Global Heat Flux Predictions for Landing Sites: Polar Advantages. M.A. Siegler, S. Nagihara M. Grott, S. Smrekar, J Feng, R Weber, P. Hayne, D. Paige, C. Neal

Introduction: Geothermal heat flux is a critical constraint on the interior composition and thermal state. Radiogenic elements within the crust and mantle of the Moon can be constrained by the net heat they produce. Radiogenic elements are refractory, meaning they partition in know ratios to other refractory elements, like Al, Ca, and Ti, leading to a robust constraint on the global elemental composition of the Moon. Combined with other geophysical measurements (such as seismic, gravity data, geodetics, and EM sounding) a robust model for the lunar interior can be produced.

Geothermal heat flux also controls the maximum depth to which water ice and other volatiles can be stable. Constraint of heat flow in the Polar Regions will also aid in estimates of the total volume of water available on the Moon and its most likely locations.

The Moon is known to have a highly asymmetric surface composition [e.g. Joliff et al., 2000; Lawrence et al., 2003] and crustal thickness [Wieczorek et al. 2013], which is suspected to result from interior asymmetries [Wieczorek and Phillips, 2000; Laneuville et al., 2013]. This is likely to cause a highly asymmetric surface heat flux, both past and present.

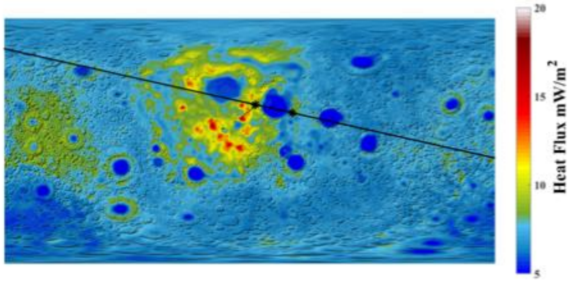

Figure 1: Global heat flux model based on the surface Th representing 10% of the crust.. The black asterisks mark the Apollo 15 and 17 HFE sites. Black line is a transect used in Figure 3.

Currently, we have only two in-situ constraints on the geothermal heat flux of the Moon, from the Apollo 15 and 17 missions. As part of the ALSEP instrument deployment, the Apollo Heat Flow Experiment (HFE) probes reached depths of about 1.5 and 2.5m, respectively constraining the local heat flux. Unfortunately, these two sites lie on the edge of a highly radiogenic-rich region known as the Procellarum KREEP Terrain (PKT) [Jolliff et al., 2000], identified by a large increase in crustal Th (Fig. 1) as measured by the lunar prospector Gamma Ray Spectrometer [e.g. Lawrence et al., 2003]. These areas therefore provide limited leverage on the understanding of the present thermal state of the lunar interior and its composition. We require further heat flow measurements beyond our two-point Apollo era measurement.

Here we present the results of new models of global lunar geothermal heat flux. We synthesize data from several recent missions to constrain lunar crustal radiogenic composition (Fig. 1), thickness (Fig. 2) and density to provide global predictions of the surface heat flux of the Moon. We also discuss implications from new surface heat flux constraints from the LRO Diviner Lunar Radiometer Experiment and Chang'E 2 Microwave Radiometer.

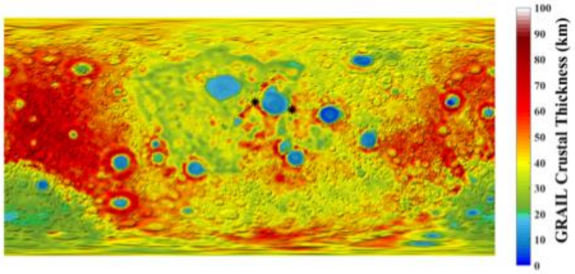

Figure 2: Global Crustal Thickness map from GRAIL "model 4" [Wieczorek et al.,2013].

In the models here we use surface composition [e.g. Lawrence et al., 2003] and crustal thickness [Wieczorek et al., 2013], to create plausible forward models for the variation of heat flux across the surface of the Moon given different fractions of a high Th surface layer and deeper, less radiogenic crust.

Fig. 1 shows an example of such a model, with predicted global surface heat flux if the crust were composed of 10% surface Th composition and 90% "typical feldspathic crust" with composition from Wieczoreck and Phillips, [2000]). The black line in Figure 1 connects the two Apollo heat flow sites. Figure 3 shows resulting surface heat flux for various models mixing surface Th and average crustal materials with an assume mantle heat flux of 4mWm^{-2}. Here we see the two Apollo values and their current error estimates plotted against these models.

Changes in mantle heat flux will cause a vertical shift of the lines in Fig. 3. Therefore, the two Apollo sites are a particularly bad place to constrain mantle composition as one could interchange mantle with enhanced lower-crustal heat production. This could be mitigated by landing in an area where radiogenic concentration is not believed to change much with depth in the crust and/or area that has very thin crust. Additionally, a proposed sub-crustal KREEP layer [e.g. Wieczorek and Phillips, 2000] would cause elevated values for points within the PKT, affecting both Apollo sites [e.g. Siegler and Smrekar, 2014]. Measurements in a region far from the PKT will mitigate this uncertainty.

