The Apollo 17 Regolith: Induced Thermoluminescence Evidence for Formation by a Single Event ~100 Million Years Ago and Possibly the Presence of Tycho Material.

Alexander Sehlke and Derek W. G. Sears

Bay Area Environmental Research Institute, NASA Ames Research Center, Moffett Field, California 95035, USA.

Corresponding author: Alexander Sehlke
Email: Alexander.Sehlke@nasa.gov
Version: 01 – Oct - 2023
Journal: *JGR – Planets ANGSA Special Issue*

Abstract

We explored the geological history of the Taurus-Littrow Valley at the Apollo 17 landing site through the induced thermoluminescence (TL) properties of regolith samples collected from the foothills of the Northern and Southern Massifs, from near the landing site, and from the deep drill core taken in proximity to the landing site. The samples were recently made available by NASA through the Apollo Next Generation Sample Analysis program, in anticipation of the forthcoming Artemis missions.

We found that the two samples from the foothills of the massifs exhibit induced TL values approximately four times higher than those of the valley samples. This observation is consistent with their elevated plagioclase content, indicating their predominantly highland material composition. Conversely, the valley samples display induced TL values characteristic of lunar mare material. The samples from the deep drill core demonstrate uniform induced TL properties, despite originating from depths of up to 3 meters. Notably, one of the samples from the lower section of the deep drill core presents anomalous induced TL readings. This anomaly coincides with elevated levels of low-potassium KREEP, along with reduced quantities of anorthositic gabbro and orange glass, and could be due to the traces of phosphate minerals. Alternatively, this observation raises the possibility that this sample contains Tycho impact material.

The induced TL data is consistent with the regolith, extending to a depth of at least 3 meters, having been deposited by a singular event approximately 100 million years ago. This timing aligns with the hypothesized formation of the Tycho crater.

Plan Language Summary

We studied the geologic history of the Taurus-Littrow Valley through the induced thermoluminescence (TL) properties of Apollo 17 regolith samples. Our investigation focused on samples that were collected from the foothills of the Northern and Southern Massifs, from near the landing site, and from the deep drill core taken in proximity to the landing site.

We found that samples from the foothills of the massifs have TL levels four times higher than those from the valley floor. We attribute this difference to their differing plagioclase content, whereby the TL of foothill samples is comparable to highland material, and valley floor TL is comparable to mare material. The induced TL properties in the deep drill core are mostly uniform. However, one of the samples within the lower section of the deep drill core exhibits anomalous induced TL levels. This coincides with elevated levels of low-potassium KREEP, along with reduced quantities of anorthositic gabbro and orange glass, which could be due to traces of phosphate minerals. Alternatively, this sample may contain Tycho impact material.

Our TL data suggest the valley floor regolith was deposited by a single event approximately 100 million years ago, aligning with the hypothesized formation of the Tycho crater.

1. Introduction

The Apollo 17 landing site lies on the perimeter of the Serenitatis Impact basin and on a light ray from the Tycho crater 2200 km away (e.g. Wolfe et al., 1981; Orloff and Harland, 2006; Schmitt et al., 2017). The area therefore contains ejecta from the impact and possibly ray material. Between two massifs of ejecta material is a valley in which there is a cluster of small craters assumed to be secondary craters produced by Tycho ejecta (Arvidson et al., 1976; Lucchitta, 1977). Apollo 17 landed very near these “cluster craters”. The astronauts collected 741 individual rock and soil samples and a 3 m deep drill core for a total mass of 110.5 kg. The considerable amount of the early work performed on the Apollo 17 samples, especially the core, was reviewed by McKay et al. (1991).

The deep drill core provides an indication of the geologic history of the valley floor. Some studies suggest that the whole 3 m depth of regolith was laid down by a single event, 108 Ma ago (Niemeyer, S., 1977) but others suggest a more complicated history that may have involved deposition over billions of years or multiple smaller depositions over a much shorter time McKay et al. (1991). For example, Taylor et al. (1979) suggest that the regolith represented by the core at lower levels was mostly ejecta from the cluster craters while the upper layers are ejecta from the nearby Camelot crater.

In this paper we discuss the nature of the regolith at Taurus-Littrow valley through the study of the induced TL properties of the Apollo 17 deep drill core and three surface samples (Fig. 1); 70180 collected near the drill site, 76240 collected under a boulder at the base of the North Massif and 72320, a sample from near a boulder on the foothills of the South Massif (Meyer, 2010a-d).

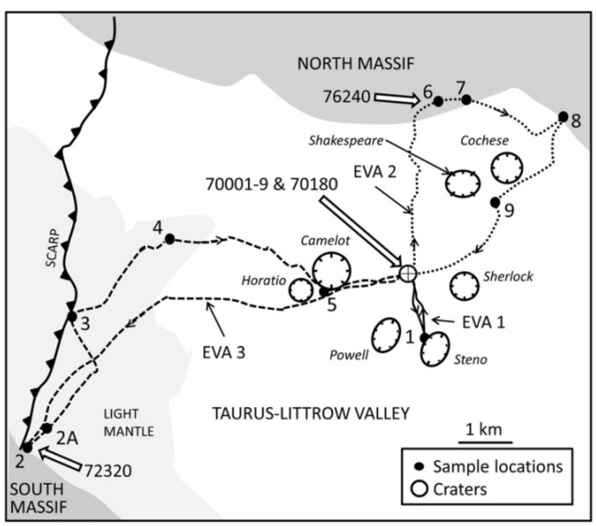

Fig. 1. The three EVAs performed in the Taurus-Littrow valley and the sites at which samples were collected (Heiken et al 1991). 76240 and 72320 were collected under boulders and the foothills of the North and South Massif, respectively. 70180 and the 70001-70009 deep drill core were collected near the landing site indicated by a cross in a circle. For the present study only samples 70001-70006 from the drill core were selected.

Induced thermoluminescence has been shown to sometimes reflect petrographic and mineralogical trends not readily detected or quantified by other methods (e.g. Sears et al., 1980; Sears et al., 2013). The TL sensitivity (the normalized light intensity that can be induced by a standard test does in samples previously drained of their natural TL) reflects the amount and composition of crystalline feldspar in the sample (Akridge et al., 2004), while TL peak temperature (the heating temperature at which light emission is at a maximum) is a measure of the degree of structural ordering of the feldspar (Guimon et al., 1984; 1985), feldspar being the major luminescent mineral present (Herschel 1899; Akridge et al 2004).

The structural ordering reflects the cooling history of the rocks while the amount of feldspar could reflect, for example the level of metamorphism experienced (Sears et al., 1980; Bachelor et al., 1997). Batchelor et al. (1997), in survey mode, described the induced thermoluminescence (TL) of a varied collection of Apollo lunar samples. Their data can be summarized by Fig. 2, which not only allows a specific view of the mineralogy and petrology of the samples but it is also a means of taxonomy. The Batchelor et al. (1997) survey included the Apollo 17 deep drill core.

