Owing to its stable magnetization over geologic timescales, hematite is an important mineral for many magnetic applications, particularly for paleomagnetism (e.g., Butler, 1992) and environmental magnetism, including the study of soils (e.g., Heller & Liu, 1982, 1984; Maxbauer et al., 2016a; Schwertmann, 1985). Despite its favorable magnetic properties, hematite’s weak spontaneous magnetization at room temperature ($M_s \approx 0.4 \text{ Am}^2 \text{kg}^{-1}$), which is similar to that of goethite ($M_s \approx 0.5 \text{ Am}^2 \text{kg}^{-1}$), but much weaker than magnetite ($M_s \approx 92 \text{ Am}^2 \text{kg}^{-1}$), makes its magnetic quantification challenging. Even when small amounts of magnetite co-occur with hematite, its $\times 230$ stronger magnetization can overwhelm, if not effectively mask, the magnetic contribution of hematite (e.g., Dekkers, 1990; Frank & Nowaczyk, 2008). The weak spontaneous magnetization of hematite also belies its environmental importance because its mass far exceeds that of magnetite in many natural environments. Likewise, remanences of interest need not be the strongest, or carried by the most abundant phase. Identification, isolation, and quantification of the contributions to the bulk remanence, thus, become paramount to many applications.

In a recent article published in the open access journal *Geoscience Letters*, Roberts et al. (2020) outlined the main magnetic parameters used to quantify relative, absolute, or partial hematite contributions to the remanence to evaluate their limitations and effectiveness.

Given the importance of the topic, we thought it useful to re-purpose these ideas here, often verbatim -no reason to reinvent the wheel- with permission from the authors and publisher, and with minor additions.

The observation

Roberts et al. (2020) reviewed the main magnetic proxies used to estimate the relative or absolute concentration of sedimentary hematite or its coercivity variations. These are: the S-ratio; the ‘hard’ isothermal remanent magnetization (HIRM); alternating field (AF) demagnetization...
The State of the Lab: an update on the Visiting Fellowship program and other activities.

After the initial reopening of the lab in late May, the IRM has resumed essential research, allowing approved graduate students and researchers from the University of Minnesota to use the facilities, all while under strict safety protocols.

Since our reopening, we have been striving to serve the needs of the rock magnetic and paleomagnetic community to the greatest extent possible. In August, the IRM started “curbside service” where IRM staff began performing measurements on behalf of the 2020 Visiting Fellows who were willing to mail us their samples in lieu of visiting in-person. Due to strict limitations on the number of people simultaneously allowed in the lab and the inability to use our office spaces, we have focused on the most automated measurements possible, including low-temperature magnetometry experiments on the MPMSs, high-temperature susceptibility measurements on the AGICO KLY-2 Kapabridge, and excitingly, sequences of hysteresis loops, backfield demagnetization curves and FORC measurements, at room and variable temperatures, all of which can be programmed (and automated) on the new Lake Shore 8600 VSM, which arrived in late 2019.

More recently, we have begun collecting measurements for colleagues outside of our Visiting Fellowship program at the rates specified on our website (www.irm.umn.edu). We take this opportunity to advertise this measurement opportunity to all members of our community, but especially to those students and early career scientists who need data in a timely manner to push their research forward.

The University of Minnesota is now beginning to allow external visitors, provided that they follow strict health and safety protocols. However, it is likely that our visitor policies may change as the global COVID-19 situation continues to evolve (e.g., at the time of writing cases in Minnesota are rising faster than a Hopkinson peak). However, for the time being we are pleased to be scheduling in-person visits for awarded Visiting Fellows and external visitors alike.

It has been a very busy summer for all of us at the IRM! We have shut down and re-started the entire lab over the course of a few months with all the unexpected hiccups that goes with it. We have tried to support our community’s research in all possible ways. We have also worked hard to install a new MPMS-3 system with remote guidance from Quantum Design, which will offer a number of tantalizing new measurement capabilities that we hope many of you will want to explore for your own research.

It has likely been a challenging year for all of you as well. We are all looking forward to a time when we can push forward with our research at a brisker, more ‘normal’ pace. Along these lines, we encourage you to contact us regarding visiting the lab, both formally or informally, or sending us your samples, and we will be happy to discuss any research needs you may have.

