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Automated AF-demagnetization on the 2G-Enterprises through-bore, cryogenic magnetometer *

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Abstract

Since the early sixties, alternating field demagnetization (AFD) has been a standard laboratory technique for demagnetizing rocks to expose the multicomponent structure of their natural remanent magnetization (NRM). In the majority of AFD implementations, however, the procedure remains as labour-intensive as ever. The implementation that we have developed at the Australian Geological Survey Organisation, automates the procedure for AFD based on the static method, and results in significant productivity and efficiency gains without compromising data quality. A properly formulated procedure for static AFD may be the only method of retrieving higher-coercivity components of natural remanence in samples prone to developing gyroremanence at higher alternating fields (AFs). Our AFD environment comprises: a 2G-Enterprises through-bore, cryogenic magnetometer; 2G AF-coils and control equipment; and personal computer software, developed by us, to control all procedural aspects for a complete AFD of a sample including, importantly, a counteracting procedure to neutralize the effects of gyroremanence build-up at higher AFs. With our system, AFD of 8 samples/day, each of 20+ steps, requires only 20 min of user attention compared with a full day for conventional systems.

Introduction

The natural remanent magnetization (NRM) of a rock is a palaeomagnetic signature of geological events that have affected it. Since each event can leave a record of its effect as a component of magnetic remanence, it is clear that NRM will generally comprise several components of magnetization, each perhaps acquired at a different period in the rock's history and collectively perhaps representing a primary magnetization and several younger overprint magnetizations. To interpret, from a palaeomagnetic perspective, the geological record of the rock, and to integrate this history with those determined from other methods so as to achieve a deeper understanding, it is evident that we need to access the component composition of the NRM. To do this we have to demagnetize the NRM, and one of the main, widely-used techniques is alternating field demagnetization (AFD; the methods and techniques of palaeomagnetism are detailed in e.g. Collinson 1983, Butler 1992). Since all samples in a palaeomagnetic study require demagnetization, the process can figure prominently in a project and can consume the majority of personnel time devoted to it. Thus, in the current contracting funding environment we have a responsibility to ensure that the demagnetization process is executed as efficiently as possible, by paring to a minimum the amount of personnel time it consumes.

The use of AFD to expose the multicomponent nature of NRM (As & Zijderveld 1958) and graphical methods for the analysis of such data to retrieve the directions of magnetic remanence in rocks (Zijderveld 1967), are some of the early and enduring contributions of Hans Zijderveld and his coworkers of the Dutch palaeomagnetism group to the embryonic development of palaeomagnetism in the late fifties and sixties. Although the advent of computers and the application of techniques such as principal-component

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analysis (PCA) to the study of multicomponent NRM (Kirschvink 1980) have accelerated the procedure for analysing demagnetization datasets, the AFD procedure for generating those datasets commonly remains as labour-intensive now as in those early days (by AFD procedure we mean both the AF treatment of rocks and the measurement of residual remanence).

Our purpose here is to report on our development of a fully-automated, AFD system, based on the static method, that removes the labour-intensive aspect of the AFD procedure, and conducts, unsupervised, progressive demagnetizations of samples and associated remanence measurements to the routine maximum peak field available on our equipment (currently 160 mT), at any number of intermediate AF treatments. We also demonstrate that data quality is not compromised and that the system delivers data quality superior to that from tumbling AFD equipment. Key features of our AFD platform are: i) a redesigned sample-holder system; ii) flexible, in-house-developed, menu-driven data-acquisition and AF-control software; and importantly, iii) a counteracting procedure to neutralize the effects of gyroremanent magnetization (GRM; Stephenson 1980) build-up at higher AF treatments (Zijderveld 1975, Dankers & Zijderveld 1981), without which results from many samples would be irretrievably compromised.

The only requirement of user time on our system is to change the sample at the end of each complete progressive AFD. A 20-step AFD of a sample to 100 mT takes about 3 min of user time and an hour of instrument time. Compared with using a conventional tumbling AFD system, which is generally labour-intensive, for the same task, user-time savings are large. For example, a 20-step AFD of each of 8 samples would consume a day of user time on a tumbling system compared with only 20 min on our automated system, even though instrument time is similar in both cases.

Automated AFD environment

We briefly describe and illustrate in this section the hardware and software components of our AFD system with particular attention to those features that have facilitated automation.

Hardware

The AFD system (Figure 1) is based on a 2G-Enterprises (Mountain View, California, USA) model 760R, 3-axis, through-bore (7.6 cm opening) cryogenic magnetometer (1a = element ‘a’ of Figure 1; principles of operation may be found in e.g. Collinson 1983), with SQUID (Superconducting QUantum Interference Device) magnetic field sensor signal display and processing electronics (1b), and a stepper-motor controller (1c) for translation and rotation of samples in the measurement and AF-coil positions. The AF equipment is 2G-supplied and comprises: i) axial (nominal 300 mT) and transverse (nominal 180 mT) AF-coil sets (1d), each with coaxial DC (direct current) bias (1 mT) coils; ii) AF generation and control electronics (1e); and iii) bias coils supply (1f). Our automated AFD uses the transverse coil set, the set whose axis is orthogonal to the long axis of the magnetometer. All control and measurement software runs on a 486–33 MHz personal computer interfaced to the various control units.

