Lunar Heat Flow: Regional Geophysical Modeling of the Apollo Landing sites.

M.A. Siegler, S.E. Smrekar, Jet Propulsion Laboratory, California Institute of Technology
(MS 183-601, Jet Propulaion Lab, 4800 Oak Grove, Pasadena, CA, 91109, matthew.a.siegler@jpl.nasa.gov)

Introduction: We re-examine the Apollo Heat Flow Experiment in light of new orbital data. Using three-dimensional thermal conduction models, we examine effects of crustal thickness, density, and radiogenic abundance on measured heat flow values at the Apollo 15 and 17 landing sites. These models show the importance of regional context for interpreting heat flux measurements. For the Moon, we find measured heat flux can be greatly altered by deep sub-surface radiogenic content and crustal density. However, total crustal thickness and the presence of a near surface radiogenic-rich ejecta provide less leverage, partially due to newly revised thinner crustal values [10,12], representing only minor (<1.5 mWm^{-2}) perturbations on surface heat flux at these Apollo sites.

Background: The two successful Apollo Heat Flow Experiments (HFE), differ from each other dramatically, with the Apollo 15 measured heat flux of 21 ± 3 mWm^{-2} and the Apollo 17 values of 15 ± 2 mWm^{-2} [1]. Many explanations have been put forward to explain these differences, but no single coherent model has looked at the relative impact of combining them.

Previous models to explain the differences between the Apollo HFE measurements can be summarized into 4 classes: **1)** *Crustal thickness variations* [1], **2)** *Crustal density variations* [2,3], **3)** *Near Surface radiogenic (KREEP) enrichment* [4], *and* **4)** *Deep radiogenic (KREEP) enrichment* [5]. Large lateral temperature changes at depth (~50 K) over short distances (~10 km) will also affect heat flow, but are only an important factor in the polar regions of the Moon. We examine these effects in detail:

1) Crustal thickness variations are a fundamental parameter controlling the loss of heat from the interior. Thicker crust will generally provide a higher surface heat flux, due to higher radiogenic concentrations in the crust as compared to the mantle. A thicker region of crust will also inhibit lateral conduction of heat from the deep interior, as the mantle conducts heat more efficiently than the low density crust. Here we examine the implications of newly revised and reduced estimates of crustal thickness and porosity based on GRAIL mission results [10].

2) Crustal density variations have been sited by several authors [2,3] as a plausible cause for elevated the heat flux at the Apollo 15 site. In this model, denser, higher thermal conductivity mare focus heat from the surrounding battered highlands crust. The thicker the mare and the larger the conductivity contrast, the greater this focusing will be. This creates a higher heat flux within the mare boarder and lower heatflux in the surrounding crust. New models of mare thickness and impact studies [6,7] help constrain how large of an effect such focusing will have. New depth dependent GRAIL models of lower than expected crustal density also have a dramatic effect on geometric focusing, generally inhibiting lateral heat transport and slowing loss of heat from the Moon as a whole [10].

3) Near surface radiogenic enrichment in the form of a buried ejecta blanket has been suggested to result from the Imbrium impact [8,4]. The impact appears to have dredged up deeper lying radiogenic material, which is detectable on the lunar surface [11]. Later impacts would have mixed this surface material into the upper crust, limited by the radiogenic concentration of the initial ejecta blanket.

4) Deep radiogenic enrichment models propose the presence of a regional layer of enhanced radiogenic content. Some models of a cooling magma ocean predict that radiogenics will concentrate in the last material to solidify [2,5]. Past modeling [5] showed that a KREEP rich subcrustal layer could explain the differences between the Apollo HFE measurements. We find that new seismic and gravity data [10,12] derived crustal thikness values limit a KREEP layer at the base of the crust to be much thinner than assumed by [5].

Model: To combine all of these effects, we have developed a 3-D finite element thermal conduction model within the Comsol Multiphysics work environment. This tool produces an irregularly spaced mesh, allowing complex shapes, such as real topography and crustal thickness models.

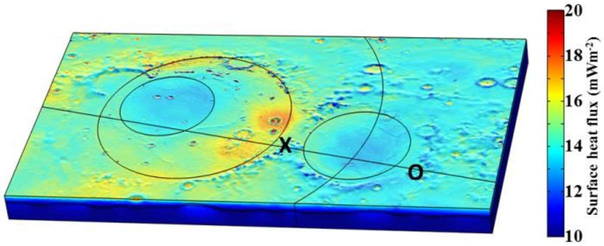

Figure 1: Nominal thermal model heat flux (Wm^{-2}) assuming crustal and radiogenic near surface KREEP heat production (with 1500 × 2700 km × 150 km dimensions). The "X" marks the Apollo 15 and "O" Apollo 17 linked by a linear transect in Figure 2.

Figure 1 shows the model area, which includes the two Apollo HFE sites and the entirety of mares Imbrium and Serenitatis. This area should capture the crustal region that could affect the HFE results. This model includes a 38 km average crust thickness [9,10] above a layer of mantle material which ends at 150 km depth (shallow enough to guarantee no convection is present). The red line marks a transect through the Apollo sites (X=A15, O=A17) along which model output is plotted (in Figure 3). The two smaller circles represent areas modeled as mare with thicknesses set by [6,7].

