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Drilling-induced remanent magnetization in basalt drill cores

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SUMMARY

Drilling-induced remanent magnetization (DIRM) in drill cores can limit their use for magnetostratigraphic studies and preclude the use of secondary viscous remanence for their azimuthal orientation. DIRM was studied in a drill core of a thick Miocene basalt flow now buried at 0.45 km. Due to zonation of the magnetic properties within the flow, DIRM was observed in specimens whose remanence is controlled by grains ranging from multidomain (MD) to single domain (SD). DIRM in this drill core has the following properties: (1) it is characterized by high intensity and low stability; (2) the DIRM intensity increases by at least a factor of 5 from the centre of the drill core to the drill string's cutting surface, where it appears to have been produced; (3) it is directed down and radially inward towards the centre of the drill core; and (4) it is relatively more dominant and more intense in magnetically less stable MD grains.

The observed DIRM can be modelled as a pure IRM acquired in a field of the order of 10 mT. Therefore, the DIRM in this drill core is most easily explained as having been produced during the initial drilling by a strong non-uniform field concentrated near the cutting rim of the drill string. Other processes which might contribute to DIRM production include tearing of grains and possible changes in strain, mechanical shocks and piezo remanent magnetization (PRM).

In this drill core, DIRM in the magnetically less stable grains was more effectively cleaned by alternating fields (AF) than by thermal demagnetization, and judicious AF demagnetization was usually successful at defining the primary remanence, especially for specimens from the centre of the drill core, which are less affected by DIRM overprinting. The use of a non-magnetic drill string would further reduce, and might possibly eliminate, DIRM production.

Key words: DIRM, drill core, IRM, PRM, secondary magnetization

1 INTRODUCTION

The use of drill cores for palaeomagnetic studies may be severely limited by the imposition of secondary remanence during drilling. We have studied drilling-induced remanent magnetization (DIRM) in a basalt drill core, and in this paper we report on the magnetic properties of the DIRM and attempt to determine its origin.

Extensive palaeomagnetic studies of Columbia River Basalt (CRB) drill cores in Washington State, USA, indicate that many of the cores have a superimposed steep secondary magnetization, which can dominate the natural remanent magnetization (NRM). This secondary remanence is usually characterized by low coercivity and low blocking temperatures. Van Alstine & Gillett (1981) reported that, in seven of 11 drill cores they studied, the NRM was severely affected by drilling. In our palaeomagnetic investigations of the nearly 60 m thick Roza flow in these drill cores, we had to analyse this secondary magnetization in order to isolate the primary remanence (Audunsson & Levi 1984; in preparation). In this paper we describe this secondary remanence, which, we believe, was produced primarily by the original drilling. In this drill core, alternating field (AF) demagnetization was usually successful at defining the primary remanence in specimens from the centre of the drill core.

The tholeiitic mid-Miocene Roza flow is about 15 Ma, and has an intermediate palaeomagnetic direction, nearly horizontal and to the south (inclination $\approx -5°$ and declination $\approx 189°$). The Roza is underlain by the normal polarity Frenchman Springs flows and overlain by the reverse Priest Rapids units; hence, the Roza probably erupted in the midst of a geomagnetic polarity transition, while the geomagnetic intensity was relatively low.

Palaeomagnetic studies of both sedimentary and volcanic rocks have documented that significant spurious magnetizations can be introduced during drilling or sawing (e.g. Kuster 1969; Rainbow, Fuller & Schmidt 1972; Sallomy & Briden 1975; Ade-Hall & Johnson 1976; Lowrie & Kent 1976; Rice, Hall & Opdyke 1980). However, the origin of this secondary remanence was examined only in a relatively few studies. Burmester (1977), Lauer (1978) and Jackson & Van der Voo (1985) observed that DIRM was produced parallel to the external field during sawing and was concentrated at the cutting surface. Furthermore, Burmester (1977) studying quartz monzonites and Jackson & Van der Voo (1985) working with carbonate rocks inferred that DIRM was primarily caused by stresses in the larger grains, which are more affected by sawing than the smaller grains, but Lauer (1978) who investigated ophiolitic lithologies suggested that the spurious magnetization acquired during drilling might be aided by shocks. Kodama (1984) noted high intensity and steep DIRM in drill cores from granites and concluded that it was similar to isothermal remanent magnetization (IRM), but had an even closer resemblance to piezo remanent magnetization (PRM). McWilliams & Pinto (1988) identified DIRM in a granite drill core, which they associated with higher fields near the tip of the drill string, and Özdemir *et al.* (1988) suggested that high-temperature IRM/VRM might have produced the DIRM they observed in a predominantly granodiorite drill core.

2 SAMPLING

To analyse the DIRM in the Roza drill cores, we sampled drill core DC12 at the Hanford Operations in the Pasco Basin, Washington, USA (46.5°N, 119.5°W). Samples were obtained from three zones within the flow with relative depths of 0.18, 0.46, and 0.81, where the total thickness of the flow is 54 m (i.e. at 9.8, 24.7 and 43.9 m from the flow's top). In this drill core the Roza is buried about 0.45 km below the surface. At each level three horizontal minicores were drilled from a continuous core segment with orientations of 0°, 90° and 180° relative to a vertical scribe-line to monitor for possible azimuthal dependence of DIRM and potential effects from the minicore drilling. The minicores, 63 mm long and 25 mm in diameter, were cut to five 11 mm thick discs, numbered consecutively along the drilling direction, −X in Fig. 1, such that discs 1 and 5 are the ends of the minicores (Fig. 1). The minicores from the top level at depth 0.18 contain relatively more stable magnetic particles, with presumably higher percentage of single domain (SD) and pseudo-SD (PSD) particles; the deeper levels at 0.46 and 0.81 are magnetically less stable with a relatively greater fraction of MD particles (see Fig. 2 and Audunsson & Levi, in preparation).

Two additional minicores at relative depths of 0.15 and 0.75 were used to compare AF and thermal demagnetization of the DIRM in the more stable and less stable parts of the flow, respectively. The discs were prepared as above.

