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NATURAL THERMOLUMINESCENCE AND TERRESTRIAL AGES OF METEORITES FROM A VARIETY OF TEMPERATURE REGIMES

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Abstract — The natural thermoluminescence of meteorites from Antarctica, the Prairie and western States of the US and the Sahara Desert has been determined and compared with estimates of terrestrial age (time since fall) obtained by isotropic measurements. After fall on Earth, the natural TL of meteorites decays from the high values caused by high cosmic ray dose rates and low temperatures of space. The decay is temperature dependent, but can be theoretically modelled. The present data show good agreement between theory and observation. It is therefore possible to determine terrestrial ages from the natural TL data and theoretical TL decay curves, selecting appropriate temperatures from meteorological data. About 20% of the meteorites have low natural TL values which result in unrealistically long terrestrial age estimates. These meteorites are readily distinguished from the others and usually have cosmic ray produced isotope activities which suggest atypical radiation histories in space. The low TL signal, and perhaps the unusual isotopic data, is readily understood in terms of passing close to the Sun.

INTRODUCTION

It can be estimated that a typical continent of 10^6 square kilometres is impacted by 9000 meteorites in 100 ka[1]. There are a number of fairly arid regions on Earth where large numbers of meteorites can accumulate and where major efforts to recover them are justified. In the 1930s and 1940s, the Prairie States of the US were a productive area for meteorite recovery[2]. Several recovered meteorites have associations with pre-Columbian settlements, and provide information on the culture and trading patterns of the local people[3]. The area continues to yield large numbers of meteorites, most noteworthy perhaps are the wind blowout sites of Roosevelt County, New Mexico[4]. Over the past few decades several nations have launched major programmes for the recovery of meteorites in the Antarctic, where not only does the dry climate favour meteorite preservation, but large scale movements of the ice tends to concentrate meteorites in relatively accessible fields along the length of the Trans-Antarctic and other mountain ranges[5]. More recently, the western plains of Australia[6] and the deserts of North Africa have proved to be important sources of new and rare meteorites[7].

Cosmic ray exposure leads to very high radiation dose rates in space. Estimates are typically ~0.1 Gy per year, although this will vary with depth in the meteorite[8] and may be subject to spatial and possibly temporal variation[9]. Temperatures are also low. Assuming black body conditions and reasonable parameters for the albedo and the other physical parameters, a meteorite at 1 AU (1 AU, the astronomical unit, is the distance between the Sun and the Earth, 1.5×10^8 km) would be at 263 K and a meteorite at 3 AU will be at 152 K. Only at distances of <~0.8 AU will temperatures be high enough (>~300 K) to affect natural thermoluminescence (TL), so that for most meteorites the natural TL at their time of fall will be at thermal equilibrium which is close to saturation[10]. Once on Earth, the higher ambient temperatures and the shielding from cosmic radiation afforded by the atmosphere means that the natural TL decays to lower values. The decay process is temperature-dependent and has been theoretically modelled in some detail by McKeever[11]. A typical glow curve and its evolution with time on Earth calculated using McKeever's methods is shown in Figure 1.

Natural TL therefore provides a means for the evaluation of the time interval that has lapsed since fall (terrestrial age) for the large numbers of meteorites being recovered from the Earth's arid regions. Pioneering studies of this technique have been reported by many authors[11–14]. These studies were primarily concerned with establishing the essential feasibility of the method and were heavily dependent on isotopic data. The main difficulty in making the method absolute is that the storage temperature is unknown. Another problem is that ~20% of the meteorites do not enter the atmosphere with saturated natural TL and their values are conspicuously low, most probably due to close solar passage[10]. Here we report on a study of the natural TL of meteorites from several very different regions of the Earth;

the Antarctic; the Prairie States of the US; Roosevelt County, New Mexico; and a region of the Sahara in Libya and Algeria. We find that although the rate of decay, as theoretically expected, is strongly dependent on temperature, reasonable estimates of the mean effective temperature at each site can be made and that terrestrial ages can be determined from natural TL with an accuracy comparable to that possible by the isotopic methods. It also seems that meteorites which have experienced close solar passage can be distinguished, because their natural TL leads to unreasonably long terrestrial age estimates.

