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Drilling-induced remanence in carbonate rocks: occurrence, stability and grain-size dependence

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Summary. A strong grouping of the directions of natural remanent magnetization in a collection of Ordovician limestones and dolomites, prior to correction for the *in situ* orientation of the samples, led us to suspect the presence of a substantial spurious magnetization acquired during sample collection and preparation. A close correspondence between the directions of the remanence vectors and the direction of the ambient magnetic field during sawing and drilling of the samples suggested that the remanence was dominated by a component acquired during cutting of the samples. Ten specimens of the Camp Nelson Limestone and Shakopee Dolomite were demagnetized to 100 mT, given an anhysteretic remanence along their axes, and then sawed again. A substantial magnetization parallel to the ambient field during cutting was acquired by all of the specimens, and the resultant directions deviated by 7–70° from the direction of the anhysteretic magnetization. Stepwise alternating-field and thermal cleaning to 60 mT and 400°C respectively failed to remove preferentially the cutting-induced magnetic contamination.

Since the fraction of magnetite grains cut during drilling and sawing must be a linear function of grain size, modified Lowrie–Fuller tests were carried out and the results are interpreted to indicate the presence of a multidomain magnetite fraction in the Shakopee Dolomite, Camp Nelson Limestone and Oregon Dolomite. Ratios of initial to anhysteretic susceptibility (χ/χ_{ARM}) correlate well with the angular deviation of magnetic directions produced by sawing. This indicates that acquisition of drilling-induced remanence is a function of magnetite grain size, compatible with the notion that the drilling-induced component resides in large magnetite grains which have been cut.

Introduction

During analysis of a large collection of Lower and Middle Ordovocian limestones and dolomites, we have made the observation that the directions of natural remanent magnetization (NRM) tend to cluster very strongly in a southerly, shallow to moderately downward direction, prior to correction for the *in situ* orientation of the samples. An attempt to explain this observation has led to this study.

The units involved included the Lower Ordovician Oneota Dolomite and Shakopee Dolomite from the Upper Mississippi River Valley and the Middle Ordovician High Bridge Group (Camp Nelson Limestone, Oregon Dolomite and Tyrone Limestone) and Lexington Limestone from north-central Kentucky. Fig. 1 shows the NRM directions of the Shakopee Dolomite and the Camp Nelson Limestone, the two formations for which the grouping in sample coordinates is most conspicuous. The directions are generally close to the present-day field (PDF) direction, though steeper. For the Camp Nelson samples the dispersion is notably increased by correction for *in situ* core orientation. The mean NRM direction for five sites has a precision parameter k of 84.4 before correction, and 19.9 after. The ratio $k_b/k_a = 4.2$, and if McElhinny's (1964) criteria for a fold test are applied, the increase in dispersion is significant at the 95 per cent confidence level. This suggests that the NRM in these samples is dominated by an overprint acquired during the process of sample collection and preparation. For the Shakopee Dolomite the slight increase in dispersion on conversion to field coordinates is not statistically significant. This follows from the fact that virtually all of these cores were drilled horizontally, so the shallow southerly direction in sample coordinates transforms to a steeply downward direction in field coordinates regardless of the azimuth of the core. Nevertheless, the directions cluster strongly enough in sample coordinates that we were led to suspect that these samples too may have acquired a strong spurious magnetization during sample collection and preparation. This was also true for the Oregon Dolomite and Lexington Limestone, and to a lesser extent for the Oneota Dolomite.

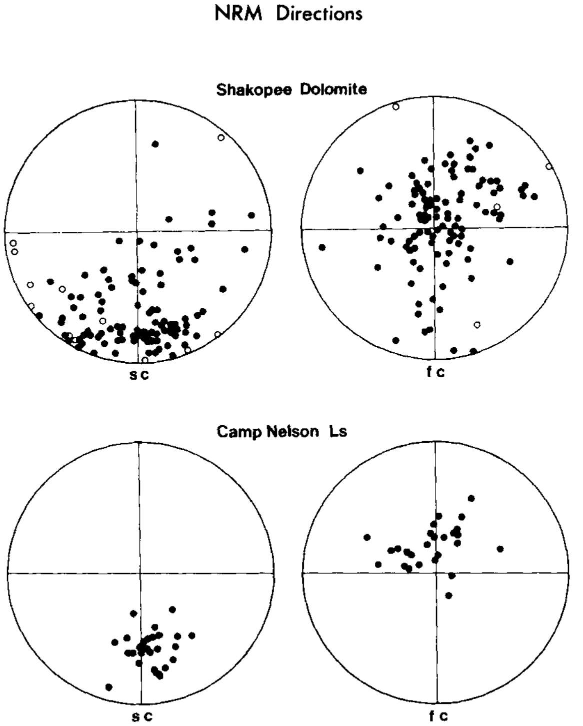

Figure 1. Equal area projections of NRM directions for the Shakopee Dolomite and Camp Nelson Limestone, open symbols on upper hemisphere, solid on lower. Left: sample coordinates; right: field coordinates.

Results of the Oneota Dolomite study will be reported elsewhere (Jackson & Van der Voo 1985).

