Examination of the Long-term Subsurface Warming Observed at the Apollo 15 and 17 Sites Utilizing the Newly Restored Heat Flow Experiment Data from 1975 to 1977

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Key Points:

- Major portions of the previously unarchived data from the Apollo Heat Flow Experiment in 1975 through 1977 have been restored.
- The newly restored data better characterize the long-term subsurface warming at the Apollo 15 and 17 sites than previously possible.
- We suggest that solar heat intake by the regolith increased slightly at the beginning of the experiment, and that resulted in the warming.

Abstract

The Apollo Heat Flow Experiment (HFE) was conducted at landing sites 15 and 17. On Apollo 15, surface and subsurface temperatures were monitored from July 1971 to January 1977. On Apollo 17, monitoring took place from December 1972 to September 1977. The investigators involved in the HFE examined and archived only data from the time of deployment to December 1974. The present authors recovered and restored major portions of the previously unarchived HFE data from January 1975 through September 1977. The HFE investigators noted that temperature of the regolith well below the reach of insolation cycles (~1 m) rose gradually through December 1974 at both sites. The restored data showed that the subsurface warming continued until the end of observations in 1977. Simultaneously, the thermal gradient decreased, because the warming was more pronounced at shallower depths. The present study has examined potential causes for the warming. Recently acquired images of the Lunar Reconnaissance Orbiter Camera over the two landing sites show that the regolith on the paths of the astronauts turned darker, lowering the albedo. We suggest that, as a result of the astronauts' activities, solar heat intake by the regolith increased slightly on average, and that resulted in the observed warming. Simple analytical heat conduction models with constant regolith thermal properties can show that an abrupt increase in surface temperature of 1.6 K to 3.5 K at the time of probe deployment best duplicate the magnitude and the timing of the observed subsurface warmings at both Apollo sites.

1 Introduction

Conductive heat flow through the surface of a rocky planetary body such as the Earth is obtained as a product of two separate measurements: thermal gradient in, and thermal conductivity of, the depth interval penetrated by a probe. The primary purpose of such measurement usually is to quantify the endogenic heat flow of the planetary body. Ideally, the thermal gradient and thermal conductivity measurements should be made within the depth interval where temperature does not fluctuate with insolation cycles. The so-called 'thermal skin depth' defined as the depth at which amplitude of the temperature fluctuation is 1/e of that of the surface (e.g., Grott et al., 2007; Hayne et al., 2017), is often used as a proxy to the depth limit for the reach of insolation. Thermal skin depth varies among planetary bodies, depending on the thermal properties of the surface material and the period of the insolation cycle.

The Earth's Moon is, so far, the only extra-terrestrial body on which heat flow measurements have been made successfully. On the Apollo 15 and 17 missions, heat flow probes were deployed as part of the Apollo Lunar Surface Experiments Package (ALSEP). At each landing site, the astronauts drilled 2 holes, roughly 10-m apart, and installed a probe in each (Langseth et al., 1976). The holes were 1- and 1.4-m deep at the Apollo 15 site and 2.4-m deep at the Apollo 17 site (Fig. 1). The probes monitored surface and subsurface temperature at different depths for multiple years. At the Apollo 15 site, the monitoring took place from July 1971 to January 1977. At the Apollo 17 site, it took place from December 1972 to the conclusion of the entire ALSEP operation in September 1977 (Bates et al., 1979). These observations showed that the annual, insolation-induced, thermal waves reached ~1.5-m depth. Langseth et al. (1976) theoretically removed the annual thermal waves from the subsurface temperature records and determined the thermal gradient associated with the endogenic heat flow. The same authors also estimated thermal conductivity of the regolith by modeling the downward propagation of the annual thermal waves. Endogenic heat flow was then determined to be 21 mW/m^2 at Site 15 and 16 mW/m^2 at Site 17.

Marcus Langseth, the principal investigator of the heat flow experiment (HFE), determined the aforementioned heat flow values at the two Apollo sites based on the observations made through December 1974. It appears that he never examined the HFE data obtained from January 1975 to September 1977. His final report on the HFE (Langseth, 1977) only describes the data obtained through December 1974. The National Space Science Data Center (NSSDC) archived the HFE dataset he processed, and it also terminates in December 1974. Langseth passed away in 1997 without publishing any more work on the HFE data.

The present authors, as well as many other contemporary researchers, have searched for the HFE data from January 1975 to September 1977, because there are some unanswered questions about the 1971-1974 data presented in Langseth et al. (1976). For example, subsurface regolith temperature gradually increased at all depths from the time shortly after the deployment to December 1974 at both Apollo sites. Possible causes of this multi-year subsurface warming have been debated in recent years. Proposed possibilities include a change in the thermal properties of the surface regolith induced by astronaut activity, radiative heat transfer down the borestem (Siegler et al., 2010), the Moon's 18-year orbital precession, and radiation from Earth (Wieczorek and Huang, 2006; Saito et al., 2007; Dombard, 2010; Laneuville and Wieczorek, 2011). We further examine these possibilities in this paper.

For the present study, we have restored major portions of the previously unarchived 1975-1977 HFE data. Using the data from the full duration of the experiment, we characterize the multi-year subsurface warming and examine possible causes. It is worth noting that much of the subsurface temperature data analysis performed by the original HFE investigators was not presented in major scientific journals. Instead, these investigators presented their work in conference proceedings and technical reports in rather fragmented fashions, as their work progressed. Some of these reports are available through the *NASA Technical Reports Sever*, but not all. We recovered these documents in the process of restoring the 1975-1977 HFE data. For that reason, the present work also reviews some of the key findings of the original investigators that were not well publicized previously.

2 Background on the Apollo Heat Flow Experiment

At the Apollo 15 and 17 landing sites, the astronauts used a rotary-percussive drill for excavating the holes for the heat flow probes. The probes were designed for 2.5-m deep holes. At the Apollo 15 site, the astronauts were not able to reach that depth. For Apollo 17, the auger flute had been redesigned, and was able to reach the target depth. The borestem used for drilling was left in place and served as the casing for the hole. The borestem extruded above ground. The astronauts slid the sensors into the borestem (Fig. 1).

The heat flow probes deployed at the two sites were almost identical. Each probe unit consisted of two major components. The upper component consisted of a cable with 4 thermocouples spaced along it, and the lower component consisted of two solid rods with a total of 8 platinum resistance temperature detectors (RTDs) embedded on them (Fig. 1). Each of the solid rods was 0.5-m long and 2.5-cm diameter. Fiberglass-reinforced epoxy was used for the material for the rods. Four RTDs were embedded on each solid rod.

The uppermost and the lower most RTDs of each solid rod were paired electronically as part of a Wheatstone bridge. The other, inner two RTDs were also paired in the same way (Fig. 1). The outer pair was called the 'gradient bridge' and the inner pair was called the 'ring bridge'. The instrumentation circuitry was designed to determine the average temperature and the temperature difference of each RTD pair. Each gradient bridge was logged with 7.25-minute intervals. The ring bridges were used mainly for the in-situ thermal conductivity measurement, which did not yield satisfactory results (Langseth et al., 1976; Grott et al., 2010). The ring bridge RTDs were logged much less frequently than the gradient bridges. The present study focuses on the measurements made with the gradient bridges. The RTDs used for the gradient bridges were able to resolve temperature difference to 0.001 K in the 'high gain' mode with an absolute accuracy of $\pm$0.05 K (Langseth et al., 1972b).

The naming scheme for the temperature sensors in Fig. 1 follows the original scheme by Langseth et al. (1976). The upper and the lower gradient bridges for Probe 1 is called 'TG11' and 'TG12', respectively. The corresponding gradient bridges for Probe 2 are called 'TG21' and 'TG22'. The upper RTD of each bridge is 'A' and the lower RTD is 'B'.

The material used for the solid rods is more than twenty times as thermally conductive as the lunar regolith in vacuum. Prior to the Apollo missions, there was a concern that the presence of the high-conductivity probe would distort the temperature field of the regolith around it and result in underestimation of the geothermal gradient. This phenomenon was termed 'thermal shorting' or 'shunting'. By carrying out laboratory experiments, Langseth et al. (1972a) determined that the thermal gradient measured by the probe is 1% less than the true value due to this effect.

For more detailed description of the HFE instrumentation, refer to Lauderdale and Eichelman (1974), Langseth et al. (1976), and Langseth (1977).

3 Recovery of the 1975-1977 HFE Data and Metadata

The ALSEP instruments deployed at the Apollo 12, 14, 15, 16, and 17 landing sites transmitted data to the Earth from 1969 to 1977. NASA's Johnson Space Center (JSC) in Houston, TX was responsible for recording the raw data received from the Moon on open-reel magnetic tapes. Principal investigators (PIs) of the ALSEP experiments received tape recordings of their experimental data from JSC and processed them. At the conclusion of the ALSEP operation in 1977, only portions of the PI-processed data were archived at NSSDC (Bates et al., 1979). The raw data tapes that the PIs used were never systematically archived, and most of them (including the ones for the HFE) have been lost since.

In the early years of the ALSEP operation, NASA was preserving the tapes recorded at the downlink stations of the Manned Space Flight Network for archival purpose. These tapes were called 'range tapes'. In April 1973, JSC started generating data tapes specifically for archiving, and they were called 'ARCSAV tapes' (Lockheed Electronics Company, 1975). The ARCSAV tapes were 7-track, digital, open-reel tapes, and each contained a day's worth of raw data as received from each of the Apollo stations. JSC generated 5 ARCSAV tapes for the 5 ALSEP stations every day from April 1973 to February 1976. In March 1976, University of Texas at Galveston (UTG) took over the work of generating archival tapes. The tapes made by UTG were called 'work tapes'. They were 9-track digital tapes, and data from all the 5 ALSEP stations were meshed together in them (Nakamura, 1992).