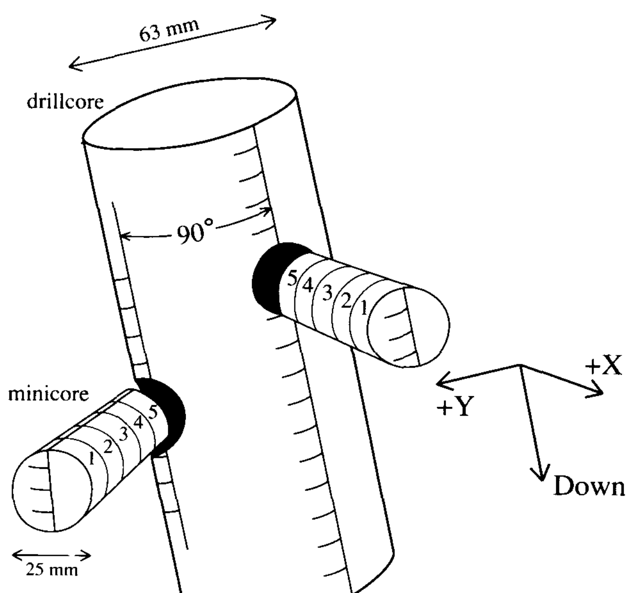

Figure 1. Sampling, orientation and disc labelling conventions for minicores drilled from the drill core.

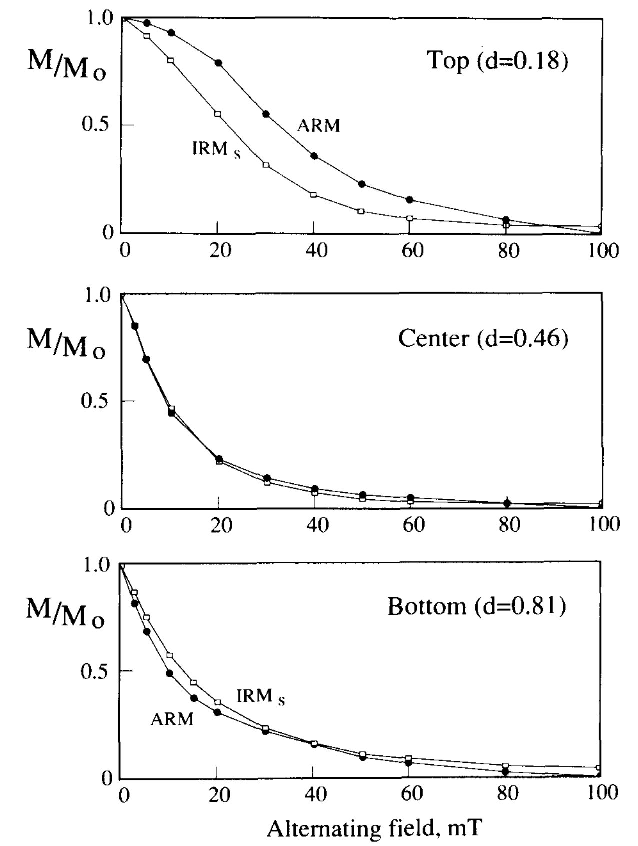

Figure 2. Normalized AF demagnetization of ARM (circles) and IRM_s (squares) of samples from the normalized depth levels at $d = 0.18$, 0.46 and 0.81, which correspond to 9.8, 24.7 and 43.9 m below the flow's top, respectively. The more stable SD/PSD specimens are near the top, and MD behaviour is seen deeper in the flow. IRM_s was produced in an external field of 0.5 T, and ARM was imposed by a 50 μT direct field applied parallel to a decaying AF with peak amplitude of 100 mT.

3 RESULTS

3.1 Magnetic mineralogy

The magnetic minerals of the tholeiitic Roza flow are titanomagnetites (Audunsson & Levi, in preparation). Microprobe analyses at various levels in the flow show bulk composition for $Mag_{1-x}Ulv_x$ with an average $x = 0.58 \pm 0.10$. However, saturation magnetization (M_s) versus temperature experiments often indicate two magnetic phases with Curie temperatures (T_c) between 90 and 580° C; the higher values are mostly from the upper third of the flow. Generally, T_c increase with height in the flow, paralleling the increase in M_s from 0.8 to 3.0 $Am^2\,kg^{-1}$.

Table 1. IRM and ARM properties

scaled depth	IRM H_{ex} (mT)	IRM M (A/m)	IRM MDF (mT)	ARM M (A/m)	ARM MDF (mT)
0.18	2.5	0.68	1.2		
	10.	12.	5.1		
	sat.	1320.	22.0	3.8	32.5
0.46	2.5	4.6	0.9		
	10.	69.	3.5		
	sat.	470.	9.3	3.5	9.0
0.81	2.5	4.3	0.9		
	10.	84.	3.6		
	sat.	500.	13.4	3.8	10.5

T: Tesla; A/m: Ampere/metre; mT: millitesla; μT: microtesla. ARM, anhysteretic remanent magnetization. IRM, isothermal remanent magnetization. *M*, intensity of magnetization. H_{ex}, applied external field. IRM_s was produced in an external field of 0.5 T and ARM was imposed by a 50 μT direct field applied parallel to a decaying AF with peak amplitude of 100 mT.

3.2 Magnetic stability

The flow can be divided roughly in two stability zones. In the top third of the flow the relatively greater stability is caused by smaller SD and PSD particles; the lower stability in the lower two-thirds of the flow is characteristic of MD particles (Audunsson & Levi, in preparation). Lowrie–Fuller magnetic stability tests (Lowrie & Fuller 1971; Johnson, Lowrie & Kent 1975) for one specimen from each of the three levels are shown in Fig. 2. In the top level, AF demagnetization of the low-field anhysteretic remanent magnetization (ARM) is more stable than the saturation isothermal remanent magnetization (IRM_s), which is characteristic of SD and PSD particles. Deeper in the flow lower absolute stabilities to AF demagnetizaion of the ARM and IRM_s and the relatively higher stability of the IRM_s than the ARM (Table 1) are indicative of larger, less stable MD particles (e.g. Dunlop 1983).

