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The natural thermoluminescence of meteorites VI: Carbon-14, thermoluminescence and the terrestrial ages of meteorites.

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Abstract–Research on meteorite finds, especially those from the Antarctic and from desert regions in Australia, Africa, and America, has become increasingly important, notably in studies of possible changes in the nature of the meteorite flux in the past. One important piece of information needed in the study of such meteorites is their terrestrial age which can be determined using a variety of methods, including ^{14}C, ^{36}Cl, and ^{81}Kr. Natural thermoluminescence (TL) levels in meteorites can also be used as an indicator of terrestrial age. In this paper, we compare ^{14}C-determined terrestrial ages with natural TL levels in finds from the Prairie States (central United States), a group of finds from Roosevelt County (New Mexico, USA), and a group from the Sahara Desert. We find that, in general, the natural TL data are compatible with the ^{14}C-derived terrestrial ages using a 20 °C TL decay curve for the Prairie States and Roosevelt County and a 30 °C decay curve for the Saharan meteorites. We also present TL data for a group of meteorites from the Sahara desert which has not been studied using cosmogenic radionuclides. Within these data there are distinct terrestrial age clusters which probably reflect changes in meteorite preservation efficiency over ~15,000 years in the region.

INTRODUCTION

The past few decades have seen a virtual explosion in the number of known meteorites, largely because of the discovery and exploitation of meteorite concentrations in the Antarctic. Meteorite concentrations have also been discovered in other desert regions of the world, notably in Australia (Bevan and Binns, 1989) and in the Sahara Desert of Africa (Otto, 1992). One of the major difficulties of assimilating and using this vast collection of meteorite finds is their largely unknown terrestrial age. This uncertainty has implications in interpretation of concentration mechanics (Huss, 1991; Benoit *et al.*, 1992), the question of possible flux changes in meteorites over time (Lipschutz and Samuels, 1991; Benoit and Sears, 1992), and in calculations of the total meteorite flux (Zolensky *et al.*, 1990; Huss, 1990; Halliday *et al.*, 1991). While it is possible to date individual finds using isotopic methods (Nishiizumi *et al.*, 1989), it is often difficult to apply these data to groups of meteorites in light of possible terrestrial age variations *within* collection sites (Benoit *et al.*, 1992). Natural thermoluminescence (TL) measurements, which are highly suitable for batch processing of large numbers of samples, offer information which, in principle, should be directly related to terrestrial ages. In practice, the need to assume various pre-fall TL parameters has limited the TL technique to qualitative terrestrial age determinations (Hasan *et al.*, 1987). In this paper, we discuss several cases involving non-Antarctic meteorite collections in which TL and isotopic data are in good agreement. These data show that the two techniques can determine terrestrial ages for meteorites and identify meteorites with unusual recent radiation exposure and thermal histories in space.

The use of the decay of ^{14}C (Boeckl, 1972; Jull *et al.*, 1989, 1990, 1993) and natural thermoluminescence (Sears and Durrani, 1980; Sears, 1988) to determine the terrestrial ages of meteorites has been covered in detail elsewhere. For the purposes of the present work, it is important to stress both the similarities and differences between the two techniques. Both techniques measure the decay of a quantity (^{14}C content or natural TL level), produced by exposure to cosmic rays in space, from saturation levels to much lower levels. Both techniques are viable because of the high degree of "shielding" from cosmic rays by the Earth's atmosphere, which essentially reduces the amount of *in situ* production of either natural TL or ^{14}C to levels far below the very high saturation levels observed in modern falls, thus minimizing terrestrial age corrections. In the case of ^{14}C measurements, the presence of this *in situ* production limits the method to meteorites with terrestrial age less than approximately 40,000 years (Jull *et al.*, 1989). Both techniques also depend on assumed saturation values (Jull *et al.*, 1989; Benoit *et al.*, 1991a) which may not be valid for all meteorites, even within petrologic classes. The primary difference between the ^{14}C and natural TL techniques, at least in terms of terrestrial age determinations, is that the rate of decay of natural TL is a function of temperature as well as time. Therefore, the natural TL of meteorites at relatively warm sites will decay faster than meteorites from the Antarctic and other "cold" sites (Melcher, 1981). The implication of this temperature dependence is that, while the measureable temporal range for terrestrial age determinations using natural TL ranges from 5,000 to 40,000 years for most localities, this range is vastly extended for the relatively cold Antarctic sites (McKeever, 1982). However, as discussed below, this also means that TL levels of meteorite finds are a function of the terrestrial and, in some cases, pre-terrestrial thermal history of each meteorite rather than just providing a straightforward terrestrial age.

In this paper, we discuss ^{14}C and natural TL data for three non-Antarctic sites, including Roosevelt County (New Mexico, USA), the Prairie States (including the states of Texas, Oklahoma, Kansas, and Colorado, USA), and the Sahara desert. We also discuss natural TL data for a separate group of Saharan meteorites and the implications of these data in terms of regional paleoclimate and the preservation of meteorites.

METHODS AND RESULTS

The methodology for ^{14}C and natural thermoluminescence measurements and data reduction have been described in some detail elsewhere (Jull *et al.*, 1989, 1993; Sears, 1988) and are not repeated here.