The range tapes and the ARCSAV tapes were never sent to NSSDC for unknown reason. Most of these tapes were lost in the years following the conclusion of the Apollo program. In year 2010, the present authors recovered 440 ARCSAV tapes at the Washington National Records Center (Nagihara et al., 2011). These tapes contained data from April through June 1975 for all of the 5 ALSEP stations. This accounts for less than 10% of the ARCSAV tapes that were generated during the Apollo era. The rest of the ARCSAV tapes are still missing. Digital copies of the work tapes survived in their entirety, and they have been recently archived at the National Space Science Data Coordinated Archive (NSSDCA), the successor to NSSDC.

Even though the 440 ARCSAV tapes recovered from the Washington National Records Center are more than 40 years old and degraded, we were able to recover most of their contents by trying multiple data-recovery service providers. Some of the files extracted from the tapes included a number of bit errors. Fortunately, because the report describing the bit-level data organization for these tapes survived (Lockheed Electronics Company, 1975), we were able to correct many of these errors (Nagihara et al., 2017).

The recording on the ARCSAV tapes and work tapes consisted of data from multiple experiments intermeshed. Using the bit-level data organizations for these archival tapes described previously, we extracted the HFE packets from the data recorded on the tapes. For the HFE, data packets on the archival tapes consisted of digital counts representative of the voltage outputs from the Wheatstone bridges and the thermocouples. They needed to be processed into scientifically meaningful temperature values. The reports outlining the data processing procedure for the HFE have also survived (Lauderdale and Eichelman, 1974; Langseth, 1977). However, they lack information on the instrument calibration. Because the RTDs of the heat flow probes needed absolute accuracy of ~0.05 K (Langseth et al., 1972b), each probe unit was calibrated by the companies that designed and fabricated them. The calibration data were not included in any of the reports or research articles previously published by the original investigators. The present authors conducted a search.

At the conclusion of the ALSEP operation, thousands of engineering reports and memos generated by the companies involved in the instrument development were moved from JSC to two external locations. One was the Lunar and Planetary Institute (LPI) in Houston, TX and the other was the National Archives storage facility in Fort Worth, TX. We conducted an inventory of the ALSEP documents kept at these two locations. In addition, we conducted a search of the documents left behind by the late Marcus Langseth at his home institution of the Lamont-Doherty Earth Observatory of Columbia University. Through these searches, we were able to recover the documents that described the calibration test data and the data processing procedure for each of the heat flow probe units (Nagihara et al., 2014; 2017).

In addition to these engineering reports, we recovered the ALSEP Performance Summary Reports (APSRs) at LPI. These reports were weekly logs summarizing the operational status of each of the ALSEP instruments from 1973 to 1977. The logs included temperature readings from the deepest sensors of all the 4 heat flow probes on the Moon once a week ('TG12B', 'TG22B' in Fig. 1). Though the reports rounded the temperature values to the order of 0.1 K and did not record the exact time of the day of the measurements, the temperature values are useful for the periods for which archival tapes are still missing (i.e., January through March 1975, July 1975 through February 1976). They are also useful in checking the validity of the data we processed for the other periods.

The APSRs also documented how the performance of the Apollo 15 heat flow probes degraded in 1976. The main electronics unit for the probes began to overheat frequently in February 1976, and the temperature values became erratic. From then on, the instrumentation was turned off frequently for extensive cool-down periods. The instrument appeared to stabilize in the late 1976, but the problem recurred in January 1977, when the instrument was commanded off permanently.

Figure 2 summarizes the current archival status of the HFE data. As previously mentioned, no ARCSAV tape has been found for January through March 1975 and July 1975 through February 1976. In addition, from mid-August 1976 to late April 1977, the Apollo 17 HFE data were not recorded on tapes due to the fact that its data channel was used for the Lunar Seismic Profiling Experiment. For those periods, only the temperature values reported weekly in the PSRs are available.

It should be noted that Saito et al. (2007) were the first who attempted to process the HFE data recorded on the work tapes for the period of March 1976 through September 1977. However, these authors lacked the probe calibration data. They assumed that all the RTDs had an identical characteristic. Our comparison of the temperature values obtained by Saito et al. (2007) and those reported in the APSR shows discrepancy up to 0.3 K.

Figure 3 combines the subsurface temperature values for 1971 through 1974, archived by Langseth, and those for 1975 through 1977, obtained for the present study. Here, only the values for the gradient bridges (Fig. 1) are shown. Even though the gradient bridge RTDs were logged every 7.25 minutes, for reasons unexplained, the original HFE investigators down-sampled the RTD temperature data to 58-minute intervals for the 1971-1974 data set archived at NSSDC. The 1975-1977 data, restored from the ARCSAV and work tapes for the present study, contain the data with the original 7.25-minute sampling intervals.

The temperature values for the deepest sensors ('TG12B' and 'TG22B' in Fig. 1) reported in the PSRs are also shown in Fig. 3. The availability of the APSR temperature values allowed us to check the temperature values of the lower gradient bridges we processed from the archival tape data. Recall that the instrumentation was designed to measure the average temperature and the temperature difference between the paired RTDs for each bridge. Therefore, if the temperature values for the deeper RTD can be validated by those reported in the PSR, it is mostly likely that the temperature values for the upper RTD of the same pair ('TG12A' and 'TG22A' in Fig. 1) are also valid. For the Apollo 15 probes, the temperature values obtained from the tape data matched the PSR values within 0.05K (Nagihara et al., 2017). Note that the PSR temperature values had been rounded to the order of 0.1 K.

For the Apollo 17 probes, the two sets of temperature values (the processed tape data vs. the PSR) for the deepest sensors did not match up as well as they did with the Apollo 15 probes. Those processed from the tape data for the Apollo 17 probes are ~0.2 K lower than those reported on the PSR. Documents we recovered at the National Archives facility in Fort Worth and Lamont-Doherty Earth Observatory indicate that the Apollo 17 heat flow probes were calibrated twice in 1967 and 1971. However, we were able to recover only the 1967 calibration data. It is probable that some electronic components for the lower bridge sections of the probes may have been replaced sometime between 1967 and 1971. Therefore, for 1975 through 1977, we only show the PSR temperature values for the lower bridges ('TG12' and 'TG22' in Fig. 1) of the Apollo 17 probes. In contrast, the upper bridge ('TG11' and 'TG21' in Fig. 1) temperature values for the Apollo 17 seem more reliable, because their temperature values from the December 31, 1974, processed by Langseth, and those from April 1, 1975, processed for the present study are within 0.05 K from one another.

The temperature values for the upper bridge for Apollo 15 Probe 1 (TG11A and TG11B) for 1971-1974, which were processed by the original HFE investigators, show an odd behavior. The temperature values for TG11A rose and fell with exactly 1-K steps for each lunar day. In addition, the temperature values of TG11B rose as high as those of TG11A at noon, even though the former is buried nearly 0.5 m deeper. The data from the same RTDs in 1975, which we processed, do not show such oddity. We believe that the Apollo 15 TG11 data for these sensors were not processed correctly for the 1971-1974 set.

The temperature values for the upper gradient bridge of Probe 2 ('TG21' in Fig. 1) of Apollo 15 are omitted here, because the upper part the rod was above ground (Fig. 1) and was heavily influenced by the insolation cycle.

4 Subsurface Temperature Record for 1971 through 1977

Here we interpret the subsurface temperature record for the entire duration of the HFE operation. The HFE temperature record (Fig. 3) begins when the probes had just been emplaced in the holes. At both sites, the deployment took place during a lunar day. Prior to deployment, the probe equipment, heated by the Sun, was much hotter than the subsurface regolith. When the astronauts excavated the holes, the surrounding regolith was heated by the friction of the auger rotation. For these reasons, the very beginning of the subsurface temperature record shows that the excess heat of the probe and the wellbore regolith gradually dissipating away. This initial temperature decay took 100 to 200 days. The original HFE investigators determined the equilibrium (pre-drilling) temperatures at the depths of the RTDs by theoretical extrapolation of the decay trend to infinite time (Langseth et al., 1972b; 1973). Later, the same investigators examined the effect of the annual insolation cycle affecting the subsurface temperature measurements, but their original estimates of the equilibrium temperatures were 'largely unchanged' for TG12 of Apollo 15 and all the RTDs for Apollo 17 sites (Langseth et al., 1976; Langseth, 1977). Therefore, it is believed that these equilibrium temperature estimates (Table 1) were used for the thermal gradient determination at each site. The small spikes observed in the early part of the records are associated with the in-situ thermal conductivity measurement attempts (Langseth et al., 1972b, 1973).

At the Apollo 15 site, the RTDs shallower than 0.5-m depth ('TG11A' and 'TG22A' in Figs. 1 and 3) clearly show the influence of both the diurnal and annual insolation cycles. The annual signal can be detected down to ~1-m depth ('TG12A' and 'TG22B' in Figs. 1 and 3). The annual thermal wave penetrated deeper into the regolith than the diurnal wave, because of the longer period of oscillation. Langseth et al. (1976) and Langseth (1977) analyzed the power spectrum of the subsurface temperature records and concluded that the annual fluctuation can be detected down to ~1.5-m depth (Table 1). However, in practicality, the RTDs placed deeper than 1-m depth (TG12B at Apollo 15 and all the RTDs at Apollo 17) do not show any obvious cyclic trend, the small annual fluctuation, with amplitudes less than 0.01 K does not have significant impact on the thermal gradient determination. Therefore, 1 to 1.5 m can be considered as the depth limit for insolation-related thermal waves.

All the RTDs show gradual warming trend after the initial cool-off period of 100 to 200 days. For example, at the Apollo 15 site, TG12B at 1.39-m depth recorded its minimum temperature value (253.0 K) roughly 100 days into deployment. Since that time, temperature gradually rose to 253.7 K in December 1975, right before the instrument failure. TG12B of Apollo 17 at 2.34-m depth recorded its minimum temperature (256.5 K) about 200 days into deployment, and it gradually warmed to 256.9 K when the experiment concluded in September 1977.

