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Lodestone: Natures Only Permanent Magnet-What it is and how it gets charged

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Abstract. Magnetite and Titanomagnetite exhibit magnetic properties which are attributable to the micro-structures developed during oxidation and exsolution: All magnetite iron ores which are lodestones contain maghemite. These lodestones have Hc between 10 and 30 mT, SIRM between 8 and 18 Am^2kg^1, and R_I between 0.10 and 0.26. Magnetite, titanomagnetite and metals have REM values (ratio of NRM to SIRM) < 0.05. Samples (called fulgarites) obtained from the Smithsonian Institution have REM values ranging from 0.45 to 0.92. The REM value serves as a witness parameter to the magnetic fields associated with the lightning bolt. If a high REM value (say $>> 0.1$) can be verified as not to be due to contamination by man and does not contain MD hematite then the rock has LRM (lightning remanent magnetization). The magnetic field associated with lightning can be revealed from an isothermal remanent acquisition (RA) curve.

Introduction

Magnetic materials, in the crust of the earth, possess a natural remanent magnetization (NRM). This magnetization is acquired, via a variety of mechanisms, in the geomagnetic field (Nagata, 1961; Stacy and Banerjee 1974; O'Reilley 1984; Butler 1992; Dunlop and Özdemir 1997). There are examples of intensely magnetized natural samples (Graham, 1962; Matsuzaki, 1954; Kobayashi 1958) but only lodestone has been historically interesting because of its ability to behave as a magnet. Like a familiar hand magnet, the lodestone can pick up paper clips and other ferrous objects. In the not distant past the lodestone had great value as a source of charging for compass needles, which were a primary navigation tool (Andrade, 1958). In the middle ages much mythology and lore had been associated with the lodestone. Diamonds, goats' blood, and garlic breath had been considered as demagnetizing agents for the lodestone, but William Gilbert (1600) debunked some of these ideas. A number of excellent historical accounts of the mysterious lodestones are available (Needham, 1962; Andrade, 1958; Blackman, 1983).

Mineralogy - What is a lodestone

The magnetite collection in the Smithsonian Institution in Washington, DC was examined to discover which of the samples were lodestones. Specimens from Magnet Cove, Arkansas; Cedar City, Utah; and Iron Mountain, Missouri were the only specimens in the collection that behaved as a magnet - i.e. a lodestone, and were able to pick up the paper clip.

In the 1920's, field and laboratory research specifically considered the identity and genesis of lodestone magnetite (Newhouse and Callaham, 1927; Gruner, 1929; Newhouse, 1929; and Bandy, 1929). Newhouse and Callaham (1927) described how "brownish" magnetite appears to replace the ordinary "bluish" magnetite and they found that the brownish magnetite samples were lodestones, i.e. magnetite with great polarity. Considerable attention to the textural detail led Newhouse and Callaham (1927) to conclude that the brownish magnetite replaces the bluish one because it is an oxidation product of the latter. In the 1920's, it was clear that some lodestone magnetite was oxidized magnetite. It was also apparent that not all oxidized magnetite was lodestone. Recently, Banfield et al (1994) used electron microscopy to characterize the lodestone USNM (United States National Museum) 99484 from Cedar City (Utah), which contains the mottling observed by Newhouse. These observations showed the microstructure to be a submicroscopic intimate intergrowth of magnetite and maghemite. Bandy (1929) summarized some of the field observations associated with the occurrence of lodestone. He indicated that as a rule the lodestone is found at or near the surface and not in deep mines, and as a rule, is found at the highest point of outcrops and in the most exposed area. Williams (1890) described the occurrence of lodestone, at Magnet Cove, Arkansas, as existing only on the surface, adding that as one penetrates below ground, the lodestone deposits cease.

Intrinsic Magnetic Properties of Iron Ores

Wasilewski (1977) determined that intrinsic magnetic properties of magnetite and titanomagnetite iron ore form a continuum (see also Blackman 1983, Blackman and Lisgarten 1982): I_S (saturation magnetization) = (40 to 94) Am^2kg^{-1}; SIRM (saturation remanence) = (<1 to 18) Am^2kg^{-1}; H_C (coercive force) = (1 to 30) mT; R_I (ratio of $SIRM/I_S$) = (0.02-0.26). Aside from 2 specimens with $I_s$values ~90 Am^2kg^{-1}, all magnetite specimens show varying amounts of oxidation which will cause a reduction in I_S. Hematite ($I_S \sim 0.4\ Am^2kg^{-1}$) and Maghemite ($I_S \sim 70\ Am^2kg^{-1}$) are the oxidation products. The maghemite is readily identified with reflected light optical microscopy due to its intermediate reflectivity (and bluish cast) in the presence of magnetite and hematite. The magnetite lodestones have two step thermomagnetic curves; the first step occurring at anywhere from 250-300C (for USNM 97425) to 400C (for USNM 99484) and the second step at ~570C the Curie point of magnetite. On cooling only the single phase magnetite can be observed. The first step associated with maghemite has been eliminated because the maghemite has been converted to hematite during heating.

