JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. B2, PAGES 1875–1888, FEBRUARY 10, 1993

The Natural Thermoluminescence of Meteorites

5. Ordinary Chondrites at the Allan Hills Ice Fields

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Natural thermoluminescence (TL) data have been obtained for 167 ordinary chondrites from the ice fields in the vicinity of the Allan Hills in Victoria Land, Antarctica, in order to investigate their thermal and radiation history, pairing, terrestrial age, and concentration mechanisms. Using fairly conservative criteria (including natural and induced TL, find location, and petrographic data), the 167 meteorite fragments are thought to represent a maximum of 129 separate meteorites. Natural TL values for meteorites from the Main ice field are fairly low (typically 5-30 krad, indicative of terrestrial ages of ~ 400 ka), while the Farwestern field shows a spread with many values 30-80 krad, suggestive of <150-ka terrestrial ages. There appear to be trends in TL levels within individual ice fields which are suggestive of directions of ice movement at these sites during the period of meteorite concentration. These directions seem to be confirmed by the orientations of elongation preserved in meteorite pairing groups. The proportion of meteorites with very low natural TL levels (<5 krad) at each field is comparable to that observed at the Lewis Cliff site and for modern non-Antarctic falls and is also similar to the fraction of small perihelia (<0.85 AU) orbits calculated from fireball and fall observations. Induced TL data for meteorites from the Allan Hills confirm trends observed for meteorites collected during the 1977/1978 and 1978/1979 field seasons which show that a select group of H chondrites from the Antarctic experienced a different extraterrestrial thermal history to that of non-Antarctic H chondrites.

INTRODUCTION

During the past decade, over 14,000 meteorite fragments have been recovered in the Antarctic [*Schutt*, 1990], opening new avenues for scientific research. This collection contains many unique and rare meteorites and, even for the relatively common ordinary chondrites, appears to sample material not sampled by the non-Antarctic collection [*Dennison and Lipschutz*, 1987; *Benoit and Sears*, 1992]. In addition to their innate scientific attraction, these meteorites are potentially a powerful tool to study ice flow dynamics in the Antarctic, with each meteorite serving as an individual time marker on and within the ice. We have previously discussed thermoluminescence (TL) data for approximately 300 meteorites collected at the Lewis Cliff ice field in the Beardmore Glacier region of Antarctica [*Benoit et al.*, 1992] and in this paper we discuss TL data for 167 meteorites collected at the Allan Hills region upstream of the Mawson Glacier. Further introduction to the Antarctic meteorite collection and natural TL studies is given in our earlier paper and in the work of *Sears* (1988).

In the vicinity of the Allan Hills there are several meteorite-bearing ice fields, which have so far yielded over [illegible] meteorites. The major ice fields associated with the Allan Hills (Figure 1) are the Main ice field (close to the Allan Hills and roughly 15 x 8 km in size), the Nearwestern icefield (~6 km to the west, 3 x 3 km), the Midwestern ice field (~16 km to the west, 3 x 6 km), and the Farwestern ice field (~60 km to the west, 30 km in length and only a few kilometers wide). There are two other major meteorite-bearing ice fields in the region, namely, Reckling Moraine (~50 km distant from Allan Hills Main field) and Elephant Moraine (~75 km distant), which are not discussed in detail here.

Whillans and Cassidy [1983] have suggested a mechanism for the concentration of meteorites found on the ice fields. They suggest that meteorites fall to the surface and are buried in the snow accumulation zone. The ice then carries the meteorites toward the sea. If the ice meets a flow barrier (e.g., the Allan Hills), it becomes compressed, turns upward, and ablates by evaporative sublimation, leaving the meteorites exposed on the surface. This mechanism thus could concentrate meteorites from a fairly large catchment basin into a much smaller area by stranding them in the ablation zone and accumululating them over long periods of time. In addition, there may be a number of meteorites which fall directly in the relatively small ablation zone. An alternative idea to the Whillans-Cassidy model is that horizontal movement played little role in meteorite concentration and that, instead, the ice was once much thicker than at present and the meteorites became concentrated as the ice thinned [*Nishio et al.*, 1982].

Paper number 92JB02049.
148-0227/93/92JB-02049$05.00

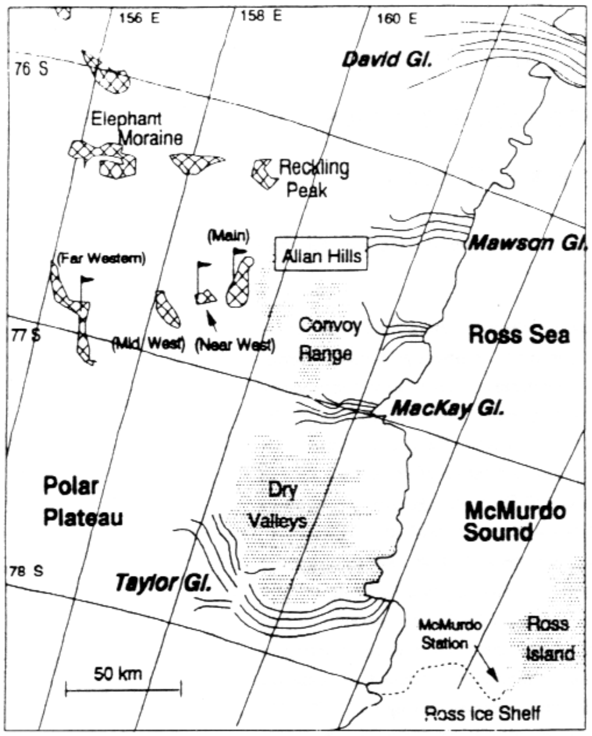

Fig. 1. Regional map of the Allan Hills vicinity. Ice fields, most of which are meteorite bearing, are shown as crosshatched areas. Exposed land is shown as stippled areas. Flags mark the ice fields of special interest in the current work.

Ongoing field work seems to show that both models are partly correct or rather, that at a given ice field one model may be predominant but that the other will be active as well. *Delisle and Sievers* [1991] have interpreted field data as favoring a Whillans-Cassidy model for the Nearwestern field at Allan Hills, but with the significant variant of a subice rather than an above-ice barrier causing the ice to turn upward. Their data seem to show that the Allan Hills Main ice field is produced by a combination of processes. They suggest that the ice field is underlain by a bedrock plateau, and as the ice advances northward, a portion of the sheet laps over this plateau, slows, and develops a northeastward velocity component [*Delisle and Sievers*, 1991; *Schultz et al.*, 1990]. High ablation rates, probably assisted by storm winds, then concentrate the meteorites on this relatively slowly moving ice. It has been argued that the Whillans-Cassidy model is largely dominant at the Allan Hills Main ice field on the basis of exposure histories for rocks from the Allan Hills themselves; cosmogenic ^{10}Be and ^{26}Al levels in these rocks suggest that they have not been buried under significant thicknesses of ice for the last several million years [*Nishiizumi et al.*, 1991].

Data on the meteorites themselves, aside from highly unusual ones such as lunar meteorites, are remarkably few. Based on mass infall statistics and ice field sizes, *Huss* [1990] suggested that the accumulation time, which cannot be directly related to average terrestrial ages of meteorites, increases among the Allan Hills ice fields as the Allan Hills are approached (i.e., west to east: 5400 years at the Farwestern field to >144,000 years at the Main field). *Nishiizumi et al.* [1989] found that the terrestrial ages of meteorites from the Main field were larger than those at other Antarctic sites and that there may be a trend of increasing terrestrial age with decreasing distance from the Allan Hills within this field, although the data are as yet rather sparse. This might reflect the exposure of older layers of ice near the east end of the field, or this might [*Delisle and Sievers*, 1991] reflect wind movement of even fairly large meteorites (up to 80 g), which might take newly exposed meteorites on the western side of the field and blow them toward the east.