We were prompted to make this study by two developments; NASA's release of these samples as part of the preparations for a return to the Moon by the Artemis program (Mitchel et al., 2020) and, secondly, the availability of a new method of analyzing thermoluminescence data by the identifying and measuring individual TL peaks corresponding to different electron traps in the feldspar (Sehlke and Sears, 2023). Our primary scientific objective is to explore the history of the Taurus Littrow Valley and of the regolith represented by the core.

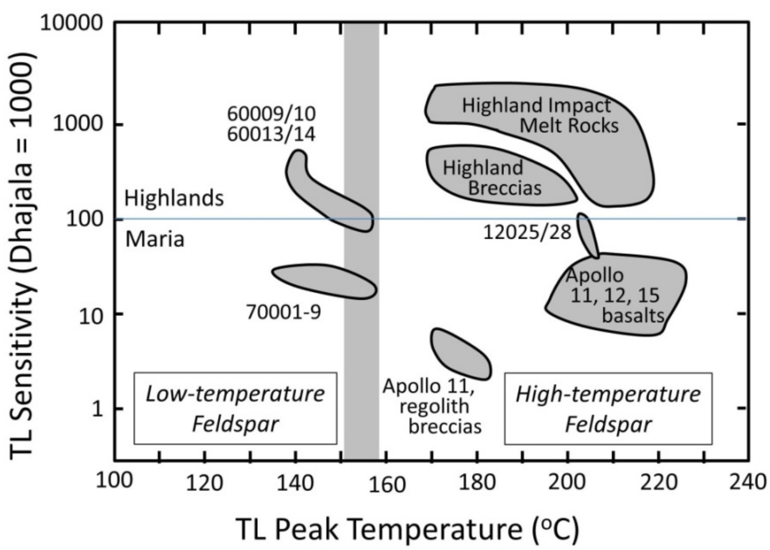

Fig. 2. TL sensitivity vs TL peak temperature for a variety of Apollo rock and core samples (Batchelor et al., 1997). TL sensitivity reflects the amount and crystalline nature of the feldspar, and therefore higher for the highlands than the maria, while the TL peak temperature reflects cooling rate during crystallization. The presence of high-temperature (disordered) feldspar implies faster cooling rates that the presence of low-temperature (ordered) feldspar.

2 Methods

2.1. Samples and sample collection

The samples used in this study are listed in Table 1. For each sample we have a duplicate, one sample was stored at room temperature and one sample was stored in a freezer to better preserve natural thermoluminescence properties (Durrani, 1972). The collection sites for the present samples are indicated in Fig. 1. 76240 was a regolith surface sample (4-5 cm depth) collected ~1 m under the overhang of a 5 x 4 x 3 meter boulder (#4) at station 6, North Massif (Meyer, 2010d). 70180 was a sample of the surface regolith, 0-5 cm depth, collected about 3 meters from the location of the deep drill sample at the ALSEP site (Meyer, 2010c). Sample 72320 was collected about 20 cm under the east – west overhang on the south side of a 2 meter diameter boulder (#2) at station 2, near the base of the South Massif (Meyer, 2010c). The Apollo 17 deep drill core was 3 meter in length and taken between Camelot and the Central Cluster Craters (Meyer, 2010a). Sample 70001 is the bottom-most segment of the drill stem and 70009 is the top. Samples 70007-9 that complete the core were not included in this study because of sample availability. Also because of sample availability the room temperature equivalent of 72320 was an identical adjacent sample 72321.

Table 1. Apollo 17 regolith samples used in this study.

Sample and split number	Depth (cm)	Storage since collection	Description*
70180,8	0-5	Room temperature	Sunlit surface regolith, petrologic unit A
70180,9		Freezer	
72321,41	0	Room temperature	Partially shaded surface regolith, petrologic unit A
72320,7		Freezer	
76240,45	4-5	Room temperature	Permanently shaded surface regolith, petrologic unit A
76240,48		Freezer	
70006, 521	95	Room temperature	Deep drill core, petrologic unit D
70006, 524		Freezer	
70005, 500	133	Room temperature	Deep drill core, petrologic unit E
70005, 501		Freezer	
70004, 590	173	Room temperature	Deep drill core, petrologic unit F
70004, 593		Freezer	
70003, 552	213	Room temperature	Deep drill core, petrologic unit G
70003, 555		Freezer	
70002, 475	252	Room temperature	Deep drill core, petrologic unit H
70002, 476		Freezer	
70001, 83	291	Room temperature	Deep drill core, petrologic unit H
70001, 84		Freezer	

* Petrographic units as identified by Taylor et al. (1979).

2.2. TL measurement.

Thermoluminescence measurements were made with a modified Daybreak Nuclear and Medical Inc. instrument (Sears et al., 2013). The modifications included the addition of a shutter, an aperture, heat and color filters and moving the heater nearer the PMT. The equipment and its associated vacuum/gas line were refurbished for this project. Samples were passed through a 250 μm sieve and 4 mg aliquots placed in a 5 mm diameter copper pan for measurement. Samples were heated from room temperature to 500ºC in the instrument and the light emitted was recorded as a function of heating temperature. The heating was performed in a static nitrogen atmosphere at a rate of 7.5 ºC/second. The data were recorded digitally and the glow curve (light against heating temperature) printed out as pdf and the data and metadata saved as an .csv text file. After removal of the natural TL by heating to 500 ºC, this is sometimes referred to as "thermal cleaning", still in the copper pans the samples were irradiated for three minutes in a 140 mCi ^{90}Sr cell. They were then allowed to "cool" for two minutes before being placed in the TL apparatus for measurement. This ensured that differential fading from sample to sample due to different cooling periods was not a problem. To monitor the stability of the equipment, lunar simulant LMS-1 (https://sciences.ucf.edu/class/simulant_lunarmare), provided by the University of Central Florida, was frequently run through the apparatus. A typical glow curve is shown in Fig.3.

Subtraction of black body radiation using the normal method, running the sample a second time after the first heating, was not used for this study. This is because a large peak just outside our range (say ~525 ºC) could not be drained by our process, so we used an empirical equation derived by running the drained curve many times until no further change occurred at the high temperature end of the glow curve. The result empirical black body equation is:

$$I_{BB} = 1.2 \text{ x } 10^{-6} \text{ x Exp} (T_C / 23.83) \qquad (1)$$

where I_{BB} is the black body radiation and T_C is the temperature in degrees Celsius. Further details can be found in Sehlke and Sears (2023).

Data reduction was performed by (1) using the Batchelor et al. (1997) method of taking measurements of the composite peak (Fig. 3a) and (2) using the new method of glow curve analysis (Sehlke and Sears, 2023; Fig. 3b).