Sample USNM 97425 presented the unique opportunity to establish with a real sample the connection between the type of microstructure, the consequent magnetic hardening and strong magnetic polarity. When observing the ability of the golf ball

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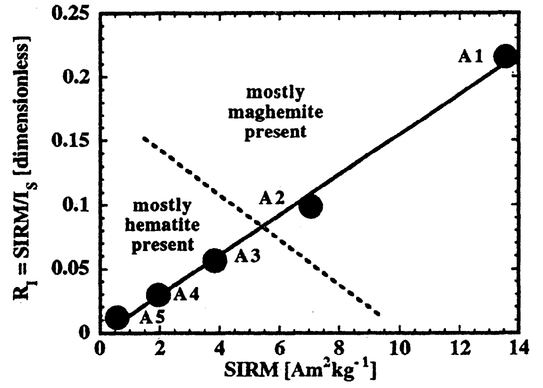

Figure 1. Diagram illustrates the relationship between R_I the SIRM/Is ratio (saturation remanent magnetization / saturation magnetization) and the SIRM for subsamples from USNM 97425. Dashed line separates specimens which have dominant hematite alteration products from those which have dominant maghemite.

sized piece of 97425 to pick up small objects, it was noted that parts of 97425 were intensely polarized while other parts were not. The basic question to be answered with this observation was simply related to what was the difference between the strongly polarized and apparently nonpolarized parts of 97425. Five specimens labeled A1 to A5 were removed from the sample, chosen to include the nonpolarized and strongly polarized regions of the sample. The relationship between R_I and SIRM for this specimen set, with SIRM ranging from < 1 Am^{2}kg^{-1} to 14 Am^{2}kg^{-1}, is shown in Figure 1. Together, with optical examination of polished sections, it became clear that the increase in SIRM and the R_I values was related to the type of microstructure. When hematite lamellae, relatively thick, are present or where large regions (near cracks) are completely converted to hematite the magnetic parameters SIRM, H_C, and R_I are not greatly enhanced such as for specimens A5, A4 and A3 with different amounts of hematite lamellae but no maghemite. Specimens A2 and A1 with the largest R_I, SIRM and H_C have definite maghemite (Wasilewski, 1977, 1979).

Physical evidence for lodestone charging

xzA magnet should have the largest possible magnetic hardness (large R_I, H_C, and SIRM) and saturation magnetization (I_S) to ensure magnetic stability and large magnetic intensity. These are the characteristics attendant to the strongest lodestones. We now know what the lodestone is as a material, but we need to know how the lodestone acquires its intense magnetization. In magnet technology terms - we need to know the charging mechanism for the lodestone.

Table 1. REM values

Material	Mecha-nism	REM	Reference
1.5µm Fe$_3$O$_4$	TRM	0.018	Parry, 1982
Titanomagnetite	TRM	0.007 – 0.01	Lewis, 1968
Fe$_3$O$_4$	TRM	0.0046 – 0.01	Hartstra, 1982, 1983
FeNi Spheres	TRM	0.0012 – 0.03	Wasilewski, 1981b
Fe$_3$O$_4$ Cedar City	NRM	0.001-0.0043	This study
USNM 99484	NRM	0.43 – 0.69	This study
Lodestones	NRM	0.14 – 0.69	Wasilewski, 1977
Fulgarites (USNM)	LRM	0.45-0.92	This study
94ADK2	NRM	0.021	This study
94ADK2	LRM	0.83	This study

The most efficient of the conventional natural magnetization mechanisms is TRM (thermoremanent magnetization) . In Table 1, the REM values for a variety of TRM experiments and natural rock samples (NRM) indicate REM is < 0.05 regardless of the type of material or the degree of magnetic hardness. The exception is the recent study by Kletetschka et al, (1999) indicating the large REM for TRM in MD hematite. Table 1 shows also (Wasilewski, 1977, 1979) that lodestones have large REM values (> 0.2). The answer to the question - How does an iron ore become a lodestone? – resides in the answer to the question - Why does a lodestone have such a large REM value? Another important point (in Table 1) is the realization that lightning struck samples (LRM) are the natural samples with large REM values.