These subsurface warming trends below the thermal skin depth were already recognized by the original HFE investigators (Langseth et al., 1976), but availability of the newly restored HFE data from 1975 to 1977 enables us to characterize them in more detail. Especially for the Apollo 17 site, the duration of data availability has more than doubled, because of the restoration. If based on the 1972-1974 data alone, it is not clear whether or not the deepest RTDs of the Apollo 17 probes show any significant warming trend. Combined with the 1975-1977 data, the full record clearly shows that their temperature rose.

At all HFE sites, the RTDs at shallower depths saw greater temperature increases. As a result, the thermal gradient decreased with time. For example, for Probe 1 of the Apollo 15 site, the thermal gradient based on the initial temperature decay of the lowest 2 RTDs is 1.74 K/m (Langseth et al., 1972a). In June 1975, the thermal gradient of the same probe was reduced to 0.75 K/m.

5 Potential Causes of the Multi-year Subsurface Warming

It is almost certain that the multi-year subsurface warming observed at both Apollo sites originated from the surface and propagated downward, rather than upward from the interior of the Moon. Two lines of evidence support this. First, the shallower RTDs experienced greater temperature increases. Second, the onset timing of the warming is later for the deeper RTDs. For example, temperature of the uppermost RTD (1.33-m depth) of Probe 1 of Apollo 17 started rising by April of 1973 and resulted in more than 1.5-K increase, while the deepest RTD (2.33-m depth) of the same probe did not start rising till mid-1974 and increased by 0.4 K.

Some previous researchers, including the original HFE investigators, offered explanations for the occurrence of the long-term subsurface warming. These explanations can be divided into two groups. The first group (Wieczorek and Huang, 2006; Saito et al., 2007; Huang, 2008) suggests that there may be fluctuations in the surface heat intake in periods longer than the annual insolation cycle and that they reach beyond 1.5-m depth. The second group (Langseth et al., 1976; Dombard, 2010) suggests that the surface thermal setting of the two Apollo sites changed abruptly when the astronauts installed the probes, and that had a long-term impact on subsurface temperature.

Resolution of this problem is crucial in two aspects. First, depending on the cause of the warming, the heat flow values determined by the original investigators may need to be revised. Note that the thermal gradients at these sites changed over time as a result of the long-term warming. Second, instruments for future heat flow measurements on the Moon must be designed to mitigate the cause of the warming. For example, if insolation-related surface temperature fluctuation can penetrate much deeper than 1.5 m, the heat flow probes on future missions may need to penetrate deeper than the Apollo probes did.

In this section, we test the previously proposed mechanisms that may have caused the subsurface warming using the newly restored heat flow data. We also review other previous researchers' arguments for and against these mechanisms. First, the original HFE investigators and Dombard (2010) suggested that the activity of the astronauts altered the thermal properties of the surface regolith and resulted in an increase of equilibrium surface temperature (Langseth et al., 1976; Langseth, 1977). The uppermost several centimeters of the lunar regolith at the Apollo landing sites consisted of loose, very fine-grained particles (e.g., Keihm et al., 1973; Carrier et al., 1991). The photographs taken by the astronauts documented that they were disturbed (Fig. 4). Using the 1971-1974 HFE data, Langseth (1977) constructed a thermal model in which the surface area within a certain radius around the probe experienced a sudden increase in the equilibrium surface temperature. Langseth's model showed that a 2 to 4 K increase in the surface temperature can explain the observed subsurface warming at both HFE sites. The original HFE investigators did not offer a specific mechanism for the surface temperature increase, however.

Second, Wieczorek and Huang (2006) and Saito et al. (2007) suggested that the Moon's orbital precession with a period of 18.6 years might have caused a temperature oscillation of the subsurface regolith well beyond the presumed skin depth. Day-time peak temperature on the lunar surface varies over a year as the Sun's altitude shifts. The orbital precession modulates the annual swing of the peak temperature. This can be seen on the temperature records from the thermocouples that lay on/over the lunar surface at the two Apollo sites (Nagihara et al., 2010). However, Laneuville and Wieczorek (2011), by carrying out numerical simulations of the heat exchange at the lunar surface, showed that this modulation results in little variation in the equilibrium surface temperature from one year to next year. Saito et al. (2008) suggested that, because the Apollo 17 site was in a valley, lunar day length at the site was affected by the surface topography, and that the combined effect of the precession and the topography might have caused the average day length to gradually increase. These authors did not discuss whether or not the same mechanism would apply to the Apollo 15 site.

Third, Huang (2008) suggested that radiation from the Earth may significantly affect the night-time surface heat exchange of the nearside of the Moon. He also observed that the pre-dawn surface temperature values recorded at the Apollo 15 site increased by 1 to 2 K from July 1971 to December 1974, and he attributed it to a possible increase in radiation from the Earth. He further argued that this period coincided with the so-called 'Global Dimming' episode (e.g., Stanhill and Cohen, 2001), during which time, the radiation reflected by the Earth should have increased by ~5%. Another study (Miyahara et al., 2008) suggests, however, that such an increase in the radiation from the Earth is negligible at the mid-latitude of the Moon, where the radiation reaching from the Earth has been estimated to be only 0.07 W/m^2.

Fourth, radiative heat transfer of the insolation down the borestem may have amplified the thermal shorting between the surface and the subsurface (Siegler et al., 2010). As mentioned previously, the RTDs placed shallower than 1-m depth detected the diurnal insolation thermal wave propagating down into the regolith (Fig. 3). There should be a considerable phase lag in temperature oscillation between the surface and several tens of centimeters subsurface due to the low thermal conductivity (0.01 to 0.02 W/mK) of the regolith. Langseth (1977) noted in the Apollo 15 Probe 1 data that the phase lag between the lunar surface temperature (observed by the thermocouples) and the RTD at 0.35-m depth (TG11A in Fig. 1) was shorter than expected. He suggested that radiative heat transfer through the borestem may have caused it. Langseth did not specifically suggest this as the cause of the subsurface warming observed.

6 Discussion

6.1 Photometric Changes in Surface Regolith Resulted from the Astronauts' Activities

Although two of the aforementioned four mechanisms (the Moon's orbital precession and the radiation from the Earth) may have some impact on the heat balance of the lunar surface, quantitative modeling (Laneuville and Wieczorek, 2011; Miyahara et al., 2008) has shown that they are not likely to have resulted in a large enough increase in the surface equilibrium temperature. Here, we primarily examine the other two mechanisms: the astronaut-induced disturbance of the regolith and the solar radiation down the borestem.

The original HFE investigators (Langseth et al., 1976) did not offer a specific mechanism on how the astronaut-induced disturbance of the surface regolith lead to an increase in its temperature. We believe that a decrease in albedo is the most likely mechanism. The astronaut-induced disturbance darkened the surface regolith and caused it on average to absorb more solar heat. There is no doubt that the astronauts' walking on the regolith altered the texture and the photometric properties of its surface. Some of the photographs taken by the astronauts show that the areas and the paths they walked (and drove the Lunar Roving Vehicles) turned darker overall (Hapke, 1972). The images recently obtained by the Lunar Reconnaissance Orbiter Camera (LROC) also show that the areas of the Apollo astronauts' activities are darker than the surrounding, undisturbed areas (Fig. 5). There is a region of regolith brightening within about 50 meters of the Apollo 17 Lunar Module, which is likely due to the descent engine's exhaust plume.

However, the darkening of the regolith along the astronauts' tracks occur far beyond the Lunar Module. So this darkening is not caused by the Lunar Module exhaust plume (Fig. 5, right).

It has been suggested that this darkening is primarily due to the roughening of the surface. Because of their extremely angular shape, lunar regolith particles are adhesive to one another (e.g., Carrier et al., 1991). When the particles are kicked up by the astronauts' steps, they fly out in small clumps, rather than as single particles (Hapke, 1972). The surface disturbed by the astronauts' activities becomes cloddy and rough in mm-cm scale (Kaydash et al., 2011). The individual small topographic features cast shadows around them and the surface appears darker overall. Isolated footprints seem brighter than the surrounding due to the compaction and local smoothing of the regolith (Fig. 4), but that also depends on the view angle. Areas of multiple, overlapping footprints appear darker (Clegg et al., 2014).

Here, we estimate how much lowering of the albedo is necessary in increasing the lunar surface temperature by 2 to 4 K, as suggested by Langseth (1977). The well-known planetary radiative equilibrium temperature equation is given as (e.g., de Pater and Lissauer, 2010):

$$T_{eq} = \left(\frac{I(1-a)}{4\varepsilon\sigma} \right)^{\frac{1}{4}}, \qquad (1)$$

where T_{eq} is the equilibrium temperature, I is the insolation, a is the bond albedo, ε is the thermal emissivity, and σ is the Boltzmann constant (5.67×10^{-8} W/(m^2·K^4)). The average insolation for the mid-latitude of the Moon has been estimated to be I = 662 W/m^2 (Miyahara et al., 2008). The recent analysis of the DIVINER data suggested ε = 0.97 to 0.98 and a = 0.05 to 0.2 globally (Vasavada et al, 2012). Using these numbers, a 3-K increase in equilibrium temperature requires less than 0.05 reduction in albedo. That is within the range of natural variation of the observed albedo.

6.2 The Effect of Surface Warming

Next, using mathematical models, we examine how such an increase in the surface temperature affects the subsurface temperature in the depth range of the heat flow probe measurements. It should be noted that Langseth (1977) performed such an analysis, but he used only the 1971-1974 HFE data, and his two-dimensional heat conduction model outcomes were somewhat affected by his estimation of the radius of disturbed area, which was not well constrained. Here we use the data from the full duration of the HFE (1971 to 1977), but limit the model to heat conduction in the vertical direction only. As seen on the LROC images (Fig. 5), the disturbed areas around the probe deployment sites are much wider than the length of the heat flow probes (1.5 to 2.5-m). Therefore, the 1-D approximation should suffice.

