The Meteoritical Society

Meteoritics & Planetary Science 46, Nr 1, 79–91 (2011)
doi: 10.1111/j.1945-5100.2010.01139.x

The natural thermoluminescence of Antarctic meteorites and their terrestrial ages and orbits: A 2010 update

Derek W. G. SEARS[1,2*], Jordan YOZZO[1,3], and Christina RAGLAND[1,2]

[1]Arkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, Arkansas 72701, USA
[2]Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, USA
[3]Department of Geosciences, University of Tulsa, Tulsa, Oklahoma 74104, USA
[*]Corresponding author. E-mail: dsears@uark.edu

(Received 18 September 2009; revision accepted 16 August 2010)

Abstract–We have examined the relationship between natural thermoluminescence (TL) and ^{26}Al in 120 Antarctic meteorites in order to explore the orbital history and terrestrial ages of these meteorites. Our results confirm the observations of Hasan et al. (1987) which were based on 23 meteorites. For most meteorites there was a positive correlation between natural TL and ^{26}Al, reflecting their similarity in decay rate under Antarctic conditions and thus in terrestrial age. For a small group with low TL and high ^{26}Al a small perihelion was proposed. Within this group, natural TL decreases with terrestrial age as determined by ^{36}Cl measurements, although the rate of TL decay is faster (half-life approximately 10 ka) and the ages that can be determined are smaller (<200 ka) than for most meteorites. The faster decay rate and lower natural TL levels are a reflection of recent exposure to higher radiation doses and higher temperatures, since this history would populate less stable TL traps with smaller electron densities. We sort the 120 meteorites by perihelion and terrestrial age. The normal perihelion group range up to approximately 1000 ka and the small perihelion group range up to approximately 200 ka. An intermediate perihelion group tends to have short terrestrial ages (20–60 ka). There is acceptable agreement between most (34 out of 43) of our present terrestrial age estimates and those determined by isotopic means, the exceptions reflecting complex irradiation histories, long burial times in the Antarctic, or other issues.

INTRODUCTION

The terrestrial ages of meteorites, the time that has lapsed since they fell to Earth, is of interest because of its relevance to (1) secular variations in the nature of material falling on Earth (Dennison and Lipschutz 1987; Lipschutz and Samuels 1991; Sears et al. 1991; Benoit and Sears 1992, 1993), (2) the nature and behavior of certain major terrestrial stranding surfaces, like the Antarctic ice sheets, prairies, and deserts (Benoit et al. 1992, 1993a, 1993b, 1993c, 1994; Benoit and Sears 1999), and (3) the task of identifying the members of large showers in the highly populated Antarctic and desert strewn fields (Scott 1984, 1989; Benoit et al. 2000).

However, terrestrial age determination is among the most difficult of the dating methods commonly used with meteorites. The isotopic methods available for terrestrial age determination involve measuring the abundance of radioactive isotopes that were produced by cosmic ray bombardment in space and which decay once on Earth (e.g., Jull 2006). Examples are ^{14}C, ^{36}Cl, and ^{26}Al, which are produced by spallation reactions in space and undergo beta-decay with half-lives of 5.7×10^3 yr, 3.0×10^5 yr, and 7.2×10^5 yr, respectively. If the terrestrial age is comparable with the half-life of a given isotope, then dating is feasible using that isotope. Thus radiocarbon is commonly applicable to prairie state meteorites where meteorites tend to have terrestrial ages of 0–40 ka, while ^{36}Cl and ^{26}Al are commonly applicable to Antarctic meteorites where terrestrial ages range up to approximately 1 Ma. Weathering conditions at the fall site largely dictate the maximum terrestrial

© The Meteoritical Society, 2011.

age of a meteorite on Earth at that site, although sometimes the dynamics of the surfaces on which the meteorites fall (ice sheet movement, wind, and wind blown sand effects) can also be a factor. Over most of the world, iron meteorites tend to survive longer than stony meteorites because of their greater resilience to weathering but this does not appear to be the case for Antarctic meteorites (Sears 1979).

The major challenge of isotopic methods of terrestrial age determination is determining the value of the isotopic abundance at the time of fall. Since this is dependent on cosmic ray fluence, target chemistry, shielding depths, and the possibility of multiple phases of irradiation under different conditions, the value is highly uncertain even after secondary methods for determining and correcting for these are applied.

In the early 1980s a large influx of Antarctic meteorites started to become available to the scientific community (Cassidy et al. 1977; Cassidy 2003). In 1987 the Antarctic Meteorite Working Group (MWG), an advisory group to NASA, NSF, and the Smithsonian Institution, added natural thermoluminescence (TL) measurements to the preliminary examination program for returned Antarctic meteorites. They did this on the basis of arguments summarized by Sutton and Walker (1986) and a pilot study by Hasan et al. (1987). While petrographic and electron microprobe data provided a geological description of the returned meteorites, natural TL and ^{26}Al determination provided information on radiation and thermal histories.

Natural TL measurements were included in the *Antarctic Meteorite Newsletter* for 14 years (1987–2001) and data for over a thousand meteorites were reported. Most of the data were discussed in depth in primary publications (e.g., Benoit et al. 1992, 1993a, 1993b, 1993c, 1994). Here we revisit the work that resulted in the inclusion of natural TL in the preliminary examination program for Antarctic meteorites, the relationship between natural TL and ^{26}Al, 22 years and 1000 meteorites later.

BACKGROUND

The Hasan et al. (1987) data that led to the inclusion of natural TL in the preliminary examination of Antarctic meteorites are shown in Fig. 1. The samples were selected by the MWG in order to encompass the full range of ^{26}Al activities observed to that date. Nineteen of the samples plot on a trend in which natural TL decreases by a factor of 100, while ^{26}Al decreases by a factor of 6. This is consistent with a number of detailed studies over many years that suggested that natural TL, like ^{26}Al, could be used to estimate terrestrial ages (Sears and Mills 1974; Sears and Durrani 1980; Melcher 1981a; Sears et al. 1990).

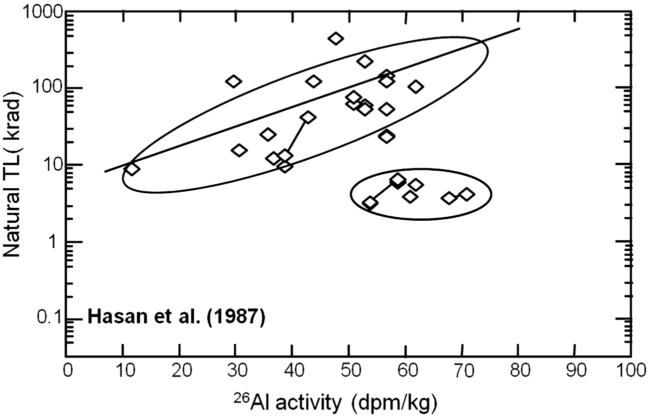

Fig. 1. Plot of natural thermoluminescence (TL) against ^{26}Al activity in 23 Antarctic meteorites chosen by the Antarctic Meteorite Working group for a pilot study of the value of natural TL in the preliminary examination of newly returned Antarctic meteorites. The study and detailed results were reported by Hasan et al. (1987) and led to the inclusion of natural TL data in the initial descriptions of newly returned meteorites reported in the *Antarctic Meteorite Newsletter* for fourteen years (1987–2001). While most meteorites plot on a correlation line between the two parameters, a small subset have high ^{26}Al and low natural TL suggestive of small perihelion. For simplicity, error bars are not shown but can be seen in the Hasan et al. (1987) paper. Tie lines connect meteorites that were separated on the ice sheet but are thought to be part of the same fall.

A second group of samples, six fragments of four meteorites, in Fig. 1 has lower natural TL (<5 krad) than the others and somewhat higher ^{26}Al. At about the time these data were reported to the MWG the Salem meteorite fell and was also found to have both very low natural TL and high ^{26}Al (Pugh 1983; Nishiizumi et al. 1990). Both the low natural TL and high ^{26}Al were attributed to a particularly close solar passage, which would lower the natural TL by thermally draining the signal while solar cosmic rays (better referred to as solar energetic particles, SEP) would drive ^{26}Al to values much higher than normally encountered, especially if the meteorite was small, because SEP have low energy and small penetrability. It thus came to be understood that, in addition to being small, these samples had experienced small perihelia, a topic that has been discussed at some depth (McKeever and Sears 1980; Melcher 1981a, 1981b; Benoit et al. 1991; Benoit and Sears 1997).