The robust sample-holder unit we have developed is a key element of the system that enables AFD to be conducted with a single AF-coil set rather than with the mixed characteristics of both sets. Aspects of this holder are illustrated in Figure 2. Use of a single AF-coil set is made possible by the incorporation of a 90° flip of the sample (2b and 2c) about an axis orthogonal to the rotation axis of the sample-holder tube. The design also has the important advantages of making measurement coverage of all sample axes (X, Y, Z) equal (±X, ±Y, ±Z), and of distributing measurement of a particular sample axis among the different SQUID channels. The design is based on an original design of Jörgen van den Berg, a former member of Hans Zijderveld’s group. Both cylindrical (2b) and cubic (2c) samples of various sizes are catered for. Flipping is executed by a bi-directional, pneumatically-driven piston (2a), which directly drives a racks-and-pinion assembly (2d) to produce a ’push-pull’ type operation. This assembly is encased in the sample-holder tube and connects to internal fibre-glass rods that end in nylon tensioner line around the sample-gripper cage (2b). Pneumatic flipping is activated electronically by a 2G-installed, flip-channel in the stepper-motor controller unit (1c). The extended-reach, sample-holder tube is supported during translation by a bridge (1g) that is shunted aside as the sample-tube trolley approaches the magnetometer. Checks are made on sample position during translation, at the no-signal and measurement positions, using two optosensors (1h) mounted along the guide rail of the sample-tube trolley. The checks are independent of the stepper-motor controller and warn against loss

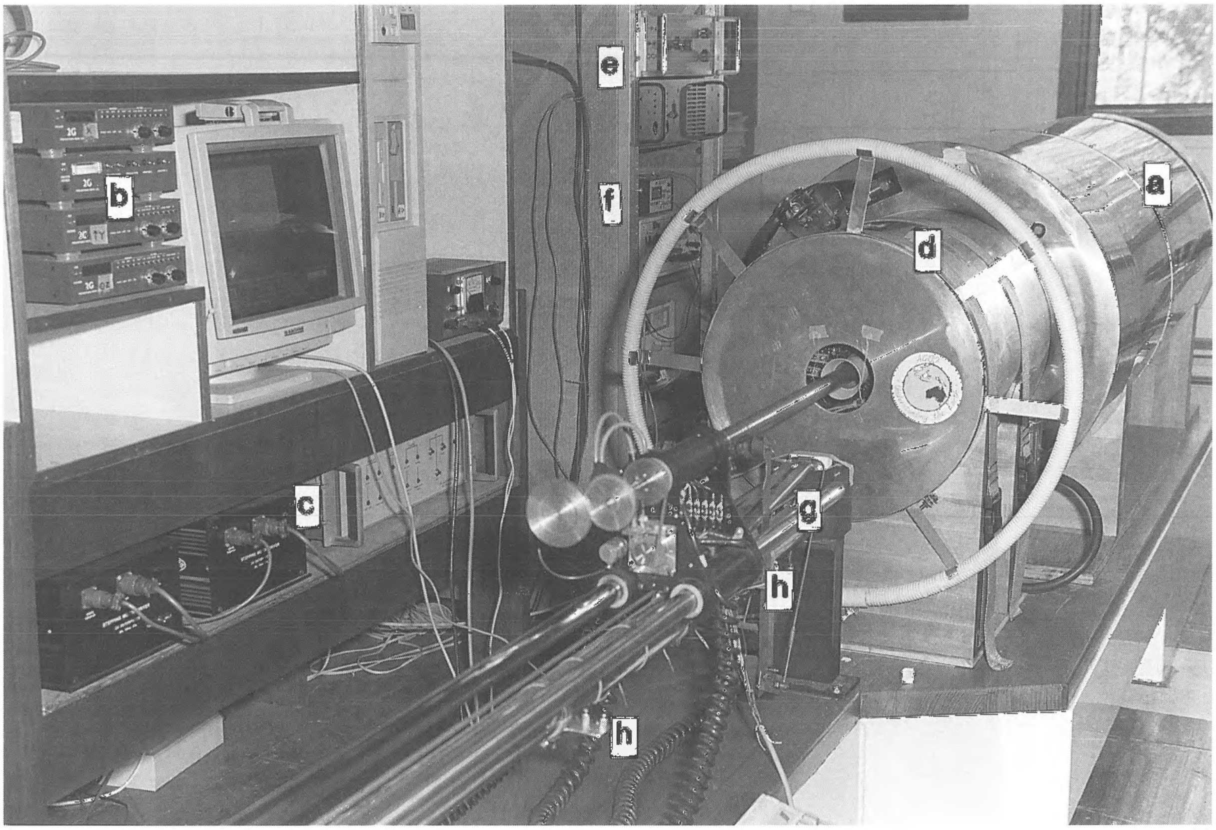

Figure 1. Overview of the automated AFD system. Explanation of tagged elements is given in the text under 'Hardware'. Note the sample-holder support bridge (g) that is pushed aside as the sample-holder trolley approaches the measurement position (trolley close to the end-stop of the guide rails).