3.3 Natural remanent magnetization

Within each minicore the end discs have consistently higher NRM intensity than the inner three; typical ratios are 3.5 and 7.5 for the top and lower two levels, respectively (Table 2a and Fig. 3). The NRM directions of the end discs are also distinct from the inner ones, which are well clustered. The remanence directions (Figs 4 and 5) and intensities (Fig. 3 and Table 2a) of the outer disc pairs (Nos. 1 and 2 and 4 and 5) are systematically correlated. This indicates that, although DIRM is mostly concentrated near the ends, it also influences the interior of the minicores. However, it is not possible to uniquely determine DIRM in the centre discs, because the expected DIRM would have a similar direction

Table 2. Stability of DIRM

(a) AF demagnetization of NRM.

scaled depth	Median demagnetizing field (mT) ends	intermediate	center	NRM intensity (A/m) ends	intermediate	center
0.18	11.4 ±1.4	21.7 ±4.2	25.0 ±1.6	5.6 ±1.7	1.8 ±0.3	1.6 ±0.2
0.46	4.9 ±0.2	4.5 ±0.5	5.9 ±1.7	10.1 ±1.7	1.5 ±0.3	1.3 ±0.3
0.81	5.2 ±0.6	4.8 ±0.6	8.6 ±4.1	8.0 ±2.0	1.3 ±0.2	1.1 ±0.2

Ends: discs nos 1 and 5; intermediate: discs nos 2 and 4; centre: disc no. 3. The average values represent six discs for the end and intermediate positions, and three discs for the centre. The uncertainties are one standard deviation. MDF and M were calculated using the intensity as a scalar sum of the stepwise removed remanences.

(b) Comparison of AF and thermal demagnetization of NRM.

scaled depth	demagne-tization	Median demagnetizing field/temperature end	interior
0.15	AF	9.7 mT	11.3 mT
	thermal	195 °C	181 °C
0.75	AF	3.6 mT	3.2 mT
	thermal	178 °C	183 °C

AF demagnetization: discs nos 1 and 3; thermal demagnetization: discs nos 2 and 5. MDF was calculated using the intensity as a scalar sum of the stepwise removed remanences.

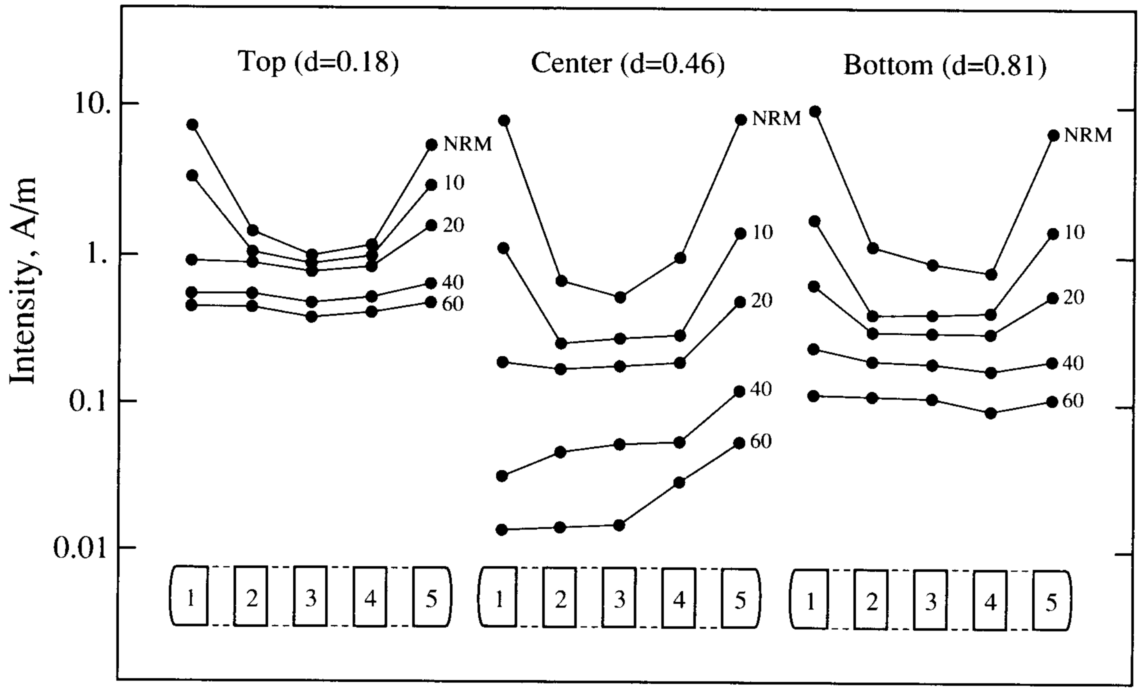

Figure 3. NRM decay during AF demagnetization of discs from minicores at different depths, showing higher intensities and faster decay for the end discs, where the DIRM is most pronounced. Numbers correspond to demagnetization levels in mT.

