Practical Magnetism III: 
What’s what in remanence anisotropy

Dario Bilardello
Institute for Rock Magnetism, University of Minnesota, Minneapolis, MN, USA
dario@umn.edu

In the IRMQ28-3 article “Commonly used experimental parameters for acquisition of anhysteretic remanent magnetization (ARM) and its anisotropy (AARM): Results and recommendations from a rock magnetic community survey” Biedermann et al. (2018) had reported results from a survey sent to our community regarding what capabilities different laboratories have to apply ARMs (peak AF fields, DC fields, AF decay rates) and which are typically used and fed into anisotropy calculations. What that article left out, however, was what properties are used for calculating these anisotropies, and note that I am not using the term AARM here, because the name we give these anisotropies is intrinsically dependent on how they are calculated.

The Rationale
Using anhysteretic remanences to compute anisotropies was first proposed by McCabe et al. (1985), for what they termed Anisotropy of Anhysteretic Susceptibility (AAS). Susceptibility of ARM (\(\chi_{\text{ARM}}\)) is a property that has been used since it was first proposed by King et al. (1982), is mostly employed in environmental magnetism, and is nothing else than the ARM normalized by the DC field used to acquire it, just like magnetic susceptibility is defined by the “in field” magnetization (low-field) divided by the field itself. The advantage of such a normalization is that it inherently makes results comparable among different laboratories or when slightly different applied fields are used, as long as the resulting susceptibility is not field-dependent. It is thus a useful quantity to report, granted that the assumption of linearity between magnetization (ARM) and DC field is maintained. Using \(\chi_{\text{ARM}}\) for anisotropy is thus a natural segue, and also determines the units of the anisotropy principal axes.

A criticism to the term AAS, however, was that the condition of linearity (field dependence) was rarely met and thus the property should not be referred to a susceptibility. Consequently, the term AAS soon faded away and was replaced by anisotropy of anhysteretic remanent magnetization (AARM) (Mike Jackson, personal communication). Interestingly enough, the same criticism has not been expressed for use of the \(\chi_{\text{ARM}}\) parameter for similar DC fields (< 1 Oe or 0.1 mT or ~80 A/m), Subir Banerjee, personal communication) and use of the terms (and proxy) survives to this day. While the criticism raised is legitimate, unfortunately it has created some confusion surrounding the determination of the anisotropies and relevant terminology (AAS versus AARM, and what is actually meant by these terms).

The problem of linearity of M versus B (in fields much less than the coercivity) has been long investigated in magnetic research and is intrinsically related to particle interactions within a sample (e.g. Dunlop & West, 1969; Sugiura, 1979) or by thermal fluctuations and particle volume in noninteracting samples (Egli & Lowrie, 2002). For synthetic samples, Sugiura (1979) determined experimentally that strongly interacting particles (concentrations of 4.3 x 10^{-3} - 2.3 x 10^{-2}) show...
Tracing thermal alteration using rock magnetism

Huapei Wang, Junxiang Miao
China University of Geosciences, Wuhan
huapei@cug.edu.cn

Introduction
The Thellier-series experiments [Thellier and Thellier, 1959] are widely considered the most reliable technique to estimate paleointensities, which can provide crucial constraints on the behavior of the geomagnetic field. During the experiments, samples need to be heated multiple times up to the Curie temperature, in order to be thermally demagnetized and to acquire laboratory-applied thermoremanences. However, the thermally induced physical and chemical alteration of magnetic minerals during the stepwise heating treatments can severely bias paleointensity estimates. In this study, we use comprehensive rock magnetic measurements to detect the thermal alteration of sister specimens of a lava sample that have been used in a previous paleointensity study, in the hope of reaching a better understanding of how samples alter during Thellier-series paleointensity experiments.

Samples and Methods
The Galapagos Archipelago consists of volcanic islands on the Nazca plate just south of the Equator [Kent et al., 2010; Wang and Kent, 2013]. We focused on a sample GA85.1 from a Galapagos lava, which yielded a very low paleointensity (4.23±1.29 µT) [Wang and Kent, 2013], and was likely associated with the Santa Rosa geomagnetic excursion event at 925.7±4.6 thousand years ago [Balbas et al., 2016].