of position (unacceptable data quality), resulting from malfunction of the stepper-motor translation system.

Software

A menu-driven, software system, written in FORTRAN77 with some communications modules written in C, running under the Microsoft DOS operating system, drives the AFD equipment. Developed in-house, the software system controls data-acquisition and processing, AFD procedure, and real-time plotting of demagnetization in progress. Key features of the software are its flexibility and a procedure to deal with GRM build-up at higher AFs thereby extending usefulness of the equipment to a broader range of rock types. Flexibility stems from customized forms that quickly initialize the system to a user's own special data-acquisition requirements (e.g. input and output recording and display, check-limits for data quality control etc), and two control files (text format) that direct the procedures for measurement (holder file) and AFD (AF file).

The holder file governs which particular measurement regime is to be used for making a complete measurement of the remanence of a sample, and the AFD equipment, if any, that may be required. Note that no particular sequence of steps is hard-coded into the data-acquisition module to achieve a complete measurement, other than commands that read SQUID values with status checking. Herein lies the flexibility: the module code does not have to be changed and recompiled to introduce a new or updated measurement regime. The holder file may contain several measurement regimes that relate to different holder types or to denser measurement coverages with the same holder. Different or specialized measurement regimes can thus be quickly implemented and existing ones readily changed merely by editing this file with a text editor. The file contains: i) the translations, rotations and flips a sample must undergo to position it for both measure-

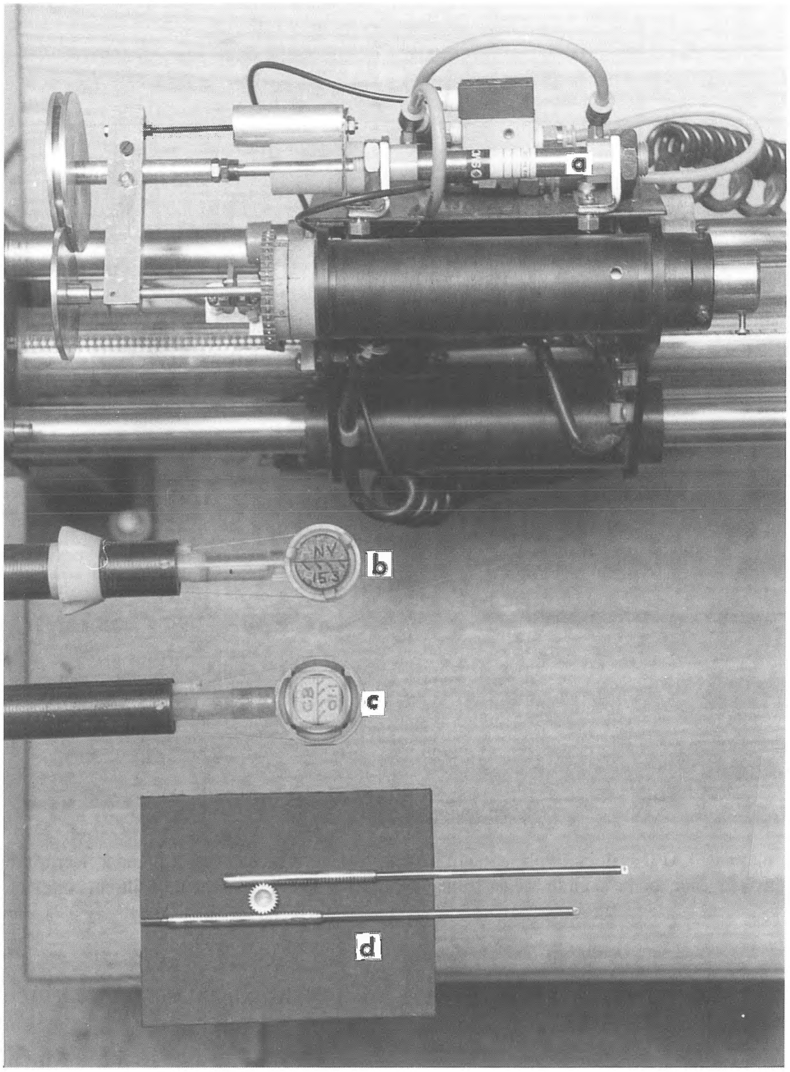

Figure 2. Overview of elements of the 90° flip mechanism installed in the sample-holder; see explanation in the text under 'Hardware'. Note the pneumatically-operated, bi-directional piston (a) which gives a push-pull drive to the racks-and-pinion assembly (d), located in one end of the sample-holder tube, to produce the 90° sample flip shown in (b) and (c).