The level of natural TL observed in a sample is the result of a competition between build-up due to radiation exposure and decay due to thermal drainage:

$$\frac{\phi}{\phi_s} = \frac{1}{1 + [s/\alpha R \exp(-E/kT)]} \tag{1}$$

where ϕ (Gy, 100 Gy = 1 rad, a unit of absorbed dose) is the level of natural TL, ϕ_s (Gy) is the value of TL at saturation, dimensionless parameter s is the Arrhenius factor, α is the rate constant (s^{-1}) for de-excitation, R is the dose rate (Gy s^{-1}), E is the trap depth (eV), k is Boltzman's constant (eV K^{-1}), and T (K) is temperature. This expression is described in various books and publications (for example, see Sears and Hasan 1986). Most of the terms in this expression depend on the nature of the absorbing material, which will be fairly uniform among the ordinary chondrites, physical and compositional differences between H, L, and LL chondrites being minor in importance compared to other factors. Of special importance are the dose rate, R, and temperature, T, which have a major influence on natural TL values and lead to a variety of common applications, including terrestrial age.

Thus the level of natural TL in a meteorite when it enters the Earth's atmosphere is a function of perihelion and the temperature at perihelion can be calculated from:

$$T = 279\,(\varepsilon/d^2)^{1/4} \tag{2}$$

where ε = absorbed/emitted radiation and d = solar distance. Most meteorites have perihelia 0.8–1 AU, others 0.5–0.6 AU (McKeever and Sears 1980; Melcher 1981b; Benoit et al. 1991; Benoit and Sears 1997).

Since most meteorites have perihelia close to 1 AU when they entered the atmosphere they have fairly similar natural TL values. Assuming this value can be applied to finds, it is possible to use the natural TL values of the finds to estimate their terrestrial ages, the time since they fell to Earth. For a single TL peak, the rate of decay for the TL is given by

$$\mathrm{d}\phi/\mathrm{dt} = -s\,\phi \exp(-E/kT) \tag{3}$$

and to calculate the actual decay curve the sum of the peaks must be determined. Several studies have shown that natural TL of ordinary chondrites decreases with increasing terrestrial age and the rate of decay decreases as increasingly stable peaks come into effect (Sears and Mills 1974; Sears and Durrani 1980; Melcher 1981a; Benoit and Sears 1993).

In Fig. 2 we show the natural TL as a function of distance from the Sun from which black body temperature has been calculated assuming typical albedos and emissivities. Relevant dose rates have been measured by spacecraft and are typically 5–10 krad yr^{-1} (Benoit and Sears 1993). Thus meteorites beyond 1.0–1.3 AU will have saturated (maximum) natural TL levels, but moving closer to the Sun they will drop rapidly (Benoit and Sears 1994). Within approximately 0.8 AU they will have values < 5 krad. While we assume black body behavior, we suspect deviations are small compared with uncertainties in emissivity and albedo.

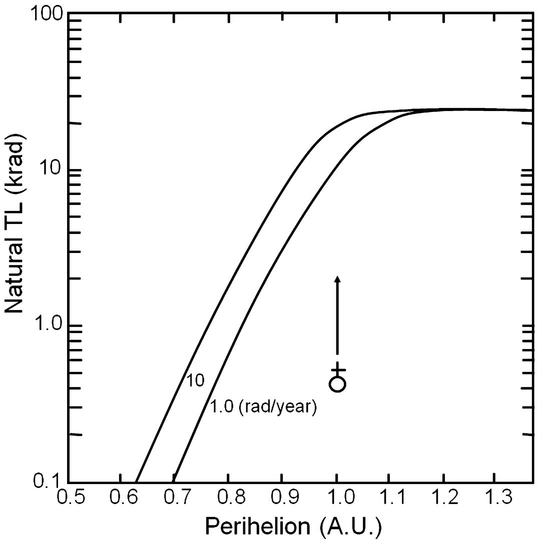

Fig. 2. Natural TL as a function of perihelion distance for two assumed space radiation dose rates (adapted from Benoit and Sears 1993). The natural TL level of meteorites is strongly dependent on storage temperature, especially the temperatures experienced at perihelion. Thus making reasonable assumptions about the thermal properties of the meteorites in space, it is possible to show that at large distances (> 1.2 AU) the natural TL will be at saturation levels, but with decreasing perihelion drops several orders of magnitude for relatively short changes in perihelion. Thus for perihelia within, say, 0.8 AU, the natural TL will decrease by about two orders of magnitude.

The largest cause of uncertainty in terrestrial ages determined by isotopic methods is the range of values displayed by observed falls, and this reflects mostly the different levels of shielding experienced by the meteorites in space. The same theoretical and experimental data that are used to determine cosmogenic isotope abundance as a function of depth (e.g., Reedy 1985, 1987; Michel et al. 1996) can be used to calculate total ionization and thus natural TL levels. There are several papers that experimentally explore depth effects on the natural TL levels of meteorites (Valladas and Lalou 1973; Sears 1975a, 1975b; Benoit and Sears 1993). A typical result is shown in Fig. 3 (Benoit and Sears 1993). For an unusually large meteorite, in this case an H5 chondrite, a drop of a factor of about 0.3 is observed for smaller more likely objects the drop is less. This relatively small depth-dependence is not a surprising result, because natural TL is a low energy process. In such cases, the build-up of secondary radiations is offset by the attenuation of the primary radiations.

Recent laboratory data for ^{26}Al are shown in Fig. 4 (Michel et al. 1996). Since ^{26}Al is a low energy product, the major target being ^{28}Si (with a small mass difference

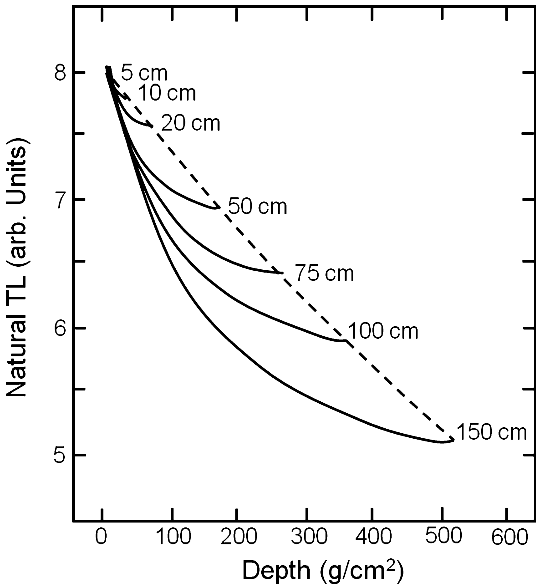

Fig. 3. Natural TL as a function of depth inside H chondrites of the sizes indicated. For a large meteorite (approximately 150 cm), the variation is approximately 35%, for smaller meteorites it is less. This is because for natural TL, like low-energy cosmogenic nuclides, the rate of decay due to attenuation of primary cosmic radiation is approximately balanced by the rate of build-up due to secondary radiations. The thermal drainage due to atmospheric heating is restricted to the outer 6 mm or so, and is not significant on these distance scales (Sears 1975a, 1975b). Figure from Benoit and Sears 1993.

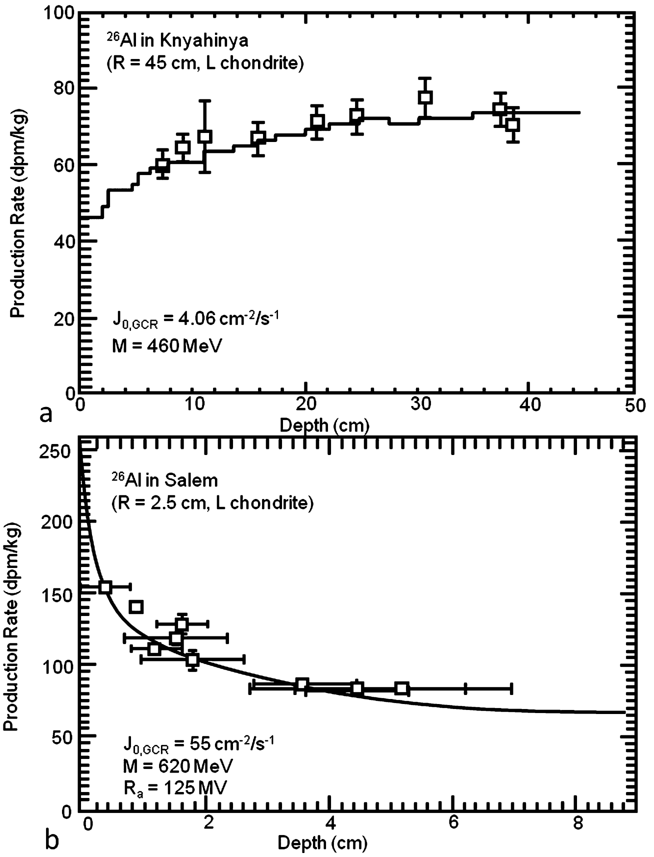

Fig. 4. Profiles for ^{26}Al in two meteorites, (a) the L chondrite Knyahinya (radius 45 cm) and (b) the L chondrite Salem (radius 2.5 cm). The data points refer to laboratory measurements, the lines refer to values calculated from theory and laboratory measurements. These images are simplified versions of figures appearing in Michel et al. (1996). For most meteorites, ^{26}Al shows a shallow profile that increases slightly with depth as secondaries contribute more to the ^{26}Al production. For especially small meteorites, solar energetic particles make an important contribution to ^{26}Al production, especially at small perihelia because their flux decreases with an inverse square of solar distance. However, they have lower energy than galactic cosmic rays and thus poorer penetrability, so the profile drops off quickly with depth.

relative to ^{26}Al), there is little depth-dependence in Kynahinya (Fig. 4a). Saturation levels are usually 60 dpm kg^{-1} in H chondrites and 56 dpm kg^{-1} for L chondrites, these are the values normally assumed in terrestrial age applications (Jull 2006, quoting values from Evans et al. 1982 and Vogt et al. 1990). In contrast, the small (2.5 cm) Salem meteorite has a very steep profile, the low-energy SEP-like radiations have high flux and small penetrability, and result in ^{26}Al activities as high as 100–150 dpm kg^{-1} (Fig. 4b).

