

FACTORS INVOLVED IN THE VARIATION OF THE EFFECT OF STRESS
ON THERMOREMANENT MAGNETISATION

THESIS

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ABSTRACT

The variation in the effect of stress on the thermoremanent magnetisation of rocks with a number of naturally occurring factors is described, grain size and compositional variation being the relevant factors.

To examine the effect of shear stress an apparatus has been constructed which permits the stressing of 8 cc. cubic rock specimens to their yield point while being heated to above the Curie points of their magnetic constituents. A Helmholtz coil magnetising system allows fields of the order of the Earth's Field to be applied at any inclination while the specimen is cooling under stress to room temperature.

A uniaxial pressure apparatus has been used to determine the dependence of thermoremanent pressure effects on the grain size and mineral composition of the magnetic constituent of a rock.

All three factors have been shown to be of importance in the production of pressure effects, measured as angular

rotations and intensity changes of the thermoremanent moment.

The investigation is concluded with a discussion of possible mechanisms of pressure effects together with an assessment of the relevance of the experimental results of the investigation to palaeomagnetic interpretation.

CHAPTER I

INTRODUCTION

1.1 The Magnetism of Rocks

Among the minor constituents of igneous rocks are a group of black, opaque minerals which contain a high concentration of iron. These minerals, which show natural variations in composition as do other rock forming minerals, are known collectively as magnetite.

Rarely, a rock may be found in which magnetite is a major constituent. Pieces of such rock were known as long as 2000 years ago for their tendency, when freely floating or pivoted, to rotate into a north-south direction, so providing a reliable direction finder in the absence of landmarks. These rocks, the "lodestones" of mariners, owe their natural aligning property to the magnetite within them. It is the magnetite crystals forming natural magnets which pull the fragment of rock into a north-south direction.

Not until the nineteenth century was it realised that lodestones represented the extreme examples of a great range of rocks all of which showed some degree of natural magnetism.

These rocks, the igneous rocks of geologists, first attracted the attention of an Italian, Gherardi⁽¹⁾, who began the enormous task of sampling igneous rocks to measure their magnetic properties. Gherardi hoped that if enough rocks of different ages could be studied a picture of the past history of the Earth's magnetic field might be developed. It is interesting to note that he assumed that the historic lava~~s~~ flows which he sampled carried the direction of the Earth's field at the time the lavas were erupted and had not followed the variations of the field up to the time of collection.

This was a very important assumption to make and it suggests that Gherardi already realised some of the unexpected properties of the magnetism of igneous rocks, in particular, the stability of their polarity. This is indeed possible as, two years before Gherardi made public his ideas, Förstemann⁽²⁾ had discovered that individual stones in old buildings sometimes showed completely different magnetic directions. This suggested to Förstemann that they had been magnetised before quarrying and had retained their magnetic directions even when oriented at random in the Earth's field.

At the end of the last century it had become apparent that the magnetisation of igneous rocks was much more permanent than would be expected from a magnetising field of

only half an oersted. To account for this a new magnetising process was conceived. This was the process of magnetisation by cooling a rock from the Curie point of its magnetic constituents to normal air temperatures in a weak field. Experiment showed that this process did, in fact, allow a rock to acquire a strong and stable magnetic moment in the Earth's field, even when the coercive forces of its magnetic components at air temperatures might be several hundred oersteds, and it was obvious that the cooling history of most igneous rock had resulted in them becoming magnetised in this way.

This process, which has been searchingly studied during the last fifteen years, is known as thermo-remanent magnetisation. During the first half of this century many of the properties of thermo-remanent magnetisation were elucidated, Koehigsberger⁽⁵⁾, in particular, being responsible for a detailed study of the variation in the thermo-remanent magnetic properties of a wide range of magnetic minerals. At the same time a growing number of directions of thermo-remanent moments were being measured and the idea first promulgated by Gharardi, of associating the changes in the Earth's magnetic field in historic and prehistoric times with these directions, was beginning to grow.

This new science of palaeomagnetism received a post-war

impetus from advances in the design of measuring instruments and from the discovery of oblique and inverse natural thermo-remanent magnetisations. The unexpected discovery of remanent moments in exactly the opposite sense to the present Earth's field has led to an interesting and fruitful controversy on the means by which such magnetisations have arisen. Some mechanisms of spontaneous reversal have been demonstrated but there remain a large number of instances of reversals which cannot as yet be explained by any other means than an exact inversion of the Earth's field at the time of magnetisation.

The use of the new instruments developed since the war has shown that both sedimentary and metamorphic rocks frequently show a remanent magnetisation, although this is usually much smaller than the magnetisation of igneous rocks of the same geological period.

The discovery of remanent moments in rocks such as red sandstone, for which there is definite geological evidence that the temperature of the rock has never been within 400°C of the Curie point of the magnetic constituent, hematite, established the necessity for another process of magnetisation. This process, which is more difficult to demonstrate experimentally than thermo-remanent magnetisation is called Chemical Remanent Magnetisation. The variation of the Earth's magnetic field during the Tertiary geological era

is now quite well known. The preceeding Mesozoic era is becoming equally well documented, but great difficulty is encountered in obtaining a consistent pattern when Palaeozoic and PreCambrian rocks are measured. It is obvious that the older a rock, the greater is the likelihood that the original remanence will have been wholly or partly destroyed by later influences.

1.2 Natural Processes of Magnetising Rocks

The discovery of thermo-remanent magnetisation, together with the later postulation of chemical remanent magnetisation, has already been described. To these, two further processes of magnetisation more variable and unpredictable in their effects must be added. These are isothermal remanent magnetisation and depositional magnetisation. So far as present investigation has shown, very nearly all natural remanences can be ascribed to one or more of these processes and further research in rock magnetism cannot be carried out without an understanding of the present ideas of the mechanism of these processes.

Thermo-remanent Magnetisation

Thermo-remanent magnetisation is more fully understood than the other processes and a considerable amount of theoretical study has been devoted to the underlying mechanism. Since the subject of this thesis is the effect of stress on rocks acquiring a thermo-remanent moment an understanding of the present theories of the mechanism of this process is imperative.

The most detailed and satisfactory attempts to explain thermo-remanent magnetisation are due to the continued efforts of Néel^(3,4).

Néel's first theory was developed for an aggregate of single domain magnetic grains in a matrix of non-magnetic material. Briefly, if the effect of thermal fluctuations is considered, then, at some temperature below the Curie point the effect of thermal agitation is great enough to cause the direction of the spontaneous magnetisation in a domain to jump from one direction to another. The expression describing this action is

$$\frac{1}{\tau_0} = A \left(\frac{V}{kT} \right)^{1/2} \exp \left\{ - \frac{V H_c J_s}{2kT} \right\}$$

where τ_0 is the relaxation time of the grain, V the volume of the grain, T the absolute temperature, k Boltzman's

constant, H_c the coercive force of the grain and J_s the spontaneous magnetisation and A a constant depending on the physical properties of the magnetic material. This expression indicates that T_c is critically dependent on $(\frac{V}{T})$ and for any given temperature there will be a well defined lower limit of V for a particle to be stable for an hour or so. The temperature at which the relaxation time is of the same order as the duration of the experiment is known as the blocking temperature and it follows that there will be a distribution of blocking temperatures corresponding to the distribution of particle sizes. Thus, as the temperature rises towards the Curie point the critical temperatures for various size groups will be exceeded and as this happens the spontaneous magnetisation for each particle in the group becomes randomly oriented until, at the Curie point, even the ~~largest~~ ^{smallest} are demagnetised. As the rock is cooled the blocking temperature for each particle size group is again passed and, if a field is present, at this critical temperature the spontaneous moment ceases to be able to jump from one easy direction to another, a considerable proportion of the moments being frozen in at the easy direction closest to the field direction. The random orientation of the very large number of grains in the rock causes the resultant moment to be very close to the magnetising field direction.

This theory predicts the behaviour of thermo-remanent magnetisation quite well but suffers from the drawback that magnetite grains in rocks are almost always much too large to be monodomain in nature. The maximum size for which ~~it~~ energy considerations make it permissible for a magnetite grain to consist of only one domain can easily be calculated.⁽¹⁵⁾ This calculation gives a grain diameter of $0.2\mu - 0.3\mu$. The smallest magnetite grains in rocks have diameters of the order of 1μ while many igneous rocks contain magnetite only in the grain size range of $10\mu - 100\mu$. In addition, it has been shown that massive metallic nickel acquires a weak but definite thermo-remanent moment. This bulk of evidence for thermo-remanent magnetisation occurring when the particles were multidomain caused Néel⁽⁴⁾ to extend his theory to cover such particles, basing his ideas on the expansion of the hysteresis cycle which must take place during cooling. At this stage it is worthwhile describing the two postulated mechanisms of magnetisation. The first, which must occur in single domain particles, is magnetisation by rotation of the single domain, while the second, which has been shown to occur in multidomain particles, is magnetisation by domain wall movement, the walls of domains with spontaneous moments aligned near to the field direction expanding at the expense of domains with moments oriented in other directions.

This more general theory invokes domain wall movement rather than domain rotation as the carrier of thermo-remanent magnetisation. Unfortunately, this later theory fits only qualitatively to many observed phenomena of thermo-remanent magnetisation. For example, the theory predicts that

where $J_{TRM} = \frac{H_{ex}}{N} \left(\frac{H_c}{H_f} \right)^{1/2}$ is the thermo-remanent moments.

H_{ex} the ambient field and N the shape demagnetising factor.

H_c and H_f are the coercive force and a thermal fluctuation field respectively. In practice it is commonly found ~~that~~ that J_{TRM} varies linearly with H_c in a manner which varies from sample to sample, and not with $(H_c)^{1/2}$ as predicted by the theory. This raises a new point of considerable importance to this present work. Apart from quantitative discrepancies between Néel's revised theory and the general behaviour of thermo-remanent magnetisation it is found that different specimens cut from the same sample behave, in detail, in different ways, although each specimen shows great consistency on successive heating and remagnetisation.

This small discrepancy between the behaviour of similar specimens may well be related to the difference in number and arrangement of the stressed regions surrounding discontinuities in the grains. It has been demonstrated that these discontinuities, which may be either fine cracks or particles of foreign matter, acquire special domains in their vicinity,

so reducing the overall magnetic and elastic energy of the grain to a minimum.

In a recent summary of the properties of thermo-remanent magnetisation Verhoogen⁽⁶⁾ has suggested that the origin of this type of magnetisation is complex. It is considered that any moment consists of three parts.

- (i) A relatively soft part, having similarities with isothermal remanent magnetisation and originating in domain wall movement.
- (ii) A part originating in the rapid decrease of magnetocrystalline energy near the Curie point and related to the sudden increase in remanence in this region. The origin of this part is in domain rotation.
- (iii) The hardest part originating in the stressed regions around dislocations.

The reason for invoking this number of sources lies in the individual behaviour of different rock specimens, the spectrum of coercive forces seen in A.C. demagnetisation curves and the dependence of the thermo-remanence of metallic samples on their annealing history.

Verhoogen was able to show that the stressed regions surrounding dislocations would have the same properties as predicted for single domains on Néel's first theory, which

agreed quite well with experimental evidence except that of grain size.

Thus it appears that the origin of thermo-remanent magnetisation is complex, with contributions from domain wall movement and rotation in the magnetic material as a whole and from local stressed regions surrounding dislocations the number and distribution of which will vary from specimen to specimen. An important feature which has not previously been mentioned is the change in the properties of thermo-remanent magnetisation with grain size. It is found that the moment acquired by fine grained rocks is greater than that acquired by coarse grained rocks for the same magnetising conditions and masses of magnetite. A similar relationship exists for the coercivity while the susceptibility shows an inverse relationship with grain size.

The reason for this change of properties with grain size is uncertain but two possible contributory factors may be suggested.

- (i) A change in the mechanism of magnetisation with grain size may occur, domain rotation being predominant in small grains and domain wall movement in large grains.
- (ii) In naturally occurring rocks a fine grain size always implies rapid cooling which must cause poor annealing

of the material and a consequently greater number of dislocations around which stressed region domains will form.

This discussion of the importance of grain size concludes the main ideas concerning the mechanism of thermo-remanent magnetisation.

Isothermal-Remanent Magnetisation

This term probably covers several processes, all of which lead to the production of soft and generally small moments which are acquired at room temperature. Rocks showing a tendency to acquire isothermal moments are generally of little use in palaeomagnetism unless the secondary isothermal moment is first removed by alternating current or thermal demagnetisation.

Chemical Remanent Magnetisation

As mentioned previously the magnetisation of many sedimentary rocks must originate in this process. Secondary magnetisation in igneous or metamorphic rocks, due to either sub-aerial weathering or magmatic solutions may be ascribed

to chemical magnetisation. Little is known about the mechanism of this process but it is likely that ionic migration during the lithification of a sediment is affected by the Earth's field resulting in the formation of very fine oriented crystals. Such a process of chemical magnetisation could take place very slowly at normal crustal temperatures.

Depositional Magnetisation

This process accounts for the magnetisation of some sedimentary rocks. Magnetised grains removed by weathering from igneous rocks are deposited in still water such that partial orientation of the grains by the Earth's field takes place immediately prior to settling. Lithification of the material results in a rock with a remanent moment.

Several other processes of magnetisation can be demonstrated in the laboratory but the four processes described here cover together the great majority of natural remanences.

1.3 Criticisms of the Interpretation of Palaeomagnetic Measurements

The inspiration of Gharadi, that the magnetisation of rocks reflected the history of the Earth's magnetic field, has been greatly exploited. The last ten years in particular has been a period of enormous activity. Samples of rock of all ages from every continent have been examined and a great number of directions of magnetisation discovered. It has become customary to calculate the pole positions of the field that would be responsible for the direction of magnetisation in a rock. A recent survey⁽⁷⁾ of pole positions calculated from direction measurements of stable rocks gives values ranging in age from Quaternary to Pre Cambrian.

This survey shows that, in general, positions derived from rocks in the age range Recent to Eocene (Lower Tertiary) are close, at least in latitude, to the present pole positions, and, since the values are calculated from measurements made on relatively stable rocks, it is highly probable that the majority of the value do indicate true pole positions.

The value quoted for the Mesozoic era generally indicate pole positions in lower latitudes than the Tertiary values, but it is here that the scatter of the values becomes much greater than can be allowed for by any possible experimental

or structural errors. For example, the pole positions calculated for the short Jurassic period vary in latitude from 13°N to 83°N . Pole positions for the Palaeozoic era show an even greater scatter, although again, the values are usually in low latitudes.

The variation of the apparent pole positions during geological time, together with the scatter of results obtained from older rocks, are generally explained as being the result of two possible causes,

- (i) The positions of the magnetic poles have moved across the Earth's surface
- (ii) The continents, or parts of them, have slid and rotated en bloc on a lower and more continuous layer in the Earth's crust.

These two explanations, acting separately or together, will indeed explain the variations and scatter of the pole positions, but a more critical assessment of some of the values suggests that a third general explanation must be invoked. This is interference at a later date with the original magnetisation of a rock.

An excellent example of a group of rocks showing a wide scatter of pole positions which does not seem to be explicable by either of the means just quoted is that comprising the Carboniferous rocks of Great Britain. Lower

Carboniferous lava flows from Fife, Scotland, show a variation in pole positions of 30° of latitude in one succession. Polar movement of 30° in such a short time seems unlikely, as also does continental drift since the Lower Carboniferous lavas of Derbyshire, only 200 miles to the South, indicate a pole position agreeing reasonably well with the lower of the Fife lava flows. Geological evidence fails to indicate any great relative movement of the two areas since that time.

The difficulty in reconciling the pole positions indicated by these two series of lavas has since been resolved by showing that the exceptional directions among the Fife values originate in a later isothermal or chemical component of magnetisation being superimposed on the original Carboniferous magnetisation.

This examples is intended to illustrate that the variation and scatter of pole positions found for older rocks cannot justifiably be explained only by the pole wandering or continental drift mechanisms without further examination of the relevant material. It is easy to think of a number of mechanisms which will change the overall direction of magnetisation of a rock. Most rocks that are obtained for palaeomagnetic study come from the weathered layer of rocks near to their surface. This weathered material may

have suffered some oxidation as a result of atmospheric exposure even if no discolouring is evident to the eye, and, as a consequence, may have acquired a chemical remanent moment in the direction of the present day field. With the remainder of the original thermo-remanent moment the new chemical remanent moment will cause the rock to show some resultant intermediate direction of magnetisation.

Similarly, a component of secondary chemical magnetisation may be acquired at depth from ionic migration and recrystallisation of the magnetic minerals caused by fluids of magmatic origin.

The intrusion of a rock formation by younger magma will cause a partial thermo-remanence to be superimposed on the surrounding rocks with the later field direction (partial thermoremanence implies the magnetisation of grains with their blocking temperatures within a limited temperature range). Combinations of these effects and others may be expected in older rocks which have more complicated geological histories and which are likely to have been buried at greater depth in the crust where disturbing influences are probably more important. These processes by which an original moment can be obscured are all effective after the original moment has been formed, and it is assumed that if the

original direction of magnetisation can be isolated a valid estimate of pole position can still be made.

This assumption itself is open to question. Several mechanisms have been postulated which would cause a rock acquiring thermo-remanence to have a resulting moment not in the direction of the ambient field. If it is assumed that the rock is at a temperature above the Curie point of its magnetic constituents when it is intruded or extruded, and that it solidifies while still above this temperature, two mechanisms may cause the resulting moment not to be in the ambient field direction,

- (i) If the rock is under directional pressure of some sort ~~while~~ the moment is being acquired, the pressure may influence the direction of the moment, the underlying mechanism being the well known stress dependence of the magnetic properties of ferromagnetics. The later removal of stress may not cause a complete reversal of the original high temperature pressure effect.
 - (ii) If the magnetic constituent of the rock is not distributed with random orientation throughout the rock, magnetic anisotropy in the grains may cause the moment to be deflected away from the ambient field direction.
- An experimental investigation of the importance of the first mechanism forms the subject of this thesis, and it will be

shown that the direction of the moment acquired by a rock under conditions of directed pressure does, without exception, differ from the field direction, for the wide range of rock forming magnetic minerals studied.

