THE GREAT MAGNETIC LOW OF THE MOON.

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Introduction: Magnetic field data acquired from both the Lunar Prospector and Kaguya spacecraft have been used to construct a global model of the Moon's magnetic field with a spatial resolution of about 6 km [1]. This model shows that the field strengths at 30 km altitude are on average a few μT, reaching up to about 20 μT in several isolated regions. At least some of the strongest anomalies are related to iron-rich impact deposits [2,3] and the weaker fields associated with the highland crust are related to deep magnetization when the crust formed [4].

In contrast to the dispersed distribution of strong magnetic anomalies, one sizeable region of the lunar crust has extremely weak magnetic field strengths of less that 0.1 μT. These fields are an order of magnitude lower than average, and span a province that covers 6% of the Moon's surface area. This great magnetic low encompasses Mare Imbrium, a portion of Oceanus Procellarum, and a portion of Mare Frigoris (Fig. 1).

The weak crustal fields of this region are not an artifact of the magnetic field model as maps of the surface field strength derived from the Lunar Prospector electron reflectometer also show weak field strengths in the same region [5]. Furthermore, a localized spectral analysis of the Moon's magnetic field shows that this same region has crustal magentizations that are weaker by an order of magnitude than elsewhere [4] (Fig. 2). We propose that this region could have escaped becoming magnetized when the core dynamo field was strong as a result of prolonged high crustal temperatures that were above the Curie temperature of iron metal.

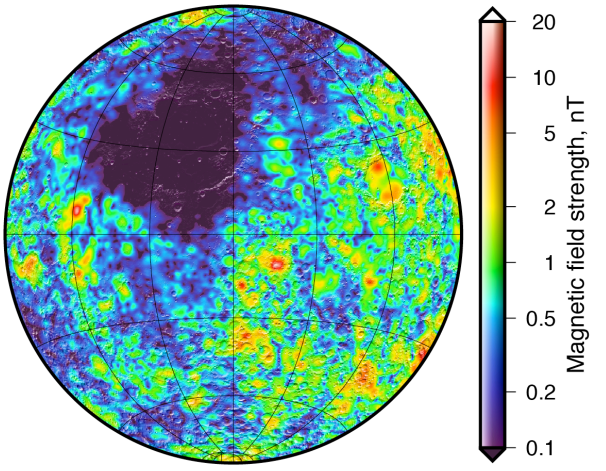

Figure 1. Total magnetic field strength over the nearside of the Moon at 30 km altitude from the model of [1].

An impact origin? One explanation for the nearside magnetic low is that it is a result of crustal demagnetization related to large impact events [6]. The nearside magnetic low correlates well with the Imbrium impact basin (Fig. 2), and it is well known that shock waves generated during impact events can partially demagnetize magnetic minerals [5,7,8]. It would thus not be surprising if the Imbrium impact partially demagnetized the surrounding crust [9].

Nevertheless, even though some impact basins have relatively low magnetic field strengths in their interiors, none have absolute strengths as low as those near the Imbrium basin, nor as large in spatial extent. The Orientale basin has weak field strengths in its vicinity, but the size and magnitude of this anomaly (~0.5 μT) are unlike those of the older Imbrium basin. The Crisium basin, which is the only basin intermediate in size between Imbrium and Orientale, does not have any clear demagnetization signature at all, and in fact its interior is strongly magetized. Though the magnetic low is coincident with the Imbrium basin, it is not entirely symmetric about the center of the Imbrium basin. These observations suggest that the Imbrium impact is unlikely to be the sole cause of the nearside magnetic low.

Late magnetization as a result of high heat production? An alternative explanation for the nearside magnetic low is that it is related to high crustal temperatures that were above the blocking temperature of metallic iron at the time when the lunar dynamo was strongest. As shown in Fig. 2, the nearside magnetic low lies entirely within the confines of the Procellarum KREEP Terrane (PKT) [10], which is a unique geologic province that has high concentrations of the heat-producing elements K, Th, and U.

The high heat-production within this province certainly had a major influence on the thermal evolution of this region, and thermal evolution models predict the crust and underlying mantle of the PKT to have been considerably hotter than other regions of the Moon [e.g., 11]. It is thus conceivable that large portions of the crust within the PKT could have had temperatures above the Curie temperature of metallic iron at the same time when other regions of the highland crust had already cooled below this temperature.

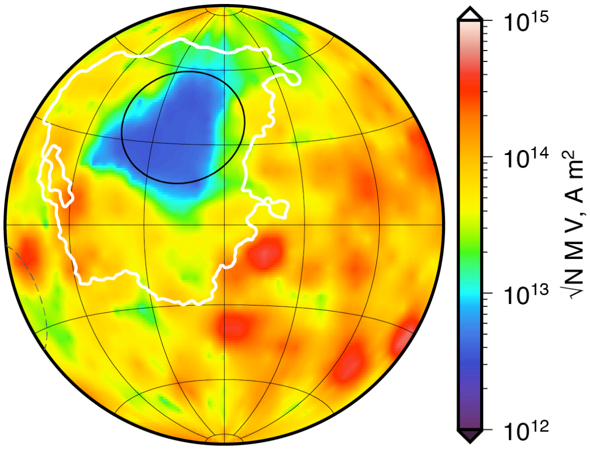

Figure 2. Map of a parameter that is proportional to the average magnetization of the crust from the localized spectral analysis of [4]. The white contour represents the confines of the Procellarum KREEP terrane using 4 ppm Th, and the solid and dashed circles represent the sizes of the Imbrium and Orientale impact basins, respectively.