The base model assumes mare, crustal and mantle thermal properties and radiogenic composition from [5] with updated density models from early GRAIL data [10]. Observed surface radiogenics [11] are also included as a thin surface layer, mixed within the crust. A variable thickness unit was also added to the base of the crust, which can be used to examine a hypothetical KREEP-rich layer.

Results: Our nominal model (with a constant 2550 kgm^{-3} density, Figure 1) includes only the effects of radiogenics in the crust and near surface consistent with GRS data [11]. The model is given a 10 mW m^{-2} basal heat flux to represent heat flow from the mantle.

Figure 2 illustrates a transect along the transect line in Figure 1. Edges of the mare are marked with dotted lines. The blue line shows that a nominal crustal radiogenic concentration is not enough to create the heat fluxes observed at both Apollo sites. Even if mantle heat fluxes are much higher than the assumed 10 mW m^{-2}, crustal thickness variations alone will not explain the contrast between the two Apollo sites.

Figure 2 also shows 2 other model results for a crust with decreasing density near the surface (falling as e^{-5km}). This low density crust causes a stronger density contrast at the Mare-Highlands boundary, and thus greater heat shunting, resulting in a spike in heat flux near the boundary (as in Hypothesis #2). The first of these models (in green) adds a sub-crustal KREEP layer. This layer is 2.5 km thick (¼ the thickness used in [5]) and is circular, 1200 km in radius. This combinationrequires a higher mantle heat flux (12 mW m^{-2}) to be consistent with Apollo 15 and 17 HFE measurements.

A second model, in red, shows that a thicker, 5km (1/2 the thickness used in [5]), KREEP layer can raise heat flux at the Apollo 15 site over that at Apollo 17 site by enough that only 10 mW m^{-2} of mantle heat flux are required to match both data points within error.

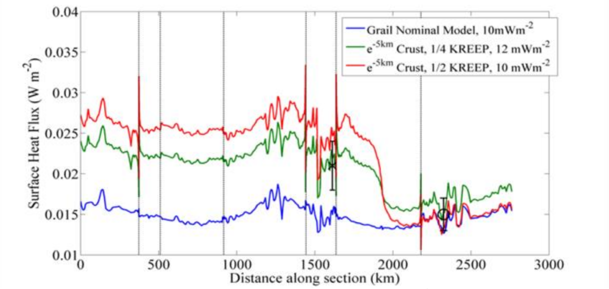

Figure 2: Comparison of model heat flux (Wm^{-2}) for a transect of the Apollo HFE sites. X marks Apollo 15 and O Apollo 17 with errors from [1].

Table 1 shows a suite of model combinations, the mantle heat fluxes they require, and the resulting temperature at depth at each landing site. These plausible variations constrain mantle heat fluxes to lie between 9 and 13 mWm^{-2}. This leads to a total mantle heat production of 2.8-4.1×10^{11}W. These heat flow values could imply that the lunar interior is similar to, or slightly less radiogenic than, the Earth's mantle; perhaps implying a considerable fraction of terrestrial mantle material was incorporated at the time of formation. These results may also imply that heat flux at the crust-mantle boundary beneath the Procellarum KREEP Terrain (PKT) is anomalously elevated compared to the rest of the Moon. These results also suggest a limited KREEP-rich layer exists beneath the PKT crust. If a subcrustal KREEP-rich layer extends below the Apollo 17 landing site required mantle heat flux can drop to roughly 7 mWm^{-2}, underlining the need for future heat flux measurements outside from the radiogenic-rich PKT region.

Heat Flux **A15: T at 150km** **A17: T at 150km**	¼ KREEP	½ KREEP	e^{-5km} Ejecta	¼ KREEP + e^{-5km} Ejecta	½ KREEP + e^{-5km} Ejecta
Nominal Crust	12mWm^{-2}	10 mWm^{-2}	13 mWm^{-2}	11 mWm^{-2}	9 mWm^{-2}
	1103 K	1100 K	1053 K	1051 K	1048 K
	986 K	872 K	1046 K	932 K	819 K
e^{-5km} Crust	12 mWm^{-2}	10 mWm^{-2}	13 mWm^{-2}	11 mWm^{-2}	9 mWm^{-2}
	1156 K	1047 K	1016 K	1007 K	999 K
	919 K	816 K	974 K	871 K	769 K

Table 1: Model result consistent with both Apollo 15 and 17 HFE values. White rows show mantle heat flux values found to be consistent with Apollo measurements. Grey rows highlight the reutling temperature at 150km depth under each site.

References:[1]Langseth *etal.*,1976, LPSC 7; [2]Warren and Rasmussen, 1987, JGR 92; [3]Connel and Morton, 1975, The Moon 14; [4]Hagermann and Tanaka, 2006, GRL 33; [5]Wieczorek and Phillips, 2000, JGR 105; [6]Thomson, 2009, GRL 36 [7] Solomon and Head, 1980, Rev Geophys and Space Phys 18; [8]Haskin, 1998, JGR 103; [9]Ishihara, 2009 GRL 36; [10]Wieczorek *et al.*, 2012, Science; [11]Lawrence *et al.*, 1998, *Science* 281. [12] Lognonné *et al.*, 2003