INTRUSIVES AND LAVA TUBES: POTENTIAL LUNAR SWIRL SOURCE BODIES?

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Introduction: Lunar swirls are enigmatic albedo features that appear in several regions across the lunar surface (e.g., ref. [1]) and consist of bright and dark markings alternating over length scales of typically 1–5 km. Most swirls are not readily associated with conspicuous geological features, such as impact craters (e.g., the archetypal swirl at Reiner Gamma lies atop a relatively smooth mare plain) but instead appear to be surficial in nature. Swirls are most plausibly the result of electrostatically or magnetically-driven sorting of regolith fines [2,3] or solar wind interactions with localized remanent crustal magnetism (e.g., ref. [4]). In either scenario, the complex geometry of the albedo pattern must be a function of the structure of the near surface magnetic field. This, in turn, requires that the magnetic source bodies responsible for lunar swirl formation be both narrow (<~5 km wide) and shallow (<~3 km deep) [5]. These geometries raise the possibility that intrusive dikes and lava tubes may be good candidates for the magnetic source bodies associated with lunar swirls.

The magnetization intensity conundrum: While intrusive bodies and lava tubes may have appropriate geometries for their magnetic fields to enable the development of swirl patterns, a longstanding issue is that no known magmatically-derived lunar rock has the requisite natural remanent magnetization (>0.5 A/m) to reproduce the magnetic anomalies observed at various swirl locations (e.g., ref. [5]). Instead, mare basalts and highlands materials typically have natural remanent magnetizations (NRMs) of ~0.01 A/m and ~0.001 A/m, respectively. Therefore, for dikes or lava tubes to be lunar swirl source bodies, they must be at least an order of magnitude more magnetic than typical mare basalts. This would require the dikes and lava tubes to have unusally high metallic iron(-nickel alloy) contents. Here we discuss mechanisms that may be able to produce metal enrichment in magmatically-derived lunar rocks.

Achieving higher magnetization intensities: The emplacement of dikes or the formation of lava tubes within the lunar crust could produce strong magnetizations in two ways. The material within the dikes or lava tubes may be sourced from unusually reduced magmas (thereby producing more metal-rich rocks). The emplacement of dike intrusions or lava tubes also exposes adjacent host rocks to very high temperatures that may alter the remanent magnetization within host rocks either purely thermally or via thermochemical alteration. High temperatures may modify existing ferromagnetic grains or create new ones. This process is exemplified by heating experiments on lunar samples or their analogs in a controlled oxygen fugacity environment. Heating synthetic mare basalts in a reducing atmosphere ~1 log unit below the iron-wustite buffer (i.e., IW-1; the oxygen fugacity conditions inferred for a majority of lunar rocks studied thus far) to temperatures in excess of 600°C has produced subsolidus reduction of ilmenite and the associated growth of metal (Fig. 1) [6].

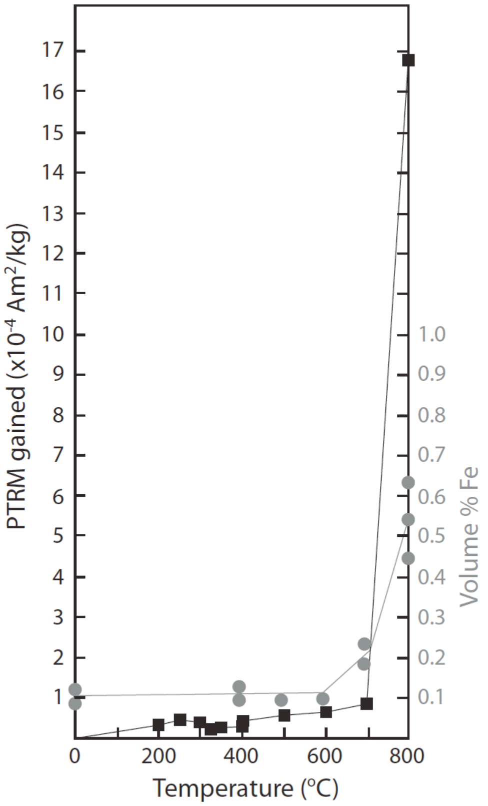


Fig. 1. Heating experiments on a synthetic lunar sample. Black squares represent the amount of PTRM gained by the sample after heating to different temperatures. Gray circles represent the inferred metallic Fe content in the sample following each heating step. Modified from [6].

To assess whether conductive heating from dike emplacement or lava tubes could produce pervasive alteration in adjacent host rocks, we conducted a series of dike cooling models that explored scenarios utilizing different dike thicknesses and peak intrusion temperatures. In all cases presented herein, we assume basaltic dikes with widths of 10 m to 1.5 km intrude into basaltic rocks at a depth of 3 km below the lunar surface (assigning a geothermal gradient of

13.5°C/km). We assume intrusion temperatures of 1200°C (i.e., a typical temperature for diabase intrusions on Earth) or 1500°C (i.e., a typical temperature for the emplacement of ultramafics, which may have occurred on the Moon in limited cases [7]).

