Earth and Planetary Science Letters 465 (2017) 70–81

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Paleomagnetic field reconstruction from mixtures of titanomagnetites

Thomas Berndt [a,*], Ricardo S. Ramalho [b,c,d], Miguel A. Valdez-Grijalva [a], Adrian R. Muxworthy [a]

[a] Department of Earth Science and Engineering, Imperial College London, SW7 2AZ, UK
[b] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[c] School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, UK
[d] Lamont–Doherty Earth Observatory, Columbia University, Comer Geochemistry Building, PO Box 1000, Palisades, NY 10964-8000, USA

ARTICLE INFO

Article history:
Received 21 October 2016
Received in revised form 6 February 2017
Accepted 19 February 2017
Available online 8 March 2017
Editor: B. Buffett

Keywords:
titanomagnetite
magnetic mineral mixture
Zijderveld plot
paleointensity

ABSTRACT

Stepwise thermal demagnetization and alternating field (AF) demagnetization are commonly used in paleomagnetic studies to isolate remanent magnetic components of different origins. The magnetically hardest, i.e. highest unblocking temperature/peak field component is often interpreted as the primary magnetization and magnetically softer components as subsequent remagnetizations due to geological events posterior to the formation of the rock, such as reheating or formation of new magnetic minerals. The correct interpretation of the sequence of the geological events such as tectonic rotations from paleomagnetic data often relies on correctly attributing the observed magnetic directions to the remanence carriers and acquisition mechanisms. Using a numerical model to simulate remanence acquisition and stepwise thermal and AF demagnetization experiments, we show that the presence of mixtures of different magnetic minerals, such as magnetite and titanomagnetites of varying titanium-content can have very significant effects on Zijderveld plots. In thermal demagnetization experiments a spurious third component at intermediate temperatures or a continuous curvature may arise from an overlap of the primary remanence with a subsequent thermal or viscous remagnetization carried by small-grained iron-rich magnetite and large-grained titanium-rich titanomagnetite. AF demagnetization plots of magnetic mixtures are even more complex: primary and secondary remanences carried by different minerals may appear as either three or four components in Zijderveld plots. During alternating field demagnetization the highest coercivity component is not necessarily equivalent to the primary remanence and does not necessarily correspond to the highest temperature component in an analogous thermal demagnetization experiment, i.e., the primary remanence direction cannot be recovered. The effects are shown to be due to the different responsiveness of magnetite and titanomagnetites towards viscous or thermoviscous remanence acquisition: remanent magnetizations with long acquisition times are more effectively recorded by titanium-poor minerals, while short acquisition times are equally well recorded by titanium-rich minerals. In demagnetization experiments on laboratory timescales, the relative contribution of two minerals to Zijderveld plots differs to the relative contribution of remanence acquisition over geological timescales, leading to overlapping components in Zijderveld plots. The model was also used to simulate paleointensity (ancient magnetic field intensity) experiments and it was found that the grain distribution affects the slope of Arai plots, but is negligible compared to the effect of the cooling rate of NRM acquisition. The simulations suggest that for slowly cooled rocks a cooling rate correction of up to 1.5 to 1.6 may be required depending on the mineralogy.

1. Introduction

Paleomagnetic observations continue to provide constraints on some of the most fundamental theories of the deep Earth structure, the dynamics of near surface processes and the evolution and development of the geodynamo (Tarduno et al., 2015; Biggin et al., 2015; O'Rourke and Stevenson, 2016). Reliable interpretation of paleomagnetic data can only be achieved through correct identification of the natural remanent magnetization (NRM) components and their directions; we are usually, but not always, interested in the primary remanent magnetization's intensity and its direction carried by the magnetic minerals within rocks. Among the most common magnetic minerals occurring in rocks are both stoi-

* Corresponding author.
E-mail address: t.berndt13@imperial.ac.uk (T. Berndt).

http://dx.doi.org/10.1016/j.epsl.2017.02.033
0012-821X/

chiometric magnetite (Fe_3O_4) and titanomagnetites x ($Fe_{3-x}Ti_xO_4$), where titanium atoms substitute the iron atoms at varying proportions x (Dunlop and Özdemir, 1997). In nature, rocks do not always contain only a single type of magnetic mineral but may contain mixtures, for example of titanomagnetites of varying compositions. The grain-sizes of the magnetic mineral have been found to correlate with the titanium content in oceanic basalts (Zhou et al., 1997, 2000) and the process of exsolution can move titanium cations in the crystal lattice of the $Fe_{3-x}Ti_xO_4$, accumulating them in some places and depleting them in others, thereby effectively creating an amalgam of high titanium content titanomagnetite grains and pure magnetite or low-titanium content titanomagnetite grains (Dunlop and Özdemir, 1997). To correctly interpret paleomagnetic signals of natural rocks, it is important to understand the effect of such magnetic mineral mixtures on the paleomagnetic recording fidelity. We developed a numerical model to predict the behavior of titanomagnetite mixtures with respect to three of the most fundamental paleomagnetic studies: (1) directional analysis in thermal demagnetization experiments, (2) directional analysis in alternating field (AF) demagnetization experiments, and (3) Thellier-type paleointensity estimates (Thellier and Thellier, 1959).