We carefully crushed a piece of the fresh sample into several small chips, which were named “GA85.1w”, “GA85.1u”, “GA85.1t”, etc. To track the thermal alteration during heating, we used the HT-VSM (a vibrating sample magnetometer equipped with a high-temperature furnace in the Institute for Rock Magnetism) to measure hysteresis loops (Fig. 1a), back-field direct current demagnetization (DCD) curves (Fig. 1c) at elevated temperatures on specimen GA85.1w. After the first heating round (up to 880 K), we repeated the same measurements to gauge thermal alteration (Figs. 1b, d), which allowed us to observe differences in rock magnetic properties between the first and the second heating rounds. We also calculated the hysteresis parameters such as saturation remanent magnetization (Mr), saturation induced magnetization (Ms), magnetic coercivity (Bc), remanent magnetic coercivity (Bcr) at successive temperature steps (Figs. 1e, f) to indicate any signs of alteration.

Utilizing the above DCD curves measured at elevated temperatures, we performed thermal fluctuation tomographic (TFT) calculations [Jackson et al., 2006; Wang et al., 2013] to gain more information on the thermal alteration characteristics of specimen GA85.1w (Fig. 2). Although the TFT inverse calculations from DCD measurements for plotting size-shape distribution diagrams are only strictly valid for stable single-domain (SSD) and superparamagnetic particles [Jackson et al., 2006], the inverted volume-microcoercivity diagrams and size-shape diagrams still provide useful insight on thermal alteration.

Utilizing the hysteresis loops and DCD curves measured at elevated temperatures (Fig. 1), we also plotted the Day diagram (Mr/Ms versus Bcr/Bc) [Day et al., 1976] of specimen GA85.1w for the first and second heating rounds (Fig. 3a). We also measured FC-ZFC (field cooled, zero-field cooled) curves [Moskowitz et al., 1993] and SIRM (saturation isothermal remanent magnetization) cooling/warming curves from 10 K to 300 K for specimen GA85.1u (Fig. 3b), using a Quantum Designs magnetic property measurement system (MPMS) at the Institute for Rock Magnetism. In order to directly gauge thermal alteration, we measured FORCs...
Results

These rock magnetic measurements at different temperatures allow us to monitor the thermal alteration of sample GA85.1 during heating treatments, which can provide critical information on the reliability of its paleointensity result. From the first and second heating rounds (Fig. 1), we found that the Ms-T curves were similar, while the Mr-T curves show significant differences, which indicated that the thermal alteration was physical (magnetic domain state) but not chemical (magnetic mineralogy). The resultant Bc and Bcr curves for the first and second heating also show clear discrepancies, which also showed in the Day plots (Fig. 3a). TFT plots (Fig. 2) from the first and second heating rounds show clear changes in effective volume, shape and microcoercivity, with reduced effective ferromagnetic grain size and increased microcoercivity after the first heating. FC-ZFC curves of specimen GA85.1u show PSD-MD magnetite behavior (Fig. 3b). FORC diagrams for specimen GA85.1t before and after heating (Figs. 3c, d) show relatively significant alteration, with a shift of the central ridge and a decrease of the peak of the microcoercivity distribution. Our comprehensive rock magnetic results of GA85.1 suggests that it’s not suitable for Thellier-series experiments due to thermal alteration, which is supported by its paleointensity results from a sister specimen GA85.1c [Wang and Kent, 2013].

In conclusion, comprehensive rock magnetic measurements at room temperature and elevated temperatures can provide critical information in determining the thermal alteration of samples during heating treatments, which can be used to determine the qualification or justify the reliability of their paleointensity results.