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The ^{14}C contents were measured by accelerator mass spectrometry (AMS) using a RF melting extraction procedure as described by Jull *et al.* (1989; 1993). This procedure offers much more accurate results than the previous bulk methods (Boeckl, 1972), which were highly prone to terrestrial ^{14}C contamination. Although there has been some minor technical improvements in the TL apparatus, the technique and TL data reduction methods are essentially the same as those used for the earlier measurements on a portion of the samples in the current study (Sears and Durrani, 1980). Bulk samples of ~150 mg weight from each meteorite were ground to a fine powder in an agate mortar. No mineral separations, which are common in archeological TL applications (Aitken, 1985), were done because the TL of equilibrated meteorites is dominated by a single bright phosphor, namely sodic feldspar (Sears, 1988). One significant change in data reduction techniques has been adapted for this particular study. As described by Sears (1988) there are two common procedures for reporting TL data, namely equivalent dose and peak ratios. Peak ratio measurements are the simplest to determine, are highly reproducible, and are essentially internally calibrated; thus, they do not require a well-calibrated radiation source for induced TL measurements. Equivalent dose, however, reports natural TL levels which have been normalized using the TL levels induced by a given radiation dose at a specified glow curve temperature. It has become common practice to use 250 °C in the glow curve for equivalent dose measurements in meteorites; this being one of the most sensitive regions of the glow curve in many applications. Equivalent dose measurements are, however, highly prone to significant experimental errors due to compounded statistical scatter from use of multiple glow curves and from radiation source differences among laboratories. In practice, it has become common to determine peak ratios, which are highly reproducible, and then convert these to equivalent doses using laboratory-specific conversion factors derived from many measurements. For this particular study, we have measured many meteorites which have very low peak ratios and, in the case of the Saharan meteorites, many which have had all of the natural TL at 250 °C in the glow curve drained. We have, thus, used true equivalent dose measurements for the Roosevelt County and Saharan meteorites for this study. For reasons that will be explained below, we also report equivalent doses at 300 °C in the glow curve for many of these meteorites. The TL data for the Prairie State meteorites, which are taken from Sears and Durrani (1980), are converted from peak ratios.

As is also the case with ^{14}C terrestrial age determinations, it is necessary to address the question of the saturation level of TL of meteorites, that is, the TL level of the meteorites prior to Earth impact. We have previously established that there is a range of natural TL in modern falls, reflecting variations in shielding depths and heating in space (Benoit *et al.*, 1991a). Clearly, this range adds uncertainty to any absolute terrestrial age determined by TL; the amount of uncertainty introduced is the subject of work in progress (Benoit and Sears, 1993). However, for the present study, we compare our data against the calculated decay curves obtained for a single meteorite, namely Lost City. Lost City has a natural TL level of ~40 krad and, hence, its TL is very similar to most modern falls, which typically range from 20–80 krad (Benoit *et al.*, 1991a). In terms of TL decay parameters, Lost City is similar to other equilibrated ordinary chondrites (McKeever, 1980). Lost City is, therefore, an average meteorite from the standpoint of natural TL and deviations from this average on the part of individual meteorite finds will result in scatter in comparison plots. The question we address in this paper, through empirical comparision with other techniques, is whether this uncertainty invalidates the use of natural TL as an indicator of terrestrial age.

Twelve meteorites from the Prairie States, 11 from Roosevelt County, and 12 from the Sahara were examined by both TL and AMS ^{14}C. The Roosevelt County group is a subset of those examined by Jull *et al.* (1991), and the Saharan group represents most of the independent falls identified by Jull *et al.* (1990). The ^{14}C and natural TL data for meteorites from the Prairie States and Roosevelt County are given in Table 1. Induced TL parameters for the Roosevelt County meteorites are also given in Table 1 for pairing purposes. Natural and induced TL data for the Saharan meteorites are given in Table 2.

TABLE 1. Natural and induced thermoluminescence parameters and terrestrial ages derived from ^{14}C (Jull *et al.*, 1991; 1993).

Meteorite†/Class		Nat. TL 250 °C (krad)	Ind. TL Sensitivity (Dhajala = 1)	Terrestrial Age (ka)
Prairie States				
Bluff	L5	0.59 ± 0.03	--	15.7 ± 1.3
Brownfield (1937)	H3	5.8 ± 0.3	--	2.2 ± 1.3
De Nova	L6	10.7 ± 0.5	--	4.6 ± 1.3
Densmore (1879)	L6	0.54 ± 0.03	--	43.5 ± 3.5
Dimmitt	H4	20.0 ± 1.0	--	3.4 ± 1.3
Estacado	H6	4.6 ± 0.2	--	46 ± 4.0
Keyes	L6	7.2 ± 0.4	--	11.5 ± 1.3
Ladder Creek	L6	0.10 ± 0.01	--	1.3 ± 1.3
Texline	H5	45 ± 2	--	0 ± 1.3
Tulia	H3-4	21 ± 1	--	4.0 ± 1.3
Weldona	H4	10.1 ± 0.5	--	6.0 ± 1.3
Unnamed find‡	L6	7.6 ± 0.1	--	5.6 ± 1.3
Roosevelt County				
RC032	H5++	2.0 ± 0.3	0.27 ± 0.02	26.2 ± 1.6
RC037	H4-5	0.3 ± 0.1	0.079 ± 0.001	>46.0
RC041	L5	1.0 ± 0.1	0.14 ± 0.01	22.6 ± 1.3
RC043	H5++	0.7 ± 0.2	0.33 ± 0.03	32.3 ± 1.4
RC044	L6	0.5 ± 0.2	0.12 ± 0.01	31.0 ± 2.0
RC046	H5++	0.7 ± 0.1	0.69 ± 0.06	25.9 ± 1.3
RC048	L6	0.9 ± 0.4	0.045 ± 0.001	>44.0
RC049	LL4	0.4 ± 0.1	0.016 ± 0.001	>37.5
RC058	LL4	2.9 ± 0.4	0.26 ± 0.01	7.0 ± 1.3
RC063	L4	2.0 ± 0.4	0.23 ± 0.02	8.3 ± 1.3
RC064	H5	0.2 ± 0.1	0.22 ± 0.02	22.8 ± 1.3

‡ Source of samples: Max-Planck-Institut für Chemie (Mainz), Roosevelt County meteorites; Professor H.E. Suess and Dr. M. Herndon, Prairie State meteorites.

