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Low-temperature demagnetization isolates stable magnetic vector components in magnetite-bearing diabase

G. J. Borradaile,[1] K. Lucas[1] and R. S. Middleton[2]

[1]*Geology Department, Lakehead University, Thunder Bay,* ON, P7B 5E1, *Canada. E-mail: borradaile@lakeheadu.ca*
[2]*East-West Resources,* 402-905 *West Pender Street, Vancouver,* BC, V6C 1L6, *Canada*

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SUMMARY

It may be difficult to isolate stable palaeomagnetic vectors of different ages if they lie in grain assemblages with overlapping ranges of coercivity or of unblocking temperature. This is because some moments associated with either vector may demagnetize at the same stage of experimental demagnetization. The sharp transition between vector components may be obscured and stable components may appear less linear on the demagnetization plot. Thermal and alternating field (AF) demagnetization techniques remove vector components on a quantitative basis, according to a discrete limiting unblocking temperature or coercivity. Low-temperature demagnetization (LTD) differs in that it removes vector components discretely, wherever there are mobile domain walls. Experiments tested the ability of LTD to improve the effectiveness of AF demagnetization on isothermal and anhysteretic remanent magnetizations (IRM, ARM) in diabase. Multicomponent NRMs were simulated IRMs or ARMs in different, non-overlapping coercivity ranges, along three orthogonal axes or along two non-orthogonal directions. The known directions of the experimentally applied vector components were always more successfully verified by AF demagnetization if LTD was first applied. For the same specimens, LTD reduced the same artificial remanences by ~50 per cent for the coercivity range 0–15 mT, by ~25 per cent for the range 15–30 mT, and negligibly for higher-coercivity fractions. LTD demagnetizes polydomain magnetite as domain walls rearrange on passing through a low-temperature transition, near 120 K.

Key words: coercivity spectrum, drill-core remagnetization, low-temperature demagnetization, magnetite, multicomponent remanence, palaeomagnetism.

1 INTRODUCTION

The goal of most palaeomagnetic investigations is to isolate the orientations of magnetization directions that correspond to ancient geomagnetic fields. Depending on the particular goals of the study, the geomagnetic fields may range from those of archaeological duration, of the order of centuries, to geologically useful ages measured up to billions of years. The principal complications in identifying the geomagnetic field direction arise from the following, almost universal, situations.

First, most rocks preserve more than one geomagnetic field orientation. At the very least, a primary or characteristic magnetization (ChRM) may be obscured by a viscous overprint acquired during the current Brunhes epoch of normal geomagnetic polarity. Second, whether the overprint is viscous and superficial, or ancient and due to a significant remagnetization event, its distinction from any earlier ChRMs, is critical in palaeomagnetism. Unfortunately, traditional laboratory demagnetization techniques may simultaneously remove components of different ages because they reside in grains with overlapping ranges of coercivity or unblocking temperature. Domain structure, in effect grain size, is the most important control on relaxation time in magnetite. Consider a spectrum of grain sizes in which smaller grains retain the older *A* component and larger multidomain grains retain most of the younger moments (Fig. 1a). Some degree of overlap is inevitable in natural grain-size distributions and a small proportion of grains of similar coercivity will retain both moments. Thus, any technique of isotropic demagnetization cannot remove the *B* component exclusively. This problem is attributed principally to overlapping coercivity spectra, and palaeomagnetists have struggled with the issue of how best to define separate vector components from curving (smeared) vector plots, Figs 1(b) and (c) (e.g. Dunlop 1979; Halls 1979; Hoffman & Day 1978). Of course, different demagnetization techniques may remove soft components to differing degrees in different lithologies, depending also on the remanent acquisition process.

Alternating field (AF) demagnetization in the tumbling mode or the three-axis static mode may leave some spurious remanence in a certain direction as a rotational or gyroremanence (R. W. Stephenson 1976; A. Stephenson 1980, 1983). Nevertheless, AF demagnetization, like thermal and chemical treatments, is essentially isotropic in character, reducing the magnetic moment equally in all directions. Historically, the direct-field technique was used to overprint a

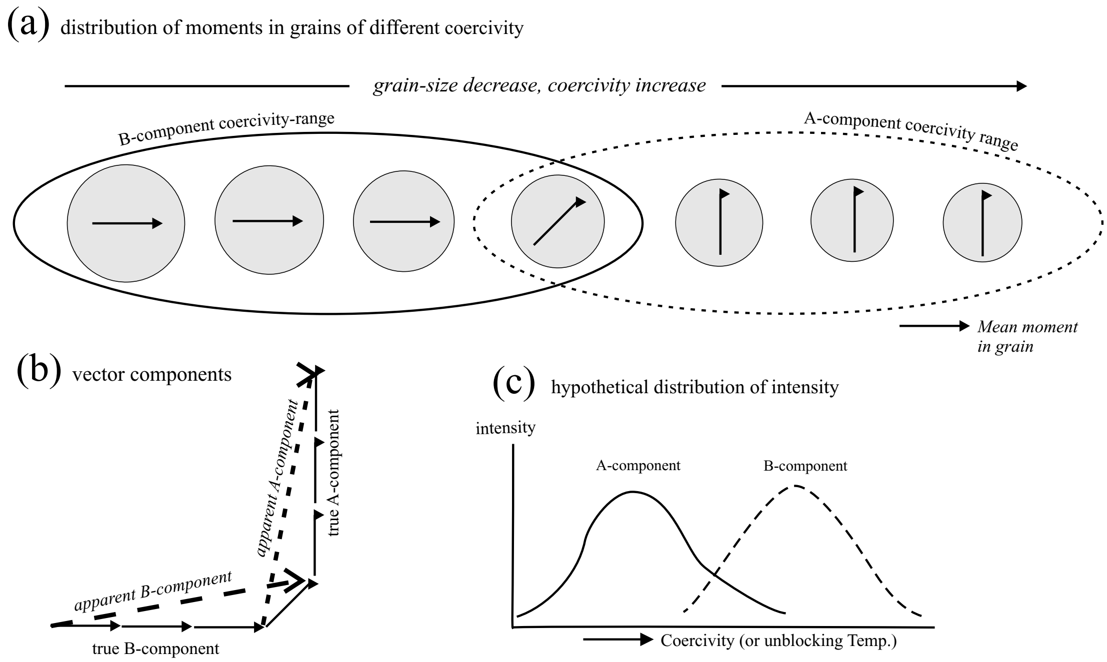

Figure 1. Hypothetical distribution of magnetic moments in grains of different coercivity. (a) Grains with different vector components may have overlapping coercivity ranges. (b) Consequently, it may not be possible to completely isolate the vector components, since some demagnetization steps simultaneously remove both. (c) Corresponding overlap of the distribution of remanence with respect to the coercivity of the grains in which it is found.

magnetic vector of pre-determined or estimated orientation. In theory it provides a method to remove only the vector of a certain direction but in practice, due to errors incurred in attempting to reverse-overprint a magnetization of poorly known direction, it is likely to introduce more problems than it solves. At the present time, we must contend with the isotropic nature of demagnetization techniques and the consequent difficulties that occur when the demagnetization spectra of differently oriented components overlap. (Although our AF demagnetization procedure is applied to static specimens along three successive axes, its net effect is essentially isotropic.)

