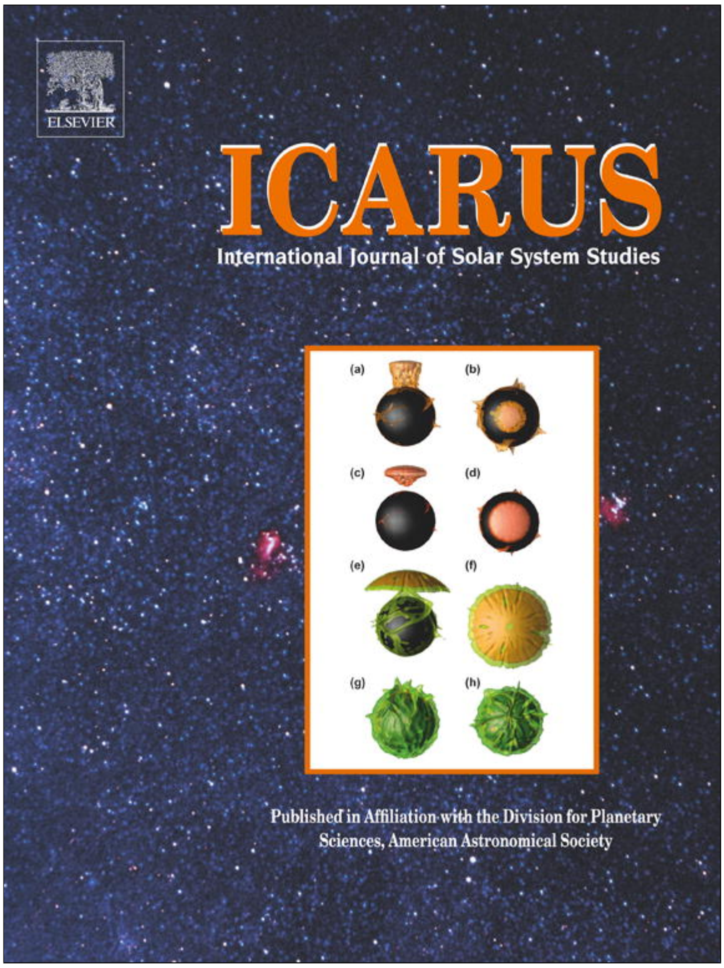
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Correlation of deep moonquakes and mare basalts: Implications for lunar mantle structure and evolution

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ABSTRACT

The genesis of mare basalts and deep moonquakes are important events that have major implications for understanding the thermal evolution and interior dynamics of the Moon. The eruption of mare basalts predominantly from 3.9 Ga to 3 Ga ago represents one of the most important events in lunar geological history. Deep moonquakes recorded by the Apollo Seismic Network show the dynamic nature of the present-day lunar mantle. In this study, we have correlated the presence of the mare basalts, using FeO concentration as a proxy, with the epicenters of 52 well-located deep moonquake (DMQ) clusters. We determine FeO concentrations of 13 wt.% or higher to be representative of the mare basalt deposits. Our analysis shows that over 63% of the DMQs occur within 1° from the mare basalt deposits, while over 80% of the DMQs are within 5° from the mare basalt deposits. Our analysis also shows that for the same amount of randomly distributed DMQs within a spherical cap on the nearside that encompasses all the nearside DMQs, the probability of over 80% of the DMQs occurring within 5° from the mare basalt deposits is about 0.01, thus rejecting a random distribution of the DMQs with respect to the mare basalts. The correlation between mare basalts and the DMQs from our analysis suggests that the mare basalts may be derived from melting processes at relatively large depths, consistent with previous petrology and geodynamic studies. We propose that the water and volatiles in the mare basalt source material (i.e., a mixture of ilmenite cumulates and olivine orthopyroxene, together called MIC) play an important role in causing the DMQs and that the DMQs delineate the present-day locations of MIC in the deep mantle. Since the mare basalts are predominately distributed on the nearside, our results further suggest that the DMQs may indeed be largely nearside features, which is a prediction that can be tested in future lunar seismic exploration.