‡ Probably from Kansas, USA. Property of the family of Mr. B. Martin. Research sample (50 g) at University of Arkansas, USA.

++ Breccia

PRAIRIE STATE METEORITES

Figure 1 shows the natural TL of the Prairie State meteorites against their terrestrial ages determined by AMS ^{14}C measurements (Jull *et al.*, 1993). Also shown are the theoretical curves for TL decay at various temperatures, derived from the TL parameters of Lost City (McKeever, 1982). With the exception of Ladder Creek, all the meteorites appear to cluster near the line for decay at a 20 °C storage temperature. Ladder Creek's low natural TL is possibly the result of its failure to obtain TL saturation prior to fall; the ^{26}Al content of this meteorite is also very low, indicative of a short period of exposure to cosmic rays in space (Nishiizumi, 1987). Natural TL in meteorites achieves saturation in a few 10^5 years (Sears, 1988), a very short period of time relative to cosmic ray exposure ages for most ordinary chondrites. It is, however, also possible that Ladder Creek was heavily shocked prior to Earth impact, an event which would have reheated the meteorite sufficient to reset TL levels.

ROOSEVELT COUNTY METEORITES

The Roosevelt County, New Mexico, area has proven to be a prolific source of meteorite finds (see Huss and Wilson, 1973; Scott *et al.*, 1986; Sipiera *et al.*, 1987; Jull *et al.*, 1991, for

TABLE 2. Natural and induced thermoluminescence parameters and terrestrial ages derived from ^{14}C (Jull *et al.*, 1990) for meteorite finds from Libya† and Algeria.†

Meteorite/ Class‡	Nat. TL 250 °C (krad)	Nat. TL 300 °C (krad)	Ind. TL Sensitivity (Dhajala = 1.0) N+	A+	Terr. Age (ka)
DA002/L4	0.17 ± 0.06	10 ± 3	1.90 ± 0.09	–	5.8 ± 1.3
DA008/H5	0.10 ± 0.04	3 ± 3	1.3 ± 0.1	–	3.5 ± 1.3
DA009/H5	0.024 ± 0.001	0.9 ± 0.3	1.11 ± 0.09	–	5.4 ± 1.3
DA011/H3	0.35 ± 0.06	1.6 ± 0.7	0.45 ± 0.06	–	4.4 ± 1.3
DA013*/H5	0.7 ± 0.2	15 ± 2	0.82 ± 0.03	–	4.5 ± 1.3
DA014/L6	1.17 ± 0.04	17 ± 1	0.064 ± 0.006	–	6.6 ± 1.3
DA016/H6	0.13 ± 0.04	6 ± 2	0.30 ± 0.02	–	4.4 ± 1.3
DA102*/H5	0.7 ± 0.1	14.5 ± 0.9	1.13 ± 0.07	–	3.9 ± 1.3
DA108/LL5	0.11 ± 0.02	2.4 ± 0.2	0.85 ± 0.04	–	7.6 ± 1.3
DA114/H4	0.12 ± 0.04	3 ± 2	0.29 ± 0.01	–	16.3 ± 1.3
DA115/H6	0.69 ± 0.08	11.2 ± 0.8	0.45 ± 0.03	–	3.9 ± 1.3
DA119/L4	0.06 ± 0.02	0.69 ± 0.03	0.22 ± 0.02	–	35.0 ± 3.0
Acfer005/H4	0.32 ± 0.07	7.3 ± 0.2	0.34 ± 0.02	3.5 ± 0.6	
Acfer006/H4	0.8 ± 0.1	16.4 ± 2.2	0.20 ± 0.01	0.45 ± 0.03	
Acfer022/H3.7	0.21 ± 0.01	0.10 ± 0.01	0.21 ± 0.01	0.84 ± 0.06	
Acfer023/H3.8	0.10 ± 0.07	3.1 ± 1.2	0.43 ± 0.01	1.6 ± 0.1	
Acfer028/H3.9	0.33 ± 0.03	0.43 ± 0.08	0.33 ± 0.03	2.2 ± 0.2	
Acfer039/L3.8	0.18 ± 0.02	9 ± 1	0.64 ± 0.02	1.8 ± 0.2	
Acfer066/L3.8	0.40 ± 0.09	12 ± 1	0.30 ± 0.02	1.9 ± 0.2	
Acfer080/L3.9	1.5 ± 0.3	28 ± 3	0.43 ± 0.04	2.5 ± 0.2	
Acfer129/H3.7	n. d.	0.44 ± 0.02	0.12 ± 0.01	0.46 ± 0.02	
Acfer153/H3.8	0.16 ± 0.01	7.2 ± 0.1	0.43 ± 0.02	2.1 ± 0.4	
Acfer159/H3.8	0.54 ± 0.04	17 ± 1	0.19 ± 0.01	1.13 ± 0.08	
Acfer160/LL3-6	0.26 ± 0.05	8.4 ± 0.6	0.64 ± 0.04	1.6 ± 0.2	
Acfer163/H3-5	0.14 ± 0.03	6.2 ± 0.4	0.36 ± 0.02	1.23 ± 0.07	
Acfer169/H4	0.22 ± 0.07	9.8 ± 0.6	0.40 ± 0.02	1.2 ± 0.1	
Acfer171/H3.7	0.6 ± 0.1	20 ± 5	0.30 ± 0.04	0.82 ± 0.07	
Acfer178/H3.7	0.3 ± 0.1	3.6 ± 0.2	0.199 ± 0.009	0.48 ± 0.02	
Acfer180/H5	0.4 ± 0.1	12 ± 3	0.41 ± 0.03	2.7 ± 0.4	
Acfer188/H3.9	0.3 ± 0.1	11 ± 3	0.35 ± 0.03	2.8 ± 0.2	
Acfer192/H3.9	0.12 ± 0.04	6.5 ± 2.3	0.48 ± 0.04	3.1 ± 0.4	
Acfer210/H3.7	0.2 ± 0.1	3.4 ± 0.6	0.15 ± 0.01	0.46 ± 0.03	
Acfer211/H3.8	0.33 ± 0.09	9.3 ± 1.4	0.30 ± 0.01	2.0 ± 0.2	
HaH004/H3.9	0.27 ± 0.06	8 ± 3	0.31 ± 0.03	3.6 ± 0.3	
HaH028/H4	n. d.	0.26 ± 0.05	0.45 ± 0.02	1.05 ± 0.07	
Ilafegh013/H3.5	0.89 ± 0.03	23 ± 2	0.12 ± 0.01	0.19 ± 0.04	
Reggane003/H4	0.7 ± 0.1	9 ± 1	0.7 ± 0.04	3.6 ± 0.7	
Tanezrouft006/ H3.7	0.12 ± 0.07	4 ± 2	0.34 ± 0.03	0.52 ± 0.03	

