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Direction Changes of Isothermal Remanent Magnetization (IRM) for Multidomain Particles Produced by Stationary Alternating Field Demagnetization

SAHAT SADIKUN and ALAN STEPHENSON*

Department of Earth Service, UKM Sabah Campus Locked Bag 62, 88996 Kota Kinabalu, Sabah

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ABSTRAK

Pengawamagnetan ulang-alik (a.f) satu-paksi dan tiga-paksi ke atas remanen pemagnetan isoterma (IRM) untuk zarah magnetit beraneka saiz telah dikaji. Pengawamagnetan satu-paksi ke atas IRM mengalihkan vektor remanen tegak lurus terhadap paksi a.f. sejurus sebelum semua remanen dinyahkan. Peralihan sudut apabila dilakarkan terhadap pecahan remanen dinyahkan, tidak menunjukkan sebarang pergantungan terhadap saiz zarah. Pengawamagnetan tiga-paksi terhadap IRM pula menghasilkan perubahan arah secara progresif.

ABSTRACT

Single-axis and three-axis alternating field (a.f) demagnetizations of isothermal remanent magnetization (IRM) for magnetitie particles of various sizes have been investigated. Single-axis demagnetization of IRM shifted the remanent vector perpendicular to the a.f. axis just before the remanence was completely removed. The angular shift when plotted against the fraction of remanence lost, did not show any dependence on particle size. Three-axis demagnetization of IRM produced progressive direction changes.

INTRODUCTION

The angle between the a.f. axis and the magnetization vector is important in the stationary a.f. demagnetization process. Its role significance was investigated as early as 1937 by Schmidlin (1937). Stephenson (1983) showed theoretical and experimental results of single-axis demagnetization at various angles to the remanence i.e. isothermal remanent magnetization (IRM) and anhysteretic remenent magnetization (ARM) or thermo-remanent magnetization (TRM). The demagnetization was most effective when the a.f. was parallel to the remanence vector and least effective when the a.f. was perpendicular to the remanence vector. In other cases, it produced an angular shift and the remanence moved to a direction normal to the a.f. axis.

Stephenson also (1983) showed theoretical and experimental results of three-axis demagnetization of ARM and IRM. Three-axis demagnetization of ARM did not produce any angular shift. Three-axis demagnetization of IRM caused the remanence vector to move towards the nearest direction which made an angle of $\cos^{-1}(1/\sqrt{3})$ with the a.f. axes unless the initial IRM was in the plane of two of the a.f. axes, in which case it moved to an orientation which lay at 45° to the two a.f. axes defining that plane.

* Department of Geophysics, School of Physics, University of Newcastle upon Tyne, Newcastle upon Tyne, NE2 7RU, United Kingdom.

The above results can be explained theoretically for single domain particles and it is of considerable interest to repeat the above experiments on multidomain particles to determine whether these behave in a similar way. It might be expected that the multidomain particles would behave differently in which case single-axis a.f. demagnetization at an angle to the remanence vector might prove to be a useful way of distinguishing between single and multidomain particles.

MATERIALS AND METHODS

Magnetic Minerals

Iron appears to be the most abundant transistion element on earth. It has a high spontaneous magnetization at room temperature, about 218 $JT^{-1}Kg^{-1}$ (Collinson 1983) and combines with other elements to form remanence carrying minerals as shown in the ternary diagram of *Fig. 1.*

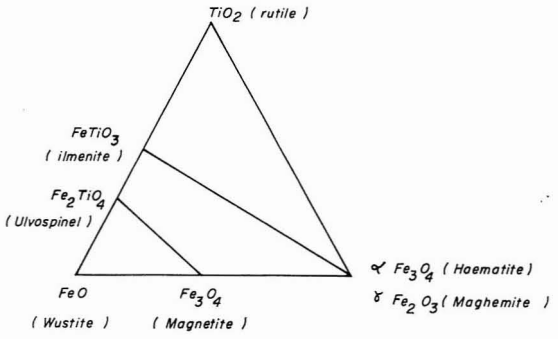

Fig. 1: Ternary diagram showing the composition of the most important remanence carrying minerals.

A fundamental question of rock magnetism is whether in a particular rock, the remanence carrying minerals are in the single domain or multidomain state. If the particle size is below a critial value, domain walls will not form and the most stable state is uniform magnetization. Kittel (1946) estimated the critical sizes of single domain particles in the form of rods, cubes and spheres. He found that the critical values for an iron sphere was about 0.01 μm but larger critical values applied for elongated particles. Single domain particles generally have high coercivity. Smaller particles exhibit superparamagnetism at room temperature and do not contribute to the remanence.

