Origin and stability of drilling induced remanence

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Summary. To provide reliable palaeomagnetic data, rock specimens must be cleaned of less stable, usually secondary magnetizations. Yet the very process of preparing standard cylindrical specimens with diamond drills and saws can impart to the specimens of some coarse magnetite-bearing rocks a strong magnetization whose stability to alternating field demagnetization may exceed the cleaning field selected using minimum dispersion, stability indices or other criteria. This added magnetization, here referred to as drilling induced remanence (DIR), was studied using both natural (NRM) and artificial thermal (ATRM) remanent magnetization of two granitic plutonic rocks. Although the DIR is less stable than the NRM or ATRM, its coercivity spectrum extends at least to 925 Oe. It originates as a stress-aided viscous magnetization acquired in the direction of the ambient field during cutting of the larger magnetite grains. Because the grains are exposed, they, and the DIR, can be removed by etching with concentrated HCl. This solution, however, may have serious drawbacks if fine-grained magnetite carrying the stable remanence can also be attacked. The best approach is to demonstrate that the particular rocks being studied are immune to DIR acquisition or, if not, to avoid imparting a DIR by preparing specimens in low magnetic fields.

Introduction

To be useful for palaeomagnetic studies, not only must a rock contain a stable magnetization of known age, but any younger secondary magnetizations must be less stable to some demagnetization technique and removable. Such secondary magnetizations should include remagnetization during sampling and preparation. Theoretically, sampling with a hammer will not affect the magnetization residing in single domain grains although it might produce piezo-remanent magnetization of less stable grains (Hargraves & Banerjee 1973). Most specimens today are not sampled and trimmed with a hammer but with high-speed diamond tools. The questions that need to be answered are: (i) does such preparation affect the stable carriers of primary remanence, and (ii) can such preparation affect the less stable magnetic grains in such a way as to mask the true primary remanence? The consistency of most
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palaeomagnetic data suggests that the answer to the first question is no, at least for the most stable rocks. The answer to the second question, however, is yes as demonstrated for some rocks by Kuster (1969) and in this paper.

Lack of agreement between the magnetic direction of a large core sample of Palaeozoic volcanic rock and the directions of several small cores obtained from it, even after demagnetization to 300 Oe, led Kuster (1969) to conclude that a strong and stable parasitic magnetization was acquired during the second drilling, that the direction of the parasitic component was related to the direction of drilling or the ambient field, and that vibration of the sample in the Earth's field during drilling might be responsible for the parasitic component. The only other rock type in which the effects of drilling have been reported to cause difficulties is granodiorite (Rainbow, Fuller & Schmidt 1972).

Material

The specimens used in this experiment were obtained from a single unoriented block of Cathedral Peak quartz monzonite collected from a fresh road cut on Highway 120 about 6 miles west of Tuolumne Meadows in Yosemite National Park, and from a single core of quartz monzonite of the Bryan Mountain stock near Eldora, Colorado. The first rock is coarse-grained and porphyritic with the main magnetic mineral magnetite occurring as euhedral partly skeletal and irregular grains from 0.3 to 1.0 mm in diameter. The magnetite is nearly pure with less than 0.3 per cent oxides other than iron by analogy with electron-probe microanalysis of another sample (Burmester 1974). Hematite is rare, existing along (111) planes in magnetite (1 per cent average) and as ex-solution lamellae in rounded grains of ilmenite included in sphene.

The second rock is fine-grained with magnetite 0.01–1 mm in diameter, some grains of which contain coarse lamellae of ilmenite and grains of pyrite. Hematite, as an oxidation product of pyrite and as elongate grains or plates in biotite, appears to be the carrier of stable remanence. Pyrrhotite is present within some of the pyrite but probably is magnetically unimportant.

