Experimentally Testing Whether Magmatic Processes Can Produce Strong Lunar Crustal Magnetism.

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Introduction: A combination of paleomagnetism and remanent crustal magnetism studies have suggested that the Moon may have generated a core dynamo magnetic field at least intermittently between 4.25 Ga and 1.5 Ga, with intensities reaching ~40-110 μT prior to ~3.56 Ga [1]. Intense magnetic anomalies within impact basins are likely caused by impactor-added metal within melt sheets [2], but anomalies associated with lunar swirls are more difficult to explain [3]. It is hypothesized that some swirl anomalies could be related to magmatic features like dikes, sills, and laccoliths. However, basalts returned from Apollo missions are generally weakly magnetized (<0.01 A/m) and are incapable of producing the magnetization intensities required for swirl formation (>0.5 A/m). In this study, we test the hypothesis that subsolidus reduction of ilmenite can enhance metallic FeNi contents within the lunar crust when it occurs in or near cooled mafic intrusive bodies.

Methods: We conducted reduction kinetic experiments using pristine (0.5-3 mm diameter) samples of a naturally occurring kimberlitic ilmenite megacryst. The starting material contained approximately 3 mol% hematite (calculated from stoichiometry considerations using electron microprobe data) and had a natural remanent magnetization of 0.186 A/m. Reduction experiments were conducted using different fO_2 conditions (IW-2, IW-1, IW, and QFM), different grain sizes, and for different durations (2, 4, 8, and 16 days) at 800 °C (above the Curie temperature of metallic Fe).

The magnetic properties of each experimentally reduced product were characterized using magnetic hysteresis experiments, which provide information on magnetic mineral abundance and grain size. A sample is placed within a Vibrating Sample Magnetometer in an initially zero field. The field (B) was increased to an intensity of +1 Tesla (T) in the positive direction, before being reduced in intensity and then applied in the reverse direction to the same intensity (i.e., -1 T) prior to cycling the field back up to +1 T. The hysteresis loop enables determination of the saturation magnetization (M_s) of a sample. Measuring the residual remanence after the 1 T field is turned off gives another parameter, the saturation remanent magnetization (M_{rs}). We use M_s and M_{rs} as indicators for the abundance and remanence-carrying potential of metal produced by our reduction experiments.

Results: Following reduction experiments, we observed reaction rims around the crystals and within cracks that were 20-30 μm-wide. Reaction products consist of pure ilmenite (i.e., no hematite solid solution), Cr-spinel, rutile exsolution, and 1-2 μm nodules of kamacite in the IW-1 and IW-2 experiments (no FeNi metals formed at IW and QFM) (**Fig. 1**). The at% of Fe_2O_3 decreased from ~11 at the centers of crystals to ~0 at reaction rims and crack edges.

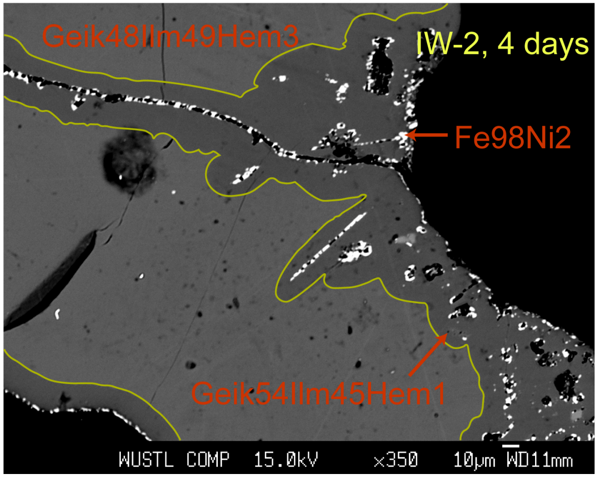

Fig. 1. Backscatter electron image of fO_2 = IW-2 for the 4-day experiment. Yellow lines separate the light grey unreacted starting material zone from the dark grey reaction zone. The composition of the reaction zone changes from Geik48Ilm49Hem3 of the starting material to Geik54Ilm45Hem1. The average composition of the metal (bright white phase) is Fe98Ni2.

Following our initial IW-1 experiments, M_{rs} values increased by up to an order of magnitude from the starting material, indicating that kamacite was likely the created phase rather than taenite (the latter is paramagnetic at room temperature for <30% Ni). FeNi formation appears to positively correlate with lower oxygen fugacities, smaller grain size of starting material (i.e., higher surface area to volume ratio) (**Fig. 2**), and possibly the duration of heating experiments (**Fig. 3**).

Based on ratios of the hysteresis parameters M_{rs} and M_s, we also found that FeNi grains formed during our subsolidus reduction experiments were on average smaller (pseudosingle domain; M_{rs}/M_s ~0.1) than those naturally occurring within mare basalts (multidomain M_{rs}/M_s ~0.001-0.01). This is of interest because pseudosingle grains can more efficiently record thermal remanent magnetization than multidomain grains in a given ambient field intensity (**Fig. 4**).

