CRUSTAL EFFECTS ON LUNAR HEAT FLOW.

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Introduction: In light of new spacecraft data and advances in computer modeling tools, a fundamental questions about the Apollo Heat Flow Experiments (HFE) and their implications for the lunar interior can now be addressed in unprecedented detail. Recent crustal thickness models from the GRAIL and Selene missions, laser altimetry data from the LRO and its predecessors, and crustal radiogenic composition from several Gamma ray instruments can all be combined with thermal models to produce major advances in our ability to predict local heat flow. The Apollo HFE will serve as a calibration for global models. These models will also help separate the importance of several competing theories for why the two Apollo HFE sites differ and what implications that has on mantle heat production.

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 14-16 ± 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 thermal conductivity variations* [2,3], **3)** *Near Surface radiogenic (KREEP) enrichment* [4], *and* **4)** *Deep radiogenic (KREEP) enrichment* [5]. Large 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.

1) Crustal thickness variations will affect surface heat flux in two district ways. The first, the average abundance of radiogenic crust, requires only a 1-D thermal model. As the minerals that form the crust contain more radiogenic material than the mantle, a thicker crust will lead to a higher heat flux [1]. The second effect requires a 3-D thermal model, as a thicker crustal root will receive mantle heat flux from both the bottom and sides.

2) Crustal thermal conductivity variations have been sited by several authors [2, 3] as a plausible cause for elevated heat flux at the Apollo sites. 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 heat flux in the surrounding crust. New models of mare thickness and impact studies [6, 7] will help constrain how large of an effect such focusing will have.

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 is suggested to have dredged up deeper lying radiogenic material and will be well mixed with less radiogenic crust. This would provide higher radiogenic concentrations nearer to the Imbrium basin. The subsurface distribution of the material or its horizontal extent are not addressed in this model [4].

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 [9]. Such a layer may be the source of surface KREEP material. If this layer is global in extent, its effect would be similar to an increase in mantle heat production. [5] show that the subsurface temperature below such a layer may be large enough to cause melting in the mantle, further increasing heat flow at the surface. The presence of KREEP at depth below Apollo 17 but not 15 could explain the measured differences [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.

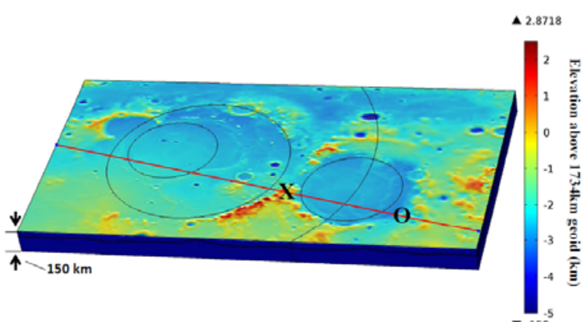

Figure 1: Basic 3-D thermal model including LOLA topography and Selene crustal thickness. X marks Apollo 15 and O Apollo 17. The red line identifies the transects in Figure 3.

Figure 1 shows the basic model area, which includes the two Apollo HFE sites and the entirety of mares Imbrium and Serenitatis. This region should capture the crustal region that could affect the HFE results. This model includes crust with thickness values of [10] above a layer of mantle material which ends at 150 km depth. The red line marks a transect through the Apollo sites (X=A15, O=A17) as plotted in Fig 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 [11]. Observed surface radiogenics [12] are also included as a thin surface layer, mixed within the top 5 km of the crust. A 10 km unit was also added to the base of the crust, which can be used to examine a hypothetical KREEP-rich region.

Preliminary Results: The nominal model is given a 4 mW m^{-2} basal heat flux based on [1], to represent heat flow from the mantle. This initial model includes only the effects of crustal thickness (and observed surface radiogenics). As seen in Figure 2, this gives a general enhancement in heat flux (except around the mare, where crust is thin and radiogenics sparse) to about 9 mW m^{-2}. There is no substantial increase in heat flux between the Apollo 17 and 15 sites.