In this paper we present natural TL data for 167 meteorites from the Allan Hills region including 70 from the Main ice field, 18 from the Nearwestern field, and 76 from the Farwestern field. Most of these meteorites were collected by U.S. teams between 1985 and the present, but about 50 were collected by the German expedition of 1988/1989 [*EUROMET*, 1991]. We have examined these data for information on meteorite pairing (i.e., identification of fragments of individual prefall meteorites), terrestrial age, orbit, and relationships between ice fields in the Allan Hills region and with other ice fields in the Antarctic.

Experimental Procedure

Our experimental procedures and a critique of data quality are described in an earlier paper [*Benoit et al.*, 1992]. In general, the meteorites we analyzed were sampled and measured following the same procedures and using the same equipment. The meteorite samples from the 1988/1989 German expedition were obtained by cutting with a propanol lubricated wire saw, instead of fragmenting with chisels as is the usual procedure followed by curators at Johnson Space Center. During the earliest portion of this study, a number of very small (<20 g) meteorites were mistakenly sent to us and we were concerned that samples from these meteorites might have been taken too close to the fusion crust which would result in a low natural TL, thus biasing our data set. However, there is no indication that these small meteorites have systematically lower natural TL than larger meteorites (Figure 2) which suggests that most of these small meteorites are probably fairly fresh fragments of fractured larger meteorites. In any case, it is likely that these small meteorites will have been moved by the strong Antarctic storm winds [*Schutt et al.*, 1986; *Delisle and Sievers*, 1991] so in subsequent figures and discussion they are disregarded.

Results

The natural TL data are compiled in Table 1 and presented in Figure 3, broken down by individual ice fields and with data for non-Antarctic chondrites and for chondrites found at Elephant Moraine for comparison. Comparing the cumulative Allan Hills data with those of Elephant Moraine and the non-Antarctic chondrites, it might seem that the Allan Hills data are skewed to higher natural

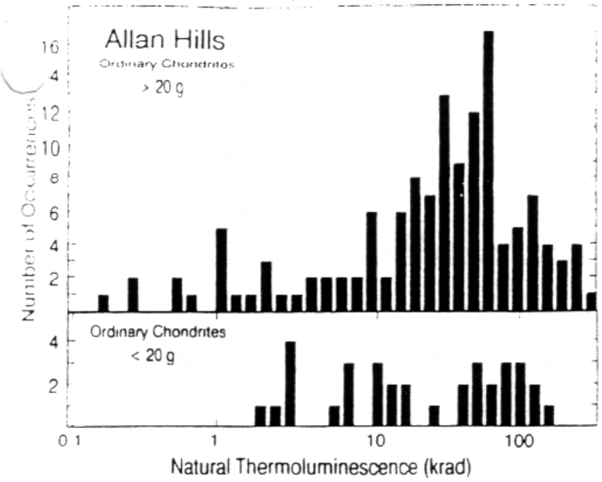

Fig. 2. Natural TL data for ordinary chondrites of weights of <20 g and >20 g. In general, there does not seem to be any tendency for the smaller meteorites to have low natural TL values, suggesting that most of them are interior fragments of larger fractured meteorites rather than pieces subjected to atmospheric passage.

TABLE 1. Natural TL Data for Ordinary Chondrites Greater Than 20 g in Weight From the Allan Hills Locality (ALH and ALHA)

Meteorite/ Class		Weight, g	Natural TL TL,* krad	Ice Field$^+$
76008	H6	1150	10.3±0.1	M
77002	L5	235	17.2±0.4	M
77004	H4	2230	35.5±0.3	NW
77155	L6	305	25.4±0.2	M
77191	H4	642	34.5±0.3	NW
77258	H6	597	48±1	M
77261	L6	412	14±0.3	M
77262	H4	862	65±3	M
77296	L6	963	1.54±0.08	M
77297	L6	952	2.5±0.2	M
78043	L6	680	11±0.1	M
78076	H6	276	58±2	M
78102	H5	337	23.4±0.4	M
78105	L6	942	45.3±0.5	M
78112	L6	2485	27.9±0.7	M
78114	L6	808	14.9±0.8	M
78115	H6	848	48±2	M
78251	L6	1312	49.6±0.5	M
79007	L6	142	27.6±0.1	M
79033	L6	281	0.2±0.1	M
81099	L6	152	2.6±0.1	NW
84066	L6	356	0.4±0.1	NW
85014	L6	75	2±0.1	FW
85016	L	1412	40±3	FW
85017	L6	2361	3.6±0.6	FW
85018	H6	812	33.9±0.6	FW
85020	H6	744	39±2	FW
85021	H5	647	0.13±0.1	FW
85023	H6	439	55±1	FW
85026	L6	817	36±2	FW
85027	L6	370	67±4	FW
85028	H6	326	18±1	FW
85029	L6	389	28.2±0.9	FW
85030	H6	620	29±1	FW
85031	H6	201	0.9±0.4	FW
85033	L4	250	258±3	FW
85034	L6	343	40±3	FW
85035	L6	420	6±0.1	M
85037	H6	141	6.2±0.4	M
85038	H5	125	27.2±0.3	FW
85039	L6	140	26.6±0.	FW
85040	L6	96	40.5±0.	FW
85041	H6	168	17.8±0.	M
85042	H5	128	48±1	FW
85043	H5	205	107±11	FW
85044	H6	105	20.2±0.3	M
85045	L3	145	63±2	FW
85054	H5	55	7.7±0.6	FW
85062	L3	167	59±6	FW
85075	L6	36	45.9±0.7	FW
85076	L6	78	16.9±0.4	M
85079	LL	8	92±1	FW
85080	L6	54	57±5	FW
85083	L6	93	52±5	FW
85091	H5	31	24±2	FW
85095	L6	33	1±0.1	FW
85097	H5	61	93±2	FW
85100	H5	58	57±2	FW
85103	L6	87	58±1	FW
85104	H5	99	0.56±0.01	FW
85107	H5	37	19.1±0.6	FW
85110	H5	22	148±2	M
85112	L6	23	48±0.5	FW
85115	L6	22	10±1	FW
85118	L5	48	38±0.3	M
85122	H5	61	1.9±0.4	M
85124	L6	64	6.9±0.3	FW
85129	LL6	127	36±2	FW
85130	H6	100	0.5±0.1	FW
85131	L6	34	32.2±0.5	FW
85132	L6	49	13±1	FW
85133	H5	91	57±4	FW
85136	H6	75	20±1	FW
85142	H5	51	26.2±0.2	FW
85145	H5	46	0.24±0.0	FW
85146	H5	40	59±2	FW
85152	LL6	36	88±2	FW
85156	H6	32	8.8±0.2	M
85157	L6	20	8.9±0.2	FW
86600	L6	411	25.4±0.5	M
86601	H5	309	4±0.4	M

TABLE 1. (continued)

