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Ejecta deposit thickness, heat flow, and a critical ambiguity on the Moon

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[1] The Apollo lunar heat flow measurements gave values of 21 and 16 mW m⁻² which, after extrapolation based on thorium abundances, yields a global estimate of 18 mW m⁻². A refinement of the assumptions of the subsurface structure and the resulting focusing of heat flux later led to a revision of the global value to 12 mW m⁻². We think that to date none of the models linking the Apollo heat flow measurements has sufficiently highlighted a critical source of ambiguity. Little attention has been paid to the full magnitude of the uncertainty in these measurements caused by near-surface Thorium abundances and the local thickness of the ejecta blanket generated by the Imbrium impact. In a simple study we show that lunar heat flow is contingent upon the thickness of the ejecta blanket of the hypothetical impact. A model with an exponential decrease of Th concentration with depth can explain the difference in surface heat flow between the Apollo 15 and the Apollo 17 measurements. A constant Thorium concentration within the ejecta layer amplifies this effect. The variation in local surface Th abundance, if taken as representative of the subsurface Th distribution within the ejecta blanket, amplifies the uncertainty. We conclude that further measurements are essential for making well-founded statements about the subsurface abundance of radioactive elements, mantle heat flux and the thermal state of the Moon. **Citation:** Hagermann, A., and S. Tanaka (2006), Ejecta deposit thickness, heat flow, and a critical ambiguity on the Moon, *Geophys. Res. Lett.*, 33, L19203, doi:10.1029/2006GL027030.

1. Introduction

[2] With the scientific interest in the Moon rekindled anew, it appears timely to look at the Apollo heat flow measurements and their impact on models of lunar origin and evolution. Lunar heat flow measurements were carried out during the Apollo 15 and 17 missions, at Hadley Rille and Taurus Littrow. First estimates of 33 mW m⁻² ± 15% at Hadley Rille were soon revised and final estimates for the two sites were 21 and 16 mW m⁻² ± 15%, respectively [Langseth *et al.*, 1972, 1976]. Assuming these sites were representative, a global value of 18 mW m⁻² was estimated after extrapolation, suggesting a significant difference in heat flow. Rasmussen and Warren [1985] and Warren and Rasmussen [1987] finally suggested adjusting the Apollo measurements for the effect caused by the measurement site being located

near the highlands/mare boundary, resulting in a focusing of the heat flux by a variation of megaregolith thickness. Their corrected value was 12 mW m⁻², so the bulk U content they derived was less than half of what Langseth *et al.* [1976] had estimated. Recently, Saito *et al.* [2003] have shown how location and magnitude of the focusing effect are highly dependent upon location and angular orientation of the transition from thick to thin megaregolith, suggesting that the final word on the Apollo values has not yet been spoken. Moreover, Wieczorek and Huang [2006] showed how important other factors like e.g., the precession of the lunar orbit are to the analysis. In addition to these fundamental problems in interpretation, the design of the Apollo heat flow experiments limits accuracy and reliability of the results. On the one hand, the nominal insertion depth of 3 m was almost never achieved due to technical difficulties. On the other hand, the insertion procedure and setup limit the reliability of the active thermal conductivity measurements; a fiberglass tube lined the borehole, making thermal contact very difficult to estimate.

2. Heat Flow From a Th-Enriched Ejecta Layer

[3] Give or take a few mW m⁻², the Apollo measurements should be able to tell us what the local and global crustal abundances of radioactive elements are and what the heat flow from the mantle could be. This brings up the question of the (in)homogeneity and thickness of KREEP-rich surface and subsurface material, a potentially substantial contribution to the surface heat flux because of its high content of radioactive heat sources. We are therefore trying to re-assess the relevance of the Apollo heat flow data against the assumption that material rich in incompatible elements was excavated from what is known as the Procellarum KREEP Terrane (PKT) and re-distributed on top of a refractory-poor crust in the Imbrium impact event [Haskin, 1998]. The surface Th abundance derived from the Lunar Prospector gamma-ray spectrometer shows considerable variation in surface concentration within what can be considered as the Imbrium ejecta. Moreover, the thickness of the ejecta layer is dependent on the size of the original impact basin and varies with distance from its center.

