Experimental stress remagnetization of magnetite

Graham J. Borradaile *
Geology Department, Lakehead University, Thunder Bay, Ont. P7B 5E1, Canada

Received 6 January 1995; revised 17 October 1995; accepted 17 October 1995

Abstract

Pseudo-single-domain (PSD) and multidomain (MD) magnetite grains remagnetize in weak magnetic field (30 μT) during experimental triaxial deformation. The magnetite is supported in a calcite-cement matrix. Minor remagnetization occurs with hydrostatic stress of 100 MPa. Significant remagnetization requires hydrostatic pressure of 150 MPa with differential stress of ≥ 5 MPa superposed on the sample. Intergranular differential stresses must be much higher due to amplification at grain asperities. Stress remagnetization does not need chemical or thermal energy.

New components of magnetic remanence are added parallel to the remagnetizing field. However, this only happens in grains or parts of grains with coercivities of remanence < 15 and > 60 mT. Grains with coercivities of 20–55 mT remember the primary magnetization and are not stress magnetized. These coercivity limits do not depend on the differential stress or strain rate of the experiment.

The spatial distribution of vector components of remanence was isolated by AF demagnetization. After deforming a magnetized sample, the components of remanence spread along a partial great circle between the initial remanence and the direction of the remagnetizing field. The directions of the original magnetization and the remagnetizing field are the only factors controlling the course of the remagnetization path. Triaxial deformation shortened these samples by < 17%. Thus, grain rotation fails to explain the changes in directions of magnetism. The remagnetization is attributed to the low field during stress deflection of domain walls that were possibly locked in place by deformation features.

If the experimental results are transferable to nature, it is possible that a pulse of excess crustal stress > 25 MPa could partially remagnetize low-dislocation-density magnetite. The experiments show that the directions of the remagnetizing field and the primary magnetization are the only variables that affect the demagnetization vector path. We do not need to know the strain history (coaxial or noncoaxial), finite strains or principal strain directions to detect the paleofield directions, unlike paleomagnetic vectors affected by large strains.

Permanent changes in magnetic structure occur as a result of experimental deformation. Regardless of the differential stress, the proportion of grains with remanence coercivities < 25 mT decreases, and the proportion above 25 mT increases. Even hydrostatic stress can cause this. Thus, grain sizes should only be inferred from hysteresis parameters if their stress histories are similar. This is of some importance in environmental magnetism.

1. Introduction

Paleomagnetists are familiar with thermal or chemical remagnetization related to metamorphic or igneous activity. Remagnetization may also form...
part of the general process of thermoviscous remanence acquisition (Kent, 1985; Dunlop, 1989). Now, however, we know that remagnetization accompanies large-scale tectonic events (e.g., Hudson et al., 1989; McWhinnie et al., 1990, Lombard et al., 1991, Wang and Van der Voo, 1993) and their subtle microstructural events (Housen et al., 1993). Diagenesis or the migration of low-temperature postorogenic fluids may also remagnetize (McCabe et al., 1989; McCabe and Elmore, 1989; Jackson, 1990; Elmore and McCabe, 1991; Lu et al., 1991; Saffer and McCabe, 1992; Elmore et al., 1993). Thus, a variety of almost "petrographically invisible" processes can alter the primary paleomagnetic signature of a rock. Whereas this is troublesome to those seeking evidence of primary magnetization, the remagnetization evidence itself provides a simple means of recognizing the event, its areal extent and its chronological position in the paleomagnetic record.

In this paper, triaxial deformation experiments, maintaining a differential stress for 1.5 h and producing < 17% axial shortening, remagnetize magnetite-bearing synthetic sandstone. The experiments produce no significant petrofabric (e.g., cleavage or grain alignment) or magnetic fabric, although calcite twinning is obvious and has been studied in earlier experiments. Hydrostatic pressure was 150 MPa (≈ 2.4 km) and additional differential stresses simulate short-lived tectonic stress pulses in these computer-controlled experiments. All remanence acquisition is influenced by temperature but this study isolates the effects due to stress at 22°C.

Earlier studies showed the potential for magnetite to show pressure-induced, remanent magnetism (PRM) or partial pressure demagnetization (Domen, 1962; Carmichael, 1968a,b,1969; Dunlop et al., 1969; Nagata, 1970). It is reviewed by Borradaile (1994) in an analysis of the effects of strain. The earlier work was not directly concerned with syndeformation remagnetization, the possible consequences of "tectonic" remagnetization nor with the practical interpretation of partially remagnetized paleomagnetic signatures.

