FIVE DECADES OF THERMOLUMINESCENCE STUDIES ON LUNAR SAMPLES: FIRST RESULTS OF NASA'S UNIQUE FORTY-SIX YEAR EXPERIMENT AND ITS IMPLICATION FOR RESOURCE PROSPECTING ON THE MOON. A. Sehlke[1], D. W. G. Sears[1], and the ANGSA Science Team, [1]NASA Ames Research Center and Bay Area Environmental Research Institute, Moffett Field, California 95035, USA. alexander.sehlke@nasa.gov.

Introduction: We are interested in the natural thermoluminescence (TL) of the lunar regolith because of its ability to determine the thermal and radiation history in which these samples were located. As such, natural TL may be useful for prospecting cold traps on the Moon that have sequestered resources relevant for NASA's Artemis program, such as water [1]. Several groups have proposed the development of TL instruments for lunar and Martian science and exploration purposes [2-4].

In 1972 NASA placed Apollo 17 regolith samples in long-term storage, some at room temperature and some at -20 ºC, and in view of the upcoming return of humans to the Moon, recently made these samples available to researchers through its Apollo Next Generation Sample Analyses Program (ANGSA) [5]. Since these samples were the subject of TL studies in 1976 [6,7], NASA has effectively performed a 46-year experiment enabling us to study the TL stability and the kinetics of lunar regolith. Such studies are essential if we aim to fulfill the promise of natural TL for the applications mentioned earlier. We recently performed our first measurements on these newly available samples, and here we describe our first look at the results.

Experimental: We used the modified Daybreak Nuclear and Medical TL apparatus used for previous studies [8], refurbished in 2020 to improve vacuum and gas lines and include new safety measures. Our day-to-day standard is basalt from the Blue Dragon flow at Craters of the Moon, Idaho. It has TL properties similar to the lunar regolith and is calibrated against our primary Dhajala standard, which is too bright to use as a day-to-day standard for lunar samples. We routinely resolve our glow curves using the well-known TL theory [9] and the Solver routine in Excel [10]. We report data for two samples, 76240,45, a sample collected from the shadow of a boulder at station 6 [11], and 70180,8, a sample from a sunlit location near the site of the deep drill core [12]. Figures 1a and 2a show views of the sites.

Results: The glow curves for these two sites within the Taurus-Littrow valley are shown in Figures 1 and 2. Several first-order observations are worth mentioning:

(1) Apollo 17 samples removed from its natural environment and brought to Earth nearly 50 years ago still retain a strong natural TL signal. On average, the observed TL intensity is about 1/5 that of a type 3 H-chondrite (Dhajala).

(2) The natural TL of both sampling sites are different. The large band of luminescence present between 200 ºC and 300 ºC in the glow curve of sample 76240,48 is completely missing in the glow curve for sample 70180,8. The glow curve shape for 76240,45 consists of apparently two peaks, one at 250 ºC and one at and one at ~415 ºC, while the curve for 70180,8 consists of a single peak at ~440 ºC. The glow curves for both sides are diagnostic of major differences in the thermal history of the two sites, even after the samples were removed from their locations nearly five decades ago.

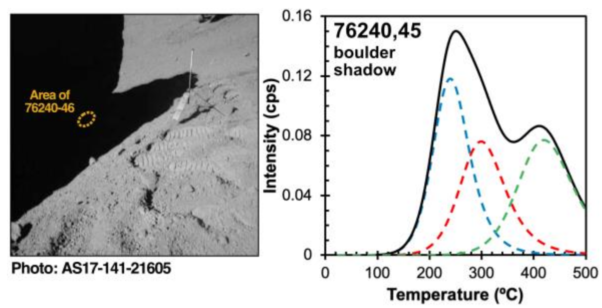

Figure 1. ***Left:*** **Apollo sample 76240,45 was collected inside the shadow of boulder 4 at station 6.** ***Right:*** **Measured glow curve (black solid line) for sample 76240,45 stored at room temperature. TL readout begins ~110 ºC with two maxima located at ~250 ºC and 415 ºC. Glow curve analysis reveals three underlying peaks (dashed lines) with separate TL parameters** ***E*** **(trap depth in eV) and** ***s*** **(frequency factor). TL intensity of Dhajala reference standard is 1.**

