DEPTH AND ORIGIN OF LUNAR MAGNETIC ANOMALIES FROM A LOCALIZED MAGNETIC POWER SPECTRUM ANALYSIS. Mark A. Wieczorek, Institut de Physique du Globe de Paris, Paris, France (wieczor@ipgp.fr).

Summary. *Inversions of localized magnetic power spectra on the Moon show that the depth to the top of magnetization in the crust varies laterally from about 0 to 20 km. The highest magnetizations are associated with the northern portion of the South Pole-Aitken basin where the magnetic sources are close to the surface. For other regions, the magnetic sources are generally at 10-20 km depth, where they could have formed when the primordial crust cooled slowly in the presence of an ancient core-generated magnetic field more than 4.25 billion years ago. The absence of near-surface magnetic sources in these regions is likely a result of impact-related shock demagnetization processes that occurred early in lunar evolution.*

Introduction. Before the Apollo missions, it was often thought that the Moon was a primordial, undifferentiated relic of the early Solar System. It was thus a great surprise when the Apollo subsatellites and surface magnetometers detected magnetic fields originating from the lunar crust. These magnetic anomalies were most plausibly produced when crustal rocks cooled in the presence of an ancient magnetic field generated by a core dynamo, but many aspects of this story remain unresolved [1, 2].

One key aspect that is currently unknown concerns the depth of the magnetized materials that give rise to the observed magnetic field. Plausible sources of near-surface magnetization include the mare basalts, impact melt sheets of large impact basins, and basin ejecta deposits. Deep magnetic sources could be the result of either magmatic intrusions, or simply the slow cooling of the primordial crust early in lunar history.

The model. The power spectrum of a planet's magnetic field depends upon the distribution and geometry of magnetic sources. This problem was studied previously by Voorhies and coworkers [3-5], who gave expressions for the power spectrum when the magnetized regions were spatially uncorrelated dipoles, depth correlated dipoles, or infinitesimally thin radially magnetized spherical caps.

We expand upon this model by considering two scenarios, as illustrated in Figure 1. The first model assumes that the power spectrum can be approximated by an ensemble of magnetized spherical cones, each of which possesses a random lateral position, random volumetric magnetization, and random magnetization direction. The fixed parameters of this model include

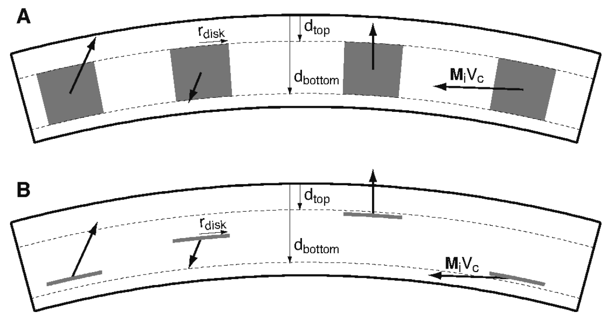

Figure 1. Schematic diagram of the two stochastic models of crustal magnetization used in the magnetic field power spectrum analysis. (A) Spherical cones, and (B) sills distributed within a spherical shell.

the angular radius of the cones, a parameter that depends on the average-squared magnetization, and the depth to the top and bottom of the magnetized region. The second model is a generalization of the first, and accounts for the case of infinitesimally thin magnetized caps that are placed randomly within a spherical shell.

The theoretical power spectra depend upon all model parameters, but the depth to the top of the magnetized region has by far the largest influence. Figure 2 shows example spectra for the two models (solid and dashed lines) where the depth to the top of magnetization varies from 0 to 20 km. For all curves, the depth to the bottom of the magnetized region and the angular radius of the sources were set to 30 and 3 km, respectively. The two models show behavior that is in general similar, but different in detail.

Inversion approach. Give the complexity of lunar geologic evolution, we expect that the depth and geometry of magnetic materials will vary laterally. For this reason, we calculate power spectra localized to a specific region using a localized spectrum analysis procedure [6, 7]. For a given set of model parameters, we calculate the expectation of the localized theoretical model, and then calculate the misfit between the model and observations. Using an exhaustive grid search, the misfit function is quantified, and the best-fit parameters determined.

Two parameters determine the quality of the localized magnetic power spectra: the angular radius of the localization windows, and their spectral bandwidth L. As a good tradeoff between spectral and spatial localization, we use windows with a radius of 12° (720 km

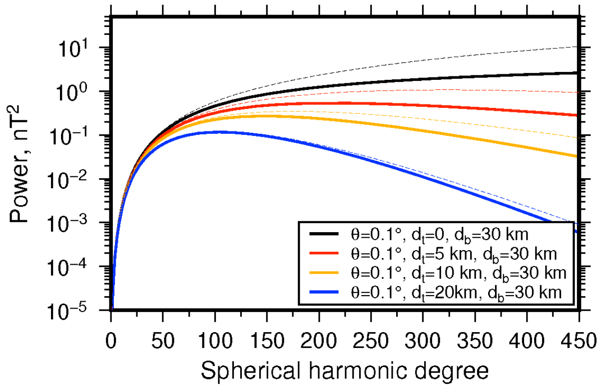

Figure 2. Example power spectra for ensembles of randomly magnetized cones (solid lines) and sills (thin dashed lines) showing the dependence of the depth to the top of the magnetized region. For all curves, the depth to the bottom of the magnetized region is 30 km, and the angular radius of the cones is 3 km.

diameter) and a spectral bandwidth of 50, which provides 12 orthogonal windows whose concentration factors are greater than 0.99.

