TESTING THE LUNAR DYNAMO HYPOTHESIS USING GLOBAL MAGNETIC FIELD DATA.
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Introduction: Although the Moon does not presently have a magnetic field generated by its core, it is possible that in early lunar history the core might have once powered a geodynamo. Such a field, if directionally stable, could have magnetized lavas and impact melt sheets at the surface and magmatic intrusions deep in the crust. However, some of the strongest magnetic anomalies appear to be correlated with the antipodes of large impact basins, and this has led to the alternative hypothesis that transient magnetic fields generated during impacts might be responsible for magnetizing portions of the lunar crust [see 1,2,3].

In this work, we use lunar paleomagnetic constraints combined with orbital magnetic field measurements to test the hypothesis that an ancient dipolar field is responsible for magnetizing the lunar crust. We calculate the expected magnetizations of lunar materials, estimate the magnetic field intensities for various distributions of magnetization, and perform a localized magnetic-field power spectrum analysis to estimate the magnetization depths.

Constraints on crustal magnetization: To model the orbital magnetic signatures, it is necessary to estimate the expected magnetizations of lunar materials. For this, we assume the presence of a 100-μT field at the surface (the strongest value inferred from Apollo samples), and make use of an approximately linear relationship between the magnetizing field and the ratio of thermoremanent to saturation remanent magnetization [4]. Our extensive compilation of lunar rock magnetic analyses demonstrates that the mafic impact-melt breccias should be some of the most magnetic non-regolith materials, with an average thermoremanent magnetization (TRM) of 0.4 A/m. These impact melts are commonly believed to be derived from the Imbrium impact basin, and they contain up to 1.5 wt.% metallic iron that was probably derived from a metal-rich impactor [5]. The mare basalts are less magnetic, with an expected average TRM of 0.1 A/m, and 4 pristine highland rock analyses yield an average expected TRM of only 0.02 A/m.

We performed an ideal body analysis to obtain the minimum layer thickness that would be required to account for the orbital magnetic anomalies [6,7]. For the Reiner-γ anomaly, the observed field intensities could be explained by an approximately 10 km thick layer of magnetized basalt. This is potentially consistent with the observation that metallic iron exsolves from basaltic magmas at depths less than 9 km below the surface [8]. The slow cooling of such a thick intrusion would seem to require the presence of a stable magnetic field, most plausibly generated by an internal dynamo. Two kilometers of mafic impact-melt ejecta could also explain this anomaly, but there is no topographic evidence for such a locally thick ejecta deposit in this region.

Global magnetization models: If the lunar core ever generated a dipolar magnetic field, it is possible that large portions of the crust could have been magnetized as it cooled through the Curie isotherm of iron. Runcorn's theorem [9] states that no field would be observable after the dynamo shut off if the magnetized region was perfectly spherical. However, given the non-spherical shape of the Moon, some magnetic expression could perhaps be seen from orbit.

Following [10], we calculated the expected magnetic field intensities at an altitude of 30 km for three different global distributions of magnetization. We used the average magnetic characteristics of the pristine highland samples and assumed a 100-μT field strength near the Apollo landing sites. If a dipolar field magnetized the entire Moon, the expected magnetic intensities would be about 1 nT, and the strongest of these would be located close to the poles. If only the upper 10 km of the Moon were magnetized, the field strengths would be about 4 times smaller. Finally, if the entire crust were magnetized, the expected magnetic field strengths could reach up to 5 nT in the central portions of some impact basins. Given these low intensities (compare with Fig. 2), even if a dipolar field magnetized large portions of the lunar crust, it is unlikely that we would detect such a signature from orbit.

Magnetization of mare basalts: If the mare basalts erupted at a time when the Moon possessed a core dynamo, they might be expected to have a magnetic signature when observed from orbit today. We calculate the required basalt thicknesses and magnetizing field strengths that are required to give rise to a detectable magnetic signature (~1 nT at an altitude of 30 km). As seen in Fig. 1, for average basalt compositions and a 100-μT magnetizing field, a magnetic signature would only be seen if the basalts were more than 1 km thick and uniformly magnetized. Since most mare on the nearside are thinner than this, we do not expect to see orbital magnetic anomalies associated the mare, even though they might be magnetized. Therefore, the lack of anomalies above the mare is in fact consistent with a strong, ancient lunar dynamo.

Mare Crisium: The Crisium impact basin is unique in that it possesses two strong magnetic anomalies that are entirely confined to the basin's interior (see Fig. 2). If we assume that a 100- T field magnetized 1 km of basalt in this basin, the predicted magnetic intensities would be less than half of the observed values. Furthermore, the surface expression of the magnetic anomalies is not consistent with the entire expanse of Mare Crisium being uniformly magnetized. Thus, it is not likely that the basalts are the origin of these anomalies.

