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THE THERMOLUMINESCENCE OF METEORITES: A BRIEF 2010 PERSPECTIVE

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Abstract: Early work on meteorite thermoluminescence, influenced by pottery dating and dosimetry applications, demonstrated a relationship between natural thermoluminescence and (1) the orbital perihelion of a meteorite and (2) the terrestrial age (time since fall) of a meteorite. For 14 years natural TL measurements were routinely made on newly recovered Antarctic meteorites to help identify unusual thermal and radiation histories, and to sort them by terrestrial age and perihelion. Two examples of the value of such data are presented, an Antarctic meteorite that underwent a major orbit change prior to fall and the collection mechanics of meteorites at the Lewis Cliff collection site. A second major area of focus for meteorite TL, that has no non-meteorite heritage, is the use of their induced TL to provide an extraordinarily sensitive and quantitative means of exploring metamorphic intensity and palaeothermometry. While especially valuable for unequilibrated ordinary chondrites, these types of measurement have proved useful with virtually every major class of meteorite, asteroidal and planetary. The challenge now is to extend the technique to small particles, micrometeorites, interplanetary dust particles, and cometary particles.

Keywords: Thermoluminescence, Meteorites, Orbits, Terrestrial Age, Metamorphism.

1. INTRODUCTION

Observations of meteorite luminescence date to the very origins of meteorite research. In the first few years of the nineteenth century Edward Charles Howard, in reporting the first modern chemical analysis of meteorites, noted that the Benares meteorite became luminous for nearly a quarter of an hour when heated by an electrical discharge (Howard, 1802). Towards the close of the century, when the Middlesbrough meteorite fell in Yorkshire in 1898, Alexander Herschell wrote that grains of the meteorite, sprinkled on a hot plate, glowed quite distinctly. He correctly suggested that the mineral responsible was feldspar (Herschel, 1899). Through the twentieth century enormous progress was made in understanding solid-state structures and luminescence mechanisms (Harvey, 2005) and many of the basic formulations for thermoluminescence were described (Garlick, 1949). By the 1960s the community was vibrant with studies on the returned Apollo samples and there was a flurry of thermoluminescence research, focusing on such issues as the temperature gradient in the lunar regolith (Walker *et al.*, 1972).

Emerging from the post Apollo era were a variety of studies on the thermoluminescence (TL) properties of meteorites, both the natural TL properties that provide information on their thermal and radiation history, and induced properties that provide information that is essentially of a mineralogical and petrographic nature. The purpose of this paper is to briefly review some of the main features of post-Apollo work.

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2. NATURAL THERMOLUMINESCENCE

The equilibrium level of natural TL in a meteorite is given by the relationship:

$$\frac{\phi}{\phi s} = \frac{1}{1 + \dfrac{s}{\alpha\, R\, exp\left(-\dfrac{E}{kT}\right)}} \tag{2.1}$$

where ϕ (Gy, 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 reciprocal of the mean dose (the dose to fill 1/e of the traps, Gy^{-1}), R is the dose rate (Gy/s), E is the trap depth (eV), k is Boltzmann's constant (eV/K) and T (K) is temperature. Aside from the physical constant, there are two types of variable in **Eq. 2.1**, those that describe the properties of the solid (*s*, *α*, and *E*), and those that describe the environment (*R*, and *T*). The luminescence properties of the solid can be determined by the methods described in Garlick's (1949) book and have been applied to meteorites in several papers (e.g. McKeever, 1980; Akridge *et al*., 2001).

The level of natural TL in a meteorite is determined by the temperature at the perihelion. This can be calculated by the inverse square law and Stefan's law, and is given by

$$T = 279\left(\frac{\varepsilon}{d^2}\right)^{\frac{1}{4}} \tag{2.2}$$

where ε = the ratio of the absorbed radiation to that of the emitted radiation and *d* = distance to the Sun.

Terrestrial age can be determined by measuring the present level of natural TL in a sample and calculating the time required to decay from an assumed extraterrestrial natural TL value to the present level. The required kinetic parameters can be measured experimentally in the laboratory and corrected for ambient storage temperatures for the meteorites. The extraterrestrial natural TL value is determined by averaging the values for a number of recent observed falls. The major unknown is the temperature of decay, which has to be assumed depending on the known history of the sample. Then we have:

$$\frac{d\phi}{dt} = -s\,\phi\, exp\left(-\frac{E}{kT}\right) \tag{2.3}$$

recognizing that several peaks with different E and s parameters are involved.

