THE LUMINESCING LUNAR REGOLITH.

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We have examined three thin sections from the Apollo 16 double drive tube 60009/60010 using cathodoluminescence (CL) petrography. The observed CL intensity, as assessed visually from mosaics of photographic prints covering the entire sections, is governed primarily by maturity. Mature regolith from 4 cm depth has relatively low CL intensity, while immature regolith from 53 cm has relatively high CL intensity and submature regolith from 29 cm depth displays intermediate intensities. We suggest that these differences reflect progressive destruction of the CL phosphor (feldspar) by regolith working and is consistent with our earlier suggestion that thermoluminescence sensitivity variations provide a new quantitative means of evaluating regolith maturity. We found that unshocked monomineralic feldspar grains exhibit green CL, possibly due to Fe^{2+} acting as an activator, while recrystallized feldspar in lithic clasts exhibits blue CL, which may result from higher sodium concentrations. Notably, not all recrystallized feldspar in clasts exhibits blue CL. Our previous thermoluminescence (TL) results indicated that the most "primitive" lunar highland material was found in immature soil samples. Our present data suggest that the primitive component is monomineralic feldspar grains which dominate the TL (and CL) signal in immature soil samples. The blue-luminescing clasts, which are larger and thus more resistant to destruction during regolith gardening, dominate the TL signal in mature soils.

Introduction. It is clear that regoliths and regolith processing have been important in the history and evolution of extraterrestrial samples [1]. It also seems that interpretation of asteroid reflectivity data, our only source of direct information about asteroid compositions, may require a knowledge of regolith processes [2] and it has been suggested that regolith processes may account for some of the important properties of chondritic meteorites (*e.g.* the formation of chondrules [3] and the metal-silicate fractionation [4]). Since the best regolith samples available to us are among the lunar samples [5], and since we have shown that CL petrography affords new and unique insights into the thermal history of extraterrestrial samples [6], we have examined the CL properties of three thin sections from drive tube 60009/10. We also made electron microprobe analyses of the CL phosphors to help interpret the CL data.

Methods and results. The samples studied include 60010,6019 (~4 cm depth; mature), 60009,6019 (~29 cm depth; submature), and 60009,6028 (~53 cm depth; immature). Photomosaics of the cathodoluminescence from these three thin sections were made using a Nuclide Luminoscope operated with a beam energy of 15±1 keV, 7±1 mA beam current, 1cm × 0.7cm elliptical beam, and a magnification of 50× Exposure times ranged from 45 seconds for the brightly luminescing immature sample to 1 minute for the duller, more mature sample. Photographs were taken using Fujicolor 1600 film (developed with the commercial C-40 process) and mosaics of the prints assembled to cover the entire section. Chemical analyses of luminescent grains were made using the Cameca Camebax scanning electron microprobe at JSC and the data reduced according to a PAP matrix correction program.

We found that (1) the overall level of CL intensity, as assessed qualitatively from the CL mosaics produced and the exposure times required to produce suitable images, decreased as maturity increased (see Fig. 1) and (2) there are two distinct luminescing phases, namely monomineralic feldspar grains which exhibit green luminescence, and the feldspathic phases in clasts, which either luminesce blue or green. Grains emitting green or blue CL have FeO concentrations of ~0.2 wt% and MnO concentrations << 0.01 wt%, while grains showing blue CL have significantly higher sodium concentrations. Feldspar grains in our sections which exhibit features indicative of strong shock (strong undulatory extinction or diaplectic glasses) are generally non-luminescent as is also the case for phases other than feldspar (*e.g.*, pyroxene) and glass fragments and spherules.

Discussion. Studies of the CL of synthetic plagioclase feldspars indicate that the various CL colors sometimes result from the presence of transition metal activator ions. A greenish-yellow CL could be produced by doping synthetic feldspar with either Fe^{2+} (0.x-1.0 wt% FeO) or Mn^{2+} (0.0x wt% MnO), while 0.05-1.0 wt% TiO_2 can produce a blue CL peak [7]. The FeO concentrations in the green luminescing monomineralic feldspar grains in our sections is in the appropriate range for Fe^{2+} to act as a CL activator, whereas the MnO content is generally far below activation levels. Thus, it is possible that Fe^{2+} is the major CL activator in all of these grains.

