SPATIAL CORRELATION OF DEEP MOONQUAKES AND MARE BASALTS AND IMPLICATIONS FOR LUNAR PRESENT-DAY MANTLE STRUCTURE, MAGMATISM AND THERMAL EVOLUTION.
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Introduction: Knowing the thermal, spatial, and temporal conditions under which mare genesis occurred is necessary for understanding the history of the Moon and the current state of the interior. The Moon is dominated by two different magmatic episodes: global magma ocean and basaltic volcanism [e.g. 1,2,3]. Ilmenite-rich cumulates (IC) were the last to crystallize out of the magma ocean and would therefore contain high levels of incompatible, radioactive elements which were not incorporated into the crystals of olivine, pyroxene, and plagioclase [4]. The IC would have formed a thin, dense layer at the base of the crust overlaying less dense material in the mantle, making it gravitationally unstable [4,5]. Whether the IC stayed at shallow depths or sunk to the CMB is a topic of debate, but distinguishing between these two possibilities is necessary for understanding the past and present state of the mantle and the depth of origin of the mare basalts. The mare basalts erupted from 3.9-3 Ga and flowed into topographic lows due to hydrostatic pressure variations [6]. This, however, cannot be the sole explanation for the asymmetrical distribution of mare basalts since there are little to no mare basalts in the largest impact basin on the Moon, South Pole-Aitken [e.g. 7].

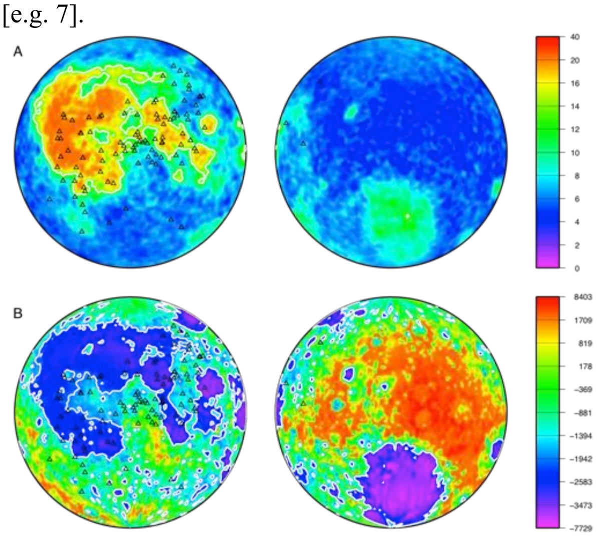

Figure 1. A: Weight percent FeO with 13wt% contour in white. B: Topography (in meters) with -2000 meter contour in white. Locations of deep moonquakes nest shown on both. The nearside is on the left.

The Apollo Seismic Network recorded thousands of moonquakes [e.g. 8,9]. The most significant for understanding the interior are the deep moonquakes (DMQ), which occur at depths of 700-1200 km within about 300 nests and mostly on the nearside of the Moon (Figure 1A) [10,11,12]. Magnitudes of the DMQ are very low, around 3 [12]. The DMQ demonstrate periodicities of 14-15, 27-29, and 206 days, suggesting an important role of tidal forces in the Earth-Moon-Sun system [e.g. 13,14], although tidal stresses may only contribute 0.1 MPa [15]. Frohlich and Nakamura (2009) suggest several contributing factors, that when added to tidal stresses, could explain the DMQ, most notably the fluids and partial melts in the DMQ zones. Another contribution is the presence of water in the deep mantle since recent studies have suggested that the Moon contains significant amounts of water [16], particularly in the source regions of mare basalts [17].

It has been suggested that most of the DMQ on the nearside and below young terrains of mare basalts [15], however, no vigorous statistical analysis has been done to examine the correlation between mare basalts and DMQ distribution. The main goal of this study is to understand the connection between the DMQ and the mare basalts. An additional goal is to examine the correlation between the mare basalts and topographic lows, which has long been observed but not fully quantified.

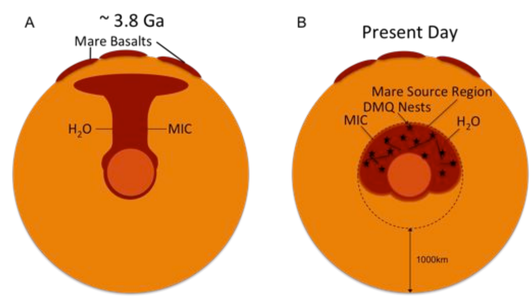

Figure 2. (A) shows the lunar interior during mare basalt emplacement. After the dense ilmenite sunk it heated because it was rich in incompatible elements and then became thermally buoyant enough to erupt. (B) shows what was left behind in the deep mantle. The heterogeneities left behind, along with tides, lead to DMQ.