Experimental procedure

The Cathedral Peak quartz monzonite in the form of several blocks 2.28 cm in thickness, and several standard size drill core specimens 2.49 cm in diameter and 2.28 cm in length were given artificial thermal remanent magnetization (ATRM) by cooling them from 700°C in a 0.52 Oe field whose direction with respect to the specimens was known to within 3°. The blocks were then drilled on a machinist's drill press using regular steel drill stem to produce standard size specimens. Control specimens were drilled before being given an ATRM. The remanent magnetizations of all these specimens were measured on a P.A.R. model SM-1 spinner magnetometer shortly after drilling and five more times during the 10 weeks the specimens were isolated from the Earth's magnetic field in double-walled mu-metal boxes (direct field probably 10^-4 Oe). All these specimens were then measured after progressive demagnetization in alternating fields to 300 Oe. Two specimens were demagnetized to 1000 Oe, measured, exposed to the Earth's field for 30 min while in an ultrasonic cleaner, then remeasured to test Kuster's (1969) suggestion that mechanical vibration was somehow responsible for the spurious magnetization.

The ATRM, however, was unsatisfactory for investigating the effect of HCl on the surface of the rock because the heating greatly increased permeability. Instead, the natural remanent magnetizations (NRM) of three other specimens 2.92 cm in length were measured before
and after the specimens were immersed for 14 hr in concentrated HCl. They were then cut with a thin, brass bladed saw into three sections, creating six freshly-sawn faces, and remeasured, immersed in acid and remeasured three more times for a total time in acid of 12 hr. Before each measurement, the specimens were stored in the mu-metal boxes to allow temporary components to decay.

Two fresh standard-size specimens were given saturation isothermal remanent magnetization (SRM) in an 8000Oe field and progressively demagnetized to 700 Oe. This magnetization—demagnetization procedure was repeated three more times on the same specimens after acid treatment which finally totalled 108 hr.

The quartz monozonite from Eldora, Colorado, was first measured as six standard-sized specimens from a single core, then four of them were cut into wafers of 1.1 mm average thickness using the brass bladed saw. The wafers were indexed with a diamond scribe to preserve their orientation and allow reconstitution of the specimens. Half of the wafers (two specimens' worth) and one standard specimen were remeasured at intervals during treatment with concentrated HCl, totalling 6 hr, then they and the untreated material were progressively demagnetized to 925 Oe. After verifying that the sum of magnetizations of individual wafers from a single specimen was the same as the magnetization of the wafers stacked to reconstitute the specimen, the wafered material was measured as stacks to expedite the measuring process.

All specimens at each stage in which they might have been different physically from before were weighed and measured for susceptibility. Susceptibilities of the wafered material were measured on a commercial bridge (Soiltest); all others were measured on a 3000 Hz, 1 Oe bridge modified after Graham (1967) (Bergh 1967).

Results

The direction and intensity of the ambient magnetic field at the drill and the saw were measured with a fluxgate magnetometer using a probe approximately 4 mm in diameter.

The effect of drilling on the specimens given ATRM is displayed in Tables 1 and 2 and in Figs 1 and 3. Because the material used is prone to erratic changes of direction and intensity, the magnetizations of the specimens drilled perpendicular to their ATRM were averaged to reduce incoherent noise.

It is obvious from Fig. 1 that the total magnetization of the drilled specimens decays spontaneously during storage in low field space in a manner that could be described as exclusive decay of a component parallel to the drilling direction. Since this component appears to have been acquired during drilling, it will be referred to as drilling induced remanence (DIR). This decay may be seen better in Fig. 2 where the change of the DIR with the logarithm of elapsed time can be portrayed with two straight line segments of negative slope whereas the ATRM component may fit best a single horizontal line. In contrast to the ATRM component, the control ATRM displays decay of remanence similar to but slower than the DIR such that the difference between the Q' (intensity/susceptibility ratio) values of the two ATRMs decreased by about ½ in 10 weeks (Table 1).
Table 1. Intensity to susceptibility ratios ($Q'$) after $t$ days in field-free storage and peak field at demagnetization for specimens given ATRM