For any magnetic material there is a maximum size of particle for a single domain, referred to as the critical size. Larger particles are divided into uniformly magnetized domains separated by domain walls. The larger the particle, the greater the number of domains. The larger the particle, the greater the number of domains. The existence of multidomain structure has been studied using many techniques. One of these is the powder pattern technique as described by Soffel (1981). The magnetic particle that is of interest in this project is magnetite.

Magnetite (Fe_3O_4) is very strongly magnetic at room temperature with spontaneous magnetization of about 90 $JT^{-1}Kg^{-1}$ (Stacey and Banerjee 1974). It is an important constituent of igneous rocks. It exhibits ferrimagnetism, i.e. the sub-lattice magnetizations are opposite but unequal thus producing a net magnetization along a diagonal of the cubic structure. At 118 K, magnetite undergoes a phase transition and becomes orthorhombic (Nagata *et al.* 1964). Dunlop (1973) studied magnetite particles and found that the critical size is about 0.05 – 0.06 μm. Data for 1.5 – 120 μm magnetite agree reasonably well with multidomain theory (Parry 1965).

A.F. Demagnetization of Single Domain and Multidomain Particles

Multidomain particles can be demagnetized whilst the monodomain particles cannot. In the latter, the a.f. only changes the direction of magnetic moment. However, there are some non perfect multidomain particles which still have finite moments after a.f. demagnetization since the lowest energy state does not correspond to zero net magnetic moment.

The orientation of the applied field relative to the easy axis is critical for bringing about the reversal of magnetization (*Fig. 2*). In a single domain particle, the anisotropy field, H_{anis} is given by $2k_u/U_oM_s$, where U_o is the permeability of free space, M_s is the spontaneous magnetization per unit volume and k_u is the uniaxial anisotropy coefficient. Stoner and Wohlfarth (1948) found that the

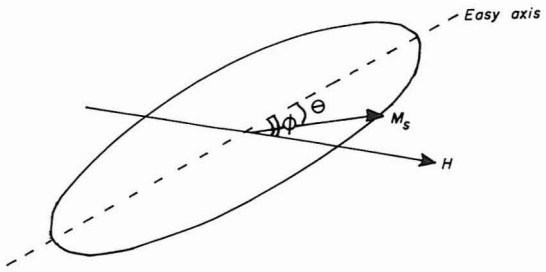

Fig. 2: A uniaxial single domain particle with the spontaneous magnetization per unit volume M_s subjected to an applied field H at an angle of Φ to the easy axis.

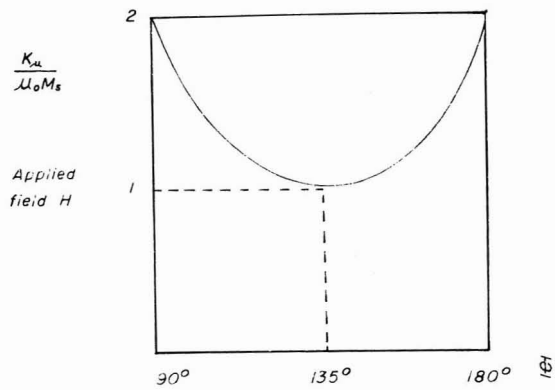

Fig. 3: Shows the field needed to give irreversible magnetization with the field applied at various angles to the easy axis.

reversal of magnetization took place most easily when the field was applied at an angle of 135° to the easy axis and required a field of $H_{anis}/2$ (*Fig. 3*). As I deviated from 135°, larger fields were needed and finally became H_{anis} at Φ = 180° or 90° i.e. when the field was applied parallel or perpendicular to the easy axis.

Theories on remanence direction changes during a.f. demagnetization for single domain particles are discussed in Stephenson (1983). Experimental results on a rock sample were also shown.

For multidomain particles such as magnetite, the coercivity (a quantitative measure of the resistance to changes) of remanence is given by the equation, (Stacey and Barnerjee 1974):

$$H_{cr} = H_c(1+NX_i)$$

where H_c and X_i are the intrinsic coercive force and intrinsic susceptibility respectively. In this case, median destructive field (MDF) is used as a measure of coercivity of remanence.

It is a necessary feature of multidomains, even when they have been given a stable remanence such as thermo-remanent magnetization (TRM), that some demagnetization occurs even in quite moderate alternating fields, whereas single domains may completely resist demagnetization until a field comparable to the coercivity of the remanence has been applied.

