Data Base of Extraterrestrial Magnetic Minerals, Test and Magnetic Simulation

A. B. Fernández[1], M. E. McHenry[2], M. Díaz-Michelena[1], C. Aroca[3], and M. Maicas[3]

[1]National Institute of Aerospace Technology (INTA), Torrejón de Ardoz, CO 28850, Spain
[2]Carnegie Mellon University, Pittsburgh, PA 15213 USA
[3]ETSIT-ISOM, Madrid, CO 28045, Spain

The description of the planetary magnetic anomalies is a difficult task that combines either aeromagnetic or *in-situ* magnetic field measurements, and further laboratory characterization of the local rocks. In the case of extraterrestrial planets this is a very difficult and costly task. With the objective to develop predictive algorithms prior to *in-situ* measurements, two complimentary lines of work have been undertaken: 1) characterization of magnetic minerals which occur in great abundance in extraterrestrial crusts; and 2) development of finite element method models (FEM) using the properties of these minerals to model possible scenarios and the variation of their magnetic behavior with temperature and temperature gradient swings on the superficial layers of the planets. The ultimate objective is the future comparison between the measurements developed by instruments on board Martian landers and rovers and the developed models.

***Index Terms*—Finite element method models (FEM) simulation, magnetic minerals, martian magnetism.**

I. INTRODUCTION

DESPITE the fact that Mars does not presently have a global magnetic field like the Earth, the Mars Global Surveyor (MGS) measured intense local magnetic fields corresponding to magnetic crustal anomalies mostly concentrated in the Southern hemisphere. That crustal rocks are magnetized is an indication of the fact that Mars had a global magnetic field in the past that induced these magnetic anomalies, so making study of Martian magnetism is interesting. Studying the remanent magnetization of rocks (Mr) makes it possible to learn about the evolution of the global magnetic field that Mars had more than 3.5 billion years ago and to correlate it with its geology. With the aim of understanding and studying the evolution of the minerals inner magnetic field, three tasks have been planned: 1) magnetic characterization; 2) modelling and characterization of minerals synthesized under conditions mimicking those on Mars; and 3) comparison with *in-situ* data.

For the first task a complete data base of terrestrial magnetic minerals is being done, recording principal magnetic properties of natural and synthetic minerals, and their variation with temperature, with a vibrating sample magnetometer (VSM).

For the second task, VSM measurements are taken as an input for the Amperes [1] (by ©Integrated Engineering Software) FEM mineral simulations as a first approach, to distinguish between different distributions of magnetized minerals on the Martian crust and compare with artificially synthesized samples.

Finally, for the third task, a magnetometer named MOURA, developed by INTA in the frame of Meiga-Metnet project [2], will be used to measure the magnetic field created by different minerals into relevant environments on Earth. The final objective is to settle an operation procedure prior to the possibility of real *in situ* Martian measurements with models intercomparison.

II. MAGNETIC CHARACTERIZATION

The objective of this part of the investigation is to start to compile a data base of magnetic properties of minerals which are potentially representative of the Martian soil.

Some minerals are natural and others have been grown by artificial techniques, specifically titanomagnetites. Paleomagnetic minerals, like magnetite and the magnetotitanates are crucial in explaining Martian field anomalies (as large as 200 nT [3]) since they are minerals with potential strong exchange (ferrimagnets) and a stable remanent magnetization. Therefore, a $x(Fe_2TiO_4)$-$(1-x)(Fe_3O_4)(0.30 < x < 1.00)$ series was produced by solid state synthesis [4], [5] for exhaustive study. In particular, the role of microstructural evolution on extrinsic magnetic properties is important for a detailed understanding of the stability of the remanent state [6].

Magnetic characterization of synthesized and natural minerals was made using a VSM (model EV-7 manufactured by ADE Magnetics) with a temperature control unit. Sintered samples are loaded in the sample holder of the VSM as powder. In the case of natural minerals, some times several fractions of the mother rock are measured. In cases with very mixed minerals the mineral will be artificially enriched so as to have not only the magnetic behavior of the mixture but the magnetic behavior of the pure mineral.

In order to discern between interesting and non interesting minerals from the paleomagnetic point of view, were performed a first magnetization curve and hysteresis loop at room temperature. Only minerals with measurable magnetic signature at room temperature followed a set of more detailed and systematic measurements:

First, Ms and Mr measurements between –160 °C and 200°C (5 °C step) were performed in three steps:

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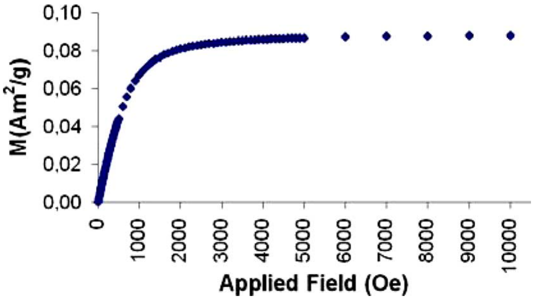

Fig. 1. First magnetization curve of magnetite taken in Huelva close to Río Tinto, a potential Martian analogous geological environment. The sample was previously demagnetized at –160 °C.

