AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1002/2015GC006178

Key Points:
- Permutation of AF axes during three-axis static demagnetization reduces the effects of gyroremanence
- An optional subsequent smoothing analysis can be used to remove gyroremanence

Supporting Information:
- Supporting Information S1
- Supporting Information S2
- Table S1–S2
- Software S1

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Citation:
Finn, D. R., and R. S. Coe (2016), A new protocol for three-axis static alternating field demagnetization of rocks, *Geochem. Geophys. Geosyst.*, *17*, 1815–1822, doi:10.1002/2015GC006178.

Received 13 NOV 2015
Accepted 28 APR 2016
Accepted article online 2 MAY 2016
Published online 27 MAY 2016

A new protocol for three-axis static alternating field demagnetization of rocks

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Abstract Static three-axis alternating field (AF) demagnetization is the most common method regularly implemented for removing magnetic components of rock samples. This method is so widely used that one of its main limitations, the acquisition of gyroremanence (GRM), is often not accounted for or even discussed. The presence of GRM likely interferes more than is recognized in accurate determination of the most stable remanence. The accepted method proposed by Dankers and Zijderveld (1981) for excluding GRM affected measurements requires nearly triple the amount of lab work, and by consequence, is almost never regularly implemented on large batches of samples. Here, we present a laboratory procedure and subsequent analysis (SI method) that removes the effects of GRM in static AF demagnetization without requiring extra laboratory work. This paper, therefore, describes a new standard protocol for efficient static AF demagnetization of rocks.

1. Introduction

The most widely used method for demagnetizing rocks requires application of an alternating field along three orthogonal directions and one measurement of remanence for each step in a sequence of progressively increased peak-field intensities. The AF causes rapid flips of the magnetic moment of grains and randomization of their direction. This sudden forced rotation of the magnetic moment vector for grains of a particular size, shape, and composition, takes a gyroscopic form due to a transient field generated antiparallel to the rotation vector during the flip [*Stephenson*, 1980]. As a result, a sample acquires a net GRM that is perpendicular to both the applied AF and direction of preferred grain alignment in the sample. This is typically thought of as a spurious unwanted component of AF demagnetization, and if large enough, can make demagnetization data unusable if it has not been accounted for (Figures 1a and 1e). *Dankers and Zijderveld* [1981] devised a measurement routine that excludes measured components affected by GRM. This procedure, which we refer to as the exclusion method, requires five AF applications (e.g., AF along y, z, x, y, then z) with measurements of remanence made after each of the last three AFs. The only component of magnetization used from each measurement is the one in which the AF was applied along just before the measurement is made. Because GRM is acquired perpendicular to the AF direction, in many cases these three measurements yield three GRM-free NRM components (Figures 1d and 1h).

Despite GRM being commonly reported in paleomagnetically important minerals, such as fine-grained magnetite, the exclusion method is not regularly implemented because it entails so much extra laboratory work. This is partly because it cannot be known in advance if a particular sample will suffer from GRM effects, and the extra precautionary steps, which nearly triple the amount of lab work, could be unnecessary. GRM can be a big problem for paleomagnetic laboratories that have automated routines for completely AF demagnetizing samples, the more so if they demagnetize large batches at a time.

To reduce the effect of GRM without extra measurements, in our Santa Cruz laboratory, we permute the order of AF axes with each progressively larger AF step [*Morris et al.*, 2009]. This has the effect of permuting the direction in which the GRM component is acquired between subsequent AF steps, enabling a significantly better determination of the stable natural remanence during routine principal component analysis if GRM is not too large (Figures 1b, 1f, and 2). In cases where GRM is excessive, we have developed a simple subsequent analysis, the Smoothing-Interpolation (SI) method, which achieves excellent results by dramatically reducing the amplitude of GRM with no additional laboratory measurements. Here we demonstrate the proposed method on both natural and anhysteretic remanence demagnetizations of a welded tuff