The luminescence properties of the lithic clasts in our sections are much more complex than those of the monomineralic grains. Petrographically similar clasts sometimes had different CL properties even within a single section. For example, several RNB/POIK suite clasts [8] in 60009,6019 (submature) display very different CL properties. The matrix of a large RNB (~ 2.5 mm) displays light green/yellow CL similar to that of several monomineralic feldspar grains within the clast. This CL is also similar to that of the monomineralic feldspar fragments seen in the coarse-grained basal unit which were derived from relatively pristine rocks of the ANT suite [9].

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Furthermore, the single-crystal grains in this clast have sharp grain boundaries (as seen both optically and in CL) which also suggests their relict nature. In contrast, the feldspar of a nearby ~2 mm long RNB is very fine-grained displaying obvious recrystallization texture and emits bright blue luminescence.

In general, blue CL appears to be associated with the recrystallized lithologies while green luminescence is associated with "pristine" monomineralic feldspar or relict feldspar grains in clasts. The cause of the blue CL in recrystallized feldspar is uncertain. Divalent europium is an efficient activator in anorthite and produces a deep blue luminescence, however the required concentrations are ~200 µg/g Eu^{2+} [10]. This concentration has not been observed in lunar feldspars [11]. A few analyzed grains contained ~0.05 wt% TiO_2, which is at the low end of the concentration range for Ti^{4+} activation, but this concentration is not typical for blue-luminescing feldspar. Several authors (*e.g.*, [12]) have suggested that blue CL in plagioclase results from lattice defects, although it is unlikely that recrystallization of impact melt would result in many lattice defects. Since the blue grains appear to have higher Na concentrations (compared to green grains), then perhaps it is their more albitic character that produces the blue CL.

Cathodoluminescence and thermoluminescence (TL) are complementary techniques, being derived from closely related physical processes in the same phosphors. In our previous TL studies of bulk samples from Apollo 16 cores [13,14] we found that induced TL intensity (sensitivity) decreased as a function of sample maturity, which we interpreted as reflecting destruction of feldspar phosphors during regolith working. The decrease in overall CL intensity as a function of maturity parallels that of the TL decrease and supports our earlier conclusion. The TL peak temperature in the glow curve increased as a function of maturity and we suggested this was caused by progressive disordering of feldspar during regolith reworking. The TL apparatus is biased towards blue luminescence and we thus suggest that the relatively modest drop in TL sensitivity as a function of maturity reflects the fact that the blue luminescing feldspar in some of the clasts is less affected by regolith reworking than the isolated green luminescing monomineralic feldspar grains. The observed increase in the induced TL peak temperature is probably produced by the same process. We suggest that the green luminescing monomineralic feldspar grains, which dominate the immature sample (Fig. 1) are predominantly ordered, reflecting their igneous origin and slow post-crystallization cooling history. As these grains are destroyed and rendered non-luminescent during regolith reworking, however, the feldspar in the larger clasts begins to dominate the induced TL signal. These larger clasts are not produced by regolith reworking but instead may have been derived from the melting or alteration of pre-existing rock by large impact events, and thus would be expected to be wholly or partially in the disordered form. Therefore, the present observations generally agree with our previous conclusions on TL peak temperature shifts as a function of soil maturity, except that, rather than reflecting conversion of feldspar from the ordered to disordered state, the shifts in TL data are probably derived from the preferential destruction of ordered feldspar in these samples.

Summary and Conclusions. The overall CL intensity of sections from three Apollo 16 drive tube samples depends on the regolith maturity of the samples, reflecting the destruction of the CL phosphor (feldspar) by regolith working. This is consistent with our earlier suggestions that thermoluminescence sensitivity variations provide a new quantitative means of evaluating regolith maturity. There are two distinct sources of CL in our soil samples, namely, monomineralic feldspar and feldspar in clasts. We suggest that progressive changes in luminescence properties of bulk soil samples reflect the preferential destruction of the former during regolith reworking.

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Fig. 1 CL Phase Abundance

Legend: ■ Non-Luminescent, ■ Yellow-Green, □ Blue. Y-axis: Modal Abundance (vol %), 0% to 100%. X-axis: 60009,6028 (immature); 60009,6019 (submature); 60010,6019 (mature).