Thermal and radiation history

Fig. 1 is a schematic diagram showing how natural TL varies throughout the history of typical meteorite (Benoit *et al*., 1991). When deeply buried inside the parent body the level is expected to be low because the only source of radiation is internal radioactivity. While dose rates are low, the duration of irradiation is long. Offset against this, over long time spans internal heating becomes significant and the TL is drained. Once the parent body breaks up, the fragments are small enough to be exposed to cosmic radiation, solar energetic particles near the surface, and galactic cosmic radiation throughout (Eugster *et al*., 2006). In about 10^5 to 10^6 years equilibrium is reached, the final TL level depending on perihelion. For the bulk of the duration of exposure to cosmic radiation (~10^8 years), natural TL levels in meteorites stay close to equilibrium, being interrupted occasionally by stochastic events such as impact shock. Dose rate variations throughout the meteorite seem to cause relatively minor differences in equilibrium level (Sears, 1975a; Vaz, 1971; Lalou *et al*., 1970). This is because attenuation of the primary radiations is counter-balanced by build-up of secondary radiations. The meteorite then undergoes orbital evolution through a variety of possible mechanisms, impact, resonant interaction with Jupiter, and thermal radiation processes (Nesvorný *et al*., 2002), until it encounters Earth's gravity well and falls to its surface. Heating during atmospheric passage is restricted to the outer few millimetres, so the interior is largely unchanged (Sears, 1975b; Bhandari *et al*., 1980; Singhvi *et al*., 1982; Bhandari, 1985; Wagner, 1985). Once on Earth, the natural TL decays to its new equilibrium value that will be lower because of higher temperatures and low cosmic ray dose rates. During this adjustment to the new equilibrium values it is in principle possible to use natural TL to derive a terrestrial age. In the case of Antarctic meteorites there is the complication that there is an addi-

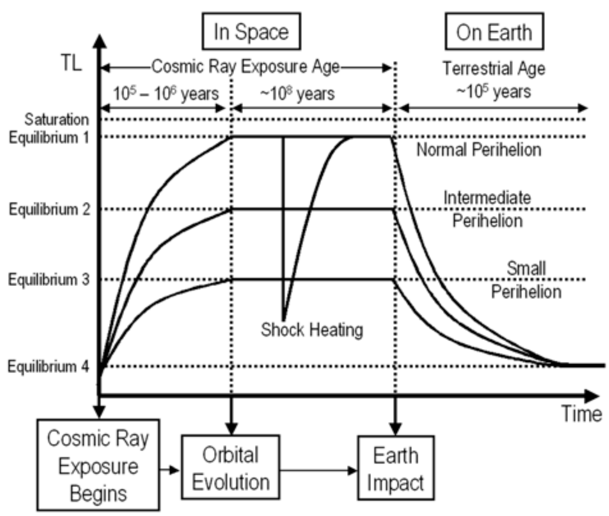

Fig. 1. *Schematic diagram showing the history of natural thermoluminescence levels in a meteorite as it passed through a typical history of formation by break-up of a larger object, exposure to cosmic rays and adjustment to an equilibrium value depending on orbit – this may be interrupted by stochastic evens such as impact shock – and adjustment to a lower value after fall on Earth. (Benoit and Sears, 1993b).*

tional phase of their history in which they are buried in the ice where they are protected from cosmic rays and solar insolation, so that the terrestrial age determined in this case is probably the duration of exposure on the surface (Sen Gupta *et al*., 1997). This complication aside, typical terrestrial ages are 10^4 for hot deserts, 10^5 years for Prairies and other open grasslands, and 10^6 years for Antarctic meteorites.

Orbits and terrestrial age

Several authors pointed out that the natural TL of ordinary chondrites decreases with increasing terrestrial age. Sears and Mills (1974) and Melcher (1981a) studied large numbers of ordinary chondrite observed falls and found this expected decrease. However, for a particular suite of meteorites there was a disappointing lack of agreement between natural TL and terrestrial ages determined by radiocarbon methods. This was remedied in spectacular fashion when the old radiocarbon estimates determined by beta counting (Boeckl, 1972) were replaced with new radiocarbon measurements determined by accelerator mass spectrometry (Jull *et al*., 1980; Sears and Durrani, 1980; Benoit *et al*., 1993a). Benoit *et al.* (1993b) recently summarized the data for meteorites from a variety of find sites, hot deserts (Otto, 1992; Bevan and Binns, 1989), prairies (Sipiera *et al*., 1987), and Antarctica (Cassidy *et al*., 1977; 1992; Cassidy, 2003), and point out that decay followed the expected theoretical curves if mean summer temperatures were assumed for the various sites (30°C, 20°C and 0°C, respectively, corresponding to approximate age spans of 10^3 years, 10^4 years, and 10^6 years, respectively).

Variation in the TL levels of recently fallen meteorites is primarily due to differences in orbit (Melcher, 1981b; McKeever and Sears, 1980; Benoit *et al*., 1991; Benoit and Sears, 1997). In fact, the distribution of natural TL levels for recent falls is very similar to the distribution of perihelia observed for near Earth asteroids with the majority having perihelia of 0.8-1.0 AU (Sears *et al*., 2011). This is also true of the ordinary chondrite meteorites with known orbits. However, the values extend to smaller perihelia, say 0.5 to 0.6 AU, which would account for TL levels being low (<5 krad).