† Finds from Libya are Daraj (DA) and Hammadah al Hamra (HaH). Finds from Algeria are Acfer, Ilafegh, Reggane and Tanezrouft. Individual descriptions for most of these are summarized in Wlotzka (1990, 1991).

+ N = normal, A = acid washed.

‡ Source of samples: Max-Planck-Institut für Chemie (Mainz), Daraj meteorites; A. Bischoff, Insitut für Planetologie (Münster), all others. N.D. = Not detected.

descriptions of both meteorites and the collection sites). The terrestrial ages of many of the meteorites from Roosevelt County are in the range of 30,000 to 40,000 years, approximately equal to the age of the overlying cover-sands (Holliday, 1989). It is thought that the rarity of meteorites with low terrestrial ages reflects losses through weathering.

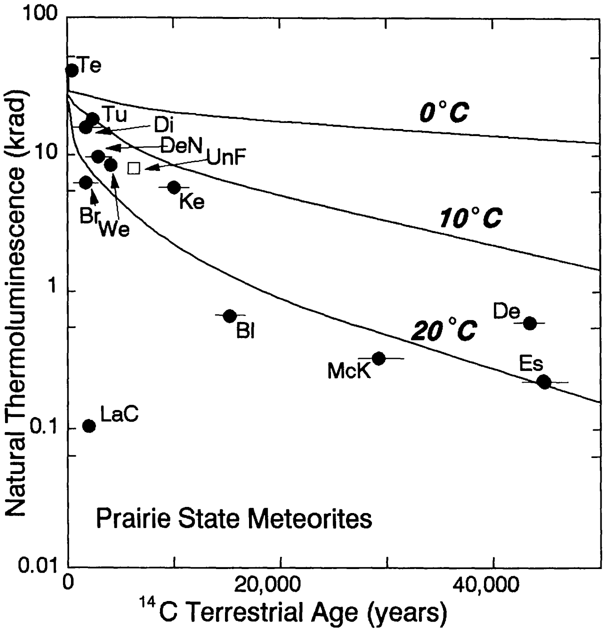

FIG. 1. Natural TL levels at 250 °C in the glow curve *vs.* ^{14}C-determined terrestrial ages (Jull *et al.*, 1993) for meteorites from the Prairie States. Theoretical TL decay lines for storage temperatures of 0, 10 and 20 °C (calculated using the TL parameters for Lost City (McKeever, 1980)) shown for comparison. There is a close correspondence between the data and the decay curve for a storage temperature of 20 °C.

Figure 2 shows the natural TL of a group of Roosevelt County meteorites *vs.* their terrestrial ages, as determined by AMS ^{14}C measurements. Aside from being heavily biased towards meteorites with high terrestrial ages, the data in Fig. 2 are remarkably similar to those in Fig. 1. The Roosevelt County meteorites cluster near or just above the 20 °C line for natural TL decay. In analogy to the Prairie State data, there is one exception, RC064, to the general correspondence between the TL and ^{14}C data. Unlike Ladder Creek, there are as yet no additional data to assist in interpreting the discrepency. RC064 may, similar to Ladder Creek, have a very low cosmic ray exposure history. Alternatively, this meteorite may have been heavily shocked and reheated ($<10^5$ years prior to Earth impact) or may have been reheated by close passage to the sun before Earth impact (Benoit *et al.*, 1991a). Petrographic data do not seem to support the idea of heavy shock for this meteorite.

