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Accumulation mechanisms and the weathering of Antarctic equilibrated ordinary chondrites

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Abstract. Induced thermoluminescence (TL) is used to quantitatively evaluate the degree of weathering of meteorites found in Antarctica. We find a weak correlation between TL sensitivity and descriptions of weathering in hand specimens, the highly weathered meteorites having lower TL sensitivity than unweathered meteorites. Analysis of samples taken throughout large meteorites shows that the heterogeneity in TL sensitivity within meteorite finds is not large relative to the range exhibited by different weathered meteorites. The TL sensitivity values can be restored by minimal acid washing, suggesting the lower TL sensitivities of weathered meteorites reflects thin weathering rims on mineral grains or coating of these grains by iron oxides produced by hydration and oxidation of metal and sulfides. Small meteorites may tend to be more highly weathered than large meteorites at the Allan Hills ice fields. We find that meteorite fragments >150 g may take up to 300,000 years to reach the highest degrees of weathering, while meteorites <150 g require <40,000 years. However, at other fields, local environmental conditions and variability in terrestrial history are more important in determining weathering than size alone. Weathering correlates poorly with surface exposure duration, presumably because weathering occurs primarily during interglacial periods. The Allan Hills locality has served as a fairly stable surface over the last 100,000 years or so and has efficiently preserved both small and large meteorites. Meteorites from Lewis Cliff, however, have experienced extensive weathering, probably because of increased surface melt water from nearby outcrops. Meteorites from the Elephant Moraine locality tend to exhibit only minor degrees of weathering, but small meteorites are less weathered than large meteorites, which we suggest is due to the loss of small meteorites by aeolian transport.

1. Introduction

Over 15,000 meteorite fragments have been recovered by American, European, and Japanese expeditions in Antarctica over the last two decades [*Cassidy et al.*, 1992]. Almost all the meteorites have been found on the surface of blue ice fields, wind-swept exposures of deep ice [*Takahashi et al.*, 1992]. Some blue ice fields have yielded thousands of meteorite fragments, but more typical in Antarctica are ice fields bearing only a few or no meteorites. Differences in meteorite abundance among ice fields are usually thought to reflect differences in the local meteorite accumulation mechanisms, ice transport, wind transport, and direct infall. The ice transport mechanism involves meteorites being buried in the ice sheets after falling on the interior of the continent and being transported laterally until they are brought to the surface by a major topographic feature such as a mountain range [*Whillans and Cassidy*, 1983; *Delisle and Sievers*, 1991]. During interglacial periods, these upwellings may suffer significant ice loss through sublimation and melting, and the entrained meteorites are exposed on the surface [*Cassidy et al.*, 1992]. Meteorite accumulations are thus periodic, being formed and destroyed with changes in ice flow conditions. Such changes generally reflect climatic changes on the 1000-year timescale [*Delisle*, 1993], although blue ice fields are probably stable on the 100-year timescale [*Bintanja and Van den Broeke*, 1995].

Wind transport has also been proposed as a meteorite accumulation mechanism, at least locally, with the strong polar winds being able to entrain meteorites up to about 60 g by saltation or rolling [*Delisle and Sievers*, 1991; *Schultz*, 1990]. Like fields dominated by ice transport, fields dominated by wind transport might be expected to be periodic as meteorite accumulation surfaces, varying with local climate. It has also been proposed that at least some of the blue ice fields in Antarctica have served as passive accumulation surfaces over long periods of time, with meteorites falling directly onto their surfaces [*Huss*, 1991; *Jull et al.*, 1998*a*]. Such a mechanism requires some of the larger meteorite accumulations to have formed on blue ice fields stable for periods of tens to hundreds of thousands of years.

It is unclear which meteorite accumulation processes is most common, and thus the stability of the accumulation surfaces over time is also uncertain. The uncertainty reflects the largely unknown terrestrial history of Antarctic meteorites. The original fall locality of Antarctic meteorites is unknown, so it is not possible to examine the role of ice flow through standard morainal analysis. The length of time the meteorites have been on Earth, their terrestrial age, can be estimated from the abundance of cosmogenic radionuclides, notably ^{14}C and ^{36}Cl. These data indicate that Antarctic meteorites have terrestrial ages up to 1 million years, but a substantial fraction have been on Earth <200,000 years [*Nishiizumi et al.*, 1989; *Jull et al.*, 1998*a*].

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Natural thermoluminescence (TL) levels suggest that at least some Antarctic meteorites spent a significant portion of their history within the ice, but others have spent most of their history on the ice surface [*Benoit*, 1995].

Another potential indicator of the terrestrial history of Antarctic meteorites is the degree of weathering. Equilibrated ordinary chondrites begin their terrestrial history essentially free of weathering products and are composed of weathering-sensitive phases, including foresteric olivine and Fe-Ni metal. The degree of weathering can be estimated by a number of techniques, including a qualitative visual description [e.g., *Grossman and Score*, 1996], quantitative estimates based on modal analysis of weathering products in thin section [*Wlotzka*, 1993], estimates of abundance of iron oxides by Mössbauer spectroscopy [*Endo et al.*, 1994; *Burns et al.*, 1995; *Bland et al.*, 1996]. major element analysis [*Nobuyoshi et al.*, 1997], minor element abundances [*Barrat et al.*, 1999], abundance of halogen elements on meteorite surfaces [*Langenauer and Krähenbühl*, 1993], and the relative abundances of cosmogenic noble gases [*Scherer et al.*, 1994].

We explore thermoluminescence (TL) sensitivity as a weathering indicator. Thermoluminescence is the light emitted from a sample during heating at temperatures 20°-500°C. The maximum intensity of TL produced as a result of exposure to a standard laboratory radiation source is referred to as TL sensitivity. In equilibrated ordinary chondrites, and most other classes of stony meteorite, the primary source of TL is feldspar [*Sears et al.*, 1991], other minerals either being nonluminescent or having much lower sensitivity [*Batchelor and Sears*, 1991].

Table 1. Classification, Mass, and Terrestrial History Indicators for Antarctic Equilibrated Ordinary Chondrites