In the light of this scientific background (Sutton and Walker, 1986), and a pilot study in which samples of known ^{26}Al were analyzed (Hasan *et al*., 1987), the Antarctic Meteorite Working group of NASA, NSF, and the Smithsonian Institution arranged for the systematic determination of natural TL in newly recovered Antarctic meteorites. The data appeared in NASA's Antarctic Meteorite Newsletter (now online http://www.curator.jsc.nasa.gov/antmet/amn/amn.cfm). Aluminum-26 is a cosmogenic isotope that decays at about the same rate as natural TL under Antarctic conditions (Hasan *et al*., 1987). Meteorites have been recovered from the Antarctica in a systematic way since 1978, on the order of a few hundred to a few thousand meteorites being returned each year (Cassidy *et al*., 1977; Cassidy, 2003). The collection is noteworthy for the primitive, lunar, and martian meteorites it has returned. The natural TL survey of Antarctic meteorites operated for 14 years and resulted in many primary scientific papers (Benoit *et al*., 1992; 1993a, b, c; 1994; Benoit and Sears, 1993b; 1999), while a similar effort to measure ^{26}Al was performed (Wacker, 1990). A similar program of natural TL measurement is underway in Japan (Ninagawa *et al*., 1998). Because of the different sampling limitations of natural TL and ^{26}Al, not all samples could be analyzed by each technique, but data for 120 common samples were obtained. They are plotted in **Fig. 2**.

The Hasan *et al*. (1987) interpretation of the natural TL vs. ^{26}Al plot was that most meteorites plotted on a line governed by terrestrial age (those with natural TL values >5 krad), but a small number had low natural TL (<5 krad) and high ^{26}Al and had experienced small perihelia. These were assumed to be small meteorites where the enhanced solar energetic particle radiation had driven up ^{26}Al and the higher temperatures had reduced natural TL (Michel *et al*., 1996; Nishiizumi *et al.* 1990). In fact, when natural TL data are compared with terrestrial ages calculated from ^{36}Cl, another cosmogenic isotope with a decay rate on Antarctic meteorite terrestrial age scales (half-life 301,000 years), these low TL meteorites also show a trend with terrestrial age but are decaying rapidly (Benoit *et al*., 1993a, c). This would be consistent with a recent intense radiation at high temperatures so that less stable TL peaks are filled. This idea is testable, since low TL-high ^{26}Al meteorites should have lower temperature TL peaks.

Based on these ideas it is possible to superimpose on the natural TL vs. ^{26}Al plot as it now stands isochrons of equal terrestrial age for a variety of perihelia and thus to

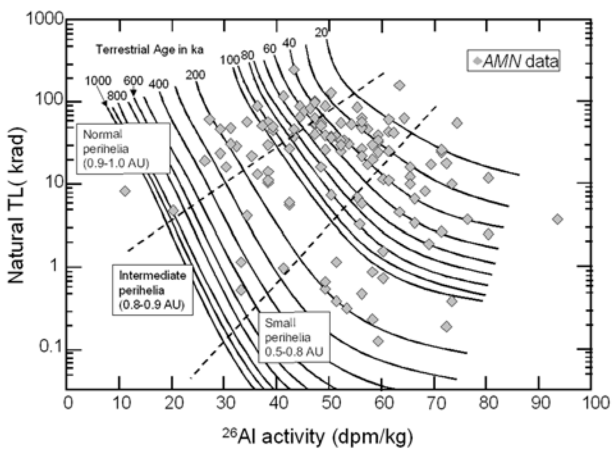

Fig. 2. *The 120 Antarctic meteorites for which both ^{26}Al and natural TL data have been published in the Antarctic Meteorite Newsletter (AMN) interpreted in terms of perihelion and terrestrial age, based on the analyses discussed earlier in this paper. On the basis of these data and our favoured interpretations, it is possible to sort the meteorites by perihelion and terrestrial age. (Sears* et al., *2011).*

sort the meteorites by terrestrial age and orbit (Sears *et al*., 2011).

Instead of monitoring the decay of natural TL as the meteorites adjust to their terrestrial conditions, it is also possible to measure the terrestrial build up in natural TL in locations in the meteorite where it was drained during fall, namely in the fusion crust or within a few millimeters of the fusion crust (Sen Gupta *et al*., 1997; Akridge *et al*., 2000). Heating during passage through the atmosphere will have drained the pre-atmospheric natural TL in this part of the meteorite and the natural TL level measured will reflect terrestrial age. The situation is very similar to that of pottery dating, where atmospheric passage is analogous to firing the pot. Then by determining the dose rate at the place of fall it is possible to determining terrestrial age by dividing equivalent dose by dose rate.