The close geographic proximity of the Roosevelt County meteorite finds raises the problem of "pairing" in this database (*i.e.*, individual meteorite falls may be represented by multiple fragments due to break up during terrestrial weathering or during atmospheric entry). Figure 2 also shows potentially paired fragments as linked data points. There have been only limited efforts to pair the Roosevelt County meteorites (Sipiera *et al.*, 1987; Jull *et al.*, 1991), partly because of the difficulty of pairing equilibrated ordinary chondrites using only petrographic methods. We have previously detailed criteria for pairing using petrographic descriptions, cosmogenic and radiogenic isotopes, natural TL levels, and induced TL parameters (Benoit *et al.*, 1992). Using these criteria, we suggest that RC032, RC043 and

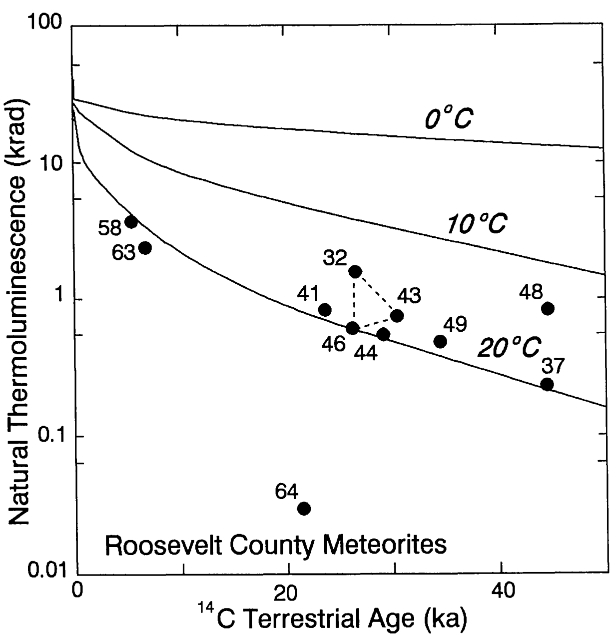

FIG. 2. Natural TL levels at 250 °C in the glow curve *vs.* ^{14}C-determined terrestrial ages (Jull *et al.*, 1991) for meteorites from Roosevelt County. TL decay lines from Fig. 1. These data also closely follow the theoretical curve for a storage temperature of 20 °C.

RC046 are possibly paired. The remainder of the meteorites appear to be independent falls.

The close correspondence of the Roosevelt County and the Prairie State data to the 20 °C TL decay line has a bearing on the meaning of "storage temperature" in relation to meteorites. In the case of the lines given in Figs. 1 and 2, storage temperature is a specific temperature which is assumed to be constant throughout the meteorite's terrestrial history. Obviously, considering the diurnal, seasonal and long-term climatic temperature variation at these sites, this is a gross simplification. The terrestrial thermal history of meteorites on the Earth's surface are complicated in that they can absorb heat from sunlight. Thus their interiors can be 10 to 15 °C warmer than air temperature (Schultz, 1990) and many meteorites have been buried in the soil during some part of their terrestrial histories and, thus, protected from climate extremes. On the other hand, the close correspondence between the actual data and the theoretical line suggests that the simplification is not unjustified. In general, 20 °C is a good approximation of the current mean annual temperature at these sites. This suggests that the TL of interior samples of meteorites is generally insensitive to transient temperature variations at typical terrestrial temperatures. This might not be the case for samples taken very close to the exterior surface of a meteorite, which would see the greatest diurnal and seasonal temperature changes. However, such samples are routinely avoided in natural TL studies in order to avoid the thin rim of fusion crust and highly heated material produced during atmospheric entry. In fact, it might be possible to study certain aspects of the terrestrial history of a meteorite find, including burial history and climatic changes, using TL profiles as a function of depth, although pre-terrestrial depth effects must also be considered (Benoit and Sears, 1993).

Another interesting feature of the data shown thus far is the slight degree of scatter observed in some individual meteorites in each database. For example, Keyes and Densmore (Fig. 1) have slightly higher natural TL than would be expected using the 20 °C decay line followed by the rest of the meteorites; RC032 and RC048 are equivalent to these two meteorites in the Roosevelt County database. There are two possible sources for this variation: (1) different (lower) storage temperatures for these meteorites relative to the others or (2) different (higher) saturation TL levels for these meteorites *prior* to fall. While the former possibility is viable if, for instance, these meteorites were buried shortly after Earth impact and, thus, protected from climatic extremes, it seems more likely that the observed scatter reflects the range of natural TL levels prior to impact. With the exception of meteorites heated by small perihelia orbits prior to impact, modern falls show a range of natural TL levels of approximately 20–80 krad (Benoit *et al.*, 1991a). While terrestrial decay at a given temperature will dramatically decrease this range in absolute terms, meteorites with pre-fall values at the upper end of the range will maintain slightly higher natural TL levels than other meteorites of the same age, with all other factors being equal.