Meteorite/ Class		Weight, g	Natural TL TL,[•] krad	Ice Field[+]
86602	L6	265	10±0.2	M
86603	H5	105	80±2	M
87900	L6	8000	19.6±0.3	M
88001	H5	428	61.4±0.1	M
88002	L4	358	60.0±0.5	NW
88003	L4	342	54.9±0.7	M
88004	LL4	316	1.2±0.1	NW
88005	L6	282	78.4±0.7	NW
88006	L4	233	71±3	NW
88007	H5	157	22.3±0.2	NW
88008	H4-5	154	23.8±0.5	M
88009	H5	153	26.3±0.1	M
88010	H4-5	141	58.4±0.3	NW
88011	H3	103	57±1	NW
88012	L6	103	1.7±0.2	NW
88013	H4	89	39.8±0.1	M
88014	H5	84	32.0±0.1	NW
88015	L6	84	18±2	M
88016	H4	74	129.5±0.3	M
88019	H5	57	1.9±0.2	M
88020	H3	54	209±2	M
88021	H6	51	169±0.9	M
88022	H5	47	14.8±0.1	M
88023	L6	44	8.5±0.2	M
88024	L6	38	9.4±0.1	M
88025	H5	37	27.7±0.3	NW
88026	H5	37	127.1±0.5	M
88027	H5	32	176.4±1	M
88028	H5	30	0.8±0.1	M
88029	H5	29	225.7±2	M
88030	H5	29	120.4±3	M
88031	H4-5	28	160.4±0.2	M
88032	H5	27	60.0±0.4	NW
88033	H5	27	117.5±0.5	M
88034	H6	27	3.7±0.1	M
88035	H5	27	212±4	M
88036	H3	26	20.0±9	M
88037	H4	25	46.7±0.1	M
88038	H5	25	27.0±0.3	NW
88039	H5	25	145.1±0.1	M
88040	H5	25	32.0±0.1	NW
88041	L5	24	56.2±0.6	M
88042	H5	23	238.3±0.3	M
88043	H6	21	20.4±0.1	NW
88044	L3	21	14±2	M
88047	H6	21	109.2±0.3	M
88048	H6	21	87.2±0.5	M
88049	H6	21	225±4	M
88050	H6	50	30.6±0.4	M

[•] Uncertainties based on triplicate measurements of single aliquots.

[+] Find location. F, Farwestern; M, Main; NW, Nearwestern. Find weights from *Score and Lindstrom* [1990] and *Wlotzka* [1990, 1991, 1992].

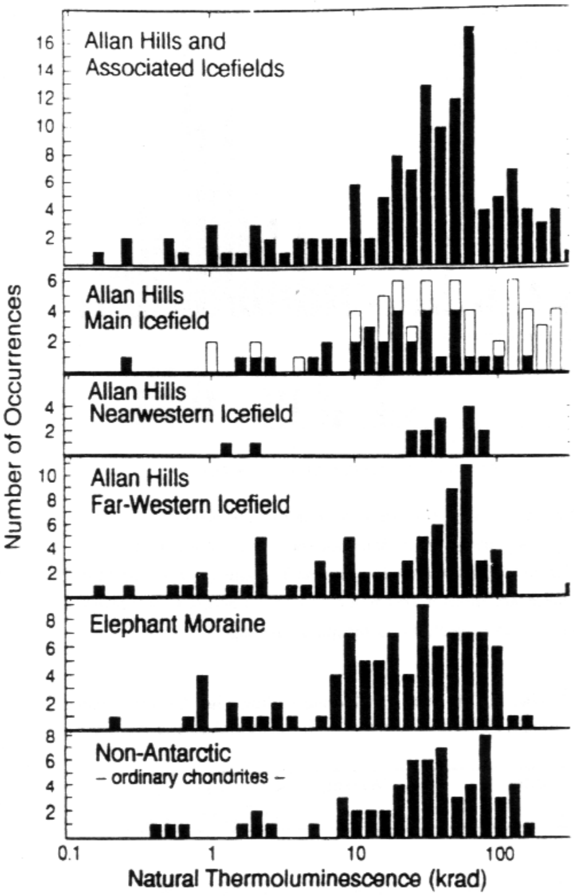

Fig 3. Natural TL data for ordinary chondrites of weights >20 g. The Allan Hills data are shown as a cumulative histogram and as individual histograms for each of the ice fields represented in our present data base. Meteorites collected by the German 1988/1989 expedition are indicated by open boxes in the Main icefield data. Data for Elephant Moraine and non-Antarctic ordinary chondrites are shown for comparison.

TL levels. This observation is, however, incorrect because the high (>100 krad) samples from the Allan Hills, almost all of which were collected by the 1988/1989 German expedition, are almost all from a small portion of the Main field (see *Delisle and Sievers* [1991] for a description of their discovery), and we suspect that these samples are a few, paired, highly unusual recent falls (see Table 3). If these high-TL samples are not considered, the Allan Hills data are skewed to somewhat lower TL values than the data for either Elephant Moraine or non-Antarctic falls. Considering the individual ice fields, it appears that the Main ice field shows a wide spread of data with a fairly large proportion of samples below 30 krad, again, not considering the unusual, probably paired high-TL samples. The Farwestern field, however, shows an almost normal distribution which appears to peak at 50-80 krad. The Nearwestern field is very poorly sampled in our present data base but shows a spread of values between 5 and 80 krad.

The TL sensitivity data for the Allan Hills meteorites are noteworthy for their general lack of spikes in the histograms, especially data for the Farwestern field (Figure 4; Table 2). This is in marked contrast to data from the Lewis Cliff ice ields (represented by the Lower Tongue in Figure 4; see *Benoit et al.*, [1992] for other fields), where a strong peak in the TL sensitivity indicates a large group of paired meteorites. Perhaps the most obvious feature of these data is the skewing of the Allan Hills data to a lower average sensitivity relative to the non-Antarctic falls. Acid-washing experiments indicate that this decrease in TL sensitivity is related to the degree of weathering undergone by the meteorites [*Benoit et al.*, 1991*a*]. Among the various Allan Hills fields, there is some indication that the Main ice field data are skewed to slightly lower values of TL sensitivity than the Farwestern field. This suggests that either most of the meteorites at the Farwestern site have been exposed to weathering relatively recently, compared with the Lewis Cliff sites and the other Allan Hills ice fields, or they were better protected from weathering (e.g., buried more rapidly) after falling to Earth.

The plots of induced TL peak temperature against peak width (measured at half peak height) are shown in Figure 5. The plot for the Main ice field is very similar to that observed previously for a group of samples collected predominantly in the 1977/1978 and 1978/1979 field seasons [*Haq et al.*, 1988; *Sears et al.*, 1991*a*]. The H chondrites have a narrow spread of peak widths but a broad range in peak temperatures and tend not to plot along the non-Antarctic H chondrite line. The data for the Farwestern and Nearwestern fields seem to be showing the same distribution, despite the paucity of samples from the latter field. The L chondrites, in general, seem to plot closer to the non-Antarctic H chondrite line.

DISCUSSION

We will first discuss pairing of meteorites seen in the present data base and then consider terrestrial age and the proportion of meteorites with low perihelion orbits. We then discuss the distribution of natural TL data as a function of location on the ice within each ice field and compare the Allan Hills data with the previously reported data set from the Lewis Cliff ice fields.