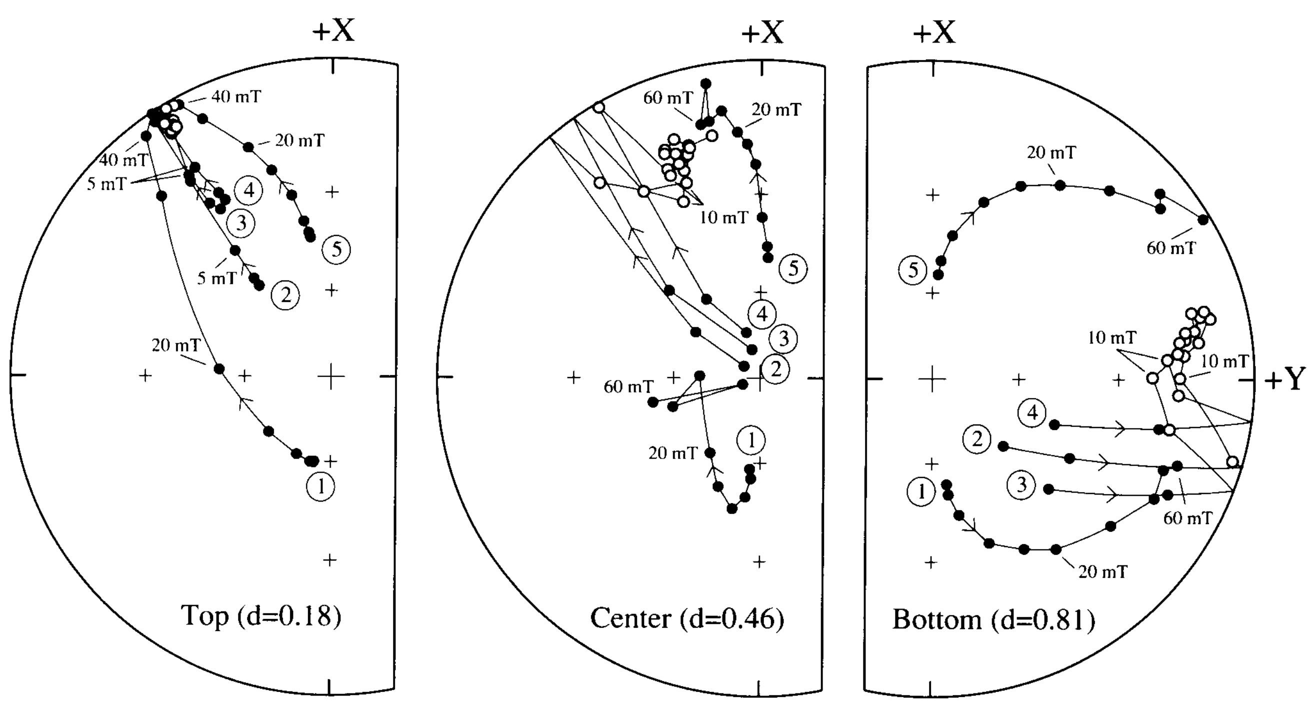

Figure 4. Stereographs showing directional changes upon AF demagnetization of NRM for discs from minicores at different depths (0, 2.5, 5, 10, 15, 20, 30, 40 mT, for discs 2, 3 and 4; and, in addition, 50 and 60 mT for end discs 1 and 5). Closed and open symbols represent remanence vectors which intersect the lower and upper hemisphere, respectively. The crosses mark inclination of 30° and 60°. Note that the minicores are azimuthally unorientated. Circled numbers are the disc designations.

