SIZE THRESHOLDS FOR UNIDIRECTIONAL REMANENCE WITHIN LUNAR MAGNETIC ANOMALIES.

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Introduction: The Moon is observed not to have a current global magnetic field, but analyses of Apollo samples and remanent magnetism in the lunar crust indicate that a near-Earth strength dynamo field was present from 4.25 Ga until about 3.56 Ga, with a weaker field persisting until sometime between 1.9 Ga and 0.9 Ga [1,2]. Preliminary results from paleomagnetic studies have suggested that the Moon may have had a predominantly dipolar field that was aligned with the Moon's axis of rotation, similar to how the Earth's magnetic field is dominantly a geocentric axial dipole [3]. The lunar crust also contains magnetic anomalies, as measured by the Lunar Prospector and Kaguya orbiters. Several anomalies, which are often attributed to basin impact melt sheets or ejecta deposits, have been used to determine magnetic paleopoles, which indicate the paleo-orientation of the ancient dynamo field [e.g., 4]. Such reconstructions do not seem to support the axial dipole hypothesis as different studies and different anomalies seem to place lunar paleopoles at essentially all latitudes [1,4]. The only way these scattered paleopoles could reflect an axial dipole is if the entire solid body of the Moon underwent significant rotations in its history, a phenomenon known as true polar wander (TPW), but evidence for extreme lunar TPW is lacking.

A possible flaw with paleopole reconstructions from crustal magnetism is that they rely on the assumption that the magnetic sources responsible for anomalies are uniformly magnetized. One mechanism for producing non-uniformly magnetized magnetic source bodies (and in turn, scattered paleopole distributions) is the recording of magnetic field reversals occurring over long timescales as large bodies cool. For example, estimated basin melt sheet cooling time scales (~10^4-10^6 years) are comparable to the timing of geomagnetic field reversals on Earth [5,6]. Therefore, melt sheets may record a complex thermoremanent magnetization that could produce inaccurate dipole fits from spacecraft data measured at ~30 km altitude. Here we simulate cooling of variably sized bodies to obtain boundary conditions for likely unidirectional versus likely complex internal magnetization patterns. We also forward model the surface field expression of a range of non-uniformly magnetized source bodies.

Methods:

Cooling of magnetic source bodies. To investigate the internal dynamics of cooling in basin melt sheets (as an example source body), we constructed a two-dimensional heat flow simulation using KWare HEAT3D. The software enabled us to specify values for heat capacity, thermal conductivity, and bulk density of both the lunar crust and the body of impact melt [7-9], which we treated as basalt and dunite respectively [10]. Our initial conditions began with an established melt sheet residing 1-10 km below the lunar surface [11]. We varied the lateral extent of cooling body diameters between 10 km and 100 km, thicknesses from 1 km to 10 km, and initial melt temperatures between 1200 and 1500 °C.

Magnetic field expression of non-uniformly magnetized source bodies. As seen below, source bodies are expected to cool from the outside-in over long timescales and may record a field reversal during this time. To determine the surface magnetic field expression of a body with concentric, near-antipodally magnetized layers, we used the Ellipsoids Python modelling package [12]. We modeled a range of potential magnetic source bodies as triaxial ellipsoids. Within each volume we then created confocal ellipsoids to represent layers that could have crossed their Curie temperature (780 °C for metallic iron) in a near-antipodally oriented background field. We assigned each ellipsoid remanent magnetizations of 0.5 A/m.

Results and Discussion:

Cooling models. We modeled cooling of melt sheets with a range of sizes and initial temperature conditions. The temperature profile of one of the smallest, low-temperature cases after 30 kyr of cooling is shown in **Fig. 1**. To compare the effect of melt sheet thickness independent of diameter, we also present 1 km, 3 km, and 5 km thick bodies starting at 1350 °C and compared after 50 kyr (**Fig. 2**). At any size, the body cools primarily from its top and bottom boundaries with additional cooling occurring on the edges. For the 10 km diameter, 1 km thick body shown in Figure 1, the entire body cooled below 780 °C after 60 kyr and 100 kyr (from initial temperatures of 1200 and 1500 °C, respectively). For comparison, a 50 km diameter, 1.5 km thick body cooled below 780 °C after 90kyr and 150kyr, respectively. While the first (smaller) body is likely to obtain a uniform magnetization, the longer cooling time in the second case could facilitate

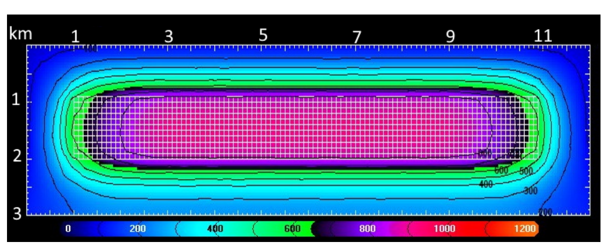

Figure 1: Model results after ~30kyr of cooling for the temperature profile of a 1km-thick, 10km-wide body located 1km below the lunar surface with initial temperature 1200 °C.

recording of multiple paleofield orientations within different concentric layers of the body.