Pairing

As has been discussed elsewhere [*Benoit et al.*, 1992; *Scott*, 1989], pairing is probably extensive among the Antarctic meteorites. It is likely that between 50 and 80% of Antarctic meteorites are paired. This estimate is based on the proportion of non-Antarctic meteorites known to have fragmented during atmospheric passage [*Graham et al.*, 1985], petrological similarities, proximity on the ice and ^{26}Al contents [*Scott*, 1984], and the proportion of the non-chondrites that have been paired [e.g. *Score and Lindstrom*, 1990]. While it is relatively easy to pair unusual meteorites it

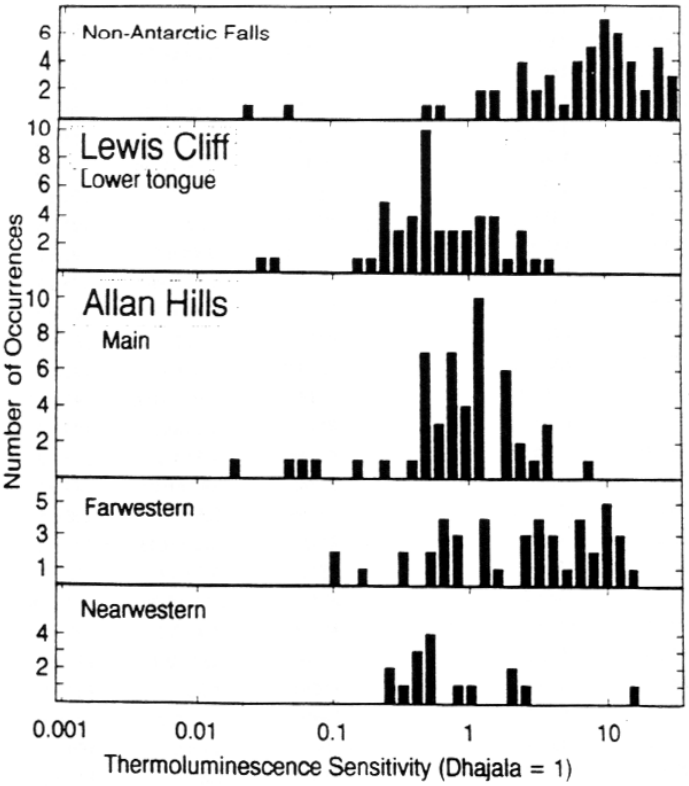

Fig. 4. Induced TL data (relative to the Dhajala H3.8 meteorite) for meteorites of weights >20 g. The values for all the Antarctic ice fields are significantly less than those for non-Antarctic chondrites, which is indicative of the much greater degree of terrestrial weathering suffered by the former. The Farwestern data seem to be skewed to slightly higher values than data for either the Main field or the Lower Tongue at Lewis Cliff.

TABLE 2. Inducted TL Data for Ordinary Chondrites From Allan Hills (ALH and ALHA)

Number	Sensitivity (Dhajala=1)	Temperature, °C	Width °C
76008	1.93±0.2	147±3	140±2
77155	0.75±0.06	169±4	125±0
79007	3.0±0.1	178±4	127±3
79033	1.14±0.05	183±4	128±3
81099	12.1±0.9	168±4	124±1
84066	2.0±0.1	156±1	125±1
85014	5.9±0.4	170±2	122±4
85016	0.25±0.03	205±5	166±2
85017	3.8±0.4	140±3	191±6
85020	1.5±0.2	201±4	137±2
85021	0.84±0.08	185±3	133±4
85023	0.46±0.04	187±3	138±2
85026	6.17±0.77	198±18	139±3
85027	0.11±0.02	181±3	137±1
85028	1.1±0.1	198±5	140±2
85029	0.46±0.05	194±1	160±3
85030	3.7±0.4	193±1	137±1
85031	2.3±0.3	197±4	136±2
85033	0.069±0.008	195±5	182±4
85034	1.9±0.3	195±2	147±4
85035	0.25±0.03	177±2	127±3
85037	0.75±0.1	192±2	139±2
85038	0.53±0.05	200±5	159±14
85039	0.37±0.07	190±3	140±7
85040	7±1	188±2	136±5
85041	1.1±0.1	195±7	136±3
85042	3.9±0.8	197±7	144±4
85043	1.9±0.2	208±6	153±9
85044	0.85±0.08	191±5	131±2
85045	0.91±0.09	214±12	153±4
85048	0.39±0.05	194±5	135±3
85052	0.69±0.09	178±3	126±5
85054	0.23±0.03	196±0	143±4
85056	0.44±0.05	197±11	128±12
85059	0.42±0.06	195±2	134±2
85062	6.5±0.7	199±1	142±3
85063	0.31±0.04	184±6	144±12
85065	6.5±0.7	192±1	142±4
85066	0.1±0.02	194±5	153±12
85070	0.4±0.1	122±5	87±5
85071	0.029±0.004	195±2	136±5
85073	7±1	188±1	138±2
85075	0.8±0.1	190±5	143±2
85076	1.0±0.1	188±8	151±2
85077	1.1±0.1	194±6	135±6
85079	1.6±0.2	195±2	155±8
85080	2.2±0.3	205±1	153±4
85082	6±1	195±6	140±3
85083	5.0±0.9	186±2	149±3
85084	0.55±0.08	197±6	159±2
85086	0.46±0.06	193±1	140±6
85087	4.4±0.6	182±2	132±12
85090	5.3±0.9	187±4	144±6
85091	1.0±0.2	199±2	134±17
85094	0.8±0.1	192±5	141±6
85095	2.1±0.1	178±3	121±6
85097	1.85±0.28	224±4	166±6
85098	0.30±0.03	193±2	138±5
85100	1.47±0.2	197±4	139±4
85102	0.48±0.07	199±6	143±3
85103	7±1	183±2	140±0
85104	0.38±0.06	202±9	137±1
85105	8.82±1.8	206±5	140±8
85107	0.59±0.1	207±9	135±3
85108	1.5±0.26	197±7	137±6
85110	1.3±0.2	190±5	139±3
85112	6±2	193±4	139±1
85114	0.54±0.08	196±4	145±1
85115	5.7±0.9	194±2	142±2
85118	0.32±0.05	191±6	141±3
85120	0.04±0.005	206±8	143±4
85122	0.05±0.007	187±4	143±2
85123	1.0±0.1	205±2	146±3
85124	0.59±0.08	176±2	143±3
85125	0.7±0.1	199±6	145±3
85127	0.36±0.04	198±5	143±6
85128	1.08±0.1	188±2	140±1
85129	0.48±0.08	198±5	146±5
85131	5±1	194±0	141±2
85132	9±1	195±6	144±2
85133	3.4±0.5	192±2	140±7
85135	0.35±0.05	198±2	155±5
85136	1.5±0.2	187±7	139±2
85137	6±1	185±3	141±8
85141	0.52±0.1	196±5	145±1
85142	0.06±0.009	199±15	135±1
85143	0.5±0.1	195±3	137±2
85144	1.1±0.1	196±9	142±4
85145	0.42±0.04	187±3	132±4
85146	2.6±0.3	208±5	145±1
85151	0.22±0.03	172±3	169±9
85152	5.7±0.8	192±8	143±1
85155	0.18±0.05	127±15	101±12
85156	1.4±0.2	193±10	147±3
86600	1.57±0.4	179±8	138±10
86601	1.3±0.3	182±1	140±5
86602	1.1±0.2	171±1	146±3
86603	2.0±0.3	160±6	130±3
88001	0.8±0.1	190±3	148±2
88002	0.3±0.03	192±3	158±1
88003	0.43±0.04	180±2	151±1
88004	0.67±0.04	178±2	152±3

TABLE 2. (continued)