1. Introduction

Mantle seismicity reflects the deformation and stress states and thermochemical structures within planetary interiors. The recognition of deep seismicity in the Earth's mantle as subducting lithosphere plays an essential role in establishing the plate tectonics theory (e.g., Isacks and Molnar, 1969) and provides an important constraint on the Earth's mantle dynamics. The Moon is the only other planetary body with known deep seismicity, known as deep moonquakes (DMQs), thanks to Apollo missions. DMQs are low magnitude events (generally less than magnitude 3) that occur predominantly at depths of 700–1200 km within about 300 nests and largely on the nearside of the Moon (Toksoz et al., 1977; Lammlein, 1977; Nakamura, 2003, 2005; Frohlich and Nakamura, 2009) (Fig. 1). The DMQs exhibit periodicities that suggest an important role of tidal forces in the Earth–Moon–Sun system in causing them (Lammlein, 1977; Weber et al., 2009). However, it remains an open question as to the exact role of the tidal stresses (Frohlich and Nakamura, 2009; Weber et al., 2009); tidal stresses may only contribute 0.1 MPa (Minshull and Goulty, 1988). It has been suggested that tectonic stress and mechanical heterogeneities associated with water and volatiles play important roles in DMQs (Toksoz et al., 1977; Frohlich and Nakamura, 2009). This is important, considering recent studies that suggest that the Moon may contain significant amounts of water (Pieters et al., 2009), particularly in the source regions of mare basalts (Saal et al., 2008). It has long been recognized that DMQs occur mostly in a broad zone trending NE–SW below mare basalts (Fig. 1A) (Lammlein, 1977; Minshull and Goulty, 1988), suggesting a possible correlation of DMQs with the mare basalts (Lammlein, 1977). Understanding the cause of the DMQs will help illuminate the current state of the deep mantle, and determining the connection between the DMQs and mare basalts will further constrain the geological history of the Moon.

Two major magmatic episodes occurred in the lunar geological history: (1) a global magma ocean and (2) mare basalt emplace-

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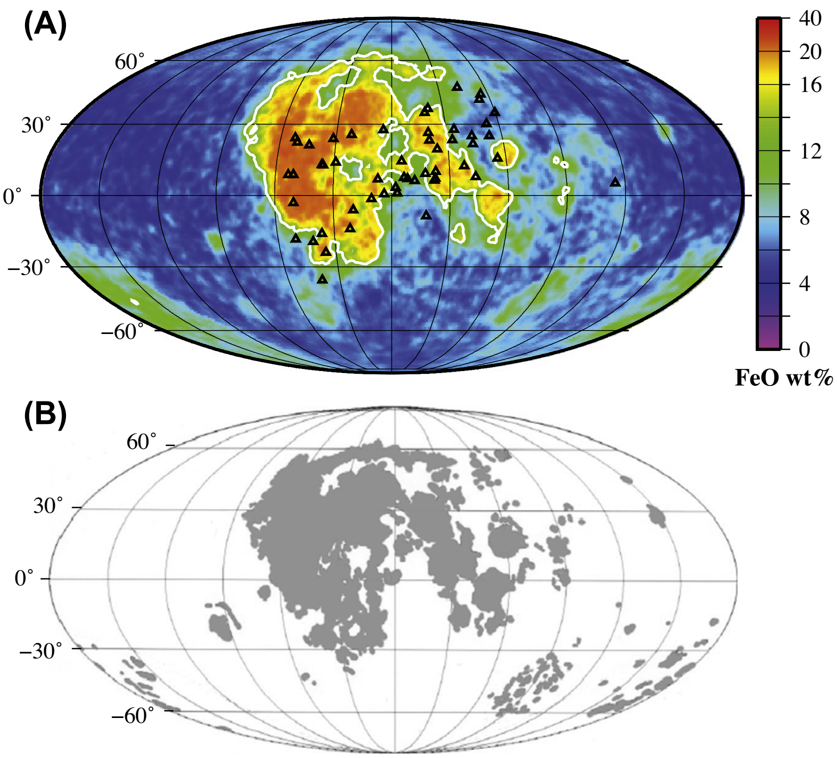

Fig. 1. (A) Distribution of the deep moonquake (DMQ) nests and FeO weight percents centered on the nearside. White contours outline 13 wt.% FeO and triangles represent locations of the DMQ nests. (B) Adapted from Wilhelms (1977) and Wieczorek et al. (2001), this map shows mare basalt distribution from geologic mapping. Visually correlating these two maps suggests that regions with FeO concentrations greater than 13 wt.% represent the mare basalts most accurately.

