The interpretation of natural thermoluminescence data for meteorites: Theoretical basis and practical application. P.H. Benoit and D.W.G. Sears, Dept. Chemistry and Biochemistry, University of Arkansas, Fayetteville, AR 72701, USA. Email: pbenoit@comp.uark.edu.

Introduction. Natural thermoluminescence (TL) data are available for a large number of meteorites, mainly through the survey of Antarctic meteorites [*e.g.*, 1-3]. The interpretation of these data is dependent on both the terrestrial and extraterrestrial environment experienced by the meteorite. In response to recent discussions at the Pilanesberg Workshop of Extraterrestrial Materials from Cold and Hot Deserts, we address the quantitative aspects of TL data interpretation. The natural TL of most meteorites can be quantitatively described by treatments that have been in the literature for over 50 years [4]. Rare meteorites (such as eucrites [5]) whose TL is influenced by a phenomenon termed "anomalous fading" do not follow classical behavior and are not discussed here.

Theory. The equilibrium natural TL level in a given TL "trap" population can be described by:

$$\frac{n_o}{N} = \left[\frac{s \cdot R \cdot \exp(-E/kT)}{\ln(2) \cdot r} + 1 \right]^{-1} \qquad \text{(Equation 1)}$$

where n_o = the number of filled traps, N = the total number of traps, R = the radiation dose required to fill half of the total traps, k = Boltzmann's constant, T = temperature, and r = dose rate [4]. TL decay in meteorites is a second order process [6], with the frequency factor, $s = s_1 n/N$, where s_1 is the first order frequency factor. The non-equilibrium behavior of a population of traps can be described by:

$$\frac{dn}{dt} = \frac{r(N-n)}{R_0} - s \cdot n_o^2 \exp\left(\frac{-E}{kT}\right) \qquad \text{(Equation 2)}$$

where the first term describes build-up and the second term describes TL decay. The glow curve of an ordinary chondrite reflects contributions from at least eight trap populations [6] and typically the TL at a given temperature is governed by at least two trap populations.

Interpretation. The interpretation of natural TL data depends on the assessment of the variables in Equation 1. Uncertainties in these variables are more important than uncertainties in the measurement of the TL signal.

Values of E and s. Values for E and s are estimated by glow curve peak fitting [6], sometimes coupled with thermal decay experiments [7]. The primary uncertainty in these values is caused by overlap between traps, and uncertainties are greatest for the high temperature TL (>300 °C). In the low temperature portion of the glow curve (<300 °C) equilibrated ordinary chondrites exhibit similar E and s values [6], and trap overlap is minimal, so that uncertainties in the theoretical treatment are at a minimum.

Values of dose rate, r. Environmental doses vary in time and spatial distribution [8], but since high energy galactic cosmic rays produce most of the natural TL in meteorites and lunar samples [9] the degree of variation in the $<10^5$ years represented by TL equilibrium is minimal. Shielding during irradiation in space appears to have minimal influence on natural TL levels for meteoroid bodies less than a few meters in diameter [9]. Radiation dose rates on Earth are orders of magnitude less than in space, about 20-30% being derived from decay of radionuclides in the sample, and the remainder from products of galactic cosmic ray interaction with the atmosphere.

Values for temperature, T. TL buildup time-scales are many orders of magnitude shorter than orbital period, and TL levels in space approximate equilibrium and thus perihelion temperature and, to a much lesser degree, surface albedo and emissivity [10]. Temperature is the primary determinant of equilibrium TL levels and decay rates for meteorite finds (Fig.1). The high temperature (>300 °C) portion of the TL glow curve has TL trap populations with higher E and s values, and has lower TL decay rates and higher equilibrium levels at any temperature.

General Interpretations for Meteorite Finds. The average annual temperature of a meteorite recovery site can be used to produce TL buildup and decay curves for that site for meteorites whose initial TL levels resemble those of modern falls. Individual meteorites can then be placed in one of four categories of terrestrial and space history (Fig. 2). TL ranges for Antarctic meteorites are given as an example (Fig. 1). History I: Very high TL levels (>100 krad) suggest non-equilibrium of nature TL for a meteorite in the inner solar system, with high radiation doses and/or low temperatures in space (perihelion >1.1 AU). A short terrestrial exposure (<20,000 years) history (<20,000 years) is also required to explain high TL levels [*e.g.*, 11]. History II: Moderately high TL levels (50-100 krad) imply a short exposure history (<50,000 years) on Earth relative to the time needed to achieve equilibrium TL levels and thus can imply a short terrestrial age. However, they can also indicate lower environmental temperatures than assumed in production of the decay curve (*e.g.*, Fig. 1). History III: (1-50 krad) Near-equilibrium TL levels convey no specific interpretation, but meteorites with these levels are the best

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candidates for having high terrestrial ages relative to other meteorites at the site or had perihelia between 0.95 and 1.0. <u>History IV</u>: Below-equilibrium natural TL levels (<1 krad) imply reheating in space within the last 10^5 years (the buildup time for perihelion = 1.0 AU) prior to fall, typically by close solar passage, and a short terrestrial exposure history (<20,000 years). Like History II, interpretation of terrestrial history is complicated by uncertainty in environmental temperature (Fig. 1).