Experimental Techniques

In general, the most widely used methods of magnetic cleaning (demagnetization) of rock samples in palaeomagnetism and rock magnetism are thermal demagnetization and a.f. demagnetization. In this paper only the a.f. demagnetization method is used. The a.f. removes the unwanted magnetization by randomizing the magnetic moments of the magnetic materials. The instrument to carry out this demagnetization is described later.

Two different techniques of a.f. demagnetization are the tumbling method and the stationary method. The tumbling method was published by Creer (1959). The sample is spun around two or more axes in the presence of an a.f. The other, stationary method, was developed by As and Zijderveld (1958).

Several ranges of grain sizes of magnetite powder were used, they were < 0.7 μm, 0.7–2.2 μm, 2.2–4.4 μm, 4.4–7.6 μm, 7.6–13.1 μm, 13.1–25.5 μm, 25.5–45 μm, 45–53 μm, 53–63 μm, 63–75 μm and 75–90 μm. A Bahco centrifugal dust classifier (courtesy of the North East Area NCB Scientific Department) was used to separate the natural magnetic powder into different particle sizes. 0.05 gram of each particle size was weighed and put into a plastic cylindrical container 1.5 cm in diameter and 1 cm in height. The magnetite powder was later mixed with Specifix resin with the magnetite powder making up only about 6% of the volume. During the hardening of the resin, the container was inverted several times to prevent the heavier magnetite powder settling at the bottom of the container. The

container was then put into a perspex sample holder making the size of the sample 2.54 cm ini diameter and 2.54 cm in height.

The measurement of remanent magnetizations were made using the Molspin magnetometer which is based on the spinner magnetometer design of Mlyneux (1971). In measuring the magnetization of a specimen, the specimen is rotated within a ring fluxgate. The signal is then read 128 times per revolution of the sample and is passed to a computer which stores and processes the data. The specimen is rotated twice about each principal axis to reduce the effect of inhomogenity of the remanence of the specimen. It takes about 2 min to obtain the direction and intensity of the magnetization of each sample from all the six rotations.

The limit of measurement of weak specimens is set by the noise level of the instrument and can be determined by doing the same measurement procedure without a sample present. The noise level decreases with the square root of the rotation time and is about 2.5×10^{-5} A/m for 24 revolutions. The calibration of the instrument is done using a standard sample.

The demagnetization process was carried out using an a.f. demagnetizer. The maximum field of the demagnetizer is 100 mT at 200 Hz. Two types of demagnetization can be carried out using this instrument. For tumbling demagnetization, the sample is put in a tumbler container and tumbled about two perpendicular axes. For stationary demagnetization, the sample is simply placed at a required orientation to the axis of the demagnetization coil. Demagnetization is carried out by the demagnetization coil which produces an a.f. along its axis. The field in the coil is then slowly returned to zero. The sample is shielded from the earth's magnetic field by a double-walled Mu metal bucket shield.

A pulse magnetizer was used in the application of IRM to samples. The instrument which is portable, produces a pulse magnetic field of width 10 msec and of variable height up to 300 mT. The pulse is produced by discharging a bank of capacitors through a coil.

Before the experiment, the magnetite samples were demagnetized by tumbling to the maximum field of the demagnetization instrument (100 mT). The samples were then given an IRM in 40 mT along their Z axes. For constancy, all samples were oriented in the same position (i.e. the x axis of every sample in a particular direction) in the pulse magnetizer for every IRM application. Then the static single-axis demagnetization was carried out by mounting the sample on a non-magnetic orientation device. The Z axis of the sample was set at 15° to the a.f. axis, i.e. the a.f. was at (0°, 45°) (declination, inclination). The demagnetization was done stepwise up to the peak field of 80 mT for all the samples.

RESULTS AND DISCUSSION

Fig. 4 shows the variation of intensity of the magnetization of the sample as the peak field is increased. According to Stephenson (1983), the application of IRM along the Z axis with the a.f. at (0°, 45°) for single domain particles would change the inclination without affecting the declination. During this demagnetization process, there was, however, also a slight change in the declination due to the orientation of the IRM being slightly misaligned with the Z axis. Hence, the angular change ψ, of the IRM vector for each demagnetization field was calculated using a computer. *Fig. 5* shows this angular change with increasing peak field.