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Component averages</th>
<th>Control ATRM</th>
<th>Percentage difference in ATRMs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DIR ATRM</td>
<td></td>
<td>$\frac{C - B}{C} \times 100$</td>
</tr>
<tr>
<td>0.1</td>
<td>4.06 4.65</td>
<td>5.45</td>
<td>14.5</td>
</tr>
<tr>
<td>2</td>
<td>3.26 4.78</td>
<td>5.20</td>
<td>8.1</td>
</tr>
<tr>
<td>3</td>
<td>3.14 4.74</td>
<td>5.15</td>
<td>8.0</td>
</tr>
<tr>
<td>10</td>
<td>2.98 4.70</td>
<td>5.09</td>
<td>7.7</td>
</tr>
<tr>
<td>24</td>
<td>2.95 4.72</td>
<td>5.05</td>
<td>6.6</td>
</tr>
<tr>
<td>78</td>
<td>2.91 4.71</td>
<td>5.06</td>
<td>6.8</td>
</tr>
<tr>
<td>[10$^8$ years]</td>
<td>2.35 4.71</td>
<td>4.71</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>$Q'_t \times 10^2$</td>
<td></td>
<td>$Q'_{af} \times 10^2$</td>
</tr>
<tr>
<td>15</td>
<td>1.65 3.86</td>
<td>4.17</td>
<td>7.5</td>
</tr>
<tr>
<td>30</td>
<td>0.96 2.90</td>
<td>3.20</td>
<td>9.5</td>
</tr>
<tr>
<td>50</td>
<td>0.58 2.19</td>
<td>2.43</td>
<td>9.8</td>
</tr>
<tr>
<td>75</td>
<td>0.33 1.60</td>
<td>1.82</td>
<td>12.0</td>
</tr>
<tr>
<td>100</td>
<td>0.19 1.21</td>
<td>1.34</td>
<td>9.6</td>
</tr>
<tr>
<td>150</td>
<td>0.049 0.71</td>
<td>0.74</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Note: The row enclosed by brackets is an extrapolation to 10$^8$ yr using the decay rates observed between 10 and 78 days.

Table 2. Comparison of a specimen drilled perpendicular to its ATRM with a specimen drilled parallel to its ATRM

<table>
<thead>
<tr>
<th>Hours in low field storage</th>
<th>Drilled $\perp$ ATRM</th>
<th>Drilled $\parallel$ ATRM</th>
<th>Percentage difference $\parallel$ - $\perp$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A B C</td>
<td>D E</td>
<td>$\frac{</td>
</tr>
<tr>
<td>DIR ATRM</td>
<td>$</td>
<td>A</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>2.22 2.22 4.64 3.29</td>
<td>4.77 2.7</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>1.98 2.49 4.47 3.18</td>
<td>4.22 5.9</td>
<td></td>
</tr>
</tbody>
</table>

Note: Numbers are total moments $\times 10^3$. Columns A and B are orthogonal components of magnetization of the specimen drilled perpendicular to its ATRM. Column C is their algebraic sum and the column A + B is their vector sum. Column D is the total moment of the specimen drilled parallel to the ATRM, and column E is the percentage difference between C and D. The two specimens have similar susceptibilities.

Table 2 shows another relationship between the DIR and ATRM components. The algebraic sum of the two components of a specimen drilled perpendicular to its ATRM agrees with the total magnetization of another specimen drilled parallel to its ATRM better than does their vector sum indicating independence of the two magnetizations. The two specimens differ in susceptibility by less than 5 per cent.
The relative stabilities to af demagnetization of DIR and ATRM can be seen in Fig. 1, and in comparison with the control ATRM, in Table 1 and Fig. 3. The DIR is much softer and decreases to about 7 per cent of the ATRM component by 150 Oe. Nevertheless, this is still strong enough to cause the resultant to deviate 4° from the true direction of ATRM. Although the intensity of the DIR after demagnetization at higher fields could not be determined accurately because of the magnetically soft behaviour of the specimens there is no indication that the bottom curve of Fig. 3 should roll off sharply above 150 Oe. Thus, even after more intense demagnetization, the DIR would continue to bias the measured remanence, but insignificantly because the intensity of the DIR would be more than an order of magnitude less than the ATRM. Table 1 also demonstrates that af demagnetization does not continue the decay of the control ATRM with respect to the ATRM component.