Specific Applications. <u>Meteorites from hot deserts (*e.g.*, Sahara, Australia).</u> Natural TL in the low temperature (<300 °C) portion of the glow curve is typically completely drained in these meteorites and thus interpretations must be based on the high temperature portion of the glow curve, which is more difficult to model [*e.g.*, 12]. Due to the low equilibrium TL levels, meteorites of History IV can be difficult to resolve from History III meteorites (Fig. 2). Equilibrium levels are achieved in a few thousand to a few tens of thousands of years.

<u>Meteorites from cold deserts (*e.g.*, Antarctica).</u> The low temperature (<300 °C) portion of the glow curve is typically well-preserved, while the high temperature portion of the glow curve is largely unaffected by TL decay. Equilibrium levels are achieved in a few hundred thousand years at surface environments ($T \approx 0$ °C). However, meteorites in cold deserts can experience extreme terrestrial thermal histories, including periods of burial in the ice at temperatures < -10 °C (Fig. 1) [13].

We have gathered natural TL data for over 1200 Antarctic meteorites representing ~753 independent falls. On the basis of theoretical decay curves (Fig. 1), 8% are candidates for History I and 64%, 21% and 7% are candidates for Histories II, III and IV, respectively. These proportions are very similar to those observed for modern falls (14%, 63%, 18%, 4%, for Histories I, II, III, and IV, respectively) [10]. At least 15% of Antarctic meteorites have terrestrial ages less than a few tens of thousands of years. The similarity of the Antarctic and modern fall data, in consideration of terrestrial age data [*e.g.*, 14], suggests that most Antarctic meteorites have spent significant portions of their terrestrial histories buried in the ice, rather than exposed on the surface [13] and thus that storage in Antarctica has had minimal affect on natural TL levels. However, at the Upper Ice Tongue at Lewis Cliff meteorites of History II are more prevalent (~70%, 69 out of 98 independent falls), suggesting that this ice field has been collecting meteorites for longer periods of time than other ice fields, including other fields in the Lewis Cliff region [1,2].

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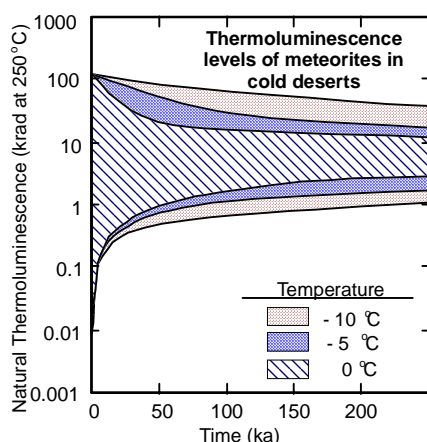

Fig. 1. Natural TL levels at 250 °C in the glow curve of meteorites from cold deserts at various environmental temperatures. Calculated using Equation 2, using the range exhibited by modern falls for t = 0 [10] and TL parameters for equilibrated ordinary chondrites [6]. Curves are the summation for two TL trap populations with E = 1.33 and 1.43 eV, and s = 9.2 x 10^{12} and 5.3 x 10^{13} s^{-1}, respectively.
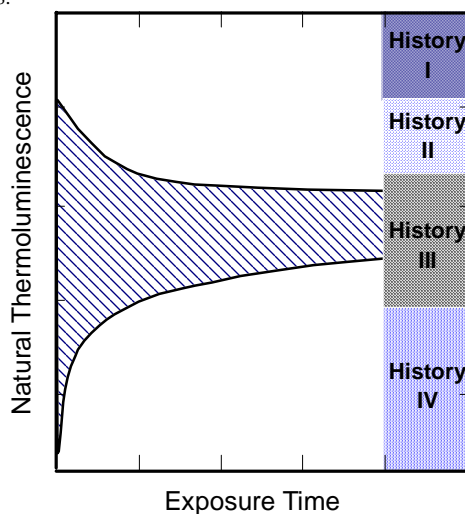

Fig. 2. Schematic of TL decay for meteorites on Earth. Shown at right are divisions of the TL curves into space and terrestrial irradiation and thermal histories. An example of quantitative axes is given in Fig. 1