LUNAR CRUSTAL MAGNETIZATION INFERRED FROM CHARACTERISTICS OF LUNAR SWIRLS

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Summary: Lunar swirls are collections of finely structured bright and dark surface markings, alternating over length scales of typically 1–5 km. If swirls are the result of plasma interactions with crustal magnetic anomalies, the magnetic field orientation must vary over similar length scales. This requires that the associated source bodies be both shallow, and narrow in horizontal extent. If >300 nT surface fields are necessary to produce observable swirl markings, the required rock magnetization must be >0.5 A/m, even for very shallow sources, and ~2 A/m if the source depth is similar to its width. This result places constraints on the geometry of the source bodies and challenges our understanding of the mineralogy and possible origins of the Moon's crustal magnetic anomalies.

Background: Lunar swirls are peculiar optical anomalies, comprising alternating bright and dark markings, found in various regions across the lunar surface. Several studies suggest that swirls are the result of spatially variable solar wind weathering due to the presence of strong crustal magnetic anomalies [e.g., 1–3]. Magnetometer-based studies of magnetic fields [e.g., 3], as well as hybrid and kinetic plasma simulations [e.g., 4–6], indicate that swirl morphology may be dictated by magnetic field topology. Large swirl complexes, such as the archetypal Reiner Gamma, can span several tens of kilometers, but are invariably ensembles of smaller, elongate structures, with the transition from bright to dark taking place over distances of typically 1–5 km (Figure 1).

Field Orientation: For crustal magnetic anomalies, magnetic field direction varies over a length scale related mainly to the depth and horizontal extent of the source body. In the case of a buried dipole, for instance, it can be shown that a 90° change in surface field orientation occurs over a horizontal distance of $\sqrt{2}d$, where d is the burial depth of the vertically magnetized dipole; if the dipole is horizontally magnetized, the distance is $\frac{1}{\sqrt{2}}d$. Hence, if swirl morphology is controlled by magnetic field topology, then the ~3 km length scale associated with the transition from dark to bright parts of swirls requires the top of the buried source to be no deeper than ~4 km, even for an infinitely compact source. Broader source bodies must be correspondingly shallower and, even in the limit of zero depth, must have half-widths narrower than the ~3 km length scale associated with the inferred change in field orientation.

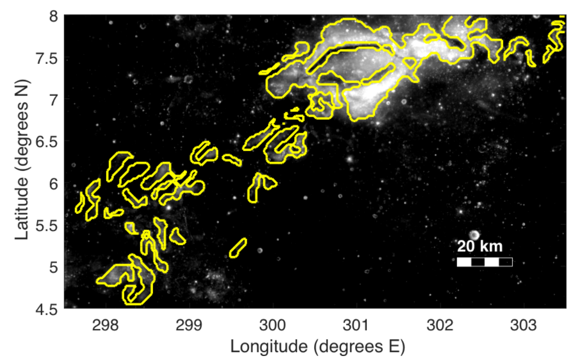

Figure 1: Swirl markings in the vicinity of Reiner Gamma, illustrating the characteristic bright-to-dark transition length scale of 1–5 km. Yellow contours highlight recognized swirls [7].

Accordingly, we predict that swirls, as they are currently recognized, should be found only in regions with shallow source magnetization—a suggestion that is supported by the spatial correlation between the locations of swirls (as mapped by [7]) and the regions of shallowest magnetization (as determined by [8]).

Field Strength: To assess the relationship between rock magnetization and surface field strength, we consider the simple case of an infinitely long buried rectangular prism that is magnetized horizontally, perpendicular to its long axis. At the surface, and directly above the prism, it can be shown that the field strength in SI units is given by

$$B = \frac{\mu_0 m}{\pi}\left(\tan^{-1}\left(2\frac{d}{w}\right) - \tan^{-1}\left(2\frac{d+h}{w}\right)\right)$$

where w is the prism's width, h is its height, d is the burial depth, m is the rock magnetization in A/m, and where μ_0 is the magnetic permeability of free space. The surface field strength is a linear function of magnetization, but only a tangential function of both the prism's depth-to-width ratio and its height-to-width ratio (Figure 2).