An independent means of examining the value of natural TL in connection with terrestrial age (independent of ^{26}Al) is to compare the natural TL values with terrestrial ages determined by ^{36}Cl (Fig. 5), another isotope for which abundant data exists and which has a decay rate appropriate for Antarctic meteorites (Benoit et al. 1993c). Unlike nuclear decay, the rate of decay of natural TL, once the meteorite has left the relatively high-radiation, low-temperature environment of space and landed on Earth, is temperature dependent (McKeever 1980). Also shown in Fig. 5 are theoretical decay curves for samples at 0 °C and −5 °C. The data for 14 of the samples clearly conform to storage of these meteorites on Earth at these temperatures. The small amount of scatter can be understood in terms of orbital or shielding differences.

It should be noted that the decay of most meteorites follows the 0 °C to 5 °C curves that tend asymptotically to a natural value of approximately 5 krad. Thus the five meteorites with natural TL < 5 krad, some << 5 krad, cannot be understood by the same kinetics. Instead, the small perihelion that caused their low natural TL values also caused the natural TL to decay with faster kinetics. In fact, we can see from Fig. 5 that in approximately 150 ka the natural TL has decayed by about two orders of magnitude.

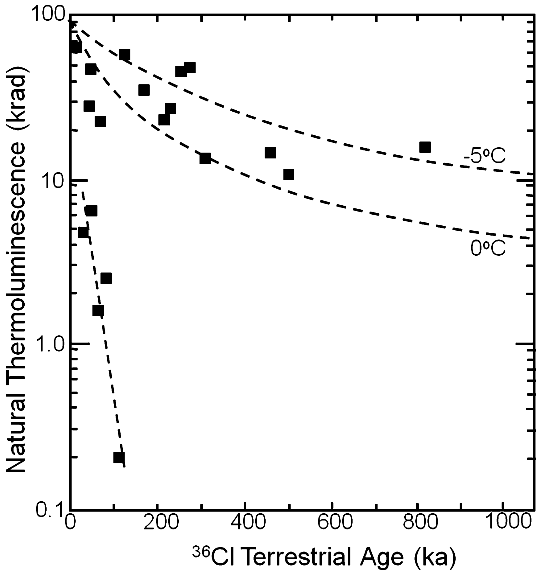

Fig. 5. Natural TL as a function of the terrestrial age of Antarctic meteorites as determined from the abundance of cosmogenic ^{36}Cl. Fourteen of the samples plot along, or reasonably near, theoretical decay curves calculated for Antarctic temperatures of 0 °C and −5 °C. Five meteorites with low terrestrial ages (< 200 ka) have especially low natural TL (too low for decay at these temperatures where the natural TL values asymptotically approach approximately 5 krad) and are presumed to be meteorites with small perihelia (Benoit and Sears 1993). Even among these low natural TL, small perihelia, meteorites there appears to be a suggestion of a relationship with terrestrial age, a two orders magnitude decay in natural TL occurring over a time scale of approximately 100,000 yr.

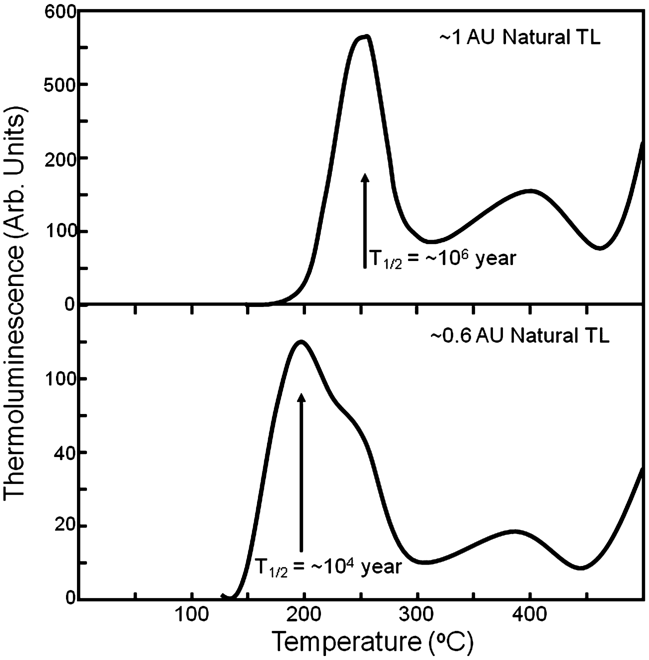

Fig. 6. Examples of "glow curves" (light emitted as a function of temperature as the sample is heated in the laboratory) for meteorite samples at two distances from the Sun intended to explain the low natural TL/high ^{26}Al group of meteorites identified by Hasan et al. (1987). At 0.6 AU from the Sun, for instance, the radiation dose from solar energetic particles will be nearly a factor of 3 larger than at 1 AU and this will result in lower temperature peaks in the glow curve being populated. Also closer to the Sun temperatures are higher and TL intensities will be lower.

This rapid decay of the natural TL of small perihelia meteorites is readily interpretable in terms of the expected differences in thermal and radiation history that might be expected for meteorites of different perihelia. The situation is illustrated in Fig. 6. The TL data are obtained as plots (referred to as "glow curves") of light emitted as a function of temperature as the sample is heated in the laboratory. The presence of a number of discrete peaks reflects different sites in the mineral lattices that can store electrons that were promoted to metastable energy states by ionizing radiation. The higher the temperature needed to release the excited electrons, in general, the more stable the electrons in that site and the longer the half-life for thermal decay. McKeever (1980) performed an examination of meteorite glow curve structure and kinetics. Eight individual peaks within the natural TL glow curves for Soko Banja and Lost City were identified and kinetic parameters determined. In our illustration in Fig. 6, a typical natural TL glow curve is shown and assumed for approximately 1 AU. The main (low temperature) peak at approximately 250 °C in the glow curve decays with a mean-life of approximately 10^6 yr under Antarctic conditions. On the other hand, higher dose rates closer to the Sun, say at 0.6 AU, will be a factor of nearly 3 higher than at 1 AU by the inverse-square law. We suggest that these higher dose rates populate lower temperature (approximately 200 °C) peaks than otherwise observed that we calculate would have half-lives approximately 10^4 yr under Antarctic conditions. These values are consistent with the decay rates observed in Fig. 5. However, the higher temperatures experienced by the meteorites at approximately 0.6 AU during irradiation would additionally mean much lower levels of natural TL. These conclusions are not yet fully quantitative, mostly because dose rate profiles throughout the inner solar system are not well known and shielding effects are also being ignored. The solar distances, glow curve temperatures, and decay rates quoted are examples only. However, these conclusions do provide an explanation of the observations, especially the data in Fig. 5.

THE CURRENT SITUATION

There are 120 ordinary chondrites for which both natural TL and ^{26}Al data currently exist, after the removal of probable pairing suggested in the *Antarctic Meteorite Newsletter*. They are listed in Table 1 and plotted in Fig. 7. The range of data is very similar to that observed in the original study of Hasan et al. (1987), say 0.1–300 krad for natural TL and 10–90 dpm kg^{-1} for ^{26}Al. Welten et al. (1995) suggested that there was a negative correlation between natural TL and ^{26}Al, but this is clearly incorrect. There was a particularly large group of meteorites in this database, 12 in number, that preliminary examination indicated might be fragments of a single fall which we refer to as the Elephant Moraine (EET) 90053 L6 chondrite pairing group (Table 2, Fig. 8). (Meteorite name abbreviations are given in the footnote to Table 1.) With one exception, these have natural TL values between 7.1 and 37.8 krad, and ^{26}Al between 59 and 82 dpm kg^{-1}. The exception, EET 90054, has natural TL of 0.3 krad and ^{26}Al of 59 dpm kg^{-1}. We will return to the EET 90053 pairing group below.