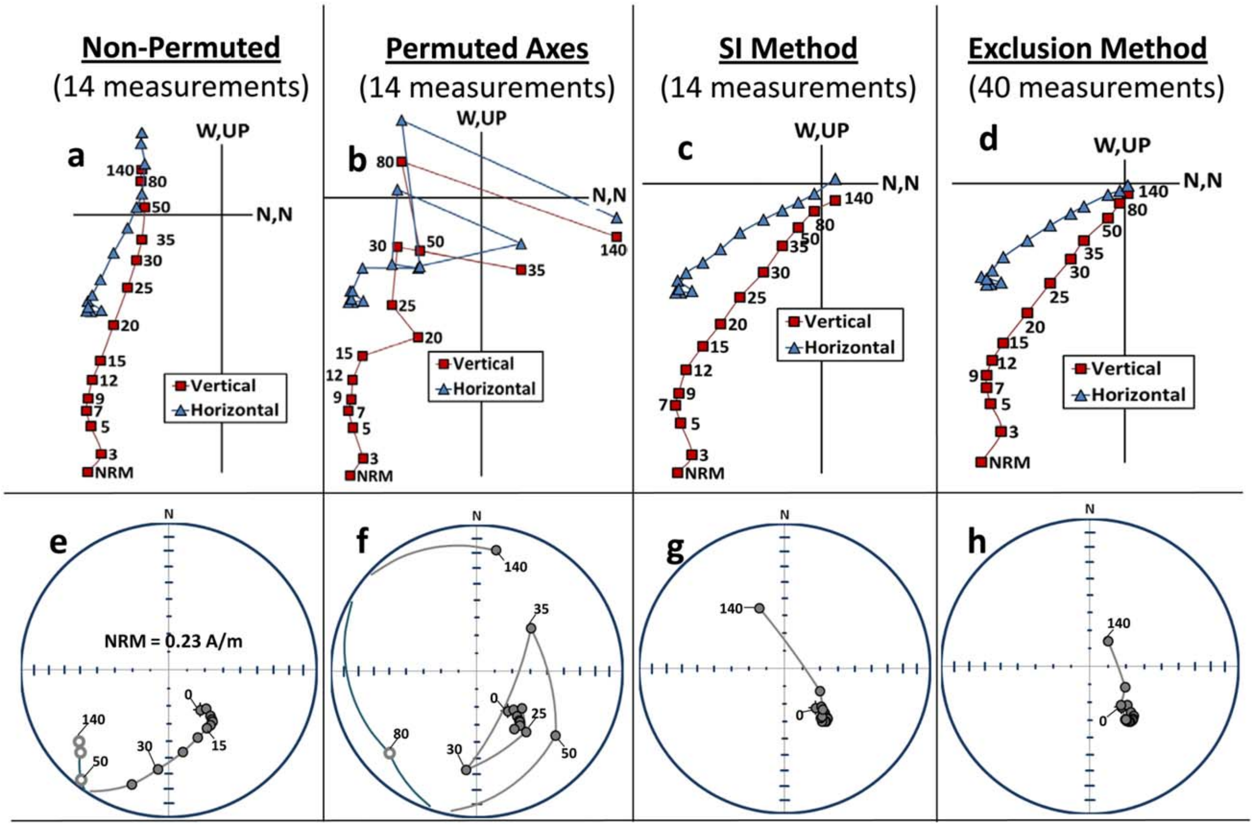

Figure 1. Zjiderveld plots (a–d) and associated stereonets are shown demonstrating the usefulness of the SI method. These plots show results from a demagnetization that does not permute the order of AF axes (1a, 1e), does permute AF axes (1b, 1f), permutes axes and implements the SI method to remove GRM (1c, 1g), and the exclusion method of *Dankers and Zijderveld* [1981] with the repeated AF applications and measurements at each peak AF step.

sample (Figures 1c, 1g, and 2). But even if one does not expect to use the SI method, we recommend that permutation of demagnetization axes be adopted as a standard procedure for three-axis AF demagnetization so that GRM effects can be dealt with if they turn out to be serious.