Meteorite Name	Class	Mass, g	Weathering Class*	Terrestrial Age†, ka	Surface Exposure Duration‡, 10^3 years	Induced Thermoluminescence Sensitivity§
ALHA76008	H 6	1150	B/C	100 ± 70	n.d.	1.9 ± 0.2
ALHA77002	L 5	235.2	B	820 ± 80	<310	0.34 ± 0.05
ALHA77258	H 6	597	B/C	270 ± 70	<110	1.46 ± 0.08
ALHA77261	L 6	411.7	B	310 ± 80	<410	1.02 ± 0.06
ALHA77285	H 6	271	C	220 ± 70	<150	0.65 ± 0.04
ALHA77294	H 5	1351	A	10 ± 1	<55	2.4 ± 0.1
ALHA77297	L 6	951.6	A	80 ± 40	<30	3.6 ± 0.1
ALHA78043	L 6	680	B	500 ± 80	n.d.	4.6 ± 0.1
ALHA78076	H 6	275.6	B	130 ± 70	<35	1.9 ± 0.1
ALHA78102	H 5	336.9	B/C	220 ± 80	<205	1.4 ± 0.1
ALHA78105	L 6	941.7	B	260 ± 70	<75	5.8 ± 0.2
ALHA78112	L 6	2485	B	230 ± 70	<190	0.96 ± 0.08
ALHA78114	L 6	808.1	B/C	460 ± 80	<370	1.6 ± 0.1
ALHA78115	H 6	847.6	B	45 ± 45	<65	2.9 ± 0.1
ALHA78194	H 5	24.5	nd	50 ± 50	<85	0.57 ± 0.03
ALHA78251	L 6	1312	B	300 ± 80	<60	3.1 ± 0.1
ALHA79007	L 6	142.3	A/B	45 ± 45	<175	3.0 ± 0.1
ALHA79033	L 6	280.8	B	110 ± 70	<3	1.14 ± 0.05
ALH 82102	H 5	48	B/C	11 ± 1	0	0.60 ± 0.05
ALH 85019	LL6	632.8	A	20 ± 1	<10	2.4 ± 0.1
ALH 85022	L 6	951.5	B	21 ± 1	<40	0.05 ±0.01
ALH 85026	L 6	817.1	A	10 ± 1	<115	6.2 ± 0.8
ALH 85032	H 6	424.2	C	8 ± 1	<15	3.3 ± 0.1
ALH 85036	H 6	231.5	C	17 ± 1	<90	3.2 ± 0.1
ALH 85037	H 6	231.5	B/C	70 ± 70	<100	0.8 ± 0.1
ALH 85038	H 5	124.9	B/C	6 ± 1	<175	0.53 ± 0.05
ALH 85040	L 6	95.7	B	9 ± 1	<95	7 ± 1
ALH 85048	H 5	16.9	C	920 ± 80	<360	0.39 ± 0.05
ALH 85095	L 6	32.5	B	15 ± 1	<10	2.1 ± 0.1
ALH 85118	L 5	48	B/C	570 ± 70	<105	0.32 ± 0.05
ALH 85123	L 5	15.3	B	45 ± 45	<15	1.0 ± 0.1
ALH 85130	H 6	99.7	B	4 ± 1	<3	3.5 ± 0.1
ALH 88029	H 5	29.1	nd	2.3 ± 1.3	0	1.5 ± 0.1
ALH 88047	H 6	20.6	nd	0.3 ± 1	<3	1.9 ± 0.2
BOW 85800	H 6	140.6	C	45 ± 45	<85	0.72 ± 0.08
DOM 85501	H 5	126.2	C	30 ± 30	<55	0.68 ± 0.05
DOM 85502	L 6	302.2	B	220 ± 70	<125	4.8 ± 0.1
EET 87536	L 6	7526.4	B/C	32 ± 1	<4	0.27 ± 0.03
EET 87549	L 6	538.6	B	26 ± 1	<8	3.2 ± 0.2
EET 87554	L 6	1293.5	B	13 ± 1	<8	1.6 ± 0.2
EET 87556	L 6	362.6	A	36 ± 1	<190	1.6 ± 0.1
EET 87566	L 6	388.1	C	36 ± 1	<30	3.4 ± 0.34
EET 87578	L 6	350	A	31 ± 1	<190	2.4 ± 0.5

Here, nd, not determined.

* Weathering class, from the compilation of *Grossman* [1994].

†Terrestrial age estimates from *Nishiizumi et al.* [1989] and Jull *et al.*[1998a].

‡Surface exposure duration estimated from natural thermoluminescence level, as described by *Benoit* [1995]. Natural TL data from *Benoit et al.* [1993, 1994]. Here, n.d., not determinable.

§Dhajala = 1.0.

The equilibrated ordinary chondrites that are unweathered and unshocked have fairly uniform TL sensitivity, small variations reflecting sample heterogeneity. However, equilibrated ordinary chondrite finds usually have significantly lower TL sensitivities than modern falls [e.g., *Benoit et al.*, 1992], which we will show is due to weathering.

2. Experimental Procedure

After recovery in Antarctica, all samples were processed and stored under controlled environmental conditions. Chips of 150-200 mg were taken at least 5 mm from any possible fusion crust to avoid heat-altered material [*Sears*, 1975]. With a few exceptions, samples were taken only from meteorites >20 g because of this sampling criteria. Five large meteorites, including four Antarctic meteorites and one modern fall (Saint-Séverin), were sampled from cores or from profiles, between 7 and 15 samples being taken from each meteorite in order to evaluate sample-to-sample heterogeneity.

About half of each chip was ground in an agate mortar to approximately 100 mesh, and the (nonluminescent) magnetic fraction was removed using a hand magnet. Three 4-mg aliquots of the silicate powder were placed in copper pans and heated to 500°C at 7.5°C/s in a nitrogen atmosphere; the intensity of light emitted as a function of temperature was measured with an EMI 9635 photomultiplier tube. Corning 7-59 and 4-69 filters were used to suppress black body radiation. The data were recorded as plots of light intensity as a function of temperature, referred to as glow curves, this initial curve being called natural TL as it reflects natural exposure to radiation. Each aliquot of meteorite powder was then given a laboratory radiation dose of ~2 krad using a ^{90}Sr-^{90}Y β source, and the induced TL glow curves were measured in the same apparatus and with the same conditions as the natural TL glow curves. We report the TL sensitivity as the maximum intensity of induced TL normalized to that of the Dhajala meteorite laboratory standard. Dhajala was also measured at the beginning and end of each analysis session to monitor the long-term stability of the apparatus.

One hundred milligram portions of powdered H4 Antarctic chondrites were acid-washed before TL measurement [*Sears et al.*, 1982; *Benoit et al.*, 1991]. Each powdered sample was washed with gentle agitation in 10 M HCl for ~45 s. The samples were then washed three times in distilled water, and then washed in acetone and allowed to dry.

