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THERMOLUMINESCENCE OF METEORITES: SHEDDING LIGHT ON THE COSMOS

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Abstract—The TL sensitivity of meteorites reflects the abundance and nature of the feldspar. Thus intense shock, which destroys feldspar, causes the TL sensitivity to decrease by 1–2 orders of magnitude, while metamorphism, which generates feldspar through the devitrification of primary igneous glass, causes TL sensitivity to increase by a factor of $\sim 10^5$. TL–metamorphism relationship is particularly strong for the lowest levels of metamorphism and has led to a new means of classification for little-metamorphosed meteorites. The TL emission characteristics of feldspar (peak temperature and peak width) are also related to the thermal history. Induced TL properties have thus found useful application to the paleothermometry of primitive meteorites, to the thermal histories of chondrules, to the ejection mechanism of martian meteorites and to arguments about different extraterrestrial sources for meteorites currently falling world-wide and those which fell 10^5–10^6 yr ago in the Antarctic.

The level of natural TL in meteorites is determined by competition between build-up, due to exposure to cosmic radiation, and thermal decay. Terrestrial conditions should result in lower levels of natural TL compared to those expected in space, and, in principle, natural TL levels should be related to the period of time on earth ("terrestrial age"). Antarctic meteorites tend to have lower natural TL than non-Antarctic meteorites whose fall was observed, presumably because of the large terrestrial ages of the latter (10^5–10^6 yr). A few meteorites have especially low natural TL suggesting that they have recently been reheated. These may have come to earth on orbits with particularly small perihelia (≤ 0.8 astronomical units), and 26 meteorites with calculated orbits show a correlation between natural TL and perihelion distance. Dose-rate variations due to shielding, heating during atmospheric passage and anomalous fading also cause variations in natural TL levels, but the effects are either relatively small, occur infrequently or can be experimentally identified.

1. INTRODUCTION

IN SOME senses, the history of thermoluminescence research on meteorites dates back to the beginnings of meteorite studies. The first modern scientific paper on meteorites is probably that of Howard (1802) who observed that a meteorite glowed for some time after an electric discharge was passed across its surface. The glow Howard observed was probably due to the combination of cathodoluminescence and thermoluminescence (TL), but he saw implications for his observation in connection with the visual phenomena that accompany meteorite falls. Pure TL from a meteorite was probably first observed by A. G. Herschel, who found that dust from the Middlesbrough meteorite sparkled as it was sprinkled onto a hot-plate in a darkened room. Herschel realised that, contrary to prevailing views, this indicated that the interior of the meteorite could not have been heated significantly during atmospheric passage. He also argued that feldspar was the mineral producing the TL. Throughout this century meteorites have received attention from a wide variety of TL laboratories, with interest focussing on the relationships between TL and terrestrial ages, cosmic-ray exposure ages, and potassium-argon ages. These relationships were reviewed by McKeever and Sears (1979).

The last decade or so has seen a major growth of interest in the petrological implications of variations in the induced TL properties of meteorites. TL sensitivity provides an indication of the amount of feldspar present in the sample, while the temperature of maximum TL emission, and often the width of the apparent TL peak, provide an indication of the thermal history of the feldspar. The close relationship between TL properties and the amount and history of the feldspar is fortunate, because feldspar properties are highly sensitive to the various physical processes experienced by meteorites; metamorphism, shock, brecciation and aqueous alteration. In the present paper, we review both the petrologically-related work on induced TL properties of meteorites and recent developments concerning the more dosimetry-related natural TL measurements.

2. THE INDUCED TL PROPERTIES OF METEORITES

The TL sensitivity of the largest class of meteorites, the ordinary chondrites, shows a 10^5-fold range, while

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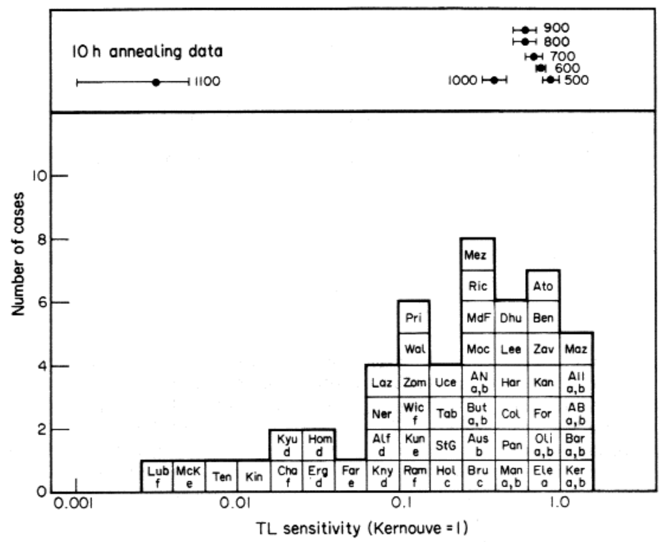

FIG. 1. Histogram of TL sensitivity levels in equilibrated ordinary chondrites with a variety of shock histories. The meteorites are identified by the first three letters of their names (see Sears, 1980, for identification) and their shock classification, where known, is indicated a–f (a, unshocked; f, heavily shocked). The data across the top of the histogram indicate the TL sensitivity for samples of an unshocked chondrite (Kernouve) which have been annealed for 10 h at the temperatures indicated (in °C). Petrographic data indicate that several chondrites of shock class e–f have experienced ≥1100°C as a result of the shock, in agreement with the TL data (Sears *et al.*, 1984b).

the shergottite achondrite class have values a factor of 10 or so lower than this (Sears *et al.*, 1980; Hasan *et al.*, 1986b). Since, with a few exceptions, the mineral responsible for the TL in meteorites is feldspar (Table 1), the range of TL sensitivity reflects the amount of this mineral present. Heavily shocked ordinary chondrites, in which the feldspar has been fused or partially converted to maskelynite, have TL sensitivities one to two orders of magnitude lower than unshocked equilibrated chondrites (Fig. 1). Such low TL sensitivities can be reproduced by annealing an unshocked chondrite to ~1100°C. Post-shock residual temperature for heavily shocked chondrites inferred from studies of the metal and sulfide are also ~1100°C (Fig. 1) (Leiner and Geiss, 1968; Sears, 1980; Sears *et al.*, 1984a).