Number	Sensitivity (Dhajala = 1)	Temperature, °C	Width °C
88005	0.9±0.1	178±6	147±6
88006	0.39±0.04	179±1	155±5
88007	0.47±0.04	171±6	124±4
88008	0.41±0.04	195±4	145±3
88009	1.17±0.09	170±5	138±3
88010	1.27±0.06	178±1	137±2
88011	0.22±0.01	156±2	150±2
88012	0.5±0.06	184±4	137±1
88013	1.17±0.08	187±2	134±1
88014	0.24±0.02	189±5	134±2
88015	0.019±0.002	185±4	188±2
88016	0.5±0.06	184±4	137±1
88017	0.45±0.06	182±3	137±1
88018	0.43±0.05	183±6	138±3
88019	0.8±0.1	176±4	134±4
88020	0.14±0.03	172±8	170±4
88021	1.1±0.1	178±0	136±0
88022	5.1±0.3	174±3	132±1
88023	1.8±0.1	165±2	144±3
88024	3.0±0.3	173±2	137±3
88025	0.39±0.03	185±4	132±3
88026	0.55±0.05	184±5	138±2
88027	1.0±0.1	180±4	135±1
88028	0.53±0.05	192±10	145±3
88029	1.5±0.1	196±8	141±5
88030	0.5±0.05	186±2	138±1
88031	1.1±0.1	196±10	142±1
88032	1.3±0.1	176±3	134±1
88033	0.79±0.09	187±3	138±2
88034	0.7±0.07	165±5	136±2
88035	0.52±0.03	173±2	151±9
88036	0.07±0.007	124±4	91±0
88037	2.74±0.3	178±5	131±4
88038	0.45±0.03	200±5	137±3
88039	0.99±0.09	190±0	138±1
88040	0.47±0.03	187±3	142±2
88041	0.85±0.04	184±3	143±1
88042	1.16±0.06	192±2	142±2
88043	0.3±0.1	187±5	141±1
88044	0.04±0.01	125±8	92±2
88047	1.9±0.2	191±3	137±2
88048	0.5±0.1	188±8	137±1
88049	0.8±0.2	194±9	138±2
88050	0.8±0.2	185±1	135±1

Uncertainties are for triplicate measurements of a single aliquot. Data include the sensitivity of the sample relative to the Dhajala (H3.8) meteorite and the peak temperature-width.

is difficult to pair ordinary chondrites using standard petrographic and chemical techniques. We have adopted the following set of criteria for identifying paired meteorites, which were described in greater detail in our earlier paper [*Benoit et al.*, 1992]:

1. Chemical-petrologic class must be equivalent.
2. We require that paired fragments are found within ~1.5 km of each other.
3. We require that natural TL values for paired meteorites should fall within 10% of each other. Exceptions are made for unusually low (<5 krad) and high (>100 krad) values.
4. We require that induced TL peak temperature and width are within 10% and 20%, respectively, and that TL sensitivities are within a factor of 2.
5. Cosmic ray exposure ages, ^{3}He/^{21}Ne and ^{22}Ne/^{21}Ne ratios [*Schultz et al.*, 1991], and terrestrial ages or cosmogenic radioactive isotope data (e.g. ^{26}Al, ^{14}C, and ^{36}Cl [*Nishiizumi* 1987] are used when available. Unfortunately, most of the samples in the current dataset have not been examined by these methods.
6. Some unusual features such as shock veins, inclusions and brecciation are sometimes useful for pairing. Olivine and pyroxene compositions are, however, of little use since most ordinary chondrites are fully equilibrated.
7. In a few rare cases, field evidence or meteorite appearance in hand specimen is strongly indicative of pairing. Sample descriptions (including weathering category, appearance of TL powder before and after heating, etc.) are sometimes useful.

We passed all our samples through filters 1-5, generally in the order given, and considered criteria 6 and 7 for each of the tentative groups. The results of this analysis are given in Table 3. Of the 167 meteorites for which we have a complete set of data, we believe that there are at least 25 groups of paired meteorites involving 63 members; i.e., there are at most 129 separate meteorite falls represented in the present paper. Pairing groups range from two to five members. Some of the larger pairing groups are ALHA77261 (L6) and ALH88026 (H5) in the Main field and ALH85021 (H5) in the Farwestern field. Since they were all found close together and have unusually high natural TL values, it seems very likely that the ALH88026, ALH88029 and, possibly, the ALH88018 groups are all paired, even though they do not quite pass our criteria.

We stress that the pairing criteria used in this analysis are extremely conservative and a large number of pairings have probably not been identified in our data set. This is particularly important to note in light of criterion 2. If meteorites are moved extensively by the wind, it becomes increasingly likely that pairings will be missed owing to geographic separation, especially in the case of smaller fragments. However, most of our meteorites are fairly large (generally >50 g; see Table 1) and, in the case of the Main field, were discovered well away from the "dump pile" of small meteorites on the downwind portion of the field. This

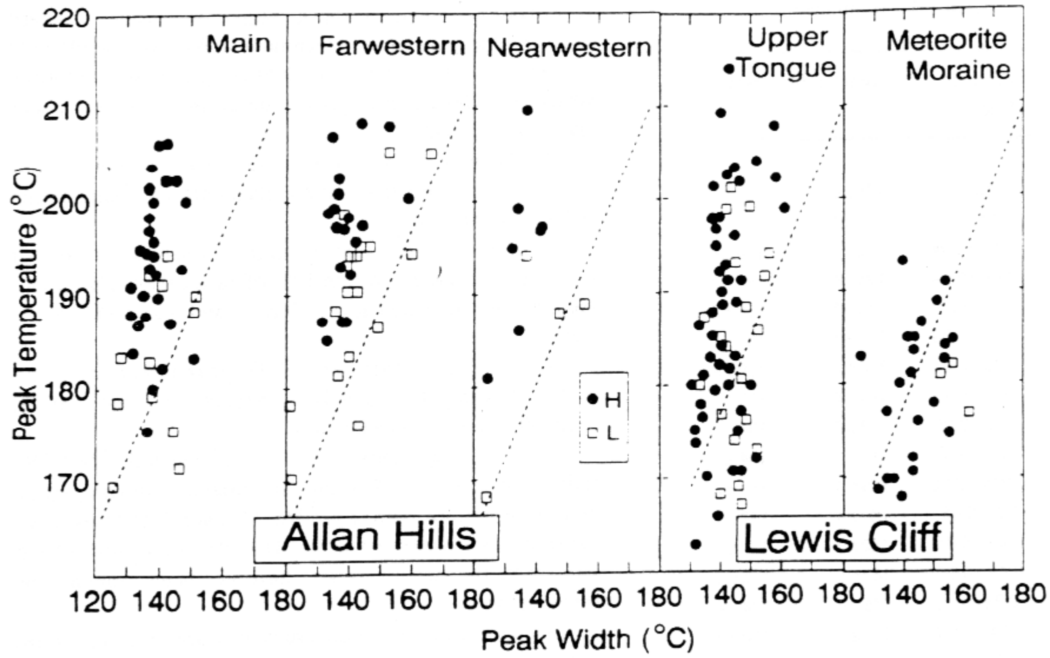

Fig. 5. Induced TL peak temperature versus peak width for ordinary chondrites of weights >20 g. All three fields show a similar wide distribution of peak temperatures for H chondrites with a very narrow spread of peak widths. The dotted lines represents the spread of non-Antarctic H chondrites [Haq et al., 1988]. The L chondrites plot fairly close to these lines.