2. Experimental materials

The experimental materials are calcite, magnetite and Portland cement. The cement has a trace of single-domain magnetite derived from the source limestone. Its contribution was swamped by the magnetite added to the sample mixture. The Portland cement is primarily a diamagnetic mixture of 3CaO·SiO₂ + 3CaO·Al₂O₃ + 2CaO·SiO₂. It reaches 95% of its ultimate uniaxial strength in 28 days but continues to harden and set indefinitely. Water is liberated into pore spaces during deformation experiments, even when the samples are more than one year old. Retesting deformed samples shows that the mechanical properties of samples bonded with Portland cement are changed by deformation.

I added chemically precipitated magnetite (using the method of Collinson, 1983) that appears to possess low dislocation densities (Borradaile and Jackson, 1993). It is of pseudo-single-domain (PSD) and single-domain size (SD). Sixty percent calcite (0.1 mm), 40% cement powder and a trace of magnetite were dry mixed and then set with water in a magnetically shielded space (< 5 nT) (see Borradaile, 1994, for details). Batches made in January 1993 and January 1994 were deformed between June and September 1994. The two batches of material differ slightly in magnetic and mechanical properties due to the progressive hydration and maturation of the cement. Alternating field (AF) demagnetization of saturation isothermal remanent magnetization (SIRM) shows that the proportion of grains with coercivities > 25 mT increases with age. This could be due to the growth of fine PSD magnetite during maturation (Fig. 1), an item of interest to archaeomagnetists. The range of differential stresses in the ranges shown in Fig. 1 is sufficient to change hysteresis properties of the magnetite to those normally associated with finer grains but grain size is unchanged. This is known as "magnetic hardening" (Jackson et al., 1993).

3. Magnetic preparation and analysis

Cylindrical samples (18 mm diameter × 15 mm high) of synthetic calcite-sandstone were magnetized with an anhysteretic remanence (ARM) using a modified Sapphire Instruments AF demagnetizer. This applied an alternating field from 140 mT down to zero with a DC bias field of 50 μT over the window from 100 mT down to zero. Remanence was measured before and after experimental deformation using a Geofyzika JR5a spinner inductometer (sensitiv-
Cylindrical acrylic sleeves with nylon setscrews retained samples in the spinner holder during remanence measurements. These holders were routinely cleaned and demagnetized.

The samples' initial ARM was 1 A/m (±0.01 mA/m). After 60 mT AF demagnetization approximately 10 mA/m remained, about 1000 times above the noise level of the magnetometer. Thus, precision of measurement is not of concern. Other sources of error could be due to the demagnetization procedure. Static (nontumbling) demagnetizers can produce unwanted, artificial magnetization for two principal reasons.

First, asymmetry of the decaying AF waveform can add an unintentional ARM, usually to weakly magnetized samples. This did not occur because: (a) the SI4 demagnetizer has an integral ARM detection and cancellation circuit; (b) upon completion of demagnetization (90 mT AF) the samples retain > 2

---

**Fig. 1.** (a) Loading arrangement for a cylindrical sample in triaxial deformation, principal stresses $P_1 > P_3$. (b) Schematic microscopic loading arrangement in a dry aggregate; $S_a$, $S_b$, $S_c$ are examples of grain-scale contact normal stresses. These will be much larger than $P_1$, $P_3$. (c) Schematic loading arrangement of (b) with pore fluid giving reduced effective normal stresses.
mA/m; (c) I use an alternating sequence of two sets of three different positions for AF demagnetization. This draws attention to spurious ARM.

Second, static demagnetizers can produce unwanted, gyroremanent magnetization (Stephenson, 1993 and earlier pers. commun.). However, this is usually a problem in magnetite of very high coercivity, which does not concern us here. Moreover, as GRM accumulates at the end of AF demagnetization sequence (> 100 mT; Dankers and Zijderveld, 1981; Stephenson, 1993) the intensity of magnetization increases. This did not happen with any of the samples in this study. Finally, Stephenson defined a “Zijderveld-Dunlop” technique that permits detection and cancellation of spurious GRM during AF demagnetization (A. Stephenson pers. commun., 1992). I wrote these into the programs for the JRSa and Molspin magnetometers. It failed to detect GRM during the high field demagnetization of the ARM samples (60–90 mT AF).

4. Experimental deformation

Teflon-jacketed, magnetized samples are placed in a fixed orientation in the pressure vessel of the triaxial rig for each experiment. The pressure vessel has a ~ 30 μT magnetic field in a direction 330°/34° with respect to the vertical axis of the sample cylinder. The strength and direction of the vessel’s field has remained constant for more than six years.

When the vessel is not under pressure, its magnetic field is determined by:

(1) Heating demagnetized samples and then allowing them to cool in the pressure vessel. This determines the field direction. By cooling the same samples in the Earth’s field outside the vessel one can estimate the relative strength of the pressure vessel’s field.

(2) Inserting a Hall probe into the pressure vessel. When the vessel is under pressure, its magnetic field is determined by:

(1) Hydrostatic or triaxial deformation of demagnetized samples and measuring the PRM they acquire.