For unshocked ordinary chondrites, TL sensitivity is strongly metamorphism-related (Fig. 2). The feldspathic constituent of unmetamorphosed ordinary chondrites is present as a glass which has little or no TL sensitivity. During relatively low-grade metamorphism the glass produces crystalline feldspar and the TL sensitivity increases accordingly. This has permitted a reliable subdivision of the least-metamorphised ordinary chondrites (the type 3 chondrites) into types 3.0–3.9 and many textural, compositional and iso-

Table 1. Thermoluminescence of minerals separated from an ordinary chondrite (Lalou *et al.*, 1970)

	Thermoluminescence (bulk = 1) Natural	Induced
Olivine	0.47	1.4
Olivine + pyroxene	0.17	0.4
Pyroxene	0.17	0.4
Phosphates	1.3	2.05
Metal and sulphide	0.03	0.05
Feldspar (plagioclase)	11.4	13.0

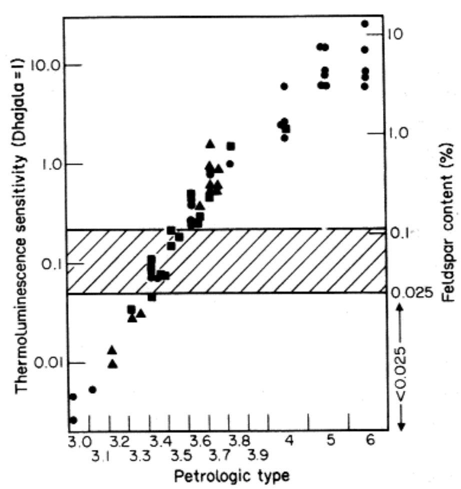

FIG. 2. TL sensitivity variations in unshocked ordinary chondrites of a variety of petrologic types (from Guimon *et al.*, 1986). "Petrologic type" refers to the intensity of metamorphism experienced, type 3 least and type 6 most metamorphosed. The cross-hatching refers to the TL sensitivity range in which the TL peak is narrow and at low glow-curve temperatures; it is thought that feldspar is in the low-temperature form in these meteorites. The right-hand axis is an estimate, based on the TL sensitivity, of the feldspar content of the meteorites. The different symbols refer to various literature sources for the data.

Table 2. Definition of petrologic types for ordinary chondrites§

	Petrologic type							
Property	3.0–3.1	3.2–3.3	3.4–3.5	3.6–3.7	3.8–3.9	4	5	6
Homogeneity of Olivine*	→ 50 →		40–50	20–40	5–20	< 5	Uniform	
Structural state of low Ca pyroxene	Predominantly monoclinic					monoclinic > 20%	monoclinic < 20%	ortho-rhombic
Feldspar	Absent → Absent or rare					< 2 μm grains	< 50 μm grains	< 50 μm grains
Primary glass	Clear isotropic → Turbid					Turbid if present	Absent	
Thermoluminescence sensitivity Dhajala = 1	< 0.01	0.010–0.46	0.46–0.22	0.22–1.0	1.0–4.6	1–10	> 5	
Heterogeneity of metal†	> 17	10–17	6.0–10	2.5–6.0	< 2.5		Uniform	
Average Ni content of sulfide minerals	> 0.5%	< 0.5% →						
Chondrule delineation	very sharply defined					well defined	readily defined	poorly defined
Matrix texture	% transparent microcrystalline: ≤ 20	10–20	~ 20– ~ 50	> 60		100	Recrystalline matrix	
Matrix $\left(\frac{FeO}{FeO + MgO}\right)$‡	> 1.7	1.5–1.7	1.3–1.5	1.1–1.3	< 1.1			

*Standard deviation of the mole % fayalite in the olivine divided by the mean fayalite expressed as a percentage.
†Standard deviation of the nickel content in the kamacite (wt%) divided by the mean nickel content expressed as a percentage.
‡Divided by the same quantity for the bulk meteorite.
§Vertical line intensities reflect strengths of boundaries.

topic variations are related to these types (Table 2). The mechanism for metamorphism-related increases in TL was recently confirmed by annealing a meteorite of a low petrologic type in a manner known to cause divitrification of synthetic glasses. A factor of 40 increase in the TL at 200°C in the glow curve resulted after only 200 h of annealing (Fig. 3).

The temperature of maximum TL emission, and the width of the TL peak (Fig. 4), also yield information relevant to thermal history (Sears and Weeks, 1983; Guimon *et al.*, 1985). At metamorphic levels equivalent to a TL sensitivity of 0.025 (using the Dhajala meteorite as a standard with a value of unity) the induced TL curve consists of a narrow peak (~100°C) at relatively low temperatures in the glow curve (~100°C), but at high levels of metamorphism the curve becomes broader (~160°C) and moves to higher glow curve temperatures (~200°C) (Fig. 5). This increase in TL peak temperature and peak width can be reproduced in the laboratory by annealing either a low petrologic type meteorite, or a terrestrial feldspar in the low-temperature (ordered) form, at > 700°C for 100 h (Fig. 5). These data suggest the possibility that thermoluminescence curve shapes can be used to estimate metamorphic equilibration temperatures, a possibility first proposed by Pasternak and co-workers (Pasternak, 1978; Pasternak *et al.*, 1976). This is particularly significant as conventional methods of palaeothermometry, based on mineral chemistry and isotope exchange, fail for these highly unequilibrated meteorites.

The glass in chondrites is located in structural components known as chondrules, essentially millimetre-sized (or smaller) silicate beads unique to meteorites. The origin of these components is unclear, as is much of their history. The TL properties of 54 separated chondrules from the Dhajala meteorite (Fig. 6) show that most chondrules ceased to equilibrate, following metamorphism, at high temperatures, i.e. have relatively low TL sensitivity (small amounts of crystallisation) and broad peaks at high temperatures. However about 20% of the Dhajala

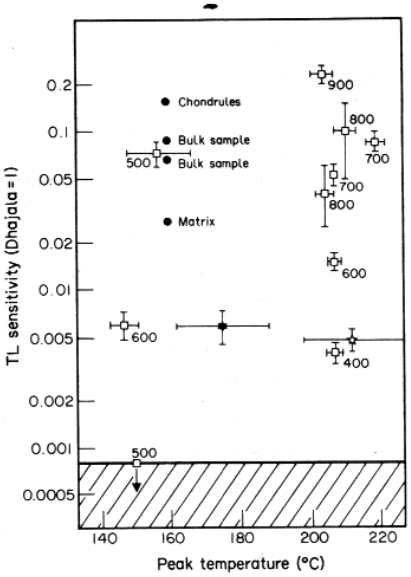

FIG. 3. TL sensitivity vs glow curve temperature for samples of the Semarkona chondrite which have been annealed at 400–900°C and 1 kbar for ~1 week with a variety of devitrification catalysts added (from Guimon *et al.*, 1987). Stars refer to two values for the unannealed meteorite. Low annealing temperatures caused a reduction in TL sensitivity (one 400°C sample excepted) to below detection limits (cross-hatched area), while temperatures >600°C produced considerable increases in TL sensitivity depending on temperature. The anomalous 500°C sample contained atypical material.

chondrules equilibrated down to temperatures ≤500°C, so they have relatively high TL sensitivity and narrow peaks at low temperatures (Sears *et al.*, 1984b; Keck *et al.*, 1986). This difference in behaviour during metamorphism probably reflects the ease with which the individual chondrules communicated with the rest of the meteorite during metamorphism, rather than suggesting that each chondrule underwent different degrees of metamorphism. This conclusion has important implications for understanding the history of chondrites, in particular whether chondrules experienced metamorphism in a separate parent body prior to being incorporated into the meteorite.