Since in practice the spectra of relaxation times are unknown, it is best to employ a demagnetization method that to some degree reverses the natural magnetization process. The unblocking temperatures (T_{UB}) determined during thermal demagnetization may produce a spectrum closely related to the acquisition process of a TRM in igneous rocks. However, for the type of experimental investigation we attempt, thermal demagnetization invariably changes the mineralogy and, in that sense, it is too destructive for replicate tests on the same specimens, as required here. Thus, we use AF demagnetization which may be repeated on artificial magnetizations in the same specimen many times, permitting a more thorough investigation of the phenomenon of overlapping coercivity spectra. Of course, our specimens were fully AF cleaned before and between successive experiments.

Since the pioneering palaeomagnetic work of DuBois (1962) on the rocks we study here, most studies used thermal and AF demagnetization to isolate their characteristic *A* component from younger overprints, but thermal demagnetization has generally been preferred for technical and rock-magnetic reasons. We found that thermal demagnetization was not always successful in isolating a stable ChRM. However, we did find a great improvement with the little-used but well-known low-temperature demagnetization technique (LTD). This cycles the specimens down to liquid nitrogen temperature (77 K) and back to room temperature in a magnetically shielded space (Ozima *et al.* 1964; Merrill 1970). Supplementary pre-treatment by LTD or even LTD on its own, produced very stable demagnetization paths for the ChRM on vector plots. We found similar benefits in some other recent studies with rocks bearing multidomain (MD) or pseudo-single-domain (PSD) magnetite (e.g. Borradaile *et al.* 2001; Maher *et al.* 2000). This paper presents our attempts to define the usefulness of LTD as a supplementary demagnetization technique.

The non-destructive nature of AF demagnetization favoured it as a method by which we could perform replicate experiments on the same specimens, comparing treatments without fear that the magnetic mineralogy had changed. We used incremental, three-axis AF demagnetization on static specimens with a Sapphire Instruments AF demagnetizer with a circuit to cancel undesirable asymmetries in the alternating field. Our software includes an alarm for spurious gyroremanence based on the concept of A. Stephenson (1983). We appreciate that AF demagnetization is not entirely non-destructive, in the magnetic sense, since high fields may irreversibly rearrange magnetite domain walls and change susceptibility to a small degree (Potter & Stephenson 1990).

2 THE MATERIAL AND ITS PALAEOMAGNETIC SIGNATURE

The specimens are of a Proterozoic diabase which, despite its age ($\sim$1108 Ma; Davis & Sutcliffe 1985), is a fresh igneous rock. It occurs as sills tens to hundreds of metres thick intruding sub-horizontal Proterozoic sedimentary rocks along the margins of a Proterozoic rift system, in the region of Lake Superior (Davies & Paces 1990; Paces & Miller 1993). The sills are exposed over $\sim$10 000 km^2, mostly comprising medium-grained diabase with plagioclase (An_{75-44}), clinopyroxene ($Wo_{30-40}En_{32-54}Fs_{14-37}$), olivine ($Fo_{70-32}$) with accessory hornblende, biotite, magnetite and ilmenite (Sutcliffe 1987). The palaeomagnetic record is carried by the magnetite, which is typically MD or PSD in its response.

However, the ilmenite contributes significantly to susceptibility in some instances. Palaeomagnetic studies reveal reversed polarity remanences, upward-directed steeply to the southeast. This is traditionally referred to as the Keweenawan geomagnetic field direction (e.g. DuBois 1962), although there is an appreciation that its ubiquitous reporting may be an artefact of the abundance of suitable rocks of a restricted age (e.g. Buchan *et al.* 2000; Green 1983). For example, since DuBois' pioneering work, studies of associated rock formations show that there may have been polarity switches around 1100 Ma (e.g. Halls 1974; Massey 1979; Lewchuk & Symons 1990; Symons 1992).

In some sites, however, ChRMs are poorly defined. For example, two typically disappointing sites show either large confidence cones or no preferred direction at all (Figs 2a and c, respectively).