The two specimens placed in the ultrasonic cleaner acquired a magnetization in the direction of the ambient field but the average intensity was only $0.16 \times 10^{-4}$ emu. This is less than 10 per cent of the initial intensity of the DIR and 30 per cent of the part of the DIR which decayed in 10 weeks.

The consequences of immersing prepared specimens in concentrated HCl are shown in Figs 4 and 5. The first 14-hr treatment reduced the $Q'$ ratios of the three long specimens by about half and shifted the directions of remanence away from the direction of the magnetic field they experienced during drilling. Segmenting these specimens produced a dramatic swing of directions by more than 90° to near the orientation of the field at the saw. Subsequent progressive acid treatment returned the directions of remanence toward their orientations prior to sawing, with closest agreement achieved after 12 hr of immersion. The strong magnetization acquired parallel to the field at the saw during sawing was, thus, destroyed by etching the magnetite exposed at the surface. The spurious magnetization acquired during sawing appears genetically related to that acquired during drilling and will also be referred to as DIR.
Figure 2. Plot of intensity of magnetization against log \( t \) where \( t \) is the time since ATRM acquisition. The top curve shows the spontaneous decay of the ATRM of the control specimen. The middle and bottom lines show the different behaviours of the average ATRM and DIR components, respectively, for the three specimens drilled at right angles to their ATRM. The error bars for time represent the maximum uncertainty in the time of measurement. Precision of the magnetization was not documented under prevailing conditions but is probably less than 1 per cent. Notice the change in slope of the top and bottom curves at \( t = 5 \times 10^5 \) s.

To a first approximation, the decrease of susceptibility for standard-size specimens of about 7 per cent during immersion in HCl for 12 hr represents the proportion of magnetite dissolved. Assuming that the magnetite is uniformly distributed and that solution progressed on a front parallel to the exterior of the specimens, the thickness of the shell of rock from which magnetite has been dissolved can be calculated from the susceptibility data for any shape specimen. Data on reduction of susceptibility versus duration of acid treatment between 1.5 and 14 hr imply an increase in the thickness of this shell at a linear rate of 0.032 mm per hr. The 12- and 14-hr treatments which seem to have caused convergence of directions in Fig. 4 correspond to removal of magnetite from only the exterior 0.4 mm of the specimens.
Origin and stability of DIR

Other effects of acid solution on standard-size specimens are shown in Fig. 5. Except for one anomalous point, the curves for demagnetization of saturation remanence, normalized by susceptibility (modified after R ratio of Koenigsberger 1938) are lower and steeper for greater duration of acid treatment, i.e. the saturation remanence itself drops, and the coercivity spectrum shifts to lower values.

The results from the wafered material are presented in Figs 6 and 7. These equal area projections are in the specimens' own coordinate system such that any DIR acquired along the core axis should plot downward in the centre and any DIR type magnetization acquired during sawing should plot near the primitive circle. For reference, the direction of the present axial dipole field (P) and the mean direction obtained from four sites in the Bryan Mountain stock (E) are rotated into this coordinate system. Notice that the two stacks of acid-etched wafers yield directions that are reversed and near E during at least part of their demagnetization whereas the two stacks of unetched wafers remain near the primitive circle, and one remains normally polarized, to 925 Oe. The difference in behaviour between S–33 and S–28 (Fig. 6) may be explained by the higher $Q'$ ratio for S–33 than for S–28.

