Thermal modeling of mare volcanism and the "Procellarum KREEP Terrane." Mark A. Wieczorek[1] and Roger J. Phillips; Department of Earth and Planetary Sciences, Washington University, Box 1169, 1 Brookings Dr., St. Louis, MO, 63130; [1]email: markw@wurtzite.wustl.edu.

Introduction. Although there are a wide assortment of thermal history models for the Moon that purport to account for the origin of mare basalts [1, 2], none of these models can account for the fact that the bulk of lunar volcanism occurred on the nearside of the Moon. Though it has been widely claimed that the "thicker" farside crust could have hindered the eruption of basaltic magmas, the thinned crust beneath the South Pole-Aitken (SPA) basin does not show evidence of extensive mare volcanism. This basin does contain lava ponds (about 10% by area), but the amount of volcanism that occurred in SPA is nowhere close to approaching that of the nearside mare. Additionally, dual-layered crustal thickness models [3] suggest that the farside crust may not be substantially thicker than the nearside crust.

The new Lunar Prospector gamma-ray data [4] suggest a different interpretation for the distribution of mare basaltic volcanism. About 80% of mare volcanism by area is found to occur within an anomalous geochemical province that is enriched in KREEP (specifically, KREEP-basalt, or the intrusive or differentiated equivalent) [Wieczorek et al., Jolliff et al., Korotev; this volume]. The areal extent of this province (the "Procellarum KREEP Terrane") is defined by the Lunar Prospector gamma-ray data, and encompasses much of Oceanus Procellarum and Mare Imbrium (see figure 1). The fact that mare volcanism is found to occur predominantly within this geochemical province suggests to us that an intimate relationship exists between the two. We show below that lunar magmatism may have been a phenomenon local to this province, and that the high concentration of heat producing elements found there may be able to account for the distribution of mare volcanism in both space and time.

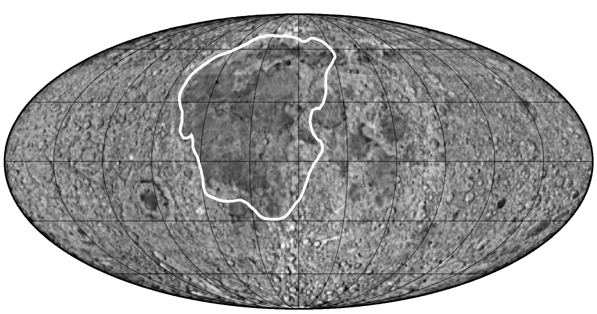

Figure 1. Image showing the areal distribution of the Procellarum KREEP terrane overlaid on a lunar shaded relief map.

Lunar Thermal Modeling. In order to test the relationship between the Procellarum KREEP terrane and mare volcanism, we have run some simple thermal models. Our approach is new in that we *do not* assume a symmetric distribution of heat producing elements within the Moon. Specifically, as a start, we place a ten-kilometer-thick layer of KREEP-basalt at the base of the crust within the Procellarum KREEP terrane (here approximated by a spherical cap 1200-km in radius). We consider ten kilometers of KREEP-basalt to be conservative, in that the models of [5; Korotev, this volume] (based on the composition of Imbrium ejecta) allow for over 30 kilometers of KREEP-basalt within this terrane. The rest of the lunar crust in our model is assumed to have a concentration of heat producing elements represented by the "farside highlands" obtained from the Apollo gamma-ray experiment [6], and the mantle heat production was taken from [7]. As an initial condition, the KREEP-basalt layer was set to its liquidus temperature (~1448 K; [8]), the top of the mantle was set to its solidus (~1480 K; [9]), and the temperature within the mantle followed an adiabat (increasing in temperature by ~50 K to the center of the Moon).

Our thermal models are simple in that they are axisymmetric and that they only consider heat transport by conduction. Although convection may have occurred in the lunar mantle, this fact would not likely change out conclusions. In fact, if there were a paucity of heat sources in the lunar mantle and core it could be argued that the mantle should be stable against convection (see [2]). By heating the mantle from the top down (as opposed from within), convective instabilities will additionally be lessened. As an extreme scenario, we have run models with no mantle heat production, and though the amount of melting that occurs is decreased, our conclusions below would not be altered.