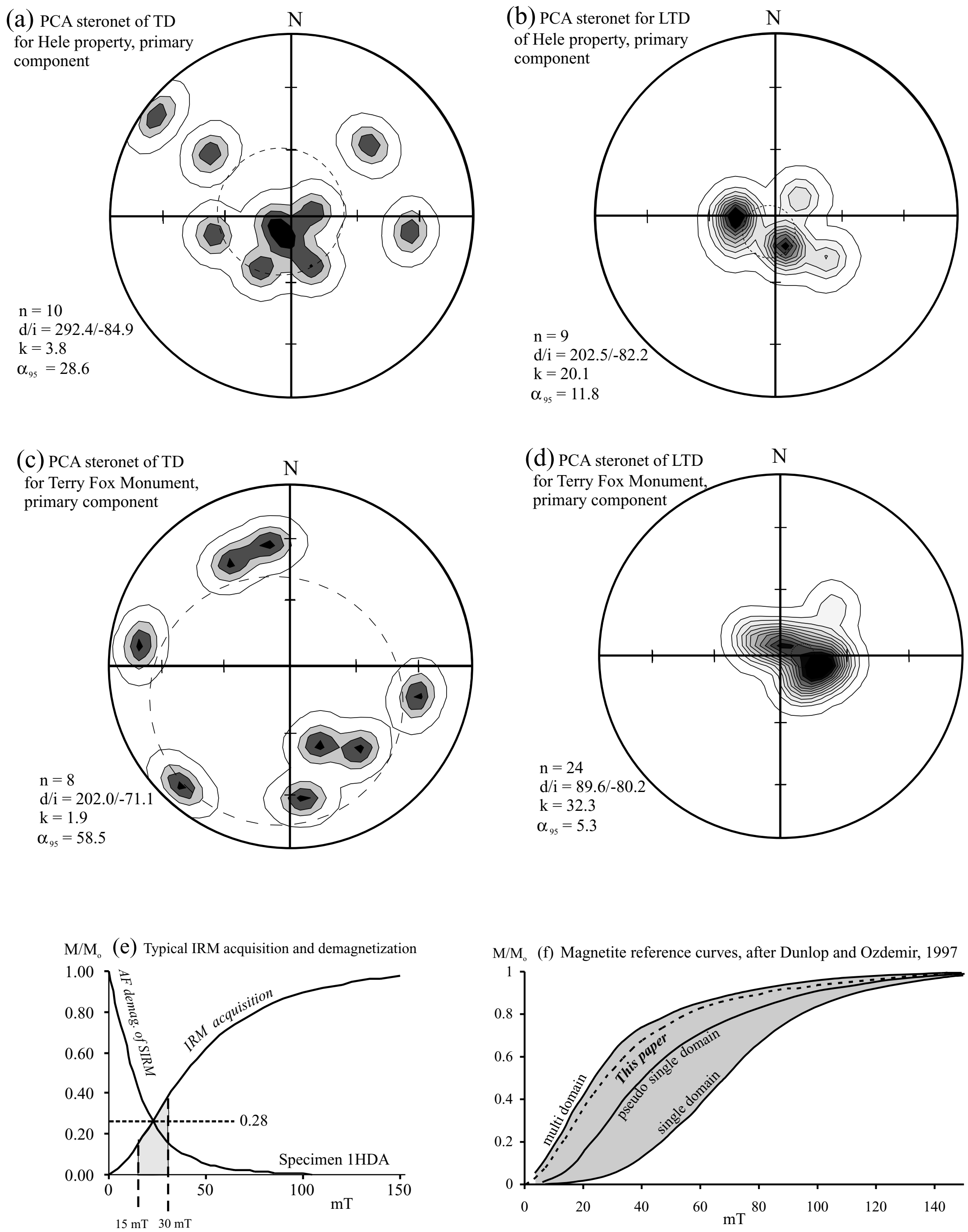

Figure 2. Palaeomagnetic results for the Proterozoic diabase of the Nipigon region, northern Ontario. (a) Hele site: thermal demagnetization poorly defines a characteristic remanence direction. (b) Low-temperature demagnetization of cores from the same specimens defines the characteristic remanence more successfully, almost perfectly identifying the established 'Keweenawan' palaeofield direction. (c) Terry Fox Monument Site: thermal demagnetization fails to identify a characteristic direction. (d) Low-temperature demagnetization of cores from the same specimens is successful. (e) Typical rock magnetic signature of multidomain magnetite with non-interacting behaviour. (f) Progressive acquisition of isothermal remanence may characterize the magnetite domain state.

Suspecting that the primary ChRM of some vector-components was destroyed during the removal of the secondary overprint, we followed the recommendation that LTD may be more effective in preserving the primary ChRM during removal of the secondary overprints (e.g. Dunlop & Özdemir 1997). Applying LTD to other cores from the same oriented hand-specimens produced stable vectors and a well-defined cluster of ChRMs (Figs 2b and d).

LTD requires cooling the specimen below the Verwey transition (∼120 K) and the isotropic point (∼135 K), which is most easily accomplished by immersion in liquid nitrogen (77 K). The specimen is equilibrated at that temperature and allowed to warm back to room temperature in a magnetically shielded space. During a crystallographic transition, domain walls are rearranged, leaving the remaining signal more like that of single-domain (SD) magnetite (Dunlop & Argyle 1991; Dunlop & Özdemir 1997). Five cycles of LTD treatment usually suffice to achieve the optimum demagnetization by this technique (Borradaile 1994a). Subsequent thermal demagnetization produces a more precise grouping of ChRM vectors with a small confidence cone. However, in many of the examples of Proterozoic diabase studied in northern Ontario, LTD alone produced an adequate result, isolating the primary ChRM more effectively than traditional incremental thermal demagnetization (Fig. 2). Since multiple cycles of LTD are more effective than the duration at low temperature, it appears that LTD owes its success to a discrete event, domain wall movement (Merrill 1970). It is most effective in MD grains and several cycles of LTD may usually reduce MD magnetization as effectively as a peak AF demagnetization of ∼15 mT. However, AF demagnetization may affect any grain if the peak field exceeds its coercivity. On the other hand, LTD affects any polydomainal grain by virtue of domain wall mobility (Merrill 1970). For this reason LTD may be beneficial as a supplement to thermal, AF or chemical demagnetization, but it will rarely be a suitable substitute.

Numerous workers have investigated the low-temperature properties of the magnetite and titanomagnetite series of spinels due to their value in palaeomagnetism (Dunlop & Özdemir 1997; Moskowitz *et al.* 1998; Muxworthy & McClelland 2000; Smirnov & Tarduno 2002). In our specimens, remanence is carried by pure magnetite for which pertinent low-temperature behaviour from the literature is shown in Fig. 3. The behaviour of remanence and susceptibility with temperature can be characteristic of composition, usually abbreviated by the subscript value *x*, in $Fe_{(3-x)}Ti_xO_4$ where pure magnetite has $x = 0$ and ocean-floor basalts have $x = 0.6$ ('TM_{60}'). Ilmenite ($FeTiO_3$) does not carry a remanence above ∼55 K, and any proportion of Ti in the magnetite structure suppresses the Curie point. For magnetite, remanences acquired at low temperature are reduced by more than 60 per cent as the specimen warms though the Verwey transition at approximately 120 K T_V; (Verwey 1939). This is true for polydomain as well as equidimensional SD grains. The transition temperature may be reduced by oxidation and masked by Ti substitution (Özdemir *et al.* 1993). Dunlop & Özdemir (1997) argue that the isotropic point T_I, at which the first constant of magnetocrystalline anisotropy takes on a zero value, is a more logical cause of demagnetization upon warming. Its value is ∼135 K, at which point magnetite resumes cubic symmetry from the monoclinic state required below 135 K (Chikazumi 1975; Miyamoto & Chikazumi 1988). However, for practical purposes, any low-temperature transition which reduces remanence between the temperature of liquid nitrogen and room temperature is valuable as a palaeomagnetic procedure to assist in the isolation of a ChRM. (In the case of remanences carried by haematite, solid CO_2 is a convenient medium in which to cool the mineral below its low temperature transition, the Morin transition at ∼258 K; Borradaile 1994a.)