1) Ms was measured between 20 °C and –160 °C applying an external constant magnetic field of 2T. 2) At –160 °C, a magnetic field was removed and temperature was raised to 200 °C measuring Mr in the temperature swing. 3) A magnetic field of 2 T was applied at 200 °C and Ms measured during the descent of temperature.

At the end we have acquire Mr and Ms measurements in all temperature range between –160 °C and 200 °C. The low range of temperatures tries to cover daily and seasonal temperature swing on Mars ranging between –143 °C and 27 °C as estimated by Viking Orbiter Infrared Thermal Mapper [7]. The higher temperatures part aims to cover relatively low temperature transition decays.

Secondly, first magnetization curves (see Fig. 1) and hysteresis loops at temperatures of interest are performed, with the aim of cataloguing properties of phases, including their Curie temperatures, saturation magnetizations and anisotropy energies.

III. MODELING

Some arrangements of minerals have been modelled using Amperes Simulator (by Integrated Engineering Software). We selected the boundary elements method (BEM) [8] to evaluate magnetic fields produced. Preliminary models have been developed as a first approach to distinguish between different distributions of minerals on the Martian crust.

These models consider the total magnetic moment for each volume of magnetic mineral in the remanent state, and the orientation of magnetization. Each mineral is defined as a new material into Amperes, this requires the use of Mr and Hc data measured previously by VSM. Because magnetic properties of mineral vary with temperature it is necessary to define as many minerals as temperatures considered.

The final goal is to draw conclusions as to the magnetic signature of the mother rock and its variation with temperature. In principle, the susceptibility of the soil will be supposed to be dominated by its magnetite volume fraction as it occurs on Earth.

To illustrate the procedures, examples of a monomineral simulation will be described. After this, a short discussion will be performed on the conclusions that can be extracted from the simulation of a different rock matrix with some magnetite inclusions, because this is the information we aim to extract from a fixed magnetometer and gradiometer on Mars or the Moon surface.

To simulate Mars crust, the variation of temperature with depth has been taken into account. During day hours, only a Sun like source of heat is considered. There are more factors to have into account to obtain a detailed knowledge of temperature dependence with depth, like radiation, diffusivity or water/ice content and porosity [9], but as a first approach, we considered conduction as the most important mechanism of heat transmission, and only conductivity with depth is being considered. Using Fourier law, a simple relation between temperature and depth is predicted:

$\mathrm{j(E)} = -\mathrm{k}\nabla T$, where j(E) is the energy per unit area and time transferred to Mars surface, evaluated on 517 W/m^2, k is the thermal conductivity of the material, in the case of magnetite is 5.1 W/Km for room temperature, being its variation with the temperature considered negligible, and ∇T the gradient of temperature.

During night, heat accumulated during Sun exposure is transferred from Martian surface layers to atmosphere. Atmosphere is cooler than soil, so the temperature increases with depth because upper layers lose more heat than inner layers which maintain day heat.

In this former example a rectangular volume of magnetite has been simulated, specifically magnetite from Huelva, near to Río Tinto, region susceptible to have a similar geological ambient to that of Mars. This volume has dimensions of 4 cm width, 4 cm height and 6 cm depth.

The magnetite piece is simulated in five layers of different depth, changing the magnetic properties of magnetite, since temperature changes with depth. Furthermore, two scenarios have been developed, one for day, using a temperature of upper layer of 0 °C, and other for night with a surface temperature of –46 °C. The selection of surface temperature was done using data taken by Curiosity Rover on NASA public web page.

IV. RESULTS

In order to understand the simulations developed, a brief description of the future *in situ* set up of measurement is introduced.

In the framework of MetNet project, INTA team has developed a miniaturized magnetic instrument (72 g of mass and 130 mm × 30 mm × 15 mm volume) with the aim to measure the vector magnetic field [10], and its gradient by means of a couple of vector anisotropic magnetoresistance (AMR) magnetic sensors, separated 1 cm each other in the direction perpendicular to the surface. The actual prototype has a dynamic range of ±65 μT (and could be extended to ±130 μT) and the resolution obtained is in the order of 0.5 nT. The instrument also integrates a gravity sensor in principle for the tilt angle detection.