2. Sample Description

The paleomagnetic sample chosen for this paper was collected from the crystalline center of the Cougar Point Tuff (CPT) XII ignimbrite in southwest Idaho, an intensely welded sheet of ash-flow tuff emplaced at high temperature over a large area in the mid-Miocene [*Bonnichsen and Citron*, 1982]. Its NRM is weak and southeast and down, indicating that it was magnetized in a weak transitional field of intermediate polarity, and thus during AF demagnetization its GRM makes a relatively larger contribution to the remanence. The GRM in these ignimbrites is carried by anisotropic fine-grained magnetite, which likely crystallized from the volcanic glass during and shortly after deposition [*Finn et al.*, 2015 and references therein]. We collected samples from the CPT XII along the Bruneau River and the East and West Forks of the Jarbidge River. The NRM of samples from this tuff typically consists of three components, a minor low and tiny high-coercivity normal component that overprints a larger intermediate transitional component acquired during initial cooling.

3. NRM Demagnetization and Analysis

We progressively AF demagnetized and measured remanence of the rhyolitic sample using a Sapphire SI-4 demagnetizer that is mounted inline with a 2G cryogenic magnetometer. Both instruments are held in a magnetically shielded room at the UC Santa Cruz Paleomagnetism Laboratory, and automated

Table 1. Results From Principal Component Analyses (PCA) are Shown for a Three-Axis Static AF Demagnetization of an NRM[a]

Method	Dec.	Inc.	MAD (°)	Error (°)
Unsmoothed	137.0	51.2	24.6	5.5
SI method	144.6	49.2	2.0	0.8
Exclusion	145.3	49.9	1.8	0.0

[a]Line fits were calculated over a 15–80 mT range before and after use of the Smoothing-Interpolation (SI) method, and with the use of the full exclusion method. Only the PCA on the unsmoothed data was forced through the origin. The table contains declination, inclination, mean angular deviation (MAD°), and angle made with the direction found using the exclusion method (Error (°)).

demagnetization is run by custom software [*Morris et al*., 2009]. To compare the effects of GRM, we followed the *Dankers and Zijderveld* [1981] procedure and applied the AF sequentially along the y, z, x, y, and then z directions, with measurements of the magnetization after the last three steps.

3.1. Nonpermuted Demagnetization

Most paleomagnetic laboratories do not permute the sample axes in which the AF is applied during a progressive demagnetization. Figure 1a and 1e show results from a nonpermuted demagnetization where we only used one of the three remanence measurements made at each step level. For the example shown in Figure 1a and 1e, the AF was applied sequentially along the y, x, and then z sample axes before remanence was measured for each peak AF step. For this procedure, GRM is not acquired along the z sample axis during demagnetization, and increases along the *x* and *y* sample axes. This causes a deflection of remanence away from the NRM direction and the illusion of a high-coercivity component of magnetization that cannot be removed.

3.2. Permuted Demagnetization

This procedure has the beneficial effect of permuting the direction in which the GRM is acquired with each subsequent AF step level. Therefore, the sum of the acquired GRM during the entire demagnetization approaches zero with increased number of steps used, which minimizes the effect of GRM on the resultant line fits to the NRM components (Table 1 and Figure 2). The more AF steps used in a demagnetization, the more effective the PCA will be in averaging out the oscillatory GRM component. In contrast to the nonpermuted AF routine, the presence of the oscillatory component in a permuted demagnetization can uniquely be identified as GRM. This feature can appear as small high-frequency perturbations to the demagnetization data if the GRM is relatively small, or as the large spiral pattern in Figures 1b and 1f if the GRM is relatively large.

Another benefit of permuted demagnetization is that the mean angular deviation (MAD) can be used as a relative measure of the amount of GRM that is acquired within the AF range in which the line fit was made. The MAD value will only take into account the amount of GRM that is perpendicular to the line fit. This easy evaluation of the GRM for large numbers of samples may help reveal possible relationships with other magnetic variables such as NRM intensity, magnetic anisotropy, remanence direction, coercivity, minerology and ultimately, the underlying physical processes. In addition, the MAD may be used as a gauge of whether the subsequent SI method proposed here is required.