Although vector magnetic field measurements have yet to be collected below altitudes of ~18 km in the vicinity of swirls, downward continuation techniques [e.g., 9] have been used to estimate surface fields of ~300–500 nT at Reiner Gamma, for example. If the prism is buried 1 km below the surface and is 2 km wide, the rock magnetization required to produce a 300 nT surface field is >1 A/m, even if the prism extends to a great depth (Figure 2). Shallower sources permit smaller rock magnetizations, but even the shal-

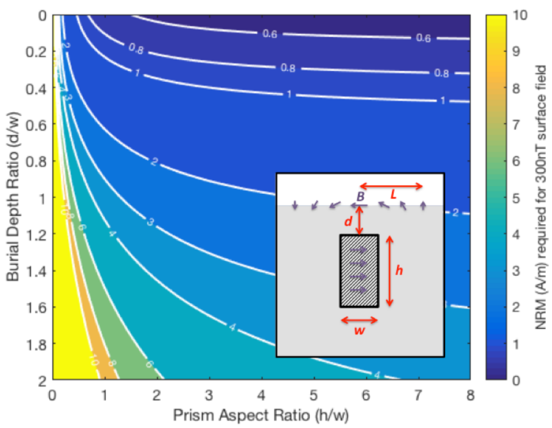

Figure 2: Source rock natural remanent magnetization (NRM) required to produce a 300 nT surface field directly above an infinitely long, horizontally magnetized rectangular prism having height *h*, width *w*, and buried a depth *d* beneath the surface (see inset). Required magnetizations are below 1 A/m only when the prism's burial depth is shallow compared to its width (*d*/*w* <0.4) and when its height is at least twice its width (*h*/*w* >2).

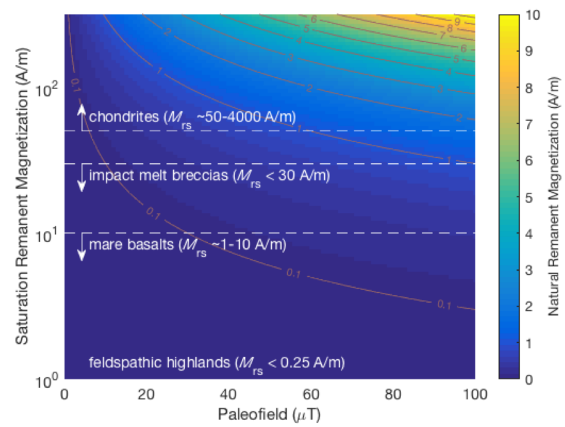

Figure 3: Natural remanent magnetization (NRM) of magnetic anomaly source rocks as a function of saturation remanent magnetization (M_{rs}) and paleofield intensity. Typical M_{rs} values for lunar rocks and chondritic meteorites are shown for context.

lowest sources require >0.5 A/m. The ~300 nT surface field estimate of [9], however, is merely a lower bound because it does not account for the possibility of unresolved finer structure in the very near surface fields. Consideration of finer structure has led to surface field estimates of ~1000 nT at Reiner Gamma [3], implying even larger rock magnetizations (perhaps 3 A/m or more, depending on the source geometry).

Discussion: Such source rock magnetization intensities are difficult to reconcile with current understanding of magnetic properties for endogenic lunar materials. Depending on lithology, lunar rocks typically have saturation remanent magnetizations (M_{rs}) ranging between 0.05 A/m (feldspathic highlands rocks) and 30 A/m (mafic impact melt breccias) [10]. From these values, we can estimate anomaly source natural remanent magnetization (NRM) intensities according to

$$\mathrm{NRM} = (B)(M_{\mathrm{rs}})/a$$

where the NRM is assumed to be a thermoremanent magnetization acquired during primary cooling, *B* is the paleofield in units of μT, and *a* is a calibration constant with a value of ~3000 μT [11]. Paleomagnetic studies suggest that surface fields on the Moon were likely <100 μT in intensity for nearly all of lunar history [12]. This implies that the NRMs of known lunar materials and melt breccias are unlikely to exceed ~1 A/m, even when utilizing upper limit values for M_{rs} (Figure 3). For comparison, the NRMs of most lunar breccia samples are ~0.1 A/m and the NRMs of most mare basalt samples range between ~0.001 and 0.01 A/m [12].

Conclusions: If our assumptions are correct, the magnetic sources associated with lunar swirls must be both narrow (half-widths smaller than the swirl's bright-to-dark transition length scale) and shallow (<3 km deep). Very shallow sources (i.e., at depths that are small compared with their widths) are most easily accommodated, as they require the smallest magnetizations (Figure 2). Impact demagnetization, however, could make such shallow sources difficult to preserve.

If the sources have NRMs >1 A/m (as required if their depth is at least half their width), these magnetic anomalies must be sourced either from rocks with unusually high metal content (e.g., meteoritic material or metal-rich intrusive rocks) or from rocks that acquired their magnetization from paleofields with intensities significantly greater than those inferred for the lunar dynamo (e.g., impact-generated fields) (Figure 3).

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