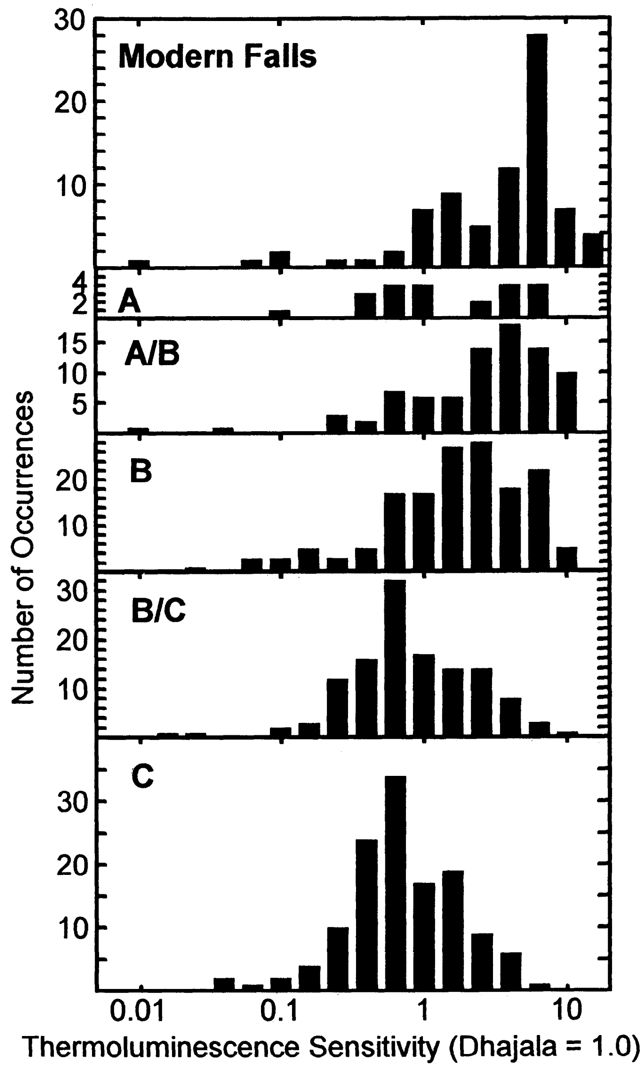

Figure 1. Histograms of thermoluminescence (TL) sensitivity of equilibrated ordinary chondrite Antarctic meteorites. Histograms are for different weathering classes, defined on the basis of hand specimen descriptions, class A having essentially no appearance of weathering and class C exhibiting significant rustiness. TL sensitivity tends to decrease with increasing degree of weathering. Induced TL data are from *Benoit et al.* [1992, 1993,1994]. Weathering class data are from the compilations of *Grossman* [1994] and *Grossman and Score* [1996].

3. Results

Induced TL sensitivity data for the Antarctic meteorites are given in Table 1 with terrestrial age estimates from ^{14}C and ^{36}Cl abundances [*Nishiizumi et al.*, 1989; *Jull et al.*, 1998*a*], estimates of terrestrial surface exposure duration from natural TL levels [*Benoit*, 1995], and weathering estimates based on hand specimen descriptions [*Grossman*, 1994]. Induced TL data for other Antarctic meteorites used in this study have been reported by *Benoit et al.* [1992, 1993, 1994].

Meteorites with the same weathering class exhibit broad ranges of induced TL sensitivity (Figure 1). The TL sensitivities of Antarctic meteorites exhibiting minimal weathering in hand specimen (classes A and A/B) are very similar to those of modern falls, while the most weathered Antarctic meteorites of classes B/C and C (which are still much less weathered than non-Antarctic meteorite finds [*Wlotzka*, 1993]) have TL sensitivities an order of magnitude lower than modern falls and classes A and A/B Antarctic meteorites. Meteorites exhibiting intermediate degrees of weathering (class B) span a wide range of TL sensitivities, intermediate to the others. Data are generally too sparse to allow detailed comparison of TL sensitivity with other weathering indices [e.g., *Langenauer and Krähenbühl*; *Endo et al.*, 1994; *Scherer et al.*, 1994; *Nobuyoshi et al.* 1997]. However, there is a general tendency for TL sensitivity of equilibrated ordinary chondrites to decrease with degree of iron oxidation determined using Mössbauer spectroscopy (Figure 2).

There is possibly a tendency for smaller meteorites (less than ~150 g) to have lower TL sensitivities than larger meteorites (Figure 3a). ALH 85022 has a tenth of the TL sensitivity of most meteorites <150 g and approximately one fiftieth the TL sensitivity of meteorites of about its own size. In contrast, modern falls do not display such a relationship (Figure 3b), although these meteorites are also significantly larger than meteorites from the Antarctic. Like ALH 85022, however,

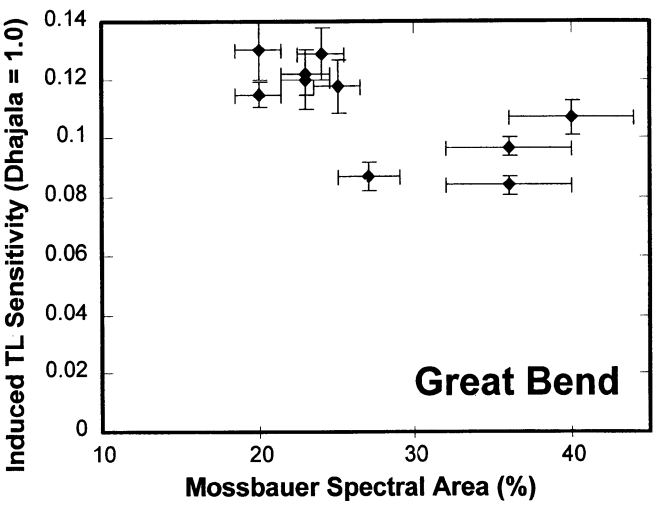

Figure 2. A comparison of TL sensitivity and Mössbauer spectral area of Fe^{3+}-containing species in the Great Bend (H6) find. TL sensitivity tends to decrease with increasing degree of oxidation, as shown by increasing spectral area of Fe^{3+} species. Mössbauer data are from *Bland et al.* [1995].

Sixiangkou, Laochenzhen, Pervomaisky, Tenham, and Karkh have much lower TL sensitivities than the others.

While there is significant variation in TL sensitivity between meteorites (Figure 1), the degree of variation within individual Antarctic meteorites and modern falls is fairly small. Induced TL data for samples taken from various depths in four large Antarctic meteorites are given in Table 2 and are plotted in Figure 4. There are no simple trends in TL sensitivity as a function of depth in these meteorites. In Antarctica, it is not uncommon for large meteorites to be broken into many subfragments, or "pairs," either during atmospheric passage or during terrestrial history (Scott,1989). One particularly large proposed "pairing" group includes numerous L5 chondrite fragments from the Queen Alexandra Range collection field (QUE). Induced TL sensitivity data for these meteorites also show a limited range (Figure 5) compared to Antarctic ordinary chondrites (Figure 1).

The TL sensitivity of fragments >150 g tends to decrease with increasing terrestrial age (Figure 6a), with some notable exceptions (ALH A78105, ALH A78043, ALH A78251, and DOM 85502). The meteorite with the longest terrestrial age, ALH A77002, has a TL sensitivity of about 0.4 relative to Dhajala, or a factor <10 times those with very short terrestrial ages. Meteorites <150 g show a weak trend of decreasing TL sensitivity with terrestrial age (Figure 6b), with a much steeper slope than for the larger meteorites, although there are few meteorites in the 100- to 400-ka range. The two meteorites with the largest terrestrial ages (ALH 85048 and ALH 85118) have induced TL sensitivities similar to ALH A77002.

We can also compare TL sensitivities of equilibrated ordinary chondrites from the Allan Hills, Lewis Cliff, and Elephant Moraine. We prepared histograms for meteorites <150 and >150 g for each locality, having removed paired fragments [*Benoit et al.*, 1992, 1993, 1994]. For the Allan Hills collection, meteorites <150 and >150 g exhibit similar ranges (Figure 7), but smaller meteorites tend to have slightly lower TL sensitivities than larger meteorites. Lewis Cliff meteorites have somewhat lower TL sensitivities than Allan Hills meteorites (Figure 8), but there is no difference in TL sensitivity between small and large Lewis Cliff meteorites. Meteorites from Elephant Moraine tend to have slightly higher TL sensitivities than Allan Hills meteorites (Figure 9). In contrast to Allan Hills meteorites, however, there is a tendency for small Elephant Moraine meteorites to have higher TL sensitivities than larger meteorites.