In Fig. 9 we compare the full set of data with the data of Hasan et al. (1987), representing the earlier data as two ellipses, one outlining the "main" field (in which natural TL and ^{26}Al activity showed a positive correlation) and another enclosing the meteorites thought to have experienced small perihelia. In addition, the field enclosing the EET 90053 pairing group (excluding the outlier) is shown, the EET 90053 pairing group clearly plots away from the main group having fairly high natural TL and ^{26}Al activities. There are also a group of previously unknown meteorites with natural TL approximately 1 krad and ^{26}Al approximately 60 dpm kg^{-1}. In fact, we suggest that the small perihelia meteorites are plotting on another positive trend with slightly steeper slope than the main trend (Fig. 5). In other words, there is nothing in the existing database to contradict the findings of Hasan et al. (1987) based on 23 meteorites and on which the 14 yr natural TL survey of Antarctic meteorites was based.

TERRESTRIAL AGE AND THE SORTING OF ANTARCTIC METEORITES BY ORBIT

Figure 10 shows the perihelion values of near-Earth asteroids in the JPL online database as of August 20, 2009. Perihelia values range from about 0.1 AU to about 1.3 AU, with a maximum at approximately 1.0 AU. Objects in the 1 AU peak are analogous to the meteorites we would consider "normal" and belonging in the main trend on the natural TL–^{26}Al plot (Fig. 9). Toward the sunward side of this peak is a gradual downward trend in

Table 1. ^{26}Al activities and natural thermoluminescence values for 120 Antarctic meteorites[a].

Name[b]	Al-26	NTL	Ref
ALHA76006	51 ± 5	0.4 ± 0.1	1 (3)
ALHA76008	11 ± 1	8.5 ± 0.3	1 (3)
ALHA76009	65 ± 5	10.4 ± 0.1	1 (3)
ALHA77001 (ave)	69 ± 6	2.02 ± 0.14	2 (1)
ALHA77002	30 ± 3	17.2 ± 0.4	4 (1)
ALHA77004 (ave)	54 ± 4	33 ± 0.2	1 (3), 2 (1), 3 (1)
ALHA77009	32 ± 2	30 ± 1	3 (1)
ALHA77111	20 ± 7	5 ± 0.1	6 (2)
ALHA77112	29 ± 1	24.5 ± 0.2	6 (2)
ALHA77155	71 ± 3	25.4 ± 0.1	2 (1)
ALHA77182	41 ± 4	1 ± 0.1	2 (1)
ALHA77258	29 ± 2	48 ± 1	2 (1)
ALHA77261	36 ± 4	14 ± 0.3	2 (1)
ALHA77262	47 ± 5	65 ± 3	2 (1)
ALHA77268	51 ± 2	1.2 ± 0.4	3 (1)
ALHA77271	39 ± 2	46.3 ± 0.3	1 (3)
ALHA77285	38 ± 4	31.2 ± 0.1	2 (1)
ALHA77294	63 ± 2	4.8 ± 0.1	2 (1)
ALHA78043	38 ± 3	11 ± 0.1	3 (2)
ALHA78047	33 ± 1	1.2 ± 0.1	6 (2)
ALHA78076	52 ± 4	58 ± 2	3 (2)
ALHA78102	35 ± 3	23.4 ± 0.4	3 (1)
ALHA78105	61 ± 7	45.3 ± 0.5	3 (1)
ALHA78112	42 ± 3	27.9 ± 0.7	3 (2)
ALHA78114	38 ± 2	14.9 ± 0.8	3 (2)
ALHA78115	43 ± 3	48 ± 2	3 (2)
ALHA78128	34 ± 2	4.4 ± 0.2	3 (2)
ALHA78134	61 ± 3	64.8 ± 0.2	3 (2)
ALHA78251	56 ± 6	49.6 ± 0.5	3 (1)
ALHA79002	34 ± 2	60 ± 1	4 (1)
ALHA79007	71 ± 4	27.6 ± 0.1	4 (1)
ALHA79025	53 ± 3	0.33 ± 0.07	4 (1)
ALHA79033	72 ± 4	0.2 ± 0.1	4 (1)
ALHA79054	63 ± 8	164.7 ± 0.4	4 (1)
ALHA80126	76 ± 7	3.9 ± 0.1	5 (1)
ALHA81037	56 ± 4	65.7 ± 0.6	6 (1)
ALHA81099	80 ± 4	2.6 ± 0.1	6 (2)
ALH 84066	73 ± 3	0.4 ± 0.1	9 (1)
ALH 85016	43 ± 5	40 ± 3	10 (1)
ALH 85017	66 ± 7	3.6 ± 0.6	10 (1)
ALH 85019	69 ± 5	17.9 ± 0.1	10 (1)
ALH 85020	50 ± 6	39 ± 2	10 (1)
ALH 85021	59 ± 3	0.13 ± 0.01	10 (1)
ALH 85022	47 ± 4	55 ± 4	10 (1)
ALH 85027	64 ± 4	67 ± 4	10 (1)
ALH 85028	57 ± 4	18 ± 1	10 (1)
ALH 85029	56 ± 3	28.2 ± 0.9	10 (1)
ALH 85030 (ave)	53 ± 4	35.5 ± 1.2	10 (1)
ALH 85033	43 ± 3	258 ± 3	10 (1)
ALH 85034	51 ± 2	40 ± 3	10 (1)
ALH 85035	42 ± 2	6 ± 0.1	10 (1)
ALH 85036	59 ± 4	41.7 ± 0.2	10 (1)

Table 1. *Continued.* ^{26}Al activities and natural thermoluminescence values for 120 Antarctic meteorites[a].

Table 1. *Continued.* ^{26}Al activities and natural thermoluminescence values for 120 Antarctic meteorites[a].

Name[b]	Al-26	NTL	Ref
ALH 85037	56 ± 3	6.2 ± 0.4	10 (2)
ALH 85038	49 ± 4	27.2 ± 0.3	10 (2)
ALH 85039	52 ± 4	26.6 ± 0.3	10 (2)
ALH 85040	49 ± 3	40.5 ± 0.2	10 (2)
ALH 85042	57 ± 4	48 ± 1	10 (2)
ALH 85043	47 ± 5	107 ± 11	10 (2)
ALH 85044	26 ± 3	20.2 ± 0.3	10 (2)
ALH 85045	27 ± 3	63 ± 2	10 (2)
ALH 85046	65 ± 3	13 ± 3	10 (2)
ALH 85054	50 ± 5	7.7 ± 0.6	12 (1)
ALH 85062	38 ± 2	59 ± 6	10 (2)
ALH 85076	48 ± 6	16.9 ± 0.4	10 (2)
ALH 85079	44 ± 2	92 ± 1	10 (2)
ALH 85080	47 ± 3	57 ± 5	10 (2)
ALH 85083	56 ± 3	52 ± 5	10 (2)
ALH 85097	49 ± 4	93 ± 2	12 (1)
ALH 85104	49 ± 4	0.56 ± 0.09	12 (1)
ALH 85124	66 ± 3	6.9 ± 0.3	10 (2)
ALH 85129	52 ± 4	36 ± 2	10 (2)
ALH 85130	56 ± 5	0.5 ± 0.1	10 (2)
ALH 85133	48 ± 4	57 ± 4	12 (1)
ALH 85142	52 ± 3	26.2 ± 0.2	12 (1)
ALH 85145	58 ± 3	0.24 ± 0.04	12 (1)
ALH 86603	45 ± 3	80 ± 2	11 (2)
ALH 90411	58 ± 4	20.5 ± 0.1	14 (2)
BOW 85800	47 ± 4	43 ± 3	10 (2)
DOM 85501	93 ± 6	4 ± 0.5	10 (1)
DOM 85502	59 ± 4	34 ± 2	10 (1)
DOM 85504	39 ± 3	52 ± 1	10 (1)
DOM 85506	54 ± 3	56 ± 1	10 (2)
DOM 85507	49 ± 3	0.7 ± 0.1	10 (2)
DOM 85509	37 ± 3	54.1 ± 0.7	10 (2)
EET 87535	65 ± 3	17 ± 2	11 (2)
EET 87536	33 ± 2	0.54 ± 0.08	12 (1)
EET 87539	38 ± 2	11.8 ± 0.4	12 (1)
EET 87544	44 ± 2	69.1 ± 0.2	12 (1)
EET 87547	71 ± 4	2.8 ± 0.2	12 (1)
EET 87549	46 ± 3	86.9 ± 0.8	12 (1)
EET 87554	55 ± 2	90 ± 1	12 (1)
EET 87555	62 ± 2	44 ± 1	12 (3)
EET 87556	68 ± 4	8.6 ± 0.2	12 (1)
EET 87557	59 ± 2	35.3 ± 0.5	12 (1)
EET 87558	60 ± 4	0.78 ± 0.05	12 (1)
EET 87564	58 ± 3	31.6 ± 0.5	12 (1)
EET 87566	56 ± 2	59 ± 6	12 (1)
EET 87573	48 ± 3	53.1 ± 0.9	12 (1)
EET 87576	74 ± 4	58.2 ± 0.5	12 (1)
EET 87578	59 ± 3	25.5 ± 0.3	12 (1)
EET 87613	60 ± 5	12.2 ± 0.1	12 (3)
EET 87744	47 ± 3	103 ± 2	12 (3)
EET 87805	42 ± 3	6.4 ± 0.1	12 (3)
EET 87818	50 ± 4	135 ± 4	12 (3)
EET 90012	61 ± 4	11.6 ± 0.1	14 (2)
EET 90030	80 ± 6	12.6 ± 0.1	14 (2)
EET 90031	61 ± 4	26.1 ± 0.1	14 (2)
EET 90051	52 ± 3	31 ± 0.3	15 (2)
EET 90053 (ave)	72 ± 4	19 ± 0.1	15 (2)
LEW 85319	55 ± 4	7.3 ± 0.1	10 (1)
LEW 85324	31 ± 1	32 ± 3	10 (1)
LEW 86012	31 ± 2	50.8 ± 0.9	11 (1)
LEW 86013	36 ± 2	93 ± 2	11 (1)
LEW 86015	41 ± 2	122 ± 6	11 (1)
LEW 86025	58 ± 5	0.9 ± 0.1	11 (1)
MBRA76001	73 ± 4	10.4 ± 0.3	1 (3)
META78003	50 ± 3	38.6 ± 0.6	3 (2)
META78006	60 ± 4	1.6 ± 0.2	3 (1)
META78028	56 ± 3	22.7 ± 0.7	3 (1)
RKPA78001 (ave)	56 ± 4	3.48 ± 0.055	4 (1, 2)