Two illustrations of science resulting from these data are given below; there are many others in the literature.

A meteorite fall with an anomalous orbit

When a field party from Germany visited the Allan Hills field site in Antarctica it was after the area had been thoroughly searched by American teams. Initially they found little. After a three day storm, in which the team was trapped in their tents, they found a large number of meteorites that had weathered out of the ice (Wlotzka, 1990; 1991). The meteorites were distributed along an escarpment with larger meteorite masses at one end of the line, as if they still retained the pattern observed in strewn fields. Perhaps the pattern was retained with the help of a crevasse, the strewn field being blown into the crevasse and relative positions of the meteorites frozen.

Benoit and Sears (1993a) found that virtually all the meteorites recovered by the German field party had natural TL levels about a factor of two higher than the previously highest levels observed among recent falls. After considering various possibilities, they concluded that these were pieces of a single meteorite that had fragmented in the atmosphere, and that the parent meteorite had recently changed orbit. These meteorites were displaying the levels of natural TL expected for a meteorite with a perihelion of ~1.2 AU, where the relatively cooler temperatures would sustain the higher natural TL levels. Apparently, the Earth had captured this meteorite before its natural TL could adjust to the new orbit, say within 10^5 years. The dynamics of asteroids in the inner solar system is a matter of considerable interest, and this discovery adds a new perspective to the process (Bottke *et al*., 2006). Apparently in some cases orbital changes can be accomplished on short timescales.

Ice collection mechanics at the Lewis Cliff

The natural TL survey data also provides insights into the mechanisms by which ice concentrates the meteorites at the find sites. It is widely believed that meteorites that fall on the ice sheets, become buried below the surface due to later snowfall and sinkage of the meteorite, and are carried towards the continental margins by the pressure of ice overload at the South Polar Dome, the coldest region of the ice covered continent. While normally the ice can escape to the sea, towards the west is a range of mountains, the Transantarctic Mountain Range, which traps the ice and forces it upwards where it is ablated and evaporated. In the process, meteorites accumulate on the blue ice fields created at the mountain bases.

In the case of the Lewis Cliff Ice Tongue, ice is being pushed in a narrow field northwards against a moraine (Cassidy, 1990). Half way along the tongue is a morphological and geophysical discontinuity, marked by firn and a step in the ice. Large numbers of meteorites accumulate on the tongue, concentrated mostly towards the western side (**Fig. 3**). If these were static collection surfaces, meteorites of all terrestrial ages and thus natural TL values, would be randomly mixed along the length of the tongue. However, the distribution of natural TL levels for the meteorites is not random (Benoit *et al*., 1992). Meteorites with "young" terrestrial ages, with natural TL >8 kGy, occur in the upper and low tongue, but avoid a region just south of the discontinuity. On the other hand, "old" meteorites (natural TL <30 krad) plot uniformly across the tongue regardless of the discontinuity. Intermediate meteorites (30-80 krad) show intermediate behaviour. Benoit *et al*. (1992) interpreted this to indicate that the ice sheet had faulted at the discontinuity and that the southern tongue was turning up and ablating and abrading as other ice fields do when they encounter a mountainous obstruction. Thus only old, deeply buried meteorites are being exposed where old ice is brought to the surface. The small perihelion meteorites (<5 krad) are randomly scattered about the ice field, their natural TL levels being determined by orbit rather than terrestrial age.

Natural TL studies of extraterrestrial materials other than ordinary chondrites

Despite the recovery of large numbers of meteorites in Antarctica, it still came as a surprise when the first lunar meteorite was recovered (GRL, 1983). We now know of over 50 meteorites on Earth that were ejected from the Moon, most recovered from Antarctica but some also recovered from the hot deserts of the world. Natural TL measurements have been used to estimate the meteorites were exposed to radiations in space, and to link meteorites ejected by a common ejection event. Most of the transit ages determined are very short, typically <2,500 years (Sutton and Crozaz, 1983; Benoit *et al*., 1996).