The effects of drilling and sawing on the magnetization of rocks has been previously studied by Burmester (1977), who worked on samples of granitic plutons whose magnetic properties were dominated by coarse-grained (0.01–1 mm) magnetite. He found that a large component of magnetization was acquired parallel to the ambient field during drilling and sawing of the samples. He termed this magnetization Drilling-Induced Remanent Magnetization (DIRM), and found it to be highly stable against alternating field (AF) cleaning, up to demagnetizing fields as high as 90 mT (900 Oe). Etching in concentrated HCl for 12 hr was sufficient to remove virtually all of the DIRM, and the concomitant decrease in suspectibility was compatible with a uniform leaching of the magnetite from the outermost 0.4 mm of the specimens. Burmester (1977) therefore concluded that the DIRM resided in magnetite grains exposed at the surface of the specimen. He found the effect was the same whether a brass or a steel blade was used to cut the specimens, thus ruling out contamination by ferromagnetic material from the cutting implements as the cause of the DIRM.

Methods

Most of the cores used in this study were drilled in the field with a portable gasoline-powered drill. The ambient field during drilling for these samples may have been close to the PDF direction in field coordinates, though perturbation of the field by the steel drill-bit was probably significant. The ambient field during drilling is therefore estimated to have been close to vertical in sample coordinates, i.e. parallel to the drill-bit axis. Some of the Lexington Limestone and all of the Oregon Dolomite samples were collected by hand and cores were obtained using the drill press in the laboratory. The field measured at the tip of the drill-bit with a fluxgate magnetometer was nearly vertical, with an intensity of 0.16 mT (1.6 G).

Specimens were cut from the cores with a steel-bladed diamond trim saw. The ambient field measured at the blade edge was north (parallel to the blade) and steep, with an inclination of about 75°, and an intensity of 0.08 mT. During sawing the samples were oriented with their axes east–west and the sample north reference line facing upward in all cases. The field seen by the specimens during sawing was therefore horizontal and southerly in sample coordinates, with a declination of 195° while cutting the top of a specimen and 165° while cutting the bottom. The average sawing field was thus south and horizontal in sample coordinates, and steeply downward in field coordinates due to the drilling orientations as previously discussed.

Fig. 2 shows the orientation of the ambient field during each stage of the collection and preparation process. It is clear that the NRM directions recorded for the Shakopee Dolomite samples correspond very closely with the direction of the ambient field during sawing. For the Camp Nelson Limestone, the NRM directions lie mid-way between the sawing-field and drilling-field directions. This again suggests that a strong overprint has been acquired by these rocks during sawing and drilling.

In order to verify this suggestion, 10 specimens of the Shakopee Dolomite were sawed again with their orientation reversed, such that the field seen by the specimens during cutting was northerly and horizontal. It is clear that the magnetization of the samples was strongly affected by the sawing, as the initial tight southerly cluster becomes highly dispersed (Fig. 3a, b). The difference vectors (Fig. 3c) are all northerly and horizontal, and the mean direction has a declination $D = 2$ and an inclination $I = -7$, with a precision parameter $k = 10$. The dispersion in declination of the resultant vectors (Fig. 3b) indicates that

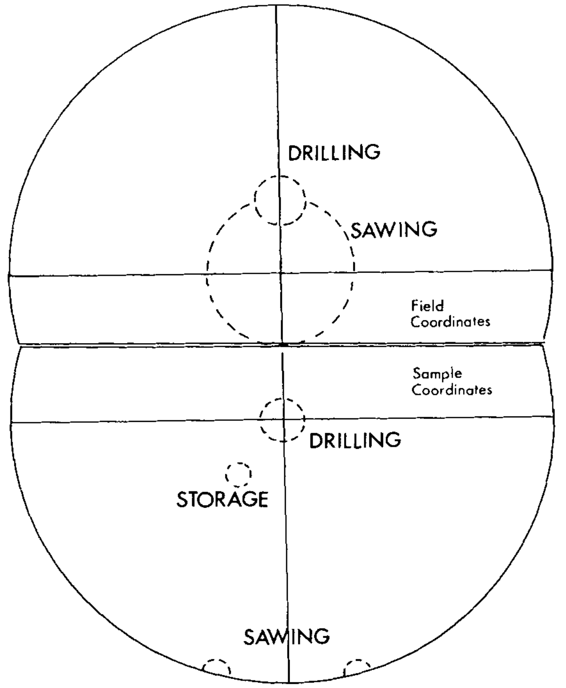

Figure 2. Ambient field orientations for each phase of sample collection and preparation, as explained in the text. Note the relation between the NRM directions and the direction of the ambient field during drilling and sawing. Equal area lower hemisphere projection.

there is still a shallow southerly component of magnetization present in addition to the shallow northerly DIRM component. If the DIRM resides in grains exposed at the sample surface, as demonstrated by Burmester (1977) for granitic rocks, then sawing should have physically removed any grains carrying a southerly DIRM. However, as previously discussed, a PDF component would also have a southerly shallow direction in sample coordinates. Our interpretation, therefore, is that the initial well-grouped shallow southerly magnetization is

