fairly constant during the period of meteorite accumulation in the Antarctic.

The percentages of meteorites from the icefields in the Elephant Moraine region with natural TL levels less than 5 krad are given in Table 5. Due to the small number of samples, data for the Elephant Moraine and Northern Icefields are not shown separately. Approximately 15% of the more numerous meteorites from Meteorite City have natural TL levels <5 krad, as do those from the less numerous Upper Meteorite City collection. Texas Bowl has a very small percentage of reheated meteorites, approximately 8% after considering pairing. This may be partly because of the unrecognized pairing mentioned above but this low number also reflects the somewhat arbitrary (considering the interfield pairing noted above) separation of this field from the others. If the contiguous Texas Bowl, Meteorite City, and Upper Meteorite City are considered as a single field, and pairing among these fields taken into consideration, the percentage of reheated meteorites is approximately 13% out of a statistically significant 85 samples.

Thus it appears that, in terms of percentage of reheated meteorites, the Elephant Moraine region icefields are similar to other Antarctic icefields and to non-Antarctic falls. Since there is little evidence for very recent (within the last 10^4 years) heavy shock in most of the reheated non-Antarctic falls [*Benoit et al.*, 1991*b*] this further emphasizes the constancy of the proportion of meteoroid bodies in low perihelia orbits over the span of time represented by the Antarctic meteorite collection.

Induced TL of H Chondrites

We have previously identified a group of Antarctic H5 chondrites which have unusually high induced TL peak temperatures and width [*Benoit and Sears*, 1993*a*]. The members of this group all have cosmic ray exposure ages of ~8 Ma, metallographic cooling rates significantly higher than those of H5 modern falls, and cosmogenic $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios indicative of smaller meteoroid bodies in space. We interpreted these data as indicating that the 8 Ma event generated two types of H chondrite material, namely, the unusual group (referred to as the >190°C group for its high TL peak temperature) and the more slowly-cooled group (the <190°C group) which includes the modern falls. We have suggested that the >190°C group, consisting of smaller meteoroid bodies, evolved to Earth-crossing orbits faster than the larger <190°C group bodies and dominated the H chondrite flux at least as long ago as 1 Ma. However, we also documented the "decay" of the >190°C group using meteorites from individual icefields as windows in time. Thus the >190°C group is very common at the Allan Hills Main Icefield, where terrestrial ages for meteorites are typically about 200,000 years [*Nishiizumi et al.*, 1989], but they are rare at the Yamato sites (terrestrial age ~50,000 years) and absent at several Lewis Cliff sites (terrestrial ages ~20,000 years suggested by ice dating by *Fireman* [1990]).

Figure 8 shows the induced TL peak temperatures and widths for H chondrites from various Antarctic icefields and the non-Antarctic modern falls. The >190°C group is apparent in the data for the Allan Hills sites, having peak widths of 135-150°C. It is also apparent, however, that the >190°C is absent in H chondrites from the Elephant Moraine region collection. The data points for Elephant Moraine H chondrites plot close to the line defined by the modern falls and only two out of about 30 meteorites might be of the >190°C group.

We had noted above that the meteorites from the Elephant Moraine collection, in general, have high natural TL levels such that they are difficult to distinguish from the modern falls. This suggests that the meteorites from the Elephant Moraine Icefields have short terrestrial surface exposure ages and hence may have shorter terrestrial ages than most other Antarctic meteorites. In this respect, the Elephant Moraine meteorites resemble those from the Lower Ice Tongue at Lewis Cliff. We thus suggest that the average terrestrial age for Elephant Moraine meteorites is about the same as the age for meteorites from the Lewis Cliff site namely ~20,000 years. The present induced data therefore falls into line with our ideas concerning the decay of the >190°C group of H chondrites. The meteorites from this region fell to Earth relatively recently and thus are more similar to the modern falls than the meteorites from the Allan Hills which fell up to 1 m.y. ago.