The demagnetization field needed to remove half the remanence MDF (median destructive field) of each sample was determined from *Fig. 4* and is listed in Table 1. Parry (1981) used MDF as an index of stability. The angular shift for each MDF for the step demagnetization was determined from *Fig. 5* and is listed in Table 1.

The experiment was repeated with each sample demagnetized at each MDF and the angular shift ψ calculated and listed in Table 1. Table 1 shows that the remanence acquired in a 40 mT IRM decreases with decreasing particle size. The intensity graphs in *Fig. 4* show that the resistance to the demagnetization process increases with decreasing particle size. The particle of 75–90 μm exhibited the

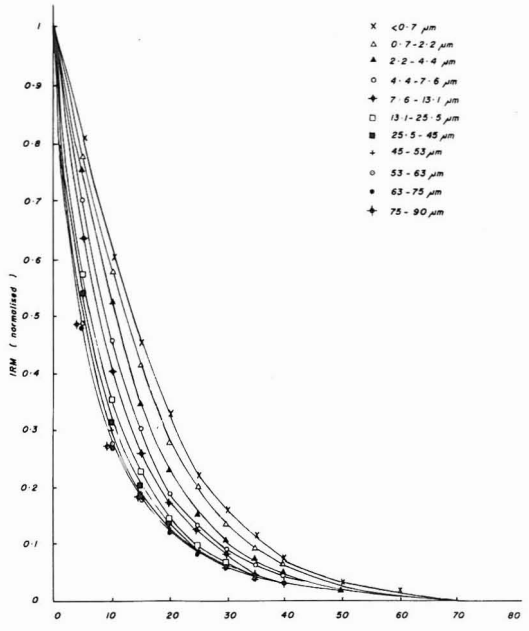

Fig. 4: Single - axis demagnetization at 45° to a 40 mT IRM as a function of particle size

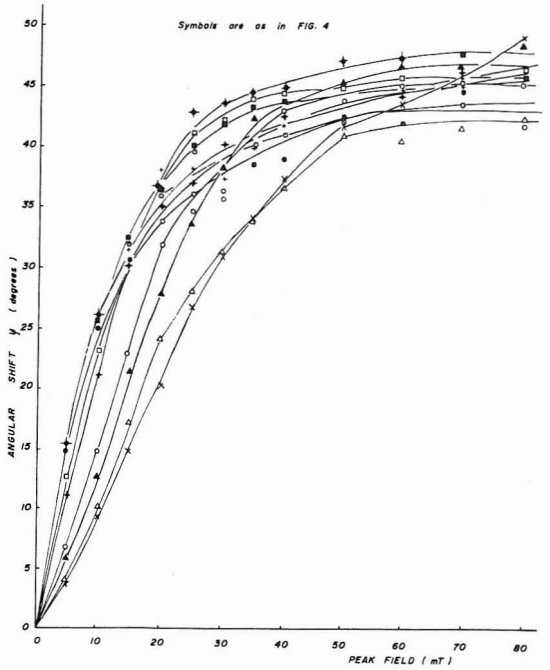

Fig. 5: Angular shift ψ of a 40 mT IRM (0°, 90°) with the a.f. applied at (0°, 45°)

TABLE 1
Variaton in IRM, MDF and angular shift with particles sizes

Particle size (μm)	IRM (10^{-3} $\frac{Am^2}{kg}$)	Field to remove half the remanence MDF (mT)	Step demagnetization angular shift (degrees)	Repeated experiment angular shift (degrees)
< 0.7	2.91	13.5	13.0	12.0
0.7–2.2	2.89	12.0	12.3	14.4
2.2–4.4	2.82	10.6	13.3	14.5
4.4–7.6	2.65	8.8	12.3	14.0
7.6–13.1	2.07	7.6	15.8	14.2
13.1–25.5	1.43	6.5	14.8	15.2
25.5–45	0.82	5.6	14.0	13.5
45–53	0.62	5.3	14.8	15.0
53–63	0.53	4.8	14.5	14.1
63–75	0.49	4.8	14.3	13.8
75–90	0.42	4.8	14.5	14.3

weakest magnetic hardness. The particles of 53–63 μm, 63–75 μm and 75-90 um gave the least resistance to the demagnetization process and shared the same curve. This phenomenon is shown again in *Fig. 6* where the field to remove half the remanence MDF increases with decreasing particle sizes.