Our models assume that thermal property of the regolith is constant through the depth interval penetrated by each probe for simplicity. Previous studies, based on their observations of the diurnal temperature swings at the surface, estimated that the uppermost 10 cm of regolith is much less thermally conductive (Keihm et al., 1973; Vasavada et al., 2012; Hayne et al., 2017) than at greater depths. Thermal conductivity of the uppermost regolith may also vary with temperature (Cremers, 1975), increasing during the lunar day and decreasing during the night. Accounting for these spatial and temporal variations would be very important if we were attempting to model the surface heat exchange associated the diurnal insolation cycle. The original HFE investigators found, however, that the thin low-conductivity layer at the surface made little difference in their modeling of the annual thermal waves reaching much greater depths (Langseth, 1977). They also found that the thermal conductivity and diffusivity of the regolith below the thin surface layer is fairly uniform (Langseth et al., 1976). Here, in modeling the multi-year warming observed at the depths beyond the reach of the insolation-induced thermal waves, we believe a 1-D models with constant thermal properties is sufficient.

The subsurface temperature responding to an instantaneous heating of the surface can be expressed mathematically as (e.g., Carslaw and Jaeger, 1959; Turcotte and Schubert, 1982):

$$T(z,t) = T_1 - (T_1 - T_0)\cdot \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right), \qquad (2)$$

where T_0 is the original surface regolith temperature, T_1 is the new surface temperature, κ is the thermal diffusivity of the regolith, z is the depth, and t is the time elapsed since the disturbance. erfc is the complementary error function. This model ignores the surface temperature fluctuation associated with the diurnal and seasonal insolation cycles. T_0 in Eq. (2) should be regarded as the long-term average surface temperature prior to the probe deployment.

Figures 6 and 7 show the results of fitting the 1-D model to the probe data. It was assumed that the equilibrium subsurface temperatures estimated by the original investigators (Table 1) were the initial temperatures at these depths. Langseth (1977) yielded a range of estimates for the overall thermal diffusivity for each probe site (Table 2), based on two types of modeling. One was the downward propagation of the annual thermal wave, and the other was the sudden heating of the surface due to the astronauts' activities. For the present models, we chose a thermal diffusivity value near the middle of the range suggested by Langseth (1977) for each probe. The model outcomes were most sensitive to the magnitude of the temperature increase at the surface, $T_1 - T_0$. We used a grid search approach, varying the $T_1 - T_0$ values with 0.1-K steps and visually examined the fit. Therefore, we do not claim that these models are the most optimal statistically, but we simply suggest that they adequately demonstrate reasonable fit with the data. Figure 6 also shows how the temperature-versus-depth relationship changed over time for Probe 1 of Apollo 17. It clearly shows that thermal gradient decreased.

We also tested a case in which surface regolith temperature increased gradually (linearly) since the time of probe deployment. The model for gradual warming is also based on a 1-D analytical solution assuming uniform thermal diffusivity (Carlsaw and Jaeger, 1959):

$$T(z,t) = kt\left\{\left(1+\frac{z^2}{2\kappa t}\right) erfc\left(\frac{z}{2\sqrt{\kappa t}}\right) - \frac{z}{\sqrt{\pi\kappa t}}\exp\left(-\frac{z^2}{4\kappa t}\right)\right\} \qquad (3)$$

where k is the rate of temperature increase.

Figure 8 shows the model prediction with the data from Probe 1 of Apollo 15. It shows that if the surface temperature increased gradually, the warming in the subsurface is too slow in the beginning. The instantaneous surface heating model fits the data better.

6.3 Possibility of Solar Radiation Influx into the Borestem

As seen in Fig. 4, the top of the borestem was left open for both Apollo 15 probes. There is a strong possibility that solar radiation directly influenced the subsurface temperature measurements by the probes. For each probe, the RTDs were housed in two solid rods, each 0.5-

m long (Fig. 1). It has already been known that the upper rod of Probe 2 was directly influenced by the diurnal insolation cycle, because it was placed very close to the top of the borestem. Here, we focus on Probe 1. The uppermost RTD of Probe 1 (TG11A) was placed at 0.35-m below surface, roughly 0.85-m below the top of the borestem.

As mentioned previously, the 1971-1974 HFE data archived by the original investigators had problems with the temperature values for TG11 of Apollo 15 (Fig. 3). Figure 9 shows a magnified view of the Apollo 15, Probe 1 subsurface temperature records for April through June 1975, restored for the present study. On May 25 (ordinal day 145), there was a total eclipse of the Moon. During the eclipse, lunar surface temperature fell from ~350 K to ~150 K (Nagihara et al., 2015). TG11A, placed at 0.35-m depth, also showed a sharp, brief, drop in temperature coincident with the eclipse. This is a clear evidence that TG11A was directly affected by solar radiation. If there was no radiative transfer down the borestem, temperature of TG11A should not have fallen this abruptly in sync with the eclipse. Because the eclipse lasted only ~5.5 hours, the negative thermal pulse resulted from it should have attenuated at shallower depths, if it propagated downward solely by conduction.

Here we examine the analytical solution to a one-dimensional boundary value problem (Carslaw and Jaeger, 1959) in which a half space has a uniform initial temperature of zero. At time zero, surface temperature fell by ΔT and returns to zero at time = t_1. Then, temperature of the half space is obtained as:

$$T(z,t) = -\Delta T \cdot \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right) + \Delta T \cdot \mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa (t-t_1)}}\right) \tag{4}$$

where ΔT is the temperature drop. Using ΔT = 200 K, $\kappa = 4 \times 10^{-9}$ m^2/s for the regolith in the shallow depths (Langseth et al., 1976), and t_1 = 5.5 hours, we obtain the temperature distribution shown in Fig. 10. The negative temperature pulse associated with the eclipse should not have reached depths below 0.15 m, if solely based on heat conduction.

Therefore, the radiative heat transfer down the borestem impacted the upper rods of the Apollo 15 probes during lunar days. However, it also appears that the upper rod blocked the radiation from reaching deeper. That can also be inferred from the temperature record (Fig. 9). TG11B and TG12A are only 8 cm apart in depth (Fig. 1), and their temperature-versus-time curves overlie each other. However, the two curves (blue for TG11B and red for TG12A) behave differently. The diurnal thermal wave is easily noticeable for TG11B, while it is very subtle for TG12A. There is also a considerable phase lag between them. TG11B, a part of the upper rod, was influenced by the insolation peeking down the borestem, while TG12A, a part of the lower rod, was essentially shielded from the direct influence of the insolation. For Probe 2 of Apollo 15, Langseth (1977) showed that the phase lag observed for TG22A (Fig. 1) is consistent with the annual thermal wave propagating downward by conduction.

For Apollo 17, the astronauts installed radiation shields to the top of the borestem (Fig. 4) and at ~0.3-m depth (Fig. 1). Therefore, the influence of radiation down the borestem should have been minimized. The phase shifts observed for the diurnal and annual thermal waves are consistent with them propagating down solely by conduction (Langseth, 1977). Therefore, if there were any radiative flux that leaked through the two radiation shields, it would not have been significant.

7 Conclusions

The Apollo Heat Flow Experiment (HFE) was conducted at the Apollo 15 and 17 landing sites from 1971 to 1977. The original HFE investigators left the data from 1975 to 1977 unarchived. The present study restored major portions of them. The restored data, combined with the 1971-1974 processed by the original investigators, were used for better characterizing the multi-year, gradual subsurface warming observed at both Apollo heat flow sites. The present study examined four previously suggested mechanisms as potential causes for the warming: the Moon's orbital precession, radiation from the Earth, albedo reduction of the surface regolith caused by the astronauts' activities, and solar radiation into the borestems. The temperature-versus-time records from the heat flow probes clearly indicate that the warming originated from the surface and propagated downward. The shallower temperature sensors show greater magnitudes of warming, and vice versa. Further, the onset timing of the warming is later for the deeper sensors. The present study has found that only the albedo-reduction-induced surface warming can satisfy the magnitude and the timing of the subsurface warming observed.

In view of planning additional heat flow measurements on future lunar-landing missions, these findings, along with the other types of thermal disturbance a lunar lander may cause (Kiefer, 2012), should be taken into consideration for the probe deployment and measurement methodologies. It is a major technological challenge to land a spacecraft and deploy a heat flow probe while minimizing the resulting surface disturbance. One way to mitigate such problem may be to equip the spacecraft with additional instruments (e.g., a radiometer) and monitor photometric properties of the surface regolith as it lands. An alternative approach may be to robotically deploy a probe quickly to the desired depth (2.5 to 3 m) and obtain thermal gradient and thermal conductivity measurements, before the surface disturbance begins to affect the subsurface thermal regime below the skin depth (e.g., Nagihara et al., 2014).

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The newly restored HFE data from 1975-1977 used in Figure 3 are available as supporting information for this article. The unprocessed HFE data recently extracted from the original ALSEP data archival tapes are available from the National Space Science Data Coordinated Archive (NSSDCA) (https://nssdc.gsfc.nasa.gov/nmc/datasetDisplay.do?id=PSPG-00921 and https://nssdc.gsfc.nasa.gov/nmc/datasetDisplay.do?id=PSPG-00922). The HFE data from 1971 through 1974, archived by the original investigators, have also been available through NSSDCA (https://nssdc.gsfc.nasa.gov/nmc/datasetDisplay.do?id=PSPG-00093 and https://nssdc.gsfc.nasa.gov/nmc/datasetDisplay.do?id=PSPG-00022). Digital copies of the

ALSEP-related technical reports referenced by this article are now available through LPI (https://repository.hou.usra.edu/handle/20.500.11753/2).