[a] Data from the *Antarctic Meteorite Newsletter*. Volume and issue number given under "Ref." Meteorite name abbreviations are as follows: ALH = Allan Hills; BOW = Bowden Neve; DOM = Dominion range; EET = Elephant Moraine; LEW = Lewis Cliff; MBR = Mount Baldr; MET = Meteorite Hills; RKP = Reckling Peak.

[b] "(ave)" indicates that paired meteorites have been averaged.

the number of asteroids in each perihelion bin, with slight suggestions of steps at about 0.8 AU and 0.6 AU. If we assume that the step at approximately 0.6 AU represents the small perihelia group of meteorites identified in Fig. 9, then the decrease in natural TL is approximately as expected (a factor of 50–100 is suggested by Figs. 2 and 5) and the number of meteorites involved is essentially as expected (approximately 20%), these "expectations" allowing for the uncertainties in dose rates and the statistics of small numbers.

Knowing the rates of decay of natural TL and ^{26}Al, we can assign ballpark figures for the terrestrial ages of the meteorites in the present database, and we can say something about perihelion values. We indicate the ages in Fig. 11, and we list values obtained this way in Table 3. In Table 3 we also indicate which perihelion group, "normal" (say, 0.9–1.0 AU), "intermediate" (approximately 0.8 AU), and "small" (approximately 0.6 AU), to which each meteorite belongs.

We can pursue this argument a little further and ask whether the proposed step at approximately 0.8 AU is reflected in the natural TL–^{26}Al data. A possibility is indicated in Fig. 12 where there is a cluster of meteorites between the proposed main group and the small perihelion group trends. What is interesting about this third group is that there is no trend, suggesting that while they are intermediate in perihelion, they are relatively recent falls. These meteorites are listed in Table 4, along with their classifications.

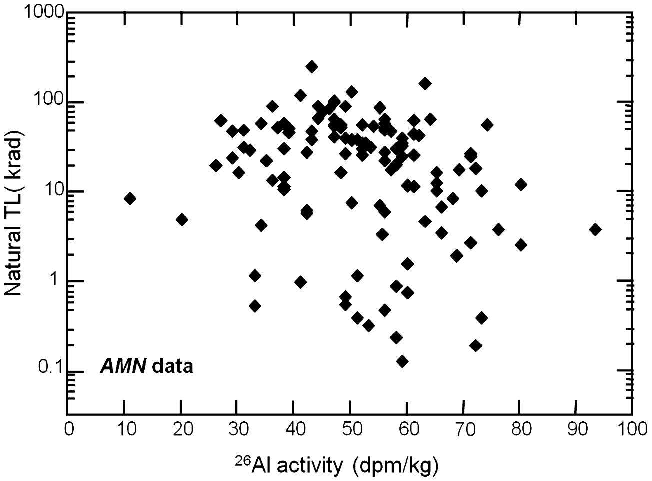

Fig. 7. Plot of natural TL against ^{26}Al activity for Antarctic meteorites measured over the duration of the natural TL survey of Antarctic meteorites, 1987–2001. Data are taken from the *Antarctic Meteorite Newsletter* and have appeared in a number of primary publications (Benoit et al. 1992, 1993a, 1993b, 1993c, 1994). The data appear to define a diamond-shaped field with (natural TL, ^{26}Al) values of (200, 50), (10, 90), (0.1, 60), and (10, 10).

Table 2. ^{26}Al activities and natural thermoluminescence values for the EET 95003 L6 paired group[a].

Name	^{26}Al (dpm kg^{-1})	NTL (krad)
EET 90054	59 ± 3	0.3 ± 0.1
EET 90053	82 ± 4	7.1 ± 0.1
EET 90207	67 ± 4	7.2 ± 0.2
EET 90115	58 ± 3	7.3 ± 0.1
EET 90157	80 ± 4	10.7 ± 0.1
EET 90121	74 ± 4	15.4 ± 0.1
EET 90152	80 ± 5	17.1 ± 0.1
EET 90158	78 ± 4	19.8 ± 0.1
EET 90071	59 ± 4	32.6 ± 0.1
EET 90204	74 ± 5	33.1 ± 0.1
EET 90138	78 ± 6	35.7 ± 0.2
EET 90177	71 ± 5	37.8 ± 0.1

[a] Data from the *Antarctic Meteorite Database*. http://www-curator.jsc.nasa.gov/antmet/us_clctn.cfm.

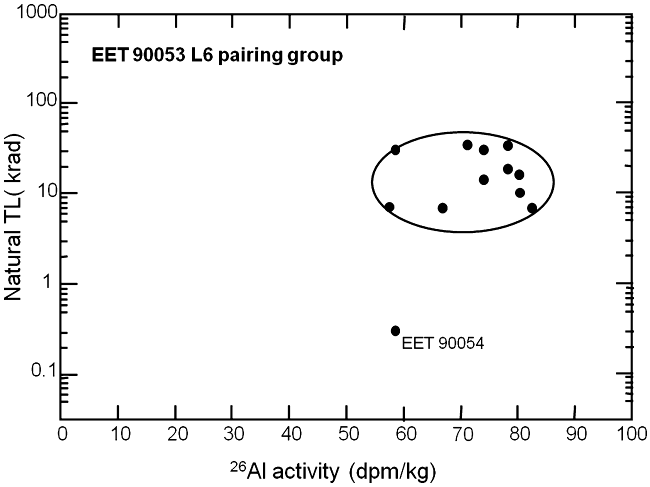

Fig. 8. Among the Antarctic meteorites for which we have both natural TL and ^{26}Al data is the large group of "paired" L6 meteorites associated with Elephant Moraine (EET). (Paired meteorites are those that were separate on the ice but thought to have been on the same object when it entered the atmosphere.) Given that these were part of the same object in space, the data provide an indication of the spread in data expected for a single meteorite and therefore the uncertainty on individual data. On the basis of these data, we suggest that EET 90054 is not paired with the others.

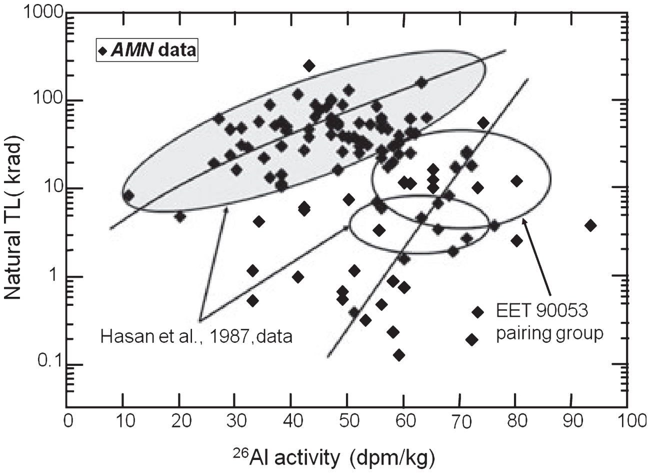

Fig. 9. An analysis of the present natural TL versus ^{26}Al plot based on the work of Hasan et al. (1987) and Fig. 5. The trend through the "normal" meteorites identified by Hasan et al. (1987), the upper trend line in this figure, agrees approximately with the theoretical curves and data for normal meteorites shown in Fig. 5, with the natural TL decaying by just over an order of magnitude in approximately 750 ka (one half-life of ^{26}Al). The lower trend line in the above figure, passing through the EET 90053 group and the small perihelia group of Hasan et al. (1987) agrees with the trend through the small perihelia group of Fig. 5, the natural TL decaying by two orders of magnitude in about one-third of a half-life of ^{26}Al.