TABLE 3. Potential Parings Among Allan Hills Meteorites, Based on Class, Natural TL, Induced TL, Location and Other Data

Name	Natural TL (krad at 250°C)	Class/ Distance,* km	Dispersion,+ km
Main Allan Hills Ice Field			
77296	1.54	L6	
77297	2.5		
78105	45.3	L6	
78251	49.6	7.25	
77004	35.5	H4	
77191	34.4		
77258	48	H6	
78115	48	2.0	
77261	14	L6	
78043	11	2.1	3.5
78114	14.9	3.5	
86062	10	1.7	
85041	17.8	H6	
85044	20.2	0	
88026	127	H5	
88030	120	0.5	1.2
88033	118	0.8	
88035	123	1.2	
88029	226	H5	
88042	238	0.25	
88018	108	H6	
88047	109	0.1	
88023	8.5	L6	
88024	9.4	0.7	
Nearwestern Ice Field			
88002	60	L4	
88006	71	2.0	
88007	22	H5	
88025	28	0.2	1.0
88038	27	1.0	
88014	32	H5	
88040	32	0.7	
Farwestern Ice Field			
85021	0.13	H5	
85056	2.5	3.8	
85104	0.56	1.1	4.0
85102	1.7	1.8	

TABLE 3. (continued)

Name	Natural TL (krad at 250°C)	Class/ Distance,* km	Dispersion,+ km
85098	5.6	H5	
85143	5.7	0.85	
85077	8.3	H5	
85114	8.9	1 km	
85091	24	H5	
85141	21.5	6	6.0
85142	26.2	3.8	
85100	57	H5	
85146	59	1.9	
85043	107	H5	
85097	93	0.4	
85018	33.9	H6	
85030	29	1.8	
85026	59	L3	
85045	63	6	
85115	10	L6	
85124	6.9	1.25	4.2
85157	8.9	4.2	
85027	67	L6	
85080	57	4.9	
85083	52	4.9	5.3
85103	58	1.4	
85105	60	3.5	
85066	77	LL6	
85073	74	3.25	3.25
85079	92	1.8	
85014	2	L6	
85017	3.6	2.1	

*Distance of the fragment from the primary member, whose class is given.

+Total dispersion of the group, i.e., maximum distance between individuals in the group.

suggests that most of our meteorites have seen limited movement by wind or other agents. While our procedure may miss numerous pairings, we attach a very high probability to the identified groupings.

Terrestrial Age

A comparison between terrestrial ages determined by cosmogenic isotopes and natural TL measurements indicates that, in general, Antarctic meteorites with natural TL between 30 and 80 krad have terrestrial ages of 150 ± 100 ka and those with natural TL between 5 and 30 krad have terrestrial ages of 400 ± 200 ka [*Hasan et al.*, 1987]. Meteorites with natural TL of >100 krad not only have very small terrestrial ages, by Antarctic standards, but have also experienced unusually high dose rates in space (i.e., low degrees of shielding or exposure in a high-radiation environment), while those with natural TL of <5 krad are either extremely old or, more likely, have been reheated while in small perihelion orbits [*Benoit et al.*, 1991*b*]. The Allan Hills Main ice field is noteworthy for the large proportion of meteorites with natural TL of 5-30 krad (Figure 3), in agreement with *Nishiizumi et al.'s* [1989] finding that the meteorites from this field have particularly large terrestrial ages. In contrast, the Farwestern ice field has a large proportion of meteorites with natural TL of 30-80 krad, suggestive of smaller terrestrial ages compared with the Main field.

Meteorite Orbit

If small perihelia are responsible for all values of natural TL of < 5 krad, as suggested by theoretical calculations [*Benoit et al.*, 1991*b*; *McKeever and Sears*, 1980], then the proportion of meteorites with natural TL this low should be approximately the same regardless of collection site, assuming orbital dynamics have not varied over the time represented by the entire collection. In the case of Antarctic meteorites, the major difficulty is removing the effects of paired meteorites. We find that the percentages of samples with natural TL of <5 krad, pairing corrected, for the Main, Nearwestern, and Farwestern ice fields are 11, 13, and 12, respectively. These proportions are in good agreement with the estimate of 15% found for the Lewis Cliff ordinary chondrites [*Benoit et al.*, 1992], basaltic meteorites [*Sears et al.*, 1991*b*], non-Antarctic ordinary chondrites [*Benoit et al.*, 1991*b*], eyewitness observations of meteorite falls [*Simonenko*, 1975] and Prairie Network fireballs [*Wetherill*, 1985].

Graf and Marti [1991*a*, 1991*b*] have suggested, on the basis of statistical A.M.-P.M. time of fall distributions of modern falls, that there is a significant difference between the orbits of H5 chondrites and other ordinary chondrites. They suggest that H5 chondrites (or their source bodies) are in an orbit with perihelion of < 1 AU, while other ordinary chondrites generally have perihelia of ~1 AU. Our calculations [*Benoit et al.*, 1991*b*] indicate that ordinary chondrites with perihelia of < ~0.8 AU will have their natural TL levels drained to <5 krad. Thus one would expect to find a greater proportion of H5 chondrites (relative to other chondrites) with very low natural TL if the model of *Graf and Marti* [1991*a*] is correct. Table 4, however, shows that this is clearly not the case in the Allan Hills data base. In fact, while the H6 chondrites make up ~ 19% (after pairing) of both the "normal TL" and the low-TL groups, the H5 chondrites are underrepresented in the low-TL group, making up only 19% of the low-TL group, as opposed to 30% of the "normal" group. This statement is, of course, subject to the problems of small numbers of samples and unrecognized pairing in the data base. Thus, for instance, the proportion of H5 chondrites in the low-TL group is lowered considerably by the existence of a single large pairing group (the ALH85021 group). Even the unpaired data, however,

TABLE 4. Proportions of L6, H5, and H6 Ordinary Chondrites >20 g With Natural TL <5 krad and >5 krad From Allan Hills, Undifferentiated by Ice Field

	Natural TL <5 krad, %		Natural TL >5 krad, %	
	Ungrouped	Paired	Ungrouped	Paired
L6	47	56	29	26
H5	37	19	32	30
H6	16	19	17	19
No. of samples	19	15	114	84

do not seem to suggest a substantial surplus of H5 chondrites with low natural TL. The apparent surplus of L6 chondrites in the low-TL group is not unexpected, since a large fraction of this class have been heavily shocked, which, as a result of the associated heating, could also lower natural TL if the event occurred $< \sim 10^5$ years ago. There does not, therefore, seem to be compelling TL evidence in the Antarctic data base for differences in H5 and other chondrite orbits, although it might be possible that this difference is a very recent development (i.e., applicable only to modern falls) or that the orbital differences suggested by *Graf and Marti* [1991*a*] are too small to have an effect on TL.

Spatial Variations in Natural TL of Meteorites at the Allan Hills Ice Fields

Figure 6 shows maps of the various Allan Hills sites with the location of meteorites for which we have natural TL data, coded according to their natural TL values. Paired meteorites are not resolved on these maps. Figure 7 shows the same maps with pairing groups outlined.

There is a fairly complete data base for the Farwestern field (Figure 7c) but the sinuous shape of this field makes it difficult to resolve any spatial trends in the data. There is a slightly higher proportion of meteorites with low TL (5-30 krad) in the northwest portion of the field, even after considering pairing. The shapes of the pairing groups generally follow the shape of the ice field; groups in the northwest portion of the ice field are generally oriented NW-SE, and those in the more central portion are oriented E-W or show no orientation. The southernmost portion of the ice field is poorly represented in our data base, at least in part due to the relatively low concentration of meteorites in this region.

The data base for the Nearwestern ice field (Figure 6b) is very small and we suspect that there are only a few individual meteorite falls present (i.e., there is extensive pairing; Figure 7b). There is a slight tendency for meteorites on the eastern portion of the ice field to have lower TL values, although most of this difference is caused by a single pairing group, ALH88025. The pairing groups are generally elongated NW-SE.