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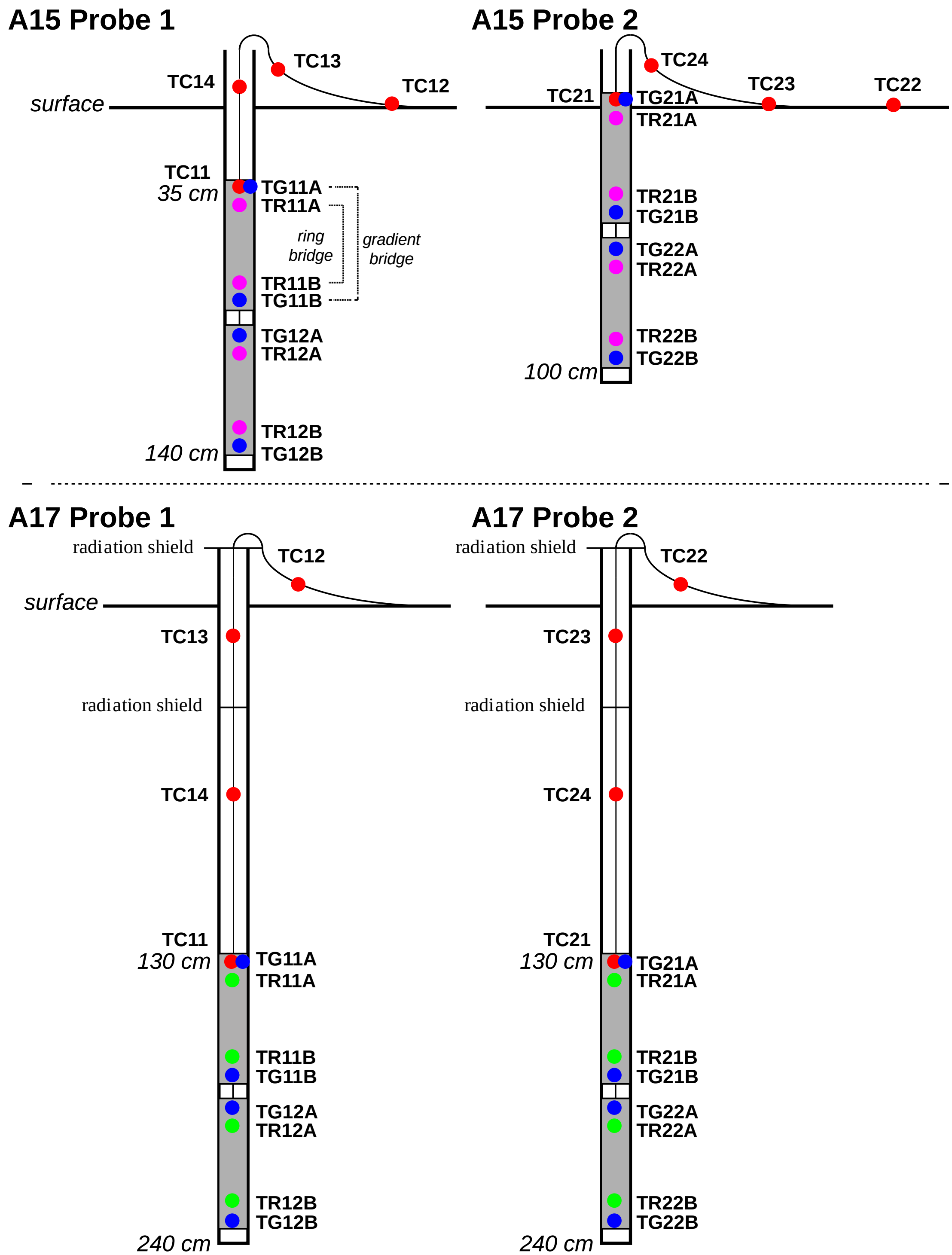

Figure 1. Schematic drawings describing the emplacement of the heat flow probes at the Apollo 15 and 17 landing sites. The temperature sensors are labeled. The red dots indicate the thermocouples. The blue dots indicate the gradient bridge RTDs. The green dots indicate the ring bridge RTDs. The probe hardware was almost identical between the two landing sites except that the Apollo 17 probes were equipped with radiation shields.

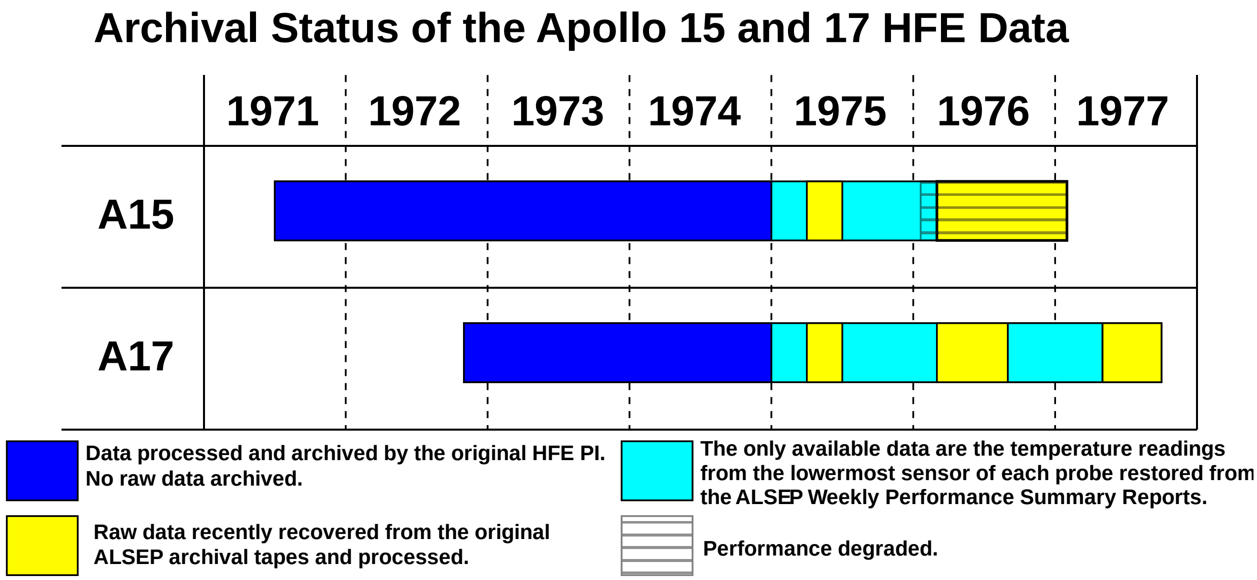

Figure 2. The current data archival status of the Apollo 15 and 17 Heat Flow Experiments.

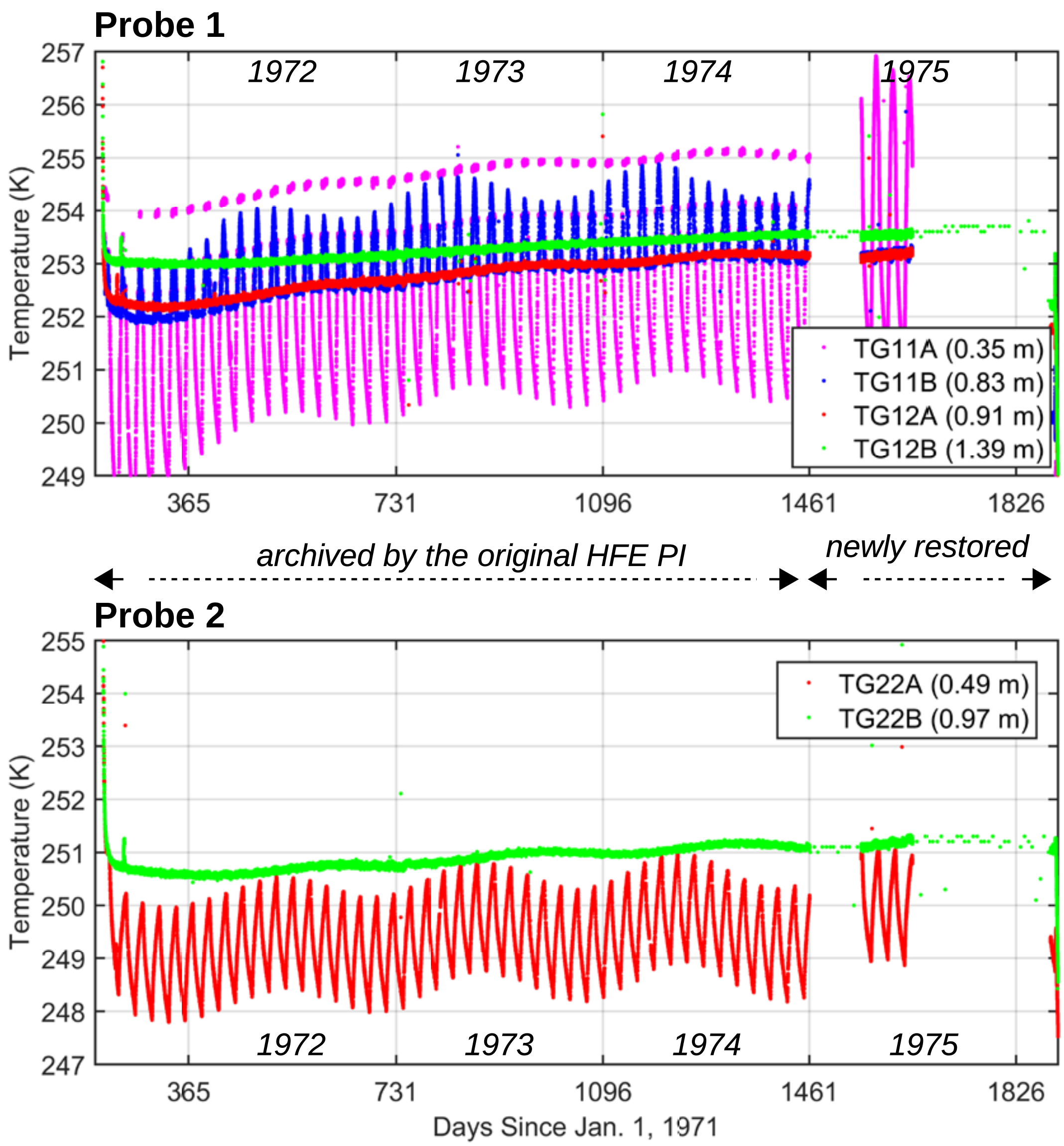

Figure 3a. Temperature versus time records for the gradient bridge RTDs of the Apollo 15 heat flow probes. The probes started operating on July 31, 1971. The data from 1971 through 1974 were processed by the original HFE investigators (Langseth et al., 1976). The data from 1975 through 1977 were restored by the present authors. Refer to Fig. 1 for the positions of the individual RTDs.