(2) Triaxially deforming magnetized samples and, by AF demagnetization, determining the components of stress magnetization added to them.

For confining pressures  250 MPa combined with differential stresses < 100 MPa, these techniques show that more than 100 samples at different stress levels remagnetized in the direction 330°/34°. The pressure vessel field is temporarily deflected only when these stress limits are exceeded.

Silicone oil provides a lateral pressure \( P_3 = 150 \) MPa to the sides of the cylindrical specimen. This value suppresses noncontinuum behavior and allows ductile deformation of the calcite-cement aggregate. Macroscopic hydrostatic stress is achieved with appropriate valves that equalize \( P_1 \) with \( P_3 \) (Fig. 2). However, \( P_1 > P_3 \) for the differential stress tests. A personal computer controls the difference \( P_1 - P_3 \) by constantly adjusting the rate of pumping to the piston. This allows simple axial flattening of the cylinder. I used two types of tests. The first were constant natural strain-rate tests in which the deformation was controlled to give a constant rate of proportional shape change in the sample. The second type of test increased the differential stress at a constant rate until a chosen stress level. That stress level was maintained for 1.5 h.

The computer records the differential stress \((P_1 - P_3)\) with a precision of ±0.1 MPa. A pressure transducer records confining pressure \( P_3 \) and a linear voltage displacement transducer measures the displacement of the piston. Their DC signals are amplified and then received via a 12-bit analog-digital converter in a personal computer. My computer program determines apparatus distortion, sample strain and macroscopic stresses and uses this information to control the syringe pump that produces the desired loading sequence. The program also records, saves and plots the data.

Hydrostatic stress \( P_3 \) is applied to the cylindrical samples (i.e., \( P_2 = P_3 \) around the sides of the sample). Initially \( P_1 = P_2 = P_3 \), \( P_1 \) is provided by a piston acting on the ends of the cylinder. Subsequently, the piston is driven against the cylindrical sample to provide differential stress \((P_1 - P_3)\) as required (Fig. 1a). During the experiment the computer records principal stresses, \( P_1 \) and \( P_3 \), \( P_2 \). However, the normal stresses acting across individual grain contacts are much larger. For example, the macroscopic stress \( P_1 \) acts over the large area of the end of the cylinder. Within the sample, forces act across small grain-contact areas to yield stresses \( S_n \).
Fig. 2. Mohr diagram for stress showing the effect of pore fluid pressure ($P_f$); macroscopic normal stresses are $P_1$, $P_3$.

$S_b$, $S_c$ etc., much larger than the externally applied stresses (Fig. 1b). Even hydrostatic stress ($P_1 = P_3$) at the sample scale causes differential stress at the grain scale. Hydrostatic stress cannot exist in a non-continuum.

This arrangement assumes that no pore fluids are present. The hydrostatic pressure ($P_1$) of a pore fluid reduces all intergranular normal stress to yield the effective stresses, e.g., $S_n - P_f$, $S_n - P_1$ of Fig. 1c. I did not introduce a pressurized pore fluid in this study. Nevertheless, the ductile cement gel and the free water not yet taken up by progressive curing provide significant pore pressure. For example, when using a vented upper piston the cement matrix flows from the pressure vessel and the extrusion of sample water suggests saturation.

A Mohr diagram for stress (Fig. 2) illustrates the state of stress for a two-dimensional cross section of the cylinder. Macroscopic normal stress ranges between $P_1$ and $P_3$. Shear stress ranges between $(P_1 - P_3)/2$ and $-(P_1 - P_3)/2$. On the circle, we find possible combinations of normal stress and shear stress for each direction in the plane of observation. Pore fluid pressure ($P_f$) of the cement gel displaces the Mohr circle toward the origin of the Mohr diagram (Fig. 2) but cannot alter shear stress. If the circle touches the failure envelope for the material, failure follows on a shear fracture ($P_1 \gg P_3$ or large $P_f$) or on a tensile fracture (small $P_1 - P_3$ and large $P_f$). I arranged conditions in the following experiments so that this would not occur. Instead, specimens compact permanently with particulate flow of the calcite and magnetite grains. Particulate flow is augmented because the frictional resistance to grain boundary sliding is reduced with lowered intergranular normal stress (Borradaile, 1981).

5. Constant strain-rate tests

A dozen natural strain-rate experiments were used. Natural strain rate refers to the change in the current length, rather than the initial length. This is preferred where we need to compare instantaneous phenomena of stress and remagnetization. I limited constant strain-rate tests to < 16% shortening. It is sufficient to test the hypothesis that the path of the remagnetized vectors in space is independent of the orientation or magnitude of principal stresses or strains and avoids the grain rotation that accompanies larger strain (Borradaile, 1993). The same strain was also use in the constant-stress tests, to be discussed below.