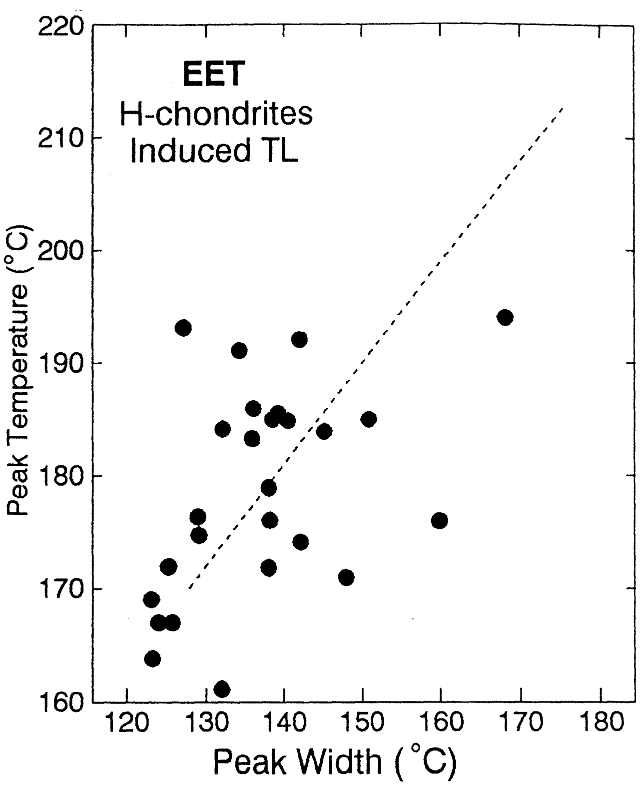

Fig. 8*a*. Induced TL peak temperature versus peak width for H chondrites from the Elephant Moraine region.

Implications for Regional Iceflow

Several ideas have been proposed to explain the formation of blue icefields [*Takahashi et al.*, 1992] and the concentration of meteorites on them [*Cassidy et al.*, 1992]. The proposed mechanisms either rely on the upturning of basal ice when the ice strikes a barrier [*Whillans and Cassidy*, 1983; *Cassidy et al.*, 1992] or upturning of deep ice as a result of ice flow over irregularities in the underlying land surface [*Delisle and Sievers*, 1991]. Both models attribute the concentration of meteorites on the surface of the blue icefields to ablation of upturned ice and emphasize the importance of lateral transport in concentrating meteorites which have fallen over a larger geographic area.

Huss [1990] used mass distributions for meteorites from the Elephant Moraine icefields to derive accumulation ages for each field. Accumulation ages reflect only the time necessary for the observed number of meteorites to accumulate on the surface of the ice and only minor lateral transport of meteorites from other areas is assumed. *Huss* [1990] derived accumulation ages ranging from 3800 to 28,500 years for icefields in the Elephant Moraine region, and the Texas Bowl Icefield was suggested to have an