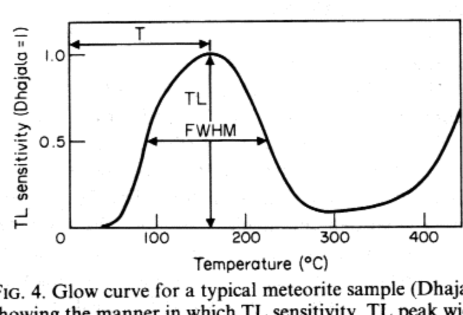

FIG. 4. Glow curve for a typical meteorite sample (Dhajala) showing the manner in which TL sensitivity, TL peak width (full width at half maximum, FWHM) and peak temperature are defined.

Peak temperature and width data for bulk chondrites presumably also contain information on the thermal history of the chondrite as a whole. Figure 7 compares peak temperature and peak width data for two classes of chondrite, the H and L chondrites. Comparison is also made between those that have recently fallen at various places on Earth and those that have been found in Antarctica. For the H chondrites especially, the peak temperature–peak width distribution for the Antarctic and non-Antarctic meteorites are different, the Antarctic H

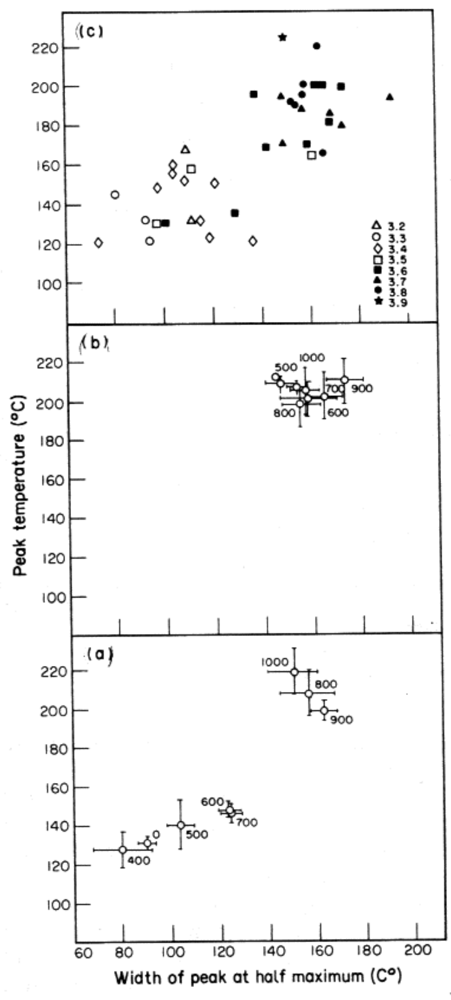

FIG. 5. Thermoluminescence peak temperature against width of the peak for (a) samples of the Allan Hills A77011 meteorite annealed at the temperatures indicated (°C; 0 = unannealed), (b) samples of the Kernouve equilibrated chondrite annealed over a similar range of temperatures and times, and (c) 39 type 3 ordinary chondrites. The petrologic type of each sample is indicated. There is a bimodal distribution in the data with type ≤3.5 in the lower cluster and type >3.5 in the upper cluster, and 77011 can be transferred from one cluster to the other by annealing. All the Kernouve data plot in the upper cluster and annealing at temperatures below 700°C does not transfer points to the lower cluster (from Guimon *et al.*, 1985).

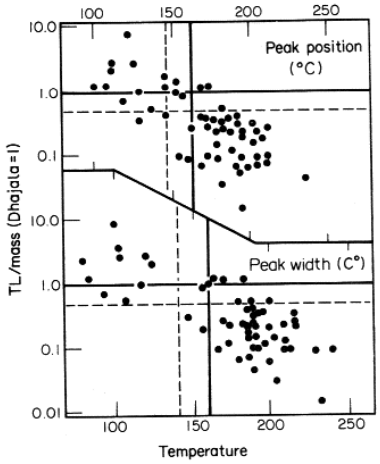

FIG. 6. TL sensitivity (mass normalised) against peak temperature and width for 54 chondrules separated from the Dhajala meteorite. Chondrules are ≤ 1 mm beads of silicate material which contain a glassy material of essentially feldspar composition; feldspar is a major source of TL in these meteorites and the extent of devitrification governs TL sensitivity. The data indicate that $\sim 20\%$ of the chondrules equilibrated down to low temperatures (high TL sensitivity, narrow peaks at low glow curve temperatures) while the remainder ceased to equilibrate at high temperatures (low TL sensitivity, broad peaks at high temperature) (from Sears *et al.*, 1984b).

chondrites having a much narrower range of peak widths. It is difficult to see how place of fall or find could explain this difference, or how terrestrial weathering could be the cause. Antarctic meteorites have been on earth much longer than the others (10^5–10^6 yr compared with ≤ 250 yr) and it could be that at different times the meteorites are coming to earth from different parts of the meteorite parent body, with different cooling histories. Lipschutz and co-workers have argued that Antarctic meteorites have a different extraterrestrial source from non-Antarctic meteorites on the basis of elemental and isotopic data (Dennison *et al.*, 1986).