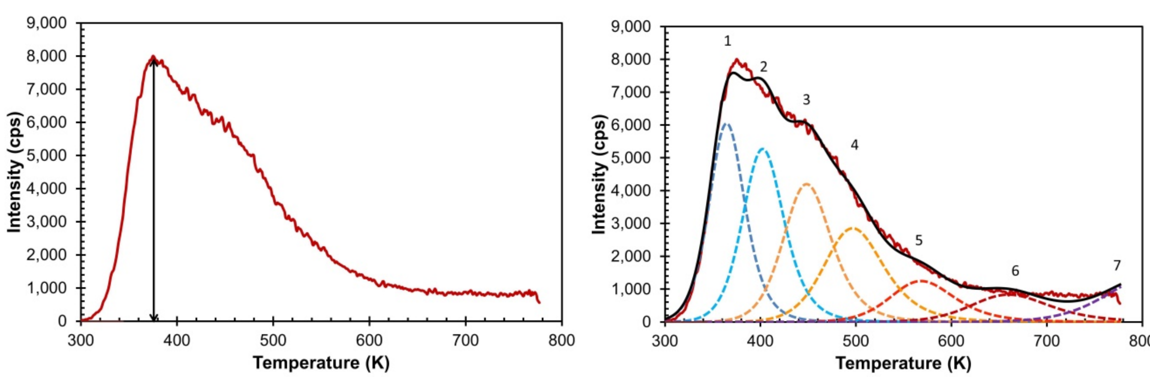

Fig. 3. (a, Left) The induced TL glow curve for one of the present samples analyzed in the manner of Batchelor et al. (1997). (b, Right). The same glow curve with the seven peaks fitted using the kinetic parameters given in Table 2. The black line is the sum of the individual peaks.

2.3. Curve fitting.

A detailed study of glow curve shapes by Sehlke and Sears (2023) found that the glow curve is a composite of seven discrete peaks each of which can be described by the equation:

$$I = n_o\, s \exp(-E/kT) \exp \{ - \int s/\beta \exp(-E/kT) dT \}, \quad (2)$$

where the integral is between 0 and 500 ºC, I is the light, n_o is the initial number of trapped electrons, s is the pre-exponential factor (also known as the "attempt to escape factor" or the Arrhenius factor, essentially a rate constant), E is the trap depth (activation energy to escape), T is heating temperature (in K), β is the heating rate, and k is Boltzmann's constant (e.g., Garlick, 1949). For the present glow curve analyses we will adopt the Sears-Sehlke values for E and s for the each peak of temperature (T_p) in Table 2. For completeness's sake, we show all seven peaks in Table 2 although for the present paper we will use only the first four peaks since they are the strongest and ample for our present purposes.

Table 2. Selected Tp, s and E values for natural glow curves (Sehlke and Sears, 2023).

T_p (ºC)	92	130	175	223	295	387	498
E (eV)	0.78	0.85	0.92	0.92	1.13	1.26	1.53
s (s^{-1})	9.95×10^9	5.13×10^9	1.85×10^9	1.41×10^8	5.83×10^8	1.61×10^8	6.11×10^7

3. Results

The heights of the composite peaks are shown in Fig 4 and listed in Table 3. The uncertainties are one sigma based on replicate measurements of the same sample.

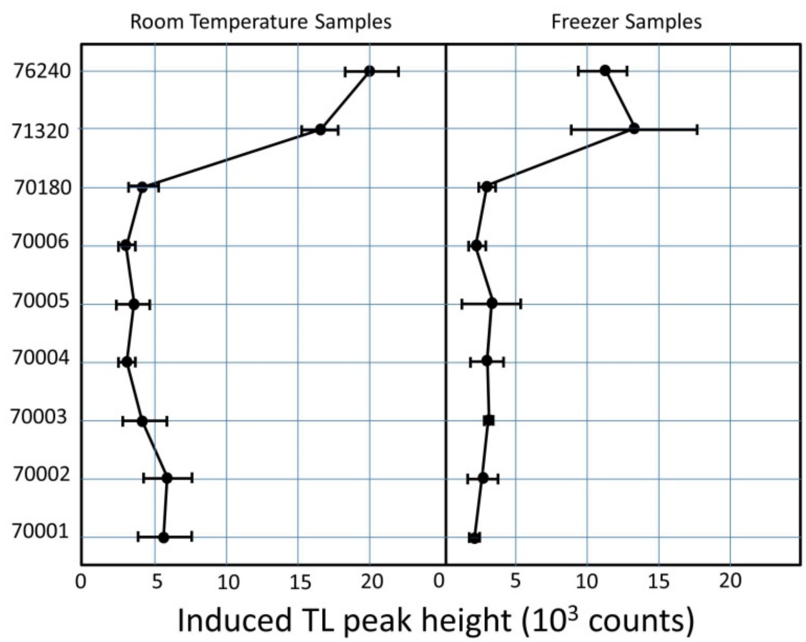

Fig.4. Data for the present samples collected by measuring the peak height (intensity at maximum) of the composite TL peak, the method used by Batchelor et al. (1997). The agreement between room temperature and freezer samples is good, except for the deepest two samples (70001 and 70002) where the room temperature samples are a factor of about two higher in peak height than the freezer samples. Otherwise, the induced TL from the surface to the bottom of the cores is remarkably uniform. Most notably, the two samples from the massifs (76240 and 72320) are about a factor of 4 – 6 higher in TL sensitivity than 70180 and the core.

First, the room temperature samples and the freezer samples, as expected, yield very similar results. More significantly, 76240 and 72320/1 have induced TL values measured this way a factor of 4 - 6 higher than the core samples and 70180. Second, there are no significant trends going down the core. 70001 and 70002 of the room temperature samples have higher TL than the other cores samples and their peaks are a different shape which is reflected by the spread from peak to peak. This anomalous behavior is not shared by the freezer samples.

Table 3. TL peak height derived by direct measurement of the composite peak in the glow curve.

	Peak height (10^3 counts)	
	Room temperature	Freezer
72320/1	17±2.0	12.4±1.8
76240	20±1.3	19±9
70180	4.2±1.2	2.9±0.5
70006	3.0±0.3	2.1±0.3
70005	3.6±0.9	3.3±2.0
70004	3.1±0.7	2.9±1.1
70003	4.1±0.5	3.0±0.2
70002	5.8±1.7	2.6±1.1
70001	5.6±1.8	2.1±0.2

The results of curve fitting are shown in Fig.5 and listed in Table 4. Again, the room temperature and the freezer samples give very similar results, there are little or no trends down the core, and the two samples from the massifs have induced TL a factor of 4 – 5 higher than 70180 and the core samples. To a very high degree, the four peaks are behaving similarly.