We found that host rocks located 100 m away from the dike contact would be heated to temperatures >500°C (for 1200°C dike emplacement) and >600°C (for 1500°C dike emplacement) for dikes ≥1 km in width (Fig. 2). Wider dikes would naturally produce even higher host rock temperatures. Correspondingly, rocks closer to the dike than 100 m would also achieve higher temperatures than those shown here. This suggests that under a limited set of conditions, it is possible for dikes and lava tubes to raise host rock temperatures to levels sufficient for them to thermochemically alter.

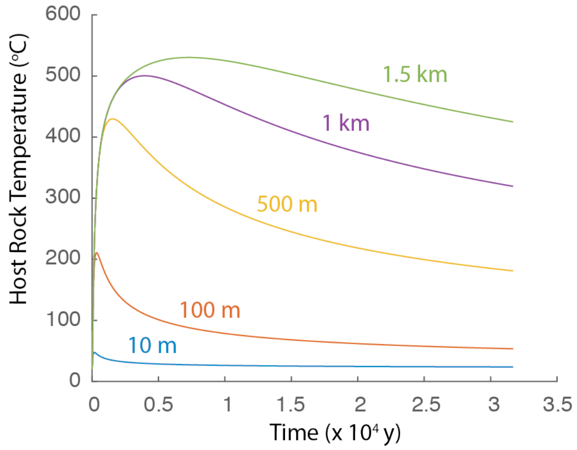
Discussion and Conclusions: The majority of reduction within lunar magmas is thought to occur when they ascend to depths <~3 km—a depth that is entirely consistent with the shallow (<~3 km) magnetic source depths required to produce lunar swirls. In this shallow environment, carbon oxidizes to carbon monoxide. The liberation of carbon monoxide in turn leads to subsolidus reduction of oxides and silicates and the formation of metal [8]. Therefore, modest variations in oxygen fugacity stemming from factors such as variable carbon contents in parent magmas may produce rocks with differing ferromagnetic mineral contents.

Haggerty [9] observed a widespread and intense subsolidus reduction of ulvospinel, chromite, and ilmenite in several mare basalts that required oxygen fugacities several log units below the canonical definition of IW-1. They hypothesized that some of this widespread reduction may be attributed to a post-crystallization reduction event rather than initial deuteric cooling. Magmatic events such as the formation of dikes and lava tubes provide conditions that may facilitate such post-crystallization reduction in surrounding rocks. The observable shape of magnetic enhancement in these rocks would trace that of the dike or lava tube, such that the shape of the resulting magnetic anomaly might resemble the shape of an anomaly produced by the dike or lava tube itself. Given the long (thousands of years) timescales for dike cooling, there would likely be ample time for host rocks to pervasively alter, producing magnetizations at least an order of magnitude greater than those of unaltered rocks.

In summary, we postulate that, under certain conditions (i.e., those involving unusually reducing enviornments, high temperature magmas, and dikes or lava tubes with thickenesses of >1 km), rocks with mare basalt compositions may be capable of acquiring NRMs consistent with those inferred for the magnetic anomalies associated with lunar swirls [5].

References: [1] Denevi B. W. et al. (2016) *Icarus, 273,* 53-67. [2] Garrick-Bethell et al. (2011) *Icarus, 212(2),* 480-492. [3] Pieters et al. (2014) *LPS XLV*. [4] Hemingway D. H. and Garrick-Bethell I. (2012) *JGR, 117,* E10012. [5] Hemingway D. H. and Tikoo S. M. *LPS XLVIII*. [6] Pearce G. W. et al. (1976) *LPS VII,* 3271-3297. [7] Ringwood A. E. (1987) *EPSL, 81,* 105-117. [8] Ringwood A. E. (1987) *EPSL, 81,* 105-117. [8] Sato M. et al. (1973) *LPS IV, 1,* 1061-1079. [9] Haggerty S. E. (1971) *Science, 234,* 113-117.

A) *intrusion temperature 1200°C*



B) *intrusion temperature 1500°C*

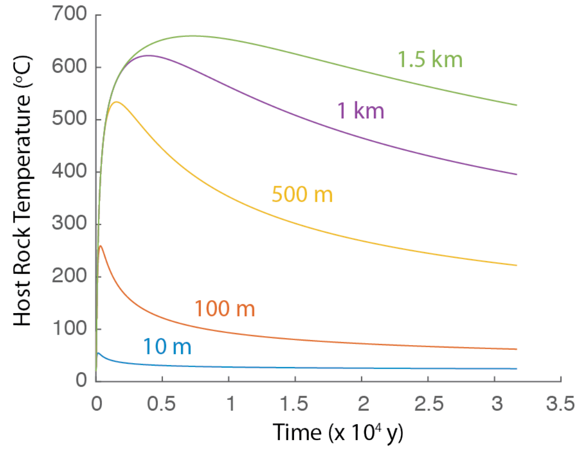


Fig. 2. Temperatures of host rocks over time following dike intrusion at initial temperatures of (A) 1200°C and (B) 1500°C. Temperatures are plotted for host rocks located 100 m away from the dike contact at an intrusion depth of 3 km. Different colored curves represent variable dike thicknesses ranging between 10 m and 1.5 km.