Acid washing of powdered samples of H4 chondrites resulted in significant increases in induced TL sensitivity (Table 3; Figure 10). Meteorites of weathering class B and some of class B/C increased to a similar level, in the range exhibited by typical H4 modern falls [*Sears et al.*, 1980]. Some meteorites of weathering class B/C and all the meteorites of class C also showed increased TL sensitivity after acid washing but to a lesser degree, reaching only the lower end of the range exhibited by H4 modern falls.

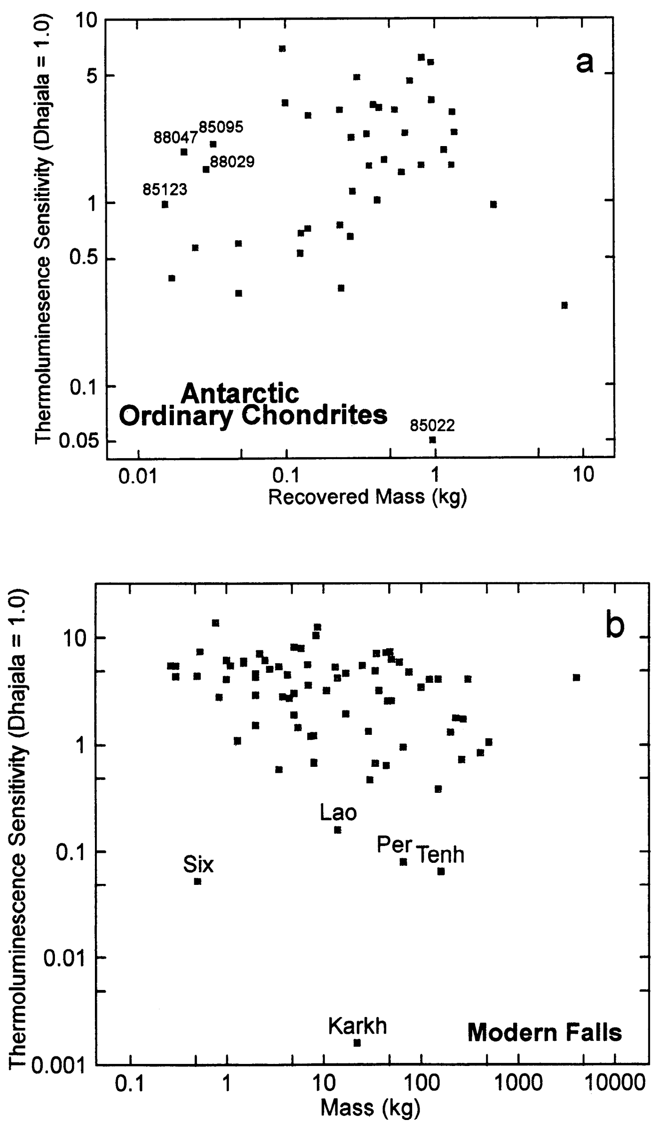

Figure 3. Mass of meteorites against TL sensitivity. Figure 3a is data for a suite of Antarctic ordinary chondrites, mostly from the Allan Hills ice field (Table 1). There is a tendency for small (<150-g) meteorites to have lower TL sensitivity than larger meteorites. Such a trend is not noted for modern falls (Figure 3b), although these meteorites are generally significantly larger than Antarctic meteorites. Numbers refer to meteorite name for Antarctic meteorites (Table 1). Abbreviations: Six, Sixiangkou; Lao, Laochengzhen; Per, Pervomaisky; Tenh, Tenham.

Table 2. Thermoluminescence Sensitivity Ranges and Averages for Samples From Large Antarctic Meteorites and the St. Séverin Modern Fall.

Meteorite	Class	Weathering Class	TL Sensitivity*
ALH A78084	H4	B/C	0.42 ± 0.02
			0.35 ± 0.02
			0.42 ± 0.04
			0.37 ± 0.03
			0.50 ± 0.04
			0.47 ± 0.02
			0.41 ± 0.03
			0.45 ± 0.05
			0.34 ± 0.02
			0.29 ± 0.02
Range			0.29 - 0.50
Average			0.40 ± 0.06
LEW 85319	L6	B/C	0.75 ± 0.03
			0.59 ± 0.01
			0.65 ± 0.05
			0.49 ± 0.02
			0.53 ± 0.02
			0.44 ± 0.03
			0.53 ± 0.02
Range			0.44 - 0.75
Average			0.6 ± 0.1
LEW 85320	H5	B	1.04 ± 0.09
			0.60 ± 0.04
			0.48 ± 0.05
			1.3 ± 0.1
			0.41 ± 0.02
			0.60 ± 0.03
			0.72 ± 0.07
			0.43 ± 0.01
			0.60 ± 0.09
			0.44 ± 0.03
Range			0.4 - 1.3
Average			0.7 ± 0.3
MET A78028	L6	B	0.99 ± 0.06
			0.67 ± 0.05
			0.76 ± 0.08
			1.3 ± 0.1
			1.25 ± 0.06
			1.19 ± 0.08
			1.7 ± 0.1
			1.42 ± 0.08
			0.64 ± 0.06
			1.6 ± 0.1
Range			0.64 - 1.7
Average			1.1 ± 0.4
Saint-Séverin	LL6	fall	4.5 ± 0.2
			2.9 ± 0.2
			2.0 ± 0.1
			3.1 ± 0.2
			1.08 ± 0.04
			2.03 ± 0.06
			2.32 ± 0.05
			1.72 ± 0.07
			0.99 ± 0.04
			1.59 ± 0.04
			1.3 ± 0.1
			2.3 ± 0.1
			1.74 ± 0.03
			3.1 ± 0.2
			1.6 ± 0.1
Range			1 - 4
Average			2.1 ± 0.9

*TL, thermoluminescence. Dhajala = 1.0.