ment and demagnetization; ii) the matrix of multipliers to be used for transforming SQUID measurements into sample coordinate system measurements; iii) the coil(s) to be used for AFD; and iv) the set of treatment operations to be applied at each peak AF (e.g. treat sample Y, Z first; treat X, Y, Z next etc).

The AF file specifies all parameters required for a complete AFD run on a sample, from the minimum peak AF applied to the maximum attainable. For each of the different peak AFs on file it specifies: i) the rampup-plateau-rampdown timing profile for each treated sample axis; ii) which sample axes are to be treated; iii) whether to skip measurement of residual remanence after certain treatments; iv) how to process the data for each peak AF (next section); v) whether to execute or ignore treatment operations identified in the holder file; and vi) for anhysteretic remanent magnetization (ARM) acquisition experiments, which sample axes and over which AF ranges during AF rampdown, the DC bias coils are to be activated (e.g. on at 70 mT, off at 30 mT) to impart partial ARMs. Once created with a text editor, the file is generally used routinely: skipping and inserting additional treatments during an

AFD run can be done dynamically if the response of a sample to demagnetization demands it.

Gyroremanence (GRM)

Our automated AFD system is based on the static method of AFD. In this method, a sample is demagnetized at a particular peak AF, by exposing each of its three orthogonal axes in turn to an AF which is smoothly ramped up from zero to the peak value, and after a short delay smoothly ramped back to zero, the complete cycle being conducted with the sample shielded from steady external magnetic fields. The static method however, has received only limited acceptance from the palaeomagnetic community as a routine method of demagnetization, because there is a high risk of contaminating results with spurious, coherently-directed components of remanence arising from harmonic distortion of the applied AFs and from the gyromagnetic effect (Stephenson 1993). The sophisticated equipment for alternating magnetic field generation and the very low, ambient steady magnetic field environment of our system rule out harmonic distortion problems. We are left, nevertheless, with the problem of GRM.

GRM manifests itself in those samples which have been demagnetized using a 3-axis, static AFD procedure (treat sample axes X, Y, Z in turn then measure the remanence), and whose magnetic mineralogy is dominated by members of the titanomagnetite and titanomaghemite mineral series. At higher AFs, typically above 30 to 40 mT, a sample will develop a component of magnetization in the plane orthogonal to the axis being treated: demagnetize X, Y then Z and a component develops in the XY plane; demagnetize Z, Y then X and a component develops in the ZY plane. These components have been observed since the early days of the static AFD technique (e.g. Zijderveld 1975; Dankers & Zijderveld 1981). The magnitude of the introduced component increases as the peak AF increases. This is illustrated in the orthogonal plots of 3-axis AFD in Figures 3a and 4a, which show a large component developing in the YZ plane above 30 to 40 mT (the axial sequence of AFD was Y, Z, X in those examples). The magnitude of the effect also seems to be grain-size dependent, being more pronounced for finer magnetic grains (Potter & Stephenson 1986). Clearly from Figures 3a and 4a, without counteracting measures to neutralize the effects of GRM build-up, GRM will seriously contaminate AFD data quality at higher AFs and even obliterate meaningful higher-coercivity components: the advantages and usefulness of automated static AFD systems will be compromised.

The GRM-counteracting procedure we use (e.g. Zijderveld 1975; Dankers & Zijderveld 1981) is based on two observations: i) GRM does not develop along the sample axis being demagnetized (Zijderveld 1975; Stephenson 1981), but only in the plane orthogonal to that axis; and ii) single-axis AFD of a single-component remanence deflects that remanence from its initial direction, to which it returns only after a 3-orthogonal-axis AFD (Stephenson 1983), the so-called 'cyclic' state. The counteracting procedure comprises both treatment and data-processing facets. For the treatment facet, the procedure involves, for a particular peak AF, initial treatment of the sample X, Y, Z axes without measurement of residual remanence, followed by a second treatment of X, Y, Z but with measurement of residual remanence after treatment of each of X, Y and Z (6-axis procedure). The initial treatment serves to place the sample in a 'cyclic' state. Our system is configured (by the holder file) so that each measurement of residual remanence yields a measurement matrix comprising four determinations of each of the X, Y and Z components of magnetization (two each of ±X, of ±Y and of ±Z). For the data-processing facet, the data from the three measurement matrices are processed for a result, freed of contamination by GRM, either by:

i) extracting the X-column data from the first matrix (GRM in YZ plane), Y-column data from the second matrix (GRM in XZ plane), and Z-column data from the third matrix (GRM in XY plane); or by:

ii) averaging all the Xs, all the Ys and all the Zs from all three matrices.