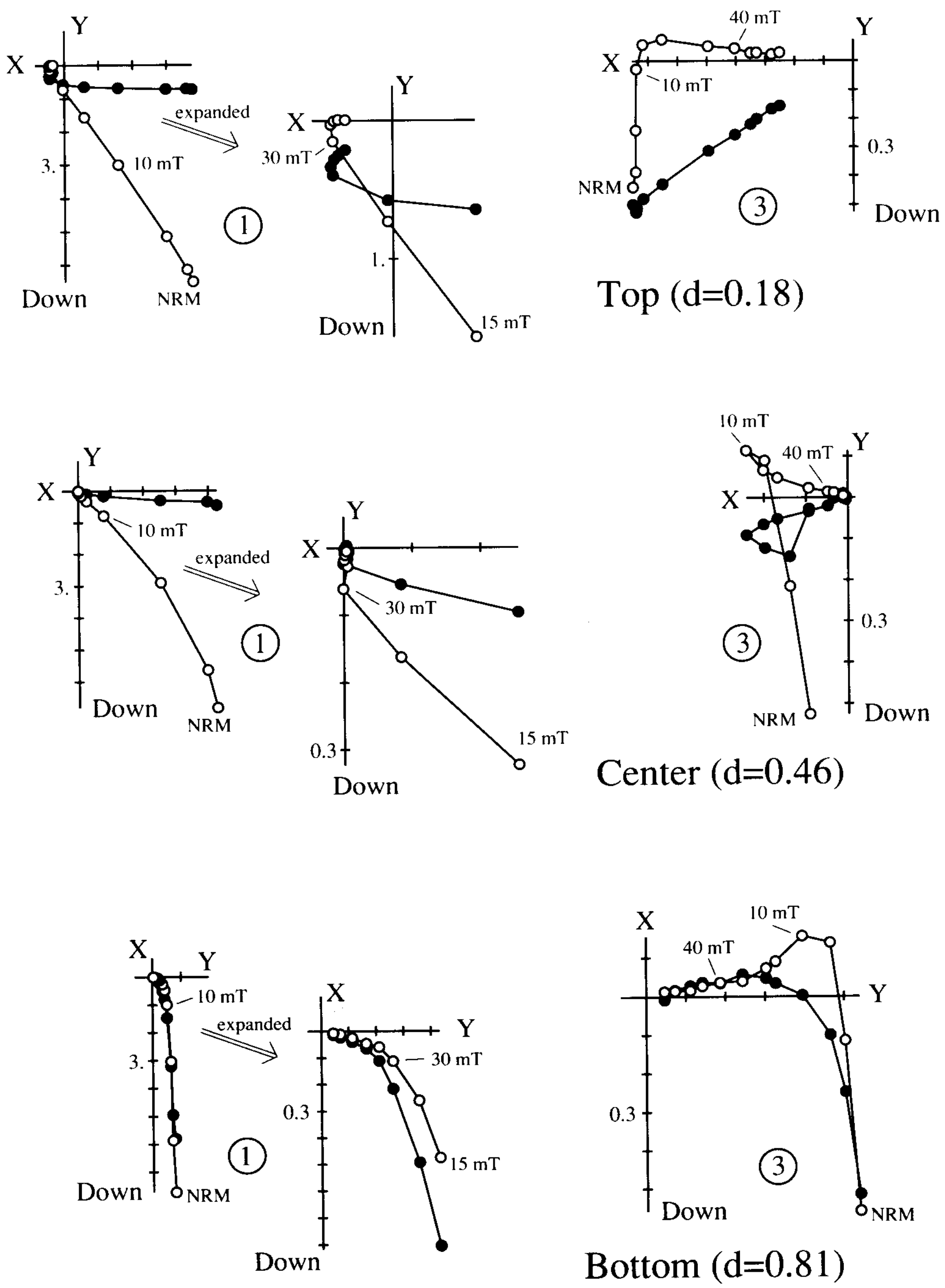

Figure 5. Vector diagrams showing the contrast in NRM decay during AF demagnetization (0, 2.5, 5, 10, 15, 20, 30, 40, 50, 60, 80 and 100 mT) between the end (circled 1) and central (circled 3) discs from different depths. AF demagnetization of the centre discs is successful at isolating the primary remanence, but it is less efficient for the end discs, due to the more dominant, steep DIRM overprinting near the ends. Open and closed symbols represent the remanence in a vertical and the horizontal planes, respectively. Note that for the end discs there is also an expanded vector diagram. The intensity units are A m^{-1}.

as the resultant of the Roza's primary remanence and the overprinting by the present field.

3.4 NRM demagnetization

All discs (total of 45) from the three depths (0.18, 0.46, and 0.81) were stepwise AF demagnetized by a single axis demagnetizer, in progressively increasing fields with steps of 2.5–20 mT up to the maximum field of 100 mT.

Thermal demagnetization in vacuum was done on discs from two minicores (relative depths of 0.15 and 0.75), increasing the temperature in steps of about 50° C. Several discs from these minicores were also AF demagnetized to compare thermal and AF demagnetization.

3.4.1 AF demagnetization

Typical directional changes during AF demagnetization are shown in Figs 4 and 5, for one minicore from each depth level, and the directions of the removed remanence between NRM and 10 mT AF are shown in Fig. 6. At higher AF levels a consistent characteristic direction can be isolated in nearly all discs from each minicore from the top level (see Figs 4 and 5). For the inner discs an alternating field of 10–15 mT appears sufficient to isolate the primary direction, but AF of almost 40 mT are needed to isolate this direction in the end discs (Figs 4 and 5; $d = 0.18$). Deeper in the flow for the magnetically less stable rock, the remanence in the three inner discs typically converges to the same characteristic direction for AF between 10 and 20 mT. The end discs approach the primary direction from distinctly different starting points but they do not always reach the stable end point (see Figs 4 and 5; $d = 0.46$ and 0.81), and for AF exceeding approximately 60 mT the directions become unstable, and the results are not shown in Fig. 4.

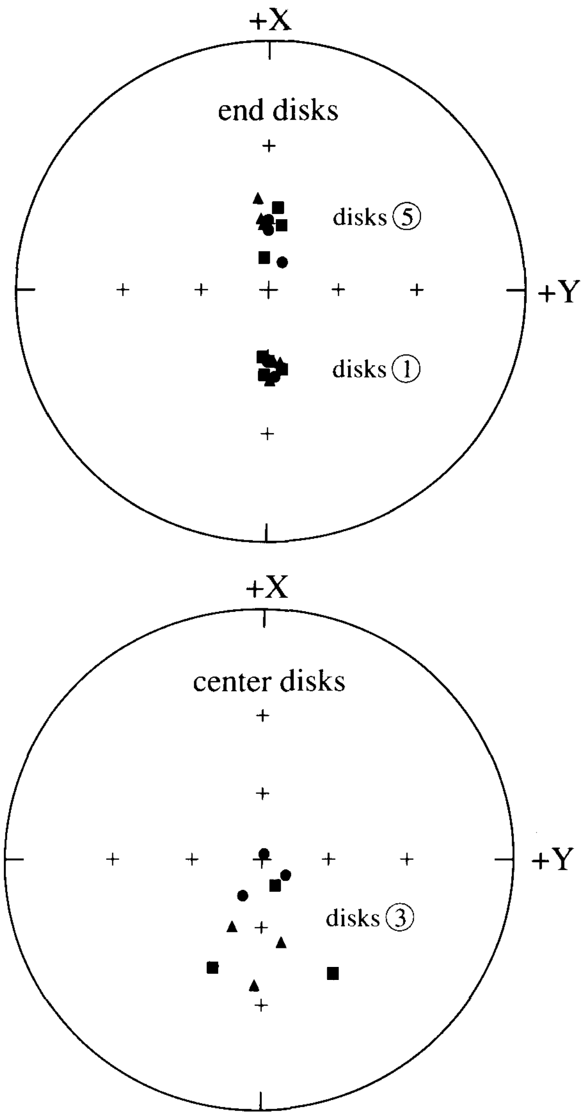

Figure 6. Stereographs showing the grouping of directions of the soft remanence removed with AF demagnetization between NRM and 10 mT. Circles, top ($d = 0.18$); squares, centre ($d = 0.46$); and triangles, bottom ($d = 0.81$). Symbol convention is as in Fig. 4.

For AF levels greater than about 20 mT, the remanence intensity becomes uniform throughout each minicore (see Fig. 3).

The decay of the remanence intensity with increasing AF is shown in Fig. 3, with higher NRM intensities and lower stabilities at the ends of the minicores. In the end discs, the directions of the softer remanence removed between NRM and 10 mT appear in two well-defined groups (Fig. 6). Both groups have the same inclination of about +60°, but the declinations of discs 1 and 5 are separated by approximately 180°. This soft remanence is directed down and radially inwards towards the centre of the minicore. The corresponding removed remanence in the centre discs is mostly down. However, the declinations of the least stable component (≤10 mT) of the removed remanence of the interior discs are biased and cluster near 180°, measured relative to the orientation of the minicores (Fig. 6), that is, parallel to the −X drilling direction of the minicores. The cause for this bias is not clear at present but it cannot be due to *in situ* viscous overprinting in the present field, because the same direction was observed for minicores drilled in three mutually perpendicular directions. Viscous overprinting in the laboratory might be the cause, provided all the specimens were stored in the same orientation. However, sample orientations in the laboratory were not monitored. Alternatively, the observed bias might have been produced during vertical drilling of the minicores in the presence of the predominantly downward ambient field. This would constitute a 'secondary' DIRM. The remanence responsible for the 180° declination bias in the interior discs is soft and does not persist beyond 10 mT AF demagnetization, and is not sufficient to significantly influence the end discs, which were mostly affected by the 'primary' DIRM, due to the drill-core coring, as was discussed in the previous paragraph.