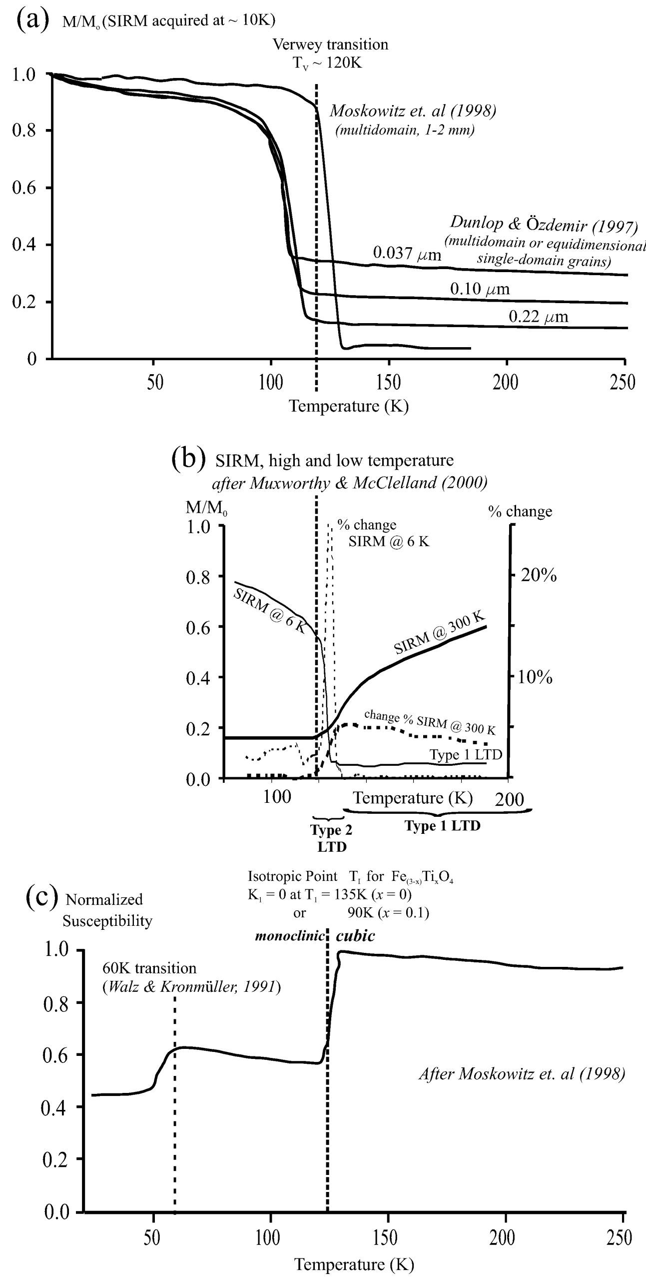

Figure 3. Synopsis of low-temperature behaviour for stoichiometric magnetite from the work of Dunlop & Özdemir (1997), Moskowitz *et al.* (1998) and Muxworthy & McClelland (2000).

To understand the applicability of LTD in palaeomagnetism, it is important to examine its effects on remanences acquired at ambient or high temperatures, although the effects on remanence acquired at low temperatures are decisive in determining transition temperatures (Fig. 3a). Muxworthy & McClelland's (2000) experiments are important in this connection for they reveal two types of LTD in MD magnetite. The authors show that both natural and experimental remanences, acquired at ambient temperatures in natural MD magnetite, mostly demagnetize above T_I and T_V during the cooling towards those transition temperatures (Fig. 3c and Table 1). It is therefore important that specimens are not removed from a

Table 1. Aspects of low-temperature demagnetization (Muxworthy & McClelland 2000) for remanences acquired at ambient temperatures in low field or high field (T_I = isotropic point; T_V = Verwey transition).

	Temp.	Mechanism	Natural, high-stressed grains	Synthetic, low-stressed grains
Type 1	293 K to T_I	Kinematic domain state reorganization domain wall transience*	Low and high field	Low field
	T_I to T_V	Minor magnetostriction, $K_1 \to 0$	Negligible demagn.	Little demagn.
Type 2	T_V to 77 K	Cubic–monoclinic transition	Little demagn.	Low and high field

*McClelland & Suguira (1987); Xu & Merrill (1989).

magnetically shielded space until they have reached room temperature because more than half the remanence intensity may be reacquired on warming from 200 K to 293 K. The proportion of magnetization intensity recovered on warming back from low temperatures appears to depend on the degree of interaction of the magnetite grains, and thus their spacing (e.g. King & Williams 2000). Remanence recovery upon warming may also restore the original remanence directions which King and Williams define as 'true' magnetic memory. This effect was first reported by Ozima *et al.* (1964), and attributed to the restoration of the initial remanence by the distribution of crystal dislocations.

LTD's simplicity, low cost and non-destructive nature recommend it as a precursor to standard thermal or AF demagnetization. Whether it removes AF-soft or AF-hard components, the true memory effect ensures that the reduced intensities preserve any original directions. It has been found useful in archaeological materials (Borradaile *et al.* 2001) and in clarifying unblocking temperatures for high-temperature viscous remanence (Maher *et al.* 2000). However, its benefits for some of our TRM-bearing diabase specimens were greater than we expected.

We investigated the effectiveness of LTD by applying non-destructive, artificial remanences to our specimens of fresh diabase. For simplicity the specimens were exposed to large magnetic fields at room temperature, imparting an isothermal remanent magnetization (IRM), with a Sapphire Instruments pulse magnetizer with a maximum field of 1.2 T, sufficient to saturate the remanence of magnetite. Large fields are sometimes considered to produce a highly concentrated orientation distribution of moments and a less stable remanence than remanences acquired in low fields, such as natural or experimental TRMs. However, this is addressed in the next section.

3 EXPERIMENTAL PROCEDURE TO TEST LTD

To better appreciate how LTD affected grains of different coercivity, we applied a three-component remanence to our specimens, as used by Lowrie (1990). Three different coercivity ranges were magnetized in each of three different, orthogonal directions (Fig. 4). An initial large IRM, sufficient to saturate the sample (1000 mT), provides the basis for the first component (Fig. 4b). Three-axis, AF demagnetization to a peak field of 30 mT randomizes moments in grains with coercivities <30 mT, thus preserving a remanence component in SD and small SD grains (Fig. 4c). Then, an orthogonal magnetization with a pulse field corresponding to 30 mT remagnetized magnetically softer grains. Finally, three-axis AF demagnetization to a peak field of 15 mT, followed by magnetization to 15 mT in a direction perpendicular to the harder components, leaves a vector component isolated in the softest MD grains (Fig. 4d). The coercivity ranges we selected, 0–15 mT, 15–30 mT and <30 mT, correspond approximately to the principal domain-response ranges reported for magnetite (MD, PSD and SD). By associating differently oriented magnetization components with each of these coercivity ranges, it is possible to understand better the effectiveness of different demagnetization treatments on overlapping coercivity spectra. This technique has been used to detect the effects of experimental deformation on remanence since deformation is in effect a demagnetization process (Borradaile 1992), although it may also permit syn-deformation magnetization in the ambient field if the experiment is deliberately unshielded (Borradaile 1994b).