The second mechanism has been demonstrated by several workers and, by an accident of rock selection, will also be seen in the experimental work described in this thesis.

1.4 Ideas and Experiments Relating to the Effect of Pressure on Rocks Acquiring Thermo-remanent Moments

The suggestion that pressure might be a factor of importance in the process of thermo-remanent magnetisation was first made by Graham⁽⁸⁾. His suggestion was followed by a series of experiments designed to measure the effect of uniaxial pressure, acting under isothermal conditions, on rocks which had already acquired a thermo-remanent moment. Quite large irreversible changes were found to occur, both in the magnitude and direction of the moment and Graham concluded that the calculation of a pole position for a rock without knowledge of its stress history was unjustified.

This conclusion was challenged by Du Bois⁽⁹⁾ and

Stott and Stacey⁽¹⁰⁾. Du Bois found that the Triassic pole positions for North America are consistent among themselves even though the stress histories of different localities have differed greatly. Stott and Stacey carried out an experiment in which a group of specimens were magnetized thermally under pressure followed by a group being magnetized without pressure. The difference in the average inclination of the two groups was well within the accuracy of the experiment and it was concluded that pressure was of little importance in thermoremanent magnetisation. A short time before Stott and Stacey's experiment Stacey⁽¹¹⁾ had tried to investigate theoretically the effect of isothermally applied stress on a magnetite bearing rock which had acquired a thermo-remanent moment. As a result of his investigation Stacey suggested that, owing to the high positive magnetostriction of magnetite the overall remanent moment should be reduced by about 0.05% per atmosphere of compression, the moment parallel to the pressure axis being reduced and that perpendicular to it being increased, while at intermediate orientations the moment would be deflected away from the pressure axis.

The experimental study of the effect of isothermal stress on remanent and saturation moments has been continued by Domen⁽¹²⁾ and Mussett⁽¹³⁾ both of whom have shown that

stress can produce important changes in the moment. Both increases and decreases in the original moment have been produced.

The more critical condition of linear pressure being applied concurrent with the acquisition of a thermo-remanent moment has been studied skillfully by Neale⁽¹⁴⁾. The results of his experiments show, in contradiction of Stott and Stacey's conclusion, that the application of pressure in these conditions does have a measurable effect on the resulting moment. Neale concluded that the deflection of the direction of the moment was too small to be of importance in palaeomagnetic interpretation but was able to show an angular effect varying linearly with pressure, a probable independence of fields at intensity comparable with the Earth's field and a variation of angular effect with the angle between the field and the pressure axis. Since this effect is similar in sense and form of variation to that predicted by Stacey for the isothermal case, Neale suggested that ~~magne~~magnetostriction was the responsible factor.

This present work has been concerned with surveying the wide range of rock forming magnetic minerals, now recognised, grain size variation and the effect of shear stress on

pressure effects. The purpose of the investigation is two fold, to satisfy the theoretical interest in the behaviour of rock forming magnetic minerals acquiring moments under pressure and to search for means of obtaining pressure effects large enough to affect palaeomagnetic interpretations.

1.5 New Experimental Factors

On the basis of Neale's decisive experiments a number of new factors were thought to be of sufficient promise to warrant investigation. They were:

- (i) the effect of shear stress contrasted with linear stress,
- (ii) the effect of the variation in grain size of ferromagnetic rock forming minerals, and
- (iii) the effect of the variation in chemical composition of ferromagnetic rock forming minerals.

At the conclusion of Neale's experimental work it seemed likely that the pressure effect found by him could be explained in terms of the magnetostrictive properties of the magnetic constituent of the rock he was using. Magnetostriction, or the change in dimensions which accompanies the magnetisation of ferromagnetic materials is described as the Joule effect, after its discoverer. The reciprocal Villari

effect (change of magnetic moment with stress induced dimension change) is more relevant to rock magnetism, and has indeed been recognised in experiments carried out by Domen⁽¹²⁾.

With the conclusion of these more comprehensive experiments it appears that the effects observed are not simply related to the magnetostrictive properties of the minerals involved and are probably complex in origin. The lack of knowledge of the sense and magnitude of magnetostrictive constants for many rock forming magnetic minerals makes interpretation difficult, as does the lack of knowledge concerning the variation with temperature of those constants that are known.

In the knowledge that few measurements of these basic factors had been made it was decided to cover the widest range of mineral types and grain sizes experimentally and finally to try to correlate the new information into a theory of the origin of pressure effects.

1.6 Rock Forming Ferromagnetic Minerals

The illustration of the discovery of thermoremanent magnetisation at the beginning of this chapter assumed

that all rock forming ferromagnetic minerals were magnetites of varying degrees of impurity.

Since these rock forming minerals are all opaque and cannot be separated by examination in refracted light the subdivision of them into different compositional groups has only become certain with advances in X-ray and reflected light analysis.

It is now clear that several compositional series of minerals exist. These are usually solid solution series with the end members belonging to the same class of crystal structure. An example of such a series is the titanomagnetite series, which contains every compositional variation between magnetite (Fe_3O_4) and ulvöspinel (Fe_2TiO_4). Recent studies have shown that the magnetic properties of rocks are very dependent on the chemical composition of their magnetic constituents.

CHAPTER II

INSTRUMENTS BUILT AND USED IN THE INVESTIGATION

2.1 The Spinning Magnetometer

This is a very precise and consistent measuring instrument, with which angular differences of 0.2° in the directions of the moments of cubical rock specimens can be differentiated.

All the specimens used in this investigation were measured with this instrument.

In principle, the magnitude and direction of the thermo-remanent moment of a rock specimen is dynamically compared with the intensity and direction of orientation of a standard permanent magnet.

Both the rock specimen and the standard magnet rotate at 30 cps at different points on a horizontal shaft. A system of detector coils is placed adjacent to each magnetic source and the E.M.F.'s generated in these coils are brought into phase, then compared in magnitude. Adjustment of the phase of the reference voltage signal from the standard magnet by orientation of the relevant detector coils, and the intensity of the reference voltage by a

potentiometer, allows the signal from the rock specimen to be cancelled out. Very precise cancellation is made possible by the amplification of the out of balance signal with a high gain-low noise amplifier, fitted with a 50 cycle rejector circuit and a "Twin-T" feedback network. The output from the amplifier is presented on a cathode ray oscilloscope. The instrument was originally designed by Bruckshaw and Robertson⁽¹⁶⁾, Vincenz⁽¹⁷⁾ introduced modifications to the detector coil system and Neale⁽¹⁴⁾ improved the amplification of the out of balance signal and the precision of balancing.

A measuring technique has been devised so that very small changes in the direction of the thermo-remanent moments, of the order of 0.2° , can be consistently detected for specimens with intensities of the order of 50×10^{-3} emu/cc or greater. This technique allows for the error introduced by the slight off-centre position of the cube holder ~~and~~² for any drift in the direction of magnetisation of the reference voltage generator magnet. The technique involves measurement of the cube in the four possible positions afforded by the holder for a cube magnetised in a direction parallel to one face. Magnetisation of cubes in a plane perpendicular to one of the edges was adopted as a standard procedure for simplicity and accuracy of measurement. Random observational

errors were reduced by repeating all measurements two or three times, the number of repeated measurements depending on the size of the angular rotation being measured. Intensity measurements with the spinning magnetometer did not achieve the high consistency of the phase measurements. This was the result of the variation in the intensity of the standard magnet due to temperature changes, together with the effect of general temperature changes in the region of the instrument. No compensating system of measurements could be adopted to eliminate this inconsistency. Nevertheless, the intensity consistency of $\pm 2\%$ was satisfactory for all but the most exacting intensity comparisons.

2.2 The Susceptibility Meter

All the measurements of initial susceptibility quoted in this thesis were made on an alternating current susceptibility meter. The principle of the design of this meter is the detection and measurement of the secondary E.M.F. generated in a detector coil by a cubical rock specimen placed in a 450 cps primary field. This secondary E.M.F. can be shown to be directly proportional to the volume susceptibility of the specimen. The energising and detector coils were

originally built to the design of Vincenz for use in a susceptibility bridge, but are now operating satisfactorily in the newly designed meter. The 450 cps energising signal is obtained from a standard "Advance" oscillator and this is passed through a power amplifier to provide suitable power to excite the energising coils. The secondary E.M.F. generated by the specimen is measured using a commercial phase sensitive amplifier^{*}. The meter is at present in a temporary form and has to be calibrated with standard specimens each time it is used. However, it is intended to fit a more stable power supply and to adjust the coil system to prevent the necessity for recalibration each time the instrument is used.

In its present form the meter can detect initial susceptibilities of 5×10^{-5} emu/cc which is adequate for the purpose of this investigation since the weakest susceptibility measured was of the order of 10^{-4} emu/cc.

2.3 The Shear Stress Apparatus

2.3.1 Introduction

This apparatus was designed to apply a simple shear stress to a cubical rock specimen while the specimen was cooling to

^{*}Synchronous amplifier type B 801/754 (Designed and built by Messrs. Elliots.)

room temperature from above the Curie point of its magnetic constituents. Throughout the experiment a constant magnetising field was to be applied to the specimen.

2.3.2 Specific Requirements of the Apparatus

There were three main requirements:

- (i) The **pressure** system should be able to apply a steady simple shear stress to a cubical rock specimen for a period of 2 hours, the magnitude of the stress to cover a range from the non-stressed state to the yield strength of the rock material. In addition, the pressure system should, in the region of the specimen, be able to withstand temperatures of 650°C without deformation for an aggregate period of 100 - 200 hours.
- (ii) It should be possible to heat the specimen to a temperature of 650°C in 1 hour while held in the pressure system.
- (iii) A magnetising field of maximum strength 5 oersted, with only a small field gradient over the volume of the specimen, should be maintained to a consistency better than 1 part in 500 for the duration of one experiment, which was intended to be of the order of two hours.

In addition, this field should be reproducible to within the same consistency for a series of experiments lasting over a period of the order of a week.

The construction of equipment to satisfy these stipulations was limited to materials that were essentially non-magnetic in order to minimise both permanent and varying field gradients over the specimen. It was also necessary that the apparatus should be designed and built so that a minimum rotation of moment of 0.3° could be detected.

2.3.3 Design and Construction of the Apparatus

(Reference should be made to the photographs of the apparatus shown in Figs. 1 and 2).

(i) The Pressure System

Two difficulties prevented the use of the conventional method of shear testing by torsion. This method of shearing a rod of material by rotating one end of the rod while the other is held firmly would mean that a cubical specimen would have to be cut from the rod for measurement after the shearing experiment. It was thought likely that

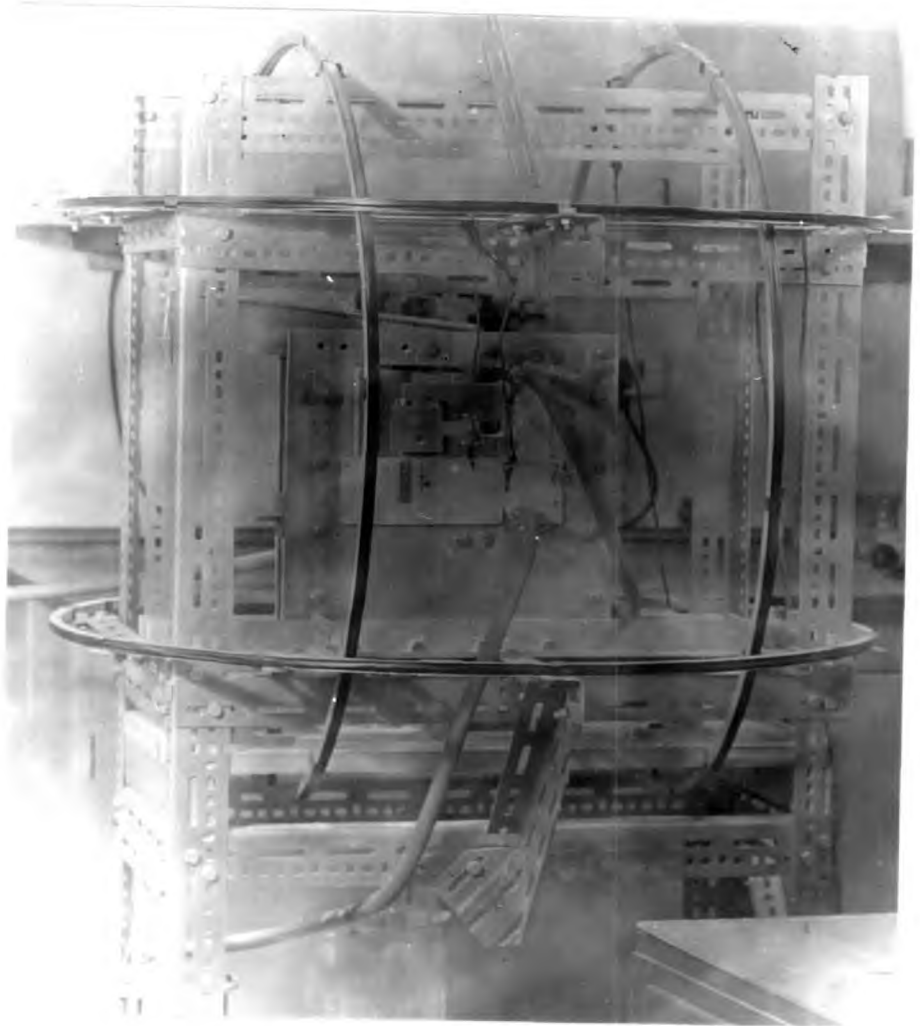


Figure 1

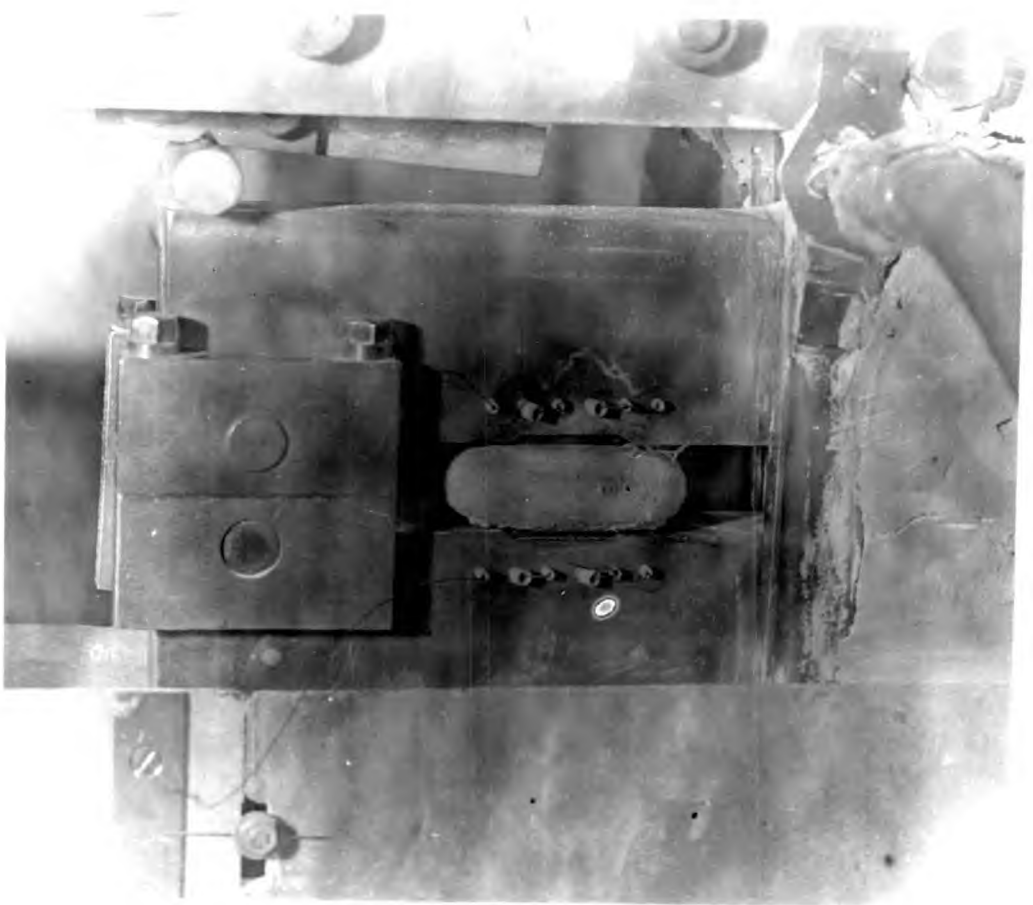


Figure 2

cutting would ^{a.} affect the moment to a small degree, but might be effective enough to obscure the very small angular rotations of moment expected. The second condemnatory factor was that shear produced in this fashion could not cause any resultant change in a magnetic moment acquired under stress. This conclusion results from a theoretical application of Neale's uniaxial pressure results to the case of shear stress. (The following conclusions are derived fully in 4.1.1). The solution derived for the effect of simple shear on a cubical specimen is shown in Fig.3. In this figure the shear stress is indicated by the large arrows outside the cube, and the direction of rotation of the thermo-remanent moment for four principal magnetising field directions is shown by the small curved arrows on the x and y axes of the cube.