The end discs usually have lower NRM stability, as measured by the median demagnetizing fields (MDF), than the inner ones. In the top level, the average MDF for the end discs is 11 mT versus 25 mT for the centre discs and 5 versus 8 mT deeper in the flow (see Table 2a).

3.4.2 Thermal versus AF demagnetization

Directional changes in two minicores during thermal and AF demagnetizations are shown in Fig. 7, and the stabilities are compared in Table 2(b). For the SD/PSD remanence at the 0.15 depth level AF and thermal demagnetizations are comparable at 'cleaning' the NRM directions, but for the MD specimens at the 0.75 level, thermal demagnetization is considerably less effective than AF demagnetization for isolating the primary remanence. In our investigations of Roza in DC12, thermal demagnetization 'cleans' the directions only after heating to about 400 °C for the end disc of the upper level and centre and end discs in the lower level. However, the directions in the deeper minicore ($d = 0.75$) become unstable near 450° C. The median demagnetizing temperatures (MDT) are approximately equal for the end and centre discs, and are relatively insensitive to the intrinsic stability of the specimens with a range from 178 to 195 °C (Table 2b).

This comparison between AF and thermal demagnetization shows that for Roza in drill core DC12, AF

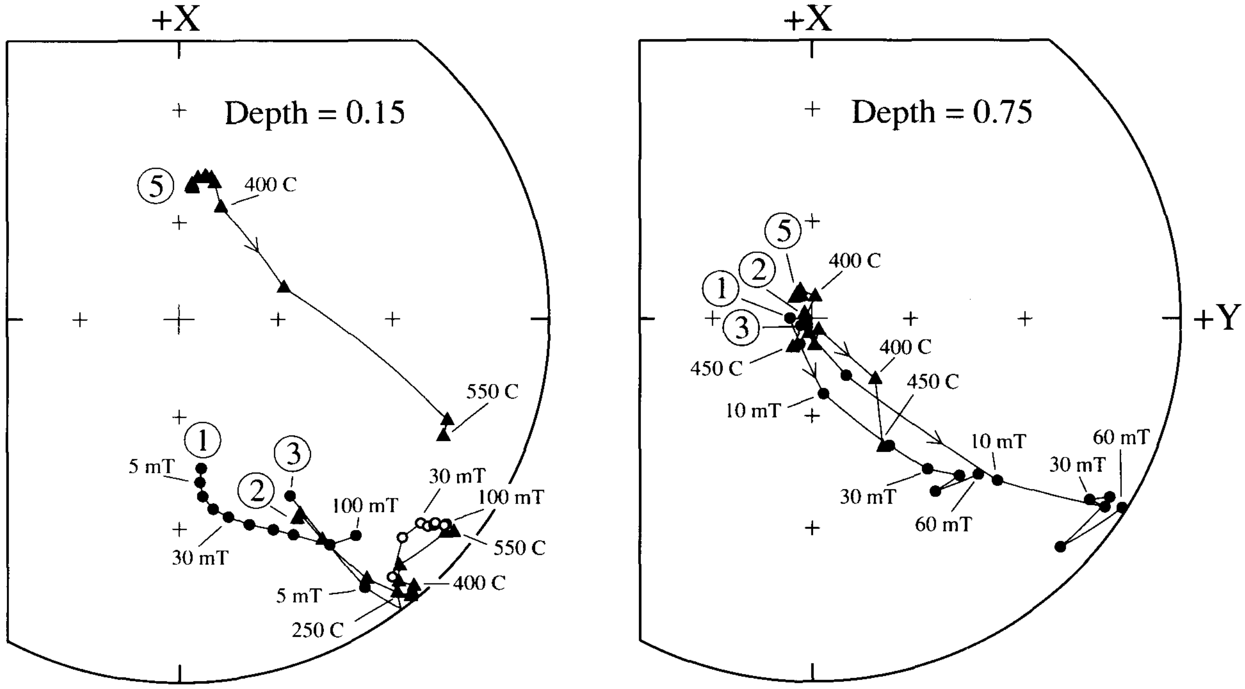

Figure 7. Stereographs showing directional changes during alternating fields (circles) and thermal (triangles) demagnetizations of NRM of separate discs from the same minicore. Symbol convention is as in Fig. 4.

demagnetization was usually more effective in removing DIRM. However, in some cases thermal demagnetization may be the only method for recovering the primary remanence. For example, Van Alstine & Gillett (1981) studied CRB drill cores which were more severely overprinted by DIRM than drill core DC12, and in these cores only thermal demagnetization was effective at removing the DIRM overprinting (Van Alstine, per. comm., 1988).

3.5 Inferences about DIRM based on NRM demagnetization

Analyses of the NRM of the Roza flow in CRB drill core DC12 suggest the following properties of DIRM:

1. DIRM resides predominantly near the surface of the drill core, and a considerably smaller effect is observed at the centre. DIRM is directed down and symmetrically inward toward the centre of the drill core.
2. DIRM has relatively high intensity and low stability.
3. DIRM has apparent AF stabilities of up to approximately 40 mT in specimens with SD/PSD particles and possibly higher AF stability in the less stable MD grains.
4. DIRM can usually be demagnetized in the more stable specimens with SD/PSD particles, and the primary remanence can be isolated. In the magnetically less stable specimens, with MD particles, DIRM can obliterate the primary remanence near the edges of the drill cores, but less complete overprinting occurs a few centimetres away from the drill core's surface, where AF demagnetization is usually effective at recovering the primary remanence.