The counteracting procedure using the columns processing method was developed empirically early on (Zijderveld 1975; Dankers & Zijderveld 1981). Both methods have been placed on a more rigorous theoretical basis by Stephenson (1993) and both should return the same result. Our experience however, favours the columns method over the averaging method: averaging still allows residual GRM to contaminate the natural remanence (see 'Results').

Stephenson (1993) regards a 5-axis procedure (e.g. treat Y and Z, then treat X, Y, Z with measurement of remanence after treatment of each of X,Y and Z) as sufficient (so long as the axes are 'cyclic') for neutralizing the effects of GRM rather than a 6-axis procedure. However, within the palaeomagnetic community, it is well-known that repeated AFD along the same axis of a sample, at the same peak AF, progressively reduces the magnetization along that axis to a steady value. The few experiments that we have conducted show that the intensity drop after a second AF treatment can vary between 3 and 12%. Clearly, from a practical perspective, a 5-axis procedure could be open to criticism of biassing the remanence direction: one of the axes is treated only once so that its magnitude, relative to the resultant of the other two axes, will be larger than if had it been treated a second time. Obviously, the amount of bias (magnitude and direction) will vary according to the magnitude of the singly-treated axis magnetization relative to the resultant magnetization of the doubly-treated axes, but simple calculation shows that the effect of the bias is not that significant. For example, assume that X is the singly-treated axis and that a second AF treatment of X causes a 5% reduction (a mid-range, probably common reduction level according to our experiments) in the magnitude of the X component. Directional bias will vary from zero when either all the remanence lies along the X axis (maximum magnitude bias of 5%) or when all the remanence lies in the YZ plane (zero magnitude bias), to a maximum of only 1.5° (magnitude bias of 2.5%) when the remanence is split evenly between the X axis and the YZ plane. For a more extreme 10% reduction, bias doubles to only 3.0° (4.9%). Compared with other errors in palaeomagnetic methodology and the fact that the bias values apply to individual points on a demagnetization trend and not to directions of remanence analysed by PCA from that trend, we see that the values are of little significance to studies dealing with directions rather than magnitudes: time may be the only criterion for choosing between a quicker 5-axis and slower 6-axis procedure.

Our AFD system incorporates such a GRM-counteracting procedure. The choice of whether the procedure is 5-axis or 6-axis is left to the individual: it is merely a question of editing the holder file (~ 1 min) to create the procedure if it is absent, or merely selecting it in the start-up menu if present. The software flexibility introduced with the holder and AF control files ensures: i) that the procedure can be easily switched in or out (reducing to standard 3-axis AFD) dynamically during an AFD run if necessary; ii) that either the columns method or averaging method can be used to process the data at each peak AF treatment; and iii) that the treatment operations applied at a particular peak AF can be made as simple or as complex as required and can be easily changed. Note that no change is required to the program code.

Operation

Once the system is initialized at sign-on time by reading the customized forms and the two control files, the program automatically switches on relevant sample-holder and AF equipment, and positions the sample-holder at the load point. It is then a matter of inserting a sample and starting data-acquisition. An initial untreated measurement of remanence (NRM measurement) is made first, followed by the treatments and measurements of remanence prescribed in the AF control file. At the finish of the treatment stack the sample is returned to the load position and the system awaits the next sample. A 20-step AFD of a sample to 100 mT takes just under 1 hour, while a 23-step AFD to 160 mT, the routine, reasonable limit of our transverse set of AF coils, takes around $1\frac{1}{2}$ hour. The 5-axis or 6-axis AFD procedure for suppressing the effects of GRM build-up routinely switches in at 25 or 30 mT, but dynamically, during an AFD run, can be switched in earlier or later.

AFD can be executed in fully-automatic, semi-automatic or manual mode, switchable at any stage by a keyboard toggle key. Indeed, the AFD mode itself can be toggled off. In this case the AF equipment is automatically shut down and the magnetometer reverts to an instrument for only measuring remanence. In semi-automatic mode, the AF procedure pauses after the current peak AF step result has been displayed so that the user can view the demagnetization progress plot; in fully-automatic mode the plot is merely flashed on the screen. The AF procedure can be interrupted at any stage to change processing parameters. Additional AF steps can be inserted during demagnetization, or existing AF steps can be skipped, depending on demagnetization progress displayed by the real-time plot. The GRM-counteracting procedure can be switched off if the response of the sample shows that it is not prone to the effect. This can readily be estimated from the measurements screen, after the final measurement of remanence for the current AF step (second demagnetization of Z in our case) has been made. The screen shows not only the individual axis data for the current measurement of remanence, but also the results of measurements after the second demagnetizations of the X, Y and Z axes, i.e. measurements not freed of a GRM contribution. The importance of GRM can be readily gauged from the dissimilarity in those three unfreed results. Directional scatter and intensity fluctuations can be large: our experience shows that individual results may have intensities 10 to 15 times larger

