

**GLIMMERINGS FROM THE PAST: THERMOLUMINESCENCE STUDIES OF SAMPLES OF THE MOON.** Derek W. G. Sears<sup>1,2</sup> <sup>1</sup>Aarkansas Center for Space and Planetary Sciences, University of Arkansas, Fayetteville, Arkansas 72701. <sup>2</sup>Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701. (dsears@uark.edu).

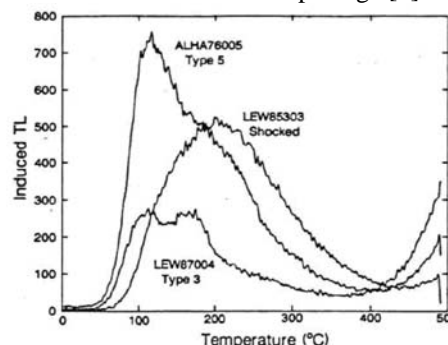
**Introduction:** While mineralogy, petrography, and elemental and isotopic analysis provide considerable information on the nature and history of lunar materials, thermoluminescence (TL) provides information complementary to these techniques as well insights into thermal and radiation history not otherwise available [1]. In fact, some phenomena that are poorly evaluated by other techniques are not only readily observed but quantified to high precision with TL, a case in point being metamorphism of primitive chondrites [2]. In view of the upcoming lunar exploration program, we here review 30 years of progress in understanding lunar materials through their thermoluminescence.

**Thermoluminescence:** Literally meaning the light released upon heating, TL results when ionizing radiation excites electrons to metastable energy sites in a crystal lattice. Heat releases the trapped electrons; the temperature required depending on the trap depth relative to the conduction band. Luminescence is released as the electron finds an appropriate pathway to the ground state, typically through d-d transitions in transition metals. Either the level of natural TL can be measured – which relates to radiation exposure and natural thermal draining – or a test dose can be applied to previously drained material and the induced signal provides information on the nature of the material. Any process that affects crystallinity or trace element chemistry will affect induced TL, metamorphism being an excellent example.

**Natural Thermoluminescence:** Lunar samples, like their terrestrial analogs, e.g. basalts, undergo fading at a rate that is not dependent on trap depth and thus normal kinetics. Nevertheless, this “anomalous fading” can be quantified in the laboratory and the absorbed dose calculated. Using calculated or measured dose rates, the duration of exposure can be calculated from the absorbed dose. In the case of lunar meteorites, this is assumed to equal the time during which the meteorites were in transit from Moon to Earth, typically  $10^4$  years (but ranging from  $<1$  to  $>100$  ka), the natural TL being drained during ejection from the Moon [3 - 6]. In the case of samples collected from the surface of the Moon, it would be equal to the time that has elapsed since the rock was excavated from depth by impact.

It is also probable that an especially low natural TL level for lunar samples would indicate recent heating,

just as 5% of the basaltic and related meteorites have low natural TL due to close solar passage [5].

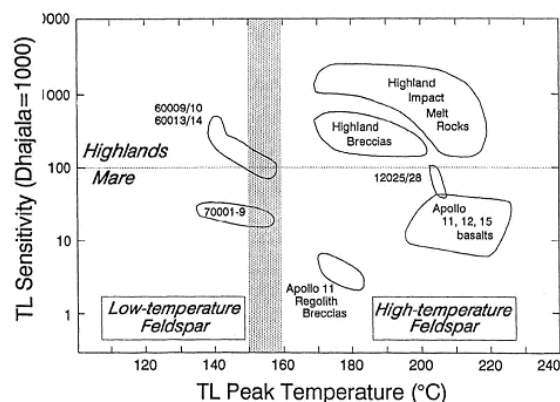


**Fig. 1.** An illustration of the influence of natural processes on the induced TL properties of extraterrestrial basalts. Type 3 and type 5 refer to different levels of metamorphism experienced by these two asteroidal basalts, while “shocked” refers to a sample that underwent an intense impact shock event.

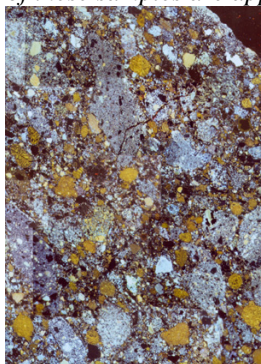
**Induced Thermoluminescence:** Batchelor and Sears observed that the eucrites, basalts from asteroid Vesta, show a factor of 10 range in the maximum intensity of induced TL (normally referred to as “TL sensitivity”), which correlates with petrologic (metamorphic) type as determined from mineralogical and petrographic data. The TL data helped resolve the question of whether there were two discrete types of eucrite (equilibrated and unequilibrated, [6]) or whether there was a continuous series [7]. The TL sensitivity data confirmed the latter [8]. When samples of different metamorphic history are identified by their differing TL sensitivities, it is clear that the metamorphic event predated the brecciation. Such was the case with the LEW85300 eucrite [9].

