GLIMMERINGS OF THE FUTURE: A POTENTIAL ROLE FOR THERMOLUMINESCENCE AND RELATED STUDIES IN ADDRESSING KEY CURRENT QUESTIONS IN LUNAR SCIENCE.
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Introduction: In a recent multi-authored publication, Brad Jolliff reviewed the current state of knowledge of the Moon (Table 1), stressing the need for an integrated and interdisciplinary approach, and listing key current questions [1]. At the LPSC this year I reviewed thermoluminescence (TL) and cathodoluminescence (CL) related research on lunar samples [2]. I pointed out that while mineralogy, petrography, and elemental and isotopic analysis provide considerable information on the nature and history of lunar materials, TL not only provides information complementary to these techniques but also unique insights into thermal and radiation history not otherwise available [3]. Here I discuss the potential role of TL and CL in these addressing some of key questions.

Table 1. Key current questions of lunar science*

Q1. What were the sources and magnitude of heating to drive secondary magmatism? • How was heat transferred from Th, U, K-rich crustal reservoirs to the mantle? • What was the role of large-scale crustal insulation? • How are the different suites of plutonic rocks related to specific or localized geologic terrains and to the global geochemical asymmetry?
Q2. Was there a significant late veneer of accretion (post-core formation/early differentiation)?
Q3. What and where are the most concentrated, extensive, and readily extractable deposits of H and ^{3}He? • What is the origin and mineralogical or physical form, thickness, and concentration of H or H_2O ice deposits in permanently shadowed craters at the poles? • Is H at the poles a viable resource? • Where are the best sites for such facilities located?
Q4. What was the initial thermal state of the Moon?

* From ref. [3]. Four questions in ref. 3 are not included.

Metamorphic history of basaltic materials (Q1): 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, [4]) or whether there was a continuous series [5]; TL data confirmed the latter [6] (Fig. 1). 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 [6]. TL data do provide a picture of the post formation thermal environment for basalts and similar rocks that help in addressing Q1.

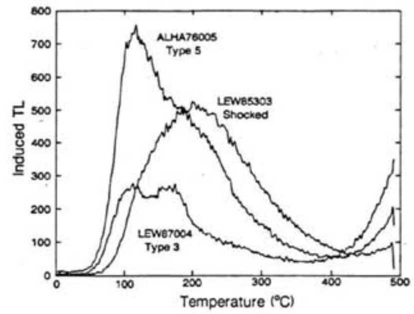

Fig. 1. *An illustration of the influence of natural processes on the induced TL properties of extraterrestrial basalts. Type 3 and type 5 refer to different levels of metamorphism experienced by these two asteroidal basalts, while "shocked" refers to a sample that underwent an intense impact shock event.*

The explanation for the dependence between induced TL properties and metamorphism is readily apparent from an examination of 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 Fe diffusing out of the feldspar during metamorphism causes this difference.

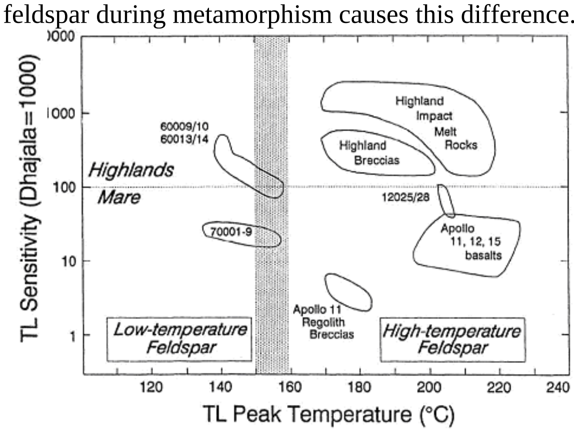

Fig. 2. *The field of lunar rocks and soils illustrates the value of induced TL properties in systematically identifying physical and thermal histories. The relative pro-portions of highland and mare material and the thermal history of these samples are apparent.*

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. 2). 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 behavior has been observed in feldspar of almost any origin and occurrence, terrestrial feldspars, lunar samples, and ordinary chondrite meteorites [7]. The low-to high transformation in lunar feldspars appears to be around 800^{o}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).

Accretionary and shock history (Q2): Luminescence observations could be part of understanding the properties of late accretional veneers.

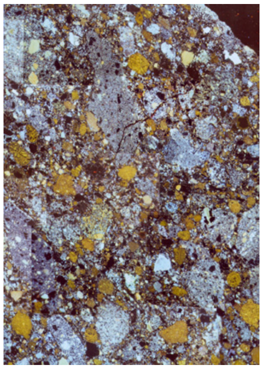

Fig. 3. *A cathodoluminescence image about 5 mm across of the matrix of a lunar highland breccia showing how the technique brings out both the variety of textures and compositions. The yellow objects are virtually all crystalline lunar spherules often likened to meteoritic chondrules. From [8, see also 9].*

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). Thus this techniques provides a novel means of quantifying regolith evolution [3].

Environmental issues (Q3): Probably the most common application of TL outside planetary science is to radiation dosimetry. This has received application to lunar studies in the determination of Moon-Earth transit times [10 – 12]. In the case of samples collected from the surface of the Moon, space exposure times could be determined that would be equal to the time that has elapsed since the rock was excavated from depth by impact. As far as exploration is concerned, the application of TL to determining the radiation environment of the lunar surface would be a relatively straightforward. TL dosimetry is used routinely for astronaut safety.

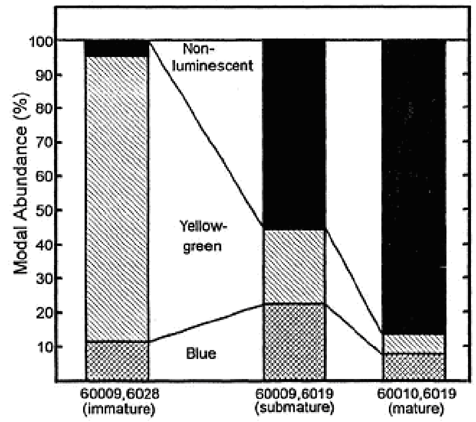

Fig. 4. *The proportion of phases with different cathodoluminescence properties changes markedly with maturity in lunar soils. Thus this techniques provides a novel means of quantifying regolith evolution. From [3].*

Initial thermal state of the Moon (Q4): The present thermal flux from the crust can determine from TL profiles in lunar cores. A value of 4 K/m was obtained [13]. This quantity can be used in thermal models to help estimate the initial thermal state of the Moon.

References: [1] Jolliff (2006) Preface. In *New Views of the Moon*. [2] Sears (2008) *LPSC* **39**, #1801. [3] Batchelor et al. (1997) *JGR (Planets)* **102**, 19,321. [4] Reid and Barnard (1989) *LPS* **10**, 1019. [5] Takeda et al. (1983) *Proc. 8th Symp. Antarct. Meteorit.* 181. [6] Batchelor and Sears (1991) *Nature* **349**, 516. [7] Sears et al. (1997) *MAPS* **32**, 917. [8] Akridge et al (2004) *JGR*, **109**, Issue E7, CiteID E07S03. [9] Symes et al. (1998) *MAPS* **33**, 13. [10] Sutton and Crozaz (1983) *GRL*. **10,** 809. [11] Benoit et al. (1996) *MAPS* **31**, 869. [12] Sears et al. (1991) *GCA* **55**, 3167. [13] Hoyt et al. (1971) *Proc. 2nd Lunar Sci. Conf.*, 2245.