Triaxial tests are coaxial at the macroscopic scale (Fig. 1). They used $P_3 = 150$ MPa (1.5 kbar) and a differential stress ($P_1 - P_3$) ranging up to 200 MPa as required by the computer program to achieve a constant strain rate of $(1 \pm 0.05) \times 10^{-5}$ s$^{-1}$. Typi-
6. Constant stress-rate tests

The bulk of the remagnetization experiments used a different computer algorithm to control the triaxial rig. This changed the magnitude of the differential stress \((P_i - P_3)\) at a constant rate \((0.06-0.08\text{ MPa/s})\) until a chosen differential stress was achieved. The computer program then maintained \(P_i - P_3\) for 1.5 h, and then unloaded the sample. Constant stress tests take into account the changing shape and flow rate of the sample. Thus, they differ from the creep tests of engineering in which axial load is constant. The constant stress tests strongly remagnetized the samples, especially for high values of \(P_i - P_3\). Details of a typical test are shown in Fig. 4; Figs. 5 and 6 review a broad selection of tests.

7. Changes in rock magnetic properties with deformation

Grain size of the added magnetite is 3 \(\mu\)m \(\pm\) 25%. It has low dislocation densities compared with natural magnetite, especially that crushed in the labora-
Triaxial deformation with $P_3 = 150$ MPa changes remanence and hysteresis properties. This is most easily shown by magnetizing the sample and then by incrementally demagnetizing it (AF demagnetization). These results are processed to yield a diagram that shows the frequency distribution of the resistance (coercivity) to demagnetization. If high coercivities dominate, normally the rock will be a faithful paleomagnetic recorder.

Several samples were magnetized with a saturation isothermal remanence (SIRM) and AF demagnetized. After deformation the SIRM was reapplied and again demagnetized (Fig. 7a). Graphs of changes in the remanence remaining at each stage in the demagnetization reveals the coercivity spectrum (Fig. 7b).

This information is useful as it shows the frequency distribution of coercivity available for recording a paleomagnetic signal. If the peak is far to the right, high-coercivity grains dominate. Such a spectrum is said to be "hard". In contrast "soft" spectra with peaks far to the left mostly contain grains that can easily lose their magnetization.

The spectrum reduces its peak and skews slightly to higher coercivities after the application of a large hydrostatic ($P_1 = P_2 \gg 0$) pressure or of combined differential stress and hydrostatic pressure ($P_1 > P_2 > 0$). In Fig. 7b and d, one sees the differences between several different spectra. A perfectly hydrostatic state of stress does not produce finite strain in an isotropic, homogeneous continuum. However, the hydrostatic stress applied macroscopically to the sample produces a nonhydrostatic stress distribution at the grain scale due to the noncontinuum nature of the framework of mineral grains.

One should also note that the cement’s magnetic properties mature with age. Two batches of the material were made, 12 months apart. Identical ingredients and identical conditions prevailed. In Fig. 7c is shown that the coercivity spectrum changes with age, in a similar way to the changes produced by deformation; grains of higher coercivity are added. Apparently, hydration of the setting cement precipitates new magnetite, in sizes smaller than that added to the mixture. This effect is only noticeable after many months whereas the deformation experiments last a few hours. Thus, cement maturation is unlikely to contribute significantly to the coercivity changes during in experiments. The coercivity changes in constant-strain-rate tests are revealed in Fig. 8. There is a significant reduction in coercivities below 20 mT and an increase above that value.

8. Constant strain-rate experiments: directional control on remagnetization

The following experiments test the hypothesis that the remagnetized direction is independent of the
Fig. 7. AF demagnetization experiments on the synthetic material. (a) Decay of normalized ARM remanence intensities before deformation, and of ARM applied to the same samples after deformation. Measurements at 2.5 mT intervals. (b) Differences between successive measurements in (a) to yield spectra of the coercivity of remanence. (c) The change in the coercivity spectrum after the synthetic material for 1 yr on the coercivity spectrum. (d) The effect of deformation on the coercivity spectrum.

Fig. 8. Changes in the coercivity spectrum of the synthetic material caused by constant strain-rate deformation (16% axial shortening). Note that the postdeformation measurements are of an ARM reapplied after deformation. Thus, the differences between pre- and postdeformation measurements show changes in the magnetic properties of the material.
initial remanence and the geometry of strain. Experimental remagnetization is reproducible if homogeneous strain is established at the sample scale where finite strain is not too large (≤ 16% shortening). Such small strains exclude the possibility of significant grain rotation that could simply turn the old magnetization.