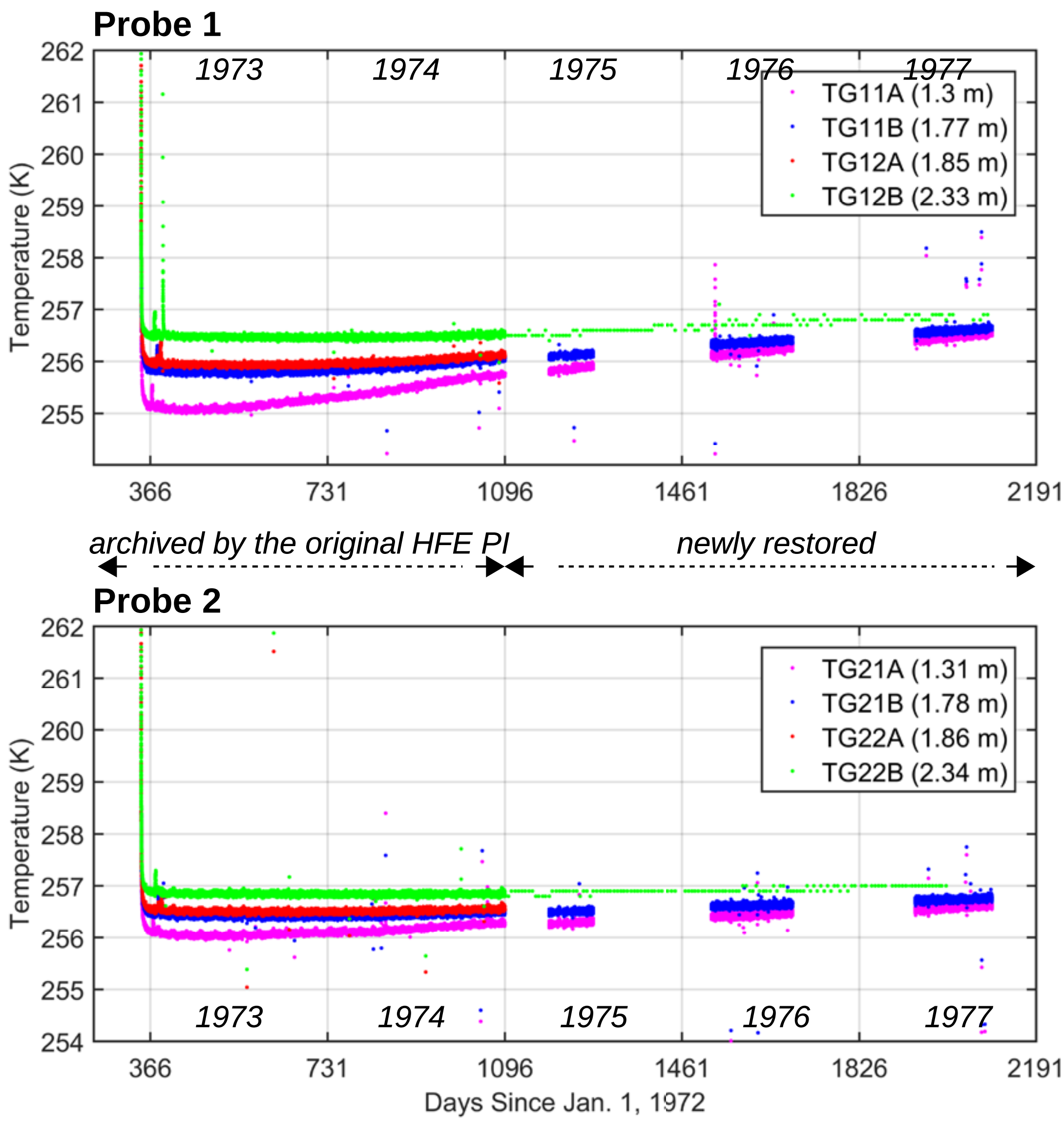

Figure 3b. Temperature versus time records for the gradient bridge RTDs of the Apollo 17 heat flow probes. The probes started operating on December 12, 1972. The data from 1972 through 1974 were processed by the original HFE investigators (Langseth et al., 1976). The data from 1975 through 1977 were restored by the present authors. Refer to Fig. 1 for the positions of the individual RTDs.

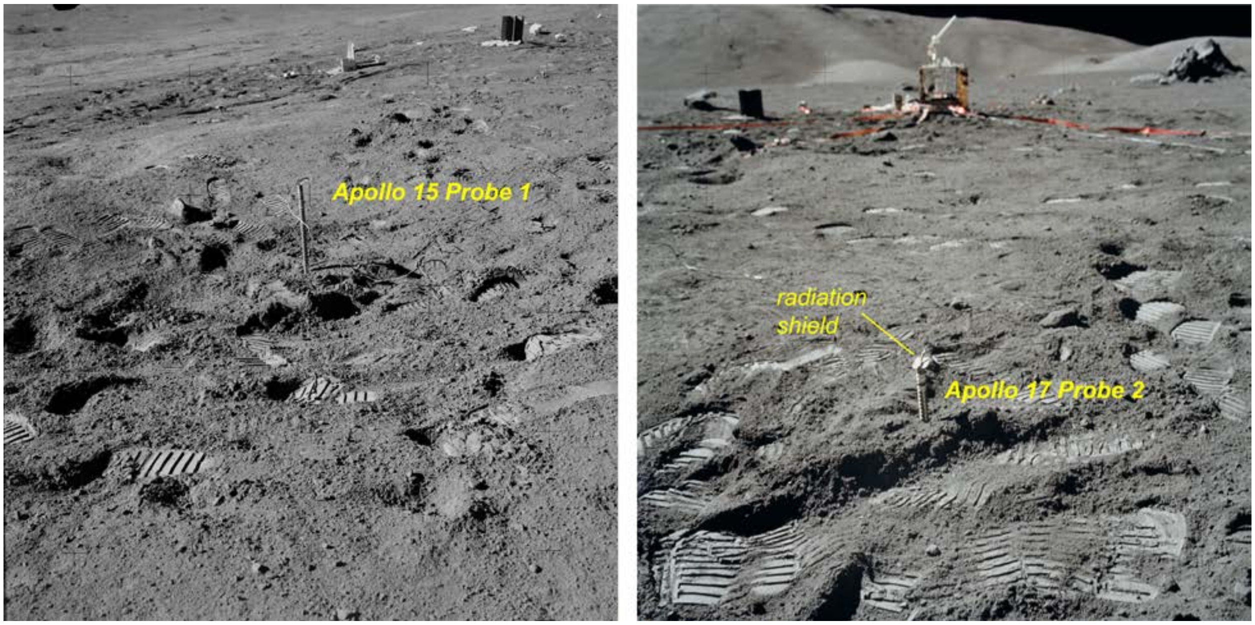

Figure 4. Left: Photograph by astronaut James Irwin showing the borestem and the cable of the Apollo 15 Probe 1 protruded from the ground. Around the borestem, footprints of the astronauts can be seen. Note that the top of the borestem is left open. The original photo was obtained from NASA, https://www.hq.nasa.gov/alsj/a15/AS15-92-12406HR.jpg. Right: Photograph by astronaut Harrison Schmidt showing the borestem and the cable of the Apollo 17 Probe 2 protruded from the ground. Note the radiation shield attached to the top of the borestem. The original photo was obtained from NASA, https://www.hq.nasa.gov/alsj/a17/AS17-134-20493HR.jpg.

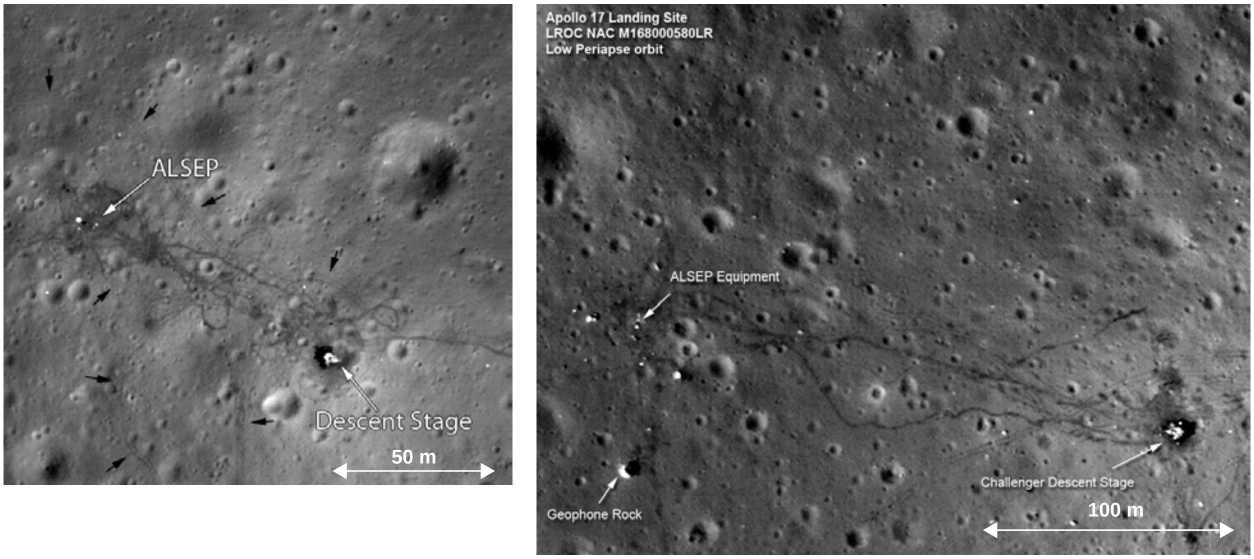

Figure 5. Left: Lunar Reconnaissance Orbiter Camera (LROC) image of the vicinity of the Apollo 15 landing site. Note that the surface around the ALSEP deployment site is darker than the surroundings. The original image obtained from NASA, https://lunarscience.nasa.gov/wp-content/uploads/2012/03/M175252641LR_ap15.png. Right: LROC image of the vicinity of the Apollo 17 landing site. Note that the surface around the ALSEP deployment site is darker than the surroundings. The original image obtained from NASA, https://www.nasa.gov/sites/default/files/images/584392main_M168000580LR_ap17_area.jpg.