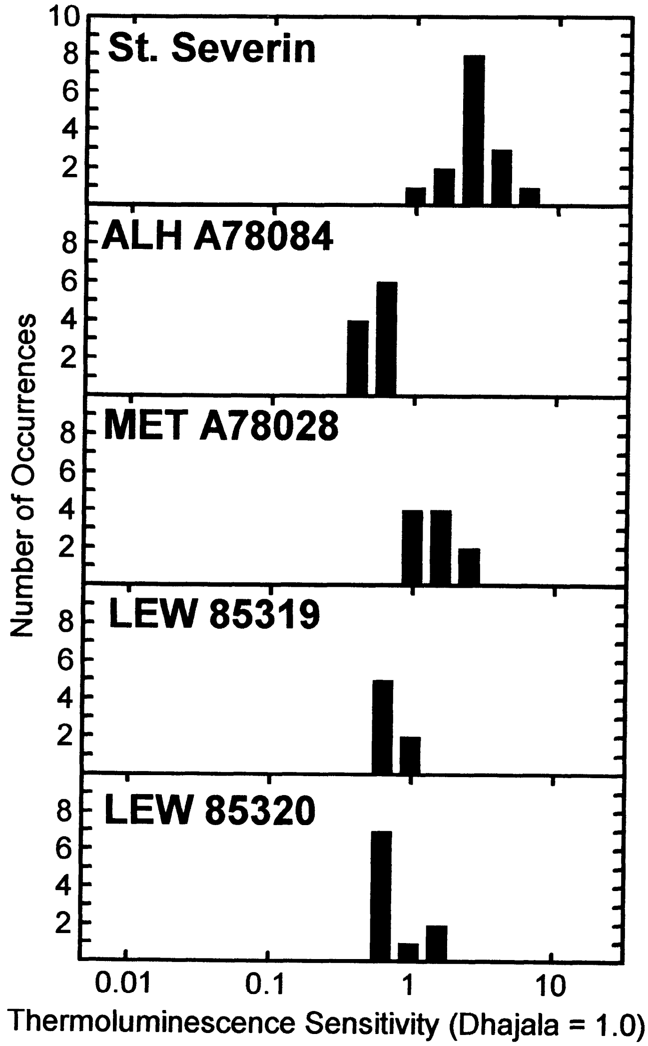

Figure 4. TL sensitivity of samples from cores or profiles of meteorites. TL sensitivity is fairly homogeneous within weathered meteorites, in comparison to meteorite-to-meteorite variation (Figure 1).

4. Discussion

4.1 TL Sensitivity and Weathering

The TL sensitivity of meteorite finds is clearly affected by weathering, but the degree of variation within weathering grades and the overlap in TL sensitivity between weathering grades show that the relationship is not simple. This is partly because weathering grade is subjective and the weathering process is heterogeneous. Weathering studies based on Mössbauer spectroscopy and thin section modal analysis [*Wlotzka*, 1993; *Wlotzka et al.*, 1995; *Endo et al.*, 1994] and bulk composition [*Nobuyoshi et al.*, 1997] are similarly poorly correlated with weathering class. Data for multiple specimens from large meteorites (Figure 4) show that variation in TL sensitivity within individual meteorites is not large and that weathering is more uniform within a meteorite than it is from meteorite to meteorite.

The TL glow curves of weathered meteorites are structurally similar to those of modern falls, differing only in their lower intensity. There is apparently no major production of new phosphors during weathering. The lower TL sensitivity presumably reflects a thin weathering coating on the feldspar grains since modest acid washing results in a restoration of their

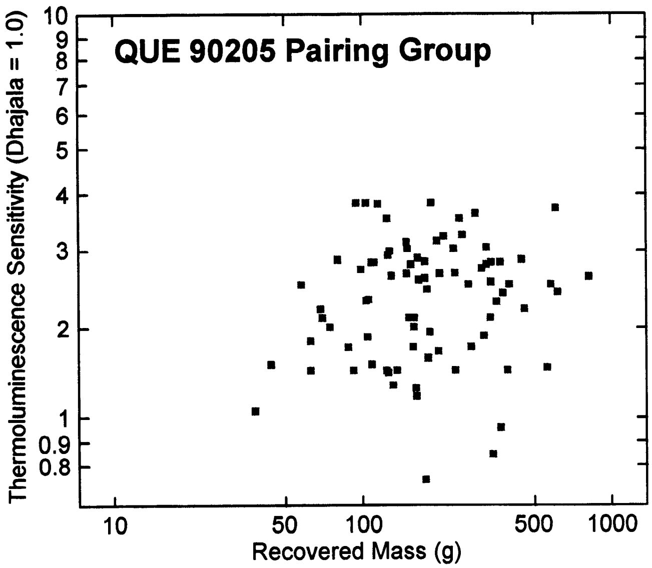

Figure 5. Mass of paired fragments of an Antarctic meteorite, Queen Alexandra Range 90205, against TL sensitivity. There is no tendency for small meteorites to have lower TL sensitivities (e.g., Figure 3a), indicating that terrestrial history is more important in determining TL sensitivity than size alone.

TL value (Figure 10) [*Benoit et al.*, 1991]. Either an outer rim of feldspar grains is rendered nonluminescent by weathering by conversion to clay minerals, for example, or feldspar grains are coated by nonluminescent iron oxides. In both cases, the feldspar is at least partly shielded from the β irradiation used for the test dose, and in the case of iron oxides, the coating would absorb at least part of any luminescence exhibited by the host feldspar grain. Acid washing has little or no effect on modern falls. Figure 10 shows that it is possible that the restoration of TL sensitivity is not complete in all cases. Even after washing, the most highly weathered meteorites (grade C) show a slight tendency to exhibit TL sensitivities near the lower end of the range of modern falls. This may reflect feldspar destruction at greater degrees of weathering.

A few Antarctic equilibrated ordinary chondrites have Dhajala-normalized TL sensitivities <0.01 (Figure 1; Figure 3a). A number of modern falls (e.g., Karkh) have similarly low TL sensitivities (Figure 3b). It is likely that the TL sensitivities of these meteorites reflect the destruction of feldspar by preterrestrial impact events [*Hartmetz et al.*, 1986; *Haq et al.*, 1988]. These meteorites typically exhibit very high degree levels of shock in thin section; typically, they are shock stage S4, S5, or S6 in the classification of *Stöffler et al.* [1991]. These meteorites are readily noted and are not considered further here. It is possible that some of the spread in the observed distributions (e.g., Figure 1) reflects shock processing, but there is no evidence that trends discussed here are a result of shock. In the case of Figure 1, for example, a broad range of meteorite types and classes occurs in each weathering class.

4.2 TL Sensitivity and Meteorite Size.

One interpretation of Figure 6 is that large samples show a relationship between weathering rate and size, most meteorites weathering to a TL sensitivity of about 0.4 from an initial value of 1-10 (relative to Dhajala) in ~300,000 years (Figure 6a). Small meteorites reach a TL sensitivity of 0.4 in <40,000 years (Figure 6b). This might reflect the greater relative surface area of smaller meteorites, enabling greater water-rock interaction. However, Figure 6 also suggests that any trend is not sufficient to explain the data for all samples, and we suggest that different terrestrial histories for small and large meteorite fragments are also important, at least at some sites. Meteorite fragments constrained to having similar terrestrial histories, such as the members of a large pairing group from the Queen Alexandra Range (Figure 5), do not exhibit any apparent size-TL sensitivity trend. We return to this point below.