2. Model

A numerical model has been built, that simulates an assembly $f(x, V)$ of titanomagnetites of different titanium content x and different grain volumes V. The model is built on Néel (1949) theory of single-domain (SD) magnetic particles. The evolution of normalized magnetic moment $\mathbf{n}$ (magnetic moment divided by the spontaneous magnetization) with time is given by the differential equation (Néel, 1949)

$$\frac{d\mathbf{n}}{dt} = \frac{\mathbf{n}_{eq} - \mathbf{n}}{\tau}, \tag{1}$$

where τ is the relaxation time and $\mathbf{n}_{eq}$ is the value of the normalized magnetic moment in thermodynamic equilibrium. The relaxation time is given by

$$\frac{1}{\tau} = \frac{1}{\tau_+} + \frac{1}{\tau_-}, \tag{2}$$

where

$$\frac{1}{\tau_\pm} = \frac{1}{\tau_0} \exp\left\{ -\frac{\mu_0 V H_K(T) M_s(T)}{2kT} \left(1 \pm \frac{|\mathbf{H}_0|}{H_K}\right)^2 \right\}, \tag{3}$$

where τ_0 is the atomic attempt time, which was set to be 10^{-10} s in the model (Berndt et al., 2015), μ_0 is the vacuum permeability, k is the Boltzmann constant and H_0 is the applied magnetic field. The equilibrium magnetic moment is given by a Maxwell–Boltzmann distribution

$$\mathbf{n}_{eq} = \tanh\left\{ \frac{V \mathbf{H}_0 M_s(T)}{kT} \right\}. \tag{4}$$

The spontaneous magnetization at high temperature is modeled using the analytical approximation (Dunlop and Özdemir, 1997)

$$M_s(T) = M_{s0}\sqrt{1 - \frac{T}{T_C}}, \tag{5}$$

and the microscopic coercivity H_K is calculated assuming that shape anisotropy dominates, for which

$$H_K = \Delta N M_s, \tag{6}$$

using a shape anisotropy factor ΔN. For titanomagnetites shape anisotropy and magnetocrystalline anisotropy are relatively weaker than for magnetite, but magnetostriction increases (Dunlop and Özdemir, 2007). For simplicity, however, we assume strongly elongated grains with dominant shape anisotropy for all titanium contents with a common value of $\Delta N = 0.5$ for all grains and alignment of their elongation axis with the field.

The titanium content is assumed to have two effects: (1) it lowers the Curie temperature T_C, and (2) it reduces the room-temperature spontaneous magnetization M_{s0}. The Curie temperature is modeled by the quadratic equation

$$T_C = T_{C,TM0} - ax^2 - bx, \tag{7}$$

where the coefficients $a = 280$ and $b = 500$ were found from a least-squares fit to the data published by Dunlop and Özdemir (1997), and $T_{C,TM0} = 580\,^\circ$C is the Curie temperature of magnetite. The spontaneous magnetization at room temperature is modeled by a linear relationship (Stephenson, 1969; Dunlop and Özdemir, 1997)

$$M_{s0} = M_{s0,TM0} - \frac{1}{0.6}\left(M_{s0,TM0} - M_{s0,TM60}\right)x, \tag{8}$$

where $M_{s0,TM0} = 480$ kAm^2 is the spontaneous magnetization of magnetite and $M_{s0,TM60} = 125$ kAm^2 is the spontaneous magnetization of TM60 titanomagnetite (Özdemir and O'Reilly, 1981).

2.1. VRM and TRM acquisition

The grain distribution is discretized by a matrix of 1000 volumes V between 10^{-24} and 10^{-21} m^3 (being equal to cubes of 10 to 100 nm), separated on a logarithmic scale, and 100 equally spaced Curie temperatures T_C between 0 °C and 580 °C (corresponding to various different titanium compositions x according to eq. (7), for clarity we quote T_C rather than x values in the diagrams). The magnetization of each of these grains can take on any magnetization value representing a large number of grains, and not just ±1, as for a single SD grain.

For viscous remanent magnetization (VRM) acquisition at a temperature T_A, the equilibrium magnetizations $\mathbf{n}_{eq}$ (eq. (4)) and the relaxation times (eq. (2) and (3)) are calculated for each grain set (V, T_C) and the resulting new magnetization state $\mathbf{n}_{new}$ is calculated from eq. (1). Thermoremanent magnetization (TRM) acquisitions are simulated by repeatedly following this procedure for 2000 temperature steps T_i, decreasing by small temperature steps ΔT until room temperature is reached. Various scenarios of different combinations of acquired VRMs and TRMs at different times and temperatures were run. Generally, linear cooling was used, but for one case Newtonian cooling was used for a paleointensity scenario, as cooling rates are known to have a significant effect on paleointensities (Dodson and McClelland-Brown, 1980; Halgedahl et al., 1980).

2.2. Thermal demagnetization

Step-wise thermal demagnetization was simulated by repeatedly applying VRMs at successively higher temperatures in zero field. This simulates the time at which the sample is kept at a high temperature in a thermal demagnetizer. After each step, the total remanent magnetization vector is calculated, which is the sum the magnetization vectors $\mathbf{n}(V, T_C)$ of all different grain sets, and the total spontaneous magnetization is calculated by summing the product of M_s, volume V and the grain distribution $f(V, T_C)$.

2.3. AF demagnetization

AF demagnetization is modeled based on the simplified assumption that all grains with a coercivity H_C less than the maximum amplitude $\tilde{H}$ of the alternating field get demagnetized. The coercivity is given by