Amperes let's us obtain values of B, Bx, By and Bz among others. In the first example we consider a volume of magnetite (see Fig. 2) with a remanent magnetization which is a function of depth because different layers achieve different temperatures. The magnetic field have been obtained by simulation for an horizontal line (see Fig. 2) right on top of the surface (see Fig. 3)

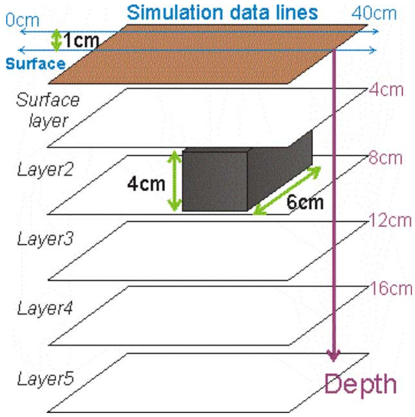

Fig. 2. Scenario of the first example where a volume of magnetite is considered. Data from simulation were obtained situating this volume of magnetite in the different layers.

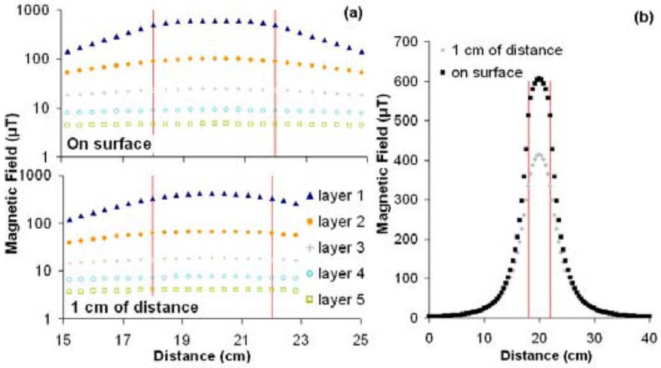

Fig. 3. Magnetic field generated by FEM simulation for the first scenario. On the left it is represented the magnetic field, on logarithmic scale, on the surface and at 1 cm of distance from the surface (at night time). The position of magnetite is indicated by vertical lines. On the right is represented the variation of the sign generated by the magnetite situated on the first layer between surface and one cm of distance.

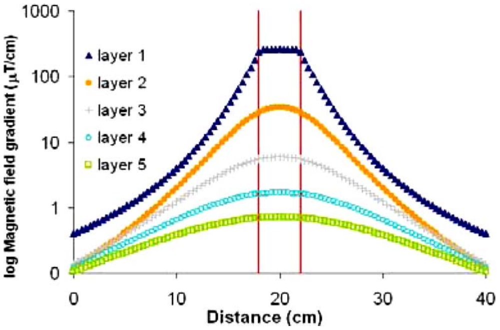

Fig. 4. Magnetic field gradient obtained by simulation (at night time) between surface data and 1 cm of distance for a volume of magnetite at different depth on a logarithmic scale.

and at a distance of 1 cm (see Fig. 3), aiming to do a study of the magnetic gradient (see Fig. 4).

Magnetic field gradient is negative because magnetic field decrease with distance, and highest values correspond to lower heights.

Magnetic field simulated at night is higher than day magnetic field, this is because Mr of the mineral increase when the temperature decrease (see Table I) [6]. The variation of Mr with the

TABLE I

	Depth (cm)	∇B (nT)
Layer 1	surface	8268.18
Layer 2	4	944.838
Layer 3	8	197.489
Layer 4	12	57.5461
Layer 5	16	18.7126

Increment of magnetic field measured at 1cm of distance of the surface, between night and day.

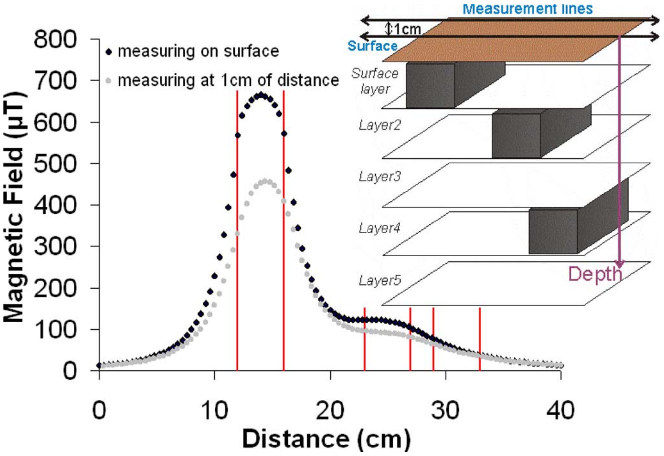

Fig. 5. Magnetic field bny simulation of a distribution of several magnetite volumes situated as it is showed on the right. The position of magnetite is indicated by vertical lines. The depths for these three volumes of magnetite, from left to right, are 0 cm (surface), 4 cm and 12 cm.

temperature is a characteristic of each mineral, so that through a complete study of the behaviour of minerals with temperature, it would be possible to discern from the data obtained by instrumentation, which minerals are present on soil, using simulation as a predictive tool.