Aside from TL sensitivity, other properties that provide information on the thermal history of the samples are (1) the temperature of laboratory heating at which induced TL emission is at its peak, and (2) the width of the induced TL peak at half maximum (Fig. 1). The luminescence of all the samples mentioned here is due to feldspar. Laboratory heating experiments and X-ray diffraction studies indicate that induced TL peak shape is governed by the degree of order of the Al, Si chain in the feldspar structure, ordered (low-temperature) feldspar having narrow induced TL peaks at low heating temperatures, while disordered (high-temperature) feldspars have broad induced TL peaks at high temperatures. This

behaviour has been observed in feldspar of almost any origin and occurrence, terrestrial feldspars, lunar samples, and ordinary chondrite meteorites [9]. The low-to-high transformation in lunar feldspars appears to be around 800°C. A consideration of both TL sensitivity and the peak temperature and width can provide a handle on several aspects of sample history and thus have taxonomic value (Fig. 2).



**Fig. 2.** The field of lunar rocks and soils illustrates the value of induced TL properties in systematically identifying physical histories. The relative proportions of highland and mare material and the thermal history of these samples are apparent.



**Fig. 3.** A cathodoluminescence image about 5 mm across of the matrix of a lunar highland breccia showing how the technique brings out both the variety of textures and compositions. The yellow objects are virtually all crystalline lunar spherules often likened to meteoritic chondrules.

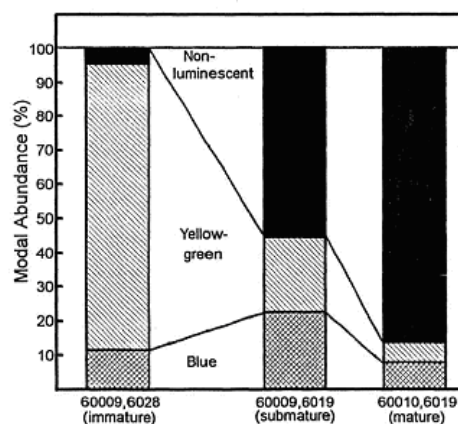
**Cathodoluminescence:** Subjecting a polished section of a sample to an electron beam activates the luminescent centers. It is thus possible to observe and analyse the minerals and phases being detected by TL. Three examples of the application of CL follow.

**Asteroidal Basalts (eucrites) and Metamorphism.** The explanation for the dependence between induced TL properties and petrographic type is readily apparent from an examination of their CL images. The low petrologic type eucrites contain feldspar with a patchy

brown luminescence while high petrologic types contain feldspar with a bright yellow CL. Electron microprobe analysis shows that this difference is caused by Fe diffusing out of the feldspar during metamorphism.

**Lunar Highland Regolith Breccias.** The overall texture of clasts embedded in a matrix is readily apparent, but more spectacular are the crystalline spherules often likened to meteoritic chondrules, that have bright yellow CL (Fig. 3).

**Lunar regolith.** The lunar regolith shows dramatic changes in the CL properties of its constituents with maturity as the yellow CL of crystalline feldspar is lost as the mineral is converted to non-crystalline forms (Fig. 4).



**Fig. 4.** The proportion of phases with different cathodoluminescent properties changes markedly with maturity in lunar soils. Thus this technique provides a novel means of quantifying regolith evolution.

**Concluding Remarks:** Luminescence techniques provide secondary information that reflects properties that can usually be determined by other techniques, such as optical and electron microscopy, or elemental and isotopic analysis. However, it can usually be applied rapidly and economically to large numbers of samples in survey mode and can sometimes provide quantitative information not possible by other means.

**References:** [1] Batchelor et al. (1997) *JGR (Planets)* **102**, 19,321. [2] Sears et al. (1980) *Nature*, **287**, 791. [3] Sutton and Crozaz (1983) *GRL*, **10**, 809. [4] Benoit et al. (1996) *MAPS* **31**, 869. [5] Sears et al. (1991) *GCA* **55**, 3167. [6] Reid and Barnard (1989) *LPS* **10**, 1019. [7] Takeda et al. (1983) *Proc. 8<sup>th</sup> Symp. Antarct. Meteorit.* 181. [8] Batchelor and Sears (1991) *Nature*, **349**, 516. [9] Sears et al. (1997) *MAPS* **32**, 917. [10] Symes et al. (1998) *MAPS* **33**, 13. [11] Akridge et al. (2004) *JGR*, **109**, Issue E7, CiteID E07S03.