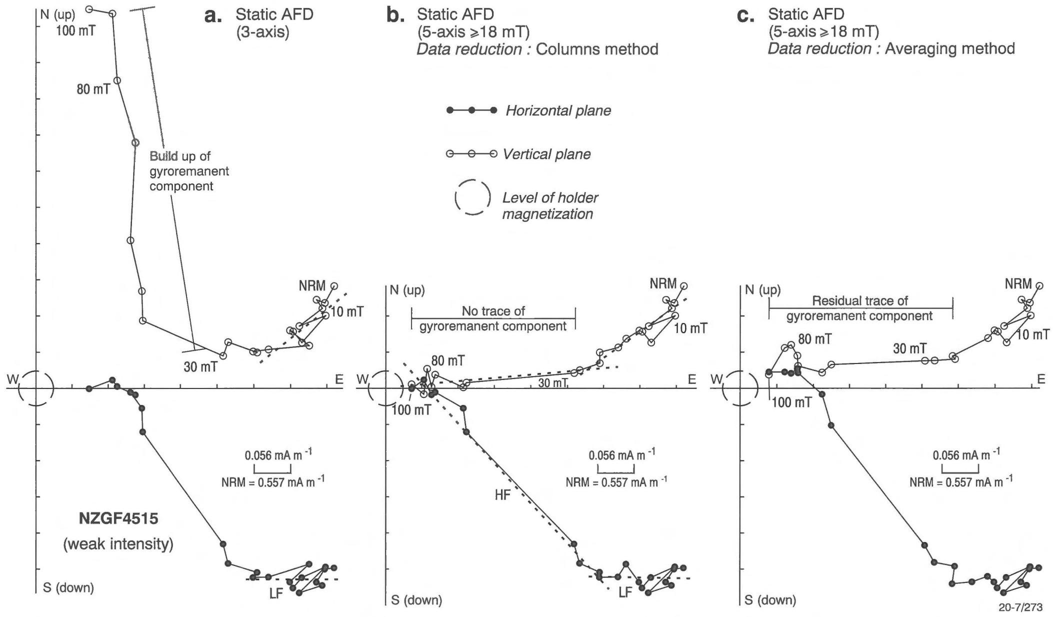

Figure 3. Orthogonal plots of automated, static AFD on a sample of weak magnetic intensity (Pliocene, shallow marine, marly mudstone) showing the success of the GRM-counteracting procedure in neutralizing the effect of GRM build-up. a) Standard 3-axis AFD, without counteracting procedure, showing the increasingly large GRM component developed at higher AFs (> 30 mT) in the ZY plane (upE) orthogonal to the last sample axis, X (N), demagnetized at each peak AF. Although the low-coercivity component of natural remanence (LF) is apparent, the high-coercivity component (HF) is obliterated by the GRM. b) The result obtained with the GRM-counteracting procedure in place (see text under 'Gyroremanence (GRM)') at AFs of 18 mT and higher. The data have been reduced using the columns method. Note that there is no detectable trace of GRM at higher AFs. The natural remanence demagnetizes to the level of holder magnetization to reveal the high-coercivity (HF) component. c) The result from using the averaging method of data reduction to neutralize the GRM effect. Above 30 mT, a trace of GRM still leaks into the natural remanence. We have adopted the columns method: it yields the cleanest result.

than the intensity of the GRM-neutralized result, and directions may differ by many tens of degrees.

Fully-automated operation poses the problem of ensuring that the best quality data is achieved. We address this problem with some inbuilt hardware and software checks. Optosensors on the guide rail of the sample-holder trolley ensure, independently of the stepper motors, that the sample reaches the no-signal and measurement positions. Slew errors trigger a switchable auto-fix procedure (slower sample translation and rotation, and flip of the sample outside the SQUID sensor region, to reduce the rate of change of flux quanta) that remeasures until an error-free result is obtained. Poor measurement statistics, perhaps the result of a baseline jump on one of the SQUID outputs, trigger a switchable auto-remeasure procedure until the statistics pass a user-defined limit set for these parameters. Ultimate failure of any check, perhaps after several attempts, causes the system to pause for user control.

Results

Results obtained to date bear witness to the efficacy of the AFD system to demagnetize cleanly and neutralize spurious magnetization. In the illustrations of results that follow, note that GRM has been counteracted using a 5-axis procedure. As previously pointed out, for studies focussed on directions of remanence rather than magnitudes, there is unlikely to be any significant difference between results obtained from a 5-axis procedure and those obtained from a 6-axis procedure.