[4] Lawrence *et al.* [1998, 2000, 2003] give the thorium distributions measured by the LP-GRS instrument. According to their data, available on the PDS, thorium abundances in the region of the Apollo 15 and Apollo 17 landing sites are 5.237 and 2.74 ppm respectively. It needs to be noted that these are indeed *surface* concentrations, gamma-ray spectroscopy being sensitive on scales of m below the surface [e.g., Evans *et al.*, 1993], whereas this study looks at the km depth range. For example, in the PKT itself, low Th mare basalts only a few km thick could be covering a thorium rich crust, and thus the surface Th abundance is probably not

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representative. In addition, the LP-GRS data have a resolution of approx. 30 km, so that the influence of low Th mare basalts within a sensor footprint might conceal a much higher Th surface abundance. Measurements near the Apollo 17 site show that about 50 km NE, i.e., farther away from the mare-highland boundary, surface Th abundances are some 0.5 ppm higher, and in the immediate vicinity of the Apollo 15 landing site, many measurements in the 6–7 ppm range suggest a probably higher abundance. The increase of Th concentrations towards the center of the Imbrium impact is compatible with cratering models, resulting in an excavation of Th-rich material from an enriched crust, possibly from greater depths. As Warren [2001] pointed out, we should expect more material from greater depths at distances closer to the center of the impact [see also Stoeffler *et al.*, 1975]. Moreover, material closer to the crater rim should also contain more primary ejecta and less substrate. In addition, ejecta deposit thickness falls as a power of $1/r$; Housen *et al.* [1983] suggest an approximate $\propto (R/r)^{e_r}$ local ejecta blanket thickness function, with e_r ranging from 2.5 to 3, R being the transient crater radius and r the distance from the crater center.

[5] The approximate location of the Imbrium impact can be estimated from geological features [e.g., Wilhelms and McCauley, 1971] as well as topography, gravity and crustal thickness estimates. We have taken the center location given by Wieczorek and Zuber [2001], who give 37.5°N latitude and 19°W longitude, based on a crustal thickness model. This should be a reasonably accurate indication for the purpose of our study. As for the possible location of the PKT, one can take the locations of the dipole axes of global elemental distributions as given by Feldman *et al.* [2002] as an indication.

[6] Assuming that the impact occurred at 37.5° and 19°W, the two Apollo sites are consequently 675 km and 1400 km away from the assumed impact, which should result in a substantial difference in ejecta thickness between the two locations. Haskin [1998] pointed out that the Imbrium transient crater radius was likely to be in the range from 335 km to 485 km [Spudis, 1993], estimates supported by the relative proportions of Imbrium ejecta and substrate in the ejecta deposits. He modeled the thickness of the Imbrium ejecta deposits as a function of distance for these two radii. In a more recent study, Haskin *et al.* [2003] investigated the possible proportions of primary fragments in the ejecta more closely, based on a transient crater radius of 370 km [Wieczorek and Phillips, 1999]. We try to look at the potential impact of the ejecta blanket thickness and therefore we adopt the two extremes from Haskin's [1998] study, dubbing them the 'large crater' and the 'small crater' models.

[7] Assuming that Haskin's [1998] models limit the reasonable range of possible crater radii, we estimate the thickness H at the Apollo 15 landing site to be around 5.5 km for a 335 km "small" crater and 22 km for a 485 km 'large' crater. Similarly, we can estimate the ejecta layer at the Apollo 17 site to be 700 m and 2500 m respectively [cf. Haskin, 1998, Figure 3]. Of course, given the rapid decrease of deposit thickness with distance, these numbers are highly sensitive to impact location and transient crater size. Additional unknowns include total ejecta volume and ejecta launch angle. The uncertainties in our knowledge of these somewhat critical parameters do therefore not justify the use of elaborate cratering models and we consider the above thickness esti-