ment (Wilhelms, 1977; Nyquist and Shih, 1992; Shearer et al., 2006; Wieczorek et al., 2006). After the global magma ocean had mostly cooled, Ilmenite rich cumulates (IC), which contained high levels of incompatible, radioactive elements, would have formed a thin, dense layer (i.e., KREEP material) at the base of the crust overlaying less dense material in the mantle (Hess and Parmentier, 1995; Shearer and Papike, 1999). Geochemical and petrological evidence supports the derivation of the mare basalts from remelting of the IC material (Shearer et al., 2006; Ringwood and Kesson, 1976). Therefore, the evolution of the IC is crucial for understanding the emplacement of the mare basalts (Hess and Parmentier, 1995; Elkins-Tanton et al., 2002).

There are two main classes of hypotheses for the origin of the mare basalts: deep versus shallow, as reviewed in Shearer et al. (2006). Wieczorek and Phillips (2000) proposed a purely conductive thermal model in which KREEP material is located in a 10 km thick spherical cap with an angular radius of 40° at the base of the crust and heats due to radioactive decay, which, in turn, melts the underlying mantle material. At the time of mare basalt emplacement melting would have reached depths of about 200 km. This model may explain some of the mare basalts as well as the connection between the mare basalts and Procellarum KREEP Terrane (PKT). Models for a deep origin of the mare basalts assume that some of the IC sinks into the lunar mantle, possibly to the top of the core, and is subsequently brought up to a depth of several hundred kilometers by fluid dynamic processes, leading to decompression melting (Hess and Parmentier, 1995; Zhong et al., 2000). The mixture (MIC) of IC and olivine orthopyroxene, formed during the sinking of IC in an olivine and pyroxene mantle, would settle deep in the mantle because it was more chemically dense (Hess and Parmentier, 1995; Elkins-Tanton et al., 2002; Zhong et al., 2000). The radioactive elements would heat the MIC until it became thermally buoyant enough to rise and undergo decompression melting to form mare basalts. Zhong et al. (2000) formulated this type of model with a MIC layer initially above the core and found that if the core's radius is relatively small (<300 km in radius for simple models with homogeneous viscosity), then the MIC may cause a single plume to rise in one hemisphere, thus explaining the hemispherically asymmetric distribution (i.e. only on the nearside) and the timing of mare basalts. While the details of these contrasting models can be improved, it is necessary to distinguish between them in order to understand the thermal history and current structure of the Moon.

The goal of this study is to test the hypothesis of correlation between the DMQs and the mare basalts that was proposed based on visual inspection by Lammlein (1977), by quantifying the correlation using the most recent observations and more robust statistical methods. Our analysis supports the correlation hypothesis. Based on this correlation we propose a new hypothesis for lunar mantle structure and dynamic evolution.

2. Methods

We used FeO weight percent (wt.%) as a proxy for the mare basalts deposits (Head, 1976; Lawrence et al., 2002). The FeO wt.% data that we used in our analyses are from Lunar Prospector's gamma-ray and neutron spectrometers and have 1-deg by 1-deg resolution (Fig. 1A). The data were previously analyzed and processed, and were described in Lawrence et al. (2002). We used the 106 DMQ nests in Nakamura (2005) for our analysis, but discarded the nests with unconstrained depths or with errors in longitude or latitude greater than 10°. This leaves 52 well-located nests, 51 of which are on the nearside (Fig. 1A).

In order to determine what FeO wt.% is representative of the mare basalts, we analyzed the surface area covered by different weight percents (Fig. 2) as well as visually comparing maps of mare basalt deposits from geologic mapping (Wilhelms, 1977;