4 ORIGIN OF DIRM

4.1 Experiments

To better understand the origin of the DIRM, we performed three experiments.

4.1.1 Surface versus interior of the drill core

A possible cause for the observed DIRM might be a contrast in the magnetic properties between the ends and interior of the minicores; for example, contamination by metal shavings from the drill string and/or the drill bit, or significant changes in the rock properties proportionate to the distance from the cutting surface, due for example to excessive heating or stress. To test for this possibility we compared some intrinsic magnetic properties of the centre and end discs for one minicore from each of three depth levels. From the results, shown in Table 3, it is evident that within each minicore the differences are very small and probably not significant with respect to the intensity and AF stability of IRM_s, nor with respect to the low field susceptibility, χ_0. Therefore, contrasts in magnetic properties and/or contamination within the minicores are unlikely sources of the DIRM.

4.1.2 ARM characteristics

The properties of ARM, produced in a peak AF of 100 mT superimposed parallel to a steady field of 50 μT, are shown in Fig. 2 and Table 1. Although the ARM intensity in a steady field of about 100 μT would be sufficient to reproduce the intensity of the DIRM, the ARM stability is two to three

Table 3. Magnetic properties of end versus interior disks

scaled depth	IRM_S (A/m) end	interior	ratio	MDF (mT) of IRM_S end	interior	ratio	χ_0(end)/χ_0(center) ratio
0.18	1200.	1180.	1.02	21.7	22.1	0.98	1.05
0.46	530.	520.	1.02	10.5	11.2	0.94	1.10
0.81	505.	505.	1.00	14.2	13.8	1.03	0.99

End: disc no. 1; interior: disc no. 4. IRM_s, saturation isothermal remanent magnetization, was produced in an external field of 0.5 T. MDF, median demagnetizing field. χ_0, low field susceptibility.

times higher than that of the DIRM. Because ARM and thermal remanent magnetization (TRM) have similar stabilities to AF demagnetization (Levi & Merrill 1976), TRM is an unlikely cause of the DIRM. However, ARM produced in lower peak AF and higher steady fields, cannot be excluded as a possible cause for the DIRM.

4.1.3 *IRM characteristics*

IRM acquisition in low fields of 2.5 and 10 mT and its stability to AF demagnetization was measured in one minicore from each level (Table 1). Both IRM intensity and stability follow simple relationships to the external field, H, for these low fields, $M \propto H^2$ and $MDF \propto H$, respectively. The intensity and stability of low field IRM are comparable to those of the DIRM.

4.1.4 *Relative DIRM in MD and SD particles*

Our results show that DIRM has comparatively greater intensity and is more pervasive for the relatively less stable specimens with MD properties. This is inferred from the higher ratios of the NRM intensity of outer to inner discs for the deeper levels in Roza (Table 2a), the higher NRM/IRM_s ratios of specimens with MD particles (Table 2a and Table 1), and the greater difficulty of recovering the primary remanence direction by demagnetization of the deeper level MD samples.

4.2 Interpretation and discussion

Based on the above experiments, we conclude that (1) the DIRM was not produced by contamination at the cutting surface, because of the uniform magnetic properties within minicores, and (2) the DIRM was not caused by secondary TRM, because of the significant differences between the DIRM and ARM, which has similar stabilities to TRM. However, the DIRM appears to be similar to IRM. The IRM analogy is also supported by the relatively higher intensities and stabilities of the DIRM in specimens with MD than SD properties.

4.2.1 *IRM analogue of DIRM*

Assuming that DIRM is purely an IRM, its intensity and stability provide limits on the inducing field strengths. Because the DIRM appears to be concentrated near the drill-core's cutting surface, the observed NRM intensity (per unit volume) of the finite-thickness end disc is a lower estimate of the maximum DIRM intensity, and the NRM stability with respect to AF demagnetization is an upper limit of the DIRM stability (see Table 2a). For the top level, where the remanence is controlled by SD/PSD grains, the MDF of the DIRM ($\leq$11 mT) requires an extrapolated upper limit of 22 mT for the inducing field and the intensity ($\geq$5 A m^{-1}) a lower limit of 7 mT. DIRM in the lower two levels, which resides primarily in MD particles, similarly limits the required external field, from the MDF and intensity, to between 14 and 3 mT, respectively. Because the DIRM contribution diminishes rapidly with distance from the cutting surface (Fig. 3, Table 2a), the apparent discrepancy in the predicted inducing field diminishes if DIRM (per unit volume) is assumed to be further concentrated in a narrow zone towards the cutting surface, rather than over the entire 11 mm of the end disc. This would increase the estimated lower limit of the inducing field strength. Moreover, the much lower NRM stabilities (MDF) in the end relative to the centre discs in the top level ($d = 0.18$) (Table 2a) suggest that an increase of the DIRM towards the core boundaries would imply lower MDFs than those observed from NRM demagnetization, thus reducing the upper limit of the inducing IRM. The differences in the estimated limits for the inducing fields are further reduced by considering the effects of time. First, the estimate for the lower limit of the inducing field would increase, because IRM decays with time. This is supported by a $4\frac{1}{2}$-month storage test in the Earth's field, during which IRM acquired in 10 mT decayed by about 20 per cent. Second, the decrease of IRM with time would lead to a parallel increase in the IRM stability, indicating a reduction in the upper limit of the inducing field. Therefore, by considering the effects of time and concentration of DIRM towards the drill core boundary, IRM modelling of DIRM predicts inducing fields of about 5–15 mT. Van Alstine (pers. comm., 1988) measured high field strengths of up to 20 mT near the top of a drill string during drilling operations at Hanford in the Pasco Basin. This is compatible with the above estimates from the IRM modelling of the DIRM intensities and stabilities.