An alternative explanation is that these anomalies are the result of a magnetized metal-rich impact-melt sheet. In this case, the iron metal would be derived from the impactor, just like the mafic impact-melt breccias. A 1 km thick melt sheet would be sufficient to explain the observed magnetic intensities, and we note that the Crisium melt sheet could reach several kilometers in thickness [11]. In any case, the slow cooling of either a melt sheet or thick basalt flows would seem to require the presence of a stable magnetic field, most plausibly from a core dynamo.

Depth of magnetization: An important constraint in determining the origin of lunar magnetic anomalies is the depth at which the magnetizations are located in the crust. We investigate this problem by interpreting the magnetic field power spectrum in terms of a stochastic magnetization model similar to [12]. In this model, the magnetization is confined to thin spherical disks that are randomly placed between two depths, the disks possess the same radius, and the magnetization directions and magnitudes are random. Since we expect the depths of magnetization to vary across the lunar surface, we use the localized spectrum analysis technique of [13].

Four of our localized spectral analyses were performed in the vicinity of the South Pole-Aitken basin. As shown in Fig. 2, the magnetic anomalies in this region appear to correlate with the northern rim of this basin, and we suspect that their origin is related to the formation of this basin in some manner. For the two western analyses, the magnetized layer is predicted to be close to the surface, with 1-σ depths to the bottom of magnetization being ~15 km. In contrast, for the two eastern analyses, the depths to the top of the magnetized layer are predicted to be in excess of 23 km.

Crustal thickness models [2] predict that the crust is about 20 km thicker to the northeast of the South Pole-Aitken basin than to the northwest. If the thick crust to the northeast of the SPA basin represents ejecta deposits from an oblique impact, then this could perhaps indicate that the ejecta from this basin buried pre-existing magnetic anomalies in this region. These deep anomalies would thus be ancient. Alternatively, we hypothesize that the magnetic anomalies in this region could be the result of metal-rich impact ejecta derived from a metal-rich SPA forming bolide.

Summary: Given the weak magnetizations of the Apollo samples, the lunar magnetic anomalies seem to demand extremely thick magnetized crustal sources. If these magnetizations are thermoremanent in origin, the slow conductive cooling timescales would require a long-lived stable field. A core dynamo, but not impact-produced fields, would meet this criterion. The amplification of ambient magnetic fields antipodal to the largest impact basins could perhaps explain some anomalies, but this model is incapable of explaining the Reiner-γ and Crisium impact basin anomalies.

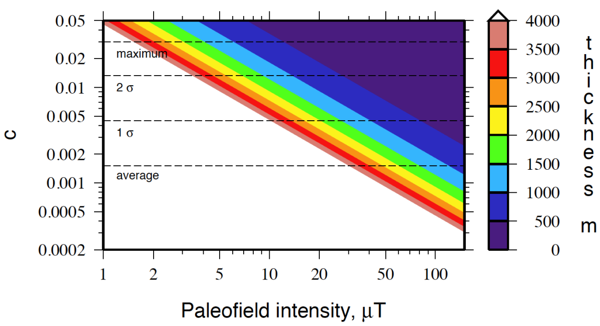

Figure 1. TRM susceptibility (*c*), dipole field strength, and layer thickness required to generate a 1 nT anomaly at 30 km altitude. Dashed lines denote the range of *c* for the mare basalts.

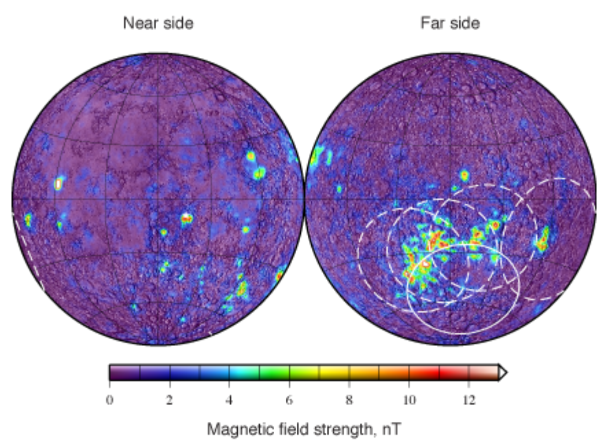

Figure 2. Magnetic field strength of the Moon at 30 km altitude [14]. The dotted circles represent 4 regions investigated by a localized spectral analysis, and the solid circle outlines the floor of the South Pole-Aitken impact basin.

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