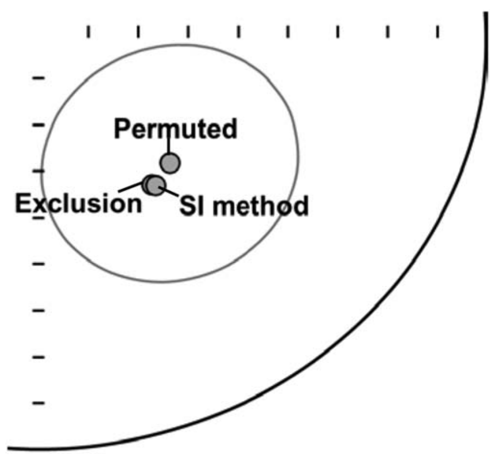

Figure 2. Stereonet plot shows the direction of thermal remanence determined for a welded tuff sample using permuted AF axes, the SI method, and using all the extra measurements required for the exclusion method [*Dankers and Zijderveld*, 1981].

3.3. Smoothing-Interpolation Method

The major advantage of permuted demagnetization is that a subsequent analysis (e.g., SI method) can be used to greatly reduce GRM (Figures 1c, 1f, and 2). The Smoothing-Interpolation (SI) method involves repeated calculation of a three-step running mean for each measured component (*x*, *y*, and *z*) and subsequent restoration of GRM-free measurements (see section 4 below). This method effectively removes the oscillatory GRM component in a progressive three-axis demagnetization with permuted AF axes. Having the option for using the SI method allows for large batches of paleomagnetic samples to be demagnetized without the need for extra measurements. The

SI method could be used to remove GRM if it is shown to be a problem after the measurements have already been made. Furthermore, smoothing demagnetization data with the SI method may dramatically reduce the relatively large effect that even a small oscillatory GRM component may have on partial remanence vectors.

3.4. Exclusion Method

The method of excluding GRM-affected measurements proposed by *Dankers and Zijderveld* [1981] greatly reduces the amount of GRM acquired during the AF demagnetization (see section 1). Results from this method provide the correct answer that we use to evaluate the effectiveness of the SI method (Figures 1c, 1d, 1g, 1h, and 2). Both the exclusion method and SI method rely on the assumption that after application of three orthogonal alternating fields, there will be no GRM along the last AF direction. This assumption is generally true for samples that contain fine-grained magnetite, but may be invalid for samples containing iron sulfides such as greigite [*Hu et al*., 1998].

3.5. How Well Does the SI Method Work?

The remanence directions calculated using PCA on the permuted demagnetization with and without use of the SI method, are .8° and 5.5° from that of the exclusion method, respectively (Table 1 and Figure 2). In this case, the additional use of the SI method was required to successfully remove the GRM effect on the line fit. Measurements made at AF levels below 15 mT were excluded due to a small overprint and the 140 mT step has error from the correction method applied to the last measurement (See Step 4a in section 4.3 below). There is a very small high-coercivity normal overprint (Figures 1g and 1h), so we do not force the PCA through the origin for any line fit except that of the unsmoothed permuted demagnetization. Forcing the line fit through the origin of the unsmoothed permuted demagnetization reduces the unwanted influence of the most GRM-affected high AF steps. Without forcing the line fit through the origin, the direction found through PCA will have considerably more error and is partly dependent on the order of AF axes.

4. Application of the Smoothing-Interpolation Method

4.1. Laboratory Procedure

To create a permuted demagnetization from the full laboratory routine required for the exclusion method (see section 3), we kept only the first measurement from the lowest peak AF step, second measurement from the second peak AF step, third measurement from the third AF step, first measurement from the fourth AF step, second measurement from the fifth AF step, etc. (supporting information). The beginning steps for the typical, much shorter laboratory procedure that would produce permuted demagnetization results are listed below as an example.