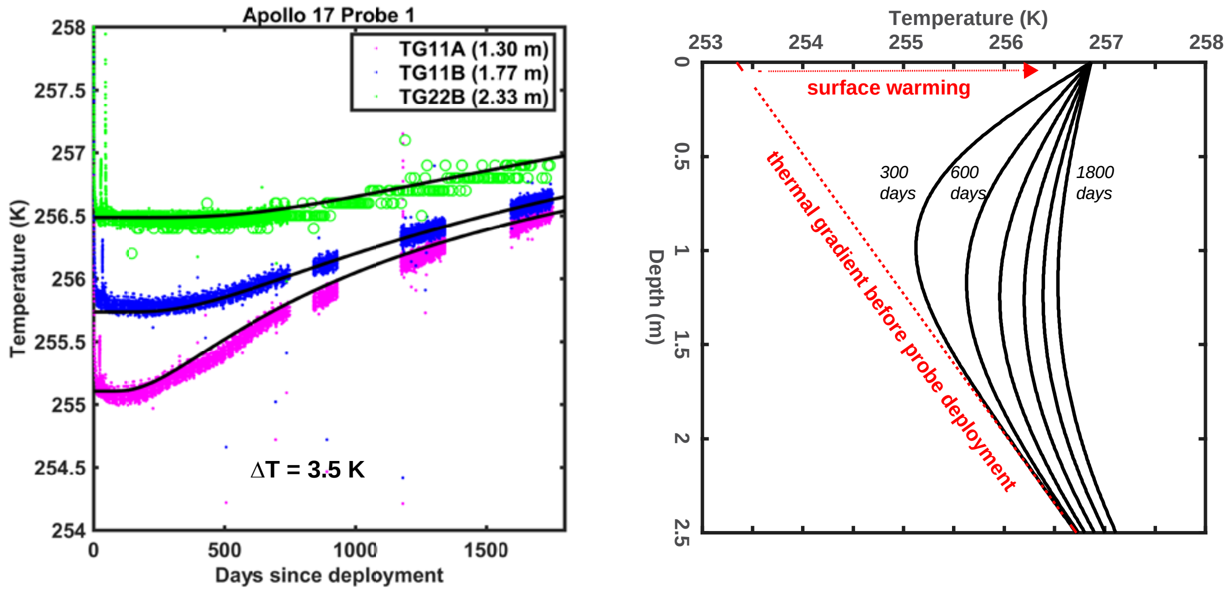

Figure 6. Left: A graph showing temperature-versus-time curves for RTDs TG11A, TG11B, and TG22B of Probe 1 of Apollo 17, predicted by the mathematical model of a sudden temperature increase at the surface at the time of probe deployment. The colored dots show the actual temperatures obtained by the same RTDs. Right: A graph showing how temperature-versus-depth relationship changed over the same time duration of the model.

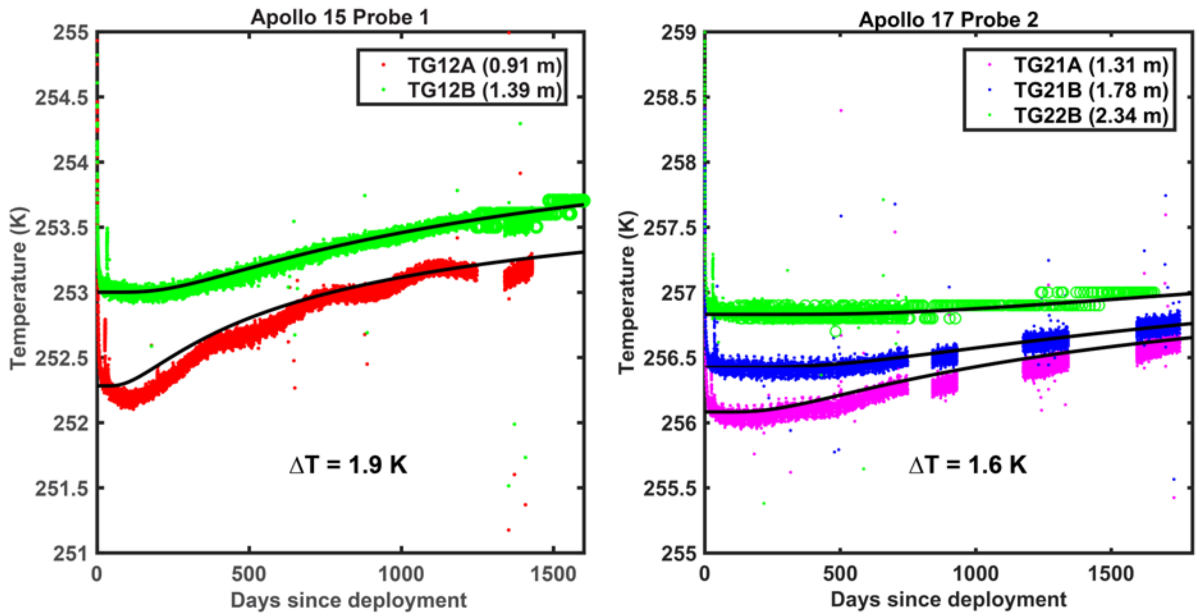

Figure 7. Temperature-versus-time curves for the RTDs of Probe 1, Apollo 15 (left) and those of Probe 2, Apollo 17 (right), predicted by the mathematical model of a sudden temperature increase at the surface at the time of probe deployment. The colored dots show the actual temperatures obtained by the same RTDs.

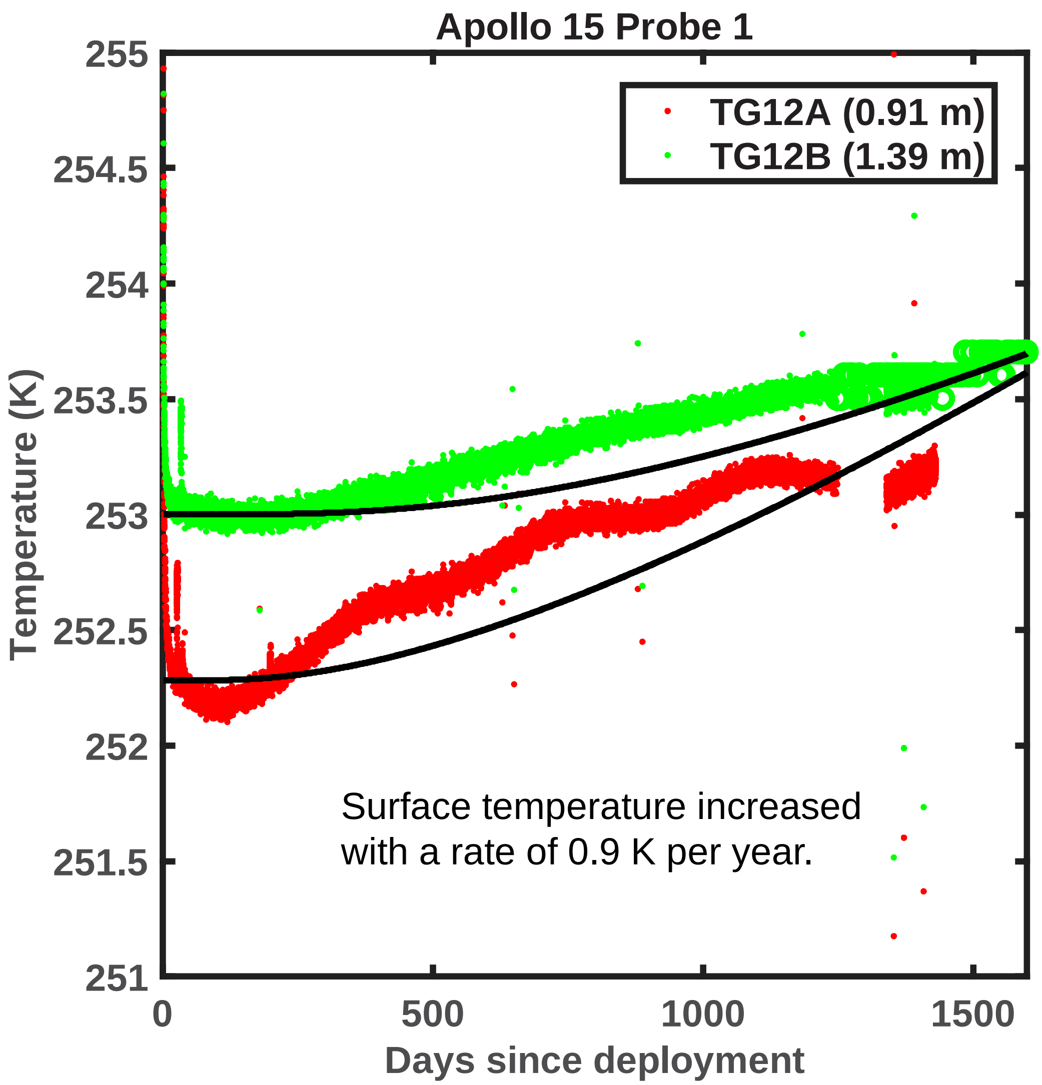

Figure 8. Temperature-versus-time curves for the RTDs of Probe 1, Apollo 15 predicted by the mathematical model of a linear temperature increase at the surface since the time of probe deployment with a rate of 0.9 K per year. The colored dots show the actual temperatures obtained by the same RTDs.