Typical AF demagnetization of a specimen with a synthetic, three-component IRM is shown in Fig. 5 The turning points between vector components are reasonably sharp, since the strong preferred

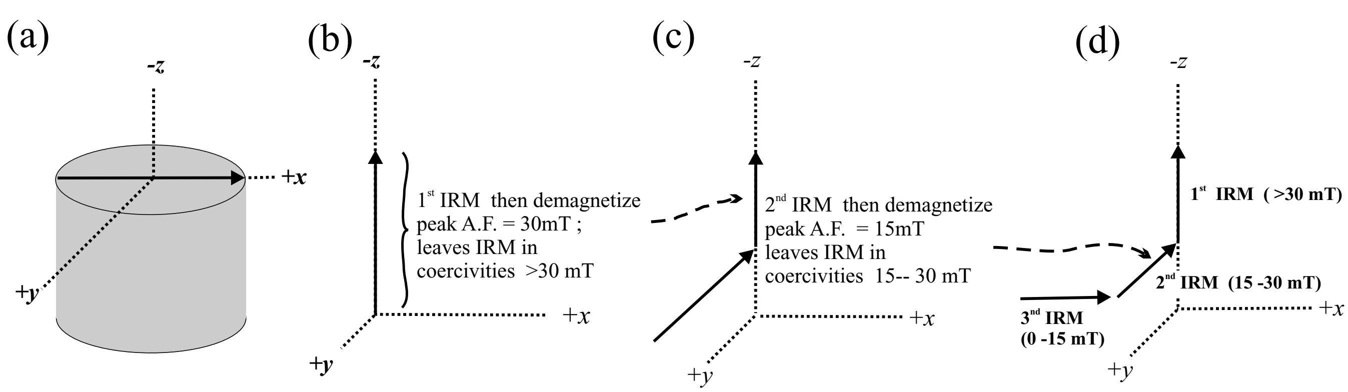

Figure 4. Experimental design used in this paper to apply three differently oriented components of isothermal remanent magnetization (IRM) to different coercivity fractions from a concept by Lowrie (1990). The same principle was used to apply multicomponent anhysteretic remanent magnetization (ARM). The effects of demagnetization may then be distinguished on different coercivity fractions. The coercivity ranges shown correspond broadly to accepted ranges for multidomain magnetite (<15 mT), pseudo-single domain magnetite (15–30 mT) and single domain magnetite (>30 mT).

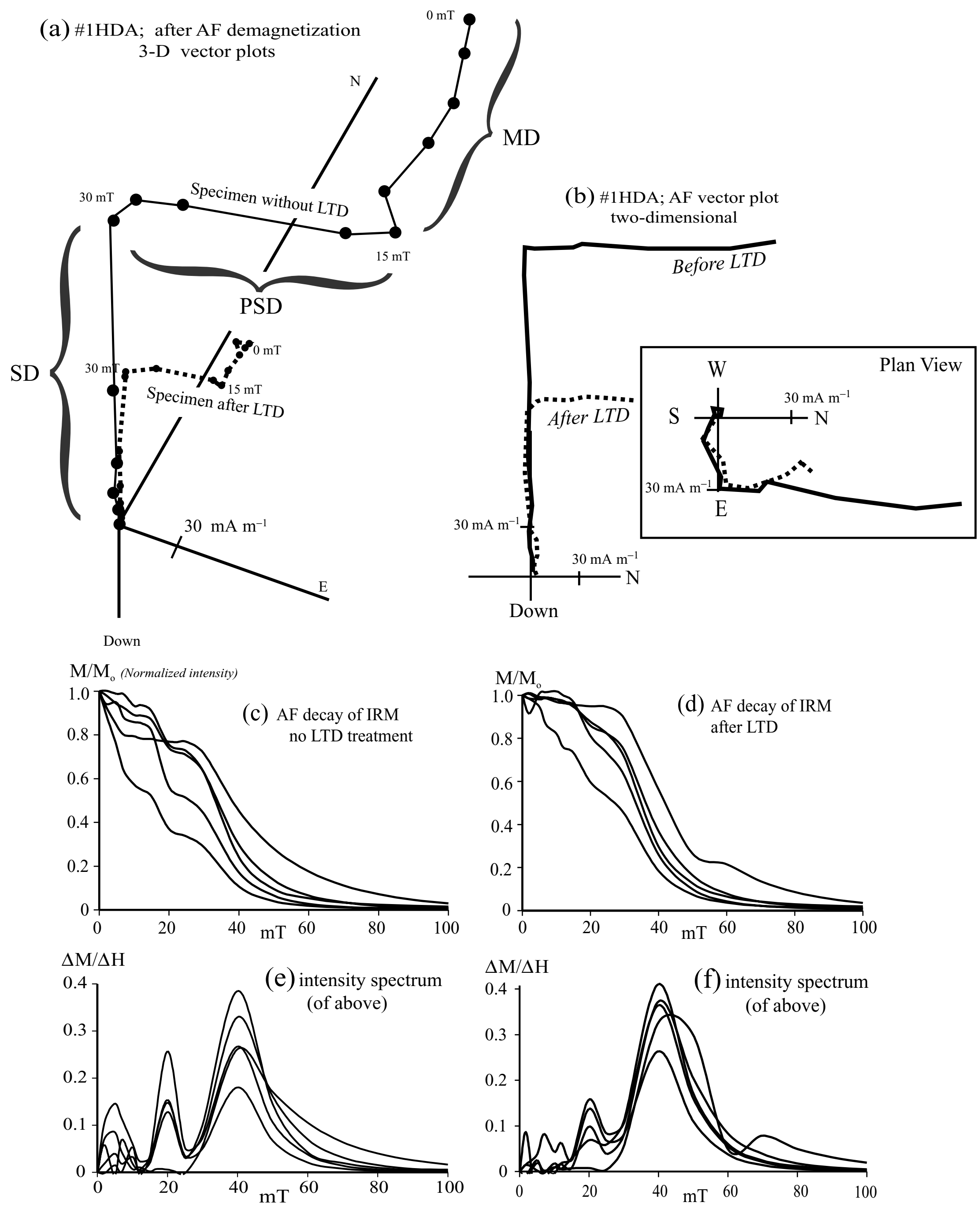

Figure 5. Demagnetization of synthetic three-component IRMs (the same procedure also used for ARMs subsequently). The multicomponent IRM was AF demagnetized, then reapplied and exposed to three cycles of LTD before AF demagnetization was repeated. (a) Incremental AF demagnetization of three-component IRM compared for the same specimen without and with LTD. Note that the vector components are reduced in magnitude approximately inversely proportionally to their upper coercivity limit. (b) Same data shown on a conventional 2-D Zijderveld plot. (c, d) Decay of net intensity during AF demagnetization for the same specimens without LTD and then with LTD. (e, f) Corresponding to the graphs above, rates of change of normalized intensity with respect to field increments, during incremental AF demagnetization.

orientation of IRM moments allows little possibility for overlapping grain coercivities to carry differently oriented IRM components. The same specimen is fully AF-cleaned and then given exactly the same three-component IRM, but subject to three-cycle LTD before AF demagnetization. This permits us to compare the AF demagnetization spectrum of the specimen with and without the effects of LTD.