SAHARAN METEORITES

Jull *et al.* (1990) measured ^{14}C levels in a suite of ordinary chondrites collected in the deserts of Libya. We have measured natural TL levels for a subset of their samples (Table 2). Unlike the Prairie State and Roosevelt County meteorites, the TL levels at the standard glow curve temperature of 250 °C have been largely drained in most of these samples. Figure 3a shows the natural TL glow curve of Lost City (H5) (time = 0) and the glow curves produced by theoretically "storing" this meteorite at a temperature of 30 °C. It is apparent that, at this relatively high storage temperature, the TL level at 250 °C in the glow curve decays at a very rapid rate and is not useful for terrestrial age determinations for meteorites >4000 years. If, however, the TL level is measured at the glow curve temperature of 300 °C, the TL decay rate is much slower, and the TL level can be used for terrestrial age determinations up to ~15,000 years. This solution is not ideal because the photon counts in this portion of the glow curve can be very low, especially in heavily weathered meteorites; errors due to counting statistics can become large. In addition, the slowness of decay at this glow curve temperature at lower storage temperatures (<25 °C) makes this procedure unsuitable for meteorites from most collection sites. This is shown in Fig. 3b, which shows the 250 °C glow curve data from Fig. 2 and the data for 300 °C in the glow curve for the same meteorites.

Figure 4 shows natural TL levels at 300 °C in the glow curve for the Libyan meteorites compared against their ^{14}C-derived terrestrial ages. Also shown are the theoretical curves for TL decay at storage temperatures of 30 and 35 °C. The 300 °C glow curve data for the Libyan meteorites generally follow the theoretical 30 °C storage temperature decay curve. There are two exceptions, DA011 and DA108, which, considering the small size of this database, is not unexpected in light of the ~15% of thermally-drained meteorites observed in the modern falls database. A storage temperature of 30 °C is very similar to the current mean annual temperature at this site.

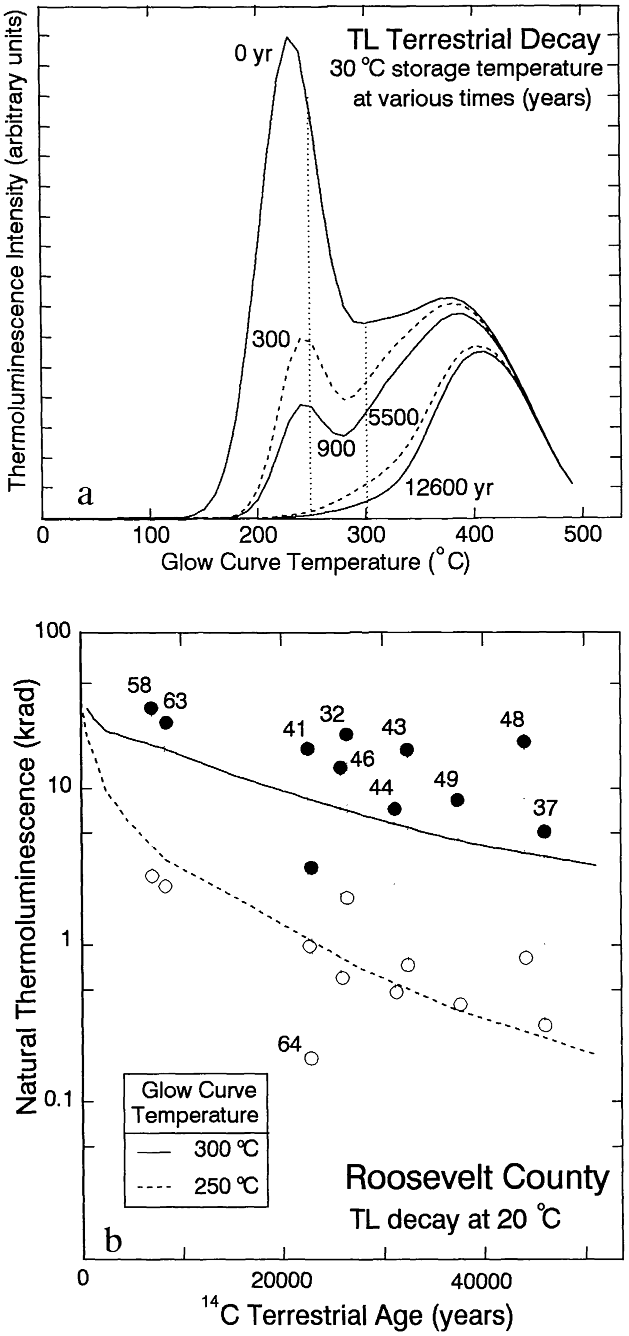

FIG. 3. (top) Glow curve for Lost City and calculated curves after decay for given time (in years) at a storage temperature of 30 °C. Note that, at this relatively high storage temperature, the TL level at 250 °C in the glow curve rapidly diminishes to very low levels and, hence, is only useful for terrestrial age determinations for ages <4000 years. The level at 300 °C decreases much less rapidly and can be used for terrestrial age determinations up to ~15,000 years at this storage temperature. (bottom) Natural TL data for Roosevelt County meteorites (Fig. 2) at both 250 °C and 300 °C in the glow curve, with theoretical decay curves for both at a storage temperature of 20 °C. Although there is a general decrease in natural TL levels with terrestrial age, the relative insensitivity of the 300 °C data make them less suitable than the 250 °C data for terrestrial age determinations at this storage temperature.