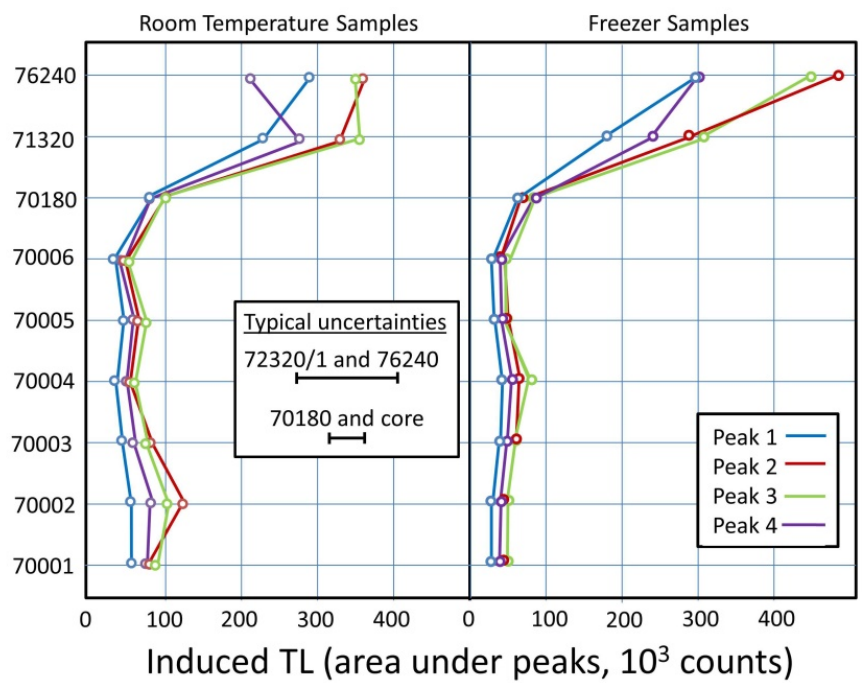

Fig. 5. The induced TL for peaks 1 to 4 determined by curve fitting for the room temperature and freezer samples. Overall the 70001-70006 core and 70180 have uniform TL within experimental limits which is about a factor 4-6 lower than that of 76240 and 72320. The discordant behavior of the four peaks for room temperature 70002 sample indicates a different mineral phase is present in this sample.

Table 4. TL peak total counts derived by curve fitting (in 10^3 counts).

Sample	Storage since collection	Peak 1	Peak 2	Peak 3	Peak 4
Surface samples					
76240,45	Room temperature	292±12	364±16	353±2	215±21
76240,48	Freezer	294±61	487±130	447±96	297±40
72321,41	Room temperature	222±31	331±44	354±50	278±50
72320,7	Freezer	165±22	245±51	263±49	197±47
70180,8	Room temperature	84±16	113±10	114±3	88±7
70180,9	Freezer	42±9	57±12	64±15	78±50
Drill core samples					
70006, 521	Room temperature	35±9	49±11	56±10	44±12
70006, 524	Freezer	28±4	39±7	45±11	36±3
70005, 500	Room temperature	49±10	69±17	79±14	62±10
70005, 501	Freezer	33±10	48±6	48±4	40±4
70004, 590	Room temperature	37±11	57±16	63±19	53±18
70004, 593	Freezer	43±13	65±19	79±30	55±17
70003, 552	Room temperature	46±5	85±15	78±7	62±5
70003, 555	Freezer	40±6	61±1	59±2	48±1
70002, 475	Room temperature	58±16	128±45	107±31	86±20
70002, 474	Freezer	38±10	65±3	65±6	54±3
70001, 83	Room temperature	59±10	84±18	90±17	78±17
70001, 84	Freezer	28±3	44±6	48±13	39±11

4. Discussion

4.1. Freezer vs. room temperature samples

Storage temperature should not affect induced TL which is governed by the stolid state properties of the mineral responsible for the TL, namely feldspar. NASA put certain samples into cold storage in response to suggestions by Durrani (1972) who was interested in natural TL. Thus for an induced TL study these two samples, room temperature and freezer, are simply duplicates that provides some indication of the heterogeneity of the regolith.

Despite the known heterogeneity of the regolith we find very good agreement between these duplicates with the exception of 70002 and possibly 70001. While the freezer sample shows uniform induced TL down the core, 70002 shows a spread in induced for the four peaks. While peak 1 has an induced TL in agreement with the rest of the core, peak 2 is about twice that value, with peaks 3 and 4 showing intermediate behavior. This is a clear indication that an unusual phase or mineral is present in this sample.

The alien component could be feldspar with a significantly different thermal history than most of the feldspar (Guimon *et al.*, 1984; 1985), or it could be a different mineral (Sears *et al*. 2021). Investigating the feldspar present and looking for evidence of different thermal histories would require a dedicated study. Sears *et al*. (2021) found that apatite contributed to the TL signal of certain samples from the Blue Dragon flow at Craters of the Moon, Idaho. Apatite has two sharp induced TL peaks, one at ~160 ºC and another at ~275 ºC. The ~160 ºC would overlap with peak 2 in the present study and this suggests that apatite is the alien species. We assume similar behavior would be displayed by Whitlockite. A peak at ~275 ºC is present in the present samples (peak 5 in Fig. 2) but its intensity is much lower than expected for apatite. Thus while apatite is a strong candidate for the alien component some uncertainty remains. We are not aware of any reports of apatite in the Apollo 17 regolith.

4.2. Comparison with previous data

Figure 6 compares the present data with previous data from Batchelor et al. (1997). These authors did not report data for 70001 or 70180 but the data for 70002-70006 agree with the present (excluding the room temperature data for 70002 discussed above) in showing no trend down the core.

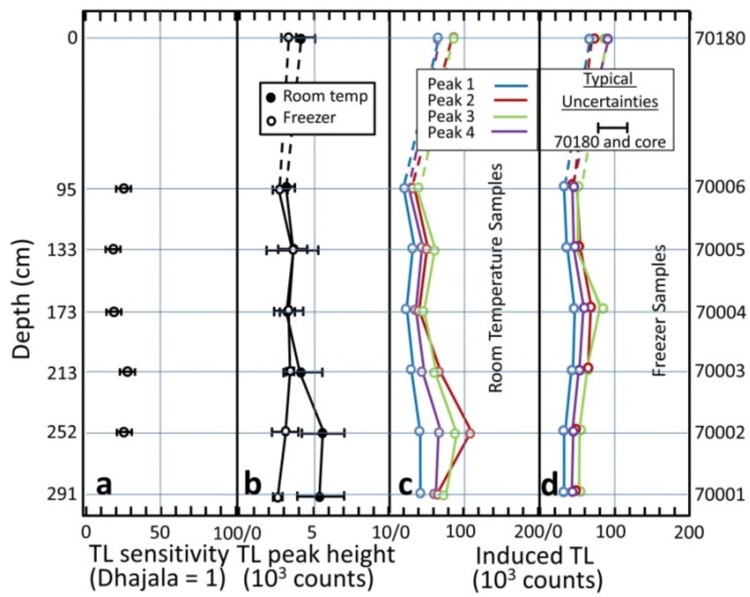

Fig. 6. The present data for 70180 and the core compared with earlier data. (a) Data from Batchelor et al. (1997). (b) Data from the present study reduced in the same manner as Batchelor et al. (1997). (c and d) Data from the present study obtained by curve fitting.