Discussion

It is apparent from Fig. 2 that both the DIR and the control ATRM decay in low-field space as linear functions of log $t$, behaviour that is characteristic of viscous remanent magnetization (VRM). The slope of each segment can be referred to by a viscosity coefficient $S'$.
Sequence of treatment, arbitrary scale

Figure 4. Response to preparation and acid treatment of three specimens. At left are plotted $Q'$ ratios in order of treatment; at right is an equal area projection of directions of magnetization connected by lines to indicate progressive changes. The orientation of the field during initial coring of the rock is within the ring labelled Drill Field. The upward orientation of the field with respect to the specimens when they were cut into three segments is shown as Saw Field. All measurements were made after the specimens had been stored for 30 to 40 hr in field-free space to allow decay of temporary components. Open symbols are upper hemisphere.

which is approximately half of the $S$ for acquisition of VRM (Shimizu 1960). The dependence on some independent variables of $S$, and therefore $S'$, can be seen by combining Raleigh’s first relation (Nagata 1961) and Street & Wolley’s (1949) theoretical model of Neel’s parameter $S_0$ to get $S = BHkT/\alpha u J_s$. Here $B$ is a constant of the material related to its susceptibility, $\nu$ is domain volume, $\alpha$ accounts for the angle between $H$ and the domain walls, $J_s$ is spontaneous magnetization at absolute temperature $T$, $k$ is Boltzmann’s constant and $H$ is the magnetizing field.

The two-stage decay evident in Fig. 2 is attributable to distribution of magnetite grain size or coercivity such that at least two distinct populations characterized by different magnetic parameters, e.g. $B$ and $\nu$, exist within the material. The difference by a factor of 2.3 between the viscosity coefficients of the DIR and the control ATRM is well beyond the variation observed between the specimens for other magnetic parameters or for $T$. If, however, the decaying portion of the control ATRM is equated with a VRM acquired in a 0.52-Oe field, the difference in slopes can be explained fully if the VRM part of the DIR was acquired in a 1.2-Oe field. This is similar to the field measured at the drill.

It is evident from Figs 1 and 2 that only the DIR of the drilled specimens decays with time if, as suspected, the DIR was acquired parallel to the drill. If the grains which carry the VRM also retained some ATRM, neither grain magnetization nor viscous decay of it would
be parallel to the DIR. Similarly, if magnetic grains were so closely associated that a grain bearing a VRM were adjacent to one carrying ATRM, the decay would be influenced by the local field of the ATRM and would not be parallel to the DIR. Within the uncertainty of the direction of the magnetizing field it appears that the VRM is the dominant magnetization of certain grains which do not interact with the carriers of ATRM. Noninteraction is also indicated by decay of the DIR faster than the control ATRM despite the stronger magnetization of the latter (Fig. 2) and by the constant algebraic sum of the DIR and ATRM components regardless of relative directions (Table 2).

How long self-demagnetization of the VRM would continue is unknown but the similarity of the $Q'$ values of the two ATRMs after 10 weeks and the fact that no demagnetization did not continue the relative decrease of the control ATRM (Fig. 2) indicates that the DIR, too, is nearly devoid of VRM after 10 weeks. Even given a generous amount of extra time for continued decay of the drill component at the second $S'$ (Table 1) the bulk of the DIR must be considered stable to self-demagnetization under the storage conditions, and, therefore, not of normal viscous origin.

Two other facts support this. One is the high coercivity of some of this component. Although low fields acting over long time can produce high-coercivity VRM, the results of Rimbert (1958) – in Nagata (1961) – indicate that it might take a month of exposure to a 2-Oe field to achieve a coercivity of 100 Oe. The other fact is that the DIR is far stronger than could be expected for a VRM acquired in a 1.2-Oe field judging from the amount of VRM acquired in the Earth's field by two specimens despite their exposure to ultrasonic vibration.