According to current understanding, low-feldspar is present in type 3.2–3.5 meteorites in small amounts enclosed in a glass. Physical separation of the feldspar, in order to perform physical measurements is exceedingly difficult. In the case of terrestrial feldspar, the X-ray diffraction patterns indicate that the TL changes in peak temperature and width are associated with the onset of disordering (Hartmetz and Sears, 1987). One difference between terrestrial and meteoritic feldspars, however, is that the fully disordered terrestrial feldspar produces peaks with higher temperatures than observed in the meteorite case (Fig. 8). This difference requires further investigation, but is probably associated with the very different means of formation of the two types of

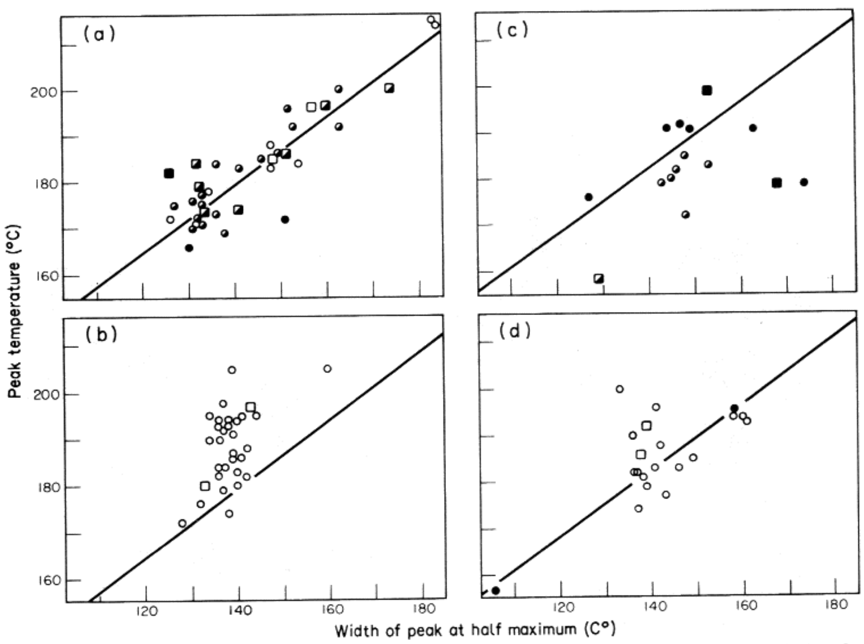

FIG. 7. Plots of TL peak temperature against peak width for type 4–6 chondrites. Filled symbols refer to shock heating class facies d–f, half-filled to facies a–c, open symbols to individuals of unknown shock-heating facies. Circles refer to type 5,6 and squares to type 4. For non-Antarctic H chondrites (a) there is a significant correlation between peak temperature and width ($r = 0.90$, $n = 30$, significance $> 99.9\%$), while this is not the case for Antarctic H chondrites (b). The data for L chondrites (c and d) are meagre, but may also show a difference between Antarctic and non-Antarctic meteorites (Haq *et al.*, 1988).

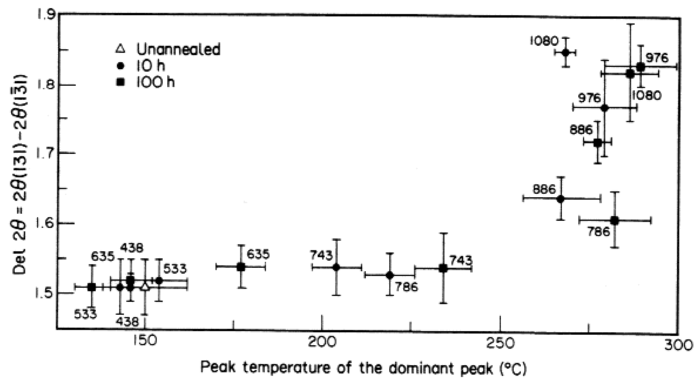

FIG. 8. Disordering as a function of TL peak temperature for a terrestrial oligoclase annealed at the temperatures and times indicated. Disordering of the Al, Si chain in the feldspar lattice is measured as the difference between the 131 and 131 reflection, the ordered phase having a del value of 1.5 and the disordered phase having a del value of 2.0 (Hartmetz and Sears, 1987).

feldspar. There is also evidence that shock, or the heat associated with shock, causes disordering or structural changes which are associated with disordering (Hartmetz *et al.*, 1986).

Three ordinary chondrites (Semarkona, Krymka and Bishunpur), which are the only known type 3.0–3.1 chondrites, not only have exceptionally low TL sensitivity, they have unusual broad, hummocky TL peaks (Sears *et al.*, 1982) and highly unusual cathodoluminescence (CL) properties (DeHart and Sears, 1986). Meteorites of types ≥ 3.4 have blue-green CL, which is especially associated with glassy material in chondrules. However, the type 3.0–3.1 chondrites have many phases with red and yellow CL and Semarkona has a distinctive fine-grained matrix with blood-red CL (Fig. 9). Low-temperature hydrothermal annealing experiments produce a decrease in TL sensitivity, presumably due to the destruction of the phosphor or its TL properties through hydrolysis reactions (Fig. 10). It is therefore plausible that the unusual properties of the type 3.0–3.1 chondrites, including especially their low TL sensitivity, reflect