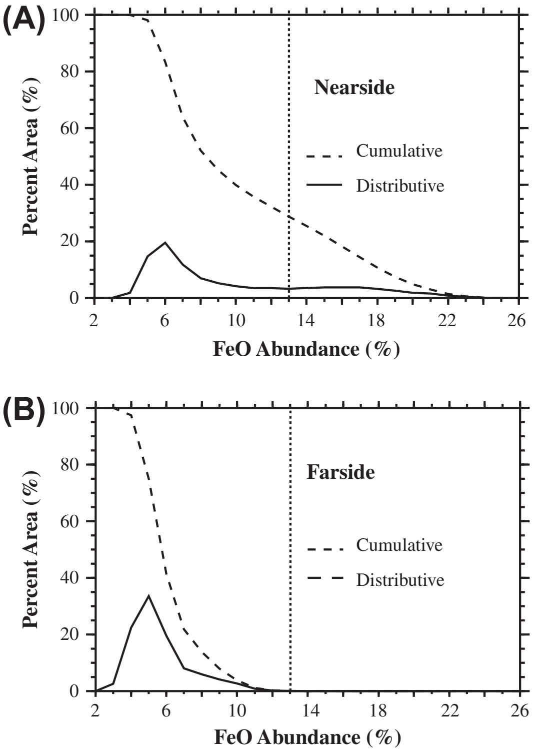

Fig. 2. The percent area distribution versus FeO abundance (i.e., weight percent) for the nearside (A) and farside (B). The dot-dash and dashed lines show the cumulative percent area and percent area distributions, respectively.

Wieczorek et al., 2001) (Fig. 1B). Fig. 2 shows the distribution of FeO deposits by plotting the percent surface area of FeO for a given concentration bin and the percent surface area of FeO equal to or greater than a given concentration. We determined that FeO weight percent of 13 wt.% and greater is the most representative of the mare basalts (Fig. 1), which is consistent with ~30% coverage of mare basalts on the nearside (Nyquist and Shih, 1992) (Fig. 2).

To quantify the spatial correlation of the DMQs and the mare basalts (FeO), we calculated the arc distance from each DMQ epicenter to the closest deposit of FeO with concentration greater than 13 wt.% (Fig. 3A). When computing the arc distance, we used the latitude and longitude coordinates of the DMQ epicenters and FeO distributions and ignored the depth of the DMQs. We then defined the correlation as the percentage ratio of the number of DMQ clusters within either 1° or 5° from the FeO deposits >13 wt.% to the total number of clusters considered. In order to prove that our method is sound, we ran a calculation in which we saturated the nearside with 10,000 random points and found that about 30% of the random points were within mare basalt deposits (i.e., >13 wt.% of FeO), which was consistent with values from Fig. 2. We then took into account the uncertainties in DMQ locations that may differ in longitudinal and latitudinal directions as documented by Nakamura (2005). We generated 1000 sets of 52 random points in Gaussian distribution around each corresponding DMQ epicenter, by using the errors in longitude and latitude (Nakamura, 2005) as the standard deviations for the Gaussian distribution in corresponding directions. We then calculated the percentage correlation for each set of the 52 random DMQ nests, in order to show that the percentage correlation is robust against the DMQ location errors.

Contrary to the hypothesis of the correlation of the DMQs with mare basalts is a hypothesis that DMQs are randomly distributed with respect to mare basalts. To test the random distribution hypothesis, we generated 10,000 sets of 52 random DMQ events on a spherical cap on the nearside, centered at the sub-Earth point of the Moon. The angular radius of the spherical cap is the largest arc distance between nearside DMQ epicenters and the sub-Earth point, and is 66°. We then calculated the percentage correlation between each random set of DMQs and the mare basalt deposits using 5-deg distance criteria. We compared the observed percentage correlation with the correlations from the random DMQs and made the randomness test.

3. Results

We now quantify the correlation between the DMQs and the mare basalts. Fig. 3A shows the frequency of the DMQs occurring within 5-deg bins away from FeO deposits for FeO concentrations greater than 13 wt.%. Our results show that out of 52 DMQs, 42 occur within 5° and 33 within 1° away from mare basalt deposits, which corresponds to the percentage correlation between the DMQs and the mare basalts of 81% and 63% for distances less than 5° and 1°, respectively. To test the robustness of our result, we generated 1000 sets of random points in Gaussian distribution around each of the 52 epicenters with errors in longitudinal and latitudinal directions as the standard deviations and calculated the correlation as the ratio of the number of DMQ clusters within 5° away from the mare basalts deposits to 52 for each set. Fig. 3B shows the frequency of the correlations for these 1000 sets of random DMQ events. The mean value of the percentage correlations is about 80%, while the standard deviation is about 3%. Assuming a Gaussian distribution for the percentage correlation, the probability that the correlation of one random set of DMQs relative to the mare basalts is larger than 70% was found to be over 99%. This indicates that the uncertainties in DMQ locations do not affect the results of high correlation percentage significantly.