The Main ice field (Figure 6a) is dominated by a small region along its eastern edge with a very high meteorite concentration. This high concentration may be at least partly the result of wind transport. Our data base contains mostly

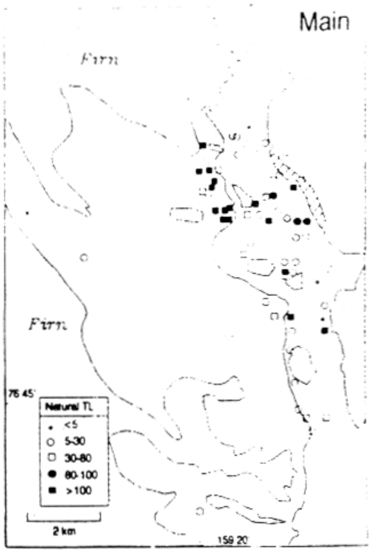

Fig. 6a.

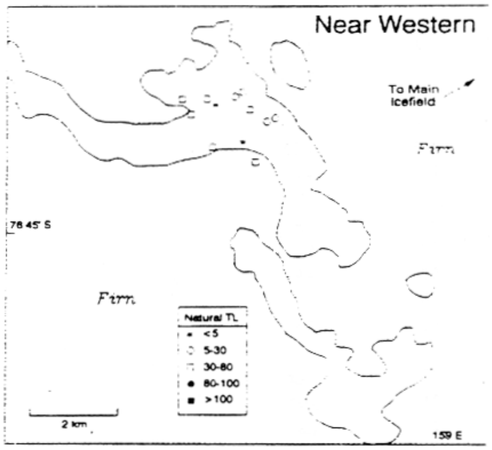

Fig. 6b.

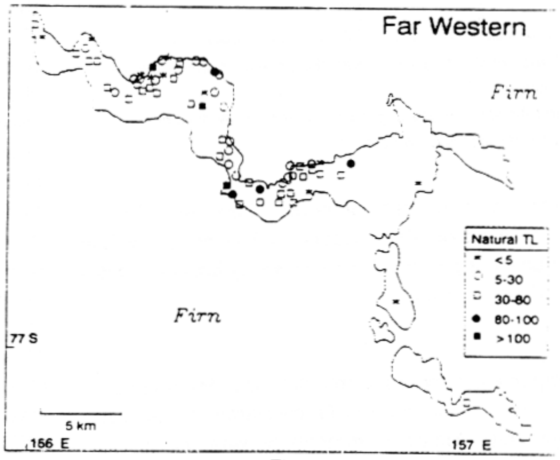

Fig. 6c.

Fig. 6. Maps of individual ice fields near the Allan Hills showing the location of the meteorites listed in Table 1, coded according to natural TL levels. Paired meteorites are not removed from these maps. Fields shown are (a) Main, (b) Nearwestern, and (c) Farwestern.

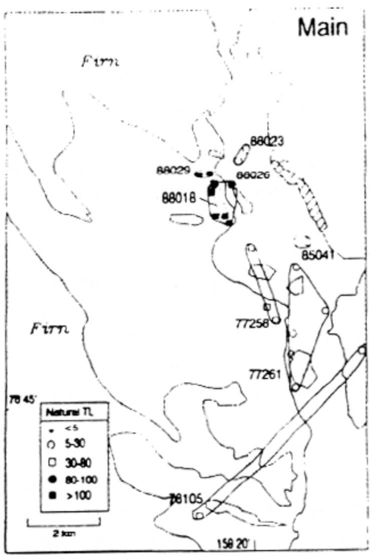

Fig. 7a.

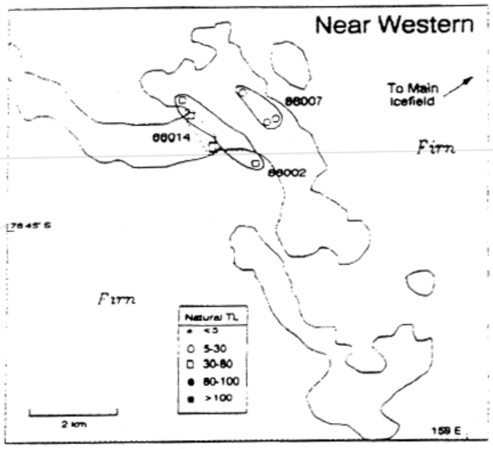

Fig. 7b.

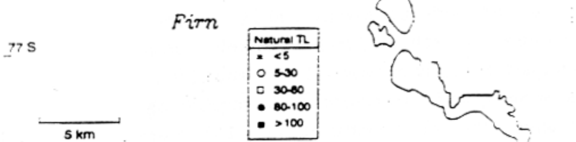

Fig. 7c.

Fig. 7. **Maps of individual ice fields showing outlines of pairing groups listed in Table 3. Fields shown are (a) Main, (b)** Nearwestern, **and (c) Farwestern. Locations of individual meteorite** fragments **within pairing groups are also shown.**

meteorites outside this high-density region, in part because of our avoidance of small samples and partly because most of our samples were recovered by the more recent expeditions. In general, as noted above, meteorites from this field have fairly low natural TL, in agreement with the long terrestrial ages suggested by other workers [*Nishiizumi et al.*, 1989]. There is a fairly large group of meteorites (including pairing groups ALH88018, ALH88029, and ALH88026) on the western portion of the field with very high natural TL which may represent a fairly recent fall. The most obvious trend, however, is the tendency for meteorites with low natural TL to be found along the eastern portion of the field.

Nishiizumi et al. [1989] found a trend in which meteorites in the southern portion of the Main ice field had greater terrestrial ages than those in the northern portion of the field. Although our data do not extend as far to the south as do those of Nishiizumi et al., we think it likely that the trend they observe is actually the same trend we have found running west to east. Our TL data indicate that the lower-TL meteorites, those with higher terrestrial ages, are located nearest to the Allan Hills barrier (i.e., to the east and southeast).

Local Ice Movements at the Allan Hills Ice Fields

Although it is clear that the general direction of ice movement in the past has been from the polar plateau (west of the Allan Hills) to the sea (east of the Allan Hills; [*Drewry*, 1980]), the exact direction and magnitude of ice flow at the individual ice fields is much less certain. Determinations of ice flow by surveying fields over a period of years is hampered by the problems of working in such a harsh environment, the slowness of ice flow compared with a project's lifespan, and the question of how modern flow relates to the flow that formed the field in the first place [***Schultz and Annexstad***, 1984; ***Annexstad and Schultz***, 1990]. Current field work seems to indicate that there is a strong south-north component of ice flow near the Main ice field.

If the Whillans-Cassidy mechanism [***Whillans and Cassidy***, 1983] of meteorite transport can be considered to work on the level of an individual ice field, then our natural TL data suggest that ice movement at the Main field during the major period of meteorite concentration had a significant west to east component (i.e., toward the Allan Hills). Likewise, ice flow at the Farwestern field probably had a significant northward component, while our limited data from the Nearwestern suggest an eastward component. These flow directions are generally confirmed by the orientations of pairing groups (Figure 7). In general, in analogy to nonspherical geologic stress markers [***Hobbs et al.***, 1976], elongate strewn fields perpendicular to the direction of ice flow will tend to preserve or even exaggerate their elongation, whereas strewn fields oriented parallel to ice flow will tend to be compacted by the time they are exposed in the ablation zone. Since any given ice field will contain a number of old strewn fields, with a variety of original orientations, one would expect to see a range of degrees of elongation in pairing groups with the predominant paleoflow direction being perpendicular to the most elongate groups. This analysis assumes that the meteorites of the pairing groups are not moved in relation to each other by storm winds or other means after surface exposure, as *Delisle and Sievers* [1991] have suggested to be a major agent in the concentration of small meteorite fragments. At the Main ice field (Figure 7a) the elongate pairing groups are oriented north-south, indicating a paleoflow direction to the east (or west, although that makes less practical sense in this situation). It is, however, possible that this orientation is purely fortuitous and merely reflects the entrapment of meteorites in near-surface crevasses (which are generally oriented N-S at the Main field) and wind transport after surface exposure [*Delisle and Sievers*, 1991]. However, the majority of meteorite fragments in this study are large enough that it is unlikely that they have been entrained by storm winds. At both the Farwestern and the Nearwestern ice field the pairing groups are oriented NW-SE, indicating that paleoflow was approximately SW-NE, with a significant northward component.