The simplest interpretation of Fig. 4 holds that the specimens have stable NRM to which are added spurious magnetizations acquired during drilling before the first measurement and during sawing before the third measurement, and that the acid treatments selectively remove these spurious components allowing the NRM to emerge. Although agreement between

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Figure 5. Semilog plot of the ratio $R_{af}$ (intensity of SRM/susceptibility) of average magnetization versus peak demagnetizing field for two specimens given saturation isothermal remanent magnetization in a 8000-Oe field.
The reduction of susceptibility in this time can be explained by complete removal of magnetite from the outer 0.4 mm of the specimens. Although it will be shown later that the HCl invades the interior of the specimens, the coincidence between solution of at least part of the exterior magnetite and the decrease of the spurious magnetization strongly suggests that this magnetization resides in magnetite exposed at the surface.

Furthermore, for standard-size specimens, about 4 per cent of the magnetite grains 1 mm in diameter would be cut in the process of preparation, 2 per cent of the grains 0.5 mm
Figure 7. Equal-area projection of the directions of magnetization of two stacks of unetched wafers during progressive af demagnetization to the same fields used for Fig. 6. Open symbols and dashed lines are upper hemisphere. Other symbols are as in Fig. 6.

Diameter would be cut, 1 per cent of the grains 0.25 mm in diameter, etc. Although cutting will reduce these grains to an average of half size, still about 1 per cent of the coarse grains in the specimen would be cut grains at the surface whereas virtually none of the very fine grains would owe their origin to cutting, assuming a broad grain size distribution. Thus the relative softness of the DIR (Fig. 3) is consistent with it residing in magnetite which has been cut, although it will be shown later that the cutting itself increases the coercivity of the cut grains.

Af demagnetization to 300e reduced the DIR and the two ATRMs by approximately equal amounts (Table 1). If this soft magnetization is presumed to reside in magnetite of 0.5 mm mean grain size and the DIR resides wholly in the 2 per cent of these grains exposed at the surface, their specific magnetization must be 50 times stronger than the ATRM
acquired by interior grains of the same coercivity. Although the strength of the field at the drill may be higher right at the cutting edge than the 1.95 Oe measured effectively 2 mm away, it is doubtful if it would reach 26 Oe as implied if the DIR is modelled as an ATRM caused by frictional heating.

More likely, the DIR is a stress-aided viscous magnetization (Stott & Stacey 1960). It has been pointed out that stress along a linear scratch in magnetite can be as high as 2500 bars compared to the 650-bar uniaxial stress which is capable of producing a piezoremanent magnetization (Soffel 1966). Stress alone, however, is insufficient. It is necessary to move dislocations in the magnetite before a strain remanence is produced (Shive 1970). This is probably where the field dependence enters in, with temporary relaxation of stress sensitive energy barriers allowing domain walls to move one way but not to return (Carmichael 1968).

Shive (1969) pointed out that strain and introduction of defects into nickel can increase its coercivity, but how important is this to the cut magnetite grains? The maximum coercivity can be calculated as a function of stress by equating expressions for magnetostatic and magnetostrictive strain energy to get $H_c = 3\lambda \sigma / J_s$ (Nagata 1961) where $\lambda$ is the average magnetostriction ($3.9 \times 10^{-3}$ emu), $\sigma$ is internal stress ($2.5 \times 10^8$ dyne cm$^{-2}$, Soffel 1966) and $J_s$ is spontaneous magnetization (480 emu). Therefore $H_c = 610$ Oe at the scratched surface, and less toward the interior of the grains. Although this seems high and is not supported by Fig. 3, it is consistent with the results in Fig. 7, where it appears that the DIR acquired by S-4 during sawing dominates the magnetization throughout cleaning to 925 Oe. That the DIR is dominant is partly due to the high surface to volume ratio of the wafered material but this does not alter the fact that the DIR is quite stable. Shape anisotropy of the wafers is not important in determining the orientation in Fig. 7 near the plane of the discs or similar orientations should show up in Fig. 6 as well. Thus it appears possible that a DIR can persist beyond the 250–400-Oe cleaning range commonly used on igneous rocks.