This agrees with the observation that smaller particles have higher coercive force (Dunlop 1973; Parry 1981). Irrespective of the initial value of the declination (inclination about 90°) after the IRM application along Z axis, the first application of a.f. at (0°, 45°) shifts the declination near to about 180°. At

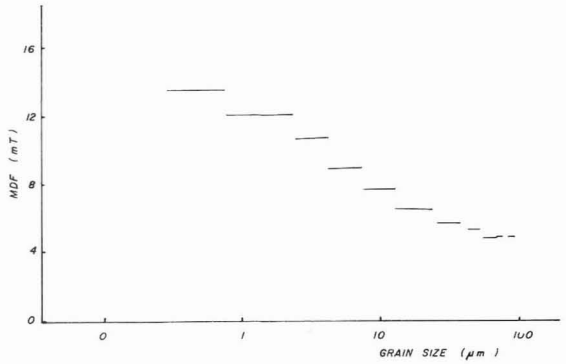

Fig. 6: MDF for the single - axis demagnetization at 45° to a 40 mT IRM as a function of particle size

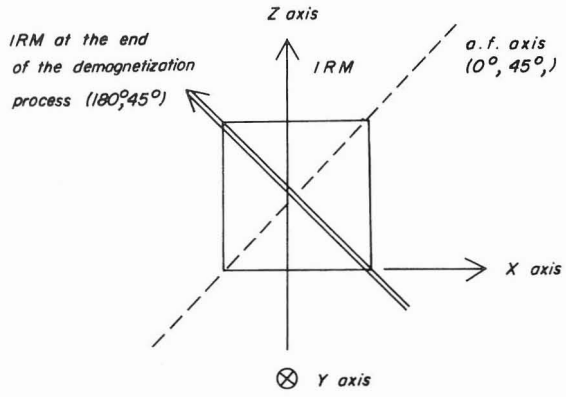

Fig. 7: The direction of the remanence vector at the end of single - axis demagnetization

the end of the a.f. demagnetization when most of the remanence has been removed, it always lies at about (180°, 45°), which is perpendicular to the a.f. axis (see *Fig. 7*).

Fig. 5 shows that at the early stage of the demagnetization process, the largest particles (75–90 μm) gave the greatest angular shift and the smallest particles (< 0.7 μm) gave the smallest angular shift. However, as the demagnetization proceeded, the angular shift for all the particle size reached a limit of about 45°. Above 30 mT, the angular shift was more scattered as more than 80% of the remanence had been removed.

The angular shift ψ as a function of the fraction of the IRM removed is plotted in *Fig. 8*. This plot allows for different magnetic hardness of different particle sizes. The angular shift ψ for all the particle sizes is a function of the IRM removed, i.e.

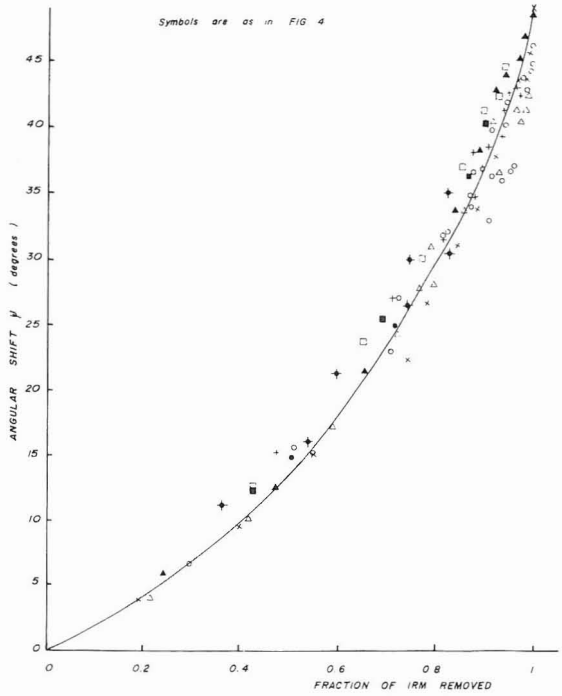

Fig. 8: Angular shift ψ for the single - axis demagnetization at 45° to a 40 mT IRM as a function of fraction of IRM removed

$$\psi = f\left[\frac{IRM_H}{IRM_o}\right]$$

where IRM_H is the remanence (IRM) at a particular a.f. and IRM_o is the initial remanence (IRM) at zero a.f.