Figure 3 illustrates a sample (Pliocene, shallow marine, marly mudstone) that is rather an extreme test: its initial remanence is weak (0.557 mA m^{-1}) and it is prone to acquiring GRM. Figure 3a displays the result of demagnetizing the sample in the absence of a procedure to counteract GRM. It shows dramatically the magnitude of the GRM introduced at higher AFs. Above a peak AF of 30 mT an increasingly large remanence develops in the ZY (upE) plane, mainly along the up-axis, Z, of the sample and orthogonal to the last

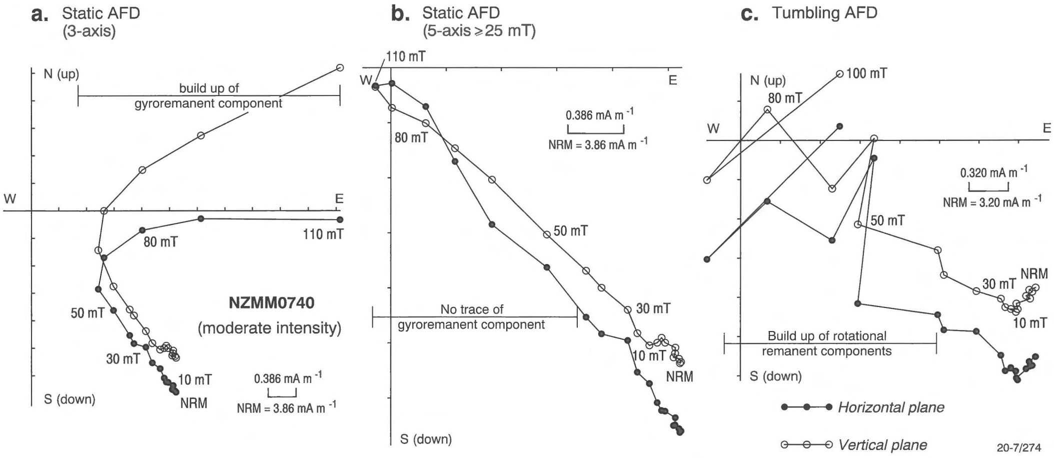

Figure 4. Orthogonal plots of automated, static AFD on a sample of moderate magnetic intensity (Pliocene, shallow marine, marly mudstone) compared with the result obtained from tumbling AFD on a duplicate sample. a) Standard, 3-axis AFD without GRM-counteracting procedure showing the build-up of large GRM in the ZY plane above 40 mT. b) Successful neutralization of the GRM effect with the counteracting procedure in place at AFs of 25 mT and above, and the columns method of data reduction. c) Tumbling AFD result. Note the increasingly large, erratic directional swings above 40 mT as incompletely randomized RRM (a form of GRM) components are induced. A properly formulated static AFD procedure may be the only method to retrieve higher-coercivity components of natural remanence in those samples prone to GRM effects.

axis demagnetized, X (North axis N in Figure 3a), at each peak field. The intensity of the final magnetization, at the highest peak AF of 100 mT, is larger than the untreated NRM. Obviously, all information on components of remanence of geological significance, between 30 mT and the highest peak AF, has been obliterated. The result shown in Figure 3b, was obtained with the GRM-counteracting procedure in place and with data reduction using the columns method. The result speaks for itself: there is no detectable trace of the GRM introduced at higher AFs evident in Figure 3a, and demagnetization of the sample proceeds down to the level of magnetization ($\sim$0.04 mA m^{-1}) of the holder. The result allows us to see the uncontaminated component structure of natural remanence. The high-field component (HF) is now revealed as a SE-directed, low-inclination, upward-pointing magnetization. The low-field component (LF), of course, is evident from either procedure: approximately E-directed with moderate upward inclination. The result shown in Figure 3c was also obtained with the GRM-counteracting procedure in place but using the averaging method of data reduction, and allows us to compare this method with the columns method. It is clear that a residual trace of GRM, particularly at higher AFs, still shows through the natural remanence. This is because the off-diagonal elements of the measurement matrices for each of X, Y and Z, at each peak AF, are not, in practice, completely equal and opposite as theoretically expected (Stephenson 1993). Our experience allows us to conclude that the columns method of data reduction delivers results superior to the averaging method.