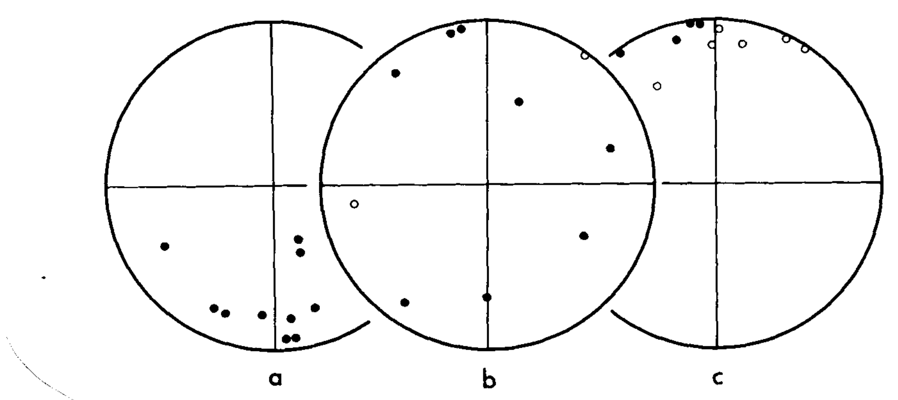

Figure 3. (a) NRM directions for 10 specimens of Shakopee Dolomite (one from each site). (b) Directions of the resultant magnetization after sawing approximately 2 mm off each end, with a northerly shallow ambient field during sawing. (c) Directions of the magnetic components acquired during sawing, determined by vector subtraction, all close to the saw-field direction. Equal area projections.

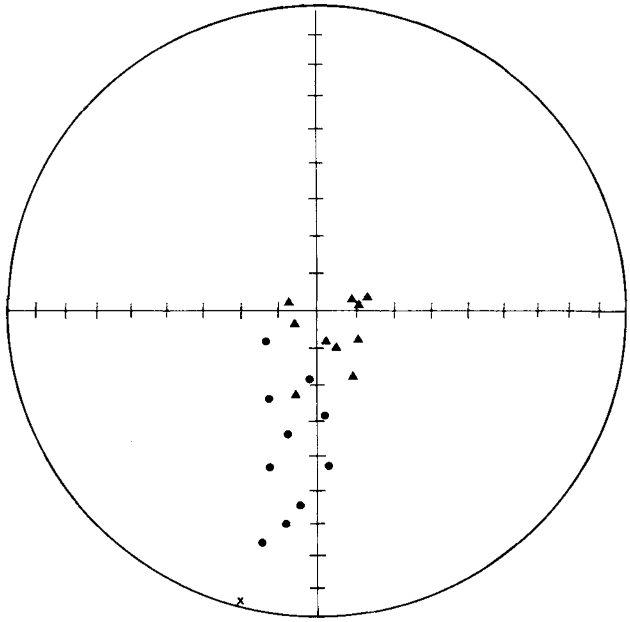

Figure 4. Equal area plot showing the change in direction of magnetization in five samples each of the Camp Nelson Ls and Shakopee Dolomite, produced by sawing 2 mm off one end, in an ambient field normal to a pre-existing vertical ARM. All samples acquire an overprinted component of magnetization parallel to the ambient field during sawing.

a composite of a PDF and a southerly DIRM component, that sawing replaces the southerly DIRM with a northerly one, and that the dispersed resultants are composed of a DIRM residing in surface magnetic grains and an antipodal PDF component residing in the interior.

To evaluate the possibility of recovering the direction of an original magnetization which has been contaminated by a DIRM, we began with a controlled, univectorial laboratory-

Table 1. Angular deviation θ in the direction of magnetization produced by sawing.

		Anhysteretic remanence		Resultant after sawing		
Formation	Sample	P	D/I	P	D/I	θ
Camp Nelson	JKC 14	3.09	162/82	1.73	176/64	18
	JKC 26	6.11	77/81	3.74	183/74	20
	JKC 35	1.64	153/79	1.32	196/46	37
	JKC 44	7.16	236/83	3.61	232/75	8
	JKC 56	1.93	275/83	0.98	206/63	25
Shakopee	JMS 14	4.44	152/70	4.23	192/24	52
	JMS 24	7.83	193/67	2.86	192/56	11
	JMS 74	5.60	125/77	10.89	175/48	34
	JMS 94	2.37	83/79	3.32	184/38	55
	JMS 104	2.81	74/77	4.19	198/30	68

P: magnetic moment, nA m^2 (10^{-6} emu).
θ: angle between ARM and resultant directions, degrees.

induced magnetization. Five specimens each of the Camp Nelson and Shakopee were AF demagnetized (100 mT) and then given an axial anhysteretic remanent magnetization (ARM) in an AF of 100 mT with a biasing steady field of 50 μT (0.5 Oe). These ARM directions are shown by triangles in Fig. 4. Approximately 2 mm was then sawed off the top of each specimen. The ambient field during this cut had an orientation of $D/I = 195/0$, and the resultant directions of magnetization measured after cutting were all deflected toward the saw-field direction (Figs 4 and 5a). The angle of deflection θ ranged from 7 to 70°, and was in general larger for the Shakopee Dolomite than for the Camp Nelson Limestone (Table 1).

