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Iron abundances in lunar impact basin melt sheets from magnetic field data

J. S. Oliveira (1,2) and M. A. Wieczorek (3)

(1) Institut de Physique du Globe de Paris, Université Paris Diderot, Paris, France, (2) CITEUC, Geophysical and Astronomical Observatory, University of Coimbra, Coimbra, Portugal, (3) Observatoire de la Côte d'Azur, Laboratoire Lagrange, Nice, France. (joansofi@gmail.com)

Abstract

Some lunar impact basins possess weak magnetic anomalies in their interiors where the basin impact melt sheet is expected to be found. Metallic iron is the likely magnetic carrier, and this iron was most probably derived from the projectile that formed the basin. We estimate the abundance of iron in the impact melt sheet by inverting for the magnetization in lunar impact basins. The abundance of iron is then derived from a relationship that depends on the magnetizing field strength. We find abundances of metallic iron ranging from 0.5 to 2 wt.%, which is consistent with the range of values found in both lunar and terrestrial impact melts.

1. Introduction

Magnetic field data acquired from orbit shows that the Moon possesses many strong magnetic anomalies [1]. Though many of these are not associated with known geologic structures, some anomalies are found within large impact basins such Serenitatis, Nectaris, Crisium, Mendel-Rydberg, and Humboldtianum. The associated magnetic anomalies are generally in the center of the basin, within the interior peak ring [2].

The primary magnetic carrier in lunar rocks is metallic iron. However, most of indigenous crustal rocks have very low abundances of iron, which are incapable of accounting for the magnitudes of the observed magnetic anomalies [3]. In contrast, lunar impact melts derived from the largest basins often contain elevated abundances of metallic iron (1-2 wt.%), and this iron is believed to be derived from the projectile that formed the basin [e.g., 4]. Terrestrial impact melt rocks often contain traces of the projectile as well, with projectile abundances in the melt sheet ranging from less than a wt.% to up to several wt. % [5, 6]. Not all impact basins possess clear magnetic anomalies, but when they do, they are in general located within the interior portion of the basin where impact melt should be prevalent. The thickest portion of the impact melt sheet is predicted to be found within the peak ring [e.g., 7].

In this study, we use orbital magnetic field data to invert for the magnetization within large impact basins. Since the magnetization in lunar rocks is related to both the strength of the magnetic field at the time the rock cooled and the abundance of iron in the rock, basin magnetization can be used to constrain the composition of the projectile, the impact process, and the time evolution of the lunar dynamo.

2. Impact basin magnetization

We invert for crustal magnetization by making use of a method developed by Parker for studying seamount magnetism on Earth [8], and which was recently applied to lunar crustal magnetism by [9]. The only assumption that this method makes is that the magnetization within the crust is unidirectional, which is what one would expect if the material cooled below the Curie temperatures in the presence of a steady main field. As shown by Parker, a unidirectional distribution of dipoles within the crust is equivalent to unidirectional dipoles placed on the surface. The main strength of this method is that no assumptions about the intensity of magnetized sources, source geometry, or statistical distributions are made.

As described in [9], many dipoles are placed within a circle of specified radius over a region that encompasses an isolated anomaly. For an assumed direction of magnetization, we solve for the magnetic moments of the dipoles and determine the misfit between the model and observations using a non-negative least squares inversions approach [10]. To avoid unwanted edge effects, the misfit between the observations and model is calculated within a circle of a slightly larger radius. Since we make use of a global magnetic field model, only one component of the magnetic field is modeled (the other two are redundant), for which we chose the radial component. The surface dipoles were placed within a circle with a diameter just smaller than the main rim, and we note that the number of dipoles with non-zero moments must be less than the number of observations. The inversion naturally finds those dipoles that are non-zero, as well as their intensities.

For our inversions we use the global gridded magnetic field maps of [11] at 30 km altitude with a resolution of 0.5° that are based on Lunar Prospector and Kaguya magnetometer observations. We consider the central magnetic anomalies on five large basins: Serenitatis, Nectaris, Crisium, Mendel-Rydberg, and Humboldtianum.

The rms misfits at 30 km altitude obtained for all basins range between 0.16 nT and 0.33 nT, which is low in comparison to their respective central anomaly strengths. The dipoles with the strongest moments are found to be located almost exclusively within the inner depression of the basins. In some cases, there are few dipoles with strong magnetic moments between the peak ring and inner depression, or near the dipoles grid edge.

The strongest magnetizations are located within the inner depression, precisely where one would expect to find the thickest portion of the impact melt sheet. Using the dipole moment intensities, and assuming that the melt sheet is 1 km thick [e.g., 7], we estimate the average magnetization of the melt sheets ranging between 0.09 and 0.36 A/m.

3. Impact melt sheet iron abundances

Our analysis of the magnetic field provides an estimate of the average magnetization of impact melt sheets. The magnetization is related to both the strength of the magnetic field when the melt sheet cooled below the Curie temperature of iron, and the abundance of iron in the melt sheet. To estimate the abundance of metallic iron, we make use of a scaling relationship that is based on laboratory thermal remanent magnetism acquisition experiments, combined with the magnetic properties of lunar rocks [12]:

$$c = 1.1 \times 10^{-6} \frac{M_{tr}}{B_0}$$

In this equation, c is the volume fraction of metallic iron, M_{tr} is the thermal remanent magnetization of the rock, and B_0 is the strength of the magnetic field when the rock cooled below the Curie temperature. Using the obtained average magnetization, M_{tr} and assuming a representative surface field strength of 50 μT when the basin formed [13], the volumetric concentrations of iron obtained range between 0.18 and 0.8%.

Taking into account the difference in density between iron and silicates, the weight percentage of iron within the inner depression for the five large basins range between 0.5 and 2 wt.%. These values agree not only with the range of values from less than 1 wt. % to several wt. % of projectile contamination in terrestrial impact melts [5, 6], but also with the abundances of metallic iron found in Apollo impact melt rocks that range from 0.1 to 1.7 wt.% [4]. Given that both the thickness of the melt sheets and surface magnetic field strength are uncertain, our estimate of metallic iron abundances is probably uncertain by a factor of about 5.

4. Conclusions

The five studied large impact basins have central magnetic anomalies that are confined to the basin's peak-ring. Inversions of the magnetic field data show that the magnetic sources are in fact confined to the smaller inner depression that corresponds to the thickest portion of the impact melt sheet. By assuming the melt sheets thickness, as well as the surface magnetic field strength when the basins formed, the abundance of iron in the melt sheets was calculated to be just under 2 %. In analogy to lunar and terrestrial impact melts, we infer that the iron in the melt sheets was derived from the impactor. Investigations of impact basin magnetic anomalies will allow us to place constraints on both the magnetic field at the time the basins formed and the amount of projectile materials that are entrained in the impact melt sheets.

References

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