

Mineral Specific Magnetic Carriers for Paleointensity Determination. G. Kletetschka^{1,2,3} and M. A. Wietzorek⁴,
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Introduction: Crustal rocks on Mars and the Moon generate magnetic anomalies whose sources are in large part a result of thermoremanent magnetic acquisition. The magnitude of thermoremanent magnetization, M_{tr} , is directly linked to the ambient magnetic field present at the time of cooling as well as demagnetizing fields within the magnetic carriers [1, 2]. When rocks cool through the blocking temperatures of their applicable magnetic minerals, the overall magnetic efficiency of the magnetic recording, as quantified by the ratio of the thermoremanent magnetization to saturation remanent magnetization, M_{tr}/M_{rs} , follows the theory developed by [3].

Various attempts have derived simplified empirical relationships for estimating the magnetizing field from the magnetic properties of rocks and minerals measured at room temperature. One approach [4] uses bulk rocks where the mineralogy is assumed. In this approach, the thermoremanent magnetization depends only upon the strength of the magnetizing field. They showed that within a factor of about two, the proportionality constant was independent of the magnetic mineral, domain state and grain size for magnetite, titanomagnetite, Fe_3N and pyrrhotite. Though this technique is applicable to many magnetic minerals, the numerical proportionality constant is based largely on data from rocks containing magnetite.

In a different contemporaneous approach, [5] considered the magnetization of single magnetic minerals. It was shown that not only was the thermoremanent magnetization of the mineral proportional to the magnetizing field, but that it was also inversely proportional to the saturation magnetization of the mineral, M_s . For many magnetic minerals, the saturation magnetizations differ only by a small factor, explaining the success of the approach used by [4]. However, for hematite, M_s is more than two orders of magnitude smaller than that of magnetite. When accounting for M_s , [5] showed that the magnetic acquisition of all minerals followed a single linear relationship, with an uncertainty of only a factor of 2. If a rock is composed of more than one magnetic species, paleointensity estimation needs to consider the fact that the magnetic efficiency for each species will be different for the same magnetizing field.

In this work, we revisit and expand upon many of the concepts developed by [5]. First, we make use of additional data for the acquisition of thermoremanent

magnetization, and show how the shape and the rate of cooling of the mineral affects the acquired magnetization. Second, we discuss how our new relationship can be used to determine the paleointensity when a rock cools below the blocking temperature. Third, based on the magnetic properties of troilite, we show that this mineral could potentially play an important role in explaining the magnetization of lunar and extraterrestrial samples where troilite is known to be abundant [6]. Finally, using our results, we demonstrate how the abundance of magnetic minerals can be estimated when the rock magnetization is known. As an example of this technique, we estimate the abundance of iron that is required to explain large-scale lunar magnetic anomalies as mapped from orbiting magnetometers.

Paleofield determination from minerals and rocks:

Paleofield research often considers samples that contain only one magnetic species, such as magnetite for terrestrial samples and iron for lunar samples. Recent advancements in magnetic scanning techniques now allow for in situ magnetic analysis of specific minerals in thin sections [7]. This technique allows identification of the specific magnetic mineralogy, which in turn allows determining which value of M_s should be used in the equations for determining the paleofield strength. Furthermore, by investigating individual minerals in the thin section, as opposed to the whole rock, paleofield estimates can be obtained from rocks that contain several magnetic species.

The insensitivity of the efficiency of thermoremanent magnetization to domain state and grain size allows evaluating the constant for the most common magnetic minerals. For convenience, we write this in terms of the magnetic induction B , as opposed to the magnetic field H ,

$$B_H = A \frac{M_{tr}}{M_{sr}}, \quad (1)$$

and group all constants in a single mineral specific constant A . Physically, the constant A corresponds to the magnetizing field that is required to obtain a magnetic efficiency of unity: for field strengths greater than this value, the thermoremanent magnetization would remain equal to the saturation remanent magnetization. In this work we provide values for A obtained under laboratory conditions for a variety of equidimensional minerals, as well as other constants such as the

mineral density, Curie temperature, and size limit of single-domain grains.