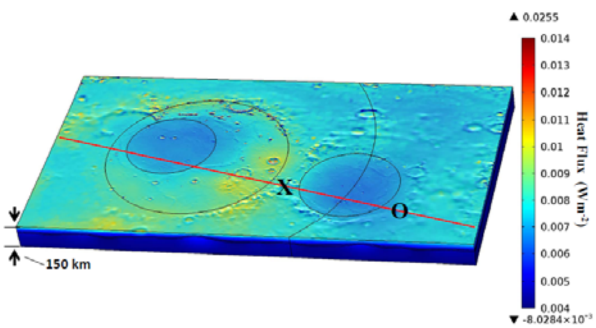

Figure 2: Nominal thermal model heat flux (Wm^{-2}) assuming crustal and radiogenic near surface KREEP heat production. X marks Apollo 15 and O Apollo 17. The red line identifies the transects in Figure 3.

Figure 3 (line 1, in blue) illustrates a transect along the red line in Figure 2, showing that a nominal crustal radiogenic concentration is not enough to create the heat fluxes observed at either Apollo site. Edges of the mare, which are generally areas of thinner crust, are marked with dotted lines. Even if mantle heat fluxes are much higher than the assumed 4 mW m^{-2}, crustal thickness variations alone will not explain the contrast between the two Apollo sites.

Line 2 (in green) shows model results assuming a crustal thermal conductivity half that of the mare (1 instead of 2 W m^{-1} K^{-1}). Here we see that due the relative thinness of the actual mare and crust as compared to early models [2, 3], thermal focusing (the small spikes at the mare edges) has a much smaller horizontal effect. At the actual mare/highland boarder, mare are thinner than 1 km [6]. Therefore, we believe conductive shunting may also be ruled out as a major component in explaining the Apollo HFE results. Interestingly neither model 1 or 2 increase Apollo 17 above the general lunar background.

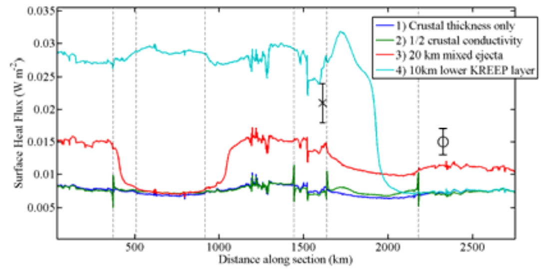

Figure 3: Comparison of model heat flux (Wm^{-2}) for a transect of the Apollo HFE sites. X marks Apollo 15 and O Apollo 17 with errors from [1].

Figure 3, Line 3 (in red) shows the effect of a near-surface radiogenic rich ejecta blanket surrounding the Imbrium basin. This ejecta blanket is fixed to observed surface Th concentrations [12] then mixed into the regolith below with decreasing concentration, here with a decrease of 1/e in the top 20km. Such an ejecta blanket shows some promise to both increase Apollo 17 above the global average and create a higher heat flux at Apollo 15. However, to be the sole cause of the enhancement, this requires the initial, non-mixed ejecta blanket to pure, or in eccess of pure, KREEP, and may be incompatible with ejecta formation models.

These models cannot however be done in isolation. Line 4 (cyan) in Figure 3 shows results assuming the model of [5], which assumes a 40 degree disc of radiogenic material lay at the base of the crust, centered on Imbrium (the largest radius arc in Figs 1 and 2). This model assumes this disc to be pure KREEP in concentration and 10 km thick. Interesting, this overpredicts the Apollo 15 heat flux, while underpredicting that of Apollo17. Therefore, we can already rule out as dramatic of a KREEP layer as previously modeled, and show that some other enhancement (either ejecta as in model 3, or higher mantle heat flux) is necessary. We will present combinations of these effects to constrain the most likely thermal state of the lunar crust in this region and discuss the implications for the bulk Moon.

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] Warren and Wasson 1979, Rev Geophys and Space Phys [10]Ishihara, 2009 GRL 36; [11]Wieczorek *etal*., 2012, Science; [12]Lawrence *etal*., 1998, *Science* 281.