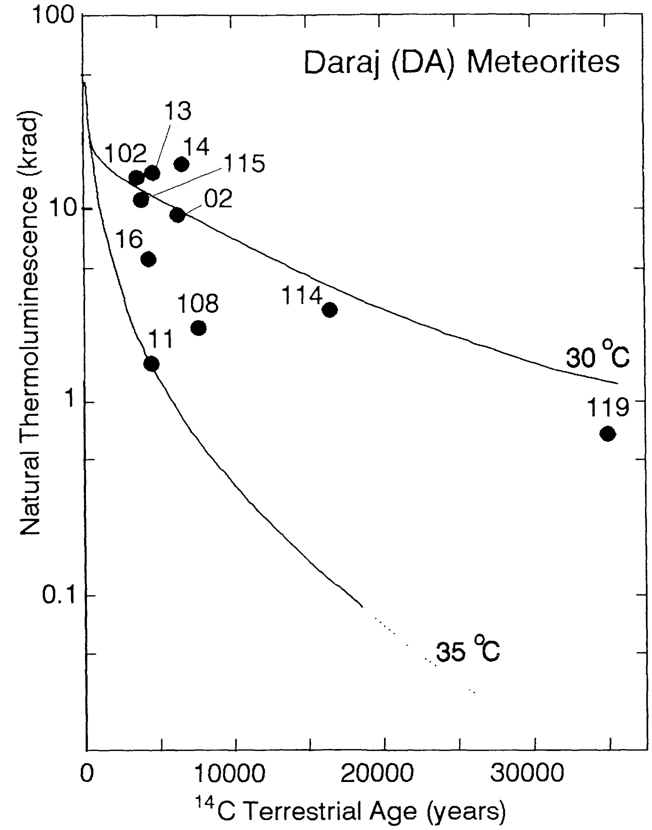

FIG. 4. Natural TL levels at 300 °C in the glow curve *vs.* ^{14}C-determined terrestrial ages (Jull *et al.*, 1990) for meteorites from Daraj, Libya. Theoretical TL decay curves for both glow curve temperatures at storage temperatures of 30 °C and 35 °C are also shown. The data follow the 30 °C decay curve.

Natural TL data for a separate group of meteorites from the Sahara desert are also given in Table 2. Measurements of ^{14}C activities have not be made for these samples. This particular dataset is heavily biased towards unequilibrated (upper type-3s) and type-4 ordinary chondrites (Bischoff *et al.*, 1992). It has been shown that using natural TL levels to determine terrestrial ages in basaltic and lower type-3 meteorites requires corrections for "anomalous fading" (Sears *et al.*, 1991). However, the upper type-3s (>3.4) are essentially equivalent to equilibrated chondrites in terms of the structural state of their feldspar (Sears, 1988), and the low natural values of these meteorites cannot be attributed to non-thermal fading.

Figure 5 shows these data plotted along the theoretical decay curve for a storage temperature of 30 °C at 300 °C in the glow curve. It should be noted that using this procedure results in terrestrial ages generally <10,000 years, similar to the range observed in Fig. 4 (see complete dataset in Jull *et al.*, 1990). The data in Fig. 5 seem to be divided into four groups, three of which are clusters on the theoretical line at terrestrial ages <15 ka and one at very low natural TL levels (<1 krad at 300 °C in the glow curve). The first three clusters, with approximate terrestrial ages of 1000–3000, 5000–7000, and 10,000 years, respectively, are at least partly caused by pairing (Bischoff *et al.*, 1992) but differences in induced TL data, petrologic classes, and

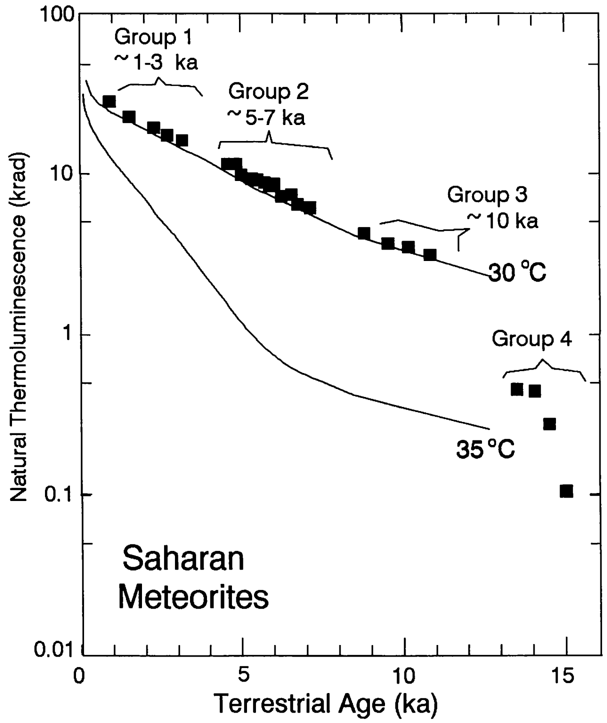

FIG. 5. Natural TL levels at 300 °C in the glow curve for a group of Saharan meteorites, plotted along the 30 °C decay curve from Fig. 4. Four data clusters are apparent, three (Groups 1–3) where TL levels probably reflect terrestrial age and one (Group 4) which probably consists of reheated meteorites.