mates to be a useful guide for the purpose of our study. We can, however, assess the sensitivity of our model to the choice of parameters, varying the parameters used by Housen *et al.* [1983] in order to quantify the remaining uncertainties. The two Apollo landing sites would be 2 and 4.2 R away from the center of the 'small' impact or 1.4 and 2.9 R for a 'large' impact. We now look at extreme cases of the ejecta blanket thickness as suggested by Housen *et al.*'s [1983] near field scaling law. Haskin [1998] used 40°, so we vary the launch angle from 35° to 45°. We further vary Housen *et al.*'s A factor from 0.08 to 0.32, exponent e_r from 2.5 to 3 [Housen *et al.*, 1983] and D from 0.63 [Wieczorek and Zuber, 2001] to 0.83. (see Housen *et al.* [1983], Piekutowski [1980], Wieczorek and Zuber [2001] and references therein for these values). In essence, choice of crater radius and Housen *et al.*'s A dominate the uncertainty in the ejecta deposit thickness; A enters proportionally with a factor of 4, while the crater radius R contributes a factor of 5. The most favourable combination of parameters yields local blanket thicknesses of 20 km vs 1.5 km, whereas, according to the above bounds, the thinnest conceivable blanket is only 500 m and a few tens of meters thick at the two sites. Note, however, that the near-field approximation we used probably underestimates the real thickness by more than a factor of two for $r < 2R$, as Housen *et al.* [1983] illustrate. While all these parameters result in some quantitative differences in ejecta blanket thickness, they do not challenge our assumption that the ejecta blanket at the Apollo 15 landing site is probably substantially thicker than at the Apollo 17 site. The extreme cases, no matter how good a description of reality, show a factor of 7.5 to 15 between the two local thicknesses, and it is primarily this large factor that determines the ejecta deposit contribution to local heat flow. There is enough scope in other model parameters, such as the Th concentration or depth distribution, to make up for a substantial deviation from Haskin's model. Admittedly, a putative blanket of only 500 m cannot be expected to contribute more than some 0.5 mW M⁻², but one needs to keep in mind that this value was obtained using a combination of the most extreme of parameters and a rather poor approximation for $r < 2R$.

[8] Given the two crater radii and resulting deposit thickness estimates based on Haskin's [1998] model, we now estimate the contribution of the ejecta layer to the total surface heat flux. For this purpose, we use the usual ratios of 3.7, 2000 and 1.19E-4 for Th/U, K/U and K/K [e.g., Papike *et al.*, 1998]. We use three different estimates for the abundance of radioactive elements: in the nominal case, we assume the LP-GRS measurements at each location to be representative. Our nominal model of different Th concentrations is supported by Stoeffler *et al.*'s [1975] observation that material which originated from larger depths (and thus possibly containing more radioactive elements) is more abundant closer to the crater. Haskin *et al.*'s [2003] study also underpins the concept of a higher proportion of Th rich primary ejecta near the crater. In order not to overestimate the quantitative nature of this effect, we consider the possibility that either of the values is not representative in two further cases, i.e., we estimate the radioactive element abundances at the surface to be the same at both locations, either based on a 'high' Th abundance of 5.237 ppm (as measured at the Apollo 15 site) or on a 'low' Th abundance (i.e., the Apollo 17 site value of 2.74 ppm). We use the ejecta thickness

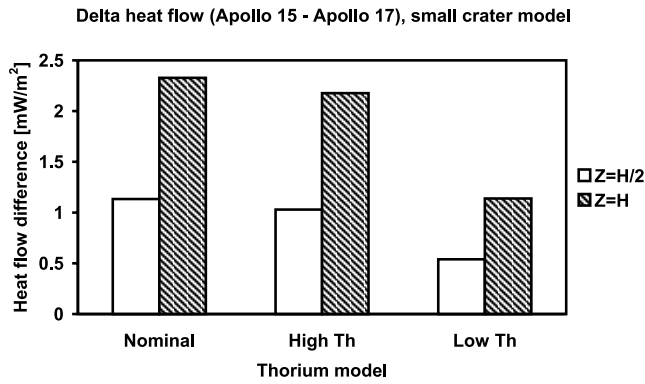


Figure 1. Difference in lunar heat flow between Apollo 15 and Apollo 17 landing sites caused by a Th-enriched layer whose thickness depends on the distance from the postulated Imbrium impact. Thorium concentration is an exponential function of depth. Skin depth is assumed to be equal to (shaded columns) or half (white columns) the thickness of the ejecta layer.

estimate of the ‘small crater’ model at the two landing sites, i.e., $H = 5.5$ km and 700 m respectively. In our first model we assume the Th concentrations c to be a function of depth z with

$$c = c_0 \exp\left(-\frac{z}{Z}\right), \quad (1)$$

where c_0 is the Th surface concentration and Z the skin depth. In two scenarios we use $Z = H$ and $Z = H/2$ at the two locations, c_0 being the surface concentration measured by LP-GRS. We calculate the heat flux contribution of the ejecta by integrating over the layer from $z = 0$ to $z = H$ and, finally, we compare the net difference between the two Apollo landing sites in surface heat flux resulting from each of the thorium abundance distributions, the delta heat flux value. The results are shown in Figure 1. We can see that a skin depth of $Z = H$ results in a difference in heat flux of more than 2 mW m^{-2} if c_0 equals the LP-GRS concentrations at *both* landing sites. This value remains largely unchanged if Thorium concentrations at both locations are around 5.23 ppm. Total heat flux from the ejecta layer at the Apollo 15 site is 2.5 mW m^{-2} . This model can contribute considerably to explaining the difference in lunar heat flow of 5 mW m^{-2} between the two landing sites as given by *Langseth et al.* [1976]. An increase of the ejecta layers to 12 km and 1.5 km respectively (i.e., considerably below the maximal layer thicknesses permitted) would explain the total difference. Similarly, a higher Th abundance — which is possible, as pointed out above — could contribute an extra 0.5 mW per ppm Th. If $Z = H/2$ (white bars), the difference in heat flow from the ejecta layer between the two locations becomes too small to explain the difference between Apollo 15 and 17.