One sample of the Shakopee, JMS 24, was not cut but was instead immersed in an ultrasonic bath with approximately the same ambient field orientation ($D/I = 195/0$) (Fig. 5b). Burmester (1977) found that samples treated in this was also acquired a magnetization parallel to the ambient field, but with an intensity only about one-tenth to one-third as large as that induced by drilling. The angle θ for JMS 24 (11°) is about one-fifth as large as the corresponding values for the other Shakopee Dolomite samples (Table 1). However, the greatest effect of the ultrasonic vibration was a reduction of the ARM intensity by almost 60 per cent. The same effect is apparent in most of the cut samples. The reduction in specimen volume was 10–20 per cent, but the reduction in vertical (ARM) moment was typically 40–50 per cent (Fig. 5). The ARM intensity thus suffered a drop of approximately 35 per cent, which is probably attributable to the vibration of the sample during sawing. The shallow southerly component of magnetization acquired, however, was too large to be due

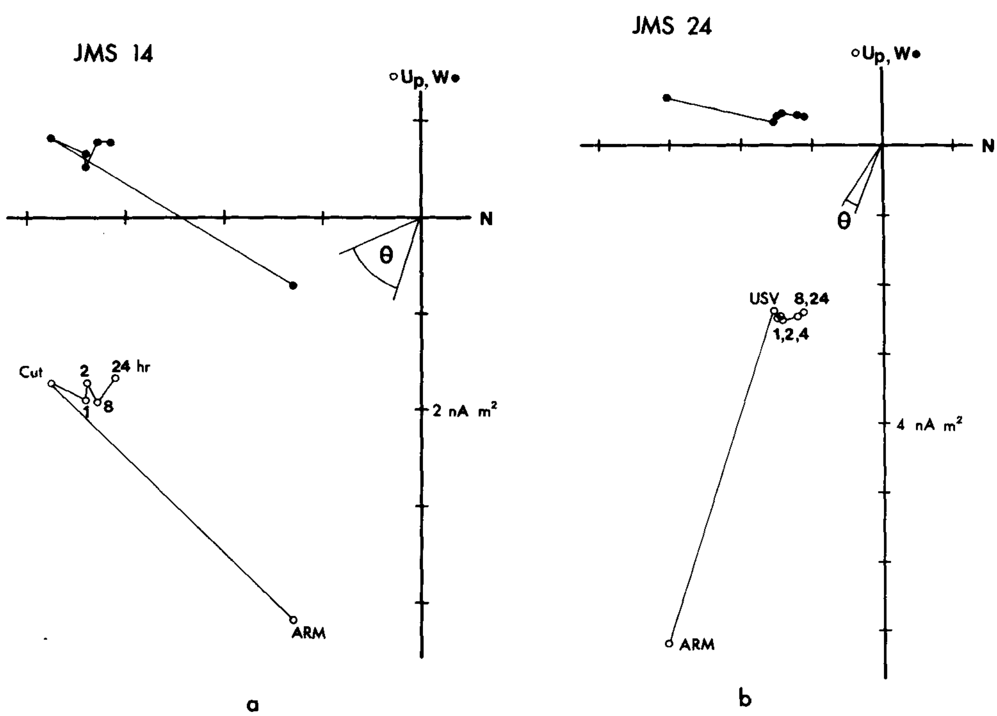

Figure 5. (a) Orthogonal projection (Zijderveld 1967) showing acquisition of a large southerly magnetic moment accompanied by the loss of about half of the steeply downward anhysteretic moment, due to sawing. θ is the angular difference between the ARM and resultant vectors. Subsequent viscous decay in zero field removes a shallow southerly component. (b) Loss of ARM accompanied by acquisition of a small southerly component, due to ultrasonic vibration (USV), and subsequent viscous decay. Open symbols on vertical projection, closed on horizontal.