Our models do not include the temperature or pressure effects on the thermal conductivity or specific heat. We do simulate melting, though, by using the mantle liquidus and solidus as determined by [9]. Melting was assumed to be spread linearly across the solidus-liquidus temperature interval with a heat of fusion of 680 kJ/kg. Though this thermal model is admittedly simple, nonetheless, it should demonstrate to first order the dramatic thermal consequences of the postulated Procellarum KREEP terrane.

Results. Figure 2 shows a plot of the fraction of material that is melted as a function of depth beneath the Procellarum KREEP terrane at times of 4, 3.5, 2.5, 1, and zero billions years before the present for the above model. Partial melting in the mantle occurs because the KREEP-basalt layer becomes superheated above its liquidus and heats the mantle *from the top down*. This plot shows that partial melting in the mantle was widespread at 500 Ma, and that the maximum depth of melting increased with time to about 600 km at the present. This type of melting history is consistent to first order with the history of lunar volcanism. Namely, mare volcanism may have commenced as early as 4.3 Ga ago, significantly tapered off around 3 Ga, and ended around 900 Ma [10]. Additionally, mare basalts are believed to have been derived from depths shallower than 500 km [11], again consistent with our model.

As an additional check to the validity of our results, we have computed the present day surface heat flux predicted from this model. Figure 3 shows our model results, as well as the measured surface heat flux at the Apollo 15 and 17 sites. It is seen that our model is consistent with the Apollo measurements, and that the higher observed heat flux at the Apollo 15 site (as compared to Apollo 17) is a direct consequence of this site being closer to the

Procellarum KREEP terrane.

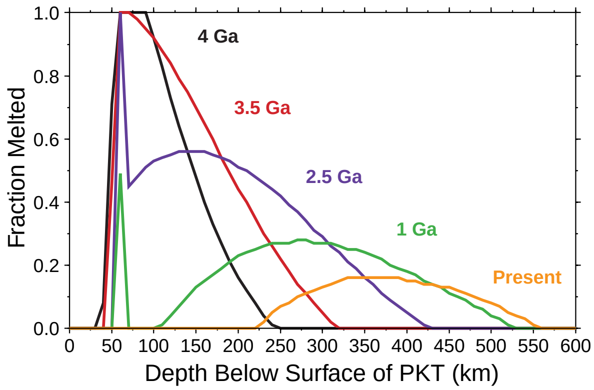

Figure 2. Plot showing the fraction of material melted beneath the center of the Procellarum KREEP terrane at times of 4, 3.5, 2.5, 1 and zero billion years before the present.

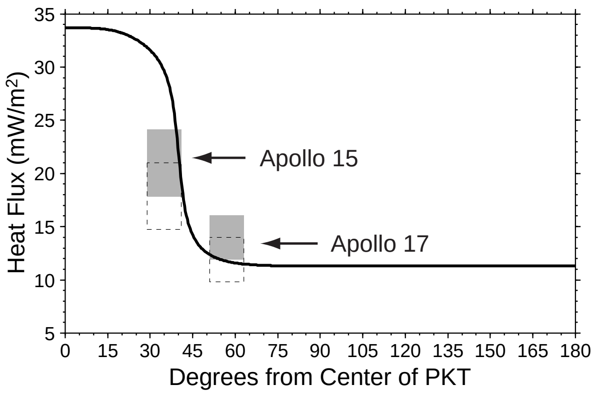

Figure 3. Plot showing the modeled present day surface heat flux as a function of distance from the center of the Procellarum KREEP terrane. Also shown are the Apollo heat flow measurements (gray boxes) at their approximate distance from the PKT. The dotted boxes represent the heat flow measurements after correction for the mare/highlands-boundary heat flow enhancement of [12].

Discussion. Most lunar thermal history models have tried to explain mare volcanism by heating the Moon from within via radiogenic decay. In contrast to this type of model, we believe that a large portion of the lunar incompatible elements (i.e., KREEP) may have been concentrated within a single crustal geochemical province [Wieczorek et al., Jolliff et al., Korotev; this volume], and that the lunar interior was instead heated from the top down. This initial distribution of incompatible elements would likely be due to asymmetric crystallization of a lunar magma ocean.