Figure 4 illustrates an AFD result for a sample of moderate intensity (3.86 mA m^{-1}, a Pliocene, shallow marine, marly mudstone) and compares it with the result obtained using a tumbling AFD unit on a duplicate sample. Figure 4a shows the standard 3-axis, static AFD result and the build-up of a large GRM component in the ZY (upE) plane above 40 mT (X is the last axis treated at each peak field). Figure 4b shows that this GRM is effectively neutralized with the counteracting procedure in place. Figure 4c shows the tumbling AFD result. Quite clearly, even with a reversible-action tumbler to minimize rotational remanence (RRM, Wilson & Lomax (1972), a magnetization that is a form of GRM (Stephenson 1993)), data at peak AFs above 40 mT are characterized by large directional scatter. This behaviour is not unexpected. If GRM is going to be a problem, then RRM, being of gyromagnetic origin, will also be a problem. The RRM components are induced by rotation of the sample, but rather than being coherently-directed, they will be dispersed (incompletely 'randomized' by tumbling), and manifest themselves as increasingly large scatter in the demagnetization trend at higher AFs. Other testing bears out the superior quality of demagnetization trends that we can obtain from our static AFD system

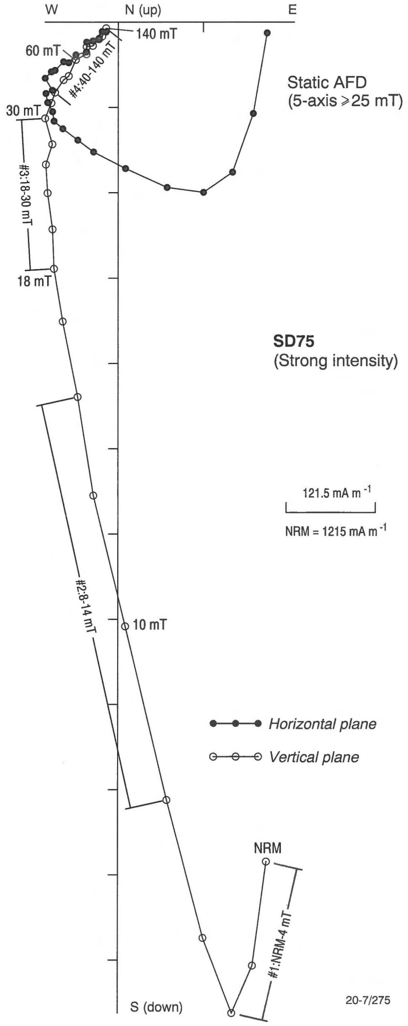

Figure 5. Orthogonal plot of a routinely-executed, automated static AFD of a sample of strong magnetic intensity (Neoproterozoic dolerite dyke), GRM-counteracting procedure in place at AFs of 25 mT and higher. Note the clean demagnetization result revealing four components of remanence labelled according to the coercivity range over which they were isolated. Component #3 is most likely hybrid and caused by the linear composite breakdown of components #2 and #4 over a region in which their coercivities overlap (analytical details in text under 'Results').

compared with what we can get from our tumbling AFD equipment.

Finally, Figure 5 illustrates a typical result for a strongly magnetized sample (1215 mA m^{-1}, a Neoproterozoic dolerite dyke). We see a clean demagnetization to a peak AF of 140 mT, revealing four, well-defined components of remanence which we list in the following format: component number (#), treatment range, declination and inclination of remanence, and maximum angular deviation (MAD) angle and linearity (two PCA parameters defined in Kirschvink (1980) that describe how 'good' the fitted line is; a MAD of 0.0° and linearity of 1.00 describe the perfect fit). The components are: #1, NRM to 4 mT, 13.1°, −51.8°, 6.3°, 0.98; #2, 8–14 mT, 117.6°, 75.7°, 0.9°, 1.00; #3, 18–30 mT, 170.1°, 74.4°, 3.1°, 0.98; and #4, 40–140 mT, 231.2°, 44.1°, 5.4°, 0.91. We note in passing that component #3 is most likely the linear composite breakdown of components #2 and #4 over a coercivity range in which the coercivities of #2 and #4 overlap. Analysis shows that the direction of #3 satisfies the necessary two conditions for its being potentially hybrid. It lies between the directions of #2 and #4, and it is almost coplanar with them (only 3.2° off the plane they define, i.e. the vector triple product $\underline{\#3} \cdot \underline{\#2} \times \underline{\#4}$ evaluates to 86.8°).

Conclusions

We have developed a fully-automated AFD system, based on a 2G-Enterprises through-bore, cryogenic magnetometer (7.6 cm opening), 2G-AF equipment, and the static method of AFD. We have shown that it conducts, unsupervised, progressive demagnetizations of samples and associated remanence measurements to the routine maximum peak field available, at any number of intermediate field treatments, and that it successfully neutralizes the effects of GRM build-up. We have demonstrated that it delivers cleaner, higher-quality demagnetizations than a conventional tumbling system with reversible-action tumbler, and we have further shown that a properly formulated, static AFD procedure may be the only method to retrieve higher-coercivity components of natural remanence in samples prone to GRM effects. The automated system delivers undeniable productivity and efficiency gains compared with conventional AFD systems, which still tend to be labour-intensive, without compromising data quality. Automated AFD of 8 samples/day, each of 20+ steps, requires only 20 min of user attention on our system compared with a full day for conventional systems.

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