One feature is clear from all the experiments. The magnitudes of the vector components were reduced in inverse relation to the coercivity range carrying the component (Figs 5c–f). Thus, the component carried by MD grains (0–15 mT) was most reduced by LTD, then PSD (15–30 mT) and finally SD grains (>30 mT) were least affected by LTD. The decay of IRM intensity during three-axis AF demagnetization, in small equal intervals of 1 to 2.5 mT, is shown for

Table 2. Isothermal magnetization intensity ratios from coercivity spectra peaks by AF demagnetization; peak height ratios with LTD to those without LTD treatment.

Specimen	Low H_c	Med. H_c	High H_c
11HC	0.97 ± 0.09	0.47 ± 0.10	1.05 ± 0.07
1HDA	0.11 ± 0.09	1.00 ± 0.10	1.15 ± 0.07
1SRD	0.50 ± 0.09	0.77 ± 0.10	1.12 ± 0.07
2SRC	0.31 ± 0.09	0.62 ± 0.10	1.33 ± 0.07
7HB	0.47 ± 0.09	0.93 ± 0.10	1.44 ± 0.07

specimens without (Fig. 5c) and with (Fig. 5d) the benefit of prior LTD treatment. LTD preserves much more of the normalized remanence in higher-coercivity grains (>30 mT). However, the spectra of coercivity changes shown in Figs 5(e) and (f) reveal the relative effectiveness of LTD on different coercivity fractions. LTD effectively removes most MD-borne remanence in the specimens. The relative magnitudes of the MD, PSD and SD peaks as ratios for treatments with LTD, divided by those without LTD, are presented in Table 2.

The preceding experiments used orthogonal vector components in order to compare the effects of treatments on different coercivity ranges. The known orientation of the experimental vector components and the static nature of the demagnetization along their axes is a luxurious convenience that is impossible in the study of natural remanent magnetizations (NRMs). NRM components are in unknown directions and are rarely orthogonal, so that even static demagnetization may remove parts of different vector components if they are preserved in grains with similar coercivities.

Thus, to simulate a more realistic multicomponent remanence, we applied non-orthogonal components in non-overlapping coercivity ranges. We applied two vector components, one to the MD assemblage ($\leq$10 mT) and the other to harder grains (>10 mT). Where they were separated by 60°, they were readily distinguishable by normal AF demagnetization but even at 45° their discrimination is not easy (Figs 6a and d). Where LTD preceded AF demagnetization, the low-coercivity component is completely eliminated, leaving easily identified ChRMs (Figs 6b and e). LTD completely removed the small low-coercivity peak from the coercivity spectrum, compared with the AF treatment without LTD for the same specimens (Figs 6c and f).

ARM may model NRM better (Jackson 1991; O'Reilly 1984), so it is logical to attempt the same experiments with multiple ARM components, applied over different coercivity windows (Fig. 7). ARMs are sometimes difficult to erase by AF demagnetization, even to the peak AF of ~190 mT available in our Sapphire Instruments SI-4 demagnetizer instrument. Dunlop (personal communication, 2002) and Stacey (1963) attribute this to unbalanced moments that are not cleaned between successive AF polarity switches. This intransigence prevents replicate tests and reuse of the same specimen for different ARM treatments, although it is still useful for demonstrating certain phenomena, particularly the smearing of vector components which is less noticeable with IRMs. It appears that LTD also improves the ability of AF demagnetization to isolate a higher-coercivity, stable component. The ARM components were applied to grains with coercivities in the ranges 0–10 mT and >10 mT, corresponding respectively to MD magnetite and to grains with a

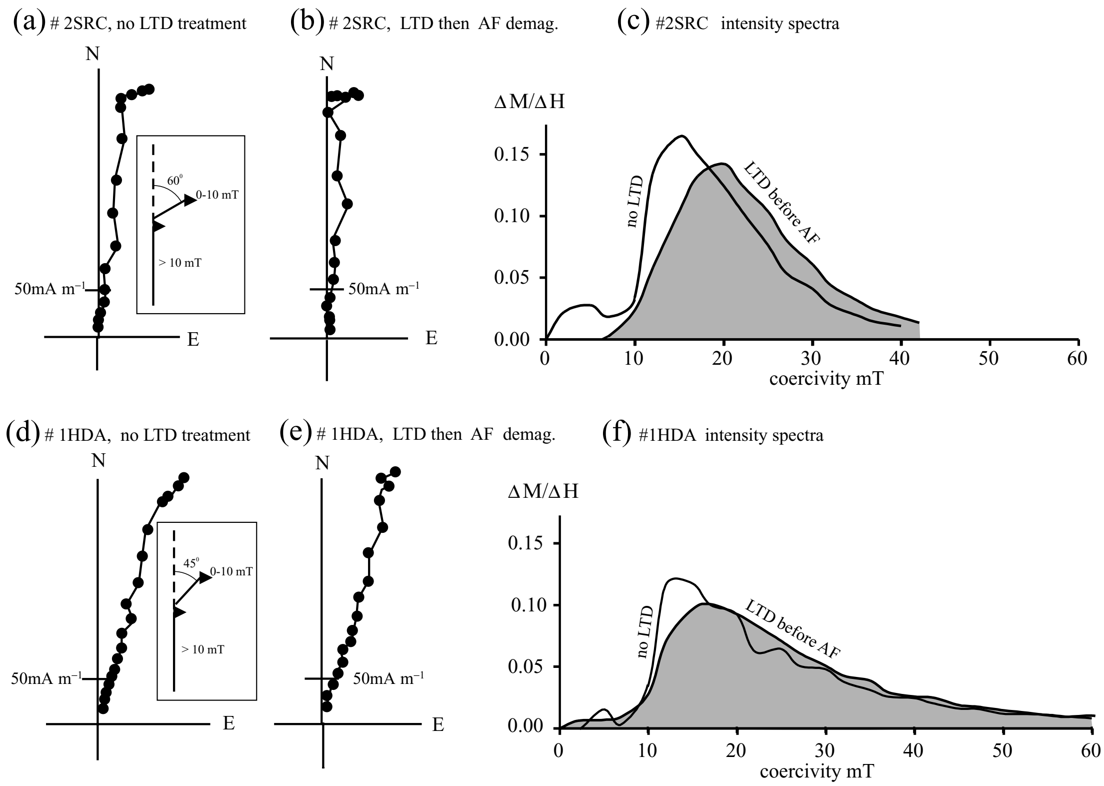

Figure 6. Two-component, non-orthogonal vector components of IRM were imposed on specimens to determine the degree to which LTD improved the isolation of oblique vectors during AF demagnetization. The IRM components were applied at 60°, as shown in the inset, and both components lay in the 'horizontal' plane. (a) AF demagnetization alone detects the two vectors. (b) The specimen is cleaned and the IRM components are reapplied, but now LTD is applied before AF demagnetization. (c) LTD has the effect of shifting remanence to higher-coercivity intervals. The vector plot shows that the soft component was successfully removed by LTD and the more coercive, stable component is isolated clearly by AF. (d–f) A further example in which the two vector components were at 45°.