The angular shift when half the remanence was removed (MDF) during the step demagnetization and the repeated

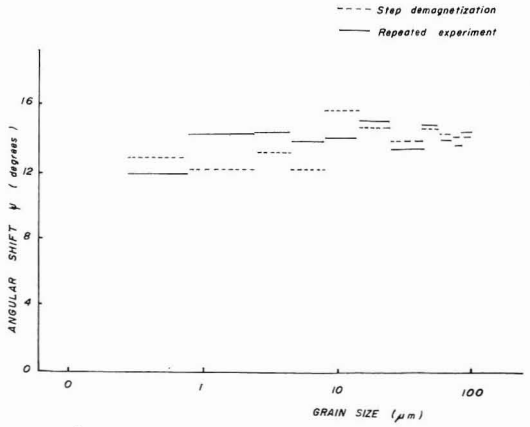

Fig. 9: Angular shift for the single - axis demagnetization at 45° to a 40 mT IRM at MDF as a function of particle size

experiment did not show any dependence on particle size. The angular shift ψ is about 12° to 16° for all the particles at the MDF as shown in *Fig. 9.*

Three-axis Demagnetization of IRM at 15° and 15°
Three-axis demagnetization of a single domain rock sample with the IRM not along the plane of two of the a.f. axes, shifted the remanence vector to 45°, 35.3° before it was removed (Stephenson 1983). Hence an experiment of a similiar kind was carried out for multidomain particles as mentioned below.

Two particle sizes of magnetite (< 0.7 μm and 75–90 μm) were used in this experiment. The acquisition of IRM in 40 mt at 15°, 15° was done by positioning the sample in a particular orientation in the pulse magnetizer. For a given peak field, three-axis demagnetization was carried out along the X, Y and Z axes in turn. The demagnetization was done stepwise until the remanence of the sample was down to the noise level of the instrument.

The variation of intensity and direction changes with increasing peak field are shown in *Figs. 10* and *11* respectively. As regards the angular changes, the direction of the samples does tend to move towards 45°, 35.3°. The final expected value of 45°, 35.3° according to Stephenson (1983) was not reached. This is probably because the intensity at the end of the demagnetization process was very small compared to the initial remanence resulting in spurious magnetization due to instrumental defects coming into effect.

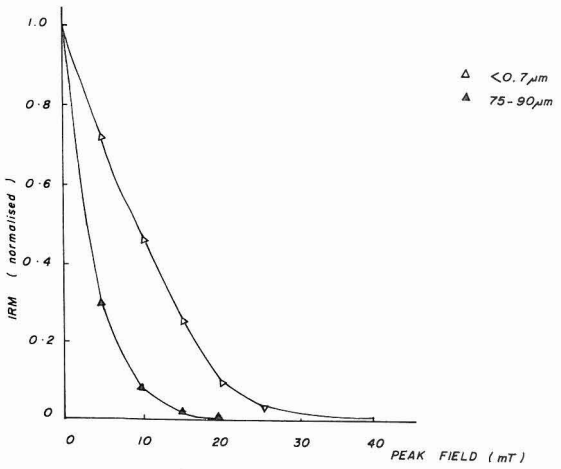

Fig. 10: Three - axis demagnetization of a 40 mT IRM at (15°, 15°)

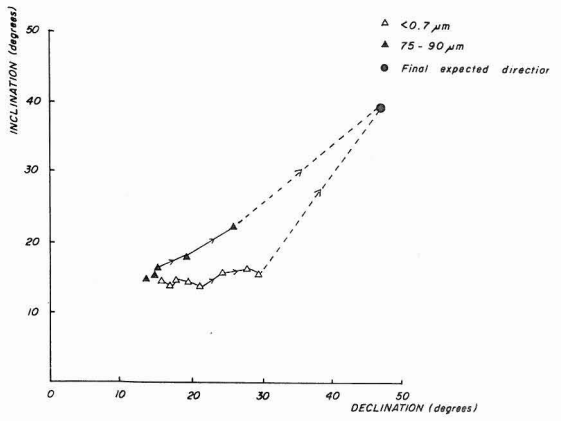

Fig. 11: Direction changes on three - axis demagnetization of a 40 mT

CONCLUSIONS

The aim of the experiment was to see whether the theories and experimental results put forward by Stephenson (1983) for single domain particles work for multidomain particles.

Single-axis demagnetization of IRM at 45° to the a.f. axis for the magnetite samples produced an angular shift of 45° which is normal to the a.f. axis. The angular shift at each MDF did not show any dependence on particle size.

In general, magnetic hardness for multidomain particles increase with decreasing particle size as can be seen from the result of single-and three-axis demagnetization. Three-axis demangnetization of IRM at (15°, 15°) showed a general migration towards (45°, 35.3°) as found by Stephenson (1983) for a rock sample.

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