[9] The ejecta generation by the Imbrium impact does not necessarily demand that the exponential depth distribution of radioactive elements be valid — we need to look at the possibility of a homogeneously enriched ejecta blanket, too. In our next model we therefore demonstrate how large

the heat flow contribution from the ejecta layer could potentially be.

3. Thorium Origin and Error Bars

[10] In our second model, radioactive element abundance within the ejecta layer does not decrease with depth, assuming that the exponential decrease used in our first model is not necessarily the only possible concentration function. We now compare the influence of total ejecta thickness, based on *Haskin's* [1998] ‘large’ and ‘small’ crater outlined above, again using the ‘nominal’, ‘high’ and ‘low’ Thorium concentration models. As is obvious from Figure 2, the expected difference in heat flow caused by the difference in thickness of the ejecta deposits can be of the order of 15 mW m^{-2} in the nominal case for the large crater model. There is little change if the 5.2 ppm Th value is representative for both Apollo sites. For the low Th abundance model we obtain a difference in heat flow of approx. 7 mW m^{-2} . Using the small crater model, i.e., thicknesses derived from an Imbrium transient crater radius of 335 km, the maximal difference in heat flux, is only $\sim 4 \text{ mW m}^{-2}$, which is still enough to explain the heat flow difference between Apollo 15 and 17.

[11] This effect is quite remarkable in that it shows that (a) it could be the thickness of the ejecta deposit layer alone (and thus, ultimately, the size of the Imbrium impact event) which causes the Apollo heat flow values to be different and (b) the Imbrium ejecta alone could contribute a substantial proportion of the surface heat flow. The magnitude of this effect might even surpass the influence of the boundary focusing effects demonstrated by *Rasmussen and Warren* [1985]. The difference in Th abundance between the two Apollo sites, on the other hand, is much subdued by the effect of the different ejecta blanket thicknesses. Notwithstanding the constraints imposed by bulk composition and thermal state, the maximal total heat flux at the Apollo 15 site (i.e., with an ejecta deposit thickness of 22 km and 5.237 ppm Th) from the enriched layer alone could theoretically be as high as 16 mW m^{-2} , more than enough to dwarf the entire contribution of lower crust and mantle, and could be even higher in

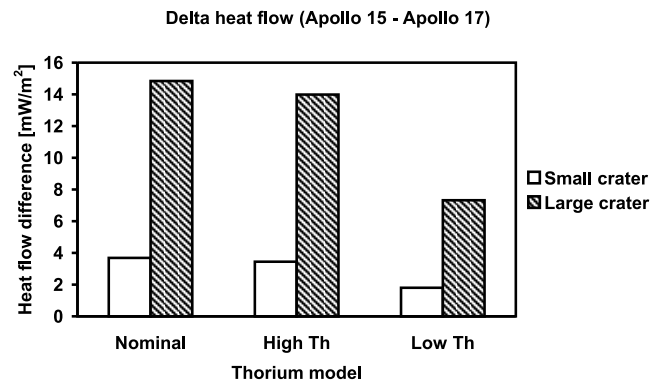


Figure 2. Difference in lunar heat flow between Apollo 15 and Apollo 17 landing sites caused by a Th-enriched layer whose thickness depends on the distance from the postulated Imbrium impact. Thorium concentration is assumed to be constant. We estimated layer thickness based on a crater diameter of 335 km (white columns) and 485 km (shaded columns) respectively.

the center of the PKT, where surface Th is a combination of pre-existing thorium enriched crust and Th-rich ejecta. This highlights the full extent of the ambiguity in interpreting the available lunar heat flow measurements: we probably do not have enough data points to derive definite conclusions with an acceptable degree of certainty.