Troilite as a potentially important magnetic carrier: We demonstrate the importance of troilite using an example. We start by considering a magnetizing field of 500 nT, which is close to what dynamo models predict the field strength would be at the surface of the Moon [8]. For laboratory conditions, the magnetic efficiency of iron in an external field of 500 nT is 4.8×10^{-5} . M_{tr} is on the order of $5 \times 10^{-4} \text{ Am}^2 \text{ kg}^{-1}$, or equivalently 3.8 A m^{-1} . The magnetic efficiency of troilite in a 500 nT external field is about 0.5, which is considerably larger than that of magnetite. To determine M_{tr} of troilite, we first need to estimate the saturation remanence magnetization, which will be grain size dependent. M_{rs} of the Cape York sample [9] to be $(4 \pm 1) \times 10^{-3} \text{ Am}^2 \text{ kg}^{-1}$, or equivalently $18.4 \pm 4.6 \text{ A m}^{-1}$. With a 0.5 efficiency at 500 nT, the thermoremanent magnetization of troilite is predicted to be about 9.3 A m^{-1} , which is about 2.4 times larger than that of iron. Thus, if lunar rocks contain a volumetric abundance ratio of iron/troilite of about 6/1 [10] then about 29 % of the total magnetization in the rock would come from troilite.

The above example used a magnetizing field of 500 nT, which gave a magnetic efficiency of 0.5 for troilite. If the magnetizing field was much larger, the thermoremanent magnetization of troilite would saturate, and the magnetization of metallic iron would become relatively more important. For example, using a magnetizing field of 50 μT , as implied by several lunar paleomagnetism studies [11], the thermoremanent magnetization of metallic iron and troilite would be about 380 and 18.4 A m^{-1} , respectively. For a 1/6 volumetric ratio of troilite to iron, just under 1% of the total magnetization in the rock would be attributable to troilite. This theoretical analysis suggests that for the Moon, both troilite and iron need to be considered as potential sources of crustal magnetism, but only when the magnetizing field strength is less than about 1 μT .

Conclusions:

The thermoremanent magnetization of a rock is related to the strength of the magnetic field when the rock cooled, as well as the properties of the magnetic carriers in the rock. The strength of the field when the rock cooled through the blocking temperature has generally been investigated by heating the rock in the laboratory, with the aim of simulating the thermoremanent magnetization acquisition process. Unfortunately, such heating experiments are not always possible for extraterrestrial materials. In some cases, the samples are invaluable, and it is difficult to justify the use of such destructive methods. In other cases, irre-

versible changes might occur while heating that might complicate the interpretation of such data.

An alternative technique for estimating the paleofield strength makes use of non-destructive isothermal techniques. Though this approach is in common use when investigating extraterrestrial samples, the fidelity of the obtained paleofield strengths has been difficult to assess. In this work, we have shown that there is a simple linear relationship between the field strength and the product of the magnetic efficiency and mineral saturation magnetization. The proportionality constant is independent of the magnetic mineralogy, grain size, and domain state, and has a simple dependence on the aspect ratio of the magnetic minerals, as quantified by the shape factor N . Furthermore, the relationship has a dependence on the timescale during which the sample cools through the blocking temperature, with a factor of two difference between laboratory and geologic conditions. This relationship allows the estimation of the paleofield strength to better than a factor of two when the magnetic mineralogy is known. It improves upon previous work that has neglected various aspects, such as the timescale dependence, mineral saturation magnetization, and demagnetization shape factor [4,5].

Our new technique allows for several applications. First, by using magnetic scanning techniques, it is now possible to investigate samples that contain more than one magnetic carrier. Second, based on the magnetic properties of troilite, we have shown that this mineral could potentially be an important contributor of magnetization in extraterrestrial samples. Finally, we have demonstrated that the abundance of magnetic minerals can be estimated from magnetizations obtained from geophysical inversions of orbital magnetic field data.

Acknowledgements: GK was supported by Grant Agency of the Czech Republic, GACR 17-05935S, RVO 67985831. MW was partially supported by the Agence Nationale de la Recherche, grant ANR-14-CE33-0012

References: [1] Dunlop, D. J., and Özdemir Ö. (1997) *Cambridge*, 573 pp. [2] Dunlop, D. J., and Kletetschka G. (2001) *GRL*, 28, 3345-3348 [3] Néel, L. (1955), *Adv. Phys.* 4, 191-243 [4] Gattacceca, J., and P. Rochette (2004), *EPSL*, 227 377-393 [5] Kletetschka, G. et al. (2004) *EPSL*, 226, 521-528 [6] Rubin (1997) *MPS*, 32, 231-247 [7] Nabelek, L et al. (2015) *MPS*, 50, 1112-1121 [8] Laneuville, M. et al. (2014) *EPSL*, 401, 251-260. [9] Cuda J. et al, (2011) *JGR*, 116, 9, B11205 [10] Anders E. (1977) *PTRS A* 285, 23-40 [11] Weiss B. P. and Tikoo S. M. *Science*, 346 1198.