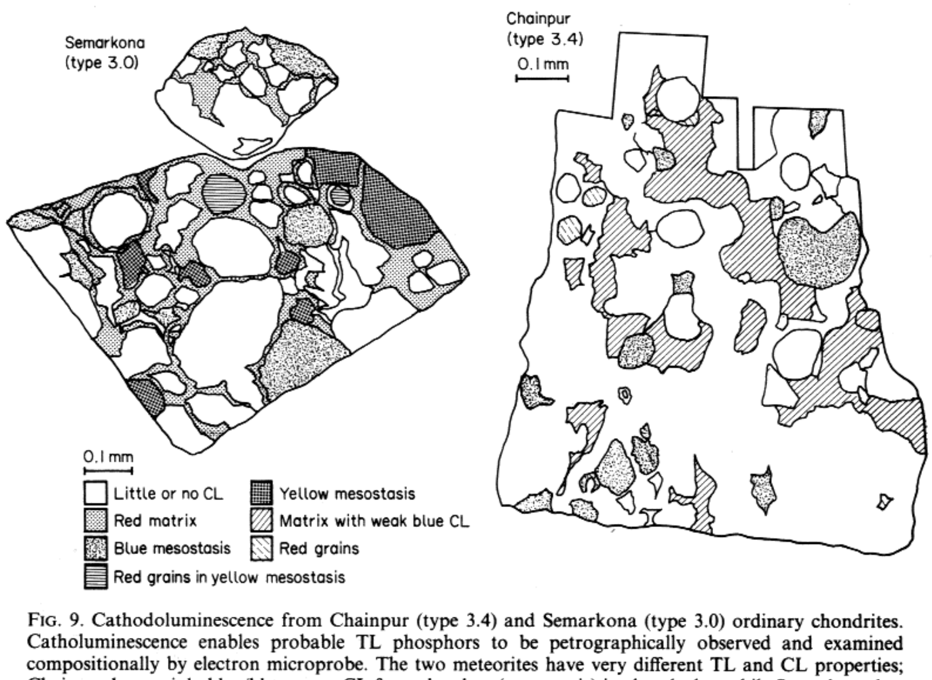

FIG. 9. Cathodoluminescence from Chainpur (type 3.4) and Semarkona (type 3.0) ordinary chondrites. Catholuminescence enables probable TL phosphors to be petrographically observed and examined compositionally by electron microprobe. The two meteorites have very different TL and CL properties; Chainpur has mainly blue/blue-green CL from the glass (mesostasis) in chondrules, while Semarkona has a wide variety of CL types, most notably the red CL coming from its fine-grained matrix. In Chainpur, and most ordinary chondrites of comparable or higher petrologic type, the CL is produced by feldspar, although traces of phosphate luminesce also.

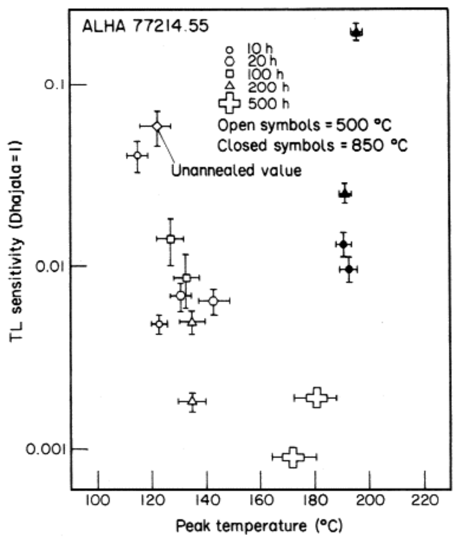

FIG. 10. Samples of the Allan Hills A77214 meteorite (split 55) show a decrease in TL sensitivity when annealed at 1 kbar in the presence of water and sodium disilicate at low temperatures (see also Fig. 3 for analogous data for Semarkona), but at higher temperatures increases again, reaching and even exceeding its original value. Two competitive processes are occurring. It is thought that at low temperatures the phosphor is destroyed by hydrolysis reactions, while at high temperatures devitrification produces new feldspar (Guimon *et al.*, 1986).

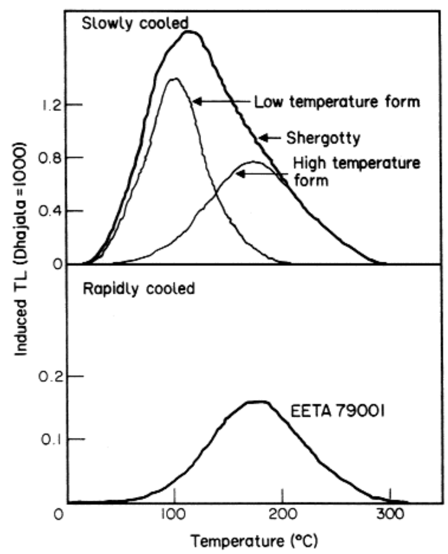

FIG. 11. Glow curves for the Shergotty and Elephant Morraine A79001 shergottites with a suggested mechanism for explaining the peak temperature, peak width, and TL sensitivity variations. It is suggested that post-shock recrystallisation of maskelynite in the meteorites produced feldspar in varying amounts and forms depending on cooling rate (Hasan *et al.*, 1986b).

aqueous alteration. There is petrographic and isotopic evidence for aqueous alteration in Semarkona and, possibly, Bishunpur (Hutchison *et al.*, 1987).

Although very different in origin, history, composition and petrology, the TL properties of the shergottite achondrites can be understood in very similar terms to those of the ordinary chondrites (Hasan *et al.*, 1986a). Mineral separation experiments indicate that the TL phosphor is also feldspar and the extensive maskelynization suffered by the class (conversion of the feldspar to a particular kind of glass by shock processes) is consistent with their very low TL sensitivity values. The shergottites also show systematic variation in peak temperature and width which can be understood in terms of feldspar being present

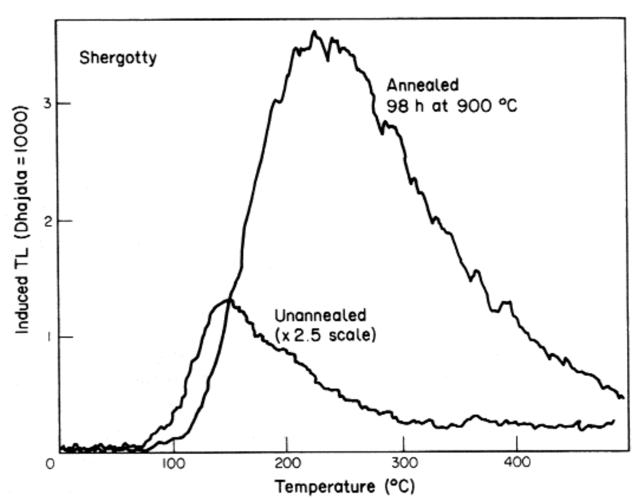

FIG. 12. Glow curves for the Shergotty meteorite before and after an annealing treatment. The annealing produced considerable crystallisation of the high temperature form of feldspar whose TL peak appears at 220°C in the glow curve (Hasan *et al.*, 1986b).

in the high and low temperature forms in varying relative amounts (Fig. 11). Annealing treatments under much milder conditions than those used for ordinary chondrites, produce spectacular TL sensitivity increases which are consistent with the relative instability of maskelynite in shergottites compared to that of the glass in type 3 ordinary chondrites (Fig. 12). Again, the temperature of the TL peak (peak position) is related to the annealing temperature.

The shergottites, together with the closely related nakhlites and Chassigny, have compositional, isotopic and petrographic properties which have convinced most workers that these meteorites and Martian in origin. The major difficulty in understanding such an origin, however, concerns the size of the objects at their time of ejection into space. Ejection mechanisms seem only to work for objects ≤ 10 m, while estimates based on diffusive loss of Ar and assumed post-shock temperatures of 400°C, suggest that the objects were ≥ 100 m in size when ejected from Mars (Bogard *et al.*, 1984). If our interpretation of the TL data is correct, then post-shock temperatures were ≥ 600°C, rather than 400°C as suggested by refractive index measurements, and the corresponding calculated ejecta sizes are ≤ 10 m.