EXPERIMENTAL

Our sample preparation, TL measurement techniques and data reduction methods were described in detail in Benoit *et al*[15]. Essentially, meteorite samples taken at least 0.6 cm from the heat-altered surface are crushed, the metal removed with a magnet, and the powder lightly ground to pass through a 100 mesh sieve. All operations are performed in red light. Modified Daybreak Nuclear and Medical TL systems are used for the measurement and the data are recorded automatically using custom-built interfaces and TI personal computers. A heating rate of $7.5^{\circ}C.s^{-1}$ and Corning 7-59 and 6-69 filters are used. The present work concerns the most common type of meteorite, ordinary chondrites which have very intense natural TL with sharp glow curve peaks. These make it experimentally difficult accurately to produce plateaux in the manner of conventional TL dating, so the equivalent dose at 250°C in the glow curve is determined using the ratio of two peaks (one at 250 and one at 400°C) and the ratio empirically converted to equivalent dose[15]. However, if the peak ratio is <0.5, or if a value at a glow curve temperature other than 250°C is required, then the equivalent dose is measured in the normal way. Unless otherwise stated, the natural TL values quoted here are those measured at 250°C.

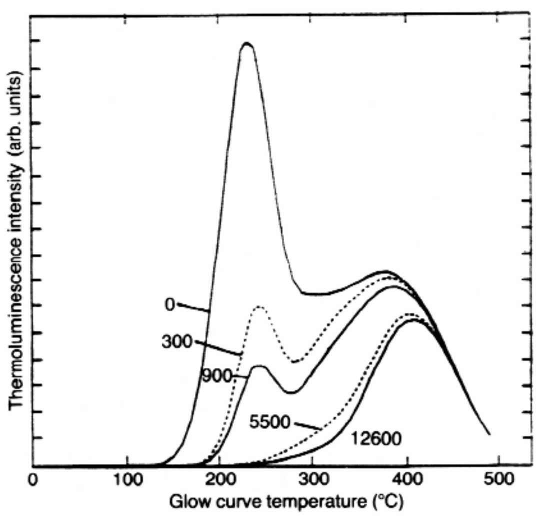

Figure 1. Glow curve for an ordinary chondrite meteorite recently arrived at the Earth's surface and calculated curves for a variety of times on Earth (given in years on each curve) using the theoretical treatment and input parameters of McKeever[11]. A storage temperature of 30°C has been assumed. The natural TL decays with time as the meteorite adjusts to the relatively low radiation, high temperature environment of Earth.

RESULTS AND DISCUSSION

Natural TL terrestrial age and storage temperature

Figure 2 shows plots of natural TL plotted against terrestrial age for meteorites from (a) Antarctica, (b) the Prairie States, (c) Roosevelt County and (d) the Sahara. We will briefly discuss each in turn.

Antarctica

The natural TL data were originally determined at the request of the US Meteorite Working Group who wanted to include natural TL measurements in the preliminary examination of newly returned Antarctic meteorites[16]. Twenty-three samples were chosen on the basis of ^{26}Al data, a cosmic ray produced isotope with a half-life (0.71 Ma) comparable to the expected terrestrial ages. This may have resulted in a slight bias, since there is a tendency for high ^{26}Al samples to have low TL, probably reflecting an atypical radiation history. Figure 2(a) compares the TL data with terrestrial ages calculated from the abundance of ^{36}Cl ($t_{1/2}$ 0.3 Ma), another cosmogenic isotope[17]. The ages typically carry a 70 ka uncertainty, which the authors do not explain but we assume is the 1σ value. Fourteen of the 19 meteorites follow the theoretical decay curve for samples stored at 0 to −5°C, decaying by nearly an order of magnitude in 1 Ma.

The remaining 5 meteorites have natural TL values consistent with terrestrial ages >1 Ma and much lower than expected on the basis of their isotopic ages and known ice movements: the maximum expected age for Antarctic ice is ~1 Ma, the time taken for ice to move from the pole to the continental edges. This has also been found to be the upper limit for the ^{36}Cl terrestrial ages[17]. Orbital studies show that about 20% of the meteorites falling to Earth had perihelia <0.8

AU[18] and therefore experienced severe draining of their natural TL during close solar passage[10,19]. It is also possible that a high ^{26}Al might be related to a small perihelion orbit, especially if meteorites with such orbits tend also to have orbits with high inclinations[20].