Figure 7 compares the present data with the Batchelor et al. (1997) survey data in the form of a plot of TL sensitivity vs. peak temperature. Batchelor et al. (1997) let peak 1 drain before measuring the curves so here we compare their data with data for the present peak 2. The present data do not show a range in peak temperature since the previous authors were looking at the composite peak whereas we plot only peak 2 which was isolated by curve fitting. With these caveats in mind the present data agree well with earlier data. The massif samples plot in the highland field and the core samples plot in the maria field. The present samples plot in the low-temperature feldspar field indicated a slow rate of cooling compared to the rock samples. This maybe a result of solid state changes in the regolith samples which cooled in an environment of very low thermal conductivity.

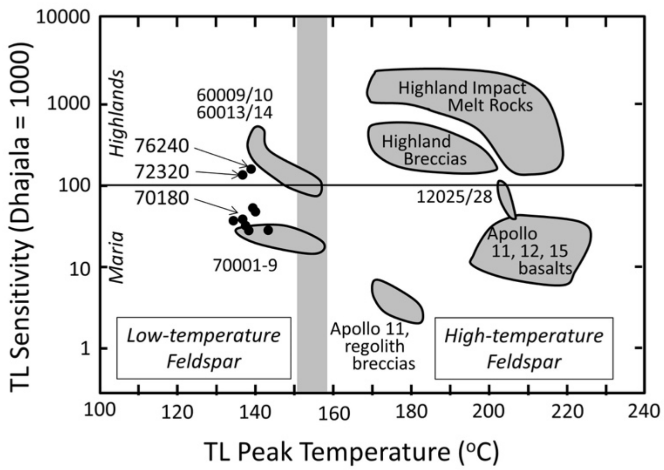

Fig. 7. Plot comparing present data with previous data for the TL properties of Apollo 17 regolith samples. The original plot is from Batchelor et al. (1997). The present data are shown as black circles. Essentially the 70001-70006 data are consistent with the earlier data. 76240, 72320 and 70180 were not analyzed in the earlier paper. See text for a detailed discussion.

4.2. Variation among surface samples

Figure 8 compares the TL properties of the surface samples as determined by curve fitting. Most striking, as discussed above, is the difference between the station two (South Massif, 72320/1) and station six (North Massif, 76240) regolith samples and the samples from the landing site (70180). The induced TL of the sample from the center of the valley is about a factor of four to six lower than the induced TL of samples from the base of the massifs. However, what is also demonstrated by Fig. 8 is the similarity of the curve shapes (i.e. relative intensities of the four peaks) for each lunar location and terrestrial storage condition. This is a clear indication that all peaks are due to the same mineral or phase in the same physical condition; catholuminescence observations and other data show that this phase is crystalline feldspar (Akridge et al., 2004).

The petrographic parameters (plagioclase, An, agglutinate and glass content) are shown with induced TL in Table 5. The difference in induced TL between the valley floor and massif foothills samples can be attributed almost entirely to a difference in plagioclase content. While induced TL value of the valley and the massifs differs by about a factor of four, the plagioclase content induced TL varies by a factor of about three. Given sample heterogeneity and the uncertainty on some of these measurements, we think the induced TL difference between valley and massifs can be attributed to differences in plagioclase content. The composition of the plagioclase and the amount of agglutinate or glass do not seem to contrast significantly between the valley floor and the massif foothills. In fact, a decrease in An from 92 to 88 produces 13% increase in thermoluminescence (calculated from Fig. 2 of Benoit et al., 2001). Neither is there a systematic variation in Is/FeO that would contribute to the difference in induced TL in the two kinds of location.

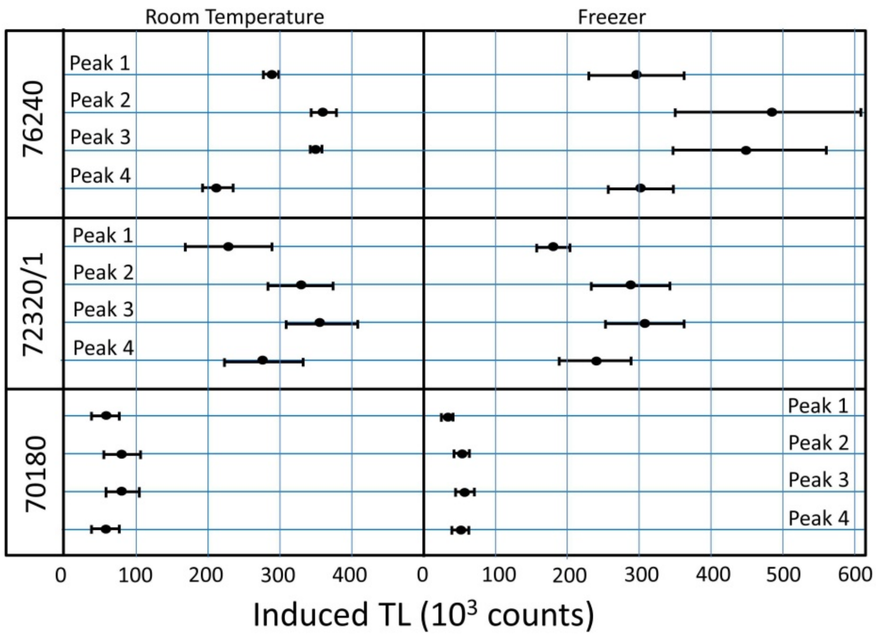

Fig. 8. A comparison of TL data for the three surface samples for the four peaks that constitute the broad intense TL emission between ~90°C and ~270°C. The peaks show the same shape (same relative intensities of peaks 1, 2, 3, and 4) but 70180 has an induced TL intensity a factor of about 4-6 lower than 7320/1 and 76240 suggesting significant differences in their geological history.

Table 5. Selected petrographic properties of the present samples*.

	Peak 1 Induced TL (10^3counts)	Plagioclase (vol %)	Plagioclase (molar An)	Agglutinate (vol %)	Glasses (vol %)	I_s/FeO
70180	84±16	4.3	90.5	56	3.0	47
72320/72321	222±31	9.3	88.8	45	5.0	73
76240	292±12	10-12	92.3	45-48	5.0	56

* Values for all but induced TL taken from the compilation of Meyer (2010b-d)

4.3. Variation down the core

We have found that the induced TL signal down the core is remarkably uniform notwithstanding an alien component in the region of sample 70002 we discussed above. We will now discuss how these TL results compare with other data. The petrography of the Apollo 17 drill core is summarized in Fig. 9. Two systems of petrographic subdivision for the core have been proposed (Fig. 9), Taylor et al. (1979) proposed a scheme involving nine units, a - h from top to bottom of the core, stressing that c - h were "tentative". Vaniman et al. (1979) proposed a scheme of five units, A- E from bottom to top of core, and about half the core was unit C. The present samples represent all but b and c in the Taylor scheme and all but D in the Vaniman scheme. The considerable amount of work that has been performed on the Apollo 17 deep drill core has been reviewed by McKay et al. (1991). Their conclusions are summarized in the right hand column of Fig. 9.