We then calculated the distances between 52 randomly generated DMQ clusters in the spherical cap of 66° radius and the mare basalts deposits. Fig. 3C shows the frequency–distance distribution of one set of 52 random events. Our calculations show that out of the 52 random events, 32 (or 62%) occur within 5° and 19 (or 37%) within 1° from the mare basalt deposits (Fig. 3C), which are much lower than that for the observed DMQs (Fig. 3A). The distribution of the 52 random events may not be uniform, and this may introduce statistical fluctuations. To examine this effect, we ran 10,000 sets of calculations with 52 random events for each set and with different initial random seeds. For each random set, we determined the percentage of the random points occurring within 1° and 5° from FeO deposits greater than 13 wt.%. The frequency distribution of these correlations for distance less than 5° for 10,000 runs is shown in Fig. 3D. The average percentage correlation is 65% and the standard deviation is 6.6% (note that Fig. 3C is for one set of such calculations). Out of the 10,000 sets of 52 random DMQ events, only a small number of them produce the percentage correlations that are greater than 80%, suggesting that the observed 80% correlation is a small probability event. We may ask what the probability is for the observed 80% or greater correlation to happen if the DMQs are randomly distributed relative to mare basalts.

We now calculate this probability using two different approaches. First, since the percentage correlation shows a normal or Gaussian distribution with mean of $x_{ave} = 65\%$ and standard deviation of $\sigma = 6.6\%$ (Fig. 3D), >80% correlation is outside of 2.4σ with a probability given by

$$p = 1 - \int_0^{0.8} \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-x_{ave})^2/(2\sigma^2)} dx = 0.012. \qquad (1)$$

This small probability suggests that the hypothesis of a random distribution of DMQ relative to mare basalts can be rejected on a sta-

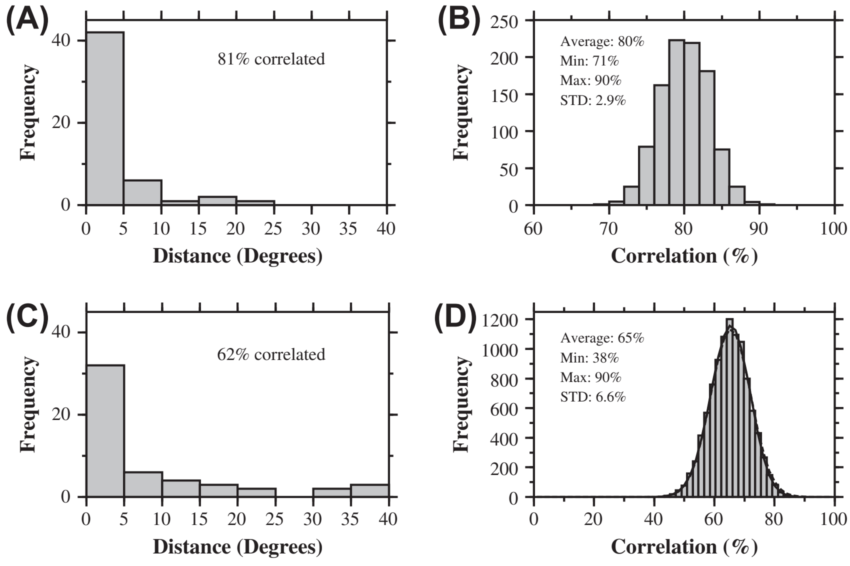

Fig. 3. (A) The distribution of DMQ frequency versus the minimum arc distance from the FeO deposits greater than 13 wt.% in 5° bins for 52 well-located DMQ nests. (B) The distribution of the frequency of the percentage correlations for 1000 sets of 52 random DMQ events in Gaussian distribution around each epicenter of the observed DMQs. The longitudinal and latitudinal errors of each epicenter from Nakamura (2005) are used as the standard deviations for Gaussian distribution in corresponding directions. The average, minimum and maximum values and the standard deviation of the percentage correlations are given in the inset. (C) The distribution of frequency versus 5° arc distance bins for one set of 52 random DMQ events generated on the spherical cap centered on the nearside, with angular radius 66°. (D) The distribution of the frequency of the percentage correlations for 10,000 sets of 52 random DMQ events generated as in (C). The solid and dashed curves in (D) are for the binomial distribution from Eq. (2) and Gaussian distribution with the average percentage correlation and the standard deviation given in the inset, which also shows minimum and maximum percentage correlations.