3. NATURAL TL LEVELS IN METEORITES

In most cases, the long cosmic-ray exposure period ($\sim 10^7$ yr) for most meteorites means that their natural TL will be saturated or at thermal equilibrium throughout most of the glow curve. Natural TL levels can be estimated in a model-dependent and semi-quantitative way using some rudimentary physics (Randall and Wilkins, 1945; Garlick and Gibson, 1948). Assuming the rate of trap filling is first-order in the number of available traps and dose rate we can write

$$\frac{dn}{dt} = \alpha R(N - n) \quad (1)$$

where n is the number of trapped electrons, N is the number of traps, R the dose rate, t is time and α is the rate constant. For a meteorite, the major source of ionizing radiation is cosmic rays, where dose rates are thought to be on the order of ~ 1 rad/yr.

Assuming first-order kinetics, the rate of decay of excited electrons is given by

$$\frac{dn}{dt} = -\beta n \quad (2)$$

where β is the first-order decay constant. The relationship between β and the trap depth (E) and temperature (T) is given by the Arrhenius equation so that

$$\frac{dn}{dt} = -Sn\exp(-E/kT) \quad (3)$$

where S is the Arrhenius, or pre-exponential, factor and k is the Boltzmann constant.

Setting the rate of decay equal to the rate of build-up, and re-arranging, the relationship between number of trapped electrons, and therefore the level of TL, and the dose-rate and ambient temperature at equilibrium is given by

$$n = \frac{N}{1 + [S/\alpha R\exp(-E/kT)]}. \quad (4)$$

There are many such models for the TL process, most of greater sophistication, and it is not clear which is applicable to meteorites. There is strong evidence that the decay kinetics of the TL of ordinary chondrites are second order (McKeever, 1980). However, all models predict that the TL will normally be at an equilibrium throughout most of the glow curve at a level related directly to dose-rate and reciprocal temperature. It is also possible, in principle, for the TL level to be out of equilibrium if insufficient time has elapsed since the system was last drained for equilibrium to be re-established. Insertion of plausible values into equations 1 and 3 suggests that it may take $\sim 10^5$ yr to achieve equilibrium. There are a dozen or so meteorites with extremely short exposure ages ($< \sim 10^6$ yr), so that it may be feasible to determine the time taken to reach TL equilibrium in an empirical way by looking for a relationship between natural TL and cosmic-ray exposure age for these meteorites.

Natural TL has to be determined in a way which removes effects due to variations unrelated to R and T, such as sample heterogeneity or TL sensitivity differences due to processes described above. The two methods available are (1) to measure the ratio of the low temperature peak (LT) to the high temperature peak (HT) (Fig. 13a), and (2) to measure the equivalent dose (Fig. 13b). The first method presupposes that HT and LT are equally sensitive to the interfering effects, and the second is subject to greater experimental errors such as thermal lag between sample and heating strip (McKeever and Sears, 1980). A plot of equivalent dose against glow curve temperature permits a convenient means of examining the extent of thermal draining (Fig. 13c).

The levels of natural TL in a number of ordinary chondrites are shown in histogram form in Fig. 14 (Sears and Hasan, 1986). Slightly different distributions are displayed by the observed falls and the finds. The falls have preferred natural TL (peak-height ratio) values between 2 and 7, but spread over 2 orders of magnitude and extend down to peak height ratio values of less than 0.1. Meteorites found in the two regions of earth best-suited to their recovery, the Antarctic and the Prairie States of the US, also show considerable spread. This is similar for each of the two sources and skewed to lower values than for the observed falls (~ 0.2 to ~ 3) (Sears and Durrani, 1980; McKeever and Sears, 1980).

The order-of-magnitude difference in natural TL between the falls and finds, is probably associated with differences in terrestrial age. Natural TL levels

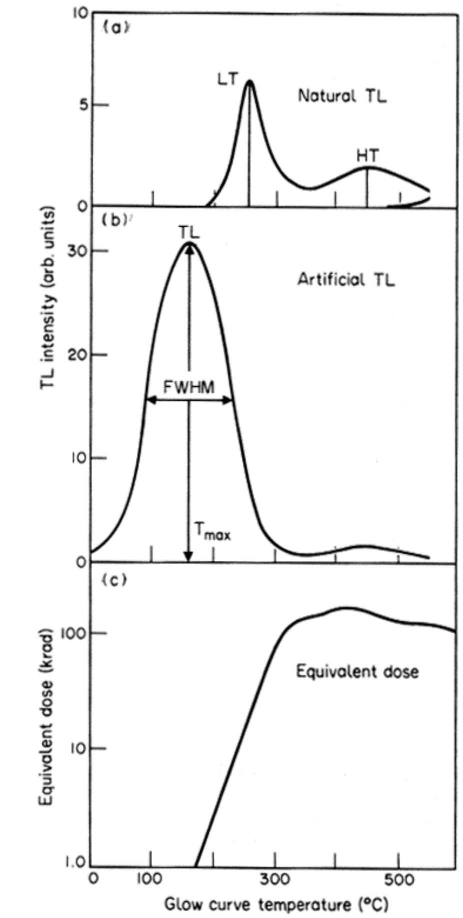

FIG. 13. Methods of data reduction for (a) natural TL and (b) induced TL (artificial TL). (c) The ratios of the curves for natural and induced TL (artificial TL) (after Melcher, 1981a).

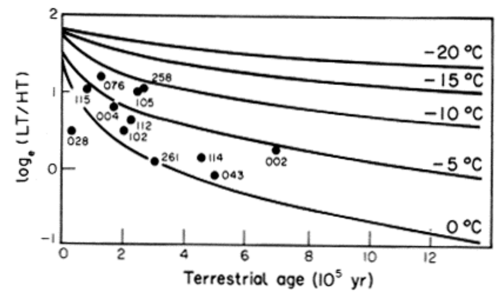

FIG. 15. Natural TL levels in meteorites as a function of terrestrial age. The data points refer to 11 Antarctic samples that plot in the TL vs ^{26}Al trend in Fig. 17 and whose terrestrial ages have been determined using ^{53}Mn, ^{10}Be, ^{26}Al, ^{36}Cl and ^{14}C (Nishiizumi, 1984). Superimposed are theoretical curves for a variety of storage temperatures, according to the theoretical model of McKeever (1982). The data are consistent with the theoretical calculations, assuming effective storage temperatures of 0°C to −5°C (Hasan *et al.*, 1987).

of Antarctic meteorites are compared with terrestrial ages calculated from a variety of cosmic-ray produced isotopes in Fig. 15, while natural TL levels in Prairie State meteorites are compared with terrestrial ages based on ^{14}C in Fig. 16. The difference in times scales covered by Figs 15 and 16 reflects the temperature-dependence of the TL decay process. Theoretical curves calculated by McKeever (1982) suggest storage temperatures for Antarctic meteorites are 0–5°C, while for the Prairie States the effective temperatures are probably 20–25°C. An experimental study of the temperature-dependence of meteorite TL was reported by Melcher (1981a).