In order to understand the meaning of the REM value we present what are conventionally referred to as isothermal Remanence Acquisition (RA) curves for a series of mafic xenoliths (Warner and Wasilewski, 1997) which have their titanomagnetites oxidized to varying degrees. These samples were chosen so that the full extent of microstructure development due to oxidation could be portrayed in illustrating the meaning of magnetic hardening and the REM values. The curves are created by measuring the magnetic remanence just after applying a magnetic field. Increasing magnetic fields are applied, up to 1 Tesla (Figure 2), at which point saturation remanence is achieved in all samples. These curves may also be used to assess the degree of magnetic hardening since proceeding from left to right, the R_I value and the H_C value increase (see Warner and Wasilewski, 1997). This is further illustrated by the RA curve for lodestone USNM 99484 showing a high degree of magnetic hardening (Figure 2) which is plotted together with the oxidation sequence.

These RA curves can also serve as magnetic contamination curves. Suppose we place small specimens from each sample represented by the curves shown in Figure 2 in an environment that is subject to a pulse field of 0.02 Tesla. Not knowing that this contamination took place we measure the NRM and SIRM and find that the contaminated REM values range from 0.1 to 0.8. Referring to Figure 2, we therefore have a series of witness

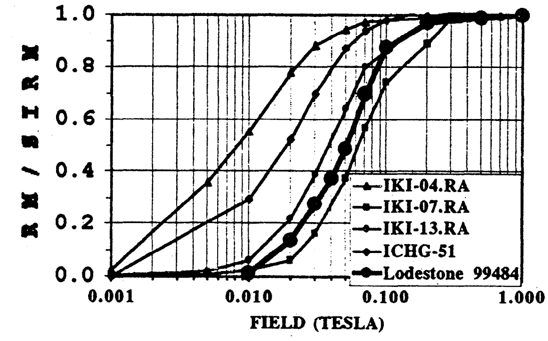

Figure 2. Isothermal remanent acquisition (RA) curves for titanomagnetite bearing gabbros oxidized to varying degrees (modified from Warner and Wasilewski, 1997). The USNM99484 lodestone RA curve is also presented to illustrate how the "identification" of the magnetizing field for this lodestone can be done.

specimens for the 0.02 Tesla pulse field. Note that the RA curves (contamination curves) in Figure 2 are normalized and therefore we have no indication what the SIRM value is. These curves also illustrate that a given pulse field can result in a different REM value. Also, regardless the level of the pulse field and the consequent REM value if the sample does not contain enough magnetic material we obtain a relatively intensely magnetized sample but not a lodestone.

Lightning Experiments

Each summer, faculty and students from New Mexico Tech occupy Langmuir Laboratory on the top of South Baldy mountain near Socorro, New Mexico for the purpose of studying, among other subjects, the properties of thunderstorm clouds. A technique used at Langmuir is called triggered lightning - a method of initiating a lightning strike to travel along a wire thereby ensuring that remote and in situ sensors can be used to study the focused strike. Our sample chamber was the "lightning rod" allowing samples inside the sample chamber to experience the lightning bolt. Sample 94ADK2, one of the samples used in the experiment (Table 1), had an original REM value of 0.021. After the lightning strike the REM_L (LRM/SIRM) value was 0.83. If it is established that lightning is responsible for the remanence, the remanence is lightning remanent magnetization (LRM). Because the remanence acquired by lightning strike is due to the magnetic field of the lightning current, magnetic properties of the lodestone varies with the distance from the center of lightning impact. In order to establish this distance we may use the lodestone REM value and compare it to the IRM/SIRM acquisition curve. Intersection of the REM value with this curve should indicate the value of magnetizing field during the strike. The REM value of 0.69 located on the acquisition curve for lodestone 99484 indicates a magnetizing field of 0.07T. By relating this magnetizing field to the currents expected for average lightning strikes we can estimate the distance between our sample and the center of the lightning strike. The general model for expression of the azimuthal magnetic field at the ground a radial distance D from the base of idealized straight, vertical lightning channel with current I can be found in Uman (1987). A simplified formula valid for distances less than about 10 m from the center of the strike (Fisher and Schnetzer, 1994) is $B(D) = 2\ 10^{-7}\ I/D$. For the common range of the currents occurring during the lightning strikes (page 31 in Fisher and Schnetzer, 1994), plots for variable distances from the center of the strike indicate that only distances 5-10 cm from the center of the strike are relevant for our lodestone in order to obtain the magnetizing field of 0.07T.

Discussion

Iron ores exhibit a broad range of magnetic properties - a continuum of magnetic hardness. The strongest lodestones are those with the greatest degree of magnetic hardness (largest H_C, SIRM and R_I) - this being similar to requirements for making magnets. Another important factor is saturation magnetization which should ideally be as a large as possible. Magnetic hardening increases R_I and since $R_I \bullet I_s$ = SIRM, the greater the I_s value for given R_I the greater is SIRM. All lodestones are massive iron ores with large REM values but there are equivalent iron ores i.e. with similar magnetic properties, that do not have large REM values indicating no lightning strike. Iron ores with low Hc, SIRM, and R_I, for example a piece of pure unoxidized magnetite, may be struck by lightning and have a large REM value, but the residual remanence intensity would be insufficient. This is apparent in the USNM 97425 example (Figure 2). Banfield et al (1994) examined sample USNM 99484 with electron microscopy and identified Fe_3O_4 and maghemite intimately intergrown. The surface of polished samples of 99484 exhibited a mottled appearance when examined with reflected light at magnifications up to 1000X. This is the same surface appearance described by Gruner (1929) in one of the lodestones samples he examined. The mottled appearance is likely attributed to the stacking faults, identified by Banfield et al (1994), which offset the magnetite structure.

The most obvious consequence of having maghemite (I_s ~70 Am^2kg-1) instead of hematite (I_s~ 0.4 Am^2kg-1) as an oxidation product is that the total magnetization remains high and therefore SIRM per mass is optimized for the magnetically hardened material About 90 to 95% of the intense magnetic remanence is thermally demagnetized by the time maghemite is converted to hematite (Wasilewski 1977,1979; Banfield et al, 1994). This associates the intense remanence with the maghemite. The Magnetic susceptibility-temperature (X-T) curve (figure 2 in Banfield et al,1994) and the coercivity-temperature and the SIRM-temperature curves (Wasilewski, 1977,1979) exhibit pronounced structure in response to heating out to 450C. The magnetic susceptibility reaches a peak near 300C which is the point where the thermomagnetic curve indicates the onset of maghemite conversion (for USNM 99484). The increase in magnetic susceptibility is accompanied by a sharp decrease in coercivity which is consistent with the X-T behavior but unusual for maghemite or magnetite. However once the susceptibility decreases, as it does beyond 300C, the coercivity increases even though the temperature is increasing. The increase in magnetic suceptibility and the decrease in coercivity is accompanied by the NRM demagnetization and we believe that this is associated with the rearrangement of structural configurations ,including the stacking faults, that allows thermal depinning of the NRM. The rearrangements must also include cation reconfigurations as there is a slight increase in the saturation magnetization if the sample is heated to temperatures below 300C and then returned to room temperature.

Identification of the large REM values for the lodestones is the crucial piece of physical evidence for the lightning mechanism of lodestone charging described by Wasilewski (1977) who explained that lightning, or some presently unknown and exotic mechanism, would be responsible for the strong lodestone magnetization. This paper presents the experimental data which explain that REM values for natural materials magnetized in the geomagnetic field are usually < 0.05. There is one exception to this rule. Multidomain (MD) hematite will obtain large REM values as a consequence of TRM acquisition in the geomagnetic field (Kletetschka et al 1999).

Conclusions

All lodestones are magnetite or titanomagnetite iron ores. Magnetic hardness in magnetite iron ores is due to oxidation; hematite produces little to moderate hardness but maghemite development is responsible for the magnetic hardness and for ensuring large bulk SIRM in all strongly polarized lodestones. Magnetic hardness in titanomagnetite iron ores is due to exsolution and then in some cases oxidation of exsolution products. We present a continuum of magnetic hardness (H_C ,SIRM, R_I) for iron ores and for lodestones in Table 2.

Table 2. Continuum of magnetic hardness

parameter	iron ores	lodestone
SIRM [Am^2kg^{-1}]	<1-18	8-18
H_c [mT]	1-30	10-30
R_I [dimensionless]	0.02-0.26	0.10-0.26

Wasilewski (1977) for the first time identified large REM values (> 0.2) in lodestones. The only way to get the large REM values found in lodestones is by a lightning strike or by touching the iron ore with a magnet. Lightning strikes were triggered at the Langmuir Laboratory of New Mexico Tech near Socorro, New Mexico and thereby verified the mechanism for charging the lodestone. REM values as large as 0.83 were found in lightning struck samples at Socorro. Knowing the shape of the REM curve (magnetic contamination curve) one can use the natural samples as witness recorders for the magnetic fields associated with lightning bolts.

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