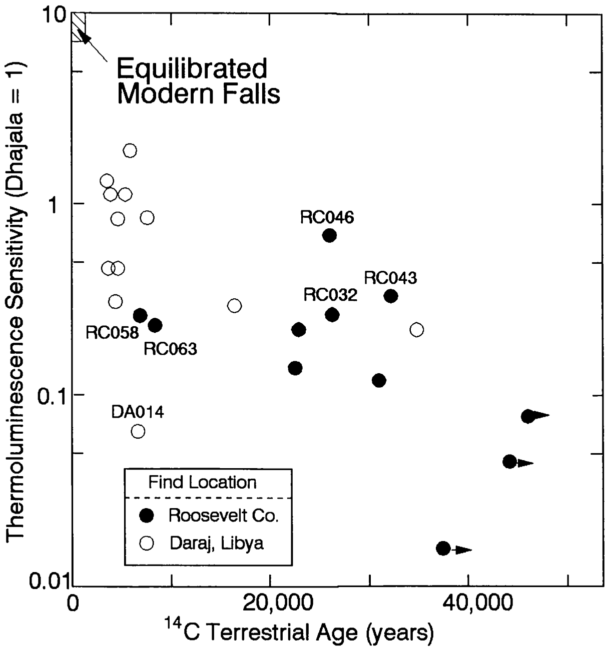

FIG. 6. Thermoluminescence sensitivity (relative to that of the Dhajala H3.8 meteorite) of Roosevelt County and Libyan meteorite finds *vs.* their terrestrial age determined by ^{14}C measurements. In general, there is a tendency for TL sensitivity to be lower for finds with the greatest terrestrial ages. This reflects the greater degree of weathering experienced by these meteorites.

collection sites within these groups indicate that pairing is not the sole cause of the clusters. Jull *et al.* (1990) observed clustering in ^{14}C terrestrial ages of an independent group of ordinary chondrites from this region, with distinct peaks in the terrestrial age histograms at 4000 and 8000 years. They did not observe any cluster at ~10,000 years, but this may be because of the relatively small number of samples in their study. A group of meteorites with a large terrestrial age would, barring unusual circumstances, be much reduced in number through normal weathering processes compared to groups with smaller terrestrial ages at the same site.

One interpretation of these temporal clusters is that collection/preservation efficiency at the Saharan sites was maximized at certain time periods. This could, as suggested by Jull *et al.* (1990), be the result of climatic changes over this time interval. Extensive geologic studies suggest that the Saharan region has had a complex history over the last 15,000 years, in which precipitation and fluvial processes were much more intense than is currently the case (Wendorf *et al.*, 1976; Pachur, 1980). Studies using ^{14}C dating of fossils suggest that fluvial sedimentation was active about 13,000 years ago and was followed by a period ranging from about 12,000 years to 7500 years B.P. in which large lakes and intermittent rivers were common in parts of the region (Pachur, 1980). This period was later followed by another period of active fluvial processes which gave way, at about 1500 B.P., to the modern aeolian processes of the (relatively) dry desert. Fluvial processes were especially active between 10,000 to 7700 years B.P. and around 5100 B.P. In the context of our TL data, it appears that separations between our clusters coincide with periods of active fluvial processes. Thus, meteorite preservation in the Sahara seems to be best in quiescent geomorphic regimes, that is, those in which stream erosion is less active. The modern dry desert regime is also conducive to meteorite preservation, probably because most meteorite finds are large enough to not be carried off by the wind

The very low natural TL group (Group 4 in Fig. 5; <1 krad at 300 °C) *could* have very large terrestrial ages (>20 ka). However, it is more likely that this group is the equivalent of the low TL group observed in the Antarctic collection (Benoit *et al.*, 1992) and in the non-Antarctic collection (Benoit *et al.*, 1991a), as well as Ladder Creek and RC064 in Figs. 1 and 2. It is likely, therefore, that the members of this group were reheated, either by shock or small perihelion orbit, prior to fall.

TL SENSITIVITY AND TERRESTRIAL WEATHERING

Jull *et al.* (1991) observed a trend of increasing qualitative degrees of weathering as a function of terrestrial age in finds from Roosevelt County. We have observed that meteorites from Antarctica generally have TL sensitivity levels much lower than their petrologic equivalents among the observed falls (Benoit *et al.*, 1991b). We have found that the TL sensitivity levels of finds can be increased to those of observed falls by washing the meteoritic powder in HCl for less than a minute.

We suggest that the low TL sensitivity levels merely reflect the amount of rust (which roughly corresponds to the degree of weathering) in the meteorites. In Fig. 6 it is apparent that meteorites with long terrestrial ages have, in general, lower TL sensitivities than those with short terrestrial ages. There is a great deal of scatter in the data; even the RC032 pairing group shows some variability, which is expected considering that weathering within meteorites need not be uniform throughout any given fragment. All the finds in this study, even those with terrestrial ages <5000 years, have significantly lower TL sensitivities compared to equilibrated ordinary chondrite modern falls (Fig. 6). This stresses the rapidity at which meteorites weather, even in relatively dry climates.

SUMMARY

We have demonstrated a relationship between natural TL levels and ^{14}C-determined terrestrial ages for meteorite finds from the Prairie States (Texas, Oklahoma, Kansas, and Colorado, USA), Roosevelt County (New Mexico, USA), and the Saharan Desert which are also in accord with calculated TL decay curves for "storage" temperatures equal to the approximate average annual temperatures at the individual sites. We do not discuss the absolute uncertainties associated with using natural TL levels for terrestrial age determinations; rather, we limit our discussion to the empirical correspondence between the two methodologies and to theoretical decay curves for a single "average" ordinary chondrite. Clearly our next step must be to delineate absolute terrestrial age determination procedures using natural TL measurements, including an analysis of uncertainties caused by the range of natural TL levels in observed falls. However, the present work indicates that variable short-term "storage" temperatures (diurnal and seasonal) do not invalidate the technique; natural TL levels are largely determined by long-term (*e.g.*, annual) average storage temperatures. In fact, the present data suggest that natural TL and cosmogenic nuclide (^{14}C, ^{36}Cl, *etc.*) concentrations in groups of meteorite finds can be used as both time markers (terrestrial age) and terrestrial temperature markers.

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