If the magnetite remains in a stressed state after cutting, it should suffer a reduction in susceptibility (Kern 1961). Susceptibility data on individual wafers did show a decrease of specific susceptibility with decreasing wafer thickness but the data taken on the commercial bridge before acid treatment were too imprecise to distinguish between stress and plucking as the origin for this correlation. The more precise data obtained after acid treatment could be explained wholly by solution of magnetite from the exterior 0.19 mm of the wafer which is the amount expected from the apparent rate of solution of 0.032 mm hr$^{-1}$. That no stress reduction of susceptibility is expected after acid treatment is indicated by Fig. 6 which shows no pronounced contribution of the DIR to the magnetization.

The success of acid treatment in reducing the DIR (Figs 4 and 6) should be acclaimed with reservations. Strain of the exposed magnetite grains may aid their rapid etching which in turn can account for the decrease in the coercivity of the specimens with 12 hr of acid treatment (Fig. 5). However, if most of the DIR is removed during this time, it seems reasonable that most of the anomalously high coercivity magnetite at the specimen's surface would also have been removed. Therefore, the continued decrease of coercivity with continued acid treatment (Fig. 5) must indicate that the HCl penetrates the specimen and, there, preferentially destroys the smaller grains with their higher surface area to volume ratios. If the stable magnetization resides in small magnetite grains, acid treatment to remove the DIR may have a serious drawback.

Conclusions

Preparation of a magnetite-bearing specimen by coring and sawing with diamond tools may add a spurious magnetization referred to here as a drilling induced remanence (DIR). The
DIR is composed of a normal VRM component which resides in the interior of the specimen and a more stable stress-aided viscous magnetization imparted to grains at the surface as they are cut. Contamination with ferromagnetic material from the drill stem is not important as the same phenomena are observed after using stainless steel stems or brass saw blades. The DIR acquired during sawing was coincident with the direction of the magnetic field at the saw suggesting that the direction of the field, not the direction of cutting or drilling, controls the direction of the DIR. Use of magnetic drill stems or motors may perturb the DIR from the ambient field.

The coercivity of the DIR probably depends primarily on the magnetite grain size distribution and on compositionally controlled $\lambda$ and $J_p$. Intensity of the DIR relative to the primary magnetization probably depends on these factors, the strength of the magnetizing field and the surface area to volume ratio of the specimen. Whether DIR poses a problem in any particular palaeomagnetic study will likely depend on the relative intensities and coercivities of the DIR and primary components and on the angle between these components.

Drilling in outcrops with nonmagnetic equipment may impart a DIR aligned with the ambient field and it could be mistaken for a recent VRM. For rocks that can be cleaned in fields of several hundred Oe, the DIR should have no effect on the mean directions if a true stable end point (As & Zijderveld 1958; McElhinny & Gough 1963) is reached. Coring of hand samples in the laboratory may increase sample and site dispersion leading to an overestimate of angular standard deviation and secular variation, but this can be reduced by using the minimum dispersion criterion (Irving, Stott & Ward 1961) to select the best demagnetization level. Bias of the mean directions by DIR may be eliminated by coring and sawing specimens such that the DIR components of the specimens from a sample or site sum to zero, or better, by preparing specimens in very low magnetic fields.

In some situations such as palaeointensity studies or when measuring rocks with low Q ratios it may be desirable to reduce the DIR before proceeding the progressive demagnetization. Since the DIR resides at the surface, it should be possible to remove or anneal the magnetite there. Chemical etching with HCl works, but some method of sealing the interior should be found or this technique may also reduce the stable component. Thermal demagnetization by heating the exterior with a torch while the specimen is in field-free space might work, but would leave the demagnetized material to add to the specimen's magnetic noise. It should also be possible to remove physically the exterior in field-free space by grinding, recoring with a smaller drill, etc.

Any of the selective demagnetization procedures above should remove the spurious magnetization residing in the exterior grains. None of these treatments, however, will cure the problem of overprinting of previous secondary magnetizations by a VRM acquired during drilling such as would be especially pronounced if a long steel drill stem intensified the Earth's field at its tip.

Acknowledgments

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