1. Measure remanence
2. Apply 5 mT AF along Z, then Y, then X
3. Measure remanence
4. Apply 10 mT AF along X, then Z, then Y
5. Measure remanence
6. Apply 15 mT AF along Y, then X, then Z
7. Measure remanence
8. Apply 20 mT AF along Z, then Y, then X
9. $>$8. Continue permutation at higher fields

4.2. Benefits and Pitfalls of the Three-Step Running Mean

The GRM that is acquired during a demagnetization with permuted axes has a periodic form in each of the three measured components of magnetization (*x*, *y*, and *z*), and which is repetitive in steps of three (Figure 3a). Ideally, the average GRM for any given three-step segment should be close to zero, with one of the three measurements having no GRM (measurement along the last AF direction), and the other two measurements should have GRM components close to equal and opposite of each other [see *Stephenson*, 1993, Figure 3]. Therefore, a simple three-step running mean may be used as a very effective means of removing GRM. Use of the running mean, however, will not perfectly correct GRM-affected measurements, and will have the unwanted effect of altering measurements that are known to be GRM-free. In addition,

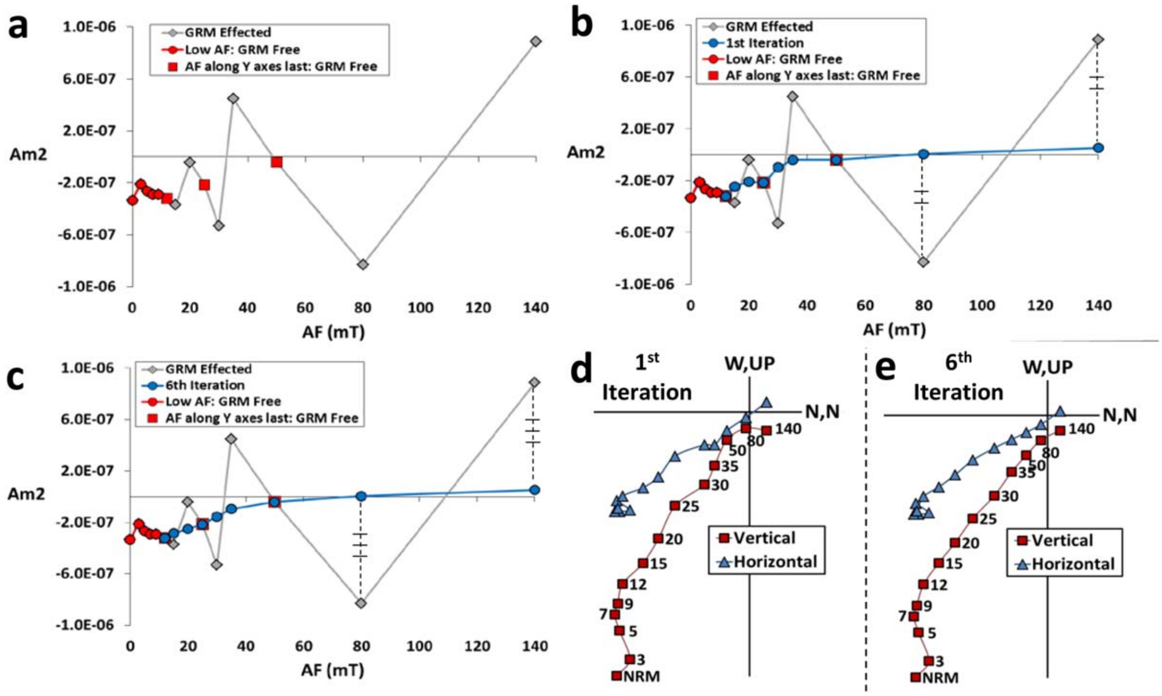

Figure 3. The Y-component of magnetization is shown to demonstrate the SI method (a–c). This method was applied to each axis and the results are shown in zjiderveld plots (d, e). The unsmoothed data are shown in "a" with the GRM-affected and GRM-free measurements indicated. The smoothed results have been added to this plot after one (b) and six (c) iterations of the SI method. The dashed black lines in plots "b" and "c" are of equal length and show one of the suggested methods (step 4a in text) of correcting for GRM in the last measurement. Most of the GRM is removed by one iteration (b, d), but in this case it takes several more iterations before the SI method produces smooth results (c, e).

the running mean will not correct that last measurement of the demagnetization, which is needed for two of the three measured components (i.e., *x*, *y*, *z*).