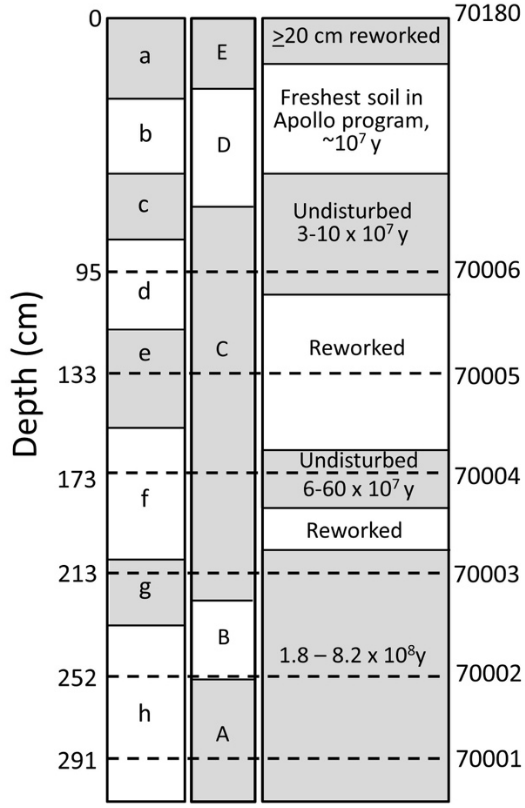

Fig. 9. Characterization of the Apollo 17 deep drill core. The left column describes the petrographic units identified, somewhat tentatively, by Taylor et al. (1979). The middle column indicates the petrographic units identified by Vaniman et al. (1979). The column on the right is the present authors summary based on the description by McKay et al. (1991). The ages refer to exposure ages determined from cosmogenic isotopes by a variety of authors (Crozaz and Plachy, 1976; Curtis and Wasserburg, 1977; Drozd et al., 1977; Blanford, 1980). The dashed lines indicate the sampling depth of the present core samples.

We make several observations that are relevant to the present study. First, the lack of agreement between the two systems of “units” proposed by Taylor et al. (1979) and Vaniman et al (1979), plus the former authors description of their system (at least units c to h) as “tentative”, suggests to us that these distinctions are subtle and that in reality the core is equally heterogeneous or equally homogenous along its length. There are no obviously distinct units that both sets of authors would independently identify. Consistent with this the layers described by McKay et al (1991) in their summary of the petrology of the core do not coincide easily with these two systems of units. Secondly, the exposure ages for the McKay layers are all ~10^8 years, given the ranges and uncertainties observed within the layers (Crozaz and Plachy, 1976; Curtis and Wasserburg, 1977; Drozd et al., 1977; Blanford, 1980). In other words the regolith does not get older with increasing depth. Thirdly, McKay et al (1991) do described some differences going down the core, related mostly to differences in the maturity of the regolith. Some layers are reworked, some are undisturbed, and a layer near the surface was described as the "freshest soil in the Apollo program".

Fig. 10 compares many other properties of the core samples with the present induced TL data. The maturity index profiles (I_s/FeO) suggest that reworked zones exist below the coarse layer at depths of approximately 112–166 cm and 188–203 cm. If this view is correct, the lower part of the core contains two more undisturbed slabs at about 40– 112 cm and 166–188 cm.

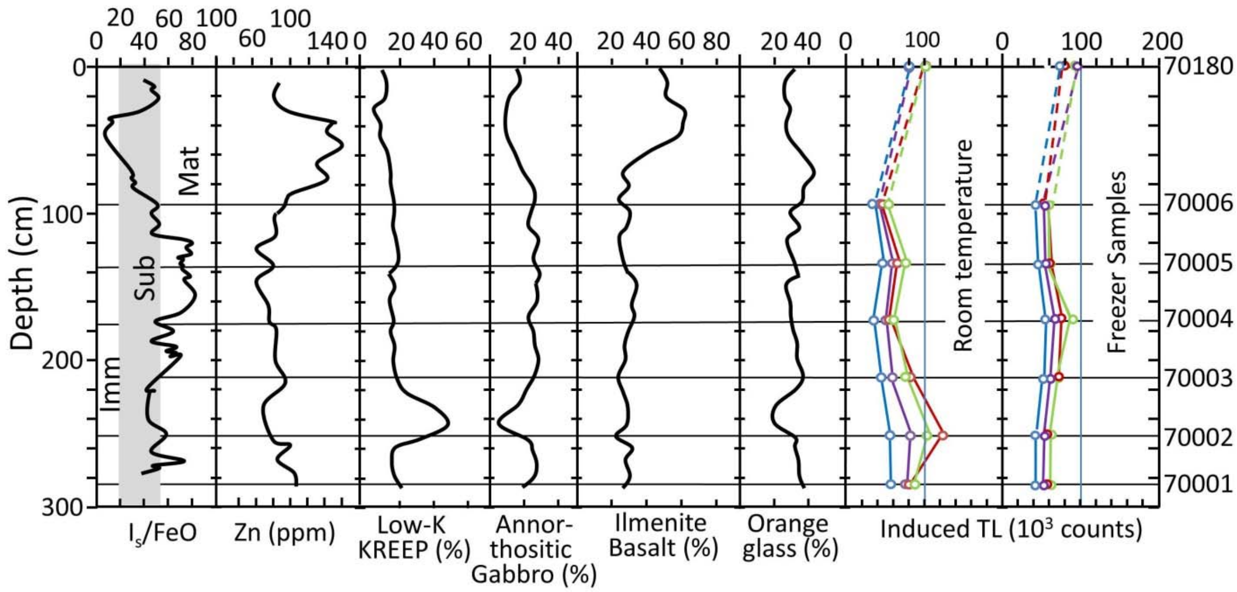

Fig. 10. A comparison of the present induced TL data with the I_s/FeO parameter, the volatile element Zn, and four major components of the regolith. These plots were taken from the summary compiled by Meyer 2010. The horizontal lines locate the core samples in the present study. Imm, immature; Sub, submature; Mat.mature.

Except for the first 1 m, where we have no data, the parameters shown in Fig. 10, like induced TL for the freezer sample, show no monotonic decrease down the core. Also like induced TL for the room temperature sample, the data suggest something has happened to the regolith in the vicinity of sample 70002. At this depth we see high levels of low-potassium KREEP and low values of anorthositic gabbro. It seems very likely that these clasts, low-potassium KREEP and anorthositic gabbro, would (1) contain feldspar with very different thermal history and, possibly, composition (Papike et al., 1976), and (2) contain apatite (Tartèse et al., 2014).