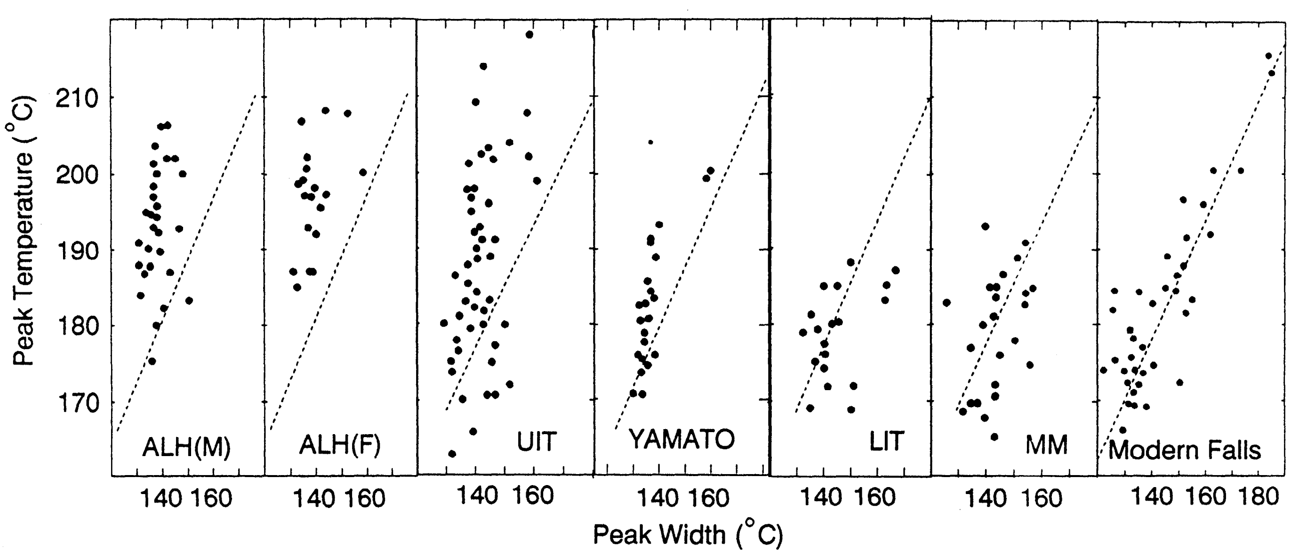

Fig. 8*b*. Same as Figure 8*a* but for the other Antarctic icefields and the modern falls. A subgroup of H chondrites with high peak temperatures (the >190°C group) is apparent at several Antarctic icefields, including the Allan Hills Main (ALH(M)) and Farwestern (ALH(F)) fields. The subgroup is rare at other sites and essentially absent at the Lewis Cliff lower Ice Tongue (LIT) and Meteorite Moraine (MM). The sites are shown in approximate order of the average terrestrial ages of the meteorites found, with the Allan Hills Main field having meteorites with ages up to 1 Ma and the modern falls having ages of only a few decades [*Benoit and Sears*, 1993*a*]. The meteorites from the Elephant Moraine region (Figure 8*a*) do not seem to contain any members of the >190°C group and thus are most similar to the Lewis Cliff lower Ice Tongue, Meteorite Moraine, and modern falls collection.

accumulation age of ~16,000 years, although new data suggest this number will be revised upwards to ~50,000 years (G.R. Huss, personal communication, 1992). We would suggest that the latter accumulation age is too high for the Texas Bowl field and does not reflect the heavy degree of pairing within this field or the transport of fragments into the icefield by the movement of ice.

As noted above, under Antarctic conditions natural TL levels of meteorite finds largely reflect their surface exposure history, which, depending on the meteorites' terrestrial histories, might not be equivalent to their terrestrial age. We find that the Elephant Moraine meteorites, with the exception of the Texas Bowl samples which are probably still biased by unrecognized pairing, are essentially indistinquishable from modern falls in terms of their natural TL distribution. Our calculations indicate that this similarity of distributions could not persist if a significant portion of the meteorites found in the Elephant Moraine region had been exposed on the ice surface for more than 12,500 years. There are two basic nonexclusive explanations for such a relatively small exposure age: (1) the Elephant Moraine region icefields began collecting meteorites only over the last 12,500 years or so, or (2) the fields have been actively collecting meteorites for a longer period of time but there has been a continuous loss of meteorites from the icefields as a result of ice movement.

From the mass distribution curve and an estimated annual fall rate, *Huss* [1990] calculated a very small accumulation age of 5400 years for the Far Western field at the Allan Hills. Carbon-14 and ^{36}Cl measurements on four meteorites from this field indicate terrestrial ages ranging from about 9500 to 21,000 years [*Jull et al.*, 1989; *Nishiizumi et al.*, 1989], although the four meteorites examined were chosen for their unusual compositions and thus their terrestrial ages may not be representative of the ordinary chondrites from the site. Data for the Allan Hills Main Icefield suggest an accumulation age of >144,000 years [*Huss*, 1990] and terrestrial ages ranging up to 1 m.y. years, with most meteorites between 0 to 300,000 years [*Nishiizumi et al.*, 1989]. Our data (Table 5) indicate that, as would be expected from the other data, the Main Icefield has the greatest abundance of "old" meteorites. The Farwestern field, however, apparently has an abundance of "old" meteorites intermediate between the Allan Hills Main Icefield and the Elephant Moraine fields and modern falls.