4.3. Detailed Description of the Smoothing-Interpolation Method

A simple iterative procedure can be used to overcome the pitfalls of the three-step running mean described above in section 4.2. In the description that follows, the term "series" will be used to refer to the component of magnetization being analyzed (i.e., *x*, *y*, or *z*), but it should be known that this analyses needs to be done on all three components.

Step 1: Choose how many measurements from the early steps of the series that should be kept fixed (Figure 3a). Measurements made at peak AF values below which GRM becomes visibly evident should be kept fixed, particularly if they contain a low-coercivity overprint of interest. For the NRM analysis presented here, we fixed all measurements that following AF applications of 9 mT or less (Figure 3a).

Step 2: Take the three-step running mean of the series.

Step 3: Restore all measurements in the series that are known to be GRM-free (e.g., low AF values and any measurement along last AF axis) to the original measured value.

Step 4: Apply a correction to the last measurement that is equal and opposite to the correction made on the previous measurement affected by GRM. The closer the GRM is to saturation over the last three AF steps the better this correction will be (Figures 3b and 3c).

Step 5: Repeat steps 2–4 along each component of magnetization until the oscillatory GRM component has been removed and the demagnetization curve is optimally smoothed (Figures 3c–3e).

5. Demagnetization of a Two-Component Anhysteretic Remanence

To conduct a more rigorous test of the SI method, we demagnetized a sample that had two orthogonal laboratory applied anhysteretic remanences (ARM) of known direction (Figure 4). Using a 0.1 mT direct field (DF), we imparted the high-coercivity ARM in the $+y$ sample direction and lower-coercivity ARM in the $-x$