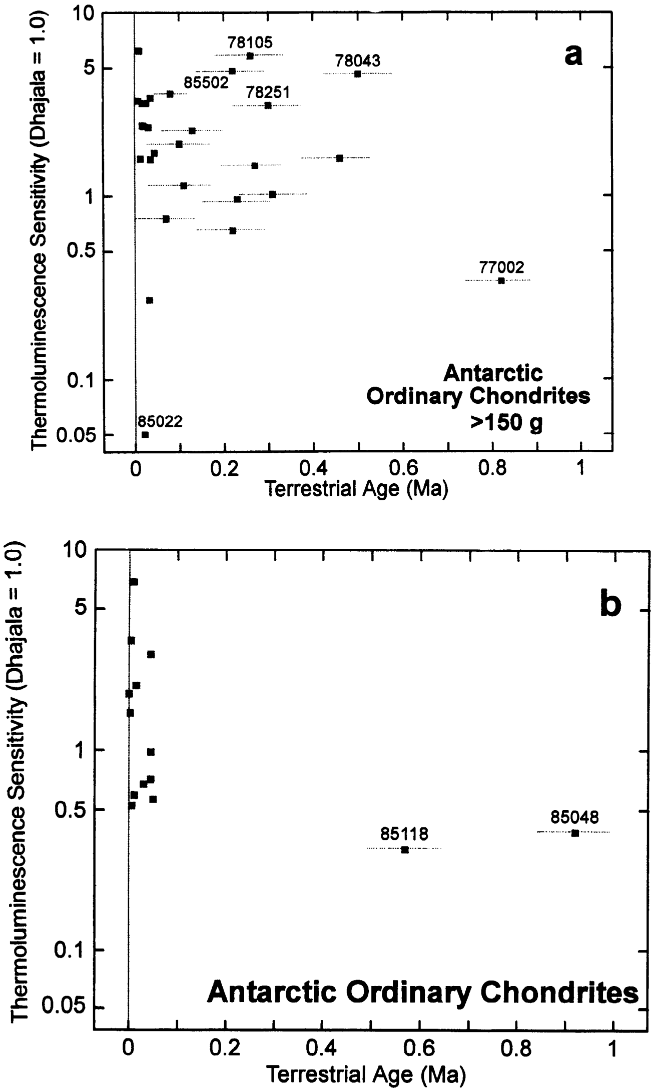

Figure 6. TL sensitivity versus terrestrial age, estimated from ^{14}C and ^{36}Cl abundances. Figure 6a is for large (>150-g) meteorites, while Figure 6b is for small (<150-g) meteorites. There is a tendency for TL sensitivity to decrease with terrestrial age, with an apparent "equilibrium" TL sensitivity of about 0.4 relative to Dhajala. Large meteorites take significantly longer to reach equilibrium than small meteorites, taking somewhat longer than 200,000 years, compared to <40,000 years. Among large meteorites, there are some notable exceptions to the trend of decreasing TL sensitivity with terrestrial age, including ALH A78043, ALH A78105, ALH A78251, and ALH 85502. Terrestrial age estimates are from *Nishiizumi et al.* [1989] and *Jull et al.* [1998*a*].

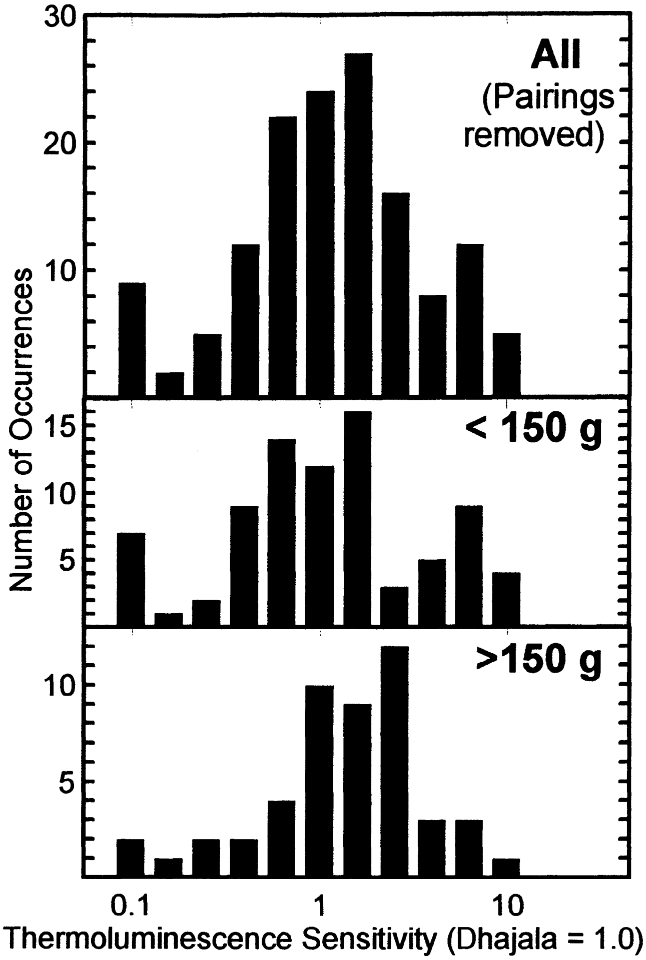

Figure 7. Histograms of induced TL sensitivities of meteorites from ice fields near the Allan Hills, Antarctica. Similar to the results for the select suite (Figure 3a), also dominated by meteorites from this field, small meteorites tend to have lower induced TL sensitivities than large meteorites. TL data are from *Benoit et al.* [1993], and sizes are from *Grossman* [1994] and *Grossman and Score* [1996].

4.3. TL Sensitivity and Surface Exposure Duration

There is no obvious trend between TL sensitivity and surface exposure duration, estimated from natural TL levels (Table 1). This, in combination with the tendency for weathering to increase with terrestrial age (Figure 6a), indicates that weathering probably occurs both on the surface and buried in the ice. It is normally assumed that the surface environment, where liquid water can be present, is the most likely site for weathering [e.g., *Dennison and Lipschutz*, 1987]. Liquid water is also found in the first meter or so of ice below the ice-air interface [*Bøggild et al.*, 1995]. Comparison of terrestrial age and surface exposure duration (Table 1) for ALH A78105, A78043, and A78251 indicates that these meteorites have spent <20% of their terrestrial histories on the ice surface and DOM 85502 spent <30% of its history on the surface. In comparison, more weathered meteorites in the same terrestrial age range, including ALH A78114, A78112, A77261, and A77285, have apparently spent >30% of their terrestrial age on the ice surface. Over the 100,000-year timescale represented by the Antarctic meteorites, there have been only a few glacial-interglacial cycles [*Imbrie et al.*, 1992]. It is likely that the interglacial periods are the warmest and the wettest in the Antarctic interior [*Cassidy et al.*, 1992], and thus it is likely that weathering of meteorites on the surface occurs predominantly during the interglacial periods [*Bland et al.*, 1996]. *Bland et al.* [1996] have suggested that meteorites experience rapid initial weathering and then enter a slower weathering stage, a suggestion supported by rapid weathering observed over a period of <100 years in the Tatahouine diogenite [*Barrat et al.*, 1999]. Our TL data seem to support the possibly of rapid weathering.

4.4 Local Effects

While both meteorite size and exposure history affect weathering, local environmental conditions also play a significant role (Figures 7, 8, and 9). Ordinary chondrites from Lewis Cliff (Figure 8) generally have lower TL sensitivities than ordinary chondrites from the Allan Hills (Figure 7), and, although the data are sparse, there is no evidence that Lewis Cliff meteorites have longer terrestrial ages than meteorites from the Allan Hills [*Nishiizumi et al.*, 1989; *Jull et al.*, 1998*a*]. The Lewis Cliff ice fields, located immediately adjacent to large outcrops and moraines, probably tend to receive more melt water compared to the more isolated Elephant Moraine and Allan Hills ice fields [*Cassidy et al.*, 1992] and thus tend to weather faster than meteorites on the ice fields near Allan Hills.