Supported by the IRM student visiting fellowship, data in this report were collected in the summer of 2011 by Huapei Wang, who was a Ph.D. student at that time. During the visit, Mike Jackson, Pete Solheid, Bruce Moskowitz, Josh Feinberg and other members of the IRM not only provided Huapei hands-on guidance to operate many sophisticated instruments at the IRM, but also shared many thoughtful and joyful discussions and the signature “Tea Time” with Huapei, who benefited greatly in terms of experiment design, sample measurements and data analyses.
Preservation of primary magnetic signals in regionally altered volcanic terranes or: How I learned to stop worrying and love the (maghemite) bump

Thomas Belgrano 1,2

1 Institute of Geological Sciences, University of Bern, Switzerland
2 National Oceanography Centre Southampton, University of Southampton, UK
thomas.belgrano@geo.unibe.ch

Introduction
The correlation between bulk Fe content and magnetism in fresh volcanic rocks is both logical and well-characterized (e.g., Gee and Kent, 1998). However, pervasive hydrothermal alteration, common to essentially all ancient submarine volcanic terranes, is generally thought to scatter and obscure these primary magnetic properties. Consequently, intra-volcanic stratigraphic interpretation of aeromagnetic maps in these terranes is commonly undertaken with apprehension, or not at all.

While producing a new geological map of upper oceanic crust of the Semail ophiolite (Oman–UAE), we noticed that conformable aeromagnetic anomalies are often aligned with the different volcanic units (Fig. 1). The key question which brought about my visit to the IRM was whether these local observations had a sound basis in rock magnetic properties and mineralogy, and thus whether they could be applied to remote mapping and identifying these units under thin gravel cover.

Using rock samples collected from the different volcanic units across the ophiolite, we measured magnetic susceptibility, natural remanent magnetization, high and low-T magnetic behavior and magnetic hysteresis. These could be compared with previously determined whole-rock geochemical data.

Relationship between bulk magnetic properties and geochemistry

References
Figure 1. Volcanostратigraphy of the Semail ophiolite and an aeromagnetic mapping example, adapted from Belgrano et al. (2019). (a) Stratigraphy of the mapped volcanic units. (b) Reduced-to-pole (RTP) aeromagnetic map, showing N–S oriented anomalies corresponding to the different volcanic units, offset by E–W faults. (c) Final geological map, confirmed by field mapping and sampling (circles), showing a volcanic section dipping ~40°E in the vicinity of the Mandoos volcanogenic massive sulphide deposit (6.7 Mt ore at 1.66 wt% Cu).

To test whether the map-scale relationship between the volcanic units and aeromagnetic data was reproducible at the sample scale, we measured the bulk magnetic properties of a series of samples differentiated on a unit-basis. Both magnetic susceptibility and natural remanent magnetization (NRM) intensity were found to be systematically lower in the units that corresponded with weak magnetic anomalies in the aeromagnetic map (Boninitic Alley and Lasail).

As these magnetic properties vary on the basis of volcanic unit, they are presumably controlled by some primary magmatic characteristic. Despite scatter due to alteration, Figure 2 shows that the magnetic susceptibility of the Semail volcanics is related to whole rock Mg# (molar Mg / (Mg + Fe)), which in turn varies systematically between the different units. This relationship is shown by the tholeite-like trend of magnetic susceptibility with Mg#, rapidly increasing from high to moderate Mg#, before dropping off at evolved compositions where lavas have undergone magnetic magnetite fractionation. The weakest magnetic samples however, mostly derive from the Lasail and Boninitic Alley units, which have the highest Mg# compositions, as corroborated by their high Mg# relict clinopyroxenes and fresh volcanic glasses (Belgrano et al., 2019).

Crucially, at Mg# >80, the relationship between susceptibility and Mg# is somewhat amplified, rather than obscured by alteration. Above Mg# >80, magnetic susceptibility drops to near zero, whereas below this Mg#, susceptibility rapidly increases. In fresh volcanic rocks, this relationship is more linear at high Mg#, with significant magnetism persisting above Mg# 80 (Gee and Kent, 1998). The strong susceptibility drop above Mg# 80 in the Semail lavas is the key reason these primitive units are so distinguishable in aeromagnetic data (Fig. 1b).

The majority of samples from these primitive units are dominantly paramagnetic. This indicates that all available Fe (5–10 wt% Fe₂O₃ equivalent) is sequestered in paramagnetic silicate phases. As magnetite is a late crystallizing-phase in tholeiitic magmas, primary magnetite would initially have been concentrated in the glassy interstices of the primitive lavas (Belgrano et al., 2019). Chlorite is the most dominant secondary mineral replacing these interstices. As a mineral that readily incorporates Mg²⁺, Fe²⁺, and a little Fe³⁺, chlorite, is the probable paramagnetic host of the Fe that previously resided in ferromagnetic oxides of the fresh lavas.