While much of the spread in natural TL values reflects differences in terrestrial age, this is clearly not the only factor involved. Several meteorites which fell within the last 250 yr have natural TL as low as those with very large terrestrial ages. This is apparent both

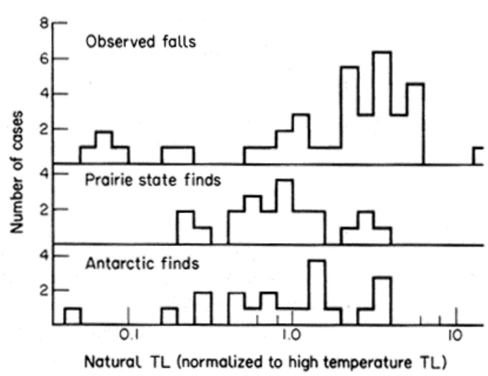

FIG. 14. Histograms of the natural TL levels in meteorites that were observed to fall within the last 250 yr (top, McKeever and Sears, 1980), meteorites that were found in the Prairie States of the U.S.A. (middle, Sears and Durrani, 1980) and those that were found in the Antarctic (bottom).

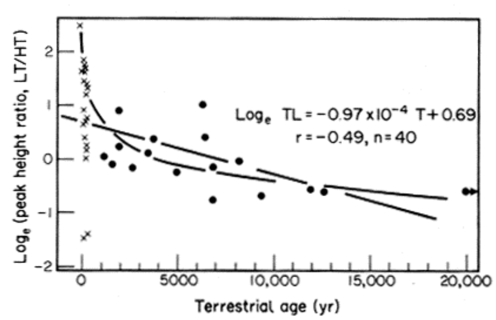

FIG. 16. Plot of natural TL against terrestrial age for observed falls (crosses) and finds whose terrestrial age has been determined from their C-14 contents (dots) (from Sears and Durrani, 1980). The straight line is a least squares fit, the regression equation and parameters are given in the box, assuming first-order decay (equation (2)), while the curve was drawn in by eye to suggest the form expected from second-order decay.

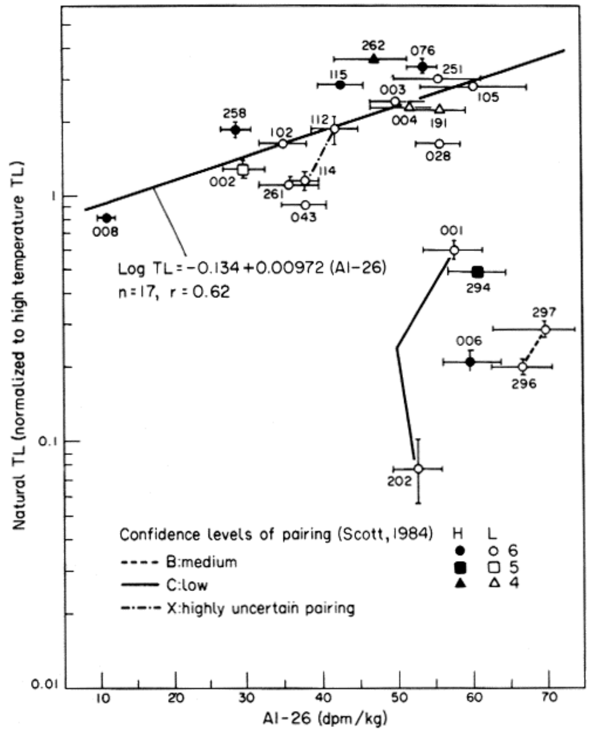

FIG. 17. Natural TL against ^{26}Al for 23 Antarctic meteorites. The H, L, 4, 5, 6 symbols refer to different classes and types, "pairing" refers to individual fragments which may be pieces of a single meteorite which broke up during or after fall to earth. 17 meteorites plot along a trend, of increasing natural TL and ^{26}As, while 6 have natural TL which is much lower than those of the meteorite producing the trend. The low TL samples have suffered recent heating, such as close solar passage or recent shock-heating (Hasan *et al.*, 1987).

in Fig. 15 and in Fig. 17, where natural TL is compared directly with ^{26}Al for 23 Antarctic meteorites (Hasan *et al.*, 1987). While 17 meteorites in Fig. 17 show a correlation between the two quantities, 6 have very low natural TL. Three of these may be low due to recent shock reheating or sampling too close to the fusion crust, but a reasonable explanation for the others is that they passed close to the Sun on the orbit that brought them to Earth.

The temperature (T) of an object d astronomical units (a.u.) from the Sun is given by

$$T = \frac{CB}{d^2 S\delta}\gamma \qquad (5)$$

where C is the solar constant, B the cross section and S the surface area of the object, δ is Stefan's constant and γ the ratio of the absorbed and emitted radiation (typically $\sim$0.5). Assuming plausible figures this becomes

$$T = 278\left(\frac{\gamma}{d^2}\right)^{1/4}. \qquad (6)$$

The important orbital parameter as far as determining natural TL is concerned is the perihelion distance. For the Lost City meteorite, whose fireball was photographed at several locations, the perihelion on was 0.967. A bright meteor whose trial was also photographed by several cameras had a perihelion of 0.722. These perihelia values correspond to temperatures of 236 and 275 K, respectively. If we assume

$$n \propto \exp(E/kT) \qquad (7)$$

then the ratio of trapped electrons for meteorites with perihelion of 0.722 and 0.967 a.u. is very approximately given by

$$\frac{n_{0.722}}{n_{0.967}} = \exp\left(\frac{E}{\mathrm{k}275} - \frac{E}{\mathrm{k}236}\right) \qquad (8)$$
$$= 0.01$$

for a trap depth of $\sim$1 eV (McKeever and Sears, 1980). A two-order of magnitude difference in natural TL is therefore consistent with known variations in perihelia and plausible TL models.