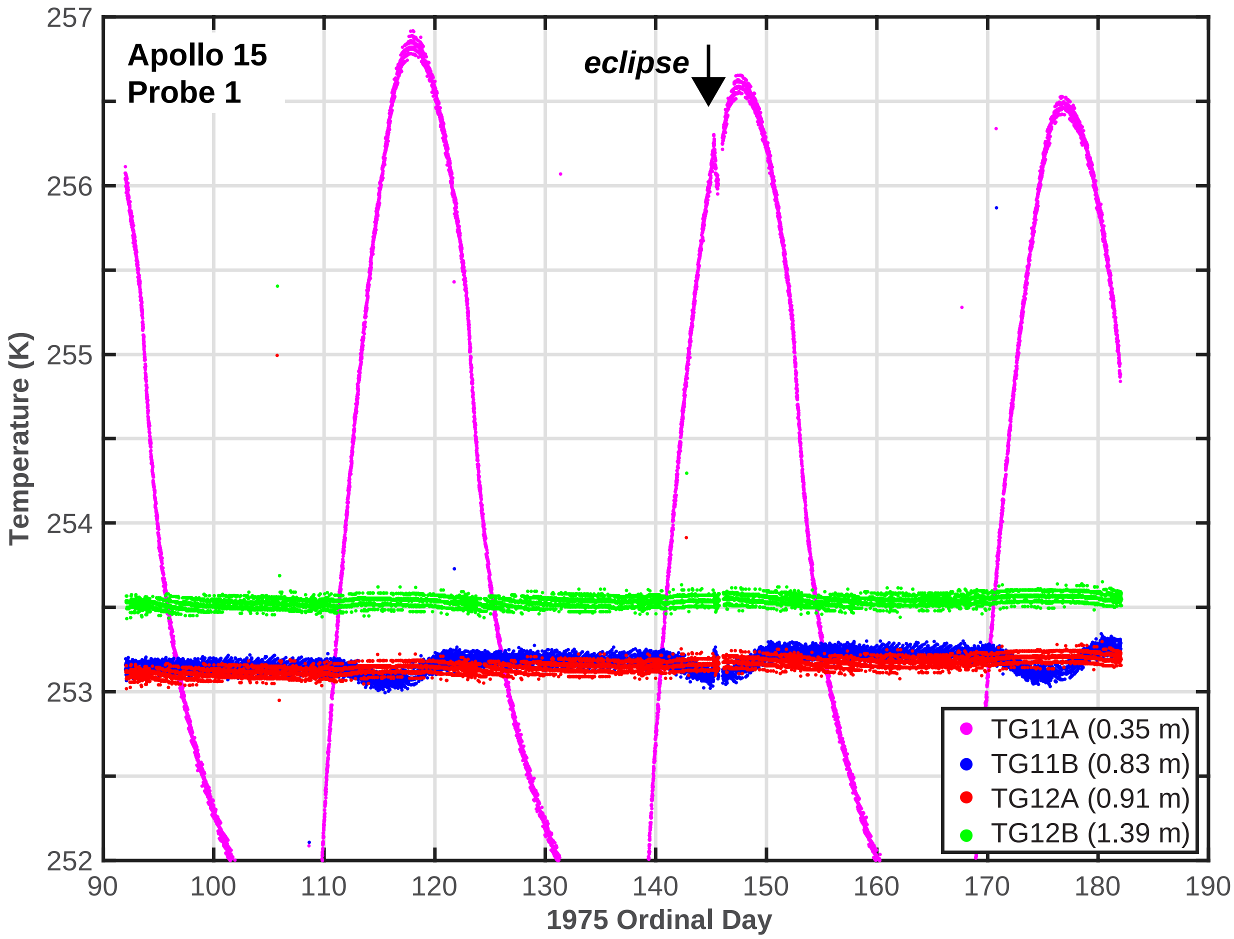

Figure 9. A magnified view of the temperature versus time records for the RTDs of Probe 1, Apollo 15 for the period of April through June 1975, restored for the present study.

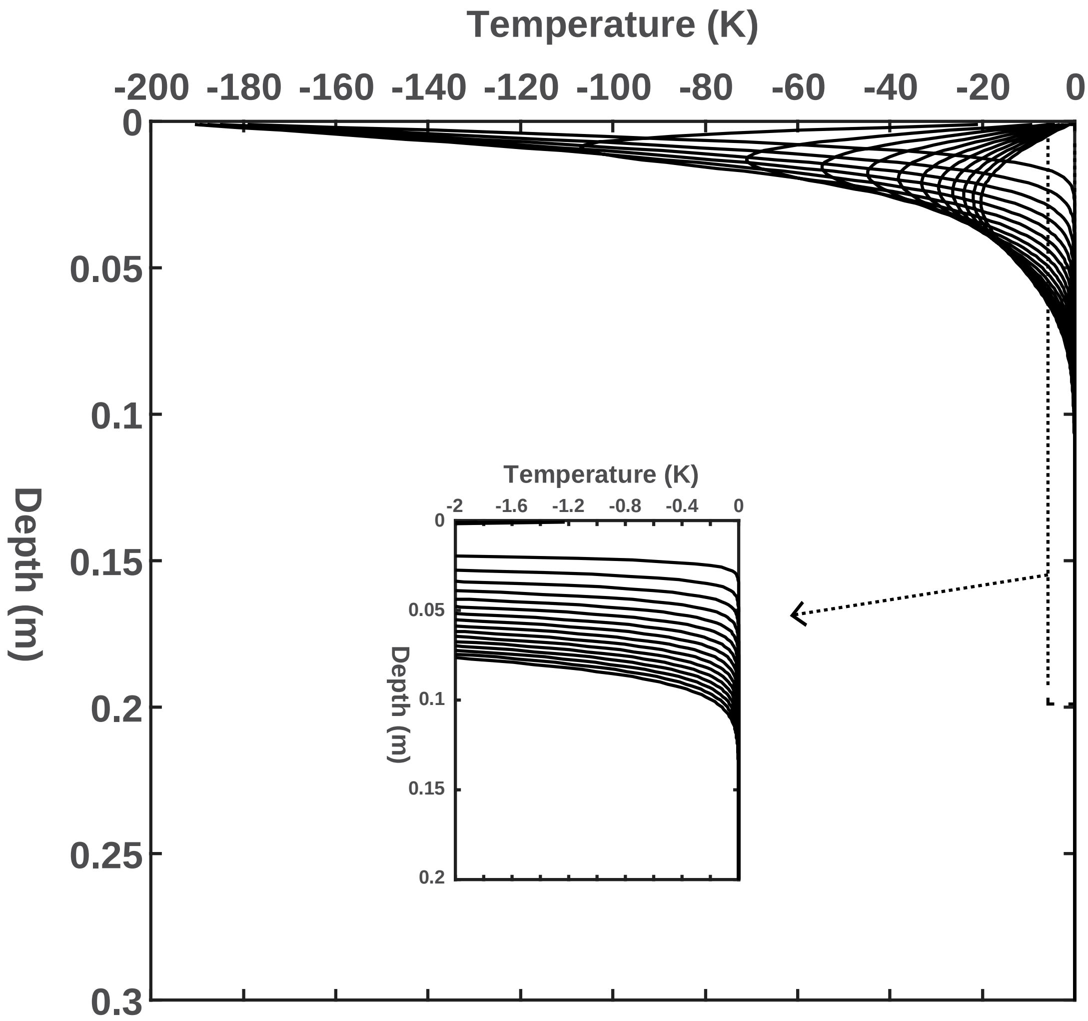

Figure 10. Temperature versus depth curves obtained from the mathematical model showing how a negative temperature drop by 200 K at the surface for 5.5 hours propagates into the subsurface. The curves are drawn with 1-hour time steps. The inset shows the magnified view of the same graph for a temperature range of -2 to 0 K.

Table 1. Equilibrium subsurface temperature values determined by the original HFE investigators.

Site	Probe#	Sensor	Depth (m)	Equilibrium Temperature (K)	Annual Fluctuation Amplitude (K)
Apollo 15	1	TG11A	0.35	---	0.29[D]
	1	TG11B	0.83	251.96[A]	0.058[D]
	1	TG12A	0.91	252.20[C] (252.28[A])	0.038[D]
	1	TG12B	1.39	253.00[A,C]	< 0.01[D]
	2	TG22A	0.49	---	0.305[D]
	2	TG22B	0.97	250.70[A]	0.056[D]
Apollo 17	1	TG11A	1.3	255.06[B,C]	0.021[D]
	1	TG11B	1.77	255.76[B,C]	---
	1	TG12A	1.85	255.91[B,C]	0.0038[D]
	1	TG12B	2.33	256.44[B,C]	---
	2	TG21A	1.31	256.07[B,C]	0.016[D]
	2	TG21B	1.78	256.44[B,C]	---
	2	TG22A	1.86	256.48[B,C]	0.0022[D]
	2	TG22B	2.34	256.82[B,C]	---

Data Sources: A: Langseth et al. (1972b), B: Langseth et al. (1973), C: Lauderdale and Eichelman (1974), D: Langseth (1977)

Table 2. A summary of the surface temperature increase estimates based on the 1-D heat conduction model of the instantaneous heating of the surface.

Probe	Surface Temperature Increase ($T_1 - T_0$) (K)	Thermal Diffusivity (m^2/s)	Thermal Diffusivity by Langseth (1977) (m^2/s)
A15 Probe 1	1.9	8.0×10^{-9}	6.0×10^{-9} to 1×10^{-8}
A17 Probe 1	3.5	8.0×10^{-9}	6.5×10^{-9} to 9.5×10^{-9}
A17 Probe 2	1.6	6.5×10^{-9}	5.5×10^{-9} to 7.0×10^{-9}