The Distribution of Mare Source Regions: Evidence Using Remote Sensing Data. Jeffrey J. Gillis[1], Brad L. Jolliff[1], Paul D. Spudis[2], Larry A. Haskin[1]. 1. Washington University, Department of Earth and Planetary Sciences, St. Louis, MO, 63130, Gillis@levee.wustl.edu. 2. Lunar and Planetary Institute, Houston, TX, 77058.

Introduction: The magma-ocean model for large scale lunar differentiation [e.g., A, B, E] describes a pathway along which crystallization proceeded, given an assumed starting bulk composition. Simply put, olivine and pyroxene crystals, more dense than their surrounding liquid, sink and formed cumulus layers filling the magma ocean from the bottom up. The first cumulates were magnesian but as crystallization progressed residual melt and later cumulates become more ferroan. This crystallization sequence would produce a gravitational instability which has been suggested to have driven convective overturn [e.g., U, S, R, L]. We suggest that, although sinking of dense Fe-Ti rich cumulates probably delivered heat producing K-U-Th in many places, this phenomenon was focused and involved large-scale overturn mainly within the Procellarum KREEP Terrane.

One of the key issues solved by the cumulate overturn model [R] is a mechanism to transport heat producing elements, coupled with late-stage cumulates, into the deep interior where they initiated remelting of cumulates and mobilization of partial-melt diapirs. Convective overturn would not be expected to mix down-going material uniformly throughout the mantle, but would instead have reacted differently with different cumulates encountered. The result would be a variety of melt sources; thus the lack of a correlation between basalt composition with space or time is expected.

Using Clementine [N] and Lunar Prospector data we assess the distribution of FeO, and TiO_2 in mare basalts and relate the duration, volume, and compositional variability of mare volcanism to the global distribution of Th. We find as a first order result that the abundance mare basalt is associated with the abundance K-U-Th in the mantle as inferred from the surface distribution of Th, and thus divide the Moon into three regions on the basis of the chemistry and volcanic production: eastern near side, western near side, and far side. In the western near side, basalts are the most voluminous and have a protracted eruptive history, followed by a relatively less frequent occurrence in the eastern mare and an even lower volume for the far side.

Data & Methods: FeO and TiO_2 [O] abundance maps based on Clementine ultraviolet-visible data were used to examine the composition of mare basalt units globally. Absolute Th abundances [P] from the Lunar Prospector mission were used to compare Th concentrations in mare basalt flows. Where available, Lunar Orbiter and Apollo images were used to establish absolute or relative age on the basis of crater density or stratigraphic relationships. Together these tools provided the necessary data to assess the distribution and composition of mare basalts globally. Mapping the chemistry and age distribution of mare basalts provides constraints on the state of the lunar interior that the magma ocean hypothesis and cumulate overturn model must satisfy.

Observations: We begin our observations with basalts on the lunar far side because less is known about their eruption history and composition. The eruption history of many of these basalt ponds contain multiple flows which are chemically diverse. Multiple basalt flows are distinguished by either differing composition, spectral characteristics, and/or crater densities. Multiple flow deposits are recognized within all of the major far side basins: Australe, Marginis, Moscoviense, Orientale, Smythii, and South Pole-Aitken. The chemistry of these flows varies on the basin scale (e.g., Moscoviense, Apollo, Orientale) and on the kilometer scale (e.g., Hanno Z, 53°S, 72°E; area east of Abel, 35°S 92°E; and the area north of Bosé, 52°S, 167°W).

Far side basalts display a range in FeO and TiO_2 concentrations that are on average lower than those observed for basalts on the near side: 8-18 wt % FeO, <1-9 wt % TiO_2. Areas with the lowest FeO and TiO_2 compositions tend to be spatially limited deposits (e.g., Buys-Ballot, 18.5°N, 175°E, 55 km dia., Kohlschütter 15°N, 154°E, 53 km dia., and small basalt deposits within Mare Australe).

However, Clementine TiO_2 maps show that some of the youngest basalts on the far side (late Imbrian-early Eratosthenian) have the highest TiO_2 compositions to erupt in that region. These areas are Mare Australe (3-4 wt % TiO_2 measured in Hanno Z) [I,K], Mare Moscoviense (6-9 wt % TiO_2) [I,K], and South Pole-Aitken basin (5.5-8.5 wt % TiO_2 measured in Apollo basin; 36°S, 152°W) [I,K].