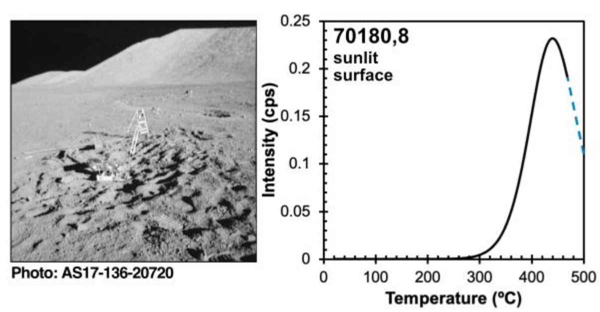

Figure 2: ***Left*****: Apollo sample 70180,8 was collected right-center in this image ~3 meters away from the Apollo deep drill core location.** ***Right*****: The measured glow curve (black solid line) for the sample stored at room temperature. TL readout begins ~270 ºC with one maximum located at ~440 ºC. Glow curve analysis reveals that the glow curve is composed of a single peak (dashed line). TL intensity of Dhajala reference standard is 1.**

Discussion: We stress that these data not only reflect current conditions at the collection site, but they represent integrated conditions over many years, probably ~10^5 years or more, the exact time depending on the kinetics of natural TL and whether the TL levels have reached equilibrium. Thus, it is arguable that this method may be uniquely suited for resource prospecting.

For example, Durrani et al. [6,7] argued that it is possible to determine effective surface temperatures and duration from these data. They suggested that the shaded sample had an effective storage temperature of 256 K and duration (time to equilibrium, thus lower limit) of 6.5 x 10^4 years, while the sunlit sample had an effective storage temperature of 371 K and duration of 3.9 x 10^4 year.

However, these calculations include assumptions on the decay or fading of the TL signal since the samples were collected. For example, in the case of Durrani et al. [6,7], TL fading over a period of ~3 years was observed to be on the order of ~40 to 50 % for low-temperature peaks (e.g., 100 to 300 ºC range).

We can now compare our glow curves to the ones measured in the 1970s because of NASA's decision to keep samples safely stored under monitored conditions for nearly five decades, enabling us to do a unique "46-year experiment" to better constrain the TL properties and their (fading) kinetics in lunar samples.

Figure 3 compares the TL glow curves from Durrani et al. [6,7] and ours. Because of differences in the apparatus used in both studies, we compare the data by curve matching the shapes of the glow curves. For the shaded sample, there appears to have been considerable decay separating them: Over the last 46 years, the samples have lost an additional ~20% of their original luminescence at low glow curve temperatures. On the other hand, the curves for the sunlit samples are nearly identical. Our results demonstrate that the kinetic parameters of glow curves in lunar samples are not uniform, meaning that fading of low temperature and high-temperature peaks cannot be treated equally, for example.

Suppose the low-temperature decay observed over 46 years is purely thermal. In that case, we have a unique 46-year experiment that should result in a much-improved estimate for the kinetic parameters than provided by Durrani et al. [6,7]. However, before we conclude, we must need to check for thermal profiles around the boulder, which we will be able to do since NASA has made available to us many samples from the boulder shadow. In short, the sample used by Durrani et al. [6,7] may have come from a different location or depth in the shadow than ours. Second, we must correct for non-thermal fading. Curve matching should eliminate this effect, but detailed measurements should enable it to be better understood and quantified. Third,

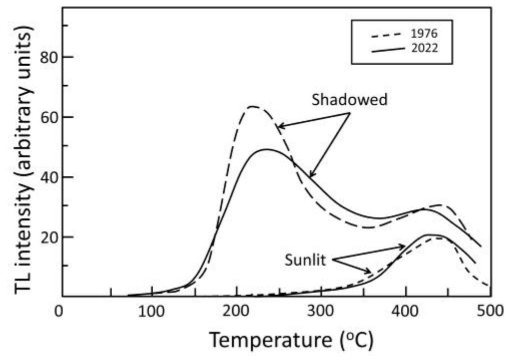

Fig. 3. Comparison of the present glow curves with those obtained 46 years ago by ref [6,7]

NASA is about to provide us samples that were stored in a freezer at -20 ºC, so we have 46-year experiments for samples stored at two different temperatures (room temperature and -20 ºC) that will enable us to identify, characterize and quantify thermal fading/decay.

Conclusions: The data provided in this abstract is the first look at the TL levels of Apollo 17 samples after nearly 50 years, but it is clear that our central conclusion is firm: Natural TL is highly sensitive to surface temperature integrated over perhaps ~10^5 years or more. This makes it a powerful tool for finding cold traps on the Moon and thus provides a method for resource prospecting of temperature and time-dependent volatiles (e.g., H_2, ^3He, H_2O, CO, CO_2, CO_4, SO_2, F_2, Cl_2).

Our second, somewhat tentative conclusion is that the low-temperature natural TL of shaded regolith appears to have undergone considerable decay over the last 46 years. Suppose this is not due to a thermal profile or another unknown cause under the boulder. In that case, we have a 46-year kinetics experiment that will help quantify natural TL kinetics and enable improved estimates of localized surface conditions (i.e., temperature & radiation history) on the Moon (or Mars).

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