If the case of the application of shear stress by the standard torsional method is considered a situation such as is shown in Fig. 4 is obtained. For simplicity the rod has been divided into quadrants and the field direction shown as bisecting one pair of these quadrants, the subdivision of the rod into an infinite number of segments and the random orientation of the field would produce an identical effect. The effect on the thermo-remanent moments in each pair of quadrants, as derived from the case of the cube is shown

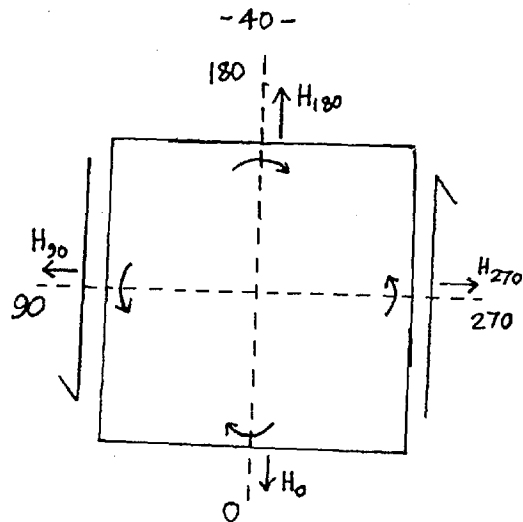


Figure 3

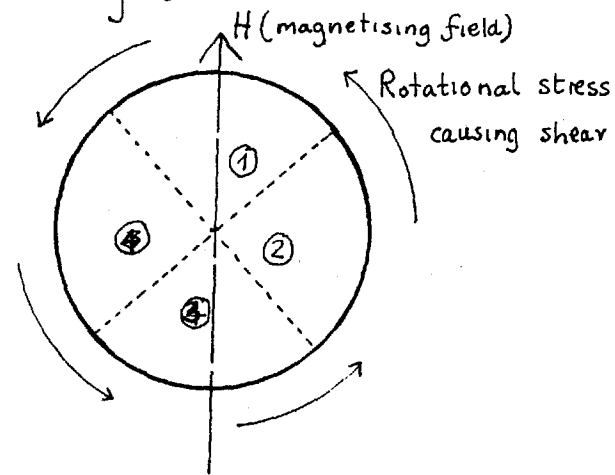


Figure 4

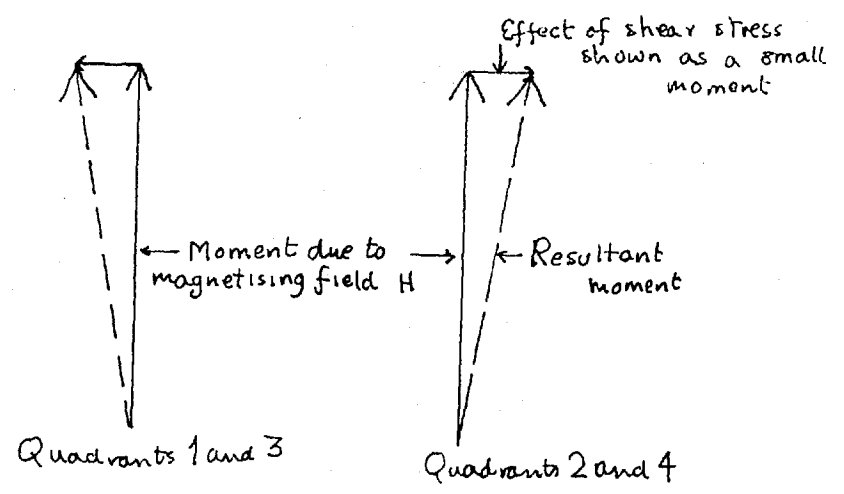


Figure 5

in Fig. 5. It is clear from this figure that the effect of shear stress will be cancelled when the resultant moments of the two pairs of quadrants are added.

The final design of the shear stress apparatus permitted the application of shear stress to a cubical specimen of standard 8 cc. volume. The design of the jaws for applying shear stress is shown in Fig. 6. The specimen is held between two jaws J_1 and J_2 . Shallow recesses are cut in the faces of the jaws to hold the cube and prevent it from sliding laterally when stress is applied. The jaws are linked at both ends and on both sides and can only move as one unit. The links L, shown at the left end of the jaws in Fig. 6 only connect the jaws and do not come into contact with the frame. For the links at the right hand end of the jaws the end plates are used. Those large end plates are, in addition, fixed to the frame of the apparatus (see photographs in Fig. 1, 2 and also Fig. 7). The pivots P_1 , P_2 , P_3 , and P_4 are simple dowels, the plane containing the axes of the dowels also contain the plane of the bottom of the cube holding recesses (See Fig. 6). Fig. 7 shows the method by which the jaws apply shear stress to the cube. The cube provides the only non frictional resistance to the rotation of the linked jaws and experiences the shear stress indicated in Fig. 7. by the small arrows to the

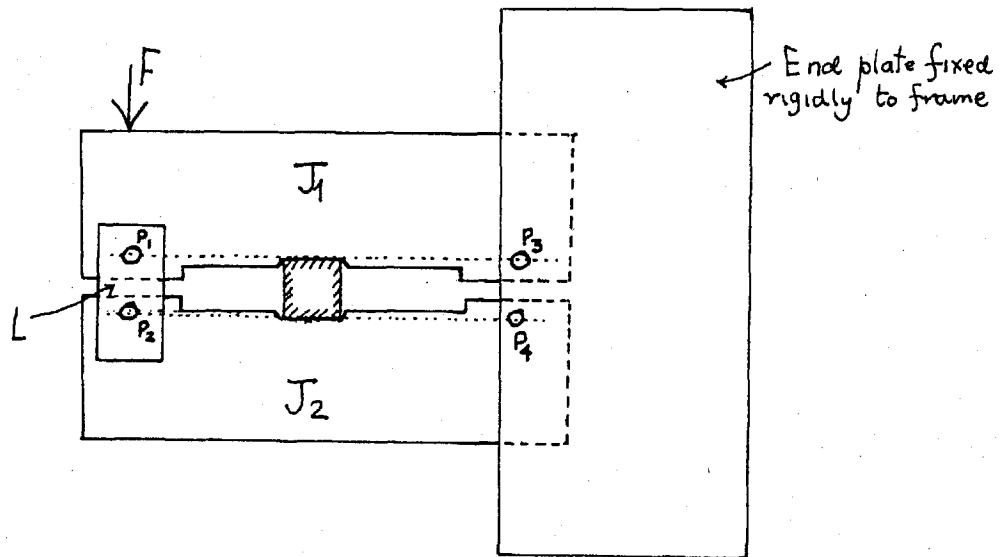
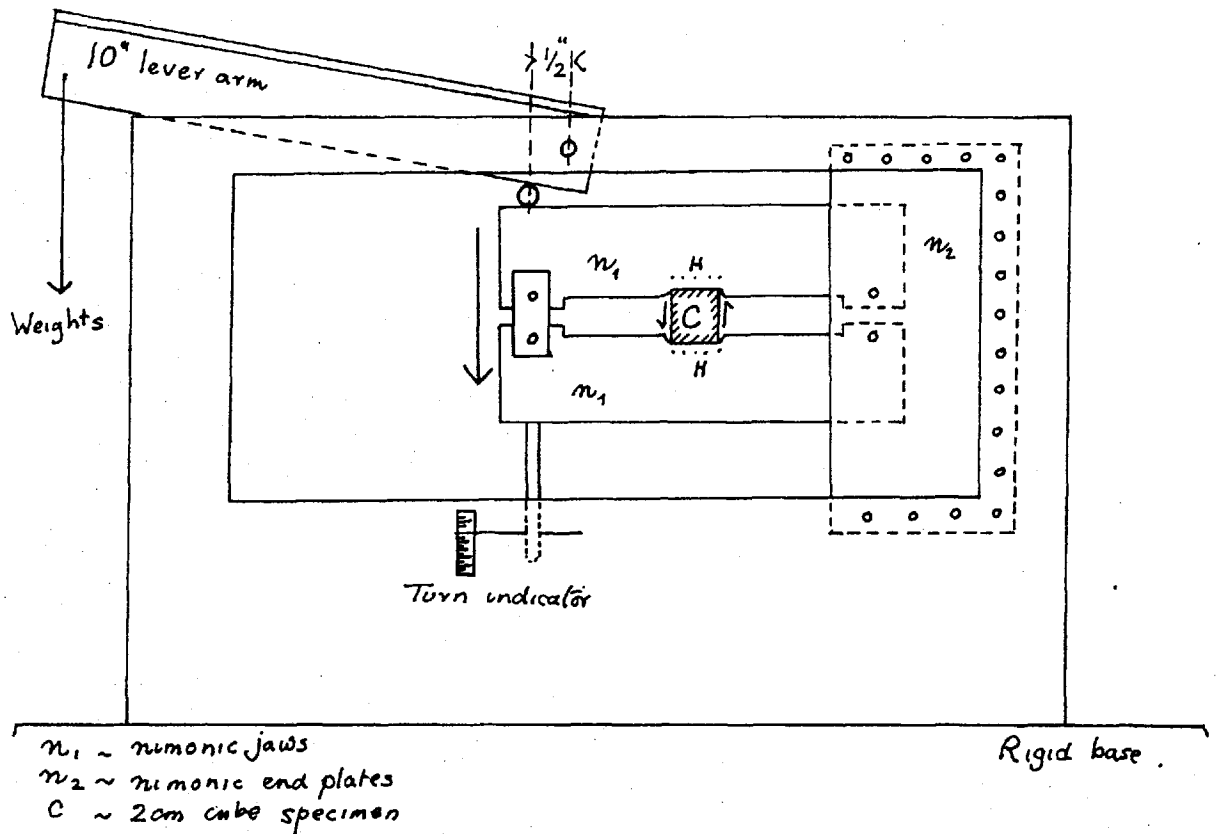


Figure 6. Shearing jaws

Figure 7. Shear stress apparatus (heating element and thermal insulation omitted.)



right and left of the cube. Since the application of shear stress involves a tensile component of stress in the specimen, the low ultimate tensile strength of rocks limits the total stress that can be applied, and a lever system, as shown in Fig. 7, is adequate to produce fracture of specimens with only 25 lbs. weight on the end of the lever arm.

The materials from which the apparatus was constructed were limited to non-magnetic metals. Non metals could not be used for the shearing jaws owing to their low tensile strength. In addition, to permit the required accuracy, it was estimated that the region of the jaws in contact with the cube should be able to withstand temperatures of 650°C for an aggregate period of 100 - 200 hours without suffering deformation amounting to more than 0.001". The final choice of materials for the pressure system is shown in the table below.

<u>Part</u>	<u>Material</u>
Jaws, free links and end plates, pivots	Nimonic 80A, (nickel chrome non-magnetic alloy resistant to creep at high temperatures)
Rigid frame of apparatus	Dural $\frac{3}{8}$ " plate separated by block and tubular spacers.
Lever arm	Aluminium T-section

<u>Part</u>	<u>Material</u>
Lever arm fulcrum and lower transmitting pressure to upper jaw	Brass rod
Frame bolts	Brass

The whole apparatus was placed on a wooden table within a dexion framework designed to carry Helmholtz coils to be used to provide the magnetising field.

To produce a true shear stress in the cube the jaws and cube would have to be completely in contact during the experiment. It was estimated that this would be practically achieved if all the nimonic parts were milled to a tolerance of ± 0.001 " on the planned dimensions. This difficult task was carried out perfectly in the departmental workshop.

A turn indicator was fitted to the bottom of the lower jaw. This consisted of a needle attached to the lower jaw and a scale fixed to the rigid frame of the apparatus. With the aid of this, rotations of the linked jaws of 0.1° could be detected, which facilitated accurate comparison of experiments.

The preparation of specimens to match the precision of the apparatus was also a critical factor. Three criteria were essential:

- (i) The top and bottom faces should be parallel and plane with a tolerance of 0.001 ".

- (ii) The separation of the top and bottom faces should be exact. Specimens one thousandth of an inch too large or too small would either not fit the apparatus at all or would allow the jaws to rotate without pressure being applied. The necessary separation of these jaws was found by trial and error to be 0.795 ± 0.0005 ".
- (iii) The sides of the specimen normal to the plane of the jaws had to be accurately perpendicular to the top and bottom faces of the specimen and had to be separated by an exact distance to within a range of 0.001 ". If this distance was exceeded the cube would not fit without the edges breaking and if the distance was too small the jaws would turn without pressure being applied. The necessary separation of the ends was found to be 0.785 ± 0.0005 ".

The smoothness and separation of the sides in the plane of the jaws was less important, but to ensure the specimen had a volume close to 8 cc. this separation was always made to be between 0.785 " and 0.790 ".

It was possible to produce cubical specimens to the required accuracy by first rough cutting and grinding on standard machines. Following this the cubes were ground more carefully by machine to ensure the critical pairs of faces were mutually perpendicular and were finished with

all the dimensions about 0.005" too large. Final grinding was carried out by hand using successively finer grades of carborundum powder on glass plates and with some practice, it was found that cubes could be ground to the required accuracy.

(ii) The Heating System

The second requirement in the design of the shear apparatus was that the cubical rock specimen could be heated to 650°C in about one hour and cooled again to room temperature in the same time without disturbing the pressure system or magnetising field.

Heating by alternating current was the method adopted, the current being switched off while the specimen was cooling. A simple coil type heater of square section consisting of 12 turns of non-magnetic nichrome wire embedded in a commercial fire cement was first tried. The heater failed to achieve the required temperatures before fusing, owing to the dissipating effect of the great metallic mass of the shearing jaws. As previously mentioned, no insulating material could be inserted in these jaws owing to the low tensile strength of all the possible materials.

Two refinements were added to the heating system to overcome this excessive heat dissipation. Rows of $1/32$ " holes were drilled through the jaws from side to side on a line $\frac{1}{4}$ " from the cube holding recesses. Each hole was fitted with a porcelain tube through which a nichrome wire, connected in series with the main heater, was threaded (see photograph, Fig. 2). The passage of the heating current through these subsidiary heaters helped to reduce the steep temperature gradients at the top and bottom of the cube. In addition, asbestos boards were cemented with araldite, around the region of the shearing jaws, to make a compartment into which aluminium oxide lagging powder could be poured during the heating part of an experiment.

With these refinements it was found by measuring temperatures on the cube, heater, and adjacent parts of the shearing jaws, that the passage of 5.2 amp. for a period of one hour was sufficient to ensure that the whole volume of the cube was raised to above 600°C . The heating system was then considered to be satisfactory. The large volume of metal which was heated during the first part of the experiment proved difficult to cool in a period of one hour, which was considered a suitable time for practical purposes.

To dissipate the heat more quickly two modifications were

made to the apparatus. The first was to arrange for the lagging powder to be dropped out of its asbestos container approximately ten minutes after the commencement of cooling (experimental cooling curves showed that the temperature had fallen to 300°C after this interval, and at this temperature most of the moment had been acquired). For this purpose a sliding bottom was made for the asbestos container. The second modification made was to fit copper pipes of oval section in a vertical position against the end plates. Cold water was passed through these pipes as soon as cooling was started, so removing some of the heat.

These two modifications proved satisfactory, with their aid the overall time of cooling was reduced to one hour. A continuous recording of the temperature of the cube where it was in contact with the upper nimonic jaw was taken. For this purpose the bead of a platinum/rhodium thermocouple was fixed near the top face of the cube with fire cement and the temperature recorded on an "Electroflo" meter.

(iii) The Magnetising System

The thermoremanent moment was produced in the specimens by a magnetising field derived from two mutually perpendicular

pairs of Helmholtz coils. These were arranged so that the vertical plane in which the magnetising field could be varied also contained the direction of the Earth's field, and the plane containing the shearing jaws was arranged to coincide with the plane containing the magnetising field. This arrangement simplified the graphical calculation of the coil currents required for various field directions, as the effect of the Earth's field could be added as a vector wholly in the plane of the magnetising field. In addition, the magnetisation of the cube in a plane parallel to one face allowed the most accurate determination of the direction of the thermoremanent moment. It had previously been found⁽¹⁴⁾ that the scatter in the directions of magnetisation of a group of specimens was inversely proportional to the strength of the magnetising field for fields of the order of the Earth's field. In the light of this knowledge it was arranged that fields of up to 5 oersteds could be obtained with the Helmholtz coil system.

The parameters of the Helmholtz coil pairs are shown below:

Helmholtz pair	Radius	No. of turns	Gauge of Wire	Oe/amp at centre of pair
Vertical field coils	46.25 cm.	210	24 S.W.G.	3.25
Horizontal field coils	45.75 cm.	210	24 S.W.G.	3.28

Since the laboratory 220 v. D.C. supply showed a 50 v. ripple on examination, the supply for the magnetising system was obtained from a specially built D.C. generator. This consisted of an A.C. motor driving a D.C. generator. The system was capable of producing 6 amp. at 240 v. (1440 Watts). Precautions were taken to make the output from the generator as steady as possible. The motor and the generator were fitted onto a strong wood and metal frame which was rigidly fixed to a concrete floor. The motor was driven by a 440 v. 3 phase industrial supply and was connected to the generator by a three belt pulley system. This proved a satisfactory connection, no appreciable stretching or whipping of the belts taking place, even after 500 hours aggregate running. The output from the generator was fitted with an $80\mu\text{F}$, 240 v. mica smoothing condenser, and with these precautions a ripple voltage having a maximum value of $1\frac{1}{2}$ v.

(about 2/3% of the total output) was obtained. Calculation and experiment showed that this ripple voltage had no measurable effect on the consistency of the experiments. It was necessary that the coil currents could be varied to obtain magnetising field directions at any angle from 0° to 360° , and that the current could be controlled ~~with a~~^{to} better than 1 part in 500 for a series of experiments lasting for a period of the order of a week.

