CRUSTAL MAGNETIC ANOMALIES PRECLUDE A STABLE SELENOCENTRIC AXIAL DIPOLE STRUCTURE FOR THE ANCIENT LUNAR DYNAMO.  T. Chaffee¹, S. M. Tikoo¹, R.E. Maxwell¹,²,³ and I. Garrick-Bethell⁴, ¹Stanford University, Stanford, CA, thomic@stanford.edu ²Center for Space Sciences and Technology, University of Maryland, Baltimore County, Baltimore, MD ³NASA Goddard Space Flight Center, Greenbelt, MD ⁴University of California Santa Cruz, Santa Cruz, CA.

Introduction: Analyses of Apollo samples and satellite observations of remanent magnetism in the lunar crust indicate that the ancient Moon likely generated a dynamo magnetic field that persisted for potentially over two billion years [1]. Constraining the paleofield geometry is crucial to understanding the nature of the lunar dynamo. Preliminary paleomagnetic results suggest that the Moon may have had a predominantly dipolar field that was aligned with the Moon’s axis of rotation [2,3].

Magnetic anomalies are located within several of the Moon’s impact basins (e.g., Mendel-Rydeberg and Crismum) [4,5], some locations antipodal to basins (e.g., anomalies within Mare Ingenii, Mare Marginis, and the Gerasimovich anomaly) [6-9], and a number of isolated regions on the Moon (e.g., the Abel, Airy, Descartes, Hartwig, Reiner Gamma, and Sylvester anomalies [10]). Many of these anomalies have been used to determine lunar paleopoles, under the assumption that the field was dipolar. The resulting paleopole reconstructions are broadly inconsistent with an axially dipolar paleofield: paleopoles are scattered across the Moon with few distinct groupings or patterns emerging [1]. It is possible that erroneous assumptions (e.g., that magnetic sources are unidirectionally magnetized) associated with common inverse methods lead to incorrect paleodirections and, in turn, paleopole determinations. Here we assess the reliability of modeled lunar paleopoles by (A) evaluating the ability of Parker’s method [11] to retrieve a true paleodirection from complexity magnetized source bodies, and (B) assessing the quality of inversions in the literature to ascertain whether the most robust paleopoles are consistent with a lunar axial dipole. We present results on the reliability of Parker’s Method for three proposed classes of lunar anomalies: (1) central magnetic anomalies within basin impact melt sheets e.g. [12]; (2) isolated anomalies attributable to intrusive or extrusive magmatism e.g. [13]; (3) spatially heterogeneous impact ejecta deposits e.g. [9].

Methods: Our models consist of three stages: source body cooling, magnetic field forward modeling, and paleopole inverse modeling. To model the internal cooling for our three classes of anomaly source bodies we employed a two-dimensional finite difference heat flow simulation (conduction and convection) with the program KWare HEAT3D [14]. We used the cooling model results to construct three-dimensional source bodies and forward model their magnetic field expression at the lunar surface and at 30 km altitude using the Ellipsoids code package in Python [15]. To model the possibility of dipole field reversals or a moving dipole, in these models we assigned differing magnetization directions to alternating concentric layers within each body that cooled below their Curie temperature (assigned as 770 °C for metallic iron) in 100 kyr increments. Finally, we employed Parker’s Method to invert magnetization directions from the forward modeled 30 km field expression of our source bodies and determined corresponding paleopoles. We then compared retrieved paleopole locations to pre-assigned locations to determine if Parker’s Method was successful.

Results: Magnetized bodies exceeding 10 km in width and 2 km in vertical thickness are capable of recording multiple 100 kyr frequency magnetic field reversals (similar to Earth’s). Relatively small magnetic sources (e.g., localized ejecta deposits and magmatic regions) may also contain records of one or two reversals at this frequency in an axially dipolar field. In our models, either the oldest or youngest paleodirection is successfully recovered by Parker’s method from small-scale anomalies with high (>5 nT) radial field strength at 30 km altitude.

Bassin scale melt structures may cool over hundreds of thousands of years and likely include several layers of material magnetized in different directions and may record multiple dynamo field reversals or other rapid temporal changes in field geometry, e.g. [16]. In our models (assuming a uniform magnetization intensity across the melt sheet), basin melt sheets may produce spurious paleopole directions due to the high number of paleofield directions they can potentially record over these long cooling timescales resulting in numerous shells of material magnetized in different directions. However, a more complex or rapid reversal history, or a non-axial or non-dipolar field, can cause Parker’s method to return a spurious paleopole.

Discussion and Conclusions: Paleopole robustness can be well quantified via the signal to background ratio (SBR) of an anomaly region [17]. Even so, an anomaly that records two orthogonal paleofields may produce a strong magnetization in a spurious paleodirection. This is least likely for anomalies with quickly cooling source bodies, such as those formed via small-scale intrusive magmatism, small impact melt sheets, or localized ejecta deposits. For example, the combined high
intensities and relatively small spatial scales of the Airy and Reiner Gamma anomalies [4] make them unlikely to record multiple paleodirections.

After filtering for high-quality inversions in the literature on high SBR anomalies (that our work indicates would be robust against recording multiple directions), the resulting dataset still produces paleopoles spanning all lunar latitudes. Scattered paleopoles could still represent an axial dipole if the Moon underwent significant (potentially up to 90°) true polar wander (TPW). However, there is no evidence that such intense TPW ever occurred on the Moon [18,19]. Alternatively, scattered paleopoles may be consistent with a non-axial lunar dipole field [4,17]. This could occur if mantle overturn caused a spatially irregular heat flux at the Moon’s core-mantle boundary, leading to rapid periodic circular motion of the magnetic pole [16]. Similarly, foundering diapirs of Ti-rich material can cause temporary, episodic enhancement of heat flow out of the core in localized regions, leading to increased surface field strength and potentially dipole migration or non-dipolar field geometries [20].

In summary, based on the best analyses of currently available observations of lunar crustal magnetic anomalies, it is unlikely that an Earth-like axial dipole field was prevalent on the early Moon when most crustal anomalies formed. The uncertainty in lunar paleofield directions may be reduced by upcoming lunar missions providing crucial data including rover magnetometer measurements (e.g., Lunar Vertex) or (potentially) laboratory paleomagnetic study of oriented lunar samples returned by the upcoming Artemis missions.

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Figure 1. Model results for a synthetic anomaly co-located with the true Abel anomaly. (a) schematic of the geometry of a cooled impact ejecta body recording both normal (pink) and reversed (yellow) polarity fields. (b) The forward modeled radial field component (nT) of this source at 30 km altitude. (c) Misfit of tested direction combinations (inclination, declination) in Parker’s method; red circle is best-fit paleopole, blue star is the assigned normal polarity direction, and green star is the assigned reversed polarity direction. The region circled in black includes the directions with an acceptable misfit. Parker’s Method successfully recovers the normal direction assigned to the outer shell within acceptable misfit.