While not involving measurements on meteorites, but on limestone from the target rocks, the age on the impact that created the Barringer Crater in Arizona has been determined by natural TL methods (essentially pottery dating methods wherein the dose absorbed is divided by dose rate to obtain an age). Barringer Crater is the first recognized and most famous of the meteorite impact

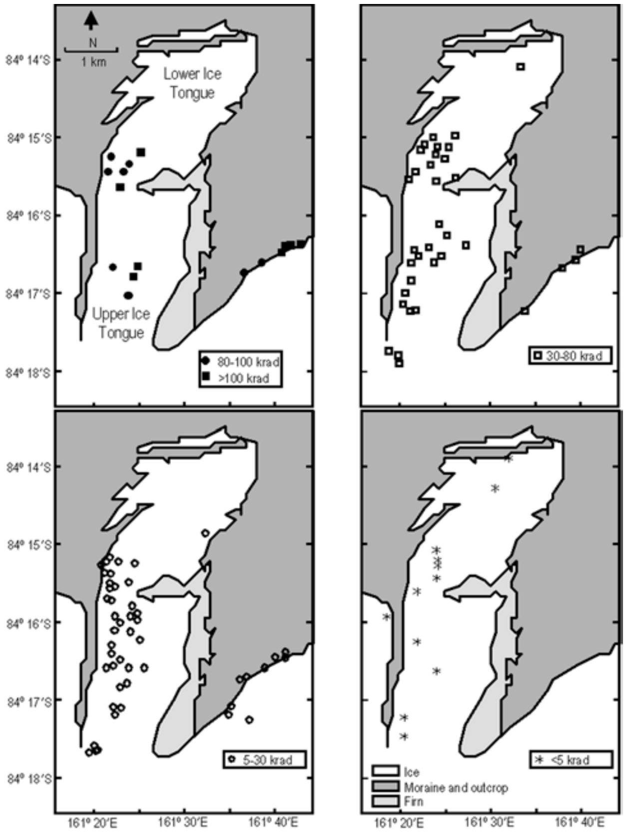

Fig. 3. *Distribution of meteorite finds at the Lewis Cliff Ice Tongue in Antarctica, separated by natural TL level. Ice is being pushed towards a moraine at the north and has faulted half way along its length. The fault's outcrop at the surface is marked by firn, unconsolidated snow. Meteorites with low natural TL (large terrestrial ages) are spread uniformly across the field, while high natural TL meteorites (small terrestrial ages) avoid the area south of the fault. Intermediate natural TL meteorites display intermediate behavior. This is interpreted as indicating that the ice is turning up at the fault line exposing old meteorites, as the ice is ablated and evaporated. Apparently, the rate at which old meteorites are brought in from depth is greater than rate of fall (Benoit* et al.*, 1992).*

craters on Earth. Calculating dose rates from concentrations of U, Th, K, and from cosmic radiation, and using natural TL to measure absorbed dose, Sutton (1985a and 1985b) calculated an age 49,000±3000 years for the crater. This is about twice the previous best estimate and is now widely accepted. The Lonar Crater in India, which is unusual for being an impact in basalt, was also dated by natural TL techniques by Sen Gupta *et al.* (1997). They found that the mean age of three pieces of impact glass was 52,000±6000 years.

3. INDUCED THERMOLUMINESCENCE

When studies of the thermoluminescence of meteorites were beginning, several authors in Russia and Switzerland thought that the radiation damage would create defects that would increase in number as radiation exposure continued. Komovsky (1961) found that several meteorites had induced TL levels that increased with K-Ar age, as if beta decay from ^{40}K was creating traps. Pursuing this idea, Liener and Geiss (1968) made a larger study and confirmed this observation. Houtermans and Liener (1966) investigated the idea that induced TL could be related to cosmic ray exposure age, the cosmic radiation producing traps. Sears (1980) tested these ideas by exposing meteorite samples to α, β, γ, and proton radiation levels well in excess of those expected in nature and found no change in induced TL. Instead, the trends observed by earlier workers were due to some of the meteorites (those with low K-Ar ages) being heavily shocked, the shock converting the luminescent mineral (feldspar) to glass. Low K-Ar meteorites are noted for their large numbers of shock effects (Heymann, 1967).

Metamorphism levels

The idea was thus established that induced TL could be used to determine the amount of feldspar in meteorite samples. This has profound importance for meteorite studies. While most ordinary chondrites have suffered high levels of parent body metamorphism (solid state alteration by high temperatures), there are a few where this is negligible or minimal (Dodd *et al.*, 1967; Van Schmus and Wood, 1967). The unmetamorphosed meteorites are especially important as they provide a record of solar system material prior to its accumulation on asteroidal parent bodies. There is a gradation from unmetamorphosed to heavily metamorphosed which are described in terms of petrographic types 3-6, the type 3 sometimes being referred to as unequilibrated and the types 4-6 as equilibrated reflecting the state of chemical equilibration within and between minerals (Dodd *et al.*, 1967; Van Schmus and Wood, 1967).

Arguably the most notable effect of metamorphism is to convert the glass characteristic of primitive ordinary chondrites, into large clean crystals of feldspar. Glass has no TL, feldspar has considerable TL so the measurement of induced TL in these meteorites provided a quantitative and extraordinarily sensitive means of assessing metamorphic alteration (Sears *et al.*, 1980). In most cases, cathodoluminescence images provide a means of understanding the mineralogical changes controlling the induced TL properties (Akridge *et al.*, 2004). Several research groups used this new means of assessing metamorphism within the type 3 ordinary chondrites in their efforts to understand early solar system processes (e.g. Grady *et al.*, 1982; McNaughton *et al.*, 1982; Huss, 1990). The technique is being systematically applied to Japanese Antarctic meteorites (Ninagawa *et al.*, 2000).