I used constant strain-rate tests with progressively increasing differential stresses (Fig. 3). The tests have $P_3 = 150$ MPa, a natural strain rate of $(1 \pm 0.05) \times 10^{-5}$ s$^{-1}$ and a nominal strain of 16% shortening of the cylinder axis. This strain is enough to allow remagnetization but prevents heterogeneous failure or barreling. I excluded a few specimens that did fail, usually due to the collapse of bubbles in the interior of the cement cores (e.g., c9404, c9405, Fig. 3). On average, the peak differential stress for these tests was 140 MPa (Fig. 3). In contrast, the constant

Fig. 9. Constant strain-rate experiments at $10^{-5}$ s$^{-1}$ at 150 MPa confining pressure yielding 16% shortening of the cylindrical samples in 4 h. This strain produces negligible strain effects on the grains and remanence (Borradaile, 1993). (a) Selected paths of vector components isolated by AF demagnetization (symbols explained in inset below). The maximum compressive stress ($P_3$) and shortening axis of the samples is vertical. (b) Great circle paths fitted to (a) intersect near the field direction (★) in the pressure vessel. (c) Contours of the orientation distribution of the vector components isolated by AF demagnetization below 15 mT. These magnetically soft components have a maximum eigenvector (and vector mean) close to the field direction (★) in the pressure vessel.
stress tests described later involved differential stresses ≤ 100 MPa (Figs. 5a and 6a).

Each sample has an initial ARM in a different direction (shown by the squares in Fig. 9a). The intensity was approximately 1 A/m in each case. I measured postdeformation remanence in 19 to 26 steps of incremental AF demagnetization to a maximum peak field of at least 70 mT. (Demagnetization was in increments of 2.5 mT until 20 mT, after that in 5 mT steps, with occasional smaller steps where needed.) The demagnetization paths are shown in Fig. 9a: note that initial remanence may be on the upper or lower hemisphere. The demagnetization shows that the lowest coercivity components lie near the direction of the pressure vessel’s field (declination 330°, inclination 34°). Components of successively higher coercivity approach the original remanence direction. Best-fit great circles to the demagnetization paths (solid lines, Fig. 9b) show that the dispersed vector components lie on the shortest path between the initial magnetization and the pressure vessel’s field. Dashed lines extrapolate these great circles, in some cases to the opposite hemisphere. They all pass close to the field direction in the pressure vessel. Magnetically soft vector components (< 15 mT) clustering around the vessel’s magnetic field direction are shown in Fig. 9c. Their maximum eigenvector corresponds to the field direction in the pressure vessel with great precision (Fig. 9c).

Vectors are illustrated for individual samples in Fig. 10. Highest coercivity components retain the predeformational remanence direction whereas successively softer components smear toward the remagnetizing field direction of the pressure vessel. Vector components isolated below 15 mT are almost parallel to the remagnetizing field. In Fig. 10b the remagnetizing field is almost antiparallel to the initial, predeformational remanence so that one can identify the turning point that marks the uppermost coercivity of remagnetization. The upper coercivity limit for remagnetization depends on the duration of the test and the peak differential stress reached; this will be discussed later.

Several tests reveal nonprogressive behavior of the vectors during demagnetization ("back-tracking"). Instead of the demagnetized vectors gradually changing orientation away from the remagnetizing field toward the initial remanence direction, they briefly reverse direction without significant change of magnitude. This usually occurs for a few vector components isolated above 65 mT (Fig. 11). It is considered that the data are not artefacts of the demagnetization procedure for the following reasons. First, vector magnitudes after 60 mT AF demagneti-

---

![Fig. 10. Vector plots of typical remagnetizations during constant strain-rate tests.](image-url)
A particular test deserves mention (Fig. 11f). It concerns a specimen that was initially magnetized incorrectly. It was first given a full spectrum ARM with the bias field applied from AF demagnetization from 200 mT. Then, I applied a second ARM in a different direction during AF demagnetization over a window from 140 mT downwards. During the post-deformation demagnetization the vector moves away from the magnetization direction and stabilizes between 30 and 60 mT near the second predeformation remanence. During further demagnetization the vector drifts toward the first predeformation remanence and then finally back toward the remagnetization direction for coercivities near 110 mT. (The smallest remanence magnitudes are a few mA/m.) This con-

---

**Fig. 11.** Stereographic projections (both hemispheres, equal area) for the vector components of remagnetization experiments in constant strain-rate tests (16% shortening). Components were isolated by AF demagnetization. (a) Low-coercivity components (< 15 mT) were added during deformation in directions close to the pressure vessel's field. Inset below is a vector plot of the most coercive components that also remagnetized parallel to the field in the pressure vessel. (b–f) Segments of stereographs that illustrate the angular distribution of vector components after deformation. Components isolated by AF demagnetization from 25 to 60 mT remember the initial remanence direction. Softer components, and in some cases a few harder components cluster around the remagnetizing field direction [★ in (a) and (f)].
firms both low-coercivity (< 15 mT) and high-coercivity (> 65 mT) grains may remagnetize.