Although our thermal models are admittedly simple in that they only consider heat transport via conduction, they do illustrate that a single province highly enriched in KREEP would have a major influence on the Moon's thermal history. A ten-kilometer layer of KREEP-basalt could cause the mantle to partially melt to a maximum depth of about 600-km below the surface. This maximum depth of melting is consistent with the petrologically constrained depths of origin of the mare basalts based on the premise that these melts were multiply saturated with olivine and pyroxene in their source region [11].

Our simple model suggests that the KREEP-basalt layer should have been molten for a few billion years (see Figure 2). Though our models most likely overestimate the internal temperatures of the Moon (since we have neglected solid state convention, as well as the heat advected by magma transport), we believe that a molten KREEP-basalt layer within the crust would persist until at least 3.9 Ga (the age of the Imbrium impact; see also [13]). Ryder [14] has determined that the age of the Apollo 15 KREEP-basalts and Imbrium ejecta are practically indistinguishable. Based on this observation he has suggested that the Imbrium impact may have "induced" KREEP-basalt volcanism. In concordance with Ryder, we suggest that KREEP-basalt volcanism occurred because the Imbrium impact excavated into an extensive molten "KREEP-basalt" magma chamber.

A molten KREEP-basalt magma chamber also explains why the search for a solid protolith to "LKFM" (Low-K Fra Mauro Basalt) has not made much progress [15]. "LKFM" is a mafic impact melt, most of which (if not all) are believed to have originated during the Imbrium impact event [16]. We believe that the reason a solid protolith to "LKFM" has not been found is that the protolith was initially molten (as originally suggested by [15]). The "LKFM" mafic impact melt breccias in our model formed during the Imbrium impact event by the mixing of molten KREEP-basalt with excavated mantle and feldspathic crustal materials [5; Korotev, this volume].

Given the size of the zone of partial to complete melting beneath the Procellarum KREEP terrane, much igneous processing between the crust, mantle, and the KREEP-basalt layer must have occurred. We believe that the Mg-rich nature of KREEP-basalt originated from mixing forsteritic mantle olivine with urKREEP. The Mg-suite rocks in our model would represent differentiation products of the molten KREEP-basalt layer.

Although our thermal model appears to be consistent with the bulk of lunar knowledge, one potentially damaging observation is the existence of a mascon over the Imbrium basin. This mascon likely represents uncompensated surface basalt flows, and/or super-isostatic Moho uplift. If the crust beneath Imbrium was indeed hot (or partially molten) then these excess stresses should probably have relaxed relatively quickly. Clearly, this observation needs to be reconciled with our hypothesis that this province had a higher than average temperature throughout lunar history.

[1] BVSP, *Basaltic Volcanism on the Terrestrial Planets,* Pergamon, 1981; [2] Parmentier, E.M., and P.C. Hess, *EPSL* **134**, 501-514, 1995; [3] Wieczorek, M.A., and R.J. Phillips, *JGR* **103**, 1715-1724, 1998; [4] Lawrence, D.J., et al., *Science* **281**, 1484-1489, 1998; [5] Korotev, R.L., New Views of the Moon, LPI 1998; [6] Metzger, A.E., et al., *Proc. LPSC 8th*, 949-99, 1977; [7] Warren, P.H., and J.T. Wasson, *Rev. Geophysics* **17**, 73-88, 1979; [8] Holmberg, B., and M.J. Rutherford, *LPSC XXV* , 557-558, 1994; [9] Ringwood, A.E., *Icarus* **28**, 325-349, 1976; [10] Schultz, P.H., and P.D. Spudis, *Nature* **302**, 233-236, 1983; [11] Longhi, J., *GCA* **56**, 2235-2251, 1992; [12] Warren, P.H., and K.L. Rasmussen, *JGR* **92**, 3453-3465, 1987; [13] Haskin, L.A., *JGR* **103**, 1679-1689, 1998; [14] Ryder, G., *GSA SP 293*, 11-18, 1994; [15] Spudis, P.D., et al., *Proc. LPSC 21st*, 151-165, 1991; [16] Haskin, L.A., et al., *Meteoritics* **33**, 959-975, 1998.