Fig. 4 shows the existing data for the induced TL (normalized to the Dhajala meteorite referred to as "TL sensitivity") of ordinary chondrite meteorites, separated by petrographic type. This plot represents all the available data, with shocked meteorites, meteorites known to be brecciated, and outliers for a given meteorite removed. In view of the large range of metamorphism detected in type 3 ordinary chondrites, they have been divided into 3.0-3.9 (Sears *et al*., 1980), and even smaller divisions at the lowest end of this range (3.00, 3.05, 3.10, 3.15) (Grossman and Brearley, 2005). The petrographic subdivisions of type 3 ordinary chondrites is sufficiently well established that other techniques are now available to assign these types and the scatter at the low end reflects some of the uncertainties inherent in studies of the highly heterogeneous meteorites. Some may have been misclassified.

Fig. 4 effectively reflects the history of feldspar by crystallization from the primary glass. The glass crystallizes throughout the type 3, and coarsens throughout the type 4 to 6. Coarsening does not affect TL sensitivity since it does not affect the solid-state properties of the minerals. However, there must be other factors causing the range within the type 4-6 that would be worth investigating.

Palaeothermometry

In a PhD thesis and a conference abstract, Pasternak *et al*. (1976) and Pasternak (1978) showed that the shape of the feldspar glow curve was governed by its crystallography. In particular, for feldspars crystallizing at low temperatures the Al-Si backbone was ordered, while for feldspar crystallizing at higher temperatures the backbone was disordered, the Al-Si being randomly arranged along the chain. The order-disorder transformation occurs at about 500-600°C for feldspars of ordinary chondrites composition, and can be monitored by X-ray diffraction measurements (McKie and McConnell, 1963). Pasternak showed that for ordered feldspars the induced TL peak was narrower and at lower glow curve temperatures, than for disordered feldspar.

In comparing the induced TL peak shapes for type 3 ordinary chondrites, Guimon *et al.* (1984, 1985) found two clusters, one with peak temperatures and widths at ~100°C and ~100°C, respectively, and another with peak temperatures and widths at ~175°C and ~150°C (**Fig. 5**). Presumably these data indicate the presence of ordered feldspar in one group (the low temperature group) and disordered feldspar in the other. Laboratory heating of a meteorite in the low cluster would move it to the high cluster, the transition being ~600°C. Significantly, meteorites in the low cluster have TL sensitivities equivalent to type 3.2-3.4, while meteorites in the upper cluster are type 3.5-3.9. The types 3.0-3.1, which have little if any feldspar, tend to scatter on the diagram. Thus we have a paleothermometer, suggesting that the middle of the type 3 metamorphic spectrum corresponds to metamorphic temperatures of ~500°C. This is consistent with rather approximate petrographic estimates. Independent confirmation that induced TL peak shape was reflecting thermal history came from an unexpected direction discussed below.

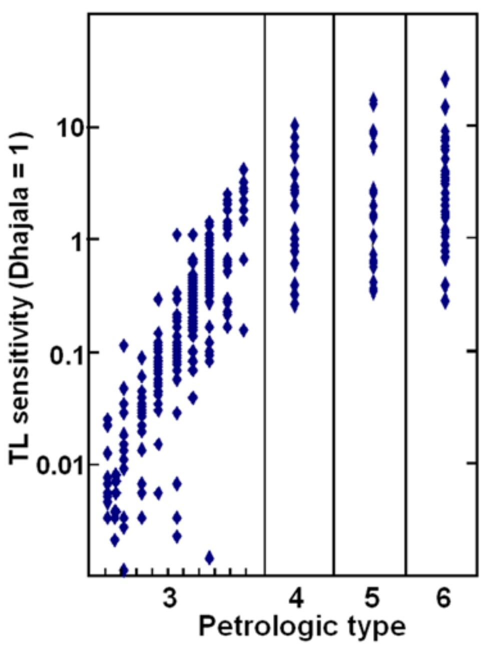

Fig. 4. *The intensity of the low temperature TL peak induced in a sample by a laboratory test dose (and normalized to that of the Dhajala meteorite) is referred to as "TL sensitivity". The dynamic range of TL sensitivity displayed by the type 3 ordinary chondrites is large, especially when compared with the other types, and clearly relates to the metamorphic alterations being described by the petrologic types. Thus subdivision into types 3.0-3.9 was proposed by Sears* et al. *(1980).*

Secular variation in the meteorites falling to Earth

The H chondrites are one of the major divisions of ordinary chondrites, the others being L and LL, these terms reflecting iron and metal content. They are noted espe-