A control panel was built to the design shown in Fig. 8 which performed both these necessities. Variation of the field direction was obtained by connecting the coils in series and arranging a variable resistance ("ratio resistance") such that it could be put in parallel with either coil pair. This circuit, together with reversing switches, allowed any field direction to be obtained. Accurate control of the current was made possible by the potentiometer circuit shown in Fig. 8. The voltage drop across the one ohm standard resistance (R_s) was continuously applied to the potentiometer circuit and the 5Ω screw type variable resistance used to adjust the current through the standard resistance so that the galvanometer spot was never allowed to drift by more than ± 10 divisions from the balance position. Calculation of the constancy obtained with this condition showed it to be better than the 1 part in 500 required for

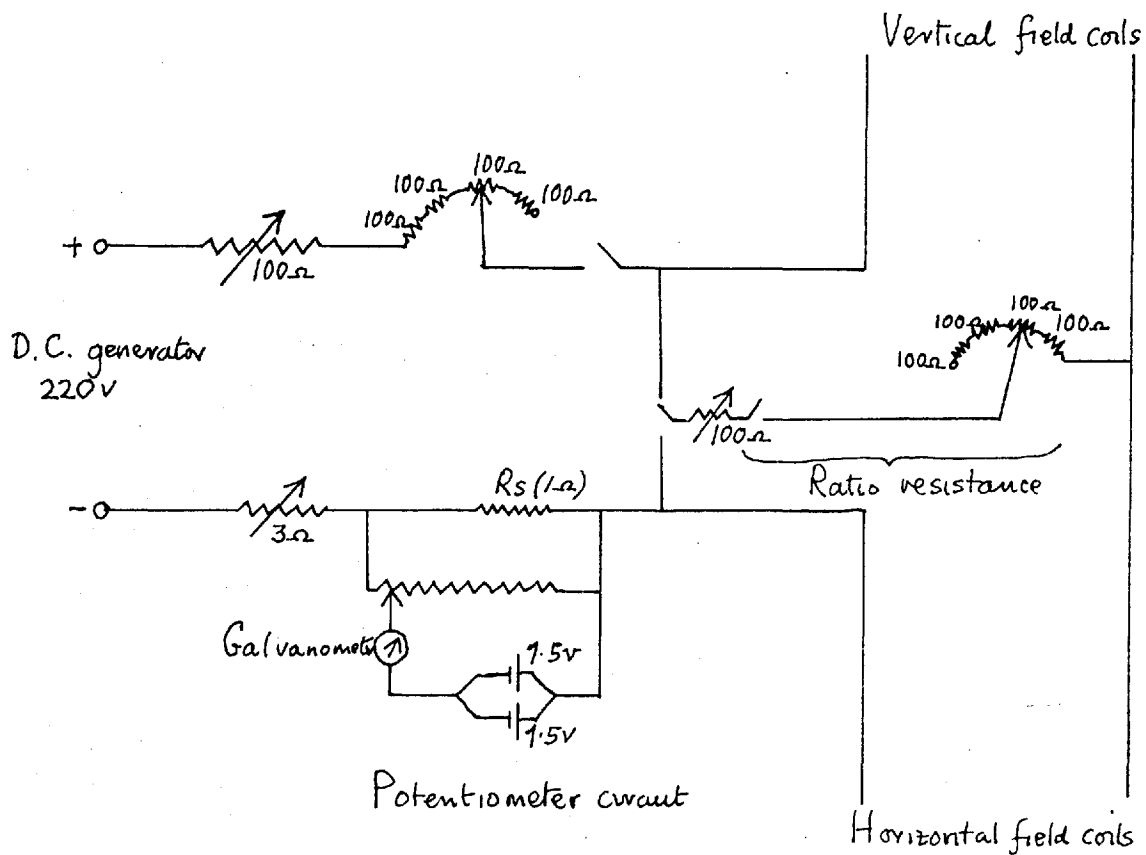


Figure 8. Outline of Helmholtz coil current control system.

the experiment. Operating experience showed that the drift in the generator output was greatest in the four hours following the commencement of running. To reduce this drift the generator was allowed to run undisturbed for periods of up to fourteen days, a practice which led to more consistent results.

2.4 The Uniaxial Pressure Apparatus

This apparatus, designed and built by Neale⁽¹⁴⁾, was only slightly modified for use in the present investigation. Briefly, the apparatus consists of a hydraulic ram, in a thick walled dural vessel, which can apply theoretical pressures of up to 1500 kg/cm^2 to cubical rock specimens acquiring a thermoremanent moment in a magnetising field. As in the shear pressure apparatus this field can be varied through 360° in a plane which also contains the Earth's field. The apparatus is best described in three sections:

- (i) the pressure system,
- (ii) the heating system, and
- (iii) the magnetising system.

(1) The Pressure System

This consists of a hydraulic ram fitted to act vertically in a thick walled dural pressure vessel (Fig. 9 shows the pressure system in section). The lower moving piston compresses the cubical specimen against the fixed upper anvil. The recessed cube holders and the opposite ends of the pistons are made from Nimonic 80A, while an intermediate disc of pyrophyllite is inserted in each piston for insulating purposes. Pressures of up to 1500 kg/cm^2 (approximately equal to 1500 atmos.) can be attained but at pressures of this order the washers below the lower piston are very quickly destroyed, only lasting for two pressure experiments (4 hours aggregate pressure). At a pressure of 880 kg/cm^2 the washers last for forty experiments before replacement is necessary, and this pressure was chosen as a standard test pressure in experiments on different rocks.

The pressures estimated theoretically for various weights applied at the exterior end of the hydraulic system in the tables of results in Chapters 4, 5 and 6 have ~~not~~ been corrected for friction between the lower piston and its containing cylinder. It is estimated that the true pressures are of the order of 20% less than the theoretical pressures quoted in this investigation⁽¹⁴⁾.

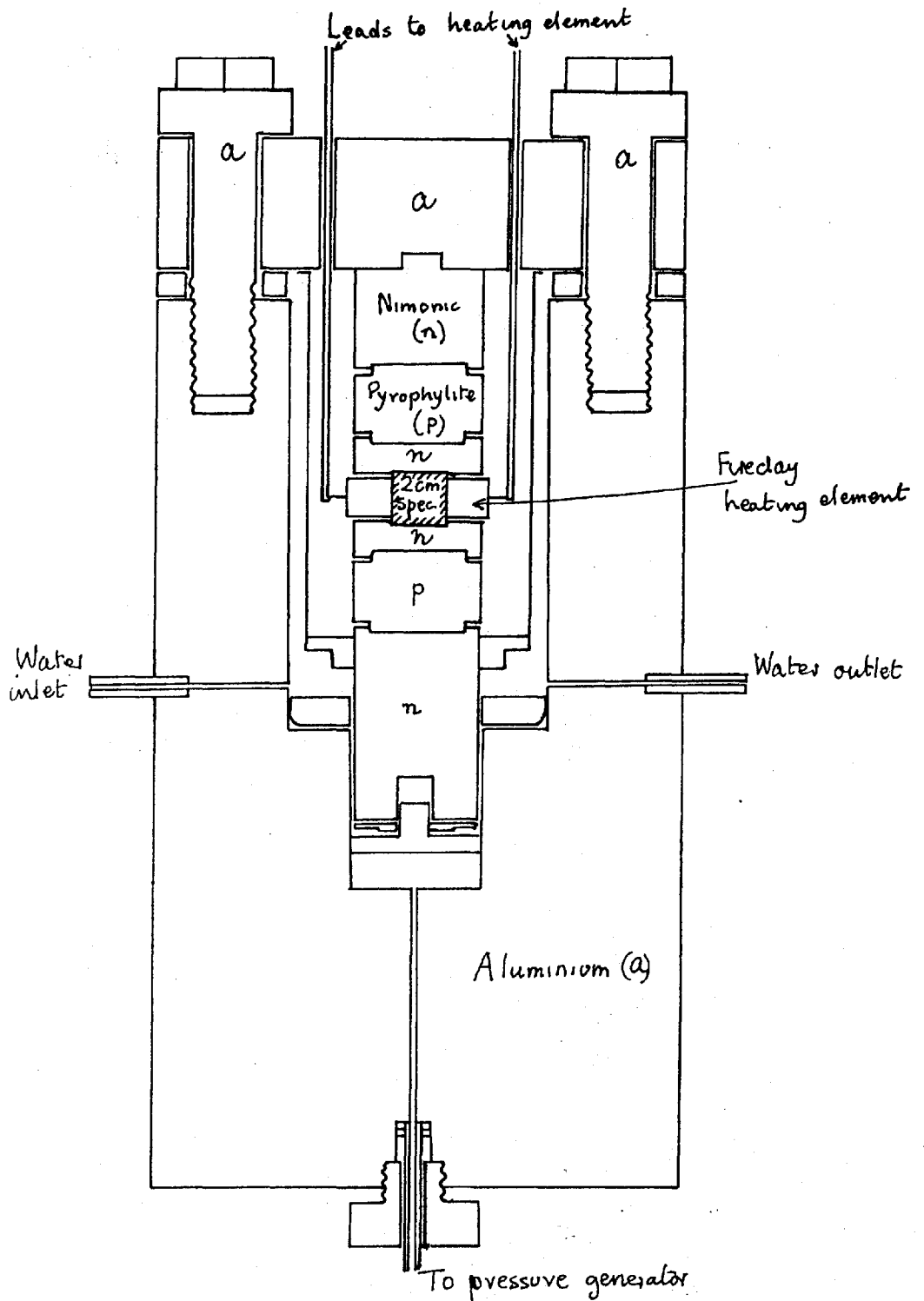


Figure 9. The Uniaxial Pressure Vessel.

Specimen preparation for this apparatus was relatively simple. Only two faces, the top and bottom, required special treatment. The distance between these faces is not critical, only their degree of parallel^e~~ity~~ and their smoothness being important. For these factors the same 0.001" tolerance as used in the preparation of specimens for the shear stress apparatus was observed.

(ii) The Heating System

The specimen was heated to 600°C by means of a nichrome wire heater embedded in fire cement identical with that described for use with the shear pressure apparatus. On account of the pyrophyllite discs incorporated in the piston and anvil no extra heating aids were required. To decrease the heating time from 45 minutes to 35 minutes a brass cyclinder, resting on a dural disc base, was fitted inside the pressure vessel, around the area of the heater and cube, to reduce convection currents. During the experiment the lower piston was prevented from expanding by a water cooling system.

Cooling was accelerated by compressed air, which reduced substantially the time taken for the cube to cool from 300°C

to room temperature and reduced the overall cooling time from one hour to forty minutes. A thermocouple of the type described for the shear pressure apparatus was fitted.

(iii) The Magnetising System

The design and construction of the magnetising system is identical with that described for the shear stress apparatus.

2.5 A.C. Demagnetisation Apparatus

An A.C. demagnetisation apparatus was available for use in the present investigation in the Physics Department of Imperial College. A.C. demagnetisation fields up to a maximum of 700 oe. could be applied to batches of six specimens at one time. For fields of less than 50 oe. accuracy to 2 oe. could be obtained. In order to protect specimens from the influence of external fields immediately after demagnetisation, cubes were placed in "mu-metal" boxes directly on removal from the apparatus.

2.6 Thermal Demagnetisation Apparatus

A number of Curie point measurements were carried out using a furnace designed by Leng⁽¹⁸⁾ in conjunction with a Blackett⁽¹⁹⁾ astatic magnetometer. The furnace allows ~~small~~ chips of rock to be heated by an alternating current in null field to 750°C in one hour, the moment of the specimen being measured at any required temperature interval (25°C. was chosen as the interval for this investigation). The application of a horizontal field of 0.5 oe. intensity during cooling gives the specimen a moment for a second Curie point determination.

2.7 Isothermal Cyclic Pressure Apparatus

A number of experiments were carried out with this apparatus using specimens which had previously been subjected to pressure treatment in the linear pressure vessel. The apparatus is generally similar to the pressure vessel described in 2.4., consisting of a brass linear pressure vessel within three pairs of Helmholtz coils. No heating system exists since the apparatus is only designed for isothermal experiments. Pressure is applied hydraulically^{al} in cycles of 1 minute period (pressure~~s~~ on for 30 seconds

and then pressure off for 30 seconds). Pressures of 5000 psi. (about 350 Kg/cm^2) are attainable.

2.8 Experimental Procedure Adopted for Pressure Experiment

(i) Shear Pressure Apparatus

A procedure similar to that used by Neale was found successful. Experiments with various field directions were carried out on groups of two or four specimens. Each specimen in each group was heated four times in all, the sequence of experiments being the first and third heatings without pressure and the second and fourth heatings with pressure. In view of the ease with which the ultimate tensile strength of the rock was exceeded, experiments were carried out at the maximum possible pressure which would not break the specimen. Generally this required loads of 15 lb. or 20 lbs. at the end of the lever arm, depending on the rock type being used.

Cubes were immediately stored in "mu-metal" boxes at the end of an experiment and were not measured for 24 hours. This procedure was used in view of the drift of up to 2° found to occur in the first few hours after removal from the pressure apparatus if the specimen was left in the

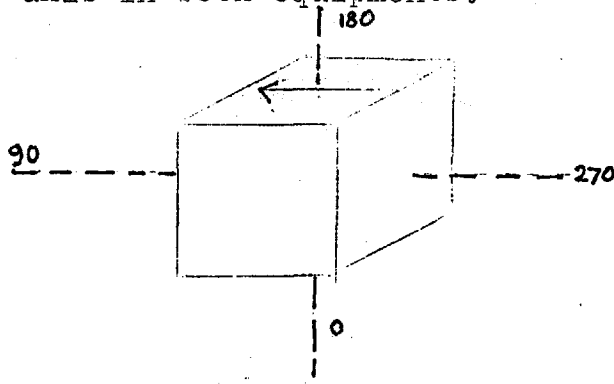
Earth's field⁽¹⁴⁾.

(ii) The Linear Pressure Apparatus

The heating sequence described above was also used for this apparatus. All experiments were made with an angle of 45° between the pressure axis and the direction of the magnetic field. Batches of four cubes were used in every instance. The stresses used varied between 0 and 1530 Kg/cm² (theoretical values).

(iii) General

All specimens were marked with a white crayon arrow on their top surface, this being used as a reference mark for orientation in the pressure apparatus equipment and in the spinning magnetometer. The orientation of specimens in both pressure vessels relative to the spinning magnetometer angular calibration is shown below, the 0-180° axis being the pressure axis in both equipments.



CHAPTER III

COMPOSITION, GRAIN SIZE AND OTHER RELEVANT PROPERTIES OF THE MAGNETIC CONSTITUENTS OF THE ROCKS STUDIED

3.1 General Petrological Properties

3.1.1 Necessary Magnetic and Mechanical Properties

Since the specimens were expected to withstand pressures of the order of 1500 kg/cm^2 without fracturing the petrological types suitable for study were limited in general to igneous rocks. This limitation was also imposed by the need to employ rocks which, in a 1.5 oe. field, would acquire a thermoremanent moment of the order of $50 \times 10^{-3} \text{ emu/cc}$ or greater.

The only easily accessible rocks which satisfied both these requirements were the basic igneous rocks, lavas, dykes, and sills, of the Hebridean Tertiary Igneous province. Accordingly, several collecting trips were made to Skye, Invernesshire, and dykes and sills of Tertiary dolerite sampled.

At a later stage in the investigation some samples of

similar rocks from the Deccan Traps of India (Cretaceous/Eocene age) were made available by the Physics Department of Imperial College. These were known to have interesting magnetic properties and were also used in the experimental determination of the effect of composition on pressure effects.

3.1.2 Petrology of the Rocks Chosen for Study

Tertiary dolerites from Skye.

The Ob lusa dolerite: This dolerite was collected from a dyke belonging to the last phase of Tertiary igneous activity in the area. The dyke is exposed on the foreshore below the Kyleaken-Broadford road to the east of Ob lusa (a small bay). The dyke consists of hard black fresh dolerite, and shows some jointing across its width. It is intruded into Precambrian red sandstones of the Torridonian Series. At the contact, the sandstone shows a loss of colour indicating the reduction of its normal hematite pigment. The dyke itself varies in width from 8' to 15' and sampling was carried out from the centre to the chilled contact dolerite.

Microscopically, the central coarser region of the dyke is seen to be a fine grained dolerite with plagioclase

felspar, augite and magnetite as the main constituents. The magnetite is mainly in the form of ~~rhombic~~^{equidimensional} sections. Towards the much finer contact two generations of magnetite are visible under the microscope, one that appears to be a finer grained version of the ~~rhombic~~^{equidimensional} grains seen in the dyke centre material and the second which consists of a very great number of small needles of magnetite lying 'en echelon' over small areas along the cleavage planes of the felspar and augite. This second generation constitutes the bulk of the magnetite in the rock. In addition, large highly corroded ~~rhombic~~^{equidimensional} grains occasionally occur and these may belong to a third generation. Calcite and pyrites also occur in the dolerite. Planes containing large numbers of small blebs of pyrite can be seen intersecting some of the cubes cut from the contact rock.

The coarser dyke centre rock was used by Neale in his pressure experiments.

The Heast Road dolerite: This dolerite occurs as a small sill in a road-side quarry on the road from Broadford to Heast (MR. 660203). The sill is composed of a dark grey dolerite showing vertical jointing, only the lower part being visible. At the lower contact the sill transgresses

over a series of interbedded shales and blue limestones of Liassic (Lower Jurassic) age. A layer of fused shale about half an inch thick is often found welded to the sill at the lower contact. Above the contact region the sill is petrologically an ophitic: dolerite consisting of plagioclase and augite with some olivene which shows signs of alteration. In the contact region the rock shows a porphyritic basaltic texture, plagioclase laths being the phenocrysts. These laths show a slight orientation, but not enough for the texture to be termed subtrachytic. The groundmass is composed of plagioclase and augite. Some calcite replacements of augite are visible. An opaque mineral in blebs, shown later to be pyrrhotite, completes the rock.

Some 10 ft. of the sill is visible in the quarry but only the lower 3 inches shows a visible decrease in grain size associated with chilling.

There is a remarkable change in the composition of the opaque minerals from the sill centre to the contact. The central coarser region contains approximately rhombohedral sections of an il^emanite-hematite solid solution while the contact contains ^lblebs of pyrrhotite of a late period of formation. It has since been suggested that either a composite sill (two sills fused together) was being sampled

or that the shales at the lower contact had contaminated the contact dolerite. No field evidence of a composite intrusion was found so contamination may explain the unusual situation.