These conclusions seem rather straightforward in hindsight; however, without making these magnetic measurements and comparing them to the geochemical trends, it was impossible to rule out other equally plausible explanations, such as calc-alkaline differentiation trends or conformable hydrothermal alteration.

Figure 2. Magnetic susceptibility vs. whole rock Mg# for the Semail ophiolite volcanic units, adapted from Belgrano et al. (2019), with additional data from Einaudi et al. (2003). The general evolution of protolith compositions from ‘primitive’ to ‘evolved’ due to magmatic differentiation is annotated.
Magnetic mineralogy & the crucial role of maghemite
To determine the origin and thus reliability of their bulk magnetic properties, it was necessary to determine the magnetic mineralogy of the different volcanic units. In particular, for geological mapping, the persistence of magnetism following alteration in the more evolved units is just as important as the weak primary magnetism of the primitive units. That both the Geotimes and Tholeiitic Alley units have similarly high susceptibilities and NRM intensities is somewhat surprising, as the more deeply-buried basal Geotimes lavas have generally suffered more intense, higher-grade greenschist facies alteration than the overlying Tholeiitic Alley lavas (Belgrano et al., 2019).

The high- and low-temperature experiments in Figure 3 provide an explanation for the persistence of primary magnetic signals in these altered rocks. These experiments firstly identified the presence of relict titanomagnetite (Fig. 3a), with a Curie temperature <500°C. As Ti has a very low solubility in seawater, this titanomagnetite is assumed to be primary, and is present in around 50% of the Tholeiitic Alley samples, but <20% of Geotimes samples. Almost stoichiometric magnetite, with a Curie temperature between 570–580°C was also commonly observed (Fig. 3b). This magnetite could either be primary, following unmixing from a Ti-rich phase during cooling, or hydrothermal.

Figures 3c & d are interpreted to show different mixtures of (weakly Ti-substituted) magnetite and maghemite. In both cases an increase in susceptibility around 130–140°C, the titular ‘maghemite bump’ (Kontny and Grothaus, 2017), precedes a loss of susceptibility between 300–400°C. This susceptibility drop is interpreted as the inversion of maghemite to hematite. In Figure 3c, the similar susceptibilities at room temperature and following inversion suggest only a modest maghemite contribution to total susceptibility. In Figure 3d, however, ~3/4 of susceptibility is lost during maghemite inversion, and a small but significant fraction of susceptibility persists above 600°C. The slight reversible component of this high-temperature, >600°C susceptibility is interpreted as hematite, either pre-existing or the inversion product of maghemite. The irreversible portion of this high-temperature susceptibility therefore cannot be due to hematite, and is instead interpreted as remaining Ti-bearing maghemite which unblocked at 610°C.

The low temperature experiments shown for the same samples in the right-hand column of Figure 3, support these interpretations. Only samples interpreted as containing magnetite exhibit a distinct Verwey transition at ~120 K, and this transition is broadened or suppressed in the titanomagnetite or maghemite dominated samples. The lack of a Besnus transition 30–35 K also militates against the unblocking of monoclinic pyrrhotite (T Curie ≈ 320°C) as the cause of the susceptibility drops on heating between 300–400°C.

Measurements on 36 samples revealed that maghemite is present in ~85% of the Geotimes samples, compared to 30% of the Tholeiitic Alley samples, whereas primary titanomagnetite is still present in 50% of Tholeiitic Alley samples, compared to only 15% of Geotimes. This trade-off of fresh titanomagnetite for oxidized maghemite at similar bulk Fe contents explains how the more altered Geotimes unit can have similar bulk magnetic properties to the fresher Tholeiitic Alley unit.