Data Sources and Methods: FeO weight percents are from Lunar Prospector's gamma-ray and neutron spectrometers [18]. In order to determine what FeO wt% is representative of the mare basalts we analyzed the surface area covered by different weight percents as well as visually comparing maps of deposits from Wieczorek et al. (2001). We determine that 13wt% is the most representative of the mare basalts, which is consistent with 30% coverage of the nearside. We used the 101 well-located DMQ nests located in Nakamura

(2005). The epicenters are shown as triangles in Figure 1. Topographic data is from Clementine LIDAR data (Figure 1B). The one degree by one degree data set was used with latitudes greater than 79° and less than -78° thrown out due to poor resolution at those latitudes [e.g. 19, 20].

Results: *Deep Moonquakes and Mare Basalts.* We calculate the arc distance from each cluster 'epicenter' to the closest deposit of FeO with a weight percent greater than a given concentration; the vertical distance is not taken into account. A distance less than or equal to five degrees is determined to be correlated (Figure 3A). To demonstrate the robustness of our results, we generated sets of random points to compare with the DMQ (Figure 3B). We conclude that DMQ are not randomly distributed and are in fact correlated to the mare basalt deposits.

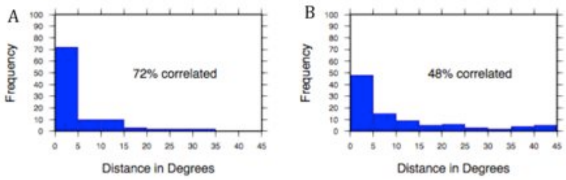

Figure 3. (A) shows the frequency of moonquakes occurring within five degrees of FeO deposits with a given FeO concentration. (B) shows the frequency of random points occurring within five degrees of FeO deposits with a given FeO concentration.

Mare Basalts and Topography. We also explored the relationship between the mare basalts and elevation. We computed the percent surface area below a certain elevation (average or basin) occupied by FeO greater than a given concentration (Figure 4). We found 85% of the mare basalts occur in topographic lows (< -2km) and 92% occur below the average height on the nearside (-1.5km). About 50% of the area below -2km (i.e. basins) contains mare basalt on the nearside. No topographic lows on the farside contain mare basalt. Mare basalts therefore preferentially flowed into basins, but are not present in all basins. It is especially significant that mare basalts are not present in large basins on the farside.

Conclusions: We found that DMQ are not random, but correlated to mare basalt deposits; 72% of the DMQ are within 5° of mare basalt deposits (Figure 3A) while only 48% of the random points can be considered correlated to the mare basalt (Figure 3B). Mare basalts are also preferentially present in basins, but are not present in all basins; 85% of the mare basalts occur in topographic lows (< -2km) and 92% occur below the average height on the nearside, but only ~50% of the area below -2km (i.e. basins) contain mare basalt on the nearside. We propose that the DMQ are occurring predominantly in the source region of the mare basalts due to presence of water in the mare basalt source region [17] which can lead to reduced strength. This points to a deep origin for the mare basalts, but more analysis must be done to fully understand the cause of the DMQ and the distribution of the mare basalts.

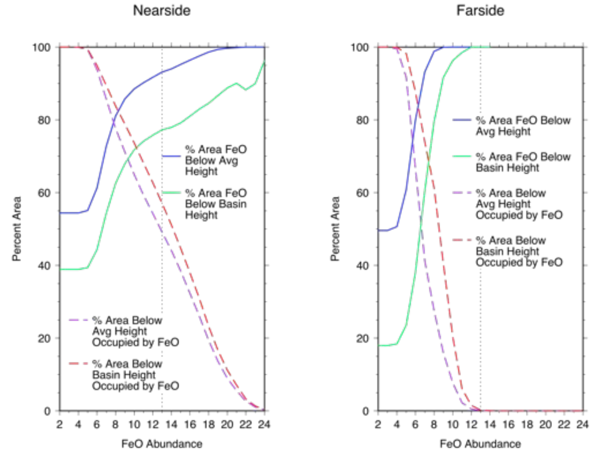

Figure 4. Blue: the percent area of FeO below the average height, -1560m on the nearside and 210 m on the farside. Green: the percent area of FeO below -2000 m, this height is defined as a topographic low or basin. Purple: the percent area below the average height occupied by FeO of a given concentration. Red: the percent area below the basin height occupied by FeO of a given concentration.

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