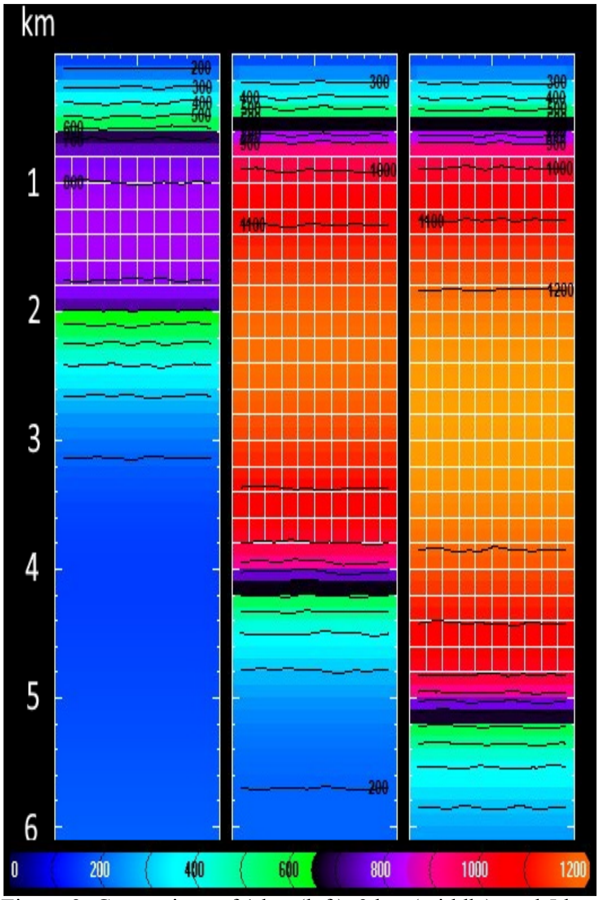

Figure 2: Comparison of 1 km (left), 3 km (middle), and 5 km (right) thick melt sheets, with initial temperatures of 1350 °C, after 50 kyr of cooling.

Field modeling. We find that the total magnetic field anomaly from a single ellipsoid corresponds well to a simple dipole (**Fig. 3a**). Inserting a smaller confocal ellipse within the same body with a near-antipodal magnetization (165° offset) produces a marked decrease in net magnetization intensity and notable changes in surface field expression (**Fig. 3b**).

Conclusions: The cooling of wide (>~50 km) or thick (>~1.5 km) magnetic source bodies produces complexities that cannot be captured in one-dimensional thermal modeling. As such, we caution that estimations of magnetization intensity and paleopole determinations from large ejecta deposits and anomalies within basin melt sheets (if they assume such sources are uniformly magnetized) may be unreliable. Future work will further test this hypothesis.

Acknowledgments: This research was conducted under an NSF Graduate Fellowship. Our thanks to Diego Takahashi for assistance with the Ellipsoids code.

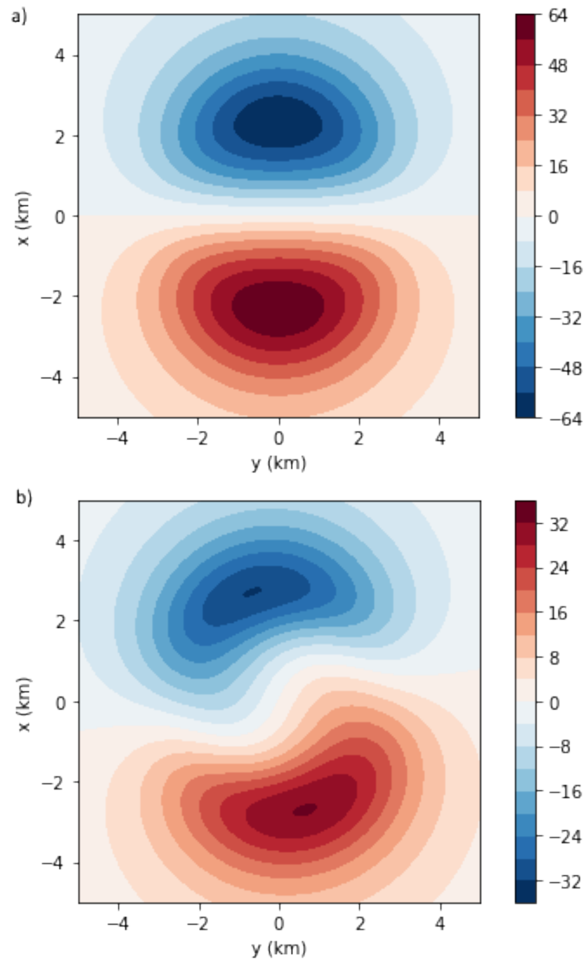

Figure 3: Total magnetic field anomaly produced by magnetized ellipsoids at 2 km from the foci. Panel a is for a single triaxial ellipse magnetized horizontally to the vertical axis. The lower panel is the total field anomaly produced by the same ellipse layered over a smaller confocal ellipse with a magnetization offset by 165°.

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