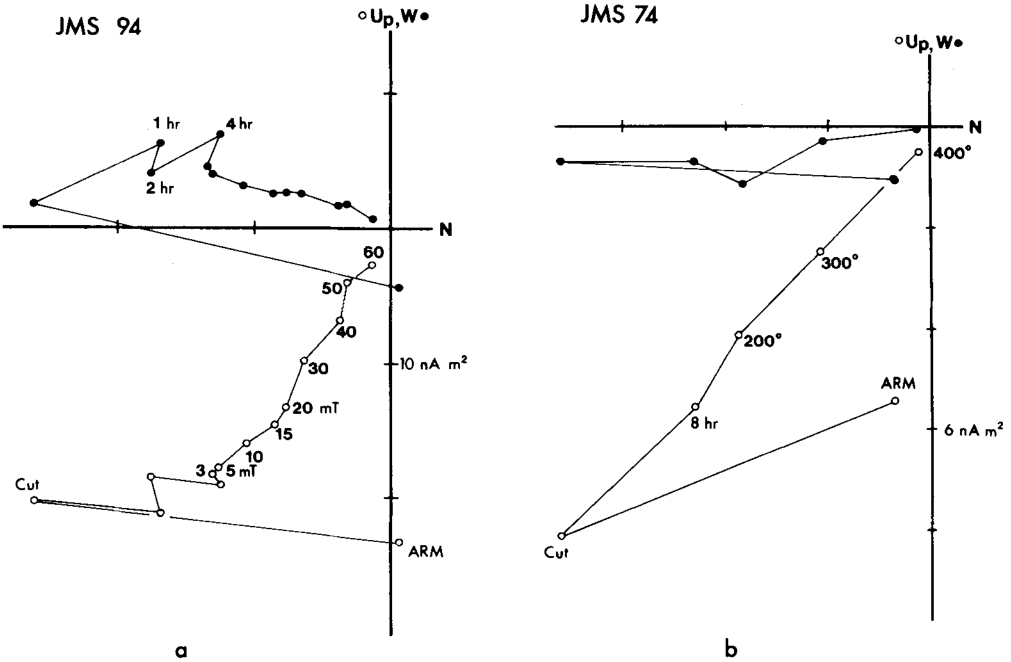

Figure 6. Symbols as in Fig. 5. (a) Viscous decay in zero field and AF demagnetization of composite ARM and DIRM achieves little separation of the two components. (b) Similar results for thermal demagnetization.

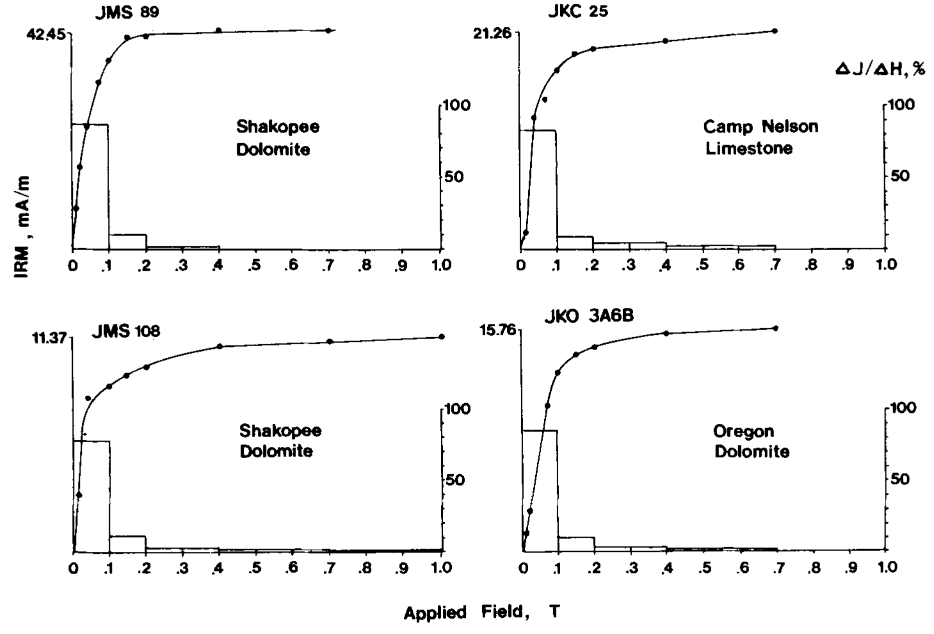

Figure 7. IRM acquisition curves (Dunlop 1972) approach saturation by 0.3 T. Magnetite is probably the dominant remanence-carrier.

to vibration, and most likely owes its origin to the stress-related mechanism proposed by Burmester (1977).

Viscous decay in a low magnetic field (~ 50 nT) of the resultant magnetization after sawing was monitored over 24 hr. In each case the component which decayed was southerly and shallow, while the magnitude of the vertical component remained constant (Figs 5 and 6). In some cases almost half of the shallow southerly component decayed over that interval. Measurements made over intervals longer than about 1/2 hr were accompanied by a moderate amount of noise, so that a viscosity coefficient could not be reliably determined. AF demagnetization up to 60 mT removed the ARM and DIRM in almost equal proportions and was unable to achieve separation of the two components (Fig. 6a). Thermal demagnetization to 400°C yielded similar results (Fig. 6b). The DIRM has sufficiently high stability against these cleaning methods that the 'primary' ARM direction is never recovered.

In order to make a preliminary identification of the remanence-carrying minerals in these rocks we used the coercivity spectrum analysis of Dunlop (1972). Room-temperature isothermal remanent magnetization (IRM) acquisition curves (Fig. 7) show that samples of both the Shakopee Dolomite and Camp Nelson Limestone approach saturation in applied fields of 0.3 T. The remanence carriers in the rocks are therefore probably dominantly magnetites (Dunlop 1972; Lowrie & Heller 1982). The slope of the curves remains slightly positive above 0.3 T, indicating the presence of small amounts of higher-coercivity material.