The second example considers a simulation of dispersed clusters of magnetized magnetite rocks with same volumes. Magnetite from Huelva data has also been used (see Fig. 5). It is possible to discern the contribution to the magnetic field of each piece of magnetite, showing highest intensity the most close to the sensor. This example is interesting in the case that several magnetometers can be deployed on the surface.

Finally in the third example, we focus on the magnetic behavior of the soil matrix. An important factor to keep in mind is the fact that at the moment all studies done with the target to study *in situ* the composition of soil and the temperature profile with depth, require the use of complex instrumentation capable of drilling into the surface and extracting samples [11]. In this example we discuss the possibility of learning which is the matrix rock by means of magnetic simulations and further measurement on the surface without the need of drilling and altering the environment.

As it has been previously introduced, empirically on Earth, the magnetization of the soil is directly proportional to the volume fraction of magnetite. Direct measurement of the field can serve us as an indirect measurement of the magnetite volume fraction.

Since magnetite magnetic signature with temperature is fairly well known, the idea is to distinguish between different soil

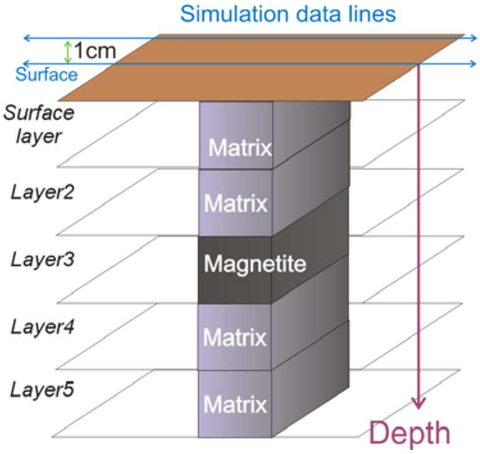

Fig. 6. Spatial distribution of the materials used at the time of performing the simulation using the third scenario.

compositions which may contain magnetite intrusion by means of surface measurement without the need of drilling.

To analyze if this method is viable, two simulations with different matrix: basaltic and granitic, and one intrusion of magnetite at a depth of 8 cm have been done (see Fig. 6).

Basalts are known to be the main constituents of the oceanic crust and are likely to be dominant in the crust of either Mars and the Moon [12]. Granite in contrast, is a typical rock of the continental crusts. Magnetic properties of granite from Panticosa in the Spanish Pyrenees have been used for the example. After substracting the contribution of the magnetite in each simulation, we have compared data corresponding to the basaltic and the granitic matrix in the two positions where we will place the magnetic sensors. It has been found a difference between the two different matrix contributions with a maximum value of 16 nT, which is easily measurable with the magnetometer.

V. CONCLUSION AND FURTHER WORK

A method or way to work is been developed aiming to develop predictive algorithms prior to in-situ measurements of magnetic field on Mars, with the ability to extend this mechanism to any other body.

This method is based on three principal items: characterization of magnetic minerals, simulation by FEM and comparisons by measurement in relevant environments and in-situ measurement. The method aims to extract information of the composition of the soil in depth without the need for drilling.

This new method is based on the empirical fact that magnetization of the soil is directly proportional to the volume fraction of magnetite it contains, so the variation of magnetization with temperature will have two main contributions, magnetite and the matrix mineral. This method is applied to discern among the different geological systems that can happen on the soil.

Characterization of magnetic minerals and simulation are the first steps in this study. The second step would be to compare simulation data with data measured by instrumentation landing on the Martian surface or other interesting planets and moons, being the final goal to compare *in situ* measurements with previous models developed by scientists of Mars Global Surveyor.

Aiming to obtain data on Earth as much similar as possible to *in situ* data, a set of experiments measuring with MOURA on relevant environment will be planed. The objective is to measure on top of soils of different paleomagnetic minerals like magnetite, hematite, titanomagnetites, etc., subject to different formation conditions. The analysis of this data will help us understand and interpretate the future data received by the magnetometer when it is on the surface of Mars.

Also, an important future task, is to better understand the temperature variation with depth on soil, including effects like diffusivity, porosity, water content, etc., being this last point of interest in the search of life.

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