4.4. The nature of the deep drill core and the history of the regolith at the Apollo 17 landing site

To a good approximation induced thermoluminescence intensity reflects the amount of feldspar. A regolith that formed, say, 10^9 years ago and that experienced only the surface working expected by micrometeorite and thermal stressing would show a steady gradient from mature at the surface to immature at depth. Apollo cores 60009/10 and 60013/14 seems to show this trend. During the process the feldspathic component, the lowest melting point component, would be converted to agglutinates or, if the impacts were large enough, glass spherules. Thus induced TL would increase with increasing depth and decreasing maturity and this is essentially what is observed with the Apollo 16 regolith cores 60009/10 and 600013/14 (Batchelor et al., 1997). This interpretation is confirmed dramatically by catholuminescence images (see Fig. 4 of Akridge et al., 2004).

Figure 11 compares the agglutinates with plagioclase as determined by point counting. Data for A, B, D and E lie on a line with an R^2 of 0.81 and this line extends to 70180 with an R^2 of 0.98. This confirms the relationship between agglutinates and plagioclase described above but among the A, B, D, E group there is no correlation with depth. As expected, 73230 and 76240 plot well off the line consistent with these samples being compositionally different and their placement in Fig. 6. Being on the surface one would expect 70180 to be the most mature and this is consistent with having high agglutinates and low plagioclase however its Is/FeO ratio indicates that is submature and its induced TL is similar to the core samples.

The surprise is sample C from the middle of the core which plots well away from the A, B, D, E group with relatively high plagioclase. The Is/FeO suggests that it is a mature sample but the induced TL is similar to 70180 and the rest of the deep drill core samples.

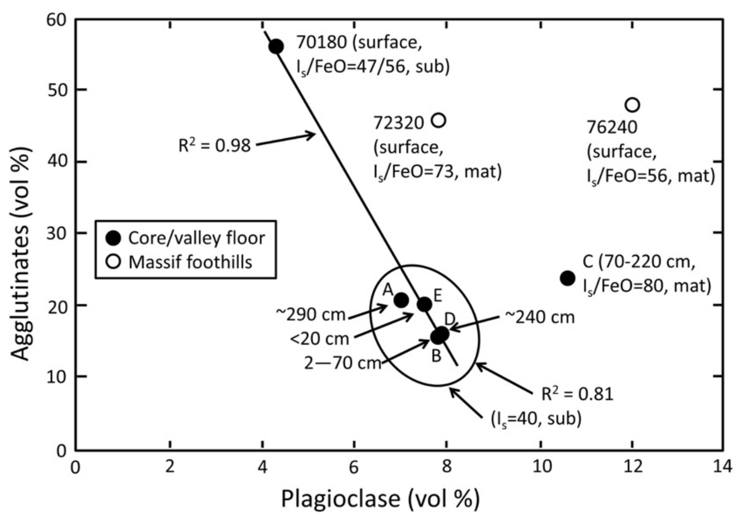

Fig. 11. The volume percent of agglutinates plotted against the volume percent of plagioclase in the present regolith samples. The letter labels refer to petrographic units defined by Vaniman et al. (1979). The encircled data points have an R^2 of 0.81 while the line connecting them to 70180 has an R^2 of 0.98. Also indicated by the data points are sample depth, I_s/FeO and maturity (sub = submature, mat = mature). Data from Meyer (2010b-d).

The relative uniformity of the induced TL from 70180 and down the core and, more especially, the lack of a systematic increase in induced TL going down the core, suggests that the regolith in the valley was laid down by one recent event and the exposure age data suggest that this event occurred ~108 million years ago (Arvidson et al., 1976). The Taurus-Littrow region lies on an ejecta ray from the Tycho crater 2200 km away. Thus, it is widely assumed that the large number of small craters south of the landing site, sometimes referred to as the "cluster craters", were produced as secondary impacts caused by ejecta from Tycho.

5. Conclusions

The level of induced thermoluminescence reflects the amount of feldspar, its composition, and, most importantly, its thermal history (Guimon et al., 1984). We find uniform induced TL levels along the core, especially for the freezer sample. The position of the major induced TL peak in the glow curve (i.e., peak temperature) suggests that regolith samples cooled more slowly in the solid state below the disorder-order transition (~500 ºC) than the Apollo rock samples, presumably because of the low thermal conductivity of the regolith. This has been demonstrated in the laboratory for meteorites, terrestrial feldspars and lunar samples where peak temperature has been compared with X-ray diffraction data and metallographic cooling rates (Sears et al., 2013).

Glow curve analysis, isolating individual peaks in the TL emission (corresponding to different electron trapping centers), shows that the anomalous behavior displayed by 70002 in the room temperature sample is caused by a distinct component, either feldspar with a different thermal history to the rest of the feldspar in the core or the presence of a second luminescent species, such as apatite or whitlockite. This anomalous TL behavior coincides with increased amounts of low-potassium KREEP (and decreased amounts of anorthositic gabbro and orange glass) and may lead to the behavior of the induced TL in the room temperature 70002 sample.

The uniformity of the induced TL signal down the core suggests that the regolith sampled by the core was laid down by a single event. Cosmic ray exposure ages suggest that this event occurred about 100 million years ago and various lines of evidence suggest that this event was the impact that formed the Tycho crater. The anomalous material in the room temperature 70002 could even represent Tycho material.

6. Open Research

6.1 Data Availability Statement: All data, namely TL glow curves, produced for this study will be made publicly available on the www.Astromat.org online archive at the time of formal publication of this manuscript. We share our data within the supplementary information for peer review purposes only. Please refer to the supplementary materials for detailed data sets and related information.

6.2 Software Availability Statement: No software or models were used to generate the data discussed in this manuscript. The data analysis and interpretation methods employed are fully described in the Methods section of this manuscript for transparency and reproducibility.

7. Acknowledgements

We express our sincere gratitude to the ANGSA Science Team for their invaluable contributions, insightful ideas, and engaging discussions, which have significantly enriched the scientific discourse surrounding this research project. We are grateful to NASA for funding this work under their ANGSA (Apollo Next Generation Sample Analysis) program and the curators at the Johnson Space Center for supplying the samples. We also thank Hazel Sears for proof reading this paper.

8. References

Arvidson R., Drozd R., Guiness E., Hohenberg C., Morgan C., Morrison R. and Oberbeck V. (1976) Cosmic ray exposure ages of Apollo 17 samples and the age of Tycho. Proc. 7 th Lunar Sci. Conf. 2817-2832.

