REEXAMINATION OF THE APOLLO 15 HEAT FLOW DATA TOWARD UNDERSTANDING POTENTIAL CAUSES OF THE LONG-TERM SUBSURFACE WARMING OBSERVED. S. Nagihara[1] Y. Saito[2], and P. T. Taylor[3], [1]Texas Tech University, Lubbock, TX 79409 (seiichi.nagihara@ttu.edu), [2]Institute of Space and Astronautical Science, Sagamihara, Japan, [3]Goddard Space Flight Center, Greenbelt, MD 20711.

Introduction: Geothermal heat flow probes were deployed at the Apollo 15 and 17 sites as part of the Apollo Lunar Surface Experiment Packages (ALSEP) [1,2]. The heat flow instrument at the Apollo 15 site operated from July 1971 through January 1977, and the one at the Apollo 17 site operated from December 1972 through September 1977 [3]. Langseth et al. [4] used the data obtained from the time of deployment to December 1974 in their determination of the endogenic (internal) heat flow at Sites 15 and 17 (21 mWm^2 and 16 mW/m^2, respectively).

It was evident then that temperatures of the subsurface reached by the probes (1.4-m depth at Site 15 and 2.3-m depth at Site 17) were steadily rising even at the depths well beyond the influence of the diurnal and seasonal insolation cycles (Fig. 1). The same group of investigators explained that the astronauts' activity associated with the ALSEP package deployment altered the radiative properties of the lunar surface soil [4], for example, by lowering its albedo. That caused greater absorption of the solar heat by the lunar soil, and resulted in the gradual warming of the subsurface.

More recent investigators [5,6] offered an alternative explanation in which the 18.6-year-cycle precession of the Moon caused solar irradiance at the Apollo sites to gradually increase during the period of the ALSEP operation and resulted in the long-term warming. They also suggested that properly accounting for the precession effect may dramatically change the endogenic heat flow values from the previous estimates. Therefore, it is imperative that we determine the exact mechanism that caused the long-term warming.

This present study reexamines the**se** data from the Apollo 15 site to investigate the potential thermal effect of the precession to the lunar surface and subsurface thermal regime.

History of the Apollo 15 Heat Flow Data: At the Apollo 15 site, two heat flow probes were deployed in drill holes a short distance apart [1]. Probe 1 reached 1.4-m depth and Probe 2 reached 1-m depth. The thermal sensors of the probe were divided in two major sections. The lower section (~1-m long) consisted of 8 bridge-sensors utilizing platinum resistance thermometers, while the upper section (~1.5-m long) consisted of a string of 4 thermocouples. Probe 1, because it did not penetrate fully into the ground, left the 3 uppermost thermocouples on or above the surface. Probe 2 left the uppermost platinum thermometer and all the thermocouples exposed on or above the surface.

The 1971-1974 data used by Langseth at al. [4] were later archived at the National Space Science Data Center (NSSDC) of the Goddard Space Flight Center. The data from the Apollo 17 heat flow experiment were handled in the same way.

The Apollo 15 ALSEP package transmitted heat flow data till January 1977. However, during the final 13 months, the data "had been anomalous" according to the ALSEP termination report [3]. The post-1974 portion of the heat flow data for both sites had been forgotten for many years after the conclusion of the Apollo program. Langseth passed away in 1997. In the early 2000s, Yosio Nakamura at University of Texas (UT) and his collaborators at the Japan Aerospace Exploration Agency recovered the heat flow data for some months in 1976 and 1977 from the work tapes stored at UT.

These recently restored 1976-1977 records show that the data from the Apollo 15 subsurface platinum thermometers were very noisy and not reliable, while the thermocouple sensors operated normally till mid-1976. Records from the entire year 1975 are still missing. In addition, it has been known that the 1971-1974 data archived at NSSDC do not contain the full record from that period. They had been resampled from the original 7.2-minute measurement intervals to ~60-minute intervals. The present authors, in collaborations with NSSDC researchers and Nakamura, are currently trying to recover the full records from both Apollo heat flow experiments.

The Long-term Warming: Figure 1D shows the temperature-time records of the two of the lower-most platinum resistance thermometers of Probe 1 of the Apollo 15 site from July 1971 to December 1974. In weeks after the deployment, the temperatures fell quickly, as the frictional heat, introduced by drilling activities, dissipated into the surrounding. After bottoming out by the end of 1971, temperatures of the subsurface rose slowly. At 0.9-m depth, temperature increased by ~1 K in the 3-year period, though it was also influenced by the annual (seasonal) variation of insolation at the surface. At 1.4-m depth, almost free from the seasonal effect, temperature rose more than 0.5 K over the same period. A similar trend was observed also at the Apollo 17 site. This multi-year warming trend in the subsurface is the focus of a recent debate.