Relation of DIRM to grain size

Larger magnetite grains in a sample have a higher probability of being cut than do small grains. Assuming a uniform distribution of spherical grains with radius r, those grains whose centres lie within a distance r of the final specimen surface will be cut. The fraction cut during drilling is thus

$$f_d = \frac{\pi(R + r)^2 L - \pi(R-r)^2 L}{\pi(R + r)^2 L} = 4Rr/(R + r)^2 \approx 4r/R \tag{1}$$

where R and L are the specimen radius and length respectively. The approximation holds for $r \ll R$. During sawing the fraction of grains cut is

$$f_s = \frac{\pi R^2(L + 2r) - \pi R^2(L-2r)}{\pi R^2(L + 2r)} = 4r/(L + 2r) \approx 4r/L. \tag{2}$$

Thus for standard-sized specimens (R = 12.5 mm, L = 20 mm), and for $r \lesssim 1$ mm, the fraction of cut grains is a linear function of grain size (Fig. 8). On average cut grains are reduced to one-half of their original volume, so the volume (or mass) fraction is one-half of the numerical fraction f.

If we presume that the DIRM resides in the cut grains (Burmester 1977), then propensity for DIRM acquisition should be related to the grain size of the magnetite in the samples. The relatively larger DIRM acquired by the Shakopee Dolomite therefore suggests the presence of coarser-grained magnetite, or a higher proportion of coarse-grained magnetite in the Shakopee than in the Camp Nelson samples. We therefore investigated other properties of these rocks which may be sensitive to grain size or domain structure.

A modified Lowrie–Fuller test (Johnson, Lowrie & Kent 1975) was performed on several samples from both formations. ARM was given with the maximum available AF of 100 mT using the solenoid of a Schonstedt AC demagnetizer while a steady biasing field of 50 μT was maintained by a large set of Helmholtz coils. In order to be able to make a comparison

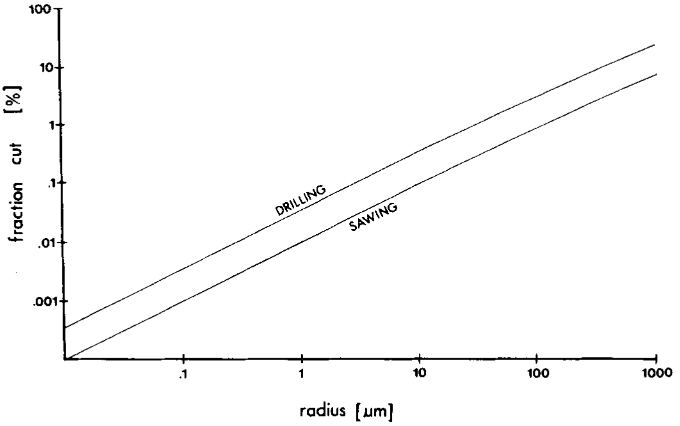

Figure 8. The fraction of magnetite grains cut during drilling and sawing of standard-sized palaeomagnetic specimens, as a function of grain size.

between ARM and IRM stabilities, the same grains must be activated in each case, so IRM was also imparted in a field of 100 mT. While this is not quite sufficient to saturate single-domain (SD) magnetite, it should be enough to activate all of the multi-domain (MD) fraction (Evans & McElhinny 1969; Stacey & Banerjee 1974). Thus these tests may be used to indicate the presence of MD magnetite, but the presence or absence of a SD fraction cannot be determined with certainty. For samples of the Camp Nelson Limestone and the overlying Oregon Dolomite, the IRM is more stable against AF demagnetization than the ARM (Fig. 9a), typical MD-type behaviour (Johnson *et al.* 1975; Dunlop 1983).

Samples of Shakopee Dolomite exhibited unusual behaviour. In all three of the samples

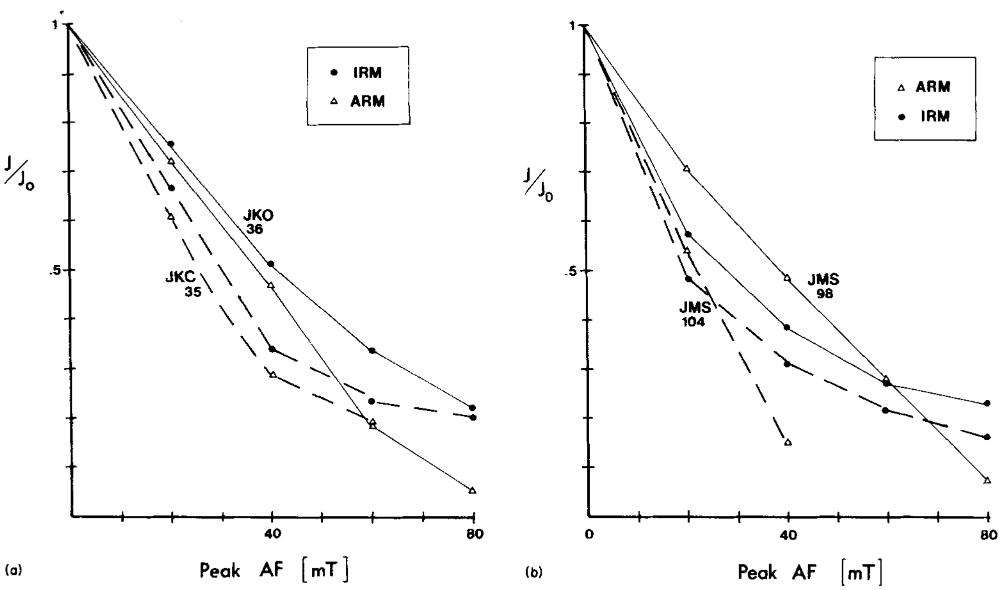

Figure 9. Modified Lowrie–Fuller test (Johnson *et al.* 1975). (a) Typical MD-type behaviour in the Camp Nelson Limestone and the Oregon Dolomite. (b) Unusual crossover behaviour in Shakopee Dolomite samples may be due to a bimodal size distribution of magnetite.