9. Constant stress experiments: differential stress and remagnetization

Macroscopic differential stresses from zero (hydrostatic compaction) up to 120 MPa were applied to different samples for 1.5 h, following the same controlled, loading rate (Figs. 5 and 6). Grains experience differential stress even if the macroscopic stress is hydrostatic \( P_1 = P_3 \). Of course, they will experience higher intergranular stresses with a macroscopic differential stress \( P_1 - P_3 > 0 \).

Coercivity spectra derived from the AF demagnetization of SIRM applied both before and after deformation are presented in Fig. 12. The small differences are significant because SIRM \( > 3 \) A/m and the JR5a spinner has a sensitivity of at least 0.01 mA/m. The graphs show spectra from hydrostatic tests (Fig. 12a) and from tests in which \( P_1 = 150 \) MPa with differential stresses of 55 and 95 MPa (Fig. 12b). In Fig. 12c and d we see the differences between the spectra for the predeformation and post-deformation state. In Fig. 12c is shown that hydrostatic compaction at \( P_1 = P_3 = 50 \) MPa produces no consistent change. However, hydrostatic compactions \( P_1 = P_3 > 50 \) MPa decrease the coercivity contribution below 25 mT and increase the contribution above 25 mT. This is also shown for differential stresses of 32, 55 and 95 MPa with

![Fig. 12. Coercivity spectra (explained in Fig. 7) for constant stress tests (shortening strain < 4%) in which peak stress was maintained for 1.5 h. (a, c) Hydrostatic compaction \( P_3 = 50, 150 \) and 250 MPa. (b, d) Triaxial tests each with a different constant differential stress.](image-url)
hydrostatic confining pressure of 150 MPa (Fig. 12d). A 25 mT boundary for the redistribution of coercivity is corroborated with constant differential stresses ranging from 5 to 85 MPa and \( P_3 = 150 \) MPa. High coercivity characterizes fine-grained magnetite and but also large stressed grains with high dislocation density (King et al., 1982; Jackson et al., 1993). It is difficult to escape the conclusion

Fig. 13. Vector plots for triaxial deformation at constant differential stress maintained for 1.5 h. Demagnetization steps are 2.5 to 20 mT and thereafter in steps of 5 mT. The initial ARM was almost antiparallel to the pressure vessel’s field (330°/35°). The remagnetized components are revealed by the first three demagnetization steps for hydrostatic compaction (a) and affect more demagnetization steps as the differential stress (DS) increases (b–e). The remagnetization is larger in (f) than in (d) despite the same differential stress level. This is because the initial loading stress rate for (f) was ten times larger.
that stress causes the redistribution of coercivity. Hydrostatic compaction ($P_1 = P_3$) below 100 MPa fails to redistribute coercivity because the microscopic, grain-scale differential stresses are too low in this material (Fig. 12c).

The remagnetization of samples with an initial ARM approximately antiparallel to the field in the pressure vessel is shown in Fig. 13. Each test used $P_3 = 150$ MPa and a constant differential stress ($D\delta$) ranging from 5 to 92 MPa for 1.5 h. Hydrostatic pressure alone (Fig. 13a) produces modest remagnetization affecting coercivities below 7.5 mT. Macroscopic differential stresses of successively higher value (Fig. 13b–e) yield a proportionately longer remagnetization vectors affecting a progressively wider range of coercivities. In experiment C9416a (Fig. 13f) the differential stress was 50 MPa but the remagnetization exceeds that of C9427 (Fig. 13d) with the same stress level. However, in C9416a the initial loading rate was ten times higher than in all

Fig. 14. Vector plots (d–f) showing remagnetization in constant stress tests. The initial ARM was almost antiparallel to the field (330°/35°) in the pressure vessel. Similar information in terms of vector magnitudes only, for other tests, is condensed in (a–c). See text for explanation.
At this point in the experimental program, I exhausted the initial batch of samples made in January 1993. A second block made from identical materials in January 1994 provided samples for the remainder of the experimental program. These samples bear "x" in the designation of experiments, e.g., C94x15. The younger material has less mature cement gel and minor differences in coercivity (Fig. 7). Vector graphs illustrate the remagnetization due to deformation in the C94x series in Fig. 14. All vector graphs are based on ≥ 19 steps of AF demagnetization.