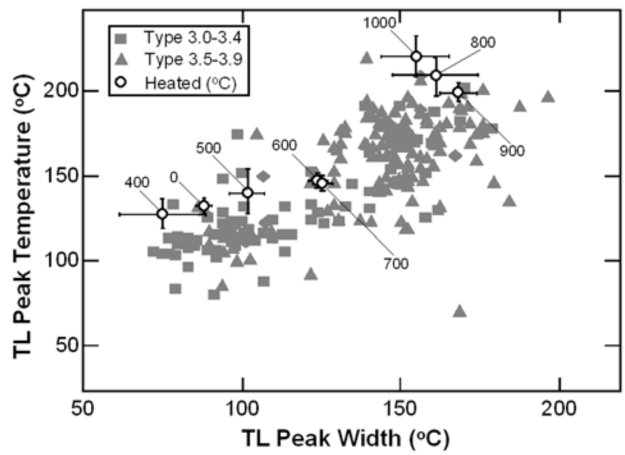

Fig. 5. *In addition to displaying large variations in TL sensitivity, type 3 ordinary chondrites show clustering in the peak shapes, as shown on a plot of peak temperature against peak width. This is also associated with thermal history, since laboratory heating of a chondrite plotting in the lower cluster will move it to the upper cluster. (Guimon* et al.*, 1984).*

cially for a very sharp peak at 8 Ma in the histogram of cosmic ray exposure ages suggesting a relatively recent major break-up event produced this class of meteorite. Looking systematically at peak shapes for equilibrated meteorites, Benoit and Sears (1992; 1993a; 1996) found that H chondrites with 8 Ma cosmic ray exposure ages that were recovered from the Antarctic had slightly higher peak temperatures than H chondrites with 8 Ma cosmic ray ages recovered from the rest of the world. The main difference in these two populations is terrestrial age, Antarctic meteorites typically falling ~40 ka ago, the others falling <250 years ago. Post metamorphic cooling rates can be calculated from Ni profiles in the Fe-Ni alloy taenite, and Benoit and Sears found that the H chondrites with higher peak temperatures cooled more rapidly than those with low peak temperatures. This is to be expected if the relative amounts of ordered and disordered feldspar (which are driving the induced TL peak shapes) are determined not just by peak metamorphic temperatures, but also by cooling rate and closure temperature. This is, of course, a common situation in interpreting mineral equilibria. The bottom line is that not only can subtle differences in thermal history be detected by a close analysis of induced TL peak temperatures, but that there is a secular variation in the nature of the meteorites reaching the Earth from their asteroidal source. Such a secular variation might result from different parts of the disrupted asteroid being placed on different Earth-bound orbits. This is an issue that has often been discussed, but generally met with skepticism because of the weathered state of Antarctic meteorites (Dennison and Lipschutz, 1987; Koeberl and Cassidy, 1991; Wolf and Lipschutz, 1992). Weathering is not an issue with TL peak shape data or metallographic cooling rate estimates.

Shock effects and induced TL

Subsequent to the study of Sears (1980), that showed shock intensities of ~30 GPa could decrease induced TL levels by a factor of about 100, Haq *et al* (1988) made a study of a large number of naturally shocked ordinary chondrites and found a similar range of induced TL levels. Shock is so prevalent in ordinary chondrites that the petrographic and mineralogical effects have been studied at some length and shock classification schemes have been developed (Stöffler *et al*., 1988; 1991). Crystal structures are changed, iron and sulfide phases form eutectic melt veins, and crystalline feldspar is melted and flows through the veins. It is undoubtedly this damage to feldspar that causes the decrease in induced TL levels and the shock levels inferred from the TL decrease are consistent with shock levels inferred for mineralogical changes.

A special case of shock effects in meteorites that can be followed by TL studies are the martian meteorites which are discussed below.

Induced TL studies of extraterrestrial materials other than ordinary chondrites

Induced TL studies on meteorites other than ordinary chondrites have followed similar lines to those on ordinary chondrites. While >90% of the meteorites observed to fall are ordinary chondrites, equally important are the small classes like CO and CV carbonaceous chondrites (Weisberg *et al*., 2006), martian meteorites (once known as the SNC meteorites) (Papike *et al*., 2009), basaltic meteorites (also known as HED, after the Howardite, Eucrite and Diogenite meteorite classes, which are thought to be ejecta from the large asteroid, Vesta) (Keil, 2002), and lunar meteorites (Korotev, 2005). Mention might also be made of lunar samples returned by the Apollo program (Heiken *et al*., 1991).