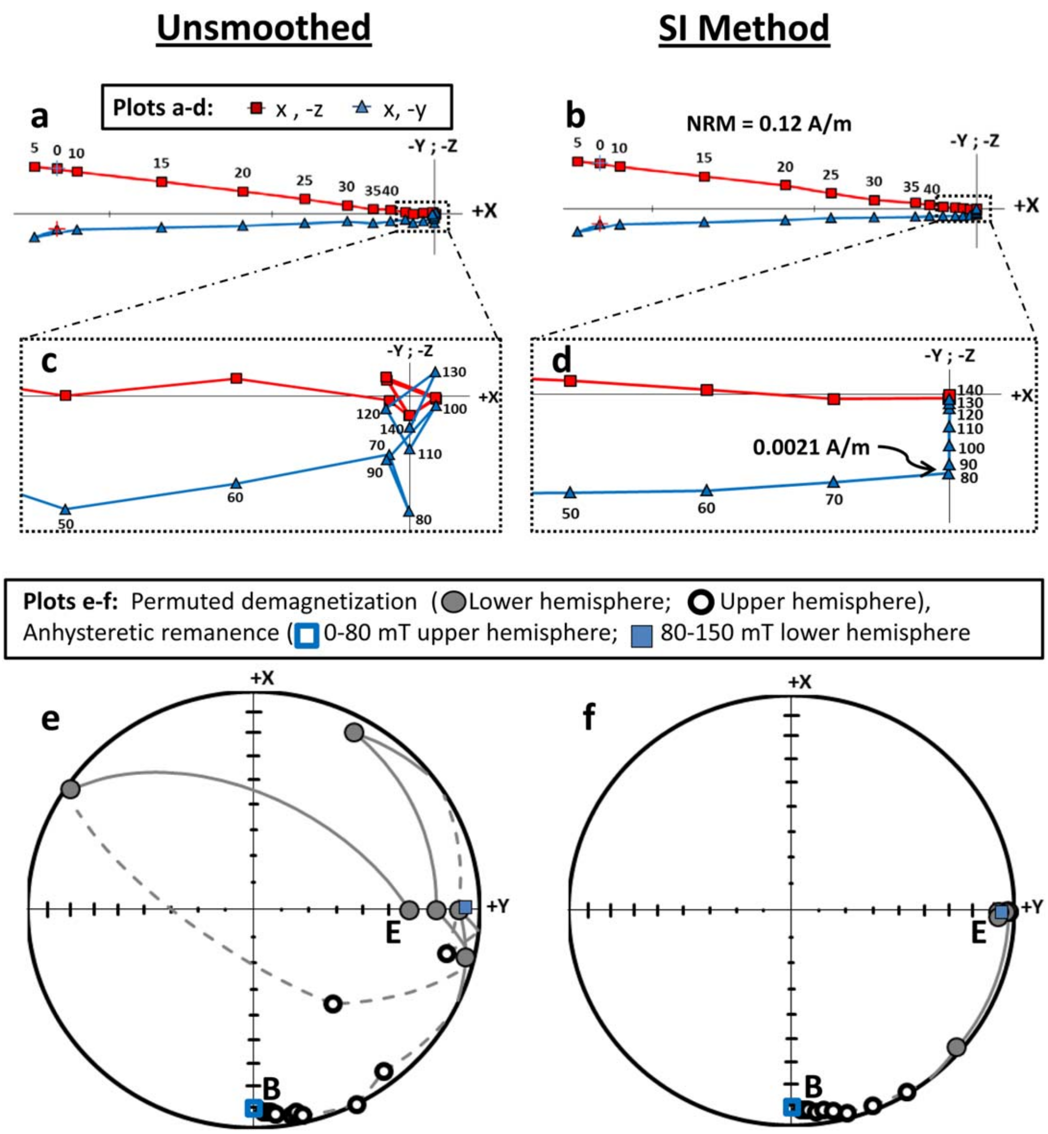

Figure 4. Demagnetization of a two component ARM using permuted AF axes is shown with (b, d, f) and without (a, c, e) using the additional SI method. The ARM is in the *–x* direction from 0 to 80 mT and in the y direction from 80 to 150 mT. The SI method was needed to accurately get the high-coercivity ARM but not the low ARM (Table 2). The ARMs are not perfectly along the axes, which primarily results from a moderate degree of magnetic anisotropy.

direction following the procedure below. The AF values at the peak ramp up, and when the DF turns on and off, are shown with this shorthand with units in mT (peak AF, DF turn on, DF turn off).

1. AF of 160 mT along x, z, and then along y
2. Measure remanence
3. Apply ARM along +y (160, 150, 80)
4. Measure remanence
5. AF of 83 mT along z, y, and then along x
6. Measure remanence
7. Apply ARM along −x (83, 80, 0)
8. Measure remanence

The two remanence measurements before and after the ARM applications have the same hard NRM component that could not be removed and have the same GRM components. Therefore subtraction of the first measurement from the second yields the laboratory applied ARM direction (Table 2). The magnetization

Table 2. Results From Principal Component Analyses on a Three-Axis static AF Demagnetization of a Two Component ARM are Shown for the Unsmoothed and Smoothed (SI Method) Data and Compared to the Known ARM Direction[a]

Method	Dec.	Inc.	MAD (°)	Error (°)
High-coercivity ARM (80–140 mT)				
Known	89.4	4.3		
Unsmoothed	93.8	7.3	18.0	5.3
SI	90.4	3.2	0.7	1.5
Low-coercivity ARM (5–80 mT)				
Known	179.3	−7.9		
Unsmoothed	177.8	−8.2	1.0	1.4
SI	177.7	−8.1	0.7	1.5

[a]The table contains declination, inclination, mean angular deviation (MAD°), and angle made with the known ARM direction (Error(°)). The PCA analyses were calculated over the 5–80 mT and 80–140 mT range.

acquired from application of the higher-coercivity ARM is $\sim$5% of the lower-coercivity ARM. The hard NRM component that could not be demagnetized by a150 mT field was subtracted from each remanence measurement made during the ARM demagnetization. The two ARMs that the sample acquired were not exactly parallel to the applied DF directions. The difference in direction is mainly a result of a moderate degree of magnetic anisotropy, though there are smaller contributions from GRM and other instrumental errors.