Results. The global magnetic field model of Tsunakawa et al. [8] is used in the inversions, which is based on magnetometer observations from both the Kaguya and Lunar Prospector missions. The gridded radial magnetic field was used to develop a spherical harmonic model of the magnetic potential to degree 449, which allows an analysis of the localized spectrum from degree 50 to 399. Using 12° windows, localized inversions were performed on a 12° equidistant grid the covered the lunar surface.

The most robust inversion parameter of our analysis is the depth to the top of the magnetized region, which is plotted in Figure 3 (centered over the farside hemisphere) for the case of magnetized sills. This depth, which is referenced to the actual surface of the Moon, varies from 0 to about 20 km. By area, the depth to the top of the magnetized region is mostly in the range of 10-20 km. However, large expanses are found to possess depths to the top of magnetization that are close to 0. These areas are largely associated with the northern portion of the South Pole-Aitken basin, a region encompassing the Smythii basin and mare Marginis, the center of the Imbrium basin, and Reiner-γ.

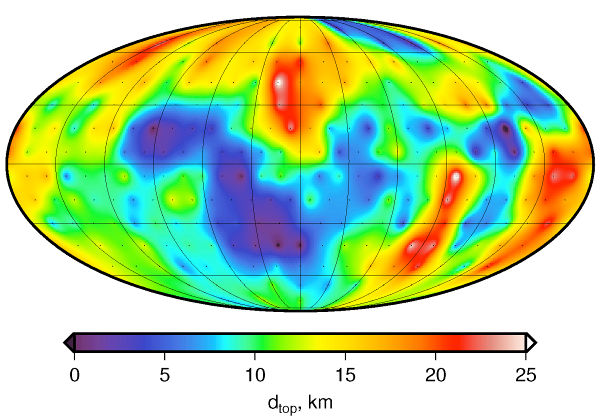

Figure 3. Best-fit depth to the top of the magnetized region determined from a localized spectral analysis of the Moon's magnetic field. The image is presented in a Mollweide projection centered over the farside hemisphere of the Moon, with grid lines spaced every 30° of latitude and longitude.

Interpretation. The vast majority of the Moon possesses depths to the top of the magnetized region that are between about 10 and 20 km. Since most of these regions are not associated with mare volcanism, it is unlikely that the magnetic sources are deep magmatic intrusions. Instead, the great depths of magnetization are here suggested to be a result of primordial crustal rocks that cooled below the Curie temperature early in lunar evolution. Using the Curie depth of metallic iron predicted from thermal evolution simulations [9], for most regions, the lower portion of the crust could have acquired a thermal remnant magnetization only during the first 250 million years of lunar evolution. This suggests that the lunar dynamo predates the oldest age of ~4.2 Ga obtained from paleomagnetic analyses [10]. The lack of magnetization in the upper 10 km of the crust in these regions is likely a result of impact shock-demagnetization processes.

The most prominent region where the top of the magnetized region is close to the surface is the northern portion of the South Pole-Aitken basin. This region coincides approximately with where the strongest magnetic anomalies on the farside of the Moon are found, and where it was suggested that iron-rich remnants of the projectile that formed this basin might be found [11]. In a similar manner, other regions with shallow depths of magnetization might also correspond to iron-rich impact basin deposits.

References. [1] M Fuller, SM Cisowski (1987), Lunar paleomagnetism, in *Geomagnetism*; [2] BJ Weiss, SM Tikoo (2014), *Science*, 346, 1246753; [3] C Voorhies (1998), *NASA Tech. Pap.*, 1998-208608; [4] CV Voorhies et al. (2002), *J. Geophys. Res.*, 107, 5034; [5] CV Voorhies (2008), *J. Geophys. Res.*, 113, E04004; [6] MA Wieczorek, FJ Simons (2005), *Geophys. J. Int.*, 162, 65; [7] MA Wieczorek, FJ Simons (2007), *J. Fourier Analys. Appl.,* 13, 665; [8] H Tsunakawa et al. (2015), *J. Geophys. Res.*, 120, 1160; [9] M Laneuville et al. (2013), *J. Geophys. Res.*, 118, 1435; [10] I Garrick-Bethell et al. (2009), Science, 323, 356; [11] MA Wieczorek et al. (2012), *Science*, 335, 1212.