Cretaceous/Eocene Basalts from Linga (U.P.) India

Basalts from the Deccan Trap series of flows were collected by an expedition from Imperial College in 1959. In view of their interesting magnetic properties two specimens from this collection were studied in this investigation.

Specimen L 6. This basalt shows a porphyritic doleritic texture i.e. it is coarser than an average basalt but since it has an extrusive origin it must be known as a basalt. Plagioclase and augitic pyroxene phenocrysts, together with large patches of reddish mineraloid which is probably an alteration product of olivine, give the rock its porphyritic texture. The groundmass of the rock is a sub porphyritic assembly of the same minerals. The opaque magnetic mineral appears as both ~~equidimensional~~ and lath like grains.

Specimen L.31. This is again a basalt showing a porphyritic doleritic texture. The phenocrysts are of plagioclase and augitic pyroxene while the groundmass is composed of these minerals together with some olivine and a green serpentinous alteration product of this mineral. The opaque minerals show the two forms described for L6.

3.2 The Compositions of the Magnetic Constituents

3.2.1 Recognised Compositional Variations

The main compositional variants at present identified in rocks belong to the ternary system $\text{FeO} - \text{Fe}_2\text{O}_3 - \text{TiO}_2$.

This system contains three main solid solution series:

- a). the magnetite (Fe_3O_4) - Ulvöspinel (Fe_2TiO_4) series,
- b). the magnetite (Fe_3O_4) - ilmenite (FeTiO_3) series, and
- c). the hematite (Fe_2O_3) - ilmenite (FeTiO_3) series.

(See Fig. 10).

The end members of series (a) and (c) are isomorphous and it is easy to conceive intermediate solid solution compounds, but the end members of series (b) have different crystallographic structures (Fe_3O_4 cubic and FeTiO_3 rhombohedral) and it is difficult to envisage the mechanism of solid solution

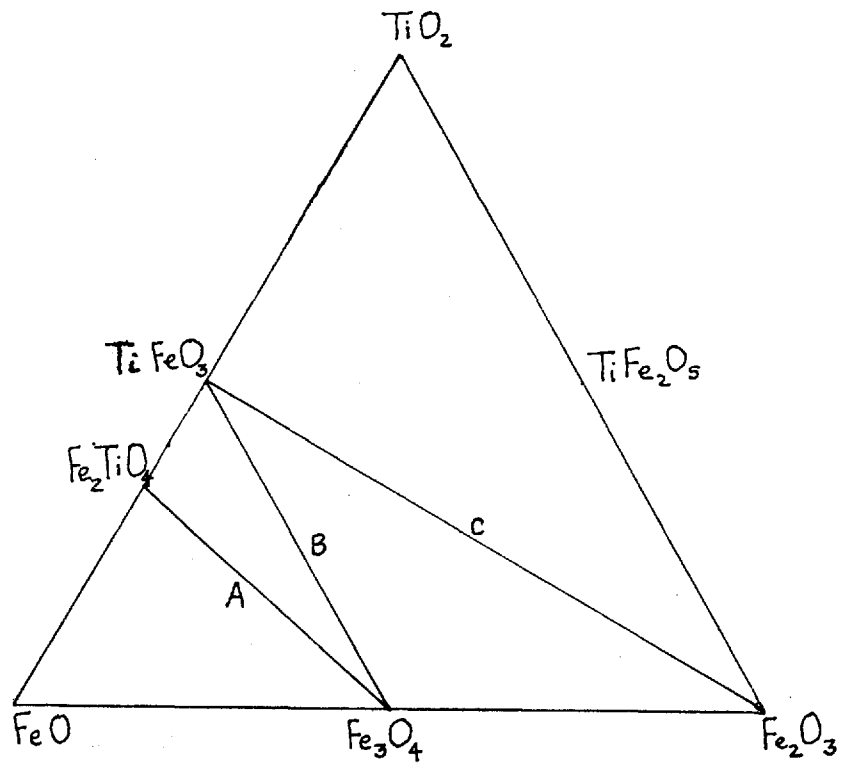
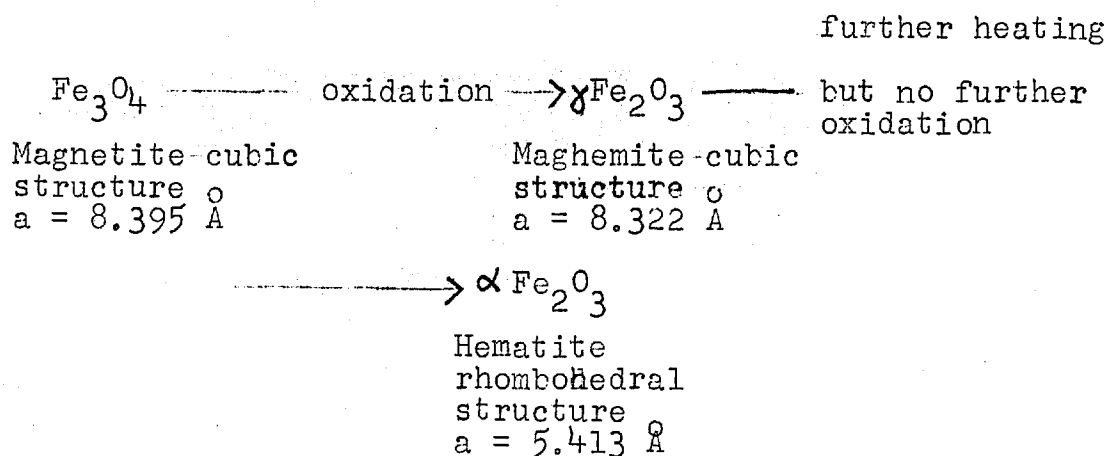


Figure 10. Ternary diagram FeO-Fe₂O₃-TiO₂

of intermediate members. These three series are not likely to be found to be exhaustive and it is very probable that solid solutions between them and other compounds will be found.

In all naturally occurring magnetic minerals impurities such as aluminium, magnesium and calcium occur in varying amounts and in usually unknown forms. The effect of these impurities may be decisive in controlling the magnetic behaviour of a mineral.

The oxidation of magnetite to hematite is accompanied by a very important intermediate stage. This process may be written as follows



$\gamma\text{Fe}_2\text{O}_3$, maghemite, may be represented as magnetite with a lattice defect caused by oxidation i.e. $4(\gamma\text{Fe}_2\text{O}_3) = 3(\text{Fe}_8/3\text{O}_4)$. The change from maghemite to hematite on further

heating is irreversible. Pure maghemite appears to be very unstable with regard to temperature, it has been found that the transformation from the γ to the α form may take place at a temperature as low as 275°C , but the addition of aluminium⁽²⁷⁾ for example, increases the stability considerably and the transformation temperature may be raised to 800°C .

Since natural maghemites may be expected to carry a considerable amount of impurities they may be expected frequently to show a high stability as carriers of thermoremanent and chemical magnetisation. It may be expected also that the range of Curie points and lattice constants for the solid solutions series of maghemite and various non-magnetic oxides would overlap with the titanomagnetite series, and Michel and Chaudron have shown this to be the case.

The remaining important group of magnetic rock forming minerals are those which are compounds of iron and sulphur. Compounds of these elements may be made with compositions varying between iron pyrites (FeS_2) and troilite (FeS). Only the members of this series which fall into the range $\text{Fe}_{11}\text{S}_{12} \leftrightarrow \text{Fe}_6\text{S}_7$ are important from the aspect of rock magnetism. Minerals in this compositional range are known collectively as pyrrhotite, and show a high thermoremanent moment and saturation magnetisation.

3.2.2 The Variation of Magnetic and Crystallographic Parameters with Compositional Change (20)

It has been found that the magnetic and crystallographic properties of magnetic minerals are very dependent on composition, and may thus be used to determine composition. Crystallographically, compositional change alters the lattice constant, a . The graphs in Fig. 11 show the variations of the lattice constant for the magnetite-ulvöspinel and hematite-ilmenite series.

The most clearly defined change in magnetic parameter with composition is ^S the change in the Curie point. The Curie point is the temperature at which the magnetism of a mineral changes from the ferro. to the para. state, or vice versa. This parameter may be used to distinguish between various magnetic series and between the members of one particular series. Other magnetic parameters are also dependent in composition and may be used to differentiate between the different compositional series, coercive force, remanent moment (in a particular field) and the Koenigsberger ratio, Q , being well documented. This latter parameter is defined as follows

$$Q = \frac{(\text{Intensity of TRM acquired in field } H)}{(H \times \text{susceptibility (K)})} \text{ measured at normal air temperature}$$

Examples of Curie point variations are shown in Fig. 12. Fig. 12 also shows that the titanohematite and titanomagnetite series overlap for this parameter, as a consequence of this it is necessary to use other parameters to decide to which series a particular mineral belongs and to use the Curie point to determine the position of a mineral within a series.

Coercive force, which may be obtained from the hysteresis cycle, is a useful parameter to differentiate between series. The coercive force of the titanomagnetite series is always less than 50 oe while that of the titanohematite series is always greater than 100 oe. Pyrrhotite shows very different magnetic properties from the members of the $\text{FeO} - \text{Fe}_2\text{O}_3 - \text{TiO}_2$ ternary diagram. The Curie point of this mineral is just over 300°C , the Q ratio about 200 and the coercive force about 250 oe.

3.2.3 Parameters Used to Ascertain the Composition of the Magnetic Constituents

Three main methods were used to estimate the compositions of the relevant minerals. Firstly the magnetic properties Curie point and Q ratio values were measured. Secondly, magnetic separations were studied by X-ray diffraction, and

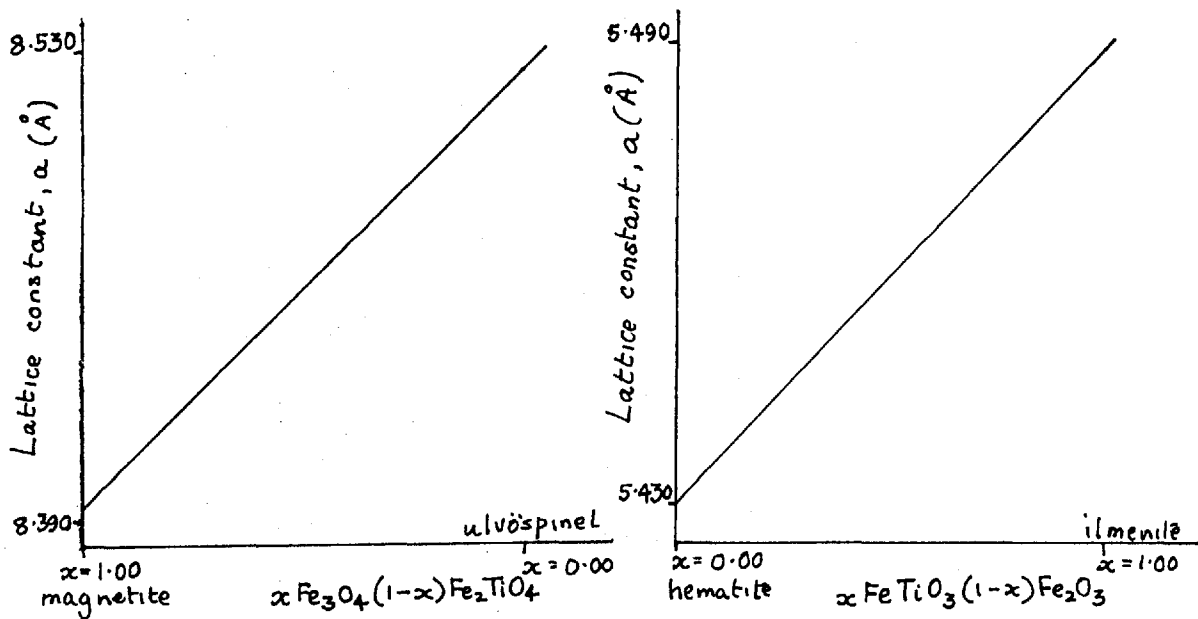


Figure 11

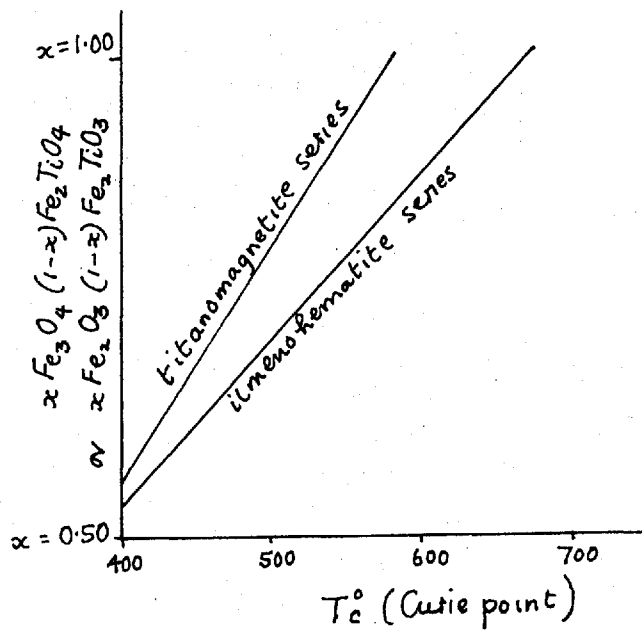


Figure 12

the lattice constant, a , obtained, and, finally, polished sections of the whole rock were studied by reflection microscopy methods. The results of these different approaches were combined to assure that the most reliable inference of chemical composition was made.

Curie Point Determinations

Curie point determinations were made in two different ways. The first method was the thermal magnetisation of specimens in steps up to the Curie point, using the uniaxial pressure vessel. The uniaxial pressure vessel was used since it provided a convenient heating and magnetising system.

The method used was to cut a fresh cube of rock and to demagnetise it in the highest A.C. field available (about 700 oe). This proved enough to reduce the natural remanent moment of the cube to less than 1% of the expected thermoremanent moment. The cube was next heated, in the pressure vessel, to a temperature of 50°C and allowed to cool to room temperature in a 1.5 oe. field, removed from the pressure vessel, and the resulting thermoremanent moment measured. After this measurement the specimen was replaced directly

in the pressure vessel and heated to 75°C , allowed to cool in the same field and remeasured. Successive heatings raised the temperature in 25°C steps until no further increase in the moment was obtained. When this was achieved the Curie point had been passed and a graph of the maximum temperature of a magnetising interval with the relevant moment indicated the Curie point (see Fig. 13).

In this thesis the measurements have been presented in the more customary form of demagnetisation curves. To permit this presentation the moment for a certain temperature interval was subtracted from the final moment obtained for the Curie point temperature interval, and this difference plotted against temperature. Thus method of Curie point determination proved only reasonably satisfactory owing to the difficulty in temperature calibration of the pressure vessel, the high thermal gradients across the specimen (up to $100^{\circ}\text{C}/\text{cm}$) and the different performance of different heaters (one heater would only last for two complete Curie point determinations).

The second method used for measuring Curie points differed from the first in that a demagnetisation curve was obtained directly from the measurements. The procedure was to place a small previously magnetised chip of rock in a quartz glass furnace directly below an astatic magnetometer.

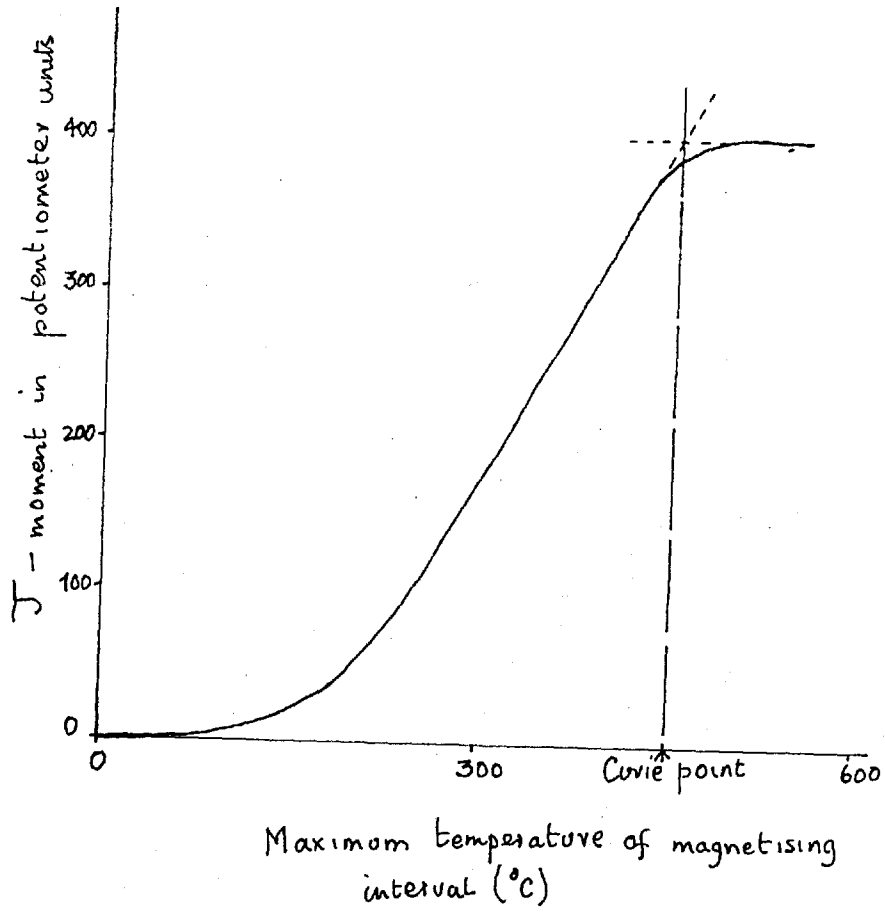


Figure 13

The temperature was raised slowly to 700°C, measurements of the remaining moment of the specimen being made at 25°C intervals. By applying a horizontal field while the specimen was cooling a new moment could be induced to allow the Curie point to be checked by a further demagnetisation. This apparatus gave consistent results when used. Specimens of the same rock were measured in both ways and it was found that the linear pressure vessel method gave a Curie point value some 20°C smaller than the value obtained with the furnace and astatic magnetometer, and the pressure vessel results were corrected for this difference.