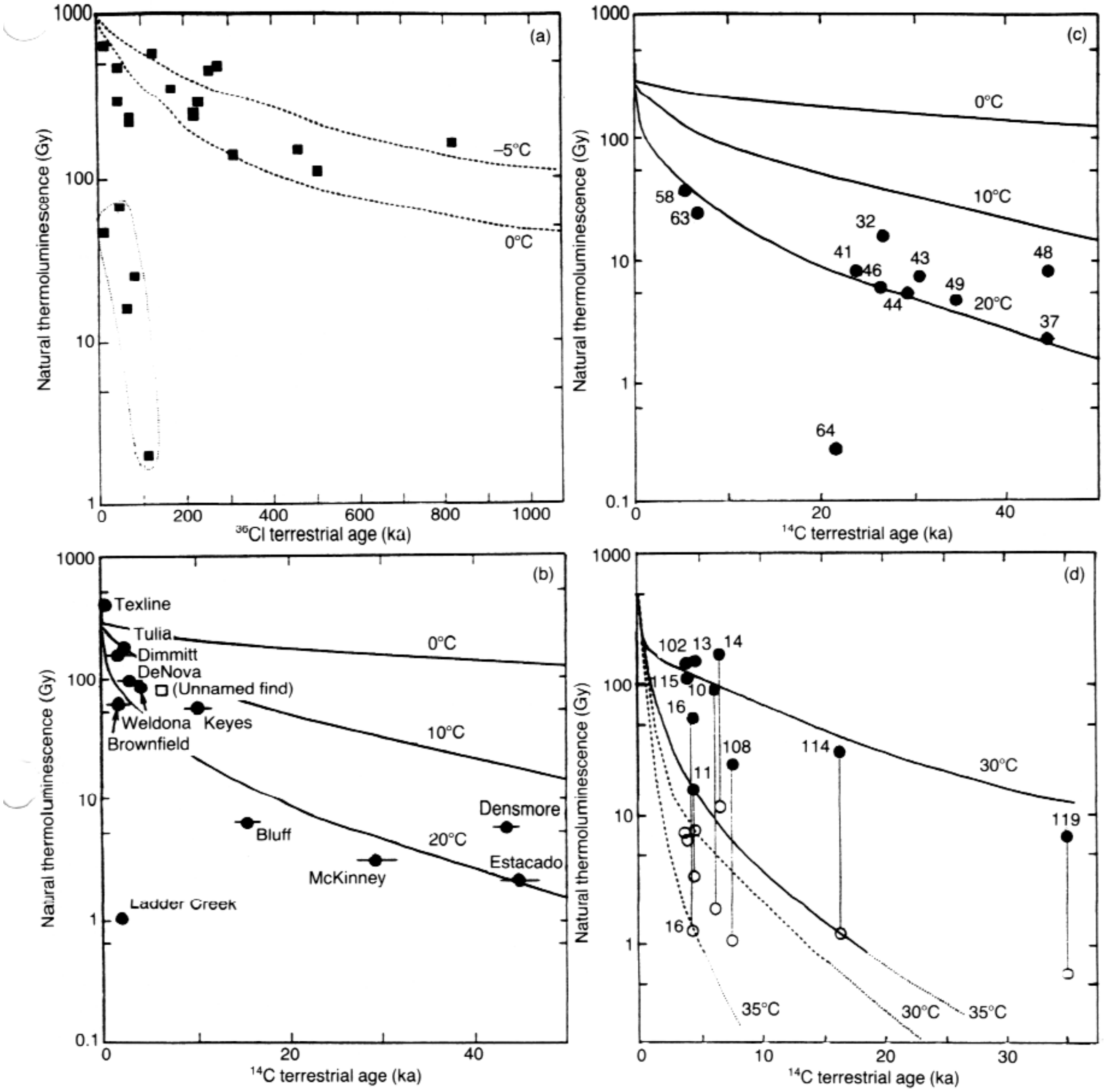

Figure 2. Plots of natural TL against the terrestrial age determined by isotropic methods compared with theoretical predictions. (a) Natural TL data for 19 meteorites from the Antarctic compared with ^{36}Cl terrestrial age. Most meteorites plot near the 0 to –5°C theory line as expected, but 5 have much lower values. These 5 meteorites, which also have unusually high ^{26}Al contents, are thought to have experienced atypical thermal/radiation histories. Most probably they passed within 0.8 AU of the Sun. (b) Natural TL data for meteorites from the Prairie States of the US compared with terrestrial age determined from ^{14}C activity. The meteorite not lying near the 20°C line (Ladder Creek) has unusual ^{26}Al activity. (c) Similar data for meteorites from concentration surfaces in Roosevelt County, New Mexico. Again the data plot near the 20°C theory line, maybe just to the low temperature side. Little is known about the outlier Roosevelt County 064. (d) Data for meteorites from the Sahara Desert. In this case, data for the natural TL at 300°C (—•) in the glow curve have been measured, since the natural TL at the normally measured 250°C (- - - o) fades rapidly and is difficult to measure accurately.

Prairie States

Since ambient temperatures are much higher, the natural TL of meteorites found in the Prairie States decays faster than in the previous case, falling more than an order of magnitude in 40 ka. The isotope whose half-life is applicable to this range is ^{14}C (5740 a). Sears and Durrani[13] originally found a suggestive but weak correlation between natural TL and the ^{14}C terrestrial ages of Boeckl[21], but new ^{14}C data obtained by Accelerator Mass Spectrometry[22,23] (rather than beta counting) produce a much better correlation (Figure 2(b)). In this instance a fairly well defined storage temperature of about 20°C is indicated and only one meteorite falls more than 2σ off this line. The natural TL of the maverick is so low that if interpreted in terms of terrestrial age would indicate an unreasonably large value. This meteorite also has atypical ^{26}Al data suggesting an unusual radiation history[17].