We would suggest on the basis of our current TL database that the model for meteorite concentration at the Elephant Moraine sites suggested by *Huss* [1990] is essentially correct. That is, the meteorites found on the Elephant Moraine Icefields either fell on the fields directly or were transported only relatively minor distances to the fields and meteorites are lost continuously from the fields as a result of ice flow. The corollary of this conclusion is that the meteorites found on the surface of the icefields were only slightly buried in the ice during their history or were not buried at all and that most of the meteorites found on the site should have small terrestrial ages. However, this mechanism is not applicable to all Antarctic meteorite-bearing blue icefields. Other fields contain significant numbers of meteorites with high TL ages, indicating that they have been exposed on the surface for >20,000 years either on the icefield on which they were found or elsewhere. We would suggest that the differences between the Elephant Moraine data and those of the other fields can be best explained by differences in ice flow dynamics. We suggest that at most icefields there is a substantial element of deep ice upwelling, bringing with it a significant number of meteorites with large terrestrial ages and meteorites are entrapped on portions of the fields composed of relatively stagnant ice. Such seems to be the case at the Allan Hills Main Icefield, which is associated with a substantial physical barrier (topographic irregularities near the Allan Hills [*Delisle and Sievers*, 1991; *Cassidy et al.*, 1992]). The Allan Hills Farwestern field does not appear to be associated with a very near-surface barrier and is thus more similar to the Elephant Moraine fields in this regard. There are insufficient field data on the Farwestern field at the Allan Hills at this time but, based on the TL data, we anticipate a fair degree of deep ice upwelling and stagnant ice at this site. We note that the TL data for Reckling Moraine meteorites (Figure 2*a*), few though they are, suggest the presence of a high proportion of meteorites with large TL terrestrial ages, and these meteorites are associated with a surficial moraine apparently derived from the base of the ice sheet [*Faure and Taylor*, 1985]. We would suggest that the Elephant Moraine fields are, in fact, unusual in that the exposed ice is from relatively shallow depths and, as a result, the meteorites from these fields are locally derived.

CONCLUSIONS

On the basis of our natural and induced TL data, we would make the following observations and conclusions.

1. The Elephant Moraine meteorite collection is biased by extensive fragmentation ("pairing") of meteorites. There is an extensive L6 shower at the Texas Bowl Icefield and this shower has relatively low natural TL levels, suggesting either that it has a relatively large terrestrial age or that it had a rather unusual orbit prior to fall. While paired fragments tend to be concentrated within single icefields, approximately half of all identified pairing groups cover several icefields. Most of these involve fields which are directly adjacent (Texas Bowl, Meteorite City, and Upper Meteorite City), but about one quarter of all pairing groups involve geographically separated fields. No pairing groups were found linking the two most widely separated fields, the Northern Icefields and the Elephant Moraine Icefield. The extensive interfield pairing suggests that the icefields of the Elephant Moraine region can be considered as a single unit.

2. The histograms of natural TL data for the meteorites found on the various icefields in the Elephant Moraine region are very similar. Using data for meteorites from other Antarctic icefields for comparison, we would suggest that the average TL terrestrial age of these meteorites is <12,500 years. Induced TL sensitivity levels are similar for all the fields and higher than most other Antarctic icefields, suggesting that these meteorites have been only mildly weathered during their terrestrial history. Sparse data for meteorites from Reckling Moraine suggest they have a much larger average TL terrestrial age than the Elephant Moraine meteorites.

3. The proportion of meteorites which have very low levels of natural TL, suggestive of reheating in space prior to Earth impact, is similar to that observed in the modern falls and meteorite collections from other Antarctic icefields. This emphasizes the constancy of the meteorite orbital distribution over the span of time represented by the Antarctic meteorite collection (<1 Ma).

4. In terms of induced TL parameters for H chondrites the Elephant Moraine region meteorites are very similar to other Antarctic fields with small average terrestrial ages, especially the Lower Ice Tongue at Lewis Cliff, and also to modern falls.

The group of H5 chondrites with unusual TL peak temperatures found at the sites with large average terrestrial ages (Main Icefield at Allan Hills, Upper Ice Tongue at Lewis Cliff) is essentially absent at all Elephant Moraine fields.

5. The mechanisms for meteorite concentration in the Elephant Moraine and Allan Hills regions are different, with the Allan Hills fields being created by upwelling of deep basal ice as opposed to ablation and erosional exposure of relative shallow ice at the Elephant Moraine fields. If these mechanisms are correct, the Allan Hills sites are more dependent on lateral transport to concentrate meteorites than the Elephant Moraine fields which have accumulated meteorites largely through infall near or on the present fields. Meteorites are continuously lost from the Elephant Moraine fields as a result of ice movement, unlike other fields where meteorites are stored for long periods of time on relatively stagnant ice.

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