In Fig. 14d is illustrated that hydrostatic compaction affects a broader range of coercivities than in the more mature samples (Fig. 13). This is true also for remagnetization at higher differential stresses (Fig. 14e and f at 65 and 95 MPa, respectively). For brevity, Fig. 14a–c summarizes most remagnetization experiments using magnitudes alone. Since the initial and remagnetization vectors are antiparallel, the changing position of the maximum (Y in Fig. 14a) shows the degree of remagnetization and the
range of coercivities affected by remagnetization. Note that the initial minimum (X in Fig. 14a) for the position of the postdeformation vector occurs at zero mT but for significant remagnetization (Fig. 14f) the shortest vector occurs at 15 mT. The displaced minimum at Z in Fig. 14c is an artefact of presentation, as the remagnetization leg of the vector path passes closest to the origin of the plot (e.g., Fig. 14f). Note

Fig. 16. Partial stereograph (both hemispheres, equal area) illustrating remagnetization at different values of constant differential stress (DS = P$_1$ - P$_3$). $\star$ = field in the pressure vessel. The original ARM is remembered by coercivity components isolated by AF demagnetization in the range 25–65 mT. Softer components, as well as some harder components show evidence of remagnetization parallel to the remagnetizing field ($\star$).
that the initial ARM was 1 A/m in each case and that after AF demagnetization the samples still retained > 2 mA/m. Thus, precision is not of concern.

Stereographic projections show spatial aspects of the remagnetization paths more effectively (Figs. 15 and 16). After deformation, remanence lies closer to the remagnetizing field than to the initial ARM. Stepwise AF demagnetization isolates successive vector components that approach the initial ARM along a great circle. Coercivities between 25 and 55 mT preserve the initial remanence. Higher-coercivity components track back toward the direction of the remagnetizing field. Thus, low- (< 25 mT) and high-coercivity (> 55 mT) grains remagnetize whereas grains of intermediate coercivity remember the initial remanence direction. The constant differential stress ranging from 5 to 92 MPa does not change these limits. However, higher differential stresses increase the upper coercivity limit for remagnetization (see also Fig. 17c).

10. Discussion

Experimental triaxial deformation at confining pressure $P_3 = 150$ MPa (1.5 kbar) simulates depths of $\geq 4$ km, but at 22°C. Constant differential stresses, chosen from the range 92 MPa > $P_1 - P_3$ > 0 MPa were applied for 1.5 h. Under these conditions, initial ARM magnitude was reduced by stress demagnetization. The 30 $\mu$T field in the pressure ves-
sel, although weaker than the Earth’s field, significantly remagnetizes the samples under differential stress. Stress remagnetization exceeds residual ARM if $P_1 - P_3 > 30$ MPa, and increases steadily until approximately 80 MPa (Fig. 17a). Higher differential stress $100$ MPa $> P_1 - P_3 > 80$ MPa causes a five-fold increase over the residual ARM (Fig. 17b). Stress remagnetization intensity increases with successively higher differential stresses. Also, the new remanence has progressively higher upper coercivity limits at higher differential stresses (Fig. 17c).

Comparison of pre- and postdeformation coercivity spectra of SIRM shows that hydrostatic stresses with $P_1 - P_3 > 100$ MPa cause a permanent redistribution of the spectrum of coercivity of remanence. This is without any macroscopic differential stress. Storage tests of up to nine months show that this is not an ephemeral effect. Larger confining pressures do not significantly enhance this effect because they do not increase the intergranular differential stresses (Fig. 12) as effectively as the application of a small macroscopic differential stress. The main batches of experiments used $P_3 = 150$ MPa, and the application of macroscopic differential stress ($92$ MPa $> P_1 - P_3 > 5$ MPa) caused no further redistribution of coercivity. Thus, differential stress at the microscopic scale must exceed a threshold value before triggering the changes in coercivity. A clear redistribution of coercivity is shown where the hydrostatic component $P_3 \geq 100$ MPa, but notably where $P_3 = 150$ MPa and the differential stress $P_1 - P_3 > 20$ MPa. The pattern is the same for differential stresses up to 92 MPa. The proportion of material with coercivity $> 25$ mT decreases and the proportion with coercivity $> 55$ mT increases. Clearly, these results relate to the grain-size distribution, loading framework and peculiar materials studied. Direct transfer to nature is not possible but the notion of a threshold stress level for the redistribution of coercivity may be general. That grain-scale differential stress cannot be estimated from the macroscopic experimental stresses $P_1$ and $P_3$ although it must be much higher than $P_1 - P_3$.

In rock magnetism, we associate coercivity of remanence of magnetite with specific grain sizes, e.g., $> 30$ mT for single domain magnetite and $< 15$ mT for multidomain magnetite (e.g., King et al., 1982). This is the basis of magnetic granulometry and is important to environmental magnetism (Thompson and Oldfield, 1986). However, Scanning Electron Microscopy of previous experiments in calcite aggregates under similar conditions show that the increase in bulk coercivity of remanence is not due to reduction in grain size (Borradaile, 1991; Borradaile and Mothersill, 1991). One may infer that differential stress moves and fixes domain walls. The grain raises its coercivity of remanence in comparison with an undeformed grain and now has the properties of a finer grain. Jackson et al. (1993) call this “magnetic hardening”, by analogy with “work hardening” of rock mechanics. Thus, magnetic granulometry is valid for comparing grain sizes only where the grains have similar stress histories. Borradaile and Jackson (1993) confirmed this by comparing the effects of hydrostatic compaction on pre-stressed magnetite with high dislocation densities and on chemically precipitated magnetite with low dislocation densities.