Concluding remarks
On face value, the task of mapping subtle compositional differences between regionally altered volcanic units using aeromagnetic data seemed extremely challenging. Two quirks of nature, however, meant that the pervasive alteration of these volcanic rocks was a tolerable, or even helpful influence. Firstly, complete chloritization of magnetic oxides in primitive volcanic rocks helped to lower their magnetism and differentiate them from their more evolved counterparts. Secondly, the prevalence of maghemite as an oxidized but nevertheless strongly magnetic phase lessened the effects of differing hydrothermal alteration on the two Fe-rich units. Fortunately, these units are stratigraphically arranged like a bar code: strong–weak–strong–weak, so these magnetic characteristics were generally useful for remote mapping and mapping under gravel cover.

Far from being the unique quirks of our study area,
the effects of chloritization and maghemitization are ubiquitous in ancient submarine volcanic suites, so these practical observations should prove useful for volcanic mapping in other ophiolites and potentially greenstone belts. More generally, our study underscores greatly enhanced utility of aeromagnetic surveys when combined with basic magnetic petrology of the targeted units.

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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.

Archaeomagnetism


Environmental Magnetism


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Extraterrestrial Magnetism


Fundamental Rock Magnetism and direct Applications


Magnetic Fabrics and Anisotropy


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linear dependence of M to B, for fields up to approximately 0.2 mT, and have suppressed ARM. However, the linear regime was found to be greatly reduced for particles with lower concentrations (1.9 x 10^{-5} - 2.6 x 10^{-6}), and thus reduced interactions. For such assemblages the non-linearity was observed for fields as small as, if not smaller than, 0.05 mT. King et al. (1982) noted that the concentration-dependence of ARM observed by Sugiura (1979) was particularly surprising, considering the very low concentrations (2.3 x 10^{-2} < C < 2.6 x 10^{-6}) at which they were observed, much below previously reported values (e.g. Banerjee & Mellema, 1974; Dankers, 1978; Schmidbauer & Veitch, 1980). They concluded that, if confirmed, the result would be particularly pertinent to the application of the $\chi_{ARM}$ parameter to soils and lake sediments for which those concentrations are common. Notably, Sugiura (1979) determined through Preisach models that the grains in their samples existed in bundles, which does affect the distribution of the interaction field intensity.

The non-linearity of ARM acquisition has been investigated numerically (Dunlop & Özdemir, 1997; Egli, 2006; Egli & Lowrie, 2002), and the initial slope (calculated for DC fields < 0.01 mT) has been used to determine non-interacting SD behavior for a variety of natural rocks: e.g. Dunlop and Özdemir (1997) for the Lambertville plagioclase; Moskowitz et al. (1993) for cultured magnetotactic bacteria; Till et al. (2011) for the Tiva Canyon Tuff; and Jackson and Swanson-Hysell (2012) for a remagnetized limestone of the Becraft Formation (Fig. 2). Note, also, that Egli (2006) investigated the effect of interactions of uniaxial SD grains to the AARM,

Figure 2. Non-linear anhysteretic remanent magnetization (ARM) acquisition for a remagnetized limestone sample of the Becraft Formation (solid line). The initial slope gives $\chi_{ARM}/SIRM = 2.1 \times 10^{-3}$ mA, comparable to theoretical values for non-interacting SD magnetite (Egli, 2006; Egli & Lowrie, 2002), and to values observed for cultured magnetotactic bacteria (Moskowitz et al., 1993) and for igneous materials such as the Tiva Canyon Tuff (Till et al., 2011) and the Lambertville plagioclase (Dunlop & Özdemir, 1997, fig. 11.6). Dashed line was superimposed to the initial acquisition steps to highlight the ~linear behavior of these data below ~0.05 mT (modified from Jackson and Swanson-Hysell (2012)).
and determined that the measured anisotropy depends on the spatial distribution of the grains, which can modulate the directional dependence of ARM intensity. For strongly interacting SD particles the AARM anisotropy parameter is heavily dependent on their concentration and microcoercivity, leading to complex behavior and introducing further caveats to anisotropy determinations (Egli, 2006).