As noted above, there is evidence that large and small meteorite fragments at Allan Hills may have somewhat different

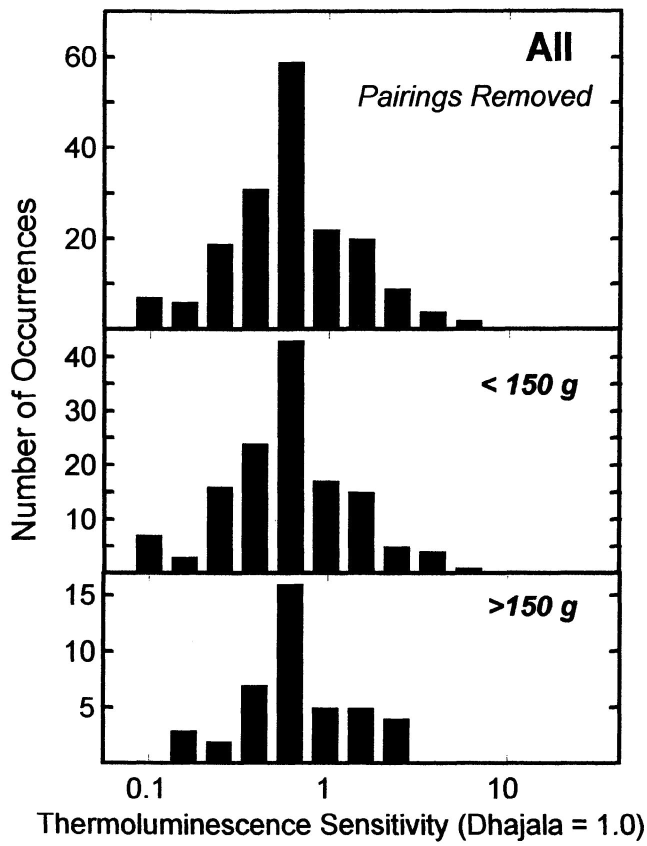

Figure 8. Histograms of TL sensitivities of meteorites from ice fields near Lewis Cliff, Antarctica. Small and large meteorites have fairly similar distributions, with a lower average TL sensitivity than observed for meteorites from the Allan Hills (Figure 7). TL data are from Benoit *et al.* (1992).

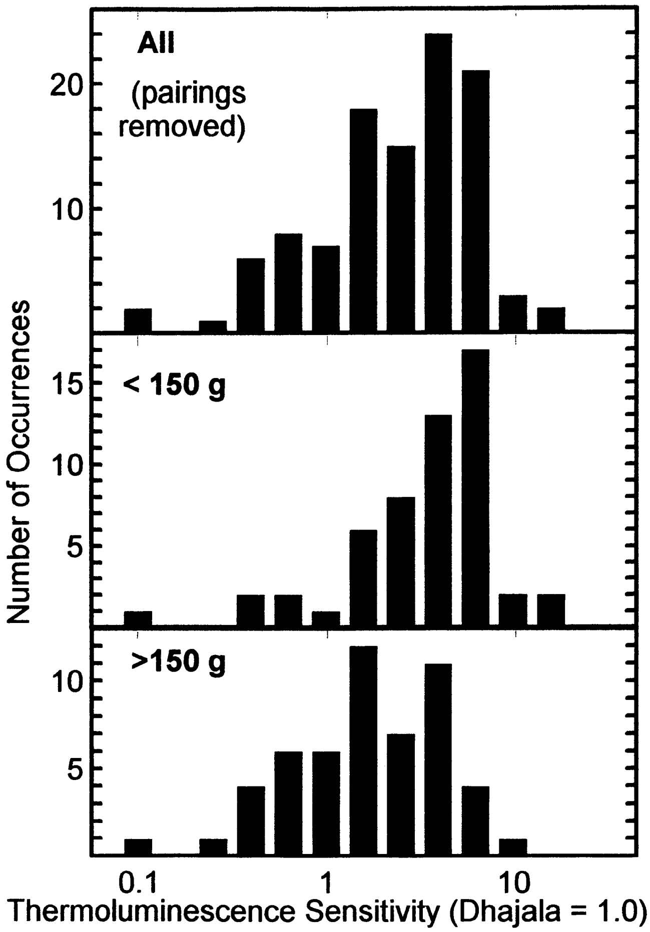

Figure 9. Histograms of TL sensitivities of meteorites from ice fields near Elephant Moraine, Antarctica. Average TL sensitivity is fairly similar to meteorites from the Allan Hills (Figure 7), but small meteorites tend to have higher TL sensitivities than large meteorites. TL data are from *Benoit et al.* [1994].

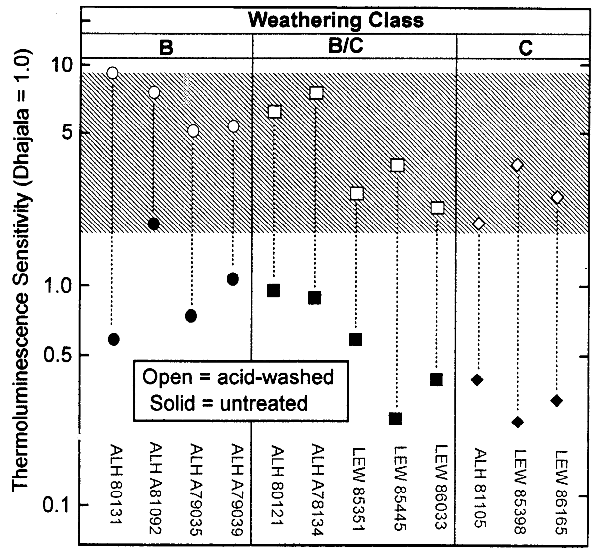

Figure 10. TL sensitivities of Antarctic H4 chondrites before and after acid washing. Samples are keyed for weathering class. The range observed for type 4 modern falls is shown in the shaded area [*Sears et al.*, 1980]. In general, after acid washing, these meteorites exhibit TL sensitivities similar to H4 modern falls. Meteorites of weathering class C and some of weathering class B/C exhibit lower TL sensitivities than the other meteorites, suggesting that some feldspar destruction has occurred in these meteorites, in addition to coating or rimming of feldspar grains.

terrestrial histories. Either small fragments were exposed to greater weathering than large fragments, perhaps because of periodic reburying of the larger fragments, or weathering is size dependent and the Allan Hills site has been a fairly stable surface. However, the relatively high TL sensitivity of some meteorites with significant terrestrial ages (e.g., ALH A78105, A78043, and A78251; Figure 6a) suggests that they were stored within the ice and only recently exposed on the ice surface. At the Lewis Cliff ice fields (Figure 7), most of the samples, regardless of size, have TL sensitivities near the long-term level of 0.4 (Figures 6a and 6b). Thus the present data cannot be used to compare concentration and loss mechanisms at this site. At the Elephant Moraine ice fields, however, small meteorites tend to have higher TL sensitivities than large meteorites (Figure 9), suggesting that they are less weathered. It could be argued that somehow the larger meteorites were exposed to more liquid water than small meteorites in this region, perhaps by being preferentially located in melt pool areas. However, a simpler interpretation of these data is that small meteorites tend to be lost at a rapid rate from these ice fields, and thus the samples collected are not weathered. The most likely agent for removal of small fragments is aeolian transport [e.g., *Schultz*, 1990]. The Elephant Moraine ice fields