4.2.2 *Directions of DIRM*

The consistent DIRM direction in the drill core, down and radially inward, suggests that DIRM acquisition occurred near the end of the drill string at the cutting rim, where the field is expected to have high gradients and non-uniform directions radiating from the cutting edge. Experiments by Stott & Stacey (1960) did not detect directional dependence of TRM on the orientation of maximum strain release in various igneous rocks. However, later work by Nagata & Carleton (1968), also on igneous rocks, showed a small dependence of piezo remanent magnetization (PRM) acquisition on the angle between the ambient field and the uniaxial pressure. If remanence acquisition is aided by mechanical vibrations and/or shocks, shock remanent magnetization (SRM), would also be approximately along the ambient field (e.g. Shapiro & Ivanov 1966; Nagata 1971). The acquisition of DIRM was observed to be parallel to the ambient field during sawing and drilling in the experiments of Burmester (1977), Lauer (1978) and Jackson & Van der Voo (1985). Therefore, it is reasonable to expect that the ambient field would be the controlling parameter in aligning the DIRM. If the drill string were made of highly permeable material with high intrinsic magnetic moment, consistent with the measurements of Van Alstine (pers. comm, 1988), the concentrated, high intensity field lines at the cutting rim would radiate, pointing inward to the interior of the drill bit and outward on the exterior. The observed patterns of DIRM intensity, stability and directions are consistent with this scenario.

4.2.3 Effect of strain and grain cutting

Drilling subjects the rock to strain through expansion and shearing near the cutting edge, where the material is disrupted. Such deformation is likely to affect DIRM acquisition and modify it from being a pure low field IRM. The increased defects and dislocation densities would be expected to increase the stability through steepening of energy barriers to domain wall movements. This might explain the observed high coercivity tail of the DIRM, up to about 40 mT, although the corresponding intensities are low. Burmester (1977) and Jackson & Van der Voo (1985) showed that larger grains are more affected by cutting, because their larger size makes them more vulnerable to physical disruption. Therefore, the effect of tearing might be the reason that specimens with predominantly MD grains are more affected by DIRM than the smaller PSD and SD grains.

4.2.4 PRM contribution

The Roza at DC12 is at about 0.45 km depth, which corresponds to an overburden pressure of the order of 10 MPa (100 bar), and the Roza drill core may have experienced stress of such magnitude during the drilling. Experiments show that rock undergoing strain in an ambient field would be affected by PRM (e.g. Domen 1962; Nagata & Kinoshita 1965). PRM is more intense than IRM acquired in the same field, and the ratio PRM/IRM increases with decreasing grain size (Domen 1962, Kinoshita 1968; Nagata & Carleton 1968). Although the stabilities of IRM and low-pressure PRM appear similar, the difference in stability increases with increasing pressure, and in MD magnetite PRM is observed to be more stable to AF demagnetization than pure IRM produced in the same field (e.g. Shapiro & Ivanov 1966; Carmichael 1968). For example, two basaltic samples exposed to an uniaxial pressure cycle up to 10 MPa and in an ambient field of 3.6 mT resulted in PRM/IRM of 1.76 and 1.24 for samples with IRM_s MDFs of 9.8 and 2.2 mT, respectively (Nagata & Carleton 1968). It is not possible to quantitatively evaluate PRM acquisition in the Roza samples, because the strain release history of this CRB drill core is unknown, and because of difficulties in distinguishing between PRM and IRM. If DIRM were PRM, low-field (~10 mT) DIRM/IRM would be greater for more stable, smaller particle sizes, which is observed (see Tables 1 & 2), and the required inducing field would be somewhat lower than what is required for pure IRM. Kodama (1984) suggested that some DIRM might be due to PRM. If the drill core experiences mechanical shocks during drilling, within the drill string, in the presence of strong fields, it can acquire shock remanent magnetization (SRM) (e.g. Kuster 1969; Lauer 1978), but for moderate impulses, SRM is closely related to PRM, and they have similar behaviour (Nagata 1971).

5 CONCLUSIONS

We have studied DIRM in a drill core of a thick basalt flow buried at a depth of 0.45 km. Due to zonation of the magnetic properties within the flow, DIRM was observed in specimens whose remanence resides in grains ranging in size from MD to SD. In this drill core DIRM is characterized by high intensity and low stability, and in the magnetically less stable rock the DIRM is more effectively cleaned by alternating fields than by heating. In addition, judicious alternating field demagnetization was usually successful at removing the DIRM and recovering the primary remanence, especially in the centre of the drill core. DIRM is concentrated near the cutting surface of the drill core and is directed down and radially inward towards the centre of the drill core. DIRM is relatively more intense and more pervasive in samples with lower stability MD particles than for samples with SD/PSD particles.

The intensities, stabilities and directions of the DIRM indicate that it is acquired at the cutting rim of the drill string, where high fields and gradients are expected and have been observed. The major characteristics of DIRM can be modelled by a pure IRM imposed by a field of the order of 10 mT. Additional effects due to the tearing of grains at the cutting surface might produce higher remanence stability and might explain the greater dominance of DIRM in rocks with predominantly MD particles. Changes in strain and mechanical shocks in the presence of strong ambient fields experienced by the rock during the initial drilling might impart PRM, which could also contribute to the DIRM. However, the similarities of IRM and PRM make it difficult to distinguish between these two sources of DIRM.

Azimuthally unorientated drill cores might sometimes be orientated using the direction of present-day overprinting by viscous remanence (e.g. Fuller 1969) and polarity (e.g. Lynton 1937). However, such orienting procedures would be severely restricted by a predominantly vertical DIRM with a horizontal component directed symmetrically inward towards the centre of the drill core. Moreover, if DIRM were predominantly due to a strong field radiating from the drill string's cutting rim, a symmetrical DIRM is predicted in the walls of the drill hole and this secondary magnetization in the exterior wall might influence field measurements in the drill hole. To improve palaeomagnetic studies of drill cores, the effects of DIRM overprinting can be significantly reduced by measuring specimens from the centre of drill cores and by using non-magnetic drill strings and drill bits.

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