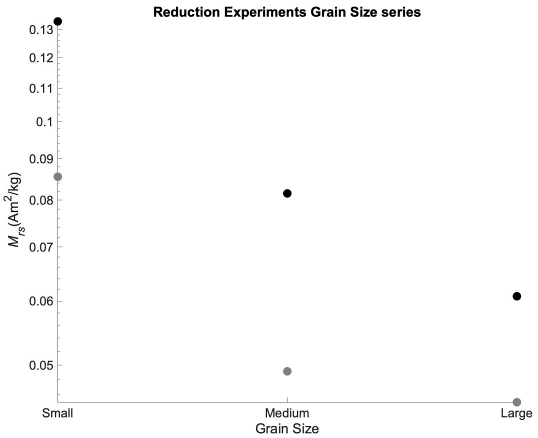

Fig. 2. Comparison of the M_{rs} of experiments with different grain sizes of starting material. The black and grey circles represent 2 different sets of experiments.

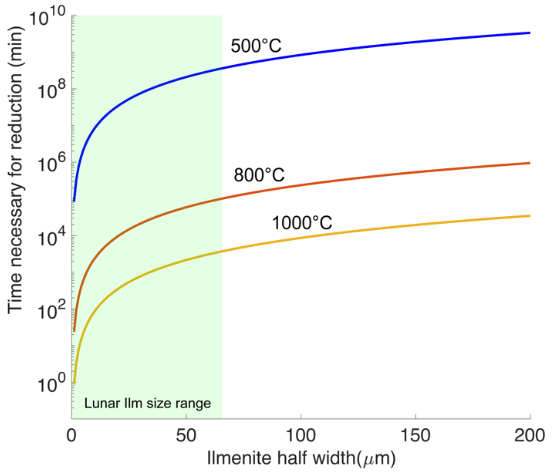

Fig. 3. Time necessary for reduction of different ilmenite half widths. Shown in this plot is the calculated time it would take to reduce ilmenite with different half-widths at given temperatures. The light green shadow area represents the range of ilmenite half-width in lunar mare basalts [3].

Conclusions: In summary, we found:

1. Hypabyssal high-Ti basalts may contain enough reduceable ilmenite to make ferromagnetic materials that can record a thermoremanent magnetization large enough to form lunar swirls. Indeed, it is possible to get very strong magnetization (>0.5 A/m inferred for swirls) if fields are >10 μT or if finer-grained Fe-Ni metals are formed (**Fig. 4**).

2. The ilmenite reduction reaction is a diffusion-controlled reaction, and thus it is temperature, grain size, and fO_2 dependent.

3. The time scale for ilmenite reduction (at 800°C) is in the range of 1 day to 70 days (**Fig. 2**). Thermoremanent magnetization could be acquired over this time scale from a directionally stable dynamo field. Transient impact-related fields formed in the absence of a global dynamo field are unlikely to last long enough or be intense enough to produce sufficiently high thermoremanent magnetization within swirl magnetic source bodies [5].

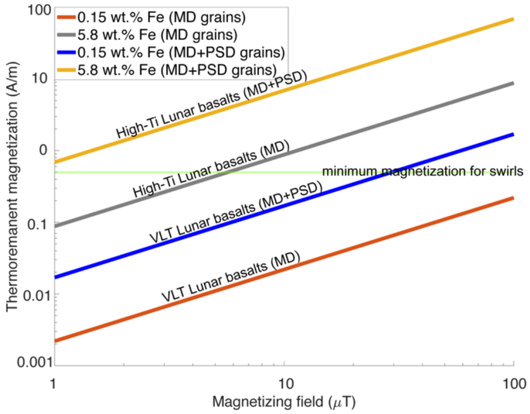

Fig. 4. Predicted thermoremanent magnetization intensity for lunar basalts following subsolidus reduction with differing magnetic grain sizes and initial mare basalt Ti contents (corresponding to different post-reduction FeNi contents). We show estimates for rocks with larger multidomain grains alone (MD) as well as mixtures of MD grains and smaller pseudosingle domain grains (MD+PSD)]. The amounts of FeNi reduced from ilmenite are calculated for both high-Ti mare basalts and VLT mare basalts (compositions from [4]). The intensity of the thermoremanent magnetization will increase with both higher metallic Fe content as well as with finer average grain sizes. Lunar swirls are inferred to need magnetization intensities >0.5 A/m (green line), which can easily be achieved for higher Ti basaltic rocks magnetized in fields of a few microteslas or stronger. Certain combinations of domain state plus ambient field intensity can achieve a magnetization intensity of >66 A/m inferred for the Reiner Gamma swirl [6].

References: [1] Tikoo S. M. and Evans A. J. (2022) *AREPS,* Vol 40, pp. 99-122. [2] Oliveira J. S. et al. (2017) *JGR: Planets*, Vol 122, pp. 2429-2444. [3] Hemingway D. J., Tikoo S. M. (2018) *JGR: Planets*, Vol 123, Issue 8, pp 2223-2241. [3] Heiken G. H., Vaniman D. T. (1990) *LPSC Proceeding,* Vol 20, pp. 239-247. [4] Papike J. J. and Vaniman D. T. (1978) *Mare Crisium: The View from Luna 24,* pp. 371-401. [5] Oran R. et al., (2020) *Sci. Adv.,* Vol 6, Issue 40, pp. eabb1475. [6] Garrick-Bethell I., Kelley M. R. (2019) *GRL,* Vol46, Issue 10, pp. 5065-5074.

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