Without use of the SI method, the high-coercivity ARM is almost completely masked by the large GRM and cannot be determined (Figures 4a, 4c, and 4e). The change in the direction of the partial remanence vector from the low-coercivity component in the $-x$ direction to the high-coercivity component in the $+y$ direction is unclear. After removing GRM with the SI method, however, the sharp bend connecting the two ARM directions can clearly be seen at the 80 mT AF step, as expected (Figures 4b, 4d, and 4f). The demagnetization of the high-coercivity ARM shows a smooth linear decay toward the origin of the zjiderveld plot. We calculated the line fits for the low and high ARMs with and without using the SI method, and compared these directions to the known ARM directions (Table 2 and Figures 4e and 4f). For this analysis, we used step 4b instead of step 4a from section 4.3 above. The SI method improved the closeness of the line fit to the known high-coercivity ARM direction from 5.3° to 1.5° (Table 2). The additional use of the SI method was not needed for the much stronger low-coercivity ARM, which was only 1.4° from the known direction without any smoothing. Our instrumentation error for applying ARMs is $\sim$1° at best.

6. Final Remarks

1. We recommend permutation of demagnetization axes be implemented as a standard protocol for three-axis static AF demagnetization. This procedure allows for detection and elimination of GRM, when its effects are significant, without the need for the many extra AF and measurement steps required for the method of *Dankers and Zijderveld* [1981]. The SI method demonstrated here on an NRM and a two component ARM, can be used as an optional step to improve the demagnetization results of samples strongly affected by GRM.
2. There are many other potentially effective analyses for removing the GRM from a permuted demagnetization besides the SI method. One method we have found useful is based on singular spectrum analysis [*Vautard et al*., 1992], which yields better results if there is significant non-GRM-related error in the measurements. For most cases, however, the simpler SI method is just as effective.
3. The SI and exclusion methods rely on the assumption that no GRM remains along the last AF axes after three orthogonal AF applications. This assumption, however, has been shown to fail for some greigite bearing samples [*Hu et al*., 1998] and for a troilite-bearing meteorite sample measured in our laboratory (W. Schillinger, et al., Development of a 0.5 T magnetic-core alternating-field demagnetizer, *Geochemistry, Geophysics, Geosystems*, submitted manuscript, 2016). The SI method will still significantly improve the results, though may have a small error from a GRM in the measurements that are kept fixed. A better approach for demagnetizing these types of samples will be a topic of a future paper.
4. *Stephenson* [1993] presented a method for measuring GRM anisotropy shape and orientation using only three demagnetization axes and assuming an anisotropy shape that is one of revolution. Using the assumptions of Stephenson, GRM anisotropy can be estimated from analysis of the GRM obtained using the SI method. This will be the topic of a future paper.
5. An Excel workbook for application of the SI method can be found in supporting information. This workbook will be added to the Demagnetization Analysis in Excel workbook [*Sagnotti*, 2013], which is available by email request to leonardo.sagnotti@ingv.it. This workbook was made using Microsoft Excel 2010

on a PC, and has been tested on Office 365 on a PC and a Mac. The built in macros and plot formatting may not function properly for other versions of Excel.

6. Both the unsmoothed and smoothed data should be made available for any publication that uses the SI method so that the results may be reproduced.

Acknowledgments
Field expenses for this work were covered by the Natural Environment Research Council (NERC) grant NE/G005372/1 awarded to Michael Branney. The salary and school fees for the first author were covered in part by a National Science Foundation (NSF) grant (EAR 1250444) awarded to X. Zhao. Please contact the first author via email at dfinn@ucsc.edu for data requests and other questions. We also would like to thank Andrew Pike for his suggestion and assistance in the use of singular spectral analysis for removing GRM from a permuted demagnetization.

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