studied the normalized ARM and IRM demagnetization curves cross, with the ARM curves higher at low AFs and the IRM curves higher above about 50 mT (Fig. 9b). This may represent a bimodal size distribution of magnetite in the Shakopee Dolomite, with both SD and MD fractions present (Dunlop 1983). While these interpretations are not without possible complications, the tests do seem to indicate the presence of a MD magnetite fraction in both the Camp Nelson and Shakopee samples. However, the test is not sensitive to grain-size variation within the MD size range (Dunlop 1983).

We therefore applied the susceptibility ratio method of Banerjee and others (Banerjee, King & Marvin 1981; King *et al.* 1982). Initial susceptibility was measured in a field of 50 μT in a cryogenic magnetometer. Samples were measured twice and inverted between measurements to subtract the remanent contribution. ARM was imparted to four samples in an AF of 100 mT and progressively increasing steady fields of 10, 20, 30 and 50 μT. ARM acquisition was in each case linearly proportional to the strength of the biasing field, so the remaining samples were given an ARM with a steady field of 50 μT only. In a plot of anhysteretic susceptibility (χ_{ARM}) versus initial susceptibility (χ), the Camp Nelson and Shakopee samples are clearly distinguished (Fig. 10). While they span the same range of χ_{ARM}, the initial susceptibilities are higher for the Shakopee samples than for the Camp Nelson. The empirical grain-size contours determined by King *et al.* (1982) shown in Fig. 10 indicate (1) the dominance of coarse-grained magnetite in almost all of the samples and (2) larger grain sizes in the Shakopee Dolomite. King *et al.* (1982) emphasized that there are several factors which complicate quantitative application of this method, including the contribution of the matrix material to the susceptibility and the dependence on magnetite concentration of both initial and anhysteretic susceptibilities. They concluded however that the method is a reliable indicator of relative grain sizes.

The similarity in room temperature saturation IRM intensities (Fig. 7) for the Shakopee and Camp Nelson samples suggests that the concentration of magnetite is not greatly different from the two rock units. However, differing contributions from the matrix material is a possibility which must be considered. Published chemical analyses show a total concentration of iron oxides of 0.41 per cent (average) for the Camp Nelson

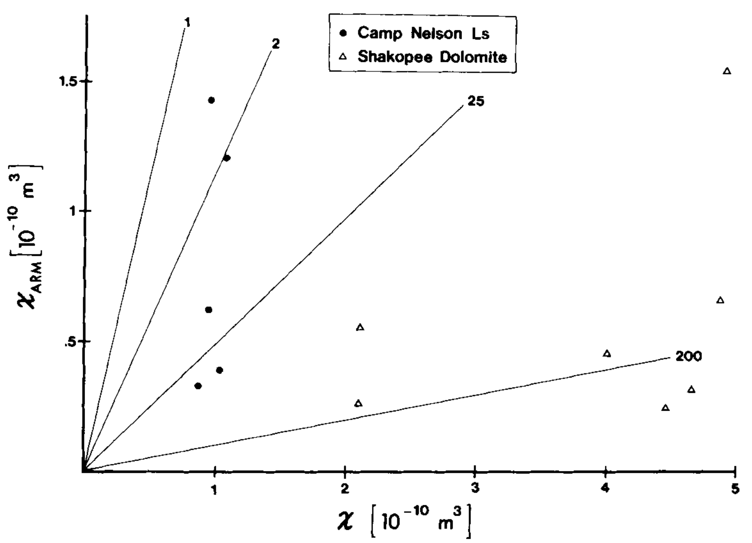

Figure 10. Plot of anhysteretic susceptibility (χ_{ARM}) versus initial susceptibility (χ), with empirical grain-size contours of King *et al.* (1982) in micrometres.

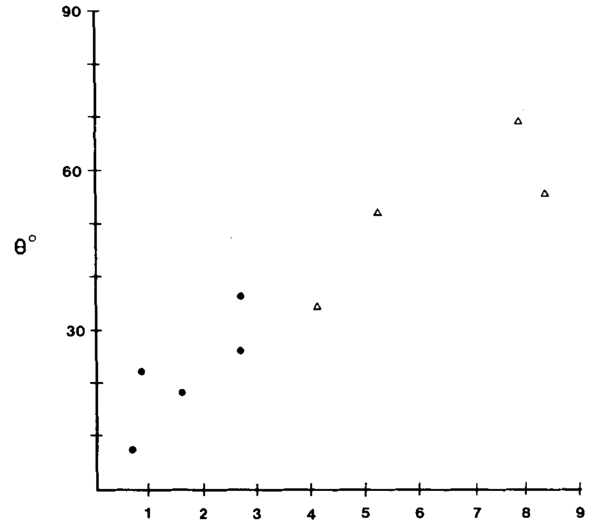

Figure 11. Correlation of the angle of deviation θ produced by sawing, with the ratio χ/χ_{ARM}. Inferred grain size increases to the right, and shows a strong correlation with DIRM acquisition.