In Fig. 13 we compare the terrestrial ages we obtained from natural TL using Fig. 12 and listed in Table 3 with terrestrial ages obtained by isotopic methods. Of the 43 meteorites for which we were able to obtain terrestrial ages that have been determined by isotopic methods, 34 show agreement between the two methods that is within a factor of 2. In fact, these 34 meteorites plot on a regression line that is indistinguishable from the unity line. Given the generally large uncertainty associated with terrestrial age determinations, this is encouraging agreement. Of the nine meteorites not showing agreement within a factor of 2, one (Allan Hills [ALH] A76008) is noted for having a complex irradiation history (e.g., Polnau et al. 1999), and we suggest this might be true of the three others lying well clear of the unity line (EET 87536,

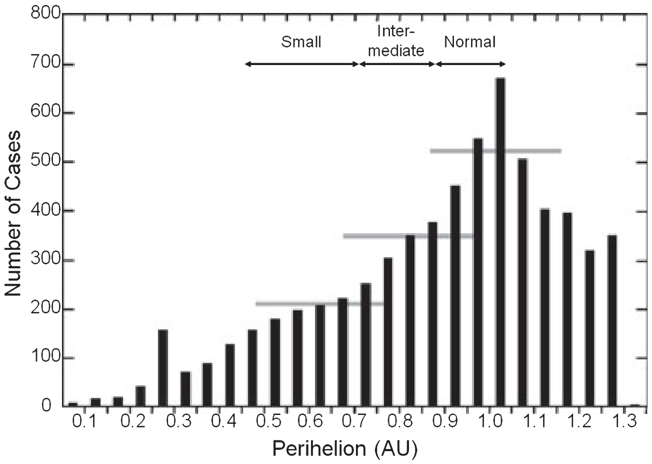

Fig. 10. Histogram of perihelia for near-Earth asteroids taken from the online database maintained by NASA's JPL (retrieved 20 August 2009). While values range all the way down to approximately 0.1 AU the frequency of occurrence peaks at approximately 1.0, with slight shoulders at approximately 0.8 and approximately 0.6 AU. Assuming NEA and meteorites share similar orbital properties, these data are consistent with the range of orbits suggested for Antarctic meteorites on the basis of their natural TL properties, and with the distribution of meteorites over these perihelia.

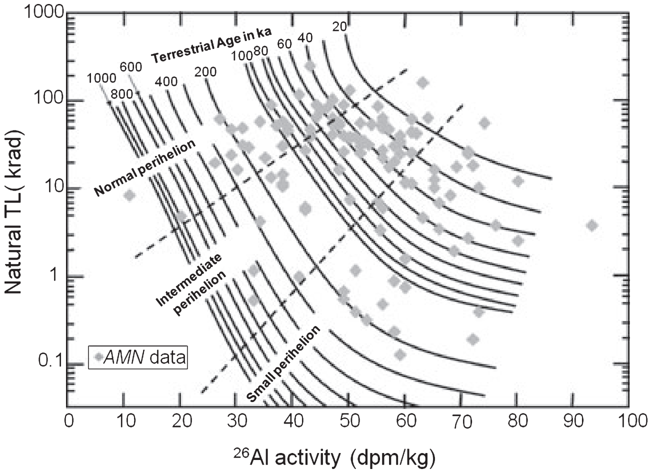

Fig. 11. The present data with a "calibration" overlaid on the data based in terrestrial ages from Fig. 5 and ^{26}Al, allowing for differences in perihelion. From placement in this grid the nature of the orbit ("normal," "intermediate," and "small" perihelion) and an indication of terrestrial age can be assigned to each meteorite. These are listed in Table 3.

ALH 85130, and AHLA78105). For the sample lying below the trend, ALHA78105, there is another possibility, which is that the meteorite spent much of its terrestrial life buried below the ice. In this case, isotopic measurements would reflect the true age while natural TL reflects time on the surface of the ice. Below the ice, temperatures are sufficiently low that natural TL fading would be reduced several orders of magnitude.

Table 3. Terrestrial ages and perihelion descriptions for meteorites in the present study[a].

Name	Terrestrial age (ka)	Perihelion (AU)
ALHA76006	200–300	Small
ALHA76008	> 1000	Normal
ALHA76009	40–50	Small
ALHA77001[b]	60–70	Small
ALHA77002	200–300	Normal
ALHA77004[b]	40–50	Medium
ALHA77009	200–300	Normal
ALHA77111	900–1000	Normal
ALHA77112	200–300	Normal
ALHA77155	20–30	Small
ALHA77182	300–400	Medium
ALHA77258	200–300	Normal
ALHA77261	100–200	Normal
ALHA77262	30–40	Normal
ALHA77268	100–200	Small
ALHA77271	90–100	Normal
ALHA77285	100–200	Normal
ALHA77294	50–60	Small
ALHA78043	100–200	Medium
ALHA78047	400–500	Medium
ALHA78076	30–40	Medium
ALHA78102	100–200	Normal
ALHA78105	< 20	Medium
ALHA78112	100–200	Medium
ALHA78114	100–200	Normal
ALHA78115	60–70	Normal
ALHA78128	300–400	Medium
ALHA78134	< 20	Medium
ALHA78251	20–30	Medium
ALHA79002	100–200	Normal
ALHA79007	< 20	Small
ALHA79025	200–300	Small
ALHA79033	100–200	Small
ALHA79054	< 20	Medium
ALHA80126	40–50	Small
ALHA81037	20–30	Medium
ALHA81099	30–40	Small
ALH 84066	100–200	Small
ALH 85016	70–80	Normal
ALH 85017	50–60	Small
ALH 85019	20–30	Small
ALH 85020	40–50	Medium
ALH 85021	200–300	Small
ALH 85022	40–50	Normal
ALH 85027	< 20	Medium
ALH 85028	40–50	Medium
ALH 85029	30–40	Medium
ALH 85030[b]	40–50	Medium
ALH 85033	40–50	Normal
ALH 85034	50–60	Medium
ALH 85035	100–200	Medium
ALH 85036	20–30	Medium
ALH 85037	60–70	Small
ALH 85038	50–60	Medium
ALH 85039	40–50	Medium

Table 3. *Continued.* Terrestrial ages and perihelion descriptions for meteorites in the present study[a].

Name	Terrestrial age (ka)	Perihelion (AU)
ALH 85040	50–60	Medium
ALH 85042	20–30	Medium
ALH 85043	40–50	Normal
ALH 85044	200–300	Normal
ALH 85045	200–300	Normal
ALH 85046	30–40	Small
ALH 85054	80–90	Medium
ALH 85062	90–100	Normal
ALH 85076	70–80	Medium
ALH 85079	40–50	Normal
ALH 85080	40–50	Normal
ALH 85083	20–30	Medium
ALH 85097	30–40	Normal
ALH 85104	200–300	Small
ALH 85124	30–40	Small
ALH 85129	40–50	Medium
ALH 85130	100–200	Small
ALH 85133	40–50	Normal
ALH 85142	40–50	Medium
ALH 85145	200–300	Small
ALH 86603	40–50	Normal
ALH 90411	30–40	Medium
BOW 85800	40–50	Normal
DOM 85501	30–40	Small
DOM 85502	20–30	Medium
DOM 85504	90–100	Normal
DOM 85506	30–40	Medium
DOM 85507	200–300	Small
DOM 85509	100–200	Normal
EET 87535	30–40	Small
EET 87536	500–600	Medium
EET 87539	100–200	Medium
EET 87544	50–60	Normal
EET 87547	30–40	Small
EET 87549	50–60	Normal
EET 87554	20–30	Normal
EET 87555	20–30	Medium
EET 87556	30–40	Small
EET 87557	30–40	Normal
EET 87558	100–200	Small
EET 87564	30–40	Medium
EET 87566	20–30	Medium
EET 87573	50–60	Normal
EET 87576	< 20	Small
EET 87578	30–40	Medium
EET 87613	40–50	Small
EET 87744	30–40	Normal
EET 87805	100–200	Medium
EET 87818	20–30	Normal
EET 90012	30–40	Small
EET 90030	20–30	Small
EET 90031	30–40	Medium
EET 90051	40–50	Medium
EET 90053[b]	20–30	Small
LEW 85319	60–70	Small
LEW 85324	200–300	Normal
LEW 86012	100–200	Normal
LEW 86013	90–100	Normal
LEW 86015	50–60	Normal
LEW 86025	100–200	Small
MBRA76001	20–30	Small
META78003	40–50	Medium
META78006	80–90	Small
META78028	40–50	Medium
RKPA78001[b]	80–90	Small

[a] Data read from Fig. 12.