Because the deeper sensors experienced less warming than the ones shallower, it is most logical to suggest that heat input on the lunar surface increased after the probe deployment and resulted in the subsurface warming.. Reduction in the soil albedo, by the previously mentioned astronaut activity, would increase heat input to the ground. However, there has been no experimental demonstration or theoretical models suggesting that lunar regolith-like soil would have a lower overall albedo after it has been walked upon than before.

Alternatively, in 1971-1976, the 18.6-year orbital precession positioned the Sun at higher altitudes in summer months over the lunar surface than in previous years. The difference in the lunar diurnal maximum temperatures between the summer and the winter gradually increased from 1972 to 1974 at the Apollo 15 site (Fig. 1B). That is consistent with the changes in solar incident angle expected for the precession. Note that at the Apollo 15 site the seasonal variation coincides with that of the southern hemisphere of the Earth.

Solar heat input on the lunar regolith is largely controlled by the incident angle and the duration of the sunlight. We obtained the duration of the insolation for each lunation from mid-1971 to 1974 from the surface temperature record (Fig. 1A). In picking the timing of the sunrise, we chose the time of the first 1-K (or more) increase seen by the uppermost thermocouple that lead to a faster warming. For the sunset, we picked the time of the steepest temperature drop. The reader should note that we used the datasets previously archived at NSSDC for this analysis, and because of the low sampling rate, these timings may be off by an hour. We believe that the scatter of the plot can be attributable to the uncertainty of the sunrise and sunset timings. The smooth curve fitted to the plot, which is a moving average of 3 lunations, shows that the insolation period in summer months steady increased from 1972 to 1974. Interestingly the longest lunar day occurs about a month after the day of the highest surface temperature (summer solstice). The discrepancy is probably due to the local terrain influencing the sunrise and sunset timings.

One of the possible observational indicators of heat input to lunar regolith is the pre-sunrise surface temperatures, because their variation depends on the total, day-time heat input and the thermal inertia of the regolith. The records from the Apollo 15 site show that pre-sunrise temperatures increased by ~0.5 K every summer in cync with the peaking of day lengths, and steadily till 1976 (Fig. 1).

Conclusions: The increase in the length of the summer day, the summer maximum surface temperature, and the pre-sunrise surface temperature at the Apollo 15 site all seem to be consistent with the hypothesis that the change in solar incident angle associated with the precession increased the overall heat input to the lunar regolith. In further testing the hypothesis, it is imperative that we find the missing 1975 data and fully restore the data with 7.2-minute intervals.

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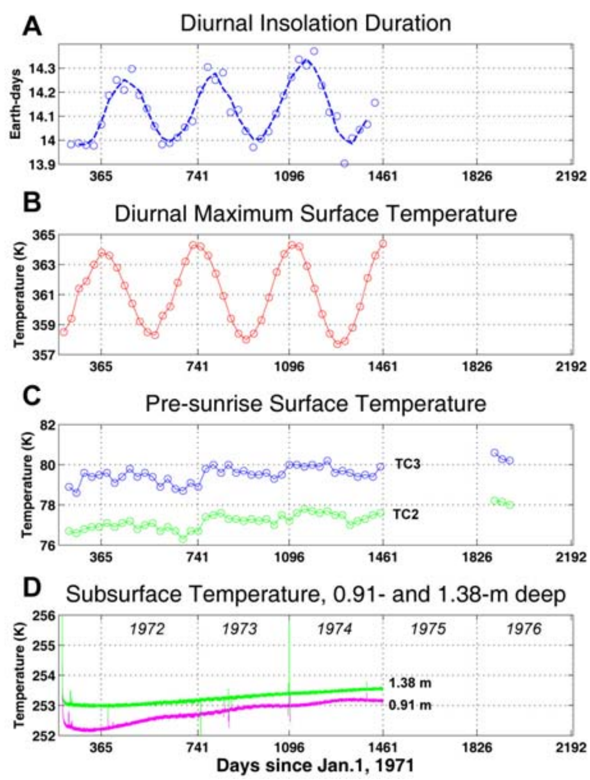

Figure 1 A): duration of insolation per lunation, derived from the surface temperature records of Probe 1, the Apollo 15 heat flow experiment. B): diurnal maximum surface temperature per lunation. C): Pre-sunrise surface temperatures per lunation. D): records from the two of the lowermost, subsurface platinum thermometers.