Limestone (Dever 1980), and an insoluble residue, 'chiefly iron oxide' of 1.8 per cent for the Shakopee Dolomite (Stauffer 1950). While these figures are not directly comparable, they suggest that the higher initial susceptibilities of the Shakopee samples may be due to the presence of more iron-bearing clays in the matrix.

There is also a grain-size trend evident among the Camp Nelson samples, however, defined by the variation in χ_{ARM}, which is not affected by the non-magnetic matrix. The grain-size trend is compatible with the pattern anticipated on the basis of DIRM acquisition, as the samples with the highest ratios χ/χ_{ARM} also had the highest deviation angles θ produced by sawing, while the sample with the lowest ratio had the smallest θ (Fig. 11, Table 2). A similar within-group correlation between θ and χ/χ_{ARM} holds for the Shakopee samples. These within-group correlations cannot be satisafactorily explained by a variation in the paramagnetic matrix susceptibility, and we therefore conclude that the matrix material is not of great importance in the differentiation of the Shakopee and Camp Nelson samples in Fig. 10. The most straightforward explanation, then, for the strong correlation demonstrated in Fig. 11 is that the samples with the largest magnetite grain sizes (highest χ/χ_{ARM}) acquired the largest DIRM components, because a greater fraction of the magnetite grains in these samples was cut during sawing.

Table 2.

Sample	χ/χ_{ARM}	θ
JKC 14	1.56	18
JKC 26	0.82	20
JKC 35	2.70	37
JKC 44	0.68	8
JKC 56	2.70	25
JMS 14	5.25	52
JMS 74	4.09	34
JMS 94	8.44	55
JMS 104	7.85	68

Discussion

The angle of deviation from an original direction of magnetization produced by drilling and sawing obviously depends on the angle between the original and cutting-induced components and their relative magnitudes. Because the NRMs carried by limestones and dolomites are typically extremely weak, they can easily be masked by spurious components of magnetization acquired during collection and preparation of the specimens, particularly when there is a significant fraction of MD magnetite present. Figs 10 and 11 suggest that the threshold size for significant DIRM acquisition may be as low as 1–2 μm, although as previously mentioned the absolute grain sizes determined from Fig. 10 are subject to considerable uncertainty (King *et al.* 1982). For $r = 25\,\mu$m ($\chi/\chi_{ARM} \approx 2$), 0.5 per cent of the grains is cut during sawing, and for the samples in this study, $\theta \approx 20°$. Since these results were obtained for a DIRM at right angles to the 'primary' ARM, θ will in general be smaller than 20°. The specific magnetization of the cut grains is greater than that of the interior grains carrying the ARM by a factor of tan $\theta/f \approx 70$. A similar factor of 50 was calculated by Burmester (1977), who therefore concluded that a DIRM origin by frictional heating was unlikely, as it would require local magnetic fields stronger by an order of magnitude than those measured in the vicinity of the cutting implements. Burmester (1977) therefore proposed that acquisition of DIRM was due to stresses suffered by the large magnetite grains while being cut, and this seems to be the most plausible mechanism for the rocks in this study as well.

The stability of the DIRM against the standard cleaning methods used on limestones is evidently high enough that primary directions may not be recoverable. In standard orthogonal projections of the magnetization vector during stepwise cleaning (Zijderveld 1967) the composite magnetizations could easily be mistaken for a single-component remanence (Fig. 6). In favourable circumstances, however, the method of converging remagnetization circles (Halls 1976) may have some success in isolating a characteristic remanence (Jackson & Van der Voo 1985). Etching in HCl may also be potentially useful, although in practice difficulties arise in preserving identification and orientation of carbonate specimens.

Identification of DIRM in these carbonate rocks resulted from the observation that the NRM directions clustered surprisingly well in sample coordinates. This was somewhat fortuitous, in that the uniform orientation of the sawing-field in sample coordinates was the consequence of uniform specimen orientation during sawing, and this was a simple matter of routine rather than a deliberate and systematic method. Furthermore, in the Shakopee Dolomite and most of the Camp Nelson Limestone samples the sawing-induced DIRM was substantial in comparison with the original NRM. In rocks containing a strong coherent NRM, grouping in sample coordinates would not generally be apparent. It is therefore not surprising that this effect has not often been recognized previously.

Conclusions

Drilling-induced components of magnetization in carbonate rock samples can be large enough to overprint significantly any primary magnetic direction recorded in the rocks, and these spurious components are highly resistant to conventional cleaning methods. The occurrence of DIRM appears to depend on the presence of coarse-grained magnetite, and the threshold size for significant DIRM acquisition may be as low as a few micrometres. In extreme cases such an overprint may be recognized by a tendency for NRM directions to group well before correction for *in situ* core orientation, but it may commonly go undetected, producing apparently univectorial but erroneous directions.

Acknowledgments

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