We wish you all the best and hope you are all staying safe and healthy!

Hope to see you soon,
The Institute for Rock Magnetism

Current Articles

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included. Special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most are taken from ISI Web of Knowledge after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Current Articles section of the IRM Quarterly are always welcome.

Aeromagnetism

Archaeomagnetism


Environmental Magnetism and Biomagnetism


Bauer, K. W., et al. (2020), Magnetic biomineralization in ferruginous waters and early Earth evolution, Earth and Plan-


Extraterrestrial Magnetism


Fundamental Rock Magnetism and direct Applications


Cruz, C., H. Sant'ovaia, and F. Noronha (2020), Magnetic mineralogy of Variscan granites from northern Portugal: an

Paleointensity, Geomagnetism and Records of the Geomag-netic Field

Magnetic Fabrics and Anisotropy

Magnetic Microscopy

Mineralogy and Petrology
**Paleomagnetism**


Zhang, W. L., X. M. Fang, T. Zhang, C. H. Song, and M. D.


Stratigraphy


of an isothermal remanent magnetization (IRM) above 100 mT; the L-ratio; combinations of AF and thermal demagnetization and low-temperature measurements; and IRM component analysis.

These parameters mainly exploit the coercivity of hematite; while high coercivities can be attributed to either hematite or goethite, the focus is on hematite because it generally saturates magnetically near 3 T (Abrajevitch et al., 2018; Dunlop, 1971) as opposed to goethite, which only acquires 2–10% of its IRM below 3 T and remains unsaturated at 57 T (Rochette et al., 2005). This makes hematite more suitable than goethite for coercivity analysis in fields available in most laboratories. Some hematite samples can also require applied fields of 4.75 T to reach saturation (Bilardello, 2015; Bilardello & Kodama, 2009; Abrajevitch et al., 2018). This high saturation field exceeds the capability of most laboratory instruments, so capturing the full coercivity distribution for hematite is not always attainable. Hematite and goethite can also be distinguished from each other using high- and low-temperature measurements (e.g. Bilardello, 2019; France & Oldfield, 2000; Lagroix & Guyodo, 2017; Lowrie, 1990; Maher et al., 2004).

The key issue addressed by Roberts et al. (2020), however, is in distinguishing between high coercivity (“hard”) and low coercivity (“soft”) hematite, which are observed frequently in sediments, soils, and dust. Low and high coercivity hematite have been distinguished using detailed high temperature demagnetization (e.g. Bilardello, 2015; Swanson-Hysell et al., 2019), or chemical leaching (e.g. Bilardello & Kodama, 2010). However, the coercivity of soft hematite could overlap that of other soft phases such as magnetite/maghemite, which complicates coercivity analysis when quantifying magnetite/maghemite and hematite contributions. These observations constitute the crux of the issue discussed by Roberts et al. (2020), as reported on here.

The details
Details of hematite-related magnetic parameters are discussed in the IRM-Q 27-4 article “Magnetic tests and characterization protocols: mineralogy and grain size / domain state Part I: isothermal strong field tests” by Volk et al. (2018) and by Roberts et al. (2020); they are not repeated here. However, the fundamental assumptions and requirements for use of these parameters are discussed here, as well as their limitations, following the outline of Roberts et al. (2020).

S-ratio: this parameter is based on the strong magnetic fields needed to saturate hematite compared to stoichiometric magnetite, which saturates below 300 mT, and the assumption that there is minimal overlap between their coercivity distributions. Typically, maximum fields of 1 or 1.5 T are used, so hematite likely remains unsaturated, and any contribution >300 mT is attributed to hematite and/or goethite, despite other minerals (e.g. oxidized phases, pyrrhotite) sometimes having coercivities >300 mT. Depending on the version of the S-ratio used, values range from -1 to 1 (Stober & Thompson, 1979), or from 0 to 1 (Bloemendal et al., 1992), which represent the range from high coercivity components only to low coercivity components only, respectively. Roberts et al. (2020), however, caution that extreme minimum (hard phase(s) only) values are not observed for either of the two S-ratios, even when magnetite comprises 0.05 wt% of the mixed sample (Fig. 1) because significant IRM acquisition also occurs below 300 mT in hematite samples (Fig. 2, and more below). Additionally, the maximum applied field used will affect how much of the hematite coercivity distribution is captured and reflected in the S-ratio value. In the examples shown in Fig. 1, maximum fields of 1 and 2 T were used, which are less than half of that required to saturate some hematite samples. Users should be aware that the S-ratio is highly non-linear; i.e., as the mass concentration of the high-coercivity mineral increases, the S-ratio does not decrease linearly owing to the contrasting spontaneous magnetizations of mag-