Q-ratio Determination

The Q ratio ($\frac{\text{Intensity of TRM in field } H}{H \times \text{susceptibility } k}$) was determined by straightforward measurements of the thermoremanent moment and initial susceptibility.

Lattice Constant Measurements

Lattice constant measurements were made on a 20 inch X-ray powder diffraction camera at the Crystallographic

Laboratory of Birkbeck College (University of London). The powder was obtained by crushing and sieving samples of rock and separating the magnetic fraction by means of a vibrating magnetic separator. The magnetic concentrate was repowdered and separated several times until an approximately 90% pure magnetic mineral sample had been obtained. The lattice constants were found by measurement of the higher order spectra on films obtained with 4 hour exposures.

Reflection Microscopy Evidence

Reflection microscopy proved a very useful method in that the whole rock could be studied, as a polished section, and fine intergrowths and heating effects recognised. Polished sections of the Skye dolerites were studied by Dr. A.P. Millman of the Geology Department of Imperial College, who was kind enough to demonstrate his findings.

Together with the normal reflection identification techniques, measurements of the Vickers microhardness were made of all the opaque minerals in the polished sections.

3.2.4 The Inferred Chemical Compositions of the Magnetic Constituents

The Ob lusa dolerite dyke

(a) Curie point determination

The Curie point of this dolerite was measured for both centre and contact specimens. The measurements were first made using the linear pressure vessel apparatus and were checked with the furnace and astatic magnetometer. The thermal demagnetisation curves obtained are shown in Fig. 14. For each specimen measured four curves were obtained and for this rock good consistency of behaviour on successive heatings was found, suggesting that little change took place in the magnetic constituents after the first heating.

The Curie points obtained are shown in Table 1.

(See Figs. Table 1
14a,b,c,d,e,)

<u>Specimen</u>	<u>Method of Measurement</u>	<u>Curie points</u> (average of 4 values)
021 (dyke centre)	Linear pressure vessel (A)	(513°C 571°C)
021	Furnace and astatic magnetometer (B)	(523°C 545°C)

Table 1 Contd.

<u>Specimen</u>	<u>Method of Measurement</u>	<u>Curie points</u> (average of 4 values)
022($\frac{1}{2}$ " from dyke contact)	A	522°C (no second Curie point evident)
022	B	(535°C 575°C)
024 (dyke centre) Neale's specimen 123	A	(529°C 575°C)

In four cases out of five the thermal demagnetisation curves show evidence of two Curie points suggesting the presence of two magnetic components. The possibility of ambiguity in the inference of composition from Curie point alone can be seen from the figures in Table 1. All the Curie points in this table could indicate compositions in the magnetite-ulvöspinel solid solution series or the ilmenite-hematite solid solution series.

(b) The Q-ratio

The Q-ratio values found for a number of dyke centre and contact specimens, together with values of initial

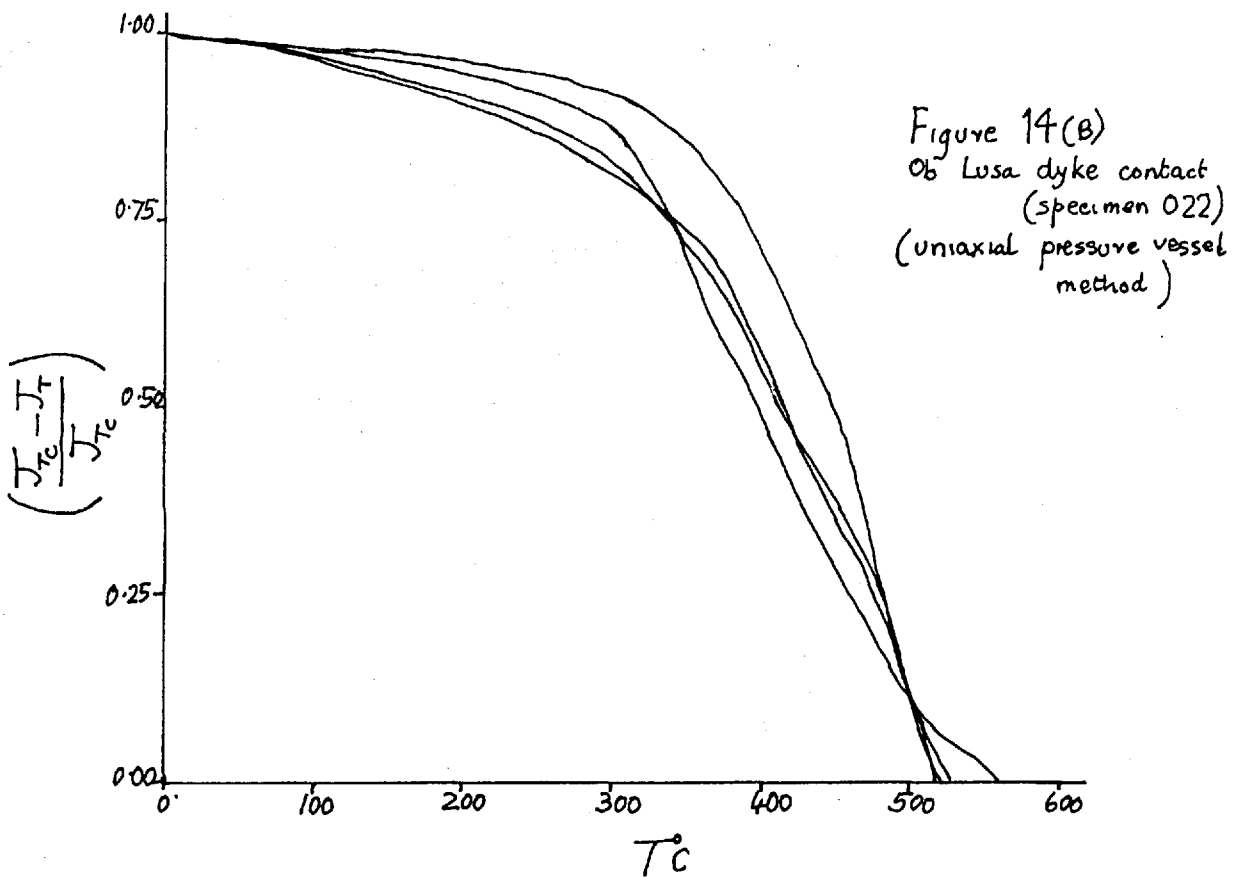
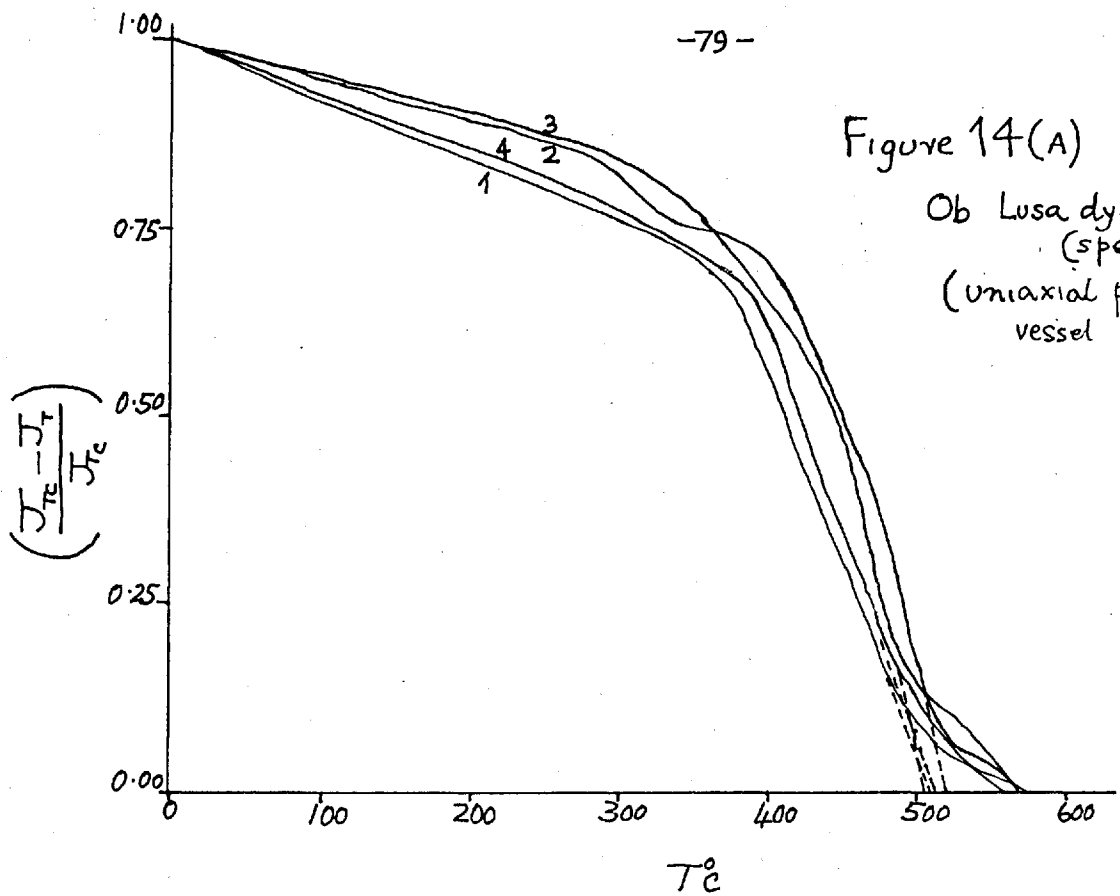


Figure 14(c)

Ob Lusa dyke centre (specimen 021)
(furnace and astatic magnetometer method)

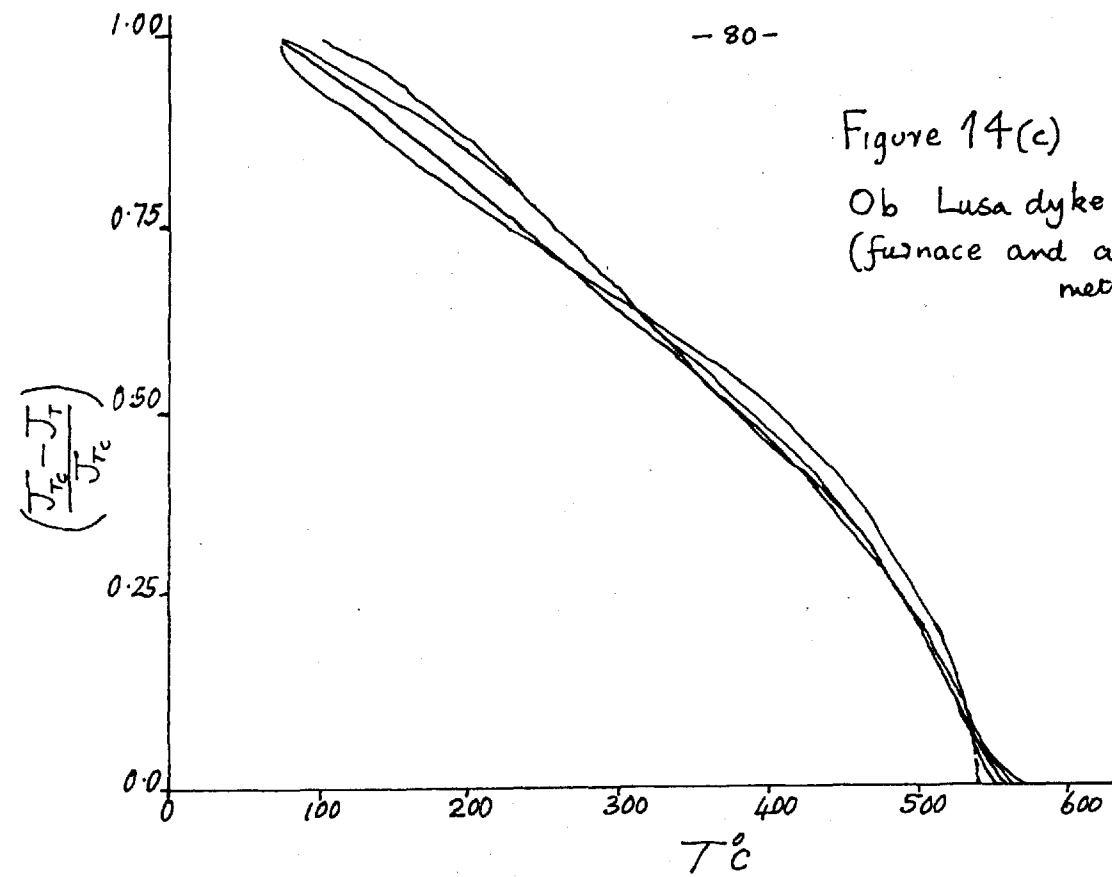
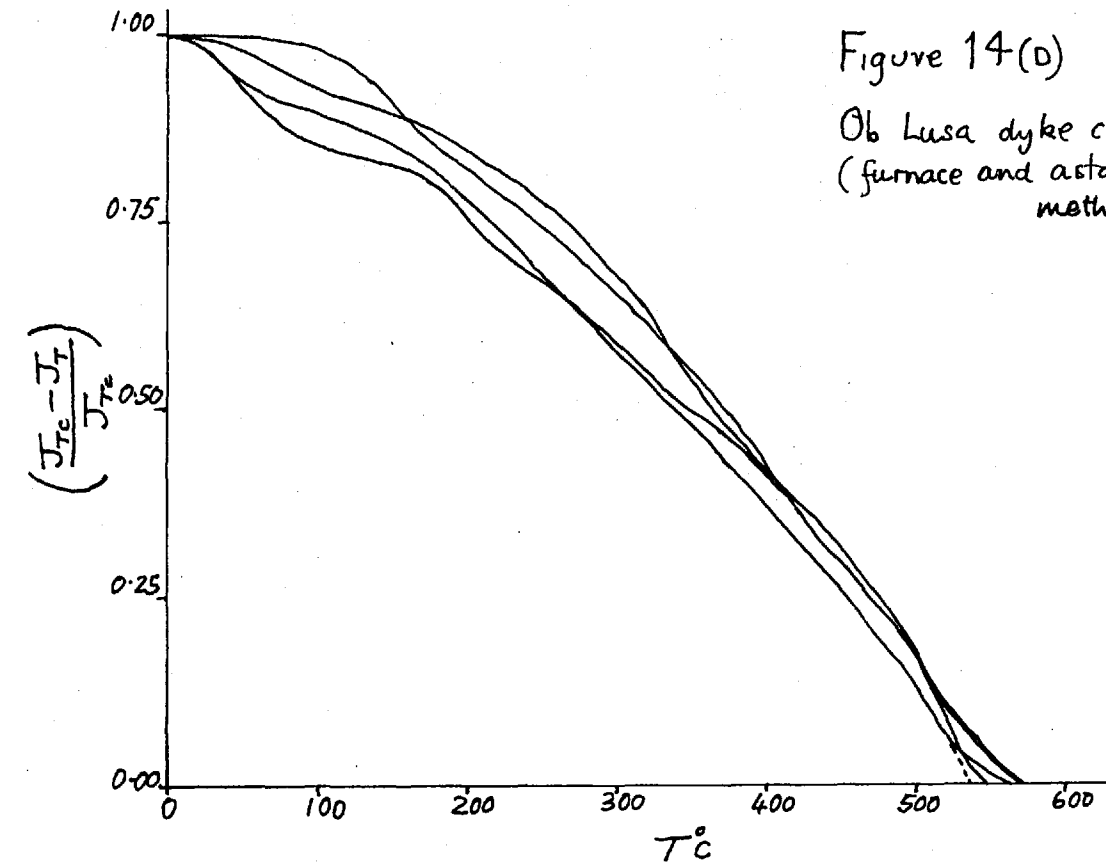
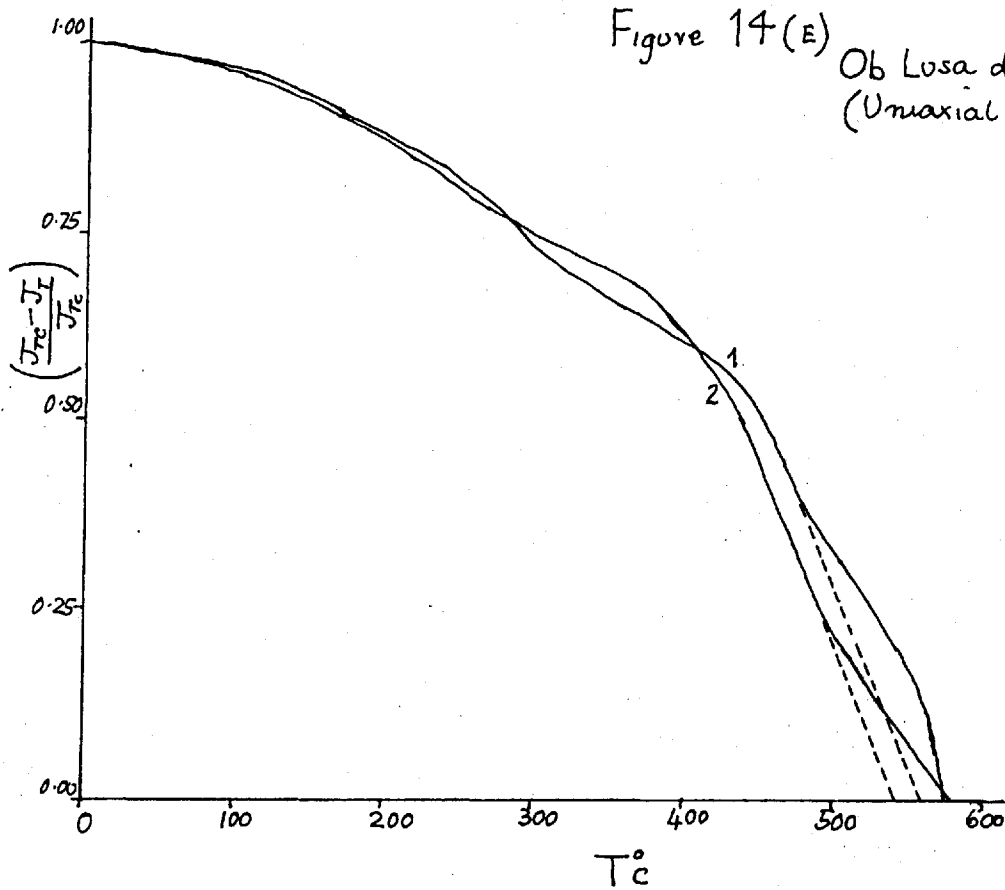


Figure 14(d)

Ob Lusa dyke contact (specimen 022)
(furnace and astatic magnetometer method)





susceptibility and remanent moment are shown in Table 2.