[b] Average of several paired fragments.

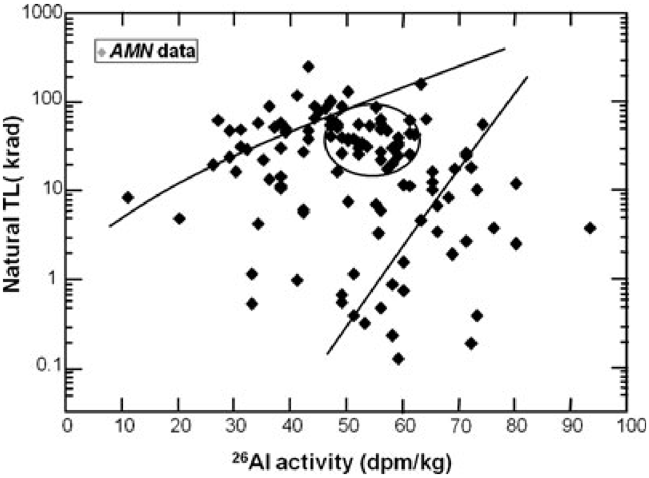

Fig. 12. Plot of natural TL against ^{26}Al for the present data indicating the two trend lines discussed above but with a fairly tightly grouped number of intermediate meteorites circled. Based on our presently favored interpretations of the significance of the two trends we suggest these are a cluster of meteorites with intermediate orbits and small terrestrial ages. These meteorites are identified in Table 4.

The cluster of samples numbered in Fig. 13 (ALH 85062, ALH 85038, ALHA77294, EET 87549, ALH 85040) seems to form a discrete population. These five meteorites have very ^{14}C low terrestrial ages (5.5 ± 1.3 for EET 87549 to 11.5 ± 1.3 ka for ALH 85062) compared to their natural TL ages (50–60 ka for EET 87549 to 90–100 ka for ALH 85062). This might be explained by a particularly low shielding that would give low ^{14}C ages. Higher than expected natural TL values seems inconsistent with the data in Fig. 9 which shows that these meteorites plot with the main band described by Hasan et al. (1987). Aside from their anomalously low ^{14}C ages, these five meteorites have little in common, being a mixture of classes and types and from various find sites.

Table 4. Details of meteorites in the "medium orbit" and "low terrestrial" age cluster[a].

Name	Class	Terrestrial age (ka)
ALHA78251	L6	20–30
ALHA81037	H6	20–30
ALH 85036	H6	20–30
ALH 85042	H5	20–30
ALH 85083	L6	20–30
DOM 85502	L6	20–30
EET 87555	L6	20–30
EET 87566	L6	20–30
ALHA78076	H6	30–40
ALH 85029	L6	30–40
ALH 90411	L3.7	30–40
DOM 85506	LL5	30–40
EET 87564	L4	30–40
EET 87578	L6	30–40
EET 90031	LL6	30–40
ALHA77004 (ave)	H4	40–50
ALH 85020	H6	40–50
ALH 85028	H6	40–50
ALH 85030 (ave)	H6	40–50
ALH 85039	L6	40–50
ALH 85129	LL6	40–50
ALH 85142	H5	40–50
EET 90051	H6	40–50
META78003	L6	40–50
META78028	L6	40–50

[a] Data read from Fig. 12.

CONCLUSIONS

The initial interpretation of the natural TL versus ^{26}Al plot suggested by Hasan et al. (1987) on the basis of 23 meteorites, and consistent with earlier natural TL studies (Sears and Mills 1974; McKeever and Sears 1980; Sears and Durrani 1980; Melcher 1981a, 1981b), is confirmed by the present study of 120 meteorites. Most meteorites (approximately 80%) show a positive correlation between natural TL and ^{26}Al (on a log-linear plot), and this reflects the decay of both as a function of terrestrial age. While the decay of ^{26}Al is first-order and the decay of TL is second-order, both reach detection limits in about 1000 ka for meteorites entering the atmosphere from normal orbits (perihelia 0.9–1.0 AU, say). About approximately 20% of the meteorites have low natural TL and high ^{26}Al consistent with these meteorites having experienced small perihelia. In small perihelia, the ^{26}Al reaches high values (>60 dps kg^{-1}) due to interaction with solar energetic particles, and the lower (less stable) temperature TL is populated, but levels are much lower than for normal meteorites because of much lower net doses. For lower-temperature TL traps, decay rates are much faster, so we observe a trend in natural TL with terrestrial age (determined independently from ^{36}Cl) for the small perihelion meteorites whereby natural TL decreases by a factor of approximately 50 in 100 ka. Thus we are able to sort the meteorites into terrestrial age and orbital types and these are listed in Table 3. In addition to the "normal" and "small" perihelia groups is a group of meteorites with intermediate orbit and small terrestrial age. That a large number of independent meteorites should share these common properties of similar terrestrial age and orbit, suggests their origin on a common asteroid. Estimates of the terrestrial age based on isotopic measurements exist for 43 of the present samples and 34 show acceptable agreement (within a factor of approximately 2) with the natural TL-based estimate. The remaining nine may have experienced complex irradiation histories, extended burial below the ice before recovery, or remain unexplained.

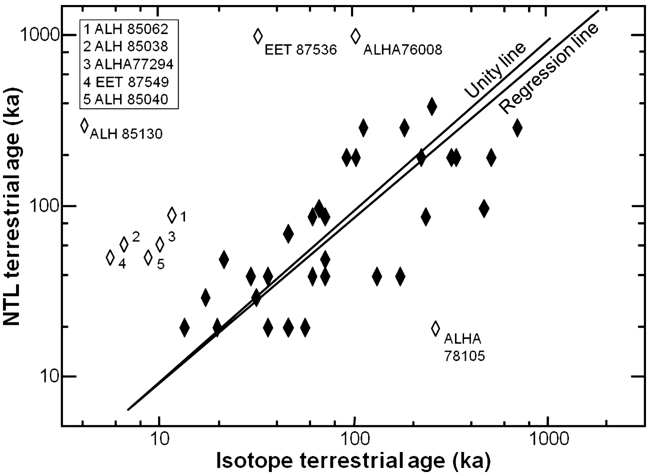

Fig. 13. Plot of terrestrial ages determined from natural thermoluminescence in the present work (see Table 3) against terrestrial age determined from cosmogenic isotope measurements. For the terrestrial age determined from natural TL, the middle of the range (which covers a factor of 1.5–2.0) is plotted, while for isotopic ages the reported value is plotted and this has a typical uncertainty of 20–70%. Data for isotopic terrestrial ages are from Jull et al. (1998), Nishiizumi et al. (1979, 1989), and Michlovich et al. (1995). Nine outliers are indicated by open symbols and are discussed in the text. The remaining 34 meteorites (out of 43 on the plot) lie within a factor of 2 of a regression line through the data, which is indistinguishable from the unity line.

Acknowledgments—We thank Tim Jull and an anonymous reviewer for comments that helped clarify and otherwise improve the paper, Hazel Sears for an internal review and proofing of the paper, and NASA (cosmochemistry) and NSF (REU site) programs for support. We also thank our many colleagues interested in thermoluminescence for many years of support and encouragement during the natural TL survey of

Antarctic meteorites and Charles Melcher, Steve Sutton, Robert Walker, Louis Rancitelli, Bill Cassidy, Don Bogard, Hermann Zimmerman, Fouad Hasan, Paul Benoit, and the Meteorite Working Group for their various contributions to establishing the survey and enabling us to participate in this way to one of the great science adventures, the recovery of meteorites from Antarctica.

Editorial Handling—Dr. Edward Scott

REFERENCES

Benoit P. H. and Sears D. W. G. 1992. The breakup of a meteorite parent body and the delivery of meteorites to Earth. *Science* 255:1685–1687.

Benoit P. H. and Sears D. W. G. 1993. Natural thermoluminescence profiles in lunar cores and implications for meteorites (abstract). 24th Lunar and Planetary Science Conference. pp. 95–96.

Benoit P. H. and Sears D. W. G. 1994. A recent meteorite fall in Antarctic with an unusual orbital history. *Earth and Planetary Science Letters* 120:463–471.

Benoit P. H. and Sears D. W. G. 1997. Orbits of meteorites from natural TL. *Icarus* 125:281–287.

Benoit P. H. and Sears D. W. G. 1999. Accumulation mechanisms and the weathering of Antarctic equilibrated ordinary chondrites. *Journal of Geophysical Research (Planets)* 104:14159–14168.

Benoit P. H., Sears D. W. G., and McKeever S. W. S. 1991. The natural thermoluminescence of meteorites—II. Meteorite orbits and orbital evolution. *Icarus* 94:311–325.