Similarly, some of the youngest basalts on the near-side, of Eratosthenian age, express elevated TiO_2 concentrations (e.g., Procellarum, 12-14 wt % TiO_2; and in places, Imbrium, 8-10 wt % TiO_2). However the TiO_2 contents of these eastern near side basalts are comparably lower than the older (~3.8 Ga.) Apollo 11 and 17 high-Ti basalts (14-16 wt % TiO_2). Furthermore, differences are observed in the visible-near IR spectra between the high-Ti basalts on the eastern near side and those in the western near side [G,J]. Pieters [G] interprets the 1-μm absorption coupled with an attenuated a 2-μm absorption in the western high-Ti basalts as indicating the presence of olivine, similar spectra are not observed for the eastern maria. In addition to the presence of olivine, the Imbrium-Procellarum high-

Ti basalts are generally higher in Th (3-6 ppm) [V, P]; Only the high-K, high-Ti basalts of Apollo 11 exhibit similar Th values, ~4 ppm. Similar high-Ti, high-Th basalts are not observed on the far side [P].

The diversity of mare basalt chemistry reflects the lateral and vertical heterogeneity of the mantle on the far side. Although volcanism on far side was extensive and multiphased, the volcanic production was not as voluminous or the stratigraphy as chemically diverse as the mare basalts on the near side.

Discussion: The observation of early and late high-Ti basalts reveals that the stratigraphy of the mantle must be more complex than assumed in a static cumulate model. Experimental evidence has shown that ilmenite, the source for high-Ti basalts, would crystallize late in the magma-ocean sequence and accumulate at a depth of ~150-200 km [E]. The static cumulate model cannot explain the existence of these late high-Ti basalts without invoking a second high-Ti layer deeper in the mantle or a jump in melting to more shallow levels. The former is unlikely because the magma ocean will not crystallize ilmenite (the precursor to the high-Ti basalts) until ~95% solidified, which would place them at too shallow level. The latter does not seem plausible because as global cooling progressed inward, the depth of partial melting increased with time. Evidence indicating that the high-Ti basalts originate from a level deeper than predicted from the magma ocean model comes from the volcanic glasses, which exceed the range of mare basalt TiO_2 concentrations [V] and are thought to represent the primitive, unfractionated compositions of the mare basalts. Analysis of these picritic glasses indicate that the source for mare basalts is >400 km or deeper [Y,Z].

We divide the Moon into three regions on the basis of chemistry (TiO_2, FeO, and Th), mineralogy (presence of olivine detected using remote sensing) and, eruption volume and duration. Region 1, western near side; basalts span range in TiO_2 and FeO, presence of olivine detected in some young high-Ti flows, and maria exhibit elevated levels of Th. Imbrium-Procellarum area contain the youngest basalts ages. Region 2, eastern near side; basalts span a range in TiO_2 and FeO, no olivine detected in remote sensing data, and Th is lower than region 1. Thermal duration and eruption volumes are comparable but not as large as in the western maria. Region 3, far side; FeO, TiO_2, and Th are, on average, lower than in mare basalts on the near side. The duration of volcanic activity is shorter and volumes much smaller than regions 1 and 2.

Conclusions: Heat-producing elements (K-U-Th) are not uniformly distributed globally. Differences in basalt composition and volume between the Imbrium-Procellarum, Tranquillitatis-Serenitatis, and far side regions was inherited from differences in mantle regions related to the concentrations of heat-producing residua, with a large proportion of the incompatible elements sequestered within, and subsequently mixed into the mantle beneath the PKT.

The detection of high-Ti basalts in all three regions is evidence that the sinking ilmenite cumulates brought with them K-U-Th. We suggest that the amount of convection is linked to the concentration of heat producing elements. The concentration of heat producing elements in the Procellarum KREEP Terrane probably produced vigorous overturn of the cumulate pile in the Procellarum region, as suggested by the (possible) presence of olivine-bearing Ti-rich basalts and olivine normative Apollo 12 and 15 basalts (both of which appear to be unique to the western maria). The far side, with low concentrations of K-U-Th, experienced little exchange or limited convection and thus less voluminous volcanism and a less protracted volcanic history.

We infer that convective overturn occurred in all three regions to some extent but that it was focused primarily in the sub-PKT mantle.

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