Considering the broad nature of rocks studied for magnetic fabrics, the linearity of ARM with DC field is no trivial point, and given the different coercivities involved it should also depend on the peak AF value and the AF window over which the bias field is applied. Short of conducting ARM acquisition experiments as a function of DC field for each rock type for which fabrics are to be measured, it may be worthwhile establishing a qualitative cut-off field, say 0.05 mT, at or below which the M-B relations may be considered linear for all intents and purposes, as shown in figure 2. For example, for a dominantly paramagnetic coarse grained gneiss sample whose remanence is carried by a range of Ti-maghemite grain sizes, and a finer-grained mafic granulite sample whose remanence is carried by MD Ti-magnetite, Bilardello and Jackson (2014) compared results obtained from different types of anisotropy techniques and acquired using different DC fields. For the two rock-types investigated they observed that DC field-normalized AARM results obtained using 0.05 mT DC fields were significantly different from results obtained using 0.1 and 0.2 mT bias DC fields, which were instead similar to each other (Fig. 3). The effect of choice of DC bias field on the anisotropy determination and degree of anisotropy in particular was also briefly discussed in Bilardello (2016) and Biedermann et al. (2020). For a more exhaustive discussion pertaining to anisotropy the reader may also refer to Cox and Doell (1967), Daly and Zinsmeister (1973), Stephenson et al. (1986) or Jackson (1991). Alternatively, if the term AAS is to be dropped for good, the variable densities of rocks, particularly when highly porous or vesiculated materials are investigated (as well as measuring mass is usually easier than volume measurements).

Specific to magnetic fabrics, a “problem/non-problem” is that the actual quantities used to determine anisotropies are very rarely reported in their absolute values (and units), and readers have to make do with what “label” is given to the anisotropy (AARM versus AAS). However, granted that anisotropy principal axes are rarely reported in their absolute terms, but normalized among each other (typically so that their sum equals 1 or 3), then the units are irrelevant. However, it does become harder to determine what has been measured, especially when the DC fields used are not reported. For the sake of completeness, and so that everyone is in the know about the different ways anisotropy of remanence can be calculated, I thought it would be didactic to write an article that details the types of remanence anisotropies that exist. I apologize to all those that will find this article “a festival of the obvious”, as my high-school philosophy teacher used to say.

The Substance
As McCabe et al. (1985) pointed out, susceptibility of ARM can be a particularly useful parameter, and fundamentally different from the initial or low-field AC susceptibility. Since it is based on a remanence, it eliminates the contribution from the paramagnetic and diamagnetic components in the sample. Additionally, the contributions of hematite and goethite are minimized (unless present as nanophases) owing to their coercivities, typically much higher than the normal range of alternating fields applied, and the contribution of MD grains is reduced because their ability to carry remanence is minimal compared to their susceptibility; thus enhancing the contribution of SD/PSD magnetite.

Just as for magnetic susceptibility, the measured ARM can be mass normalized (Am$^2$/kg) resulting in $\chi_{AARM}$ in m$^3$/kg when divided by the field in A/m, or volume normalized (A/m), and resulting in $\chi_{AARM}$ in a dimensionless quantity after normalizing by the same field. Although not formally defined, deriving anisotropies may be labeled as “mass AAS” and “volume AAS”, respectively.

Despite the above, and owing to the criticisms concerning the assumption of linearity between magnetization and applied field, AAS is rarely encountered in recent literature, and most commonly anisotropy of anhysteretic remanent magnetization (AARM) or anisotropy of anhysteretic remanence (AAR), for short, are reported instead. However, it is not always clear what these quantities actually represent, whether they are based off of ARMs in the strict sense of the term (mass or volume normalized remanences), or whether they are additionally normalized by the DC field, just as originally proposed for AAS. For example, the IRM database and software allows calculating what it reports as AARM, but in reality, is mass-normalized AAS, with principal axes in units of m$^3$/kg. This is not intuitive for a quantity termed “magnetization”.

Strictly speaking, then, AARMs should really be based off of ARMs alone, not $\chi_{AARM}$ and then can be further subdivided into mass AARM (units of Am$^2$/kg) and volume AARM (units of A/m). These anisotropies are legitimate quantities to use, and just as the IRMQ 28:3 article specifies, as long as the DC fields used to acquire the ARMs are reported, then there shouldn’t be any confusion as to what’s what. In general, normalizing by mass makes more sense in the Earth sciences given the variable densities of rocks, particularly when highly porous or vesiculated materials are investigated (as well as measuring mass is usually easier than volume measurements).