Akridge, D.G., Akridge, J.M.C., Batchelor, J.D., Benoit, P.H., Brewer, J., DeHart, J.M., Keck, B.D., Jie Lu, Meier, A., Penrose, M., Schneider, D.M., Sears, D.W.G., Symes, S.J.K., Yanhong Zhang, 2004. Photomosaics of the cathodoluminescence of 60 sections of meteorites and lunar samples. J. Geophys. Res. 109: Issue E7, CiteID E07S03. 10.1029/2003JE002198

Batchelor, J.D., Symes, S.J.K, Benoit, P.H., Sears, D.W.G., 1997. Thermoluminescence constraints on the thermal and mixing history of lunar surface materials and comparisons with basaltic meteorites. J. Geophys. Res. 102, 19,321-19,334.

Benoit, P.H. and Sears, D.W., 1993. Breakup and structure of an H-chondrite parent body: The H-chondrite flux over the last million years. *Icarus*, *101*(2), pp.188-200.

Blanford, G.E., 1980. Cosmic ray production curves below reworking zones. In *Lunar and Planetary Science Conference Proceedings* (Vol. 11, pp. 1357-1368).

Crozaz G. and Plachy A.L. (1976) Origin of the Apollo 17 deep drill coarse-grained layer. Proc. 7th Lunar Planet. Sci. Conf. 123-131.

Curtis D.B. and Wasserburg G.J. (1977) Stratigraphic processes in the lunar regolith – additional insights from neutron fluence measurements on bulk soils and lithic fragments from the deep drill cores. Proc. 8th Lunar Sci. Conf. 3575-3593.

Drozd R.J., Hohenberg C.M., Morgan C.J., Podosek F.A. and Wroge M.L. (1977) Cosmic-ray exposure history at Taurus-Littrow. Proc. 8th Lunar Sci. Conf. 3027-3043.

Durrani, S.A., 1972. Refrigeration of lunar samples destined for thermoluminescence studies. *Nature*, *240*(5376), pp.96-97.

Garlick, G.F.J, 1949. Luminescent materials. Clarendon Press: 254pp.

Guimon, R.K., Weeks, K.S., Keck, B.D. and Sears, D.W.G. (1984) Thermoluminescence as a palaeothermometer. *Nature*, **311**, 363-365.

Guimon, R.K., Keck, B.D. and Sears, D.W.G. (1985) Chemical and physical studies of type 3 chondrites - IV: Annealing studies of a type 3.4 ordinary chondrite and the metamorphic history of meteorites. *Geochim. Cosmochim. Acta*, **19**, 1515-1524.

Herschel, A.S., 1899. Triboluminescence. *Nature*, *60*(1541), pp.29-29.

Lucchitta, B.K., 1977. Crater clusters and light mantle at the Apollo 17 site; a result of secondary impact from Tycho. *Icarus*, *30*(1), pp.80-96.

McKay, D.S., Heiken, G., Basu, A., Blanford, G., Simon, S., Reedy, R., French, B.M. and Papike, J., 1991. The lunar regolith. In *Lunar sourcebook*. (Eds. G Heiken, D Vaniman and B.M. French). Cambridge University Press. pp.285-356.

Meyer, C., 2010a. Lunar Sample Compendium, 70009 – 70001 Deep Drill Core 3 meters (https://curator.jsc.nasa.gov/lunar/lsc/70009.pdf)

Meyer, C., 2010b. Lunar sample Compendium. 70180 Reference Soil. https://curator.jsc.nasa.gov/lunar/lsc/70181.pdf

Meyer, C., 2010c. Lunar Sample Compendium, 72320 (https://curator.jsc.nasa.gov/lunar/lsc/72320.pdf)

Meyer, C., 2010d. Lunar Sample Compendium, 76240 (https://curator.jsc.nasa.gov/lunar/lsc/76240.pdf)

Mitchell, J., McCubbin, F.M., Shearer, C.K., Zeigler, R.A. and Gross, J., 2020, December. Apollo Next Generation Sample Analysis (ANGSA): A segue to the next era of lunar exploration and sample return activities. In *AGU Fall Meeting Abstracts* (abs. # V017-08)

Niemeyer, S., 1977. Exposure histories of lunar rocks 71135 and 71569.Proc. 8th Lunar Sci. Conf pp. 3083–3093.

Orloff, R.W. and Harland, D.M., 2006. Apollo 17: The eleventh manned mission: the sixth lunar landing 7–19 December 1972. *Apollo: The Definitive Sourcebook*, pp.507-545.

Papike, J.J., Hodges, F.N., Bence, A.E., Cameron, M. and Rhodes, J.M., 1976. Mare basalts: Crystal chemistry, mineralogy, and petrology. *Reviews of Geophysics*, *14*(4), pp.475-540.

Pepin R.O., Dragon J.C., Johnson N.L., Bates A., Coscio M.R. and Murthy V.R. (1975) Rare gases and Ca, Sr and Ba in Apollo 17 drill-core fines. Proc. 6th Lunar Sci. Conf. 2027-2056.

Schmitt, H.H., Petro, N.E., Wells, R.A., Robinson, M.S., Weiss, B.P. and Mercer, C.M., 2017. Revisiting the field geology of Taurus–Littrow. *Icarus*, *298*, pp.2-33.

Sears, D.W., Grossman, J.N., Melcher, C.L., Ross, L.M. and Mills, A.A., 1980. Measuring metamorphic history of unequilibrated ordinary chondrites. *Nature*, *287*, pp.791-795.

Sears, D.W., Ninagawa, K. and Singhvi, A.K., 2013. Luminescence studies of extraterrestrial materials: Insights into their recent radiation and thermal histories and into their metamorphic history. *Geochemistry*, *73*(1), pp.1-37.

Sears, D.W., Sehlke, A. and Hughes, S.S., 2021. Induced thermoluminescence as a method for dating recent volcanism: The Blue Dragon flow, Idaho, USA and the factors affecting induced thermoluminescence. *Planetary and Space Science*, *195*, p.105129

Sehlke A. and Sears D.W.G., 2023. Lunar regolith thermoluminescence glow curve fitting to extract its most important physical parameters. 54th Lunar and Planetary Science Conference, abs #1870.

Taylor G.J., Warner R.D. and Keil K. (1979) Stratigraphy and depositional history of the Apollo 17 drill core. Proc. 10th Lunar Planet. Sci. Conf. 1159-1184.

Tartèse, R., Anand, M., McCubbin, F.M., Elardo, S.M., Shearer, C.K. and Franchi, I.A., 2014. Apatites in lunar KREEP basalts: The missing link to understanding the H isotope systematics of the Moon. *Geology*, *42*(4), pp.363-366

Vaniman D.T., Labotka T.C., Papike J.J., Simon S.B. and Laul J.C. (1979) The Apollo 17 drill core: Petrologic systematics and the identification of a possible Tycho component. Proc. 10th Lunar Planet. Sci. Conf. 1185-1227.

Wolfe E.W., Bailey N.G., Lucchitta B.K., Muehlberger W.R., Scott D.H., Sutton R.L and Wilshire H.G. (1981) The geologic investigation of the Taurus-Littrow Valley: Apollo 17 Landing Site. US Geol. Survey Prof. Paper, 1080, pp.280.