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Figure 2. Illustration of IRM acquisition from Roberts et al. (2020): a) hematite; and b) magnetite. Small IRM acquisition below 300 mT in a) and complete acquisition of SIRM below 300 mT in b) explains the basis for use of a 300 mT cut-off field to discriminate between low-coercivity magnetite and high-coercivity hematite. The sample in a) is red pigmentary Zebra rock (Abrajevitch et al., 2018) and the samples in b) are synthetic nanomagnetites (“particles” are equidimensional magnetite (40–85 nm diameter); rods are elongated particles with length 250–300 nm and width 60–110 nm). c) First derivative curves of the IRM (i.e., gradient) for the three samples illustrated in a, b, which provide a measure of the respective coercivity distributions in relation to the 300 mT cut-off field. Dashed vertical lines represent the 300 mT cut-off field. Note the left-hand shoulder of the hematite gradient curve that extends below 300 mT.
netite (92 Am$^2$ kg$^{-1}$) and hematite (~0.4 Am$^2$ kg$^{-1}$) (Fig. 1) (Frank & Nowaczyk, 2008).

**Hard-IRM (HIRM):** this parameter (e.g. Robinson, 1986; Thompson & Oldfield, 1986) provides a measure of the absolute contribution of the high coercivity remanence contribution. As is the case for the S-ratio, a cut-off field is used, typically 300 mT. Any IRM acquisition above the cut-off is attributed to hematite and or goethite, and if both are present their contributions may be separated by demagnetizing above the Néel temperature of goethite (~120°C). This parameter has similar drawbacks as the S-ratio.

**L-ratio:** the L-ratio (Liu et al., 2007) builds from the S-ratio by providing a way to quantify the high coercivity mineral concentration (hematite, goethite). Here, a strong IRM, typically imparted in a 1 T field, is alternating field (AF)-demagnetized in a 100 mT field (IRM$_{AF100mT}$) and subsequently in a 300 mT field (IRM$_{AF300mT}$). In contrast to the S-ratio, the L-ratio (IRM$_{AF300mT}$/IRM$_{AF100mT}$), which can also be defined as HIRM$_{200mT}$/HIRM$_{100mT}$, exploits coercivity variations of hematite and goethite and allows targeting of specific coercivity distributions. Liu et al. (2007) further proposed that the AF values used may be modified to suit the coercivity distribution of studied samples (the L-ratio is, therefore, also independent of composition (cation-substitutions) on coercivity).

**Variations and combinations of AF and thermal demagnetization:** further parameters to characterize high coercivity mineral contributions, particularly when masked by strong magnetite contributions, include cyclic direct current (DC) demagnetization of the SIRM (Liu et al., 2002), AF-demagnetizing a SIRM at ~100 mT (Larraosáñoa et al., 2003), and AF-demagnetizing at ~100 mT after each field application during an IRM acquisition experiment (Maher et al., 2004) to remove magnetite contributions. Bilardello and Kodama (2009) and Bilardello (2015) used the same approach in a double-IRM acquisition experiment to determine hematite saturation, in conjunction with heating to 125°C to remove the goethite contribution. Once saturation is reached, an AF + thermal demagnetization protocol was used in conjunction with chemical leaching by Bilardello and Kodama (2009) to separate pigmentary hematite of chemical origin from detrital hematite. Bilardello (2019) extended the HIRM test to low temperatures and incorporated the AF + thermal demagnetization approach as in the classic goethite test (Carter-Stiglitz et al., 2006; Guyodo et al.,