Paleomagnetic studies suggest that the surface magnetic field strength decreased by an order of magnitude after 3.56 Ga, from ~100 µT to ~5 µT [12]. If the crustal termperatures within the PKT were still high at 3.56 Ga, the crust there would later acquire a magnetization that would be about an order of magnitude lower than elsewhere.

One consequence of this scenario is that the size of the Procellarum KREEP Terrane could be considerably smaller than once thought. The confines of the PKT are often delimited by those regions having thorium abundances greater than ~4 ppm, but most of this region has been resurfaced by mare basalts, which obscurs from view the composition of the underlying crust. The region of extremely low magnetic field intensities might represent that portion of the crust that contains the highest abundances of heat-producing elements. If true, this would imply that the size of the PKT could be almost three times smaller than previous estimates based solely on surface composition.

Thermal evolution of the Procellarum KREEP Terrane: We have performed [13] new thermal evolution simulations to test the hypothesis that significant portions of the crust could have remained above the Curie temperature of iron metal (1073 K) up until at least 3.56 Ga when the surface magnetic field strength declined significantly. These simulations differ from previous work [11] in that we consider the possibility of a smaller PKT, as well as the possibility of an enriched mantle beneath the PKT. By assuming a thorium abundance for the PKT and underlying mantle, mass balance using bulk-Earth abundances determines the thorium abundance of the rest of the mantle.

Our simulations show that the highland crust outside of the PKT would cool entirely below the Curie temperature of iron metal in less than 100 million years after crust formation. In contrast, as shown in Fig. 3, cooling of the PKT crust to the same temperature is considerably prolonged. For models that use 5.7 ppm Th for the PKT crust, the crust cools below the Curie temperature in about 200 My. For our preferred model with a smaller PKT with 8.2 ppm Th and an underlying enriched mantle, cooling below the Curie temperature could take as long as 1.1 Gy. This time corresponds approximately to when paleomagnetic studies imply the surface field strength decreased substantially.

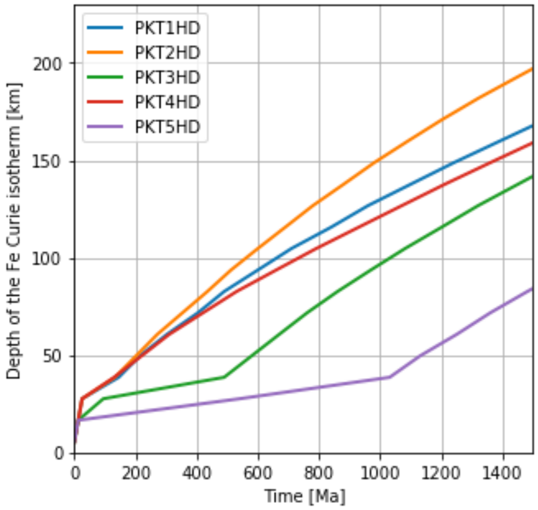

Figure 3. Depth to the Curie temperature of iron metal in the center of the PKT as a function of time for five different thermal evolution models. Models 1, 2, and 4 use 5.7 ppm for the crust of the PKT, whereas models 3 and 5 use 8.2 ppm. Models 4 and 5 include an enrichment of Th in mantle beneath the PKT.

References: [1] H Tsunakawa et al. (2015), *J. Geophys. Res*., 120, 1160; [2] MA Wieczorek et al. (2012), *Science*, 335, 1212; [3] JS Oliveira et al. (2017), *J. Geophys Res.*, doi: 10.1002/2017JE005397; [4] MA Wieczorek (2018), *J. Geophs. Res. Planets*, accepted; [5] DL Mitchell et al. (2008), *Icarus,* 194, 401; [6] JS Halekas et al. (2001), *J. Geophys. Res.,* 106, 27,841; [7] K Louzada et al. (2011), *Earth Planet. Sci. Lett*., 305, 257; [8] RJ Lillis et al. (2010), *J. Geophys. Res*., 115, E07007; [9] J Halekas et al. (2003), *Meteorit. Planet. Sci*., 38, 565; [10] BJ Jolliff et al. (2000), *J. Geophys. Res*. 105, 4197; [11] M Laneuville et al. (2013), *J. Geophys. Res. Planets*, 118, 1435; [12] SM Tikoo et al. (2014), *Earth Planet. Sci. Lett*., 404, 89; [13] M Laneuville et al. (2018), LPSC 49.