Benoit P. H., Sears H., and Sears D. W. G. 1992. The natural thermoluminescence of meteorites—IV: Ordinary chondrites at the Lewis Cliff ice field. *Journal of Geophysical Research* 97:4629–4647.

Benoit P. H., Jull A. J. T., McKeever S. W. S., and Sears D. W. G. 1993a. The natural thermoluminescence of meteorites VI: Carbon-14, thermoluminescence and the terrestrial ages of meteorites. *Meteoritics* 28:196–203.

Benoit P. H., Sears H., and Sears D. W. G. 1993b. The natural thermoluminescence of meteorites—V: Ordinary chondrites at the Allan Hills vicinity. *Journal of Geophysical Research* 98:1875–1888.

Benoit P. H., Sears D. W. G., and McKeever S. W. S. 1993c. Natural thermoluminescence and terrestrial ages of meteorites from a variety of temperature regimes. *Radiation Detection and Dosimetry* 47:669–674.

Benoit P. H., Roth J., Sears H., and Sears D. W. G. 1994. The natural thermoluminescence of meteorites 7: Ordinary chondrites from the Elephant Moraine region, Antarctica. *Journal of Geophysical Research (Planets)* 99:2073–2085.

Benoit P. H., Sears D. W. G., Akridge J. M. C., Bland P. A., Berry F. J., and Pillinger C. T. 2000. The non-trivial problem of meteorite pairing. *Meteoritics & Planetary Science* 35:393–417.

Cassidy W. A. 2003. *Meteorites, ice, and Antarctica: A personal account*. Cambridge, UK: Cambridge University Press. 364 p.

Cassidy W. A., Olsen E., and Yanai K. 1977. Antarctica—A deep-freeze storehouse for meteorites. *Science* 198:727–731.

Dennison J. E. and Lipschutz M. E. 1987. Chemical studies of H chondrites. II—Weathering effects in the Victoria Land, Antarctic population and comparison of two Antarctic populations with non-Antarctic falls. *Geochimica et Cosmochimica Acta* 51:741–754.

Evans J. C., Reeves J. H., Rancitelli L. A., and Bogard D. D. 1982. Cosmogenic nuclides in recently fallen meteorites—Evidence for galactic cosmic ray variations during the period 1967–1978. *Journal of Geophysical Research* 87:5577–5591.

Hasan F. A., Haq M., and Sears D. W. G. 1987. Natural thermoluminescence levels in meteorites, I: 23 meteorites of known Al-26 content. *Journal of Geophysical Research* 92:E703–E709.

Jull A. J. T. 2006. Terrestrial ages of meteorites. In *Meteorites and the early solar system*, edited by Lauretta D. S. and McSween H. Y. Tucson, AZ: The University of Arizona Press. pp. 889–905.

Jull A. J. T., Cielaszyk E., and Cloudt S. 1998. ^{14}C terrestrial ages of meteorites from Victoria Land, Antarctica and the infall rates of meteorites. In *Meteorites: Flux with time and impact effects*, edited by Grady M. M., Hutchison R., McGall G. J. H., and Rothery D. A. London: Geological Society of London. Special Publication 140. pp. 75–91.

Lipschutz M. E. and Samuels S. M. 1991. Ordinary chondrites—Multivariate statistical analysis of trace element contents. *Geochimica et Cosmochimica Acta* 55:19–34.

McKeever S. W. 1980. The analysis of thermoluminescence glow-curves from meteorites. *Modern Geology* 7:105–114.

McKeever S. W. S. and Sears D. W. 1980. Natural thermoluminescence of meteorites—A pointer to orbits? *Modern Geology* 7:137–145.

Melcher C. L. 1981a. Thermoluminescence of meteorites and their terrestrial ages. *Geochimica et Cosmochimica Acta* 45:615–626.

Melcher C. L. 1981b. Thermoluminescence of meteorites and their orbits. *Earth and Planetary Science Letters* 52:39–54.

Michel R., Leya I., and Borges L. 1996. Production of cosmogenic nuclides in meteoroids: Accelerator experiments and model calculations to decipher the cosmic ray record in extraterrestrial matter. *Nuclear Instruments and Methods in Physics Research Section B* 113:434–444.

Michlovich E. S., Wolf S. F., Wang M. S., Vogt S., Elmore D., and Lipschutz M. E. 1995. Chemical studies of H chondrites 5. Temporal variations of sources. *Journal of Geophysical Research* 100:3317–3333.

Nishiizumi K., Arnold J. R., Elmore D., Ferraro R. D., Goa H. E., Finkel R. C., Beukens R. P., Chang K. H., and Kilius L. R. 1979. Measurements of ^{36}Cl in Antarctic meteorites and Antarctic ice using a Van de Graaff accelerator. *Earth and Planetary Science Letters* 45:285–292.

Nishiizumi K., Elmore D., and Kubik P. W. 1989. Update on terrestrial ages of Antarctic meteorites. *Earth and Planetary Science Letters* 93:299–313.

Nishiizumi K., Nagai H., Imamura M., Honda M., Kobayashi K., Kubik P. W., Sharma P., Wieler R., Signer P., Goswami J. N., Sinha N., Reedy R. C., and Arnold J. R. 1990. Solar cosmic ray produced nuclides in the Salem meteorite. *Meteoritics* 25:392.

Polnau E., Eugster O., Krähenbühl U., and Marti K. 1999. Evidence for a precompaction exposure to cosmic rays in a chondrule from the H6 chondrite ALH 76008. *Geochimica et Cosmochimica Acta* 63:925–933.

Pugh R. N. 1983. The Salem meteorite. *Oregon Geology* 45:63–64.

Reedy R. C. 1985. A model for GCR-particle fluxes in stony meteorites and production rates for cosmogenic nuclides. *Journal of Geophysical Research* 90:C722–C728.

Reedy R. C. 1987. Nuclide production by primary cosmic-ray protons. *Journal of Geophysical Research (Planets)* 92:E697–E702.

Scott E. R. D. 1984. Pairing of meteorites from Victoria Land, Antarctica. *Memoirs of the National Institute of Polar Research, Special Issue* 35:102–125.

Scott E. R. D. 1989. Pairing of meteorites from Victoria Land and Thiel Mountains, Antarctica. *Smithsonian Contributions to Earth Science* 28:103–111.

Sears D. W. 1975a. Thermoluminescence studies and the preatmospheric shape and mass of the Estacado meteorite. *Earth and Planetary Science Letters* 26:97–104.

Sears D. W. 1975b. Temperature gradients in meteorites produced by heating during atmospheric passage. *Modern Geology* 5:155–164.

Sears D. W. 1979. Rocks on the ice. *New Scientist* March 22, 959–961.

Sears D. W. and Durrani S. A. 1980. Thermoluminescence and the terrestrial age of meteorites: Some recent results. *Earth and Planetary Science Letters* 46:159–166.

Sears D. W. G. and Hasan F. A. 1986. Thermoluminescence and Antarctic meteorites. In *International workshop on Antarctic meteorites*, edited by Annexstad J. O., Schultz L., and Wanke H. Houston, Texas: Lunar and Planetary Institute. pp. 83–100.

Sears D. W. and Mills A. A. 1974. Thermoluminescence and the terrestrial age of meteorites. *Meteoritics* 9:47–67.

Sears D. W. G., Hasan F. A., Myers B. M., and Sears H. 1990. Comment on "Update on terrestrial ages of Antarctic meteorites" by K. Nishiizumi, D. Elmore, and P. W. Kubik. *Earth and Planetary Science Letters* 99:380–382.

Sears D. W. G., Benoit P., and Batchelor J. D. 1991. Evidence for differences in the thermal histories of Antarctic and non-Antarctic H chondrites with cosmic-ray exposure ages less than 20 Ma. *Geochimica et Cosmochimica Acta* 55:1193–1197.

Sutton S. R. and Walker R. M. 1986. Thermoluminescence of Antarctic meteorites: A rapid screening technique for terrestrial age estimation, pairing studies and identification of specimens with unusual prefall histories. In *International workshop on Antarctic meteorites*, edited by Annexstad J. O., Schultz L., and Wänke H. Houston, Texas: Lunar and Planetary Institute. pp. 104–106.

Valladas G. and Lalou C. 1973. Etude de la thermoluminescence de la meteorite Saint Severin. *Earth and Planetary Science Letters* 18:168–171.

Vogt S., Herzog G. F., and Reedy R. C. 1990. Cosmogenic nuclides in extraterrestrial materials. *Reviews of Geophysics* 28:253–275.

Welten K. C., Alderliesten C., van der Borg K., and Lindner L. 1995. Cosmogenic beryllium-10 and aluminum-26 in Lewis Cliff meteorites. In *Workshop on meteorites from cold and hot deserts*, edited by Schultz L., Annexstad J. O., and Zolensky M. LPI Technical Report 95-02. Houston, Texas: Lunar and Planetary Institute. pp. 65–70.