Table 3. TL Sensitivity Data, before and after Acid Washing, for a Suite of Antarctic H4 Chondrites

Sample	Class	Weathering Class	TL Sensitivity*	Acid Washed TL Sensitivity*
ALHA 78134	H4	B/C	1.88. ± 0.04	7.4 ± 0.2
ALHA 79035	H4	B	0.73 ± 0.05	5.0 ± 0.2
ALHA 79039	H4	B	1.08 ± 0.06	5.2 ± 0.2
ALHA 80121	H4	B/C	0.95 ± 0.04	6.1 ± 0.3
ALHA 80131	H4	B	0.57 ± 0.03	9.2 ± 0.3
ALHA 81092	H4	B	1.9 ± 0.2	7.4 ± 0.4
ALHA 81105	H4	C	0.37 ± 0.02	1.9 ± 0.1
LEW 85351	H4	B/C	0.57 ± 0.09	2.7 ± 0.1
LEW 85398	H4	C	0.24 ± 0.03	3.53 ± 0.07
LEW 85445	H4	B/C	0.25 ± 0.04	3.5 ± 0.1
LEW 86033	H4	B/C	0.37 ± 0.06	2.3 ± 0.6
LEW 86165	H4	C	0.30 ± 0.04	2.52 ± 0.09

*Dhajala=1.0.

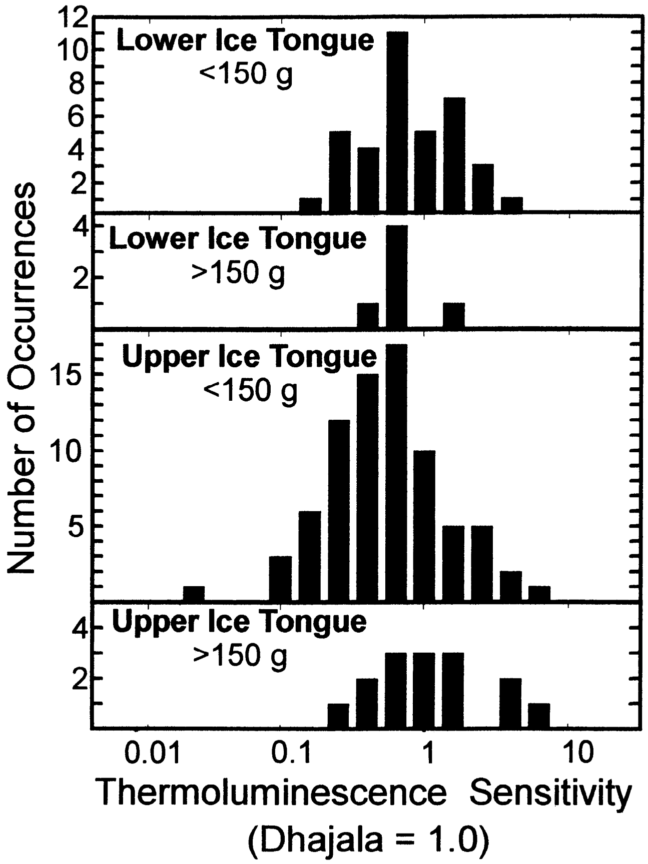

Figure 11. Histograms of TL sensitivity of meteorite fragments from the Lower and Upper Ice Tongues at Lewis Cliff. Fragments >150-g from the Upper Ice Tongue may tend to have slightly higher TL sensitivities than meteorites from the Lower Ice Tongue and meteorite fragments <150-g from the Upper Ice Tongue. TL data are from *Benoit et al.* [1992].

are located far from potential sheltering outcrops [*Cassidy et al.*, 1992] and thus perhaps more prone to aeolian meteorite loss than the other ice fields.

We have not in this paper addressed possible variation within the three major ice fields. Each of these ice fields consists of subfields separated by areas of firn or by ice steps or outcrops [*Benoit et al.*, 1992, 1993, 1994], but our database is too small to look at intrafield variations. In the case of the Lewis Cliff collection, we find possible differences in TL sensitivity between large and small meteorites from the Lower and Upper Ice Tongues, adjacent ice fields separated by an ice step (Figure 11). Meteorites from the Lower Ice Tongue and meteorite fragments <150 g from the Upper Ice Tongue exhibit similar TL sensitivity distributions, while fragments >150 g from the Upper Ice Tongue tend toward higher TL sensitivity. Presumably, meteorite fragments from the Lower Ice Tongue share similar histories involving long surface exposure under wet conditions, while fragments on the Upper Ice Tongue have experienced histories more similar to meteorites from the Allan Hills, perhaps including different histories for small and large fragments, or more recent surface exposure. Differences in terrestrial history for meteorites from these adjacent ice fields were previously suggested on the basis of natural TL data [*Benoit et al.*, 1992] and on the basis of cosmogenic radionuclide abundance (R. Wieler, personal communication, 1998).

4.5. Implications for the Weathering of Martian Meteorites

It has been suggested that ALH 84001, a meteorite inferred to come from Mars, may bear fossil Martian bacteria [*McKay et al.*, 1996]. Data used in support of this hypothesis include the presence of polycyclic aromatic hydrocarbons (PAHs) and the presence of objects with morphology somewhat similar to terrestrial bacteria on crystal faces. It has been argued, however, that the PAHs are merely terrestrial contaminants and that the "fossils" are either experimental artifacts or weathering products [*Bada et al.*, 1998; *Jull et al.*, 1998*b*]. This argument has been countered with the observation that PAHs may increase in abundance as a function of depth in the meteorite [*Clemett et al.*, 1998].

Our present work on ordinary chondrites leads to two relevant conclusions. First, weathering in Antarctic meteorites is appreciable and fairly homogeneous (factor of 2-3 effect on TL sensitivity) throughout even large meteorites (Figure 4). We find no evidence for strongly developed weathering profiles. Therefore the interiors of Antarctic meteorites cannot be considered pristine samples of the extraterrestrial environment. Second, our data indicate that weathering of meteorites can proceed fairly rapidly in Antarctica. Even Antarctic meteorites with very low terrestrial ages can have a factor of ~10 lower TL sensitivity than observed falls (Figure 1). The 13,000-year terrestrial age of ALH 84001 is thus not a strong argument in favor of preservation of extraterrestrial features. It must thus be considered possible that the PAHs distributions and bacteria-like objects in ALH 84001 are the result of terrestrial weathering products.

5. Conclusions

We argue that large (>150-g) Antarctic meteorites can weather to a uniformly low level in about 300,000 years, while smaller meteorites may weather significantly faster. Rates vary with ice field. It is likely that weathering occurs mainly during "wet" interglacial periods, and it is exposure on the surface during these wet periods that determines the degree of weathering.

Degree of weathering thus offers a new insight into the terrestrial history of meteorites. Weathering information provides surface exposure duration and local environmental conditions as well as some insight into concentration and loss mechanisms at individual ice fields. Weathering is fairly homogeneous within Antarctic meteorites but highly variable from meteorite to meteorite. However, since Antarctic weathering products are readily removed by acid washing, this process is a relatively superficial phenomenon, resulting in some minimal mineral phase destruction and the coating of other mineral grains with weathering products.

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