tistic ground. In the second approach, considering that the probability of a random event falls within 5° from the mare basalts (i.e., >13 wt.% of FeO) is q and that the random events follow a binomial distribution, the probability for n out of 52 events to fall within 5° from mare basalts is given by

$$p_n = \binom{52}{n} q^n (1-q)^{52-n}. \tag{2}$$

q is the ratio of the area within 5° of the mare basalts overlapped with the spherical cap to the area of the spherical cap, and is determined numerically to be 0.655. Eq. (2) (i.e., the solid curve in Fig. 3D is $10{,}000p_n$) agrees well with calculations from 10,000 sets of random cases (i.e., the bars in Fig. 3D). Also shown in Fig. 3D is an ideal Gaussian distribution (the dashed curve) with $x_{ave} = 65\%$ and $\sigma = 6.6\%$. This demonstrates that the Gaussian distribution in Eq. (1) and the binomial distribution in Eq. (2) describe accurately the numerical results. The probability to have >80% of the DMQs (i.e., more than 42 out of 52 events) to fall within 5° from the mare basalts is

$$p = \sum_{n=42}^{52} p_n = 0.009, \tag{3}$$

which is similar to that from the first approach in Eq. (1).

With a relaxed selection criterion to include DMQs with epicenter errors up to 20°, the number of DMQs in our analysis is increased from 52 to 64. Applying the same analysis to 64 DMQs, we found that the percentage correlations between the DMQs and the mare basalts deposits are 75% and 59%, for 5° and 1° distance criteria, respectively, which are similar to those from analysis of 52 DMQs. Also, similar to preceding analysis to test the randomness of the DMQ distribution, we generated 10,000 sets of 64 random points in the spherical cap with arc radius of 72° (note that the larger cap is caused by the increased population of DMQs that spread out more, relative to 52 DMQs) and calculated the percentage correlations for each set. The correlations are also in Gaussian-like distribution with mean value 60% and standard deviation 6.2%. The probability that more than 75% of the 64 DMQs occur within 5° from the mare basalts deposits is ~0.01, thus rejecting the randomness of the DMQs relative to mare basalts in this scenario.

Finally, if all the 106 DMQ clusters from Nakamura (2005) are considered, without constraints on depths and errors in longitude and latitude, we found that correlations between the DMQs and FeO deposits >13 wt.% were 68% and 50%, using 5° and 1° distance criteria, respectively, which are also significantly higher than those expected from random distributions of DMQs. Our results therefore indicate that the DMQs are not randomly distributed relative to mare basalts and that the DMQs are correlated to mare basalts, supporting the proposal by Lammlein (1977).

4. Conclusion and discussion

We have correlated the presence of the mare basalts, using FeO concentration as a proxy, with the epicenters of 52 well-determined DMQs. We find FeO concentrations of 13 wt.% or higher to be representative of the mare basalt deposits which account for 30% of the surface area of the nearside. Our analysis shows that over 63% of the DMQs occur within 1° from the mare basalt deposits, while over 80% of the DMQs are within 5° from the mare basalt deposits. Our analysis rejects a random distribution of DMQs with regard to mare basalts.

The DMQs are present-day processes that occur at large depths (average depth of the 52 nests used is 930 km), while the mare basalts erupted to the lunar surface over 3 Ga ago. If they are correlated as we established here, then this result has a number of implications for the causes of the DMQs, the origin of mare basalts and the evolution of the lunar interior. This suggests that mare basalts may have a deep origin, because the same processes responsible for DMQs are also likely related to mare basalts. This is consistent with some petrological evidence (Delano, 1986) and with previously presented arguments (Hess and Parmentier, 1995; Zhong et al., 2000). These results also suggest that the asymmetrical distribution of the DMQs on the nearside may be real and