These inferred flow directions compare well with the current flow directions measured in the field [*Schultz et al.*, 1990]. While field survey measurements do not extend to the Farwestern icefield, these data suggest a strong northward component of ice flow just to the west of the Main ice field, which might, according to our TL data, be the case at the Farwestern field as well. These measurements also show a eastward component to ice flow at the Main field itself, in accord with our TL data.

A Comparison of the Allan Hills and Lewis Cliff Sites

Hasan and Sears [1988] suggested that there was a significant difference in the distribution of natural TL data between the Allan Hills and Lewis Cliff ice fields. With the much bigger, geographically divided, and carefully filtered database now available, it is possible to confirm that suggestion and offer some elaboration. The following observations are based partly on data presented in our earlier paper [*Benoit et al.*, 1992]. The Nearwestern field will be largely left out of this discussion because of the very small number of data points (after pairing).

The Main ice field resembles, in its natural TL (and terrestrial age) distribution, the Upper Ice Tongue at Lewis Cliff. Both fields show a strong tendency for meteorites of longer terrestrial ages to be located in the inferred downstream flow direction. The natural TL distribution of the Farwestern field resembles the distributions of the Lower Ice Tongue and Meteorite Moraine at Lewis Cliff, suggesting that the meteorites from these fields all have relatively short terrestrial ages.

The induced TL data from the two sites also present some interesting comparisons. The induced TL peak temperature and peak width data (Figure 5) of all the Allan Hills ice fields, especially the Main field, resembles those of the Upper Ice Tongue of Lewis Cliff. The induced TL data for the Meteorite Moraine and Lower Ice Tongue at Lewis Cliff resemble most closely the non-Antarctic meteorites. It seems fairly clear that these differences in peak shape reflect differences in thermal history [*Sears et al.*, 1991*a*] which are linked to cooling history [*Benoit and Sears*, 1992]. The present data strongly suggest that terrestrial age is also a relevant factor. One possibility is that the older portion of the Antarctic meteorite collection (including all the Allan Hills sites and the Upper Ice Tongue at Lewis Cliff) contains a subset of H chondrites which have experienced different thermal histories than the H chondrites which make up the more recent Antarctic meteorite collection (Lewis Cliff Lower Ice Tongue and Meteorite Moraine) and the non-Antarctic collection. If so, it would appear that the unusual H chondrite subset ceased to form a significant portion of the meteorite falls sometime between the terrestrial age of the youngest Allan Hills sites and the Lower Ice Tongue at Lewis Cliff. *Fireman* [1990] has determined a uranium series age for tephra bands in the Lower Ice Tongue as approximately 25,000 years, much younger than the >67,000 (and probably >144,000) years for the Main ice field at Allan Hills. Terrestrial ages for three meteorites from the Farwestern ice field range from 9500 to 21000 years [*Jull et al.*, 1989], but these samples are all achondrites and chosen for their unusual character and so may not be representative of the general meteorite population at the site. Thus current knowledge of terrestrial ages of meteorites from the Farwestern and Lewis Cliff sites does not seem to mesh with the idea of a time-dependent change in the meteorite population, but much more data are needed before this idea can be thoroughly tested. An alternative hypothesis, that the induced TL differences are caused solely by a few unusual falls (i.e., pairing), has been largely discounted by meticulous pairing studies using both cosmogenic isotopes [*Schultz et al.*, 1991] and thermoluminescence [*Haq et al.*, 1988; *Sears et al.*, 1991*a*].

SUMMARY AND CONCLUSION

Our TL data allow a number of observations to be made concerning the meteorites recovered in the Allan Hills vicinity and also provide some insight into the mechanism which has concentrated them. Our data, in conjunction with chemical, petrographic and field observations, allow us to address the question of pairing among equilibrated ordinary chondrites. We have identified 25 pairing groups among our 167 samples, containing two to five members. There is thus a maximum of 129 separate meteorites in our database. The natural TL data generally confirm the terrestrial age data from other techniques [e.g., *Nishiizumi et al.*, 1989] and show that the meteorites of the Main ice field have much longer terrestrial ages than those from the Farwestern field. The proportion of meteorites with very low natural TL (<5 krad), which we suggest have been reheated by low perihelion orbits prior to Earth impact, is nearly constant (11, 13, and 12% for the Main, Nearwestern, and Farwestern fields, respectively) and is in good agreement with the estimate of ~15% based on independent techniques. This agreement between Antarctic meteorites and modern non-Antarctic falls suggests that orbital dynamics of the meteorite population as a whole have not changed over the span of time represented by the Antarctic collection.

We have found spatial variations in our TL data on each of the three ice fields considered. In general, meteorites with ow natural TL (i.e., high terrestrial age) tend to be concentrated on one side of the field, even after taking pairing into consideration. In addition, pairing groups show distinct mutual orientations of their maximum dimensions, usually perpendicular to the direction of decreasing natural TL for each field. While some of these trends could be the result of wind transport and meteorite entrapment in near-surface crevasses [*Delisle and Sievers*, 1991] we interpret these data in terms of a Whillans-Cassidy concentration mechanism working on the individual field level, with older (in terms of terrestrial age) meteorites being concentrated down ice from younger meteorites. We suggest that the orientation of pairing groups derives from the same mechanism. We suggest that these data are indicative of paleo-ice flow with a strong west-east component at the Main field and southwest to northeast at the Farwestern and Nearwestern sites.

The induced TL data for the meteorites from the various Allan Hills sites compare well with those of the Upper Tongue at Lewis Cliff but differ significantly from those of the Lower Tongue and Meteorite Moraine. Our initial interpretion of these differences, that they are the result of a change in the meteorite population over time [*Sears et al.*, 1991*a*], may be incorrect if the meteorites at the Farwestern ice field at Allan Hills have slightly smaller restrial ages than the meteorites on the Lower Tongue d Meteorite Moraine at Lewis Cliff, as preliminary work seems to indicate [*Jull et al.*, 1989]. The explanation for this group of H chondrites with unusual thermal histories may be elusive, but our data, as well as data obtained by independent techniques, show that it is clearly not the result of a few unusual falls (i.e., pairing).

Acknowledgments. We are grateful to W. Cassidy (University of Pittsburgh) for his interest and for his constructive review of this paper. We thank the Meteorite Working Group of NASA and the curators at Johnson Space Center for samples and documentation. We also thank L. Schultz (Max-Planck Institut für Chemie) and EUROMET for samples and documentation from the 1988/89 European expedition. We thank Ben Myers, Fouad Hasan, and Joyce Roth at the University of Arkansas for technical assistance. This work funded by NASA (NAG 9-81) and the NSF (DPP 86-13998) in a cost sharing arrangement.

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(Received November 15, 1991;
revised August 21, 1992;
accepted August 26, 1992.)