Figure 3. First derivative of IRM acquisition (gradient) curves and hematite components for 7 T maximum applied fields from Roberts et al. (2020). Results for hematite pigments in a decorative ‘print stone’ from the Mount McRae Shale Formation, Western Australia (Abrajevitch et al., 2014): a) hematite print stone pigment, and b) uniform pigment (see text for details). Results from Abrajevitch et al. (2015) for: c) Paleogene limestone 21 cm above the K–Pg boundary at Bottaccione Gorge, Italy, and d) limestone 46.5 cm below the boundary. For clarity, only the fitted hematite (labelled H) component of interest here is shown. Dashed vertical lines represent the 300 mT cut-off field.
IRM component analysis: magnetic components have continuous coercivity distributions, so component analysis of IRM acquisition and backfield demagnetization curves (generically referred to here as IRM acquisition curves) avoid the sharp cut-off at 300 mT or other fields. Fitting the first derivative of these curves allows coercivity contribution quantification (e.g. Egli, 2004; Heslop et al., 2002; Kruiver et al., 2001; Maxbauer et al., 2016b; Robertson & France, 1994), which deals more reasonably with inevitably overlapping component distributions. Hematite components will be evident in representations of the gradient of IRM acquisition curves (Fig. 2 c), especially if measurements are made to saturating fields or to non-saturating fields that are sufficient to define at least half of the coercivity distribution (if it is not skewed significantly).

Examples of hematite IRM components measured to 7 T by Abrajevitch et al. (2014, 2015) are illustrated in Fig. 3. Abrajevitch et al. (2014) showed that “non-uniformly” distributed pigmentary hematite (Fig. 3a) has a higher peak coercivity than a “uniformly distributed”, pigment that contains appreciable goethite in addition to poorly crystalline hematite. (Fig. 3b). The distribution of the latter is broader and has a higher coercivity tail that requires high applied fields to reach saturation, which reflects the nature of the hematite nanocrystals in addition to goethite. The terms “uniform” and “non-uniform” here reflect the decimeter scale appearance of the pigmentary print-stones, with “non-uniform” referring to patchy orange-red coloration, not to grain size distributions. Importantly, both samples have significant coercivity distributions <300 mT.

Most natural samples contain multiple magnetic minerals, as illustrated in the bimodal coercivity distributions in Fig. 3c, d for limestone/shale interbeds (Abrajevitch et al., 2015) in which the pigmentary hematite contribution is highlighted. Like the pigmentary hematite illustrated in previous examples, a significant fraction of the fitted hematite coercivity distribution extends below 300 mT. These examples demonstrate that IRM component analysis is suitable for characterizing hematite components, particularly when large inducing fields are used. At typical maximum applied fields of 1 T, hematite components will still be well defined, although they will be truncated (Fig. 3), whereas any goethite distribution, if present, may not be resolved. Additionally, detrital and pigmentary hematite distributions within the same samples may be separated by coercivity spectra unmixing. The Mauch Chunk Formation, Pennsylvania, has remanence contributions from ~15-18% magnetite, 80-83% hematite (detrital and pigmentary), and 1-3% goethite based on the classic and HIRM goethite tests (Bilardello, 2019). Unmixing of backfield curves measured to 1.5 T maximum fields reveals that coercivity spectra can be fitted with a small but broad component centered at ~64 mT, which corresponds to magnetite and likely part of the finer hematite pigment. Two largely overlapping components centered at 379 and 784 mT (with associated uncertainties) make up the dominant peak, and likely correspond to softer and harder hematite contributions, respectively, although the latter distribution is truncated (Fig. 4). No distinct goethite peak, or shoulder, is discernible. These results agree with those of Swanson-Hysell et al. (2019) for Freda Formation red beds, which have two broad, overlapping populations centered at ~300 and 700 mT, respectively. From supporting rock-magnetic evidence and unblocking temperature modeling, they attributed the latter distribution to coarser single domain hematite, whereas the former corresponds to finer-grained hematite. The observed coercivity range corresponds to hematite grains smaller than 300 nm (e.g., Özdemir & Dunlop, 2014), which can have significant coercivity contributions <300 mT.

