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Earth and Planetary Science Letters 248 (2006) 599–617
www.elsevier.com/locate/epsl

Rock-magnetic and remanence properties of synthetic Fe-rich basalts: Implications for Mars crustal anomalies

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Received 25 January 2006; received in revised form 7 April 2006; accepted 7 April 2006
Available online 27 June 2006
Editor: S. King

Abstract

We characterized the magnetic mineral assemblage and remanence properties of a set of synthetic samples patterned on the meteorite-derived basalt composition A*, which contains 18.9% total FeO. Basalts were synthesized at conditions that track 4 oxygen fugacity (fO_2) buffer curves, from 3.4 log units below the quartz–fayalite–magnetite (QFM) buffer to 5 log units above QFM, and 6 cooling rates from 10^5 to 3 °C/h. The resulting array of samples was characterized using magnetic hysteresis loops, temperature dependence of saturation magnetization and saturation remanence (10 to 1000 K), and the acquisition and demagnetization of anhysteretic remanent magnetization (ARM) and thermoremanent magnetization (TRM). The magnetic mineral assemblage characteristics are strongly dependent on fO_2. Samples synthesized at the iron–wüstite (IW) buffer have a very low concentration of remanence-carrying grains, which are likely near the superparamagnetic-stable-single-domain boundary. Samples synthesized at the QFM and nickel–nickel oxide (NNO) buffers contain a slightly higher concentration of remanence-carrying grains, which are stable-single-domain to fine pseudo-single-domain particles, respectively. Samples synthesized at the manganese oxide (MNO) buffer contain the highest concentration of magnetic grains, which are up to 100 μm in diameter. The dominant Fe–Ti oxide produced is an Mg- and Al-bearing titanomagnetite with 2.4–2.7 Fe cations per formula unit. The Curie temperatures of the QFM samples are consistent with their electron-microprobe derived compositions. Those of the NNO sample set are very slightly elevated with respect to their electron microprobe derived compositions. The Curie temperatures of the MNO samples are elevated up to 200 °C above what they should be for their composition. We attribute the Curie temperature elevation to high-temperature nonstoichiometry of the titanomagnetite. The IW sample set acquired very weak TRMs with intensities of 0.02 to 0.5 A/m. This intensity of remanence is a factor of 50–500 too low to generate the observed 1000 nT anomalies detected on Mars by the Mars Global Surveyor MAG–ER experiment. The QFM, NNO, and MNO samples acquired TRMs up to 40 A/m in a 10-μT applied field, and up to 200 A/m in a 50-μT field, with little or no dependence on cooling rate. Our results suggest that Fe-rich melts that crystallize extensive titanomagnetite can generate an intensely magnetized layer in the Martian crust, even if the remanence was acquired in a weak field. The QFM sample set can easily account for the observed 1000-nT Mars magnetic anomalies, even in a magnetized layer as thin as 15–30 km.

Keywords: rock magnetism; planetary magnetism; TRM; titanomagnetite; Mars; magnetic anomalies; Mars Global Surveyor

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doi:10.1016/j.epsl.2006.04.015

1. Introduction

One of the many extraordinary results of the Mars Global Surveyor [MGS] mission was the detection of regions of intensely magnetized crust by the MAG/ER experiment [1–5]. This was unexpected, as Mars currently does not possess a global dynamo-generated field. The most intensely magnetized regions are located in the southern cratered highlands, the ancient [∼4 Ga] densely cratered region south of the planetary dichotomy [1–5]. The anomalies are east–west oriented features that are 1000–2000 km long, up to 200 km wide, and alternate between positively and negatively magnetized bands [1–5]. These features dwarf terrestrial "sea-floor stripes," which range in width from 10 km generated by the slow-spreading Atlantic Ocean to 100 km generated by the fast-spreading East Pacific Rise.

Multiple mechanisms have been proposed to explain the alternating bands of positive and negative remanence. One possibility is past seafloor spreading on Mars in the presence of a reversing dynamo field [3]. The rate of seafloor spreading would have to be much faster than on Earth, or the frequency of field reversals much less than on Earth in order to account for the width of the magnetized regions. Conversely, the features may have been generated in a convergent boundary setting, in which differentially magnetized terranes were successively accreted [6]. Other plausible mechanisms include a succession of dike intrusions, in which the magma source has migrated north–south [7], or localized acquisition of a chemical remanent magnetization (CRM) due to hydrothermal alteration of the crust and associated formation of authigenic magnetite [8].

Equally or more intriguing than the spatial characteristics of the Mars anomalies are their intensity of remenence. The absence of a global field makes the Mars crustal anomalies easier to measure and map than their terrestrial counterparts. On Earth, any total field measurement is the sum of 3 components, the local field at the measurement location (H_E), the component of magnetization that the local field induces in the local rocks ($M_i = kH_E$), where k is the magnetic susceptibility of the rocks, and the remanent magnetization (M_R) carried by the rocks. The intensity of M_R is typically many orders of magnitude less than H_E and M_i, which makes isolating M_R a challenging process that depends on the availability and quality of H_E and k data for the region of interest. Since Mars does not possess an ambient field there is no induced component of magnetization, and the total field measurements made by MGS can be attributed entirely to M_R. The radial (vertical) component of magnetization approaches ±1000 nT at the satellite altitude of 100 km [1–5]. In contrast, the strongest terrestrial anomaly has a projected intensity of 10 nT at satellite altitudes [4].

Several variables contribute to the observed intensity of the Mars crustal anomalies, including the mechanism of remanence acquisition, the intensity of the magnetizing field, the efficiency of the magnetic recording assemblage, the thickness and geometry of the magnetized layer, and any subsequent alteration of the remanent magnetization. Possible mechanisms of remanence acquisition include a thermoremanent magnetization (TRM), acquired when magma solidifies and cools through the Curie temperature of its constituent magnetic minerals in the presence of a magnetic field, or a CRM acquired when minerals crystallize below their blocking temperatures in the presence of a magnetic field. A primary TRM is the simplest assumption for the Mars crustal anomalies, given that the southern cratered highlands region is composed of basalt, as identified by the MGS Thermal Emission Spectrometer [9]. However, the magnetization was almost certainly modified, for example via large impacts that formed the Hellas and Argyre basins, both of which were likely demagnetized by the heat and shock pressure generated by the impact, and subsequent cooling on a field-free Mars after the dynamo shut off [10–14].

Constraints on both the Martian magnetic mineralogy and the intensity of the ancient Martian magnetic field have been derived from Martian Shergotty–Nakhla–Chassigny meteorites (SNCs). Titanomagnetite, the iron sulfide pyrrhotite, and chromite have all been observed as remanence carriers in SNC meteorites [15–23]. Hematite and titanohematite are very efficient recorders of TRM and CRM and could account for the intensity of the observed anomalies [24–29]. However, these minerals have not been observed in SNC meteorites, and the existing data regarding the oxygen fugacity of the Martian mantle and crust suggest that conditions are not oxidizing enough to form igneous hematite [30,31].

Attempts to constrain the intensity of the Martian magnetic field have used both heating and non-heating experiments on SNC meteorites, yielding estimates of 0.5 to 5 μT [18,19], or perhaps an order of magnitude stronger, comparable to the present-day terrestrial field [21]. However, the SNC meteorites are thought to be much younger than the southern cratered highlands [32]. It is therefore possible that neither the field intensity nor the magnetic mineralogy of the SNCs is applicable to the Mars crustal anomalies.

This study investigates the Mars crustal anomalies using a combined experimental petrology and rock