[12] We have so far ignored many of the intricacies of impact cratering and the resulting ejecta distributions, instead focusing on parametric extremes. Assuming that the impact location is reasonably well known, we have looked at sensitivity to crater size, thorium abundance and Th depth distribution. A steeper decrease of the proportion of primary fragments with distance would increase the heat flow difference. However, it is the cumulative radioactive heat released below a location that matters, and thus surface heat flow is more sensitive to the thickness of the blanket than to a difference in Th composition between the two sites; as we have discussed above, blanket thickness is likely to vary by a much larger factor than Th abundance.

[13] *Haskin et al.'s* [2003] study of lunar ejecta thickness and composition as a function of various parameters gives a more complete picture and any detailed analysis of the data returned by Apollo (and, hopefully, future experiments) should give consideration to these parameters. With only two data points, one can of course speculate, but we prefer to postpone any quantitative investigation of these effects. We merely wanted to point out that the difference in measurements can be explained by the Imbrium ejecta thickness, irrespective of what causes the thickness to vary.

[14] While it could be argued that our approach in this study is somewhat simplistic, it nevertheless emphasizes that there is more than one possible explanation for the difference between the Apollo measurements. Another explanation is given by *Wieczorek and Phillips* [2000], who pointed out that the difference between the two Apollo measurements could be explained by the Apollo 15 landing site being closer to the center of the high-Th PKT. Crustal thicknesses, on the other hand, should be fairly similar at the two sites. Based on gravity and topography data, estimates range from 48 km to 50 km [*Wieczorek and Phillips*, 1998, 1999].

[15] The very locations of the two Apollo data points mean that thermal focussing effects, Th concentrations and thicknesses of the megaregolith and ejecta blanket all interact on similar scales in terms of surface heat flow. We think that caution is required when basing one's lunar models on the Apollo measurements because their values could critically depend on the precise size and location of an Imbrium impact and subsequent re-distribution of Th-rich ejecta.

[16] Further heat flow measurements are therefore required. Measurements within and near the PKT (and possibly at the Imbrium antipode) might help to quantify the heat flow contribution of the Imbrium ejecta deposits. LUNAR-A or a similar mission [e.g., *Mizutani et al.*, 2003] could add two more data points. LUNAR-A is expected to obtain heat flow estimates with at least 30% accuracy [*Tanaka et al.*, 1999]. Penetrators can be assumed to be in better thermal contact with the regolith than bore hole based methods, which benefits thermal conductivity measurements. They can also avoid the influence of diurnal and annual heat waves if they penetrate deep enough (unless deep holes can be drilled, avoiding secular heat waves is rather academic). However, on-board instrumentation of penetrators is limited consider-

ably by power and mechanical constraints, making thermal measurements challenging. With the resources available on Earth, accurate thermal conductivity measurements do not pose a problem [e.g., *von Herzen and Maxwell*, 1959; *Cull*, 1974], but on the moon it is very difficult to ensure perfect thermal contact whilst leaving the regolith unaltered. With respect to the Apollo experiments it needs to be said that the first, active, measurement of regolith thermal conductivity were based on observing the temperature response in the heat flow probe to a heater. *Langseth et al.'s* [1976] later, revised conductivity values are based on the thermal diffusivity derived from the depth penetration of long term heat waves, which suggests that there can be substantial benefit from long term measurements. Global measurements by remote sensing would help to reduce ambiguities by giving global coverage. *Keihm* [1984] proposed orbital microwave radiometry, but to date no further detailed studies of feasibility and potential benefit of such an experiment have been published. This is possibly due to the large uncertainties, most importantly in regolith spectral and scattering properties, which make the scientific benefit of global microwave radiometry questionable. One could, however, argue that the global coverage combined with in situ, infrared and bistatic radar data might eventually facilitate a reduction of the inherent uncertainties in this method.

4. Conclusions

[17] Our intention was to emphasize the need to treat those lunar models whose main sources of evidence are the presently available heat flow values with the necessary caution. We have done this by comparing the influence of thorium concentrations and ejecta layer thicknesses, assuming the near-surface Th enrichment at the Apollo landing sites was caused by the Imbrium impact. An exponential decrease of Th with depth based on the LP-GRS surface concentrations and ejecta layer thicknesses estimated from the postulated Imbrium impact can explain the difference in heat flow between the two Apollo measurements. We have, however, shown that ejecta layer thickness and distribution of radioactive elements with depth are critical parameters in the analysis of these measurements. Consequently, the heat flow data available do not enable us to constrain the thermal state of the Moon with 100% confidence. Our results underline the need for further, if possible global, coverage of lunar surface heat flow. In the meantime, when extrapolating from Apollo values to lunar global heat flow, we recommend the use of a very long ruler for drawing error bars.

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