Table 2.

<u>Specimen</u>	<u>Location</u>	<u>J_{Rem} ($\times 10^{+3}$ emu/cc)</u>	<u>k ($\times 10^{+3}$ emu/cc)</u>	<u>Q ($H=1.5\alpha$)</u>
		$H = 1.5 \text{ oe.}$		
06	$\frac{1}{2}$ inch inside dyke con- tact	175.5	4.32	27.0
023	"	53.5	2.93	12.2
024	"	55.8	2.99	12.4
028	"	137.0	4.22	21.7
029	"	145.0	4.48	21.6
030	"	115.0	4.95	15.5
031	"	223.3	4.82	30.8
032	"	158.4	4.68	22.6
033	"	71.3	2.95	16.1
034	"	212.7	4.64	30.6
035	"	209.2	5.18	26.8
036	"	202.5	5.65	23.9
050	Dyke Centre	56.3	7.00	5.35
051	"	58.6	7.12	5.50
052	"	48.0	7.30	4.40
053	"	71.0	8.10	5.85
055	"	49.5	6.68	4.95
056	"	49.8	6.74	4.90
057	"	68.5	5.87	7.80
058	"	58.5	6.40	6.10
059	"	51.6	6.60	5.20

The Q-ratio values for the dyke centre specimens agree well with those given in literature for magnetite bearing rocks. In addition, if the effect of grain size, as described by Roquet⁽²⁴⁾ is allowed for, the values for the finer specimens also agree with the magnetic constituent being magnetite.

(c) Lattice Constant Measurement

As described in 3.2.3, X-ray diffraction measurements were made of the lattice constants of the magnetic minerals of the Ob Lusa dyke. It is important to note that a limitation of the method is that a magnetic component too weak to be extracted in the vibrating-separator will be missed in the analysis.

The results of the measurements are shown in Table 3. The X-ray results confirm that two components are present in the heated rock and from the estimated lattice constants it is clear that both are close to pure magnetite in structure and composition (magnetite $a = 8.393$). The slight deviations from this value of lattice constant may be interpreted in two possible ways, either as substitution of titanium into the magnetite molecule to give a member of the magnetite-ulvöspinel solid solution series or by the development of an impure stable maghemite from part of the magnetite on heating. Since only maghemite and pure magnetite were seen in the rock when examined with reflected light the second explanation must be the correct one. The unheated rock shows only the presence of nearly pure magnetite. This change in the magnetic components is described in detail in the next section.

Comparison of the X-ray results, Q-ratio values and

TABLE 3

X-ray spec.	Location & state	Cubic Planes				Calculated lattice constants (Å)
		220	311	333	440	
3	Unheated dyke centre	$\frac{220}{2.97\text{Å}}$	$\frac{311}{2.53\text{Å}}$	$\frac{333}{1.618\text{Å}}$	$\frac{440}{1.487\text{Å}}$	8.39(8.387)
8	heated dyke centre	2.97	(2.53 (2.54	(1.622 (1.617 weak	(1.491 (1.486 weak	(8.43(8.431) (8.40(8.404)
5	unheated dyke contact	2.97	(2.53 (2.52 v.weak	(1.614 (1.609?	(1.482 (1.475	(8.39(8.385) (? maghemite
4	heated dyke contact	2.97	(2.53 (2.54	(1.616 (1.621	(1.485 (1.490	(8.43(8.426) (8.40(8.399)

Curie point determinations immediately shows points of similarity. All sets of measurements show two components in the heated rock. In addition the same components occur in both the dyke centre and dyke contact material, showing that little change in the composition of the magnetic constituents exists in the heated rock from the dyke centre to the dyke contact.

(d) Reflection Microscopy Evidence

The Unheated Dyke Rocks

The coarse dyke centre rock has two opaque components, magnetite and pyrite. The magnetite appears to be nearly pure having an upper limit of 1% titanium. It occurs as skeletal cubic crystals which are sometimes elongate and lamellar. The crystals are frequently strongly corroded by silicate minerals, most of which crystallised after the magnetite. Exsolution inclusions in the magnetite are rare or absent. There is an appreciable quantity of pyrite: (FeS₂), formed later than the magnetite, which it often replaces. The identification of essentially pure magnetite in this rock agrees well with the X-ray results, which show magnetite with a lattice constant of 8.39

(pure magnetite: $a = 8.393 \text{ \AA}$). The unheated contact rock shows two definite opaque minerals, and a third seems possible from the X-ray results. Skeletal magnetite of a much finer grain size than the dyke centre crystals occurs. Pyrite is again present and there is a suggestion of maghemite in the smaller grains. This again agrees with the X-ray results given in section (c).

The Heated Dyke Rocks

It must be pointed out here that there is apparent disagreement between the X-ray and reflection microscopy results. Both approaches demonstrate the existence of two magnetic components in the heated dyke material, one of which, pure magnetite, is common to both. The composition of the second component, however, may easily be differently interpreted in each case.

Reflection microscopy shows that the central region of the heated dyke centre material has fresh magnetite of the type described in the unheated rock. This only differs from the unheated magnetite in showing a slight suggestion of a lightening of colour adjacent to small cracks in the grains. In contrast to this the outer region of the specimen shows considerable alteration. This zone is

reddened and a transition in the magnetites from the fresh centre to the reddened zone is apparent. As this zone is approached the magnetite shows a paler colour and develops a microlamellar and spindle structure due to the formation of hematite in the spindles. The remainder of the magnetite crystals has been pseudomorphed by a micromosaic of maghemite sometimes rimmed by an outer zone of hematite. Locally, rare rutile has been developed and all the pyrite in this reddened zone has been altered to hematite. The changes which have taken place in the heated contact are identical with those described for the heated centre rock with the exception that the zone of reddening is shallower, presumably because of the lower porosity of the contact rock.

The difficulty in the reconciliation of the X-ray and reflection microscopy measurements is in the identification of the phase with lattice constant $a = 8.43 \text{ \AA}$ in the X-ray determinations, since maghemite has been shown to have a lattice constant of $a = 8.322 \text{ \AA}$. A very satisfactory means of resolving this difficulty results from the work of Michel and Chaudron⁽²⁵⁾. These workers have investigated the variation of lattice constant and Curie point of various impure maghemites and have been able to show that the

solution of a non-magnetic oxide in maghemite causes a decrease in Curie point and an increase in lattice constant. An example of such a variation is shown in Fig. 16.

Thus it appears that impure maghemite may have a lattice constant of $8.43 \text{ \AA}$ and a corresponding Curie point of about 500°C , as was indicated for this second phase in the heated dyke rock. This agreement between the known properties of the second phase in the Ob Lusa heated rock and the type of variation found by Michel and Chaudron is too good to be coincidental, since it is also supported by the high stability of this second phase. (The stability of maghemite is known to be highly dependent on the impurity content). The impure non-magnetic oxide in the Ob Lusa maghemite may be TiO_2 , or, more probably, $\alpha\text{-Fe}_2\text{O}_3$ which, when compared with $\gamma\text{-Fe}_2\text{O}_3$ may be taken as being non-magnetic. From the description of the heated rock recently given it is seen that both these compounds are present in the free state, TiO_2 as rare rutile and $\alpha\text{-Fe}_2\text{O}_3$ as abundant hematite in the reddened zone.

The change from one magnetic component to two, coincident with the first heating of the rock, can easily be explained. Maghemite is formed when magnetite is heated in a limited supply of oxygen, and this is certainly the case when the

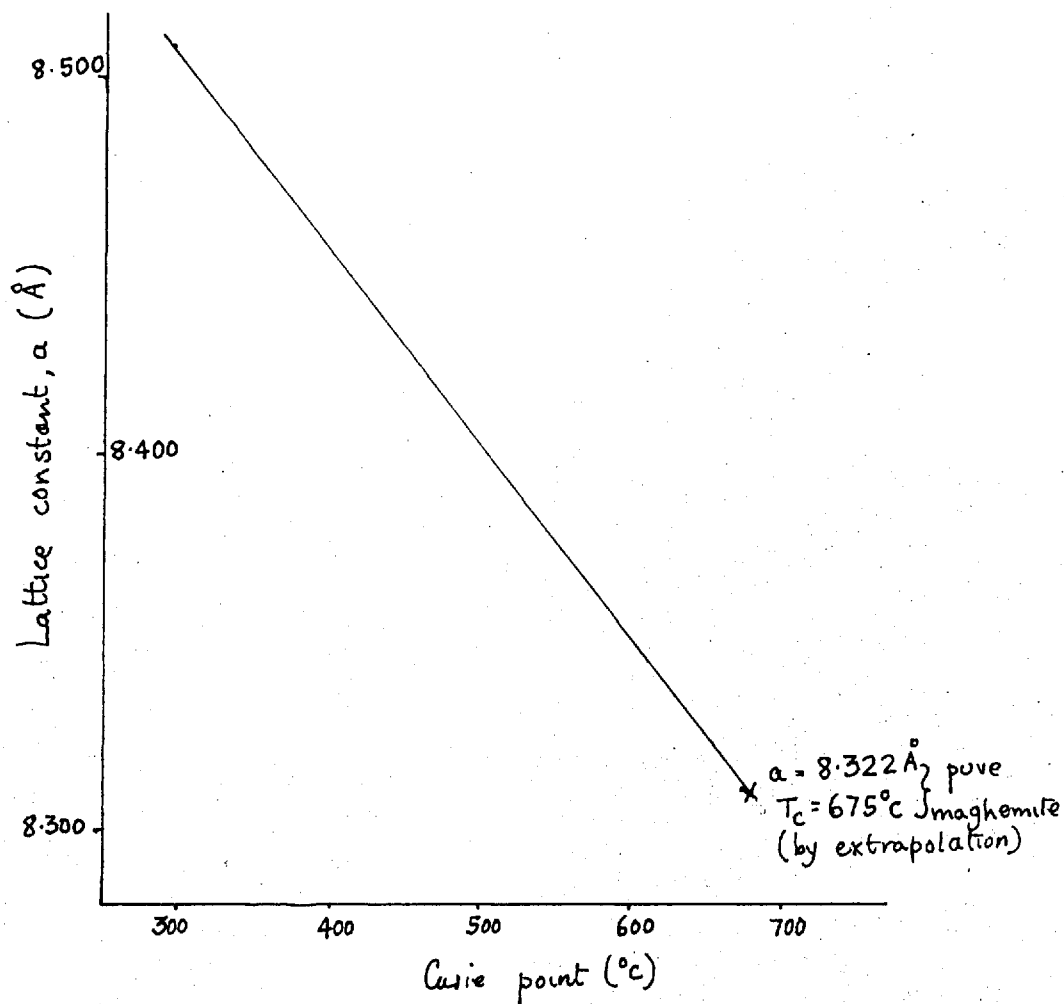
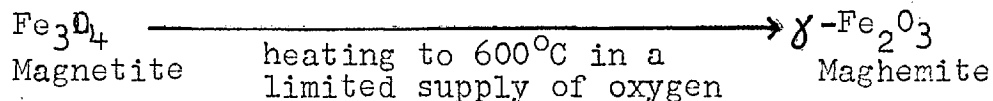


Figure 16

Variation of Curie point and lattice constant with percentage of $(\alpha\text{-Fe}_2\text{O}_3 \cdot \text{Na}_2\text{O})$ in solid solution in $\gamma\text{-Fe}_2\text{O}_3$ (after Michel and Chaudron)

magnetite is being heated while within a matrix of other minerals having a low porosity. Thus the reaction is



Owing to the heating process also providing TiO_2 and $\alpha\text{-Fe}_2\text{O}_3$ a stable maghemite-non-magnetic oxide solid solution compound is actually formed.

(e) Conclusions

The heated Ob Lusa material from both centre and contact regions has two magnetic components, the properties of which are in Table 4.

Table 4

	Curie point	Lattice constant	Reflection determination	Inferred Composition
Component 1	570°C	8.40Å	pure magnetite	Essentially pure magnetite (< 5% Fe_2TiO_4)
Component 2	about 500°C (Inexact as an intermediate Curie point on thermal demagnetisation curves)	8.43Å	maghemite	maghemite containing a considerable quantity of non-magnetic oxide ($\alpha\text{-Fe}_2\text{O}_3$ or TiO_2) in solid solution

The Heast Road Sill

In the description of the Heast Road Sill in 3.1.2 it was mentioned that the opaque minerals of the centre and contact were completely different. From the magnetic aspect it is realistic to treat the centre and contact as two different rocks.

The Sill Central Region

(a) Curie point determination: The Curie point of the rock was determined using the uniaxial pressure vessel method. Only one magnetic constituent was indicated by the demagnetisation curves, having a Curie point of $(530 \pm 15^{\circ}\text{C})$ (the mean of three heatings on two cubes). It can be seen from Fig. 17 that this rock is harder to magnetise thermally than the Ob Lusa dolerite.

(b) The Q-ratio: The Q-ratio for this rock has been determined for sixteen specimens. The scatter for these measurements was small, all the values lying between 14.7 and 18.7. The danger in inferring composition from magnetic parameters alone is made clear from these examples of Curie

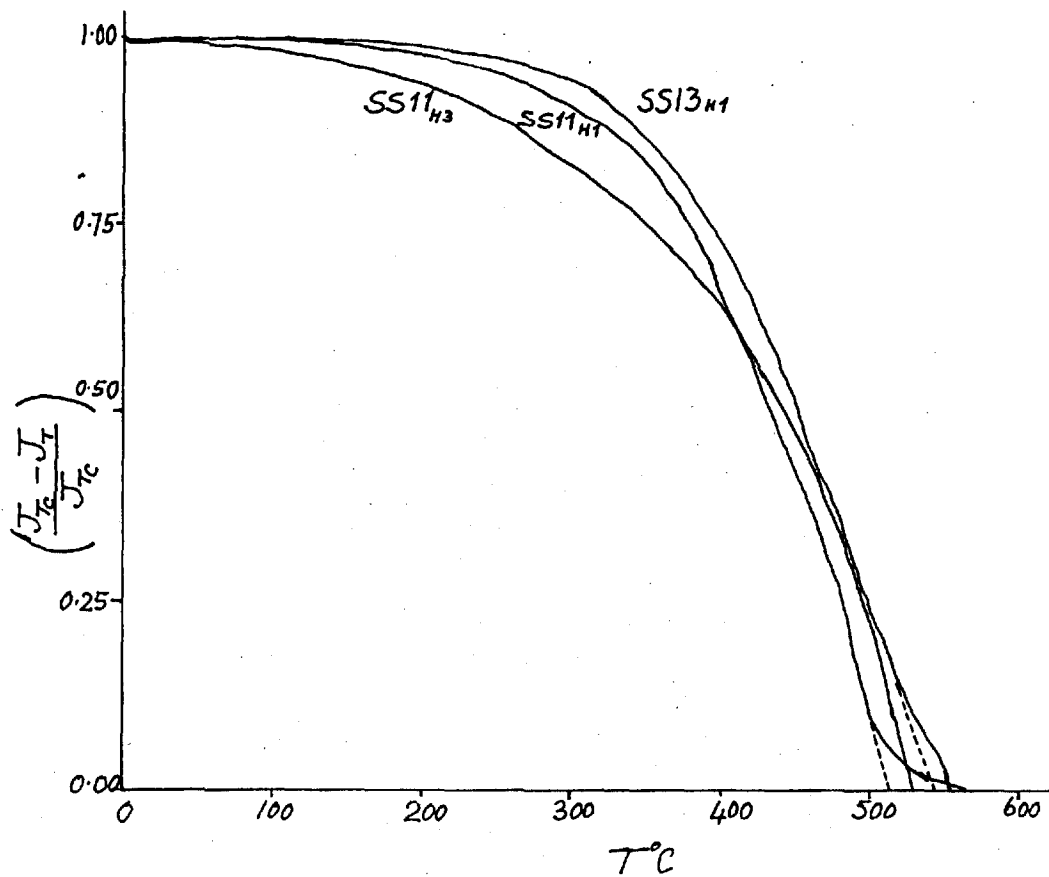


Figure 17

Heast Road Sill central region.

Thermal magnetisation using the
unaxial pressure vessel method

point and Q-ratio. The best compositional inference from the data described so far would be a titanomagnetite containing about 10% of the ulvöspinel molecule. It will be shown later that the mineral present is actually a member of the titanohematite solid solution series.

(c) Lattice constant: X-ray powder diffraction measurements on both the unheated and heated material showed the presence of two magnetic constituents, one having cubic and the other rhombohedral structure. The cubic constituents in both cases agree well with a fairly pure magnetite ($a = 8.39 \text{ \AA}$ unheated, $a = 8.41 \text{ \AA}$ heated). The rhombohedral constituent showed a large number of lines which lie close to those determined for standard ilmenite, with the exception of the lowest order line, which is close to a hematite line. All the rhombohedral lines are given in Table 5. On the basis of these lines the rock might be expected to contain magnetite together with a member of the titanohematite solid solutions series probably nearer in composition to ilmenite than to hematite.