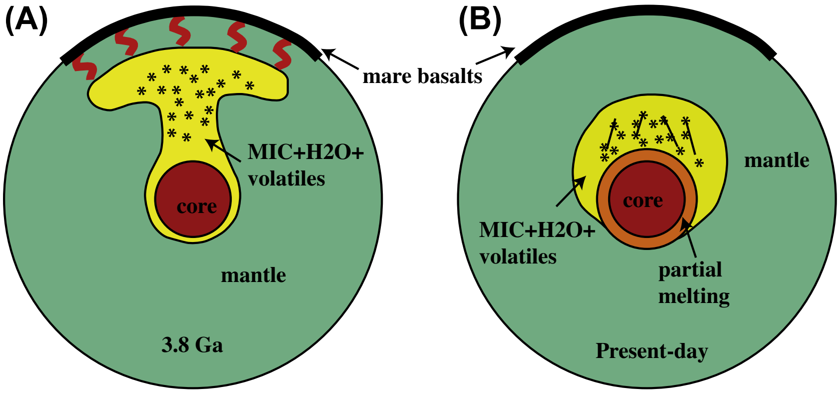

Fig. 4. A schematic representation of the lunar interior structure and state during mare basalt emplacement ~3.8 Ga ago (A) and for the present-day (B). MIC is the mixture of ilmenite cumulates (IC) and olivine–orthopyroxene formed during the sinking of the IC in olivine and pyroxene mantle after magma ocean differentiation; MIC is rich in radioactive elements, water and other volatiles. The ascending MIC plume in (A) would undergo decompression melting to form mare basalts and is the source of mare basalts. The MIC material may then sink back toward the core due to its cooling and chemically greater density. The stars denote deep moonquakes (DMQs) that in our hypothesis may form preferentially in the MIC or mare basalt source regions where the water and other volatiles may weaken the materials locally and form cracks (i.e., denoted by lines in B) (e.g., Frohlich and Nakamura, 2009). A layer of partial melting may exist in the lunar mantle above the core (e.g., Nakamura, 2005; Weber et al., 2011).

not necessarily entirely due to seismic station bias, because mare basalts are predominately on the nearside as well.

We propose a new hypothesis, in which the link between mare basalts and DMQs is the MIC material, i.e., the source materials for mare basalts. Following Hess and Parmentier (1995), the MIC material initially resided at large depths, possibly just above the CMB. Due to hydrodynamic instabilities the MIC material rises in one hemisphere (i.e., the present-day nearside) to a depth of ~400 km and results in the eruption of mare basalts mostly between 3.9 and 3 Ga ago. After the eruption of mare basalts, the MIC is significantly cooled and may become negatively buoyant again and sink back to the deep interior, possibly to the CMB. Due to the cooling and increased viscosity of the IC and lunar mantle, the sinking of the MIC may be slow, such that it may remain largely on the nearside at or above the CMB today (Fig. 4). The MIC material, as the source for mare basalts, contains significant amounts of water and volatiles (Saal et al., 2008). Under the Earth's tidal force, the water rich MIC material may fail relatively easily, because water helps facilitate failure by reducing strength (Frohlich and Nakamura, 2009). Therefore, the DMQs may delineate the regions in the deep lunar mantle where the MIC material exists. High seismic attenuation was attributed to partial melting (Nakamura, 2005; Weber et al., 2011), and may also be related to the MIC materials. This is because the MIC material is more likely to contain partial melting due to the presence of water that helps reduce melting temperatures.

While our new hypothesis (Fig. 4) appears to reconcile most of the observations, it also makes specific testable predictions, including significantly reduced DMQ activities on the farside, relative to the nearside, and distinct seismic structure at large depths on the nearside, all of which can be tested with future deployment of seismometers, particularly on the farside. Future work should explore the relationship between tidal stresses, heterogeneities in the lunar mantle, and deep moonquakes, and also the spatial correlations between Procellarum KREEP Terrane, and mare basalts, and crustal thickness variations (Wieczorek and Phillips, 2000; Parmentier et al., 2002; Garrick-Bethell et al., 2010). Finally, we suggest that DMQ may hold a key to understanding lunar mantle dynamics and evolution similar to how deep seismicity in the Earth's mantle illuminates Earth's mantle dynamics.

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