The only caveat for using AAS should always be that linearity between ARMs and DC fields is maintained. However, if this should not be the case, then not normalizing by the DC field is, in fact, preferable, and an AARM should be used. Bilardello and Jackson (2014), for example, reported “AARMs” that are technically “AASs” for anhysteretic remanences acquired using 0.05, 0.1, and 0.2 mT bias DC fields (39.8, 79.6, and 159.2 A/m, respectively) (Fig. 3). Of these, the last two were not found to be in agreement with the first, imply-
ing non-linear dependence of M to B, at least for fields greater than 0.05 mT, and should probably not have been normalized by the field. The same caveat applies to measuring high-field susceptibility and its anisotropy from hysteresis loops: the high-field slope used must define a linear portion of the loop and thus purely represent the paramagnetic contribution to the sample (e.g. Bilardello, 2016). The same applies to high-field susceptibility derived from torque measurements (e.g. Martin-Hernández & Hirt, 2001).

So what does this discussion imply for the anisotropy of isothermal remanence magnetization (AIRM, or AIR)? IRMs are typically stronger than ARMs and the linear regime is generally surpassed. Coe (1966) evaluated the validity of second order tensors for AIRM and determined that, except maybe for hematite samples, these are inadequate to accurately describe the anisotropy. Magnetists, including myself, have often been somewhat cavalier when using such remanences for anisotropy determinations (e.g. Bilardello, 2015; Bilardello & Kodama, 2009), with the justification that if anisotropies of high coercivity minerals are to be determined, then it is merely “the best one can do”. Muss es sein. In those cases, one must seek to corroborate the validity of the results by evaluating the errors of the tensor-fits and the angular uncertainties of the principal axes orientations, repeatability of the measurements, and consistencies among samples (Bilardello, 2016). A further implication is that susceptibilities of IRMs should never be even contemplated and that AIRMs should only exist in two flavors, mass and volume normalized, albeit just the one is preferable.

**Recommendation**

The discussion above revolved solely around the problem of potential non-linearity of ARMs with field, effectively making AARMs field dependent. The reality, however, is somewhat more complex, with ARMs also being decay-rate dependent (Biedermann et al., 2018, 2019; Egli & Lowrie, 2002). Combined, these effects make the tensors that are reported not unique, so that no single AARM of a sample exists, but is instead inextricably related to the DC field and AF decay rate used. The same applies to anisotropy of magnetic susceptibility (AMS) with respect to AC field and frequency. Together, these considerations highlight the importance of the experimental parameters used, and the need to report these along the magnetic fabrics they determine. These, and other “dependencies” will be the topic of a dedicated article by Andrea Biedermann and will be discussed at length there.

Following the discussion presented above it may be legitimate to propose the following guidance:

- The term AAS should be used whenever the linearity of ARMs to DC fields is maintained within the AF window used, and the results are normalized by that field. To this extent, a DC field of 0.05 mT (see figure 2) over a 100 mT AF window (or any partial ARM window within 100 mT) may be considered a generally valid threshold.
- The term AARM should be used whenever the dependence of ARM on DC field has not been determined or is not linear, and field-normalization is not applied. In the absence of linearity, however, the validity of second rank tensors may be compromised (Coe, 1966).
- Whenever there is no linearity between magnetizations and DC fields (for ARMs or IRMs), a correlation between non-linearity and tensor misfit, or non-linearity and changes in the tensors resulting from different DC fields, may be sought.
- As already stated in Biedermann et al. (2018), all experimental parameters used should always be reported when investigating anisotropy.

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**References**


Biedermann, A. R., Bilardello, D., Jackson, M., Chadima, M.,


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**RAC News**

After 4 years as chair of the IRM's Review and Advisory Committee (RAC) Mark Dekkers (Utrecht University) retires from his position. We thank Mark for his contribution to the IRM!

Please join us in welcoming Beatriz Ortega Guerrero (Universidad Nacional Autónoma de México) as new RAC member!
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Dario Bilardello
Institute for Rock Magnetism
University of Minnesota
150 John T Tate Hall
116 Church Street SE
Minneapolis, MN 55455-0128
phone: (612) 624-5049
e-mail: dario@umn.edu
www.irm.umn.edu

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