Roosevelt County

The Roosevelt County data also plot close to the 20°C line, lying slightly to the lower temperature side of the line (Figure 2(c)). These meteorites tend to have higher terrestrial ages than the Prairie State meteorites so that the two data bases together define the line rather well. Again, one meteorite is significantly off the line and if it natural TL was interpreted in terms of terrestrial age would yield an unreasonably large value. Little is known about this meteorite.

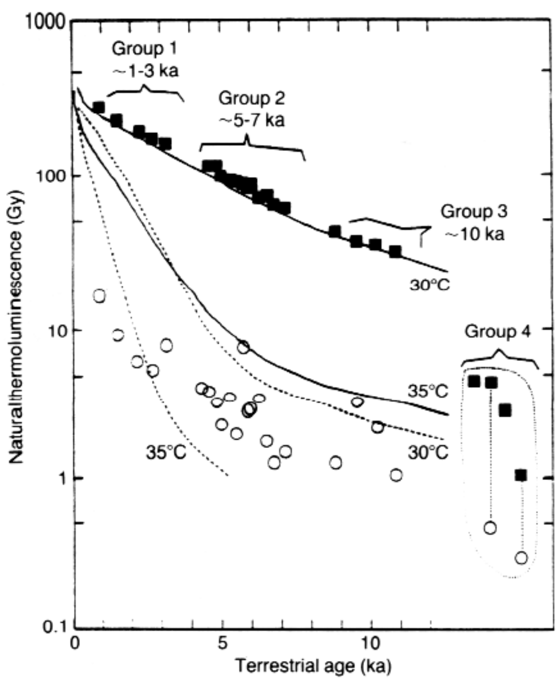

Figure 3. Theoretical curves for natural thermoluminescence against terrestrial age with data for Saharan meteorites superimposed. In this instance, isotopic information concerning terrestrial age is not available and horizontal position on the plot has been determined by placing the natural TL at 300°C on the theoretical 30°C line. Glow curve temperatures: (—■) 300°C, (- - -o) 250°C.

Saharan meteorites

The natural TL of meteorites from the Sahara Desert decays more than an order of magnitude in 7.5 ka and, because of the experimental uncertainties in the natural TL and isotopic data, scatter rather widely on the plot (Figure 2(d)). The situation improves if the natural TL is measured at 300°C in the glow curve, rather than at 250°C as in the previous cases. The natural TL as 300°C in the glow curve decays about an order of magnitude in 30 ka consistent with the theoretical curve for a storage temperature of 30°C.

Absolute terrestrial age determination

Data were recently obtained for a number of Saharan meteorites for which independent isotopic terrestrial age measurements are not available, although ^{14}C measurements determined by AMS have been made for other meteorites from the area. The data are superimposed on the theoretical curves in Figure 3. Since terrestrial ages are not known, their horizontal positions have been determined using their natural TL values at 300°C and the 30°C theoretical curve. The data for the 250°C natural TL are consistent with this approach. Note that the data labelled 'group 4' have not been placed on this curve which would require considerable extrapolation to larger terrestrial ages. It is assumed that these meteorites are equivalents of those with very low TL values which have been observed in every data base and which probably had perihelia <0.8 AU.

The terrestrial ages which are suggested by the natural TL data, as determined from Figure 3, range from 1 to 11 ka, about the same range as indicated by ^{14}C measurements. There appear to be three groups, in addition to the group which experienced close solar passage. Group 1 has ages in the range 1–3 ka, group 2 has ages 5–7 ka and group 3 has ages around 10 ka. Similar groups were present in the ^{14}C data base. Jull *et al*[24] suggested that these groups were caused by climate changes, so that only the meteorites which fell during dry periods resisted weathering long enough to become encased in the sediments. The present results confirm Jull *et al*'s suggestion of periodic meteorite preservation and are not inconsistent with their explanation.

CONCLUSIONS

The natural TL values for meteorites from the continents have been measured. When plotted against terrestrial age, as determined by isotopic methods, they plot on or near temperature-dependent theoretical curves for the decay of natural TL on Earth. The temperatures assumed for the calculations are consistent with those predicted from meteorological data. Thus it is possible to estimate typical storage temperatures from meteorological data and then use the natural TL measurements and calculated decay curves to determine absolute terrestrial ages for meteorites from any temperature regime on Earth.

One in five meteorites have experienced orbits with small perihelia, so that solar heating has drained their natural TL signal. These meteorites cannot be dated by the natural TL method. However, it is doubtful that misleading ages could be produced erroneously since such meteorites yield implausibly large terrestrial ages.

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