The CO and CV meteorites have been sorted into petrographic types, much like ordinary chondrites (Sears *et al*., 1991a; 1995). The major difference between these C chondrites and the ordinary chondrites is that the peak shape parameters indicate that which TL sensitivities suggest levels of alteration equivalent to high type 3 ordinary chondrites, metamorphism occurred below 500°C. There are thus significant differences in the thermal histories of the different chondrites classes.

In the case of the martian meteorites, the component that is feldspathic in composition and has the outline of crystalline feldspar, is in fact an unusual isotropic glass called maskelynite (Milton and deCarli, 1963). In these cases, shock has apparently caused the conversion of feldspar to glass by a solid state transformation without melts being involved. Maskelynite is an extremely unstable glass that readily crystallizes. As a result, Shergottites placed in an oven for, say, one hour at 900°C, show a 100-fold increase in induced TL levels (Hasan *et al*., 1986). This suggests that since formation of the maskelynite, these meteorites have suffered little if any thermal events. The structure of the glow curve provides information on the conditions of shock.

The eucrites, while essentially basalts, have also experienced parent body metamorphism that can be quantified using induced TL measurements (Batchelor and Sears, 1991a). The mineral responsible for the TL emission is still feldspar, but the range in TL sensitivity is smaller than for the ordinary chondrites. The cause for the variation of induced TL in eucrites is not the formation of crystals from glass but the diffusion of Fe^{2+}, a luminescence quencher, out of the feldspar (Batchelor and Sears, 1991b). This was readily confirmed by cathodoluminescence observations. Again induced TL peak shapes can be used for their insights into thermal history and indicate that their metamorphism was at low temperatures (Sears *et al*., 1997). The howardites have TL properties reflecting their brecciated nature, being a mixture of eucrite and diogenite components.

Lunar meteorites and Apollo lunar samples can be sorted into classes on the basis of their induced TL properties, reflecting the nature and amount of feldspar, and their mixing and their thermal history (Batchelor *et al*., 1997). Regolith cores show variations in induced TL properties with maturity (amount of surface gardening), reflecting the destruction of feldspar by micrometeorite bombardment that converts surface material into agglutinates, which are irregular glassy fragments on dust.

4. THERMOLUMINESCENCE STUDIES OF SMALL PARTICLES

A final class of extraterrestrial materials is the small particles, which are becoming especially important with spacecraft missions returning tiny amounts of new extraterrestrial materials to Earth (Zolensky *et al*., 2000). For many decades, interplanetary dust particles have been collected by stratospheric aircraft flights and micrometeorites have been recovered from the ice of Antarctica (Grün *et al*., 2001). The challenge for thermoluminescence studies of such particles – as with most techniques – is their tiny size and weak TL signals. Sedaghatpour and Sears (2009) recently obtained signals from four 100-200 μm micrometeorite particles, and Craig and Sears (2009) obtained signals from six comparable size matrix particles from the type 3.0 Semarkona meteorite. The major conclusion was that while the bulk of these materials is amorphous and difficult to characterize, the TL signal was being produced by forsterite, not feldspar. Forsterite is becoming an increasingly important component of primitive materials (Crovisier *et al.,* 1997; Kloeck *et al*., 1989; Koike *et al*., 2002; Steele, 1986; Zolensky *et al*., 2006). Most recently, Craig and Sears (2010) have found a way to reproducibly and reliably obtain data from 10-15 μm particles of the matrix of the Semarkona meteorite with the hope that it will eventually provide insights into the thermal history of interplanetary dust particles and cometary particles returned from the Stardust mission.

5. CONCLUDING REMARKS

Over the last four or five decades, studies of the natural and induced properties have now been performed on most of the major forms of extraterrestrial material and will soon be extended to micrometeorites and cometary dust. Something of value has been obtained for most of the meteorite classes. In the case of type 3 ordinary chondrites, induced TL measurements are critical in their study since by enabling their petrographic classification and the data are now in wide use. In the case of natural TL studies, the decision of the community was to include these measurements in the preliminary examination of Antarctic meteorites in order to spot meteorites with unusual thermal and radiation histories and provide information on orbits and terrestrial age. In some cases, new, unexpected, and novel insights were possible like the secular variation in the H chondrites flux, or the ice concentration mechanisms.

These applications are based on sound physical and mineralogical understanding, and are supported by cathodoluminescence observations, laboratory measurements, and measurements on analogous terrestrial minerals. However, there is still much to do. Studies of small particles are in their infancy, and there is a need to understand the reasons for the spread in TL sensitivity within the types 4, 5, and 6, especially the type 4 ordinary chondrites and how this related to the properties of the type 3 ordinary chondrites. Where exactly is the boundary between type 3 and type 4 and is there any evidence for metamorphic differences within type 4. There is also much to do understanding cosmic ray production systematics in meteorites, and whether, as recently suggested (Biswas, 2009), natural TL data in the high temperature region of the glow curve can be used to derive cosmic ray exposure ages.

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