The role of orbital differences in accounting for some of the spread in natural TL values was discussed by McKeever and Sears (1980) and Melcher (1981a), but an experimental investigation of the problem was reported by Hasan and Sears (1987). While there are only three meteorites for which there are photographically-derived orbits, Semenenko

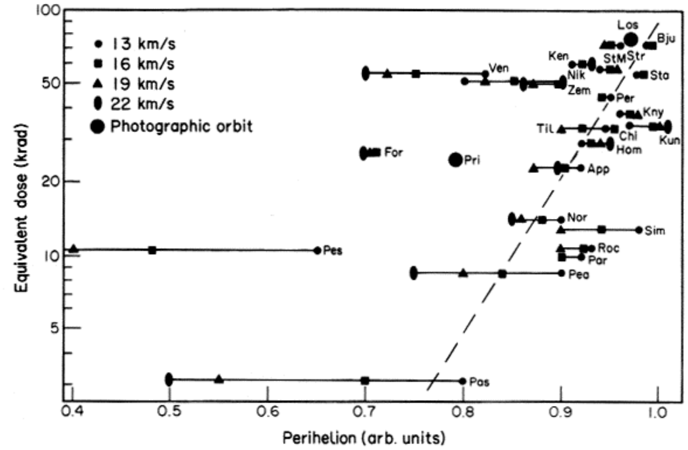

FIG. 18. Natural TL against perihelia, calculated from observed radiants, for 26 meteorites. The calculation assumes a geocentric velocity and four typical values were used, the assumption is more critical for small perihelia. The broken line is that predicted by equation (4) (Hasan and Sears, 1987).

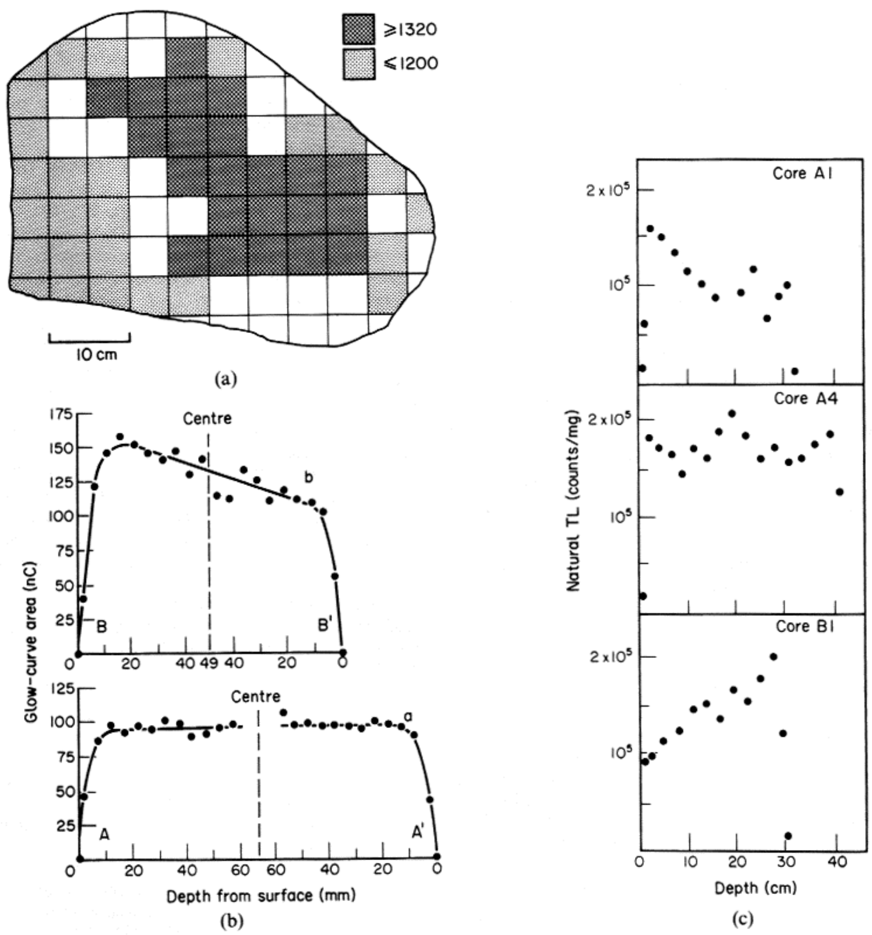

FIG. 19. (a) Natural TL in a 40 × 55 cm slab of the Estacado meteorite (from Sears, 1975). (b) Natural TL variations in two bars removed from the Ucera and Lost City meteorites. The outer 5 mm or so of each bar also shows draining of the TL due to the heat generated by atmospheric passage (from Vaz, 1971). (c) Natural TL along three cores taken from two fragments (A and B) of the St Severin chondrite. Cores A1 and A4 were approximately perpendicular (for the precise orientations, see Lalou *et al.*, 1970, from which the data were taken).

(1975) has calculated a number of orbits based on observed radiants and assumed plausible geocentric velocities. The natural TL of 26 meteorites does correlate with their calculated perihelion (Fig. 18), notwithstanding the uncertainties in the calculation, and is in approximate agreement with the theoretical prediction.

There are other instances in which dose-rate or temperature changes can occur and might be expected to influence natural TL levels. Dose-rate variations due to the attenuation of primary cosmic radiation and build-up of secondary radiation can be expected. The natural TL level is 10–15% higher at the center of a 55 × 40 cm slab of the Estacado meteorite (Fig. 19a; Sears, 1975) and a 50% variation in the TL of the Lost City meteorite was observed over a 10 cm distance (Fig. 19b; Vaz, 1971), both plausibly caused by depth-dependent dose-rate variations. Changes in natural TL by a factor of two occur in two cases samples from the St Severin meteorite (Fig. 19c; Lalou *et al.*, 1970). As yet, however, there is no indication that shielding effects can result in natural TL variations of an order of magnitude, and this effect probably only contributes to the scatter in natural TL levels. The thermal pulse caused by atmospheric passage drains the TL over the outermost 5 mm or so (Fig. 19b), but this effect can be avoided by careful sampling.

A mechanism also exists in which natural TL decays in a poorly understood but extremely rapid means in certain materials. Hasan *et al.* (1986b) found that certain shergottites and the Kapoeta howardite displayed anomalous fading and suggested that it was only affecting samples in which the feldspar is present in the low temperature form. If this is the case, then anomalous fading will not generally be a problem since such meteorites are rare, and, in any event, the process seems to be readily detected by laboratory tests. McKeever has found no evidence for anomalous fading in two ordinary chondrites, Barwell and Saratov (S. W. S. McKeever, private communication) which are known to contain high-temperature (disordered) feldspar (Van Schmus and Ribbe, 1968).

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