The explanation
While use of cut-off fields is convenient, it does not distinguish the true hematite component in the coercivity distributions shown above, and a large portion of the remanence extends below 300 mT for many hematite samples (Figs. 2, 3, and 5). Many natural soil and rock
samples also have abundant hyperfine SP nanoparticle concentrations (e.g., Bilardello et al., 2020; Collinson, 1969; Creer, 1961; Swanson-Hysell et al., 2019). Hematite particle size distributions in such samples will likely span the magnetically unstable SP to stable SD size range (corresponding to 20-25 nm threshold size) for stoichiometric hematite (Banerjee, 1971; Özdemir & Dunlop, 2014), which will contribute a substantial low-coercivity distribution. Additionally, isomorphous cation substitution (e.g., Al$^{3+}$ for Fe$^{3+}$) into the hematite lattice can lower the coercivity below 300 mT (Jiang et al., 2012). The SP/SD threshold size is ~17 nm for Al-substituted hematite (Jiang et al., 2014). Hematite particles below these threshold sizes are abundant in natural environments (e.g., Mehra & Jackson, 1960; Schwertmann, 1991), which is consistent with commonly observed magnetic viscosity in hematite (e.g., Collinson, 1969; Creer, 1961). Thus, low coercivity hematite will be important in many natural environments.

The coercivity of hematite particles increases with decreasing grain size from ~1 mm to ~250 nm (Thompson, 1986) (Fig. 5a), but, as shown above, it decreases for nanoparticles finer than ~250 nm that tend to be of greatest environmental and paleomagnetic importance. The significant hematite population below 300 mT is, thus, ignored when using a 300 mT cut-off field to calculate the S-ratio, HIRM, and other parameters, which will only reflect the highest coercivity hematite fraction. If goethite is not present, remanence acquisition above 300 mT is correctly attributed to hematite, but significant remanence acquisition from 0 to 300 mT (e.g., Figs. 3 and 5) will be attributed to other low-coercivity minerals. The S-ratio will, therefore, almost always under-estimate the relative hematite fraction, and HIRM will almost always under-estimate the absolute hematite concentration, both in favor of magnetite/maghemite. For example, for the 1 T maximum applied field used in Fig. 5a, S-ratio values vary up to 0.8 despite the fact that the samples contain no magnetite. S-ratio values up to +1 are illustrated in Fig. 6a for synthetic samples that contain only nanophase Al-substituted hematite or goethite (Liu et al., 2007). Also, owing to instrumental limitations, IRM acquisition experiments often involve measurement of hematite-bearing samples to maximum applied fields of 1 T. This will cause further underestimation of hematite contents when using the S-ratio or HIRM if a higher coercivity hematite component continues to acquire an IRM above 1 T, as in Figs. 3, 4, and 5. Routine hematite content underestimation with these magnetic methods deserves to be understood more widely. Use of such parameters could lead to significant misinterpretations, especially in quantitative environmental magnetic studies. To minimize such issues, Roberts et al. (2020) recommended combined use of magnetic and non-magnetic quantification methods.

Roberts et al. (2020) described three other issues related to the S-ratio. First, alternative formulations of the S-ratio with lower cut-off backfield values (e.g., 100 mT) are often used to assess magnetically soft components (e.g. Frank & Nowaczyk, 2008; Stober & Thompson, 1979; Stoner et al., 1996; Thompson & Oldfield, 1986). Users should be aware of the ambiguities inherent to such low-coercivity ranges, which are best used when magnetic assemblages are well constrained by other analyses. When the magnetic mineral assemblage under investigation is well understood, use of variable cut-off fields can be valuable. Second, Kruiver and Passier (2001) demonstrated that S-ratio values several percent below +1 can occur without addition of a high-coercivity mineral like hematite. S-ratio values < 1 can be due to coercivity hardening by surface oxidation of magnetite (e.g. Bilardello, 2020a; Cui et al., 1994; Kontrny & Grothaus, 2017; Van Velzen & Dekkers, 1999; Van Velzen & Zijderveld, 1995). Third, when using the S-ratio, it should be noted that standard statistics, such as arithme-
Figure 6. Coercivity variations and their influence on S-ratio and HIRM. a) S-ratio and b) HIRM versus coercivity of remanence (B_r), where the S-ratio decreases with increasing coercivity and HIRM increases with increasing coercivity because more IRM is acquired above 300 mT as coercivity hardens. Such coercivity changes represent compositional differences in the analyzed high-coercivity minerals, which can be assessed with c) the L-ratio. Constant L-ratio values indicate consistent magnetic properties of the high-coercivity component, and changing values represent variable coercivity. Open circles represent synthetic Al-substituted hematite and solid circles represent Al-substituted goethite (Redrawn by Roberts et al. (2020), without relationships for curve fits, from Liu et al. (2007)).