Table 5.

<u>Lines from record</u>	<u>Lines for standard ilmenite</u>
($\text{\AA}$)	($\text{\AA}$)
3.74	2.72
2.75	2.53
2.53	2.225
2.23	1.86
1.865	1.717
1.725	1.498
1.500	1.458
1.465	

(d) Reflection microscopy evidence: Reflection microscopy was able to show the existence of only one definite opaque component, a titanohematite nearer in composition to hematite than ilmenite. No magnetite could definitely be identified in the rock. The presence of titanohematite was confirmed by measurements of Vickers Microhardness of the mineral. The results of this test are shown in Table 6.

Table 6.

<u>Mineral</u>	<u>V.M.H.</u> (arbitrary units)
Hematite	1000+
Opaque mineral in the H.R.Sill central region	841 - 917
Ilmenite	519 - 703

(e) Conclusions: The Curie point and reflection microscopy evidence agrees in showing that a titanohematite mineral occurs in the rock. The Q-ratio however is very different from that measured by Uyeda⁽²⁰⁾ for synthetic minerals of this series near in composition to hematite (of the order of 500 compared with 17 measured for the Heast Road Sill centre). The X-ray results, although showing the presence of a rhombohedral component, do not fit completely the findings of the Curie point and reflection microscopy evidence since they suggest the presence of magnetite and that the rhombohedral phase is nearer ilmenite than hematite.

The most reasonable conclusion to draw is that a rhombohedral titanohematite is definitely present in the rock. The composition of this mineral within the solid solution series is uncertain but the balance of evidence is in favour

of a composition nearer to that of hematite than of ilmenite. Some magnetite may also be present but could not be seen in polished sections.

The Sill Contact Region

(a) Curie point determination: Curie point estimations were made using both the linear pressure vessel method and the astatic magnetometer and furnace method. The linear pressure vessel method gave a distinctive magnetisation curve on the first heating (see Fig. 18) which indicated an apparent Curie point at 370°C followed by a rapid decay of moment to indicate a second apparent Curie point at 540°C. It should be noted that to avoid giving the impression that the rock under examination was showing self reversing properties Fig. 18 has been plotted as

J_{T_c} with temperature instead of $\frac{(J_{TC} - J_T)}{J_{TC}}$ with

temperature as in other figures showing progressive thermal demagnetisation. A second test on the specimen gave a magnetisation curve of entirely different form. On this occasion the component with the Curie point of

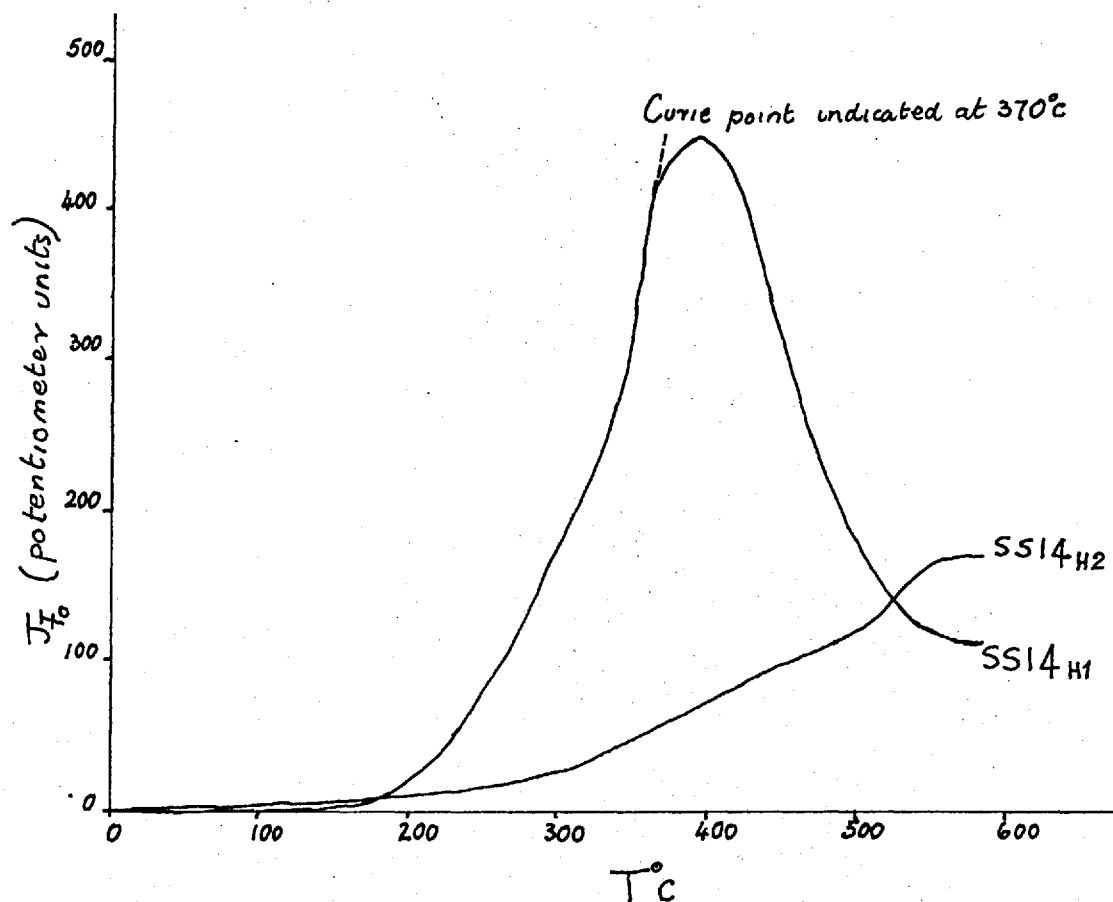


Figure 18

Heast Road Sill contact region

Thermal magnetisation using the uniaxial
pressure vessel method

370°C was completely absent, the curve rising steadily to give a value of 540°C. The explanation of this change in form must be in the destruction by heating of the mineral showing the 370°C Curie point.

An attempt at Curie point determination using the furnace and astatic magnetometer proved unsatisfactory. Demagnetisation of the natural remanent moment gave an apparent Curie point of just over 300°C while successive demagnetisations of freshly acquired moments gave a random series of values between 375°C and 600°C.

(b) The Q-ratio: Q-ratio measurements were made on two groups of contact rocks, those which had not been heated to above 375°C and those which had been heated to above 600°C. Very different values of Q-ratios were obtained for the two groups (see Table 6).

Table 6

	<u>Specimen</u>	<u>Q-ratio</u>	
Specimens not heated above 375°C	SS19	222	Mean value 267
	SS27	400	
	SS28	274	
	SS29	174	
Specimens heated to 600°C	SS16	7.2	Mean value 8.2
	SS17	8.4	
	SS18	8.9	

(c) Lattice constant: X-ray measurements of both heated and unheated rocks both show lines which agree well with standard pyrrhotite (see Table 7). In addition, the X-ray record for the heated rock shows some evidence of magnetite.

Table 7.

<u>Lines from record (Å)</u> (unheated material and material heated to 600°C)	<u>Lines for standard Pyrrhotite (Å)</u>
3.20	
2.64	
2.63	2.63
2.47	
2.145	
2.060 (strongest line)	2.062 (strongest line)
2.050	
1.719	1.718
1.518	
1.472	

(d) Reflection microscopy evidence: Reflection microscopy showed clearly the presence of pyrrhotite (confirmed by Vickers Microhardness values in the range 236 - 300) but did

not show magnetite in either the heated or unheated rock.

(e) Conclusions: All the evidence shows the presence of pyrrhotite in the unheated rock. In the heated rock its presence is also apparent but the magnetisation curves and Q-ratio values show that an irreversible change takes place in the magnetic properties at about 375°C . This change must be related to a change in the structure of the mineral, or, a change in the Fe : S ratio. The state of the pyrrhotite below 375°C agrees in its magnetic properties with the magnetic pyrrhotite described by other authors (Curie point, Q-ratio) and has been taken as standard magnetic pyrrhotite in the pressure experiments described in Chapter 6.

The presence of magnetite is suggested on the X-ray record for the heated rock but it cannot be taken as a definite constituent owing to its apparent absence from the reflection microscopy record.

Deccan Trap Rocks L6 and L31.

The magnetic components of these rocks have been determined by Mr. B.W. Weaving⁽²¹⁾ of the Physics Department, Imperial College. Measurements of Curie point and lattice

constant together with chemical composition have been made and the results of these tests are shown in Table 8.

Table 8.

Rock Type	Curie point	Lattice constant	Chemical Analysis	Inferred composition
L6	300°C	8.44 Å	Magnetite-ilmenite solid solution + ilmenite inter-growths	mg-il solid solu. and il. inter-growths
L31	75-150°C	8.495 Å	Magnetite-ilmenite solid solution	mg-il solid solu. (about 50% of each)

Table 8 shows that the magnetic and crystallographic properties of the titanomagnetite and magnetite-ilmenite solid solution series overlap making chemical analysis or possibly, reflection microscopy, the critical factor in their separation. Irreversible changes in the magnetic properties of these rocks on heating will be described in Chapter 6.

3.3 Grain Size Measurements

Grain size measurements were made from thin sections of rock viewed with a normal petrological microscope.

The microscope used had a slotted ocular which allowed a transparent scale to be interposed in the plane of the cross wires. The scale was calibrated in terms of the three objectives available on the microscope.

The principal axes of grains were measured, and when this had been done for a representative number the mean value of the principal axes were calculated. A statistical correction was applied to these calculated values to allow for the various sections of crystals visible in a thin section. This correction was derived theoretically by Krumbein⁽²³⁾ who was able to verify it by mechanical analysis of material from which thin sections had been cut and studied.

This correcting factor, which was calculated for equidimensional grains is applied as follows:

$$\text{true mean principal axis} = 1.27 \times \text{observed mean principal axis.}$$

Grains were encountered in the Ob lusa contact dolerite with ratios of principal axes often as great as 10 : 1. Krumbein's correction factor has been applied to these rocks as it appears that, although not exact, the result obtained will be a better approximation to the correct value than would be the untreated measurements.

The Ob Lusa dolerite: A complication shown by this rock is the existence of several generations of magnetic minerals. The dyke centre shows only one generation of equidimensional grains and the other of fine, cleavage controlled, acicular grains. Grain size measurements for this rock are given in Table 9.

Table 9.

Specimen	Location	Equi. Gen.	No. of grains counted	Acic. gen.	No. of grains	Acic:Equi. (areas)
01	Average $\frac{1}{2}$ " from contact	34 μ	8	28.5x3.7 μ^2	15	90A:10E
02	"	33	11	22x2.6	17	90A:10E
04	"	27	11	34.6.5	17	90A:10E
05	"	25	8	33x4.3	16	90A:10E
07	"	29	11	24x3.5	19	85A:15E
03	Average $1\frac{1}{2}$ " from contact	29	12	41.5x5.1	13	85A:15E
09	"	37	10	40.5x5.0	15	85A:15E
013	Average $2\frac{1}{2}$ " from contact	33	10	52x6.5	16	75A:25E
014	"	29	10	54x7.3	17	70A:30E

Table 9 Contd.

Specimen	Location	Equi. Gen.	No. of grains counted	Acic. gen.	No. of grains	Acic:Equi. (areas)
015	Average $3\frac{1}{2}$ " from contact	39 μ	11	64x 10 μ^2	20	85A : 15E
016	"	36	10	65x10	20	75A : 25E
017	Average $4\frac{1}{2}$ " from contact	37	12	84.5x10.6	15	65A : 35E
018	"	35	12	84.5x12.5	22	65A : 35E
019	Average $5\frac{1}{2}$ " from contact (One very large corroded phenocryst was found in the slide made from this specimen)	46.5	9	106x17	15	70A : 30E
010	Central region of dyke	103	26	no acicular generation		
011	"	104	20	"	"	"
012	"	103	22	"	"	"

Rare very large corroded phenocrysts were seen in 010-012 two in 010, one 012, the average principal axis for thses equidimensional grains was 350 μ

The Heast Road Sill: The results of the measurements made on this sill are shown in Table 10.

Table 10.

- (i) Sill central region containing equidimensional grains of a titanohematite.

Specimen	Principal axis	No. of grains counted
unheated material	64 μ	20
SS4	64 μ	20

- (ii) Sill contact region containing rounded blebs of pyrrhotite

Specimen	Average diameter of large blebs	No. of blebs counted
SS19 (block 4)	324 μ) Many smaller	15
SS27 (with SS28, SS29 from block 5)	159 μ) blebs of pyrrhotite in ground mass	12

Deccan Trap basalts: These rocks show both equidimensional and platy sections, which may be merely different sections of one shape of grain.

Table 11.

Specimen	Equidimensional sections	No. counted	Platy sections	No. counted	Ratio
L6(unheated)	163 μ	10	420x41.5 μ^2	7	50E:50P
L31(unheated)	117 μ	13	350x34 μ^2	7	50E:50P

CHAPTER 4

THE EFFECT OF SIMPLE SHEAR ON ROCKS ACQUIRING A THERMOREMANENT MOMENT

4.1.1 Introduction and Prediction of Angular Shear Effect

It has been shown that the application of uniaxial stress to a rock acquiring a thermoremanent moment causes a rotation of the resulting moment from the ambient field direction⁽¹⁴⁾. Neale was able to show that the magnitude of this rotation was dependent on two factors;

- i) the magnitude of the stress, and
- ii) the angle between the stress axis and the field direction, the effect being a maximum for an angle of 45° .

In the light of this knowledge it is relevant to examine the effect of shear stress on a rock acquiring a thermoremanent moment.

The results of Neale's experiments may be used to predict the sense and magnitude of shear stress effects providing the relationship between the two different stress

states is known.

The problem may be stated as the necessity to equate the shear stress system to an equivalent system of normal compressional and tensional stresses. The shear stress system existing in the equilibrium state in a cubic specimen is shown in Fig. 19.

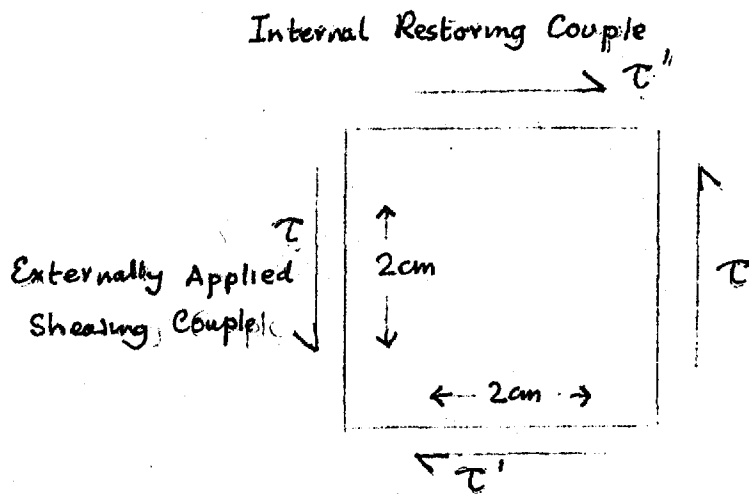


Fig 19

For equilibrium between the two couples we have

$$\tau_x = \tau'_x \quad \text{or} \quad \tau = \tau'$$

The relationship between these shearing couples and an equivalent system of normal and shear stresses may now be examined.

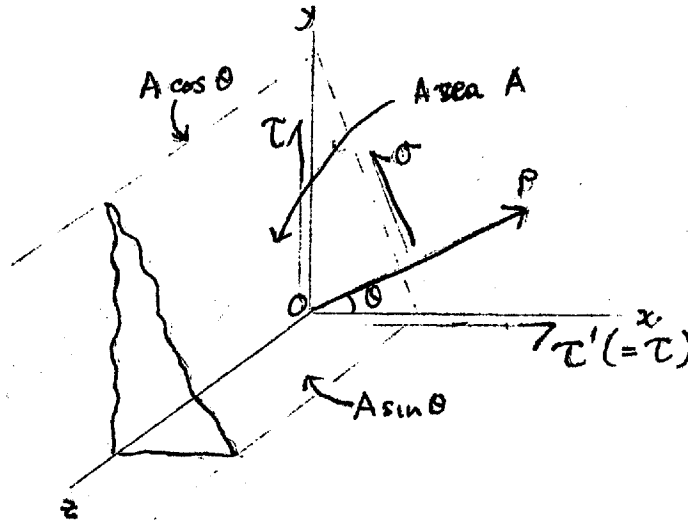


Fig 20

Fig. 20 shows a general case of two stresses τ and $\tau' (= \tau)$ which are to be related to a normal stress P and a shear stress σ referred to a plane defined as having a normal inclined angle at θ to the x axis lying parallel to the plane defined by the x and y axes.

Resolving the stresses parallel to the x axis, then for equilibrium $\tau A \sin \theta = (\sigma \sin \theta - P \cos \theta) A$

$$\text{or } \tau \sin \theta = \sigma \sin \theta - p \cos \theta \quad (1)$$

and resolving parallel to the y axis:

$$\tau A \cos \theta = -(\sigma \cos \theta + p \sin \theta) A$$

$$\text{or } \tau \cos \theta = -\sigma \cos \theta - p \sin \theta \quad (2)$$

Equations (1) and (2) may be solved for σ and p the solutions

$$\begin{aligned} \text{being } \sigma &= -\tau \cos 2\theta \\ \text{and } p &= -\tau \sin 2\theta \end{aligned} \quad (3)$$

It is next necessary to relate this general case to the conditions within a cubical specimen under shear stress of the type applied by the apparatus described in 2.3.

It is immediately evident that this general case is directly analogous to the experimental conditions (Ref. Fig. 19).

To relate the shearing couples τ to an equivalent system of normal stresses we must determine the conditions of relationships (3) for which $\sigma = 0$.

$$\begin{aligned} \text{we have } \sigma