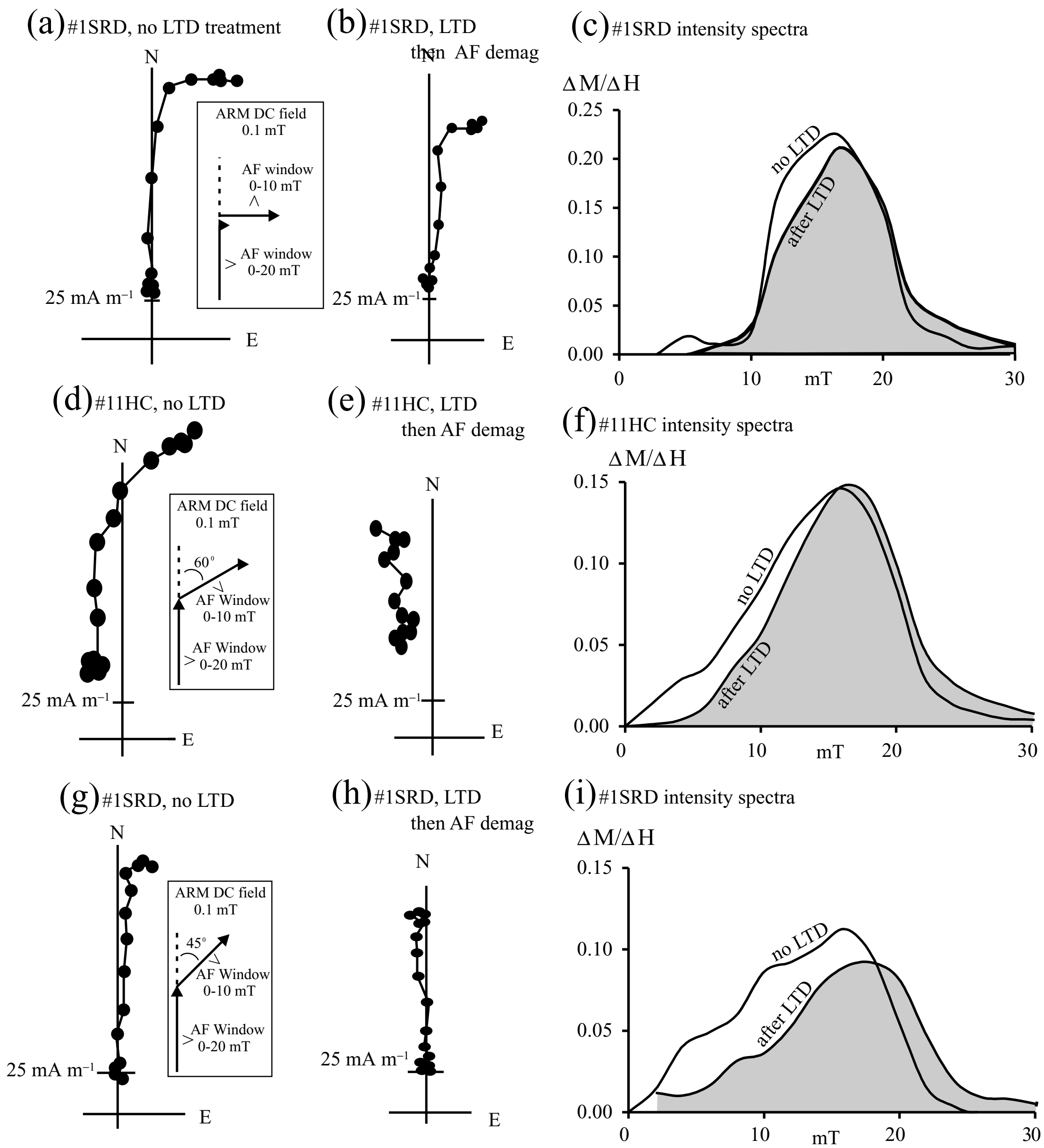

Figure 7. Two-component, non-orthogonal vector components of ARM imposed on specimens to determine the success of LTD in discriminating oblique vectors. Both components lie in the specimens' horizontal planes. (a, d, g) Without LTD, AF demagnetization yields somewhat smeared vector plots. (b, e, h) LTD improves the success with which AF demagnetization isolates the characteristic component, and generally sharpens the turning point between the two components. (c, f, i) In all cases LTD shifts the intensity spectrum to the right.

smaller effective magnetic grain size. Perpendicular and 60° components are readily distinguishable by AF demagnetization alone, although 45° components are not (Figs 7a, d and g). LTD prior to AF demagnetization effectively erases all trace of the component in grains with coercivities <10 mT, except where the components are orthogonal (Figs 7b, e and h). Pre-treatment with LTD moves the intensity spectrum to the right, to higher coercivity ranges (Figs 7c, f and i).

4 MAGNETIZATION AS AN ARTEFACT OF EXPLORATION DRILLING

During the collection of our specimens, some material was retrieved from a vertical exploration drill core to depths >600 m. The spun core lost the original remanence declinations, and down-hole magnetometry failed to determine the NRM of the wall rock. Demagnetization of retrieved cores should at least permit an estimate of the relative orientations of remanence components, with meaningful inclination values. Unfortunately, the drill core was affected by drilling, producing a visible low-grade hydrothermal alteration in places. This alteration penetrated <15 mm in from the walls of the 47 mm diameter exploration core. Using 12 mm diameter subcores, for which our JR5a and Molspin magnetometers are adapted, we were able to analyse the remanences by AF demagnetization, and to investigate cleaned samples by LTD and AF demagnetization of artificial remanences. The effects of drilling-induced remanence are well known (e.g. Jackson & Van der Voo 1985). Two possible causes exist, acting singly or in combination. First, there may be an