Low-field stress remagnetization adds new stress-remanence vector components parallel to the remagnetizing field. The attitudes of the initial remanence, the strain axes and the initial remanence are unimportant (Fig. 9). In view of the heterogeneous grain-scale deformation, these conclusions should extend to the general case of macroscopic, noncoaxial strain histories, although these experiments used a macroscopically coaxial strain history.

The initial remanence direction is preserved in grains with coercivity of remanence between 25 and 55 mT. Magnetically softer grains (especially $< 10$ mT) and some magnetically harder grains ($> 60$ mT) include vector components induced by the remagnetizing field. The magnetically soft grains must be large MD grains remagnetizing by stress-induced domain-wall rearrangement. Grains with coercivities of 25–55 mT may be small PSD grains or larger grains magnetically hardened by the introduction of dislocations; these preserve the original remanence direction.

Why do grains of high remanence coercivity ($> 60$ mT) remagnetize? One possible explanation is that these vector components reside in very small grains that are free to rotate in the plastically deforming cement gel. Bulk strains are very low, with the samples compacting by $< 10\%$ and anisotropy of magnetic susceptibility fails to detect a significant
fabric. In contrast, microscopically the cement deforms by heterogeneous, locally high strain. This has been observed by SEM and shown by the extrusion of the cement matrix through vented pistons in other experiments. Thus, tiny SD grains may rotate toward the horizontal plane during shortening of the vertical axis. These grains may then align their spontaneous moments with the shallow field in the pressure vessel.

The creation of new, fine magnetite is a second possibility. During curing, the cement’s coercivity spectrum changes so that the proportion of grains with coercivity $> 25$ mT increases (Fig. 7). One might attribute this to the precipitation of fine magnetite during the curing process, accelerated by deformation. The spontaneous moments of the newly grown SD grains would be parallel to the remagnetizing field.

A third explanation may be that crystal dislocations trap domain walls that remember the remagnetizing field direction. The appropriate vector component would preserve the remagnetizing-field direction. It may coexist in selected sites of a PSD or MD grain that also preserves the initial ARM.

Transferring conclusions from experiments to nature is, at best, a thorny issue. Nevertheless, similar small differential stresses $> 30$ MPa could trigger syntectonic remagnetization of magnetite-bearing rocks in nature. Hudson et al. (1989) tentatively proposed this for part of the Idaho thrust belt.

In this scenario thermal or chemical effects are unnecessary. The instigation of mild tectonism in the presence of a low field is sufficient to remagnetize rocks bearing suitable magnetite, preferably with low initial dislocation densities (Borradaile and Jackson, 1993). Fortunately, only the initial remanence direction and the direction of the remagnetizing field are significant. The orientations and changes in orientation of principal stresses are unimportant, possibly to the surprise of structural geologists. This is true wherever the strain accumulating during and after remagnetization is small ($< 20\%$). Otherwise grain rotation and strain effects will complicate the issue, spinning grains with their internal magnetic moments (Borradaile, 1993). Vector components of remagnetization disperse along a great circle from the initial remanence toward the direction of the remagnetizing field. Techniques for the separation of such smeared remanences are available (Hoffman and Day, 1978; Dunlop, 1979; Halls, 1979). Low-coercivity remanence components are subparallel to the remagnetizing field and very high coercivity components may remagnetize also. Intermediate coercivity components ($20–55$ mT) remember the primary remanence direction.

Elevated temperatures enhance dislocation motion so that the stress-induced remagnetization may be more effective above room temperature. However, the general process of thermoviscous remagnetization is more common, and thermal changes in magnetic mineralogy may be significant (Hirt and Gehring, 1991). Thus, thermal and stress remagnetization processes will compete. Experiments to test their relative importance would be exceedingly demanding. Nevertheless, the temperature sensitivity of thermoviscous remagnetization shown by the Néel equation for SD magnetite is much greater than the temperature sensitivity of dislocation motion. Thus, if stress remagnetization is significant in nature, it will be at low temperatures in subgreenschist, pumpellyite or blueschist facies or in upper crustal structures (e.g., Hudson et al., 1989).

Acknowledgements

This work was supported by an NSERC operating grant. Ann Hirt and an anonymous reviewer are thanked for helpful and constructive criticism.

References

Borradaile, G.J. and Mothersill, J.S., 1991. Experimental strain of