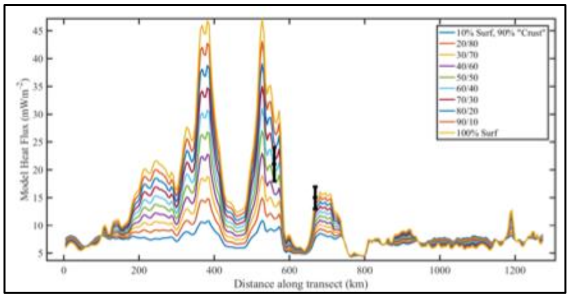

Figure 3: Forward model of possible global heat flux along transect line in Figure 3 showing that Apollo sites poorly constrain crustal composition.

Advantages of a South Polar Landing Site: The Lunar South Polar Region could be an advantageous location to measure geothermal heat of the Moon. As shown in the global perspectives in Figure 5 (left showing the standard stereographic view of the pole, right showing the pole in relation to the PKT), the South Polar region is far from the high Th anomaly of the PKT, with most accessible near side locations also being well outside the slightly elevated South Pole Aitken basin (SPA). The area outside of SPA also has fairly uniform crustal thickness.

The low surface Th in the polar region implies that a geothermal heat flux measurement near the poles is likely to be directly reflective of the surface composition and crustal thickness, much as a continental heat flux measurement on Earth [e.g. McLennan and Taylor, 1996]. With GRAIL constraints on crustal thickness [Wieczorek et al., 2013], a robust constraint of crustal and mantle heat flux components can be derived. Such a measurement would be strengthened by a coincident seismologic measurement of crustal thickness.

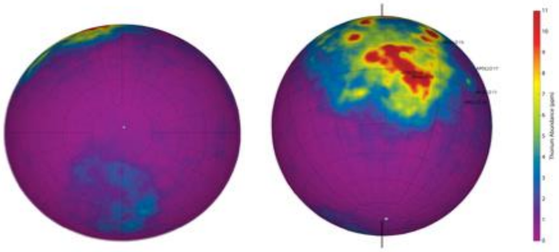

Figure 4: Global Th map from Lunar Prospector Neutron Spectrometer in spherical projection to highlight low surface Th in near polar region.

The South Polar Region also has an advantage of having locations with very low solar illumination. In such areas, diurnal thermal variations will be minimized. Therefore, the amplitude of thermal variations at depth will also be minimized (**Figure 5**), potentially allowing for a much shallower measurement to constrain geothermal heat productions (e.g. 1m instead of 2-3m).

Additionally, thermal conductivity of lunar regolith is highly temperature dependent [e.g. Woods-Robinson, et al., 2019], so a cold area will have much lower thermal conductivity regolith. This will even further diminish the depth of penetration of surface thermal perturbations (making easier deployment) and create a steeper (easier to measure) thermal gradient for the same geothermal heat flux (again, **Figure 5**).

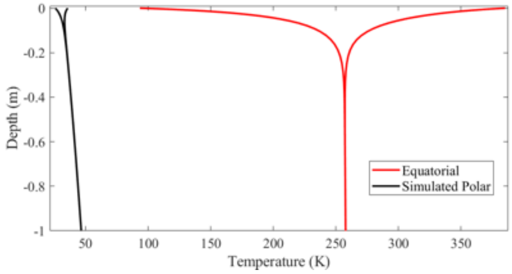

Figure 5: Likely thermal profiles with depth for an equatorial site vs PSR/near polar site. Note the polar surface temperature perturbation is shallower and the deep gradient steeper, making near polar heat flux a potentially "easier" measurement.

A South Polar deployment of a geothermal measurement would be a valuable addition to a global geophysical network of the Moon. Such a location would be valuable for a dispersed global network both of heat flow and seismic measurements. However, making a thermal measurement too close to a permanently shadowed region (PSR) could cause substantial lateral heat flux (within roughly 1 PSR radius). While interesting, might negate the ability to constrain geothermal heat by drawing heat into the PSR if a station is placed too close to a cold area. With that caveated, the South Pole has the advantage of being far from the PKT, but without the thick crust that dominates most of the lunar farside. This important measurement may be an ideal candidate for part of the scientific instrument package on our return to the Moon.

References: [1] Lawrence et al., 2003, JGR 108(E9) [2] Wieczorek and Phillips, 2000 JGR 103(E1), 1715-1724. [3] Laneuville et al., 2013 JGR, 118(7), 1435-1452 [4] Jolliff et al., 2000 JGR 105(E2), 4197-4216 [5] Wieczorek et al., 2013 Science 339, no. 6120 (2013): 671-675 [6] Siegler and Smrekar, 2014, JGR 119(1), 47-63 [7] McLennan and Taylor, 1996 The Journal of Geology, 104(4), 369-377.