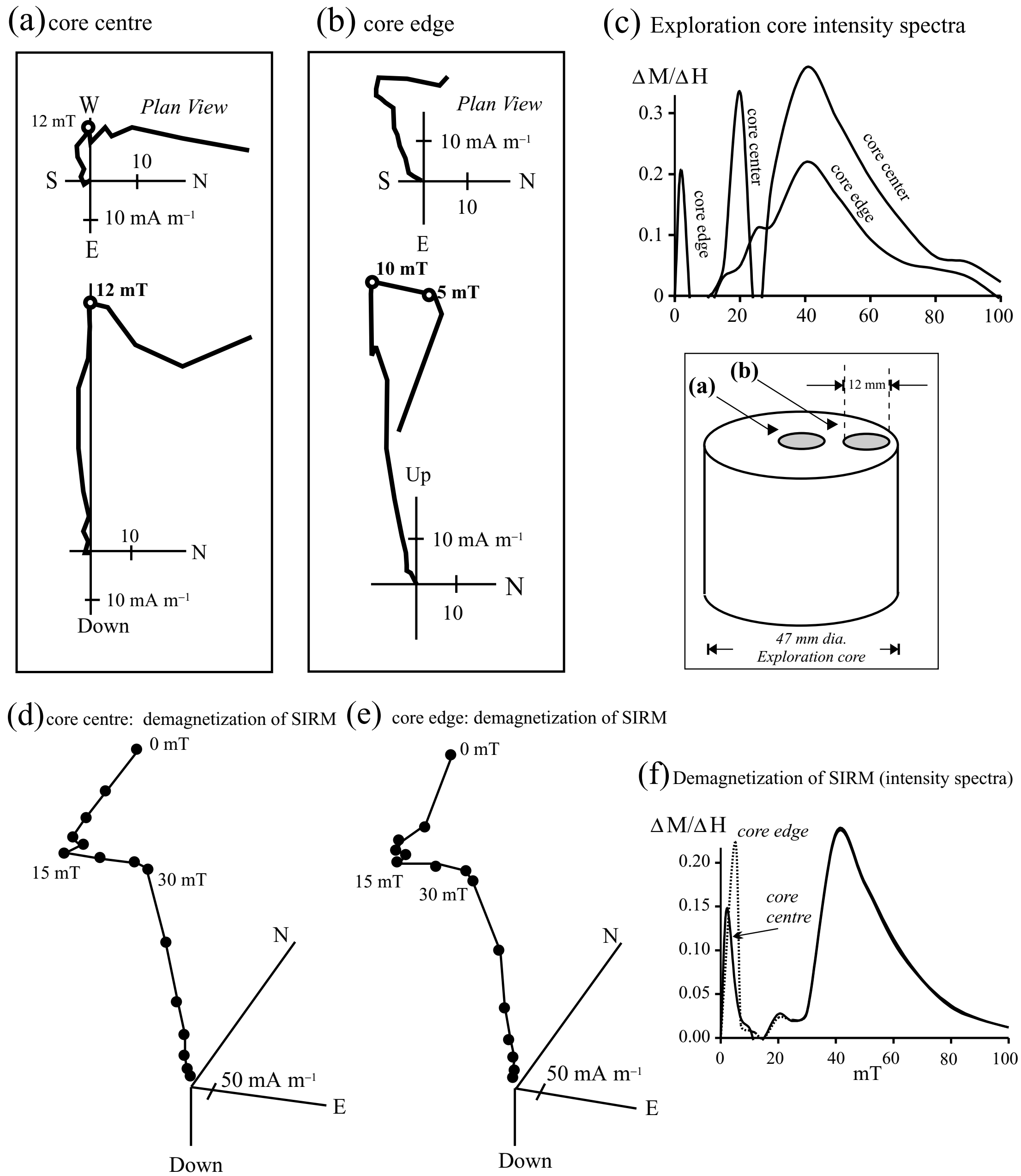

Figure 8. A large-diameter exploration drill core of the diabase was remagnetized during drilling, Incremental thermal and AF demagnetization, and measurements of *in situ* wall-rock magnetization by down-hole magnetometry, revealed strong magnetizations parallel to the drill core axis. (a–c) LTD followed by incremental AF demagnetization was applied to subcores, sampled from near the centre and near the margins of the exploration core. (d–f) The same specimens were cleaned and three-component SIRMs were applied. AF demagnetization reveals that the edge and centre of the core have a similar distribution of coercivity, thus the differences in magnetization are not of a mineralogical nature.

isothermal remanence imparted by a magnetized drill stem. Low-remanence stainless-steel drill stems reduce this effect. A second cause is low-temperature thermoremanent remagnetization due to inadequate cooling during drilling. In that case, the magnetizing field may be the geomagnetic field or that due to the drill stem. Even if the magnetic field is natural, the rotation of core fragments most likely results in steep remagnetization, as in this example.

The surface exposures of the drilled diabase show a consistent reversed primary magnetization, almost antiparallel with the geomagnetic field. Straightforward AF demagnetization does not yield a clear picture of vector components related either to drilling or to the ancient primary remanence. On the other hand, LTD pre-treatment and AF demagnetization reveal distinct vector components. For the least remagnetized, least altered core interior (Fig. 8a) a soft (<5 mT) steep component may be attributable to drilling remagnetization. The harder ChRM (>10 mT) is inclined steeply upwards, as known from surface exposures and other diabase in the region, and is recognized as a Proterozoic magnetization (the Keweenawan palaeofield). The perimeter of the exploration drill core is more heavily altered, sometimes visibly discoloured, and shows more extensive spurious magnetization in soft low-coercivity grains (<12 mT), but the primary upward-seeking remanence is still preserved in the higher-coercivity grain fraction (Fig. 8b). Without LTD pretreatment, the AF demagnetization does not yield such clear vector components, as with studies of NRM in these rocks (Fig. 2). The specimens were subsequently AF demagnetized and a three-axis saturation isothermal remanent magnetization (SIRM) test showed that the interior and the margins of the exploration core have similar distributions of coercivity (Figs 8d–f). Therefore, the differences in magnetization of the drill core are not attributable to significant mineralogical heterogeneity. However, more remanence intensity lies in grains with higher coercivities (>30 mT, Figs 8d and e), compared with the fresh rocks described in the experiments reported above. This is may be due to alteration of haematite or goethite; the exploration drill core is noticeably discoloured, particularly towards its circumference. Although the azimuth of the retrieved exploration core is unknown (compass directions are arbitrary specimen coordinates in Fig. 8), it is worth noting that LTD combined with AF demagnetization isolated a steep, reversed characteristic remanence in the core. That much is compatible with palaeomagnetic studies of fresh surface rocks which show that the Proterozoic magnetization was reversed, steeply up to the south.

5 CONCLUSIONS

LTD does not target magnetic moments for demagnetization strictly on the basis of a threshold demagnetization value, such as coercivity or unblocking temperature. LTD targets any polydomainal magnetite grains, removing the moments residing in low-coercivity fractions due to domain wall movements. In palaeomagnetic studies of a fresh Proterozoic diabase, thermal and alternating field demagnetization sometimes failed to isolate stable palaeomagnetic vector components. However, it was found that three cycles of LTD improved the ability of AF demagnetization (and thermal demagnetization) to isolate stable, geologically sensible, characteristic vector components.

Experiments with demagnetized specimens of the same diabase applied artificial multicomponent remanences to separate coercivity fractions. It was found that LTD reduced remanence intensities most effectively for low-coercivity fractions (<15 mT) associated with large MD grains. For multiple component IRMs, the intensity associated with the low-coercivity component (<15 mT) was halved, whereas remanence intensities associated with high-coercivity (SD) magnetite, >30 mT, were negligibly affected. Experiments with oblique synthetic remanence components showed that LTD improves the ability of AF demagnetization to isolate stable components and sharpen the turning points between them.

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