The highly variable coercivity of hematite (Figs. 3 and 5) means that the usefulness of simple parameters such as the S-ratio and HIRM will depend on the properties of hematite in a sample, which makes its quantification difficult. Such variations will be reflected in the L-ratio, which makes this proxy useful in scenarios with changing sediment source, cation substitution, particle size distribution, and varying hematite/goethite contents.

The Recommendation
IRM component analysis appears to be the most suitable of the methods discussed because it enables estimation of continuous, non-truncated coercivity distributions. If a hematite component is well defined, its magnitude can be calculated as a proportion of the total magnetization to allow hematite quantification even if magnetic saturation is not achieved. The 7 T maximum fields used in Fig. 3 capture the full hematite component, and a 4.75 T applied field will suffice for this purpose (Bilardello, 2015). Most studies use lower maximum applied fields, which need to be large enough to define the hematite component; fields up to 1.5 T can adequately define the hematite distribution if it is not skewed significantly. However, IRM curve analysis still has limitations for hematite quantification. Most studies provide evidence to identify whether a magnetic component is present or absent, which provides semi-supervised IRM unmixing that helps to reduce the non-uniqueness that is inherent to unmixing (Heslop, 2015). Nevertheless, the precise coercivity distribution of a magnetic component will remain unknown, as will its magnitude.

A useful “exercise” to ascertain the non-uniqueness of IRM unmixing, beyond the uncertainty of calculated fits, is to fit components to the same spectrum by starting from the lower coercivity end and then from the higher coercivity end. This will demonstrate the challenge of determining unique component fits to IRM acquisition curves; uncertainties associated with non-uniqueness of hematite component fits are, therefore, still likely to be significant. Therefore, substantial limitations exist for all existing magnetic proxies for hematite content. Additionally, room temperature remanence-based methods will not quantify ultrafine SP contents, which can be significant in hematite (e.g., Collinson, 1969; Creer, 1961). Although we lack simple ways to reliably quantify hematite contents in natural samples, the ambiguities that are inherent to hematite quantification can be reduced if proxies are used critically and in combination. For example, IRM component analysis can be used to check the coercivity range of hematite and the L-ratio can be used to check for variations in these ranges. If the L-ratio is variable, conventional use of the S-ratio and HIRM is unreasonable (Liu et al., 2007).

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RAC News

Julie Bowles (University of Wisconsin, Milwaukee) is the new chair of the IRM’s Research Advisory Committee.

Thank you Julie for accepting this position!
The IRM Quarterly is published four times a year by the staff of the IRM. If you or someone you know would like to be on our mailing list, if you have something you would like to contribute (e.g., titles plus abstracts of papers in press), or if you have any suggestions to improve the newsletter, please notify the editor:

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The Institute for Rock Magnetism is dedicated to providing state-of-the-art facilities and technical expertise free of charge to any interested researcher who applies and is accepted as a Visiting Fellow. Short proposals are accepted semi-annually in spring and fall for work to be done in a 10-day period during the following half year. Shorter, less formal visits are arranged on an individual basis through the Facilities Manager.

The IRM staff consists of Subir Banerjee, Professor/Founding Director; Bruce Moskowitz, Professor/Director; Joshua Feinberg, Assistant Professor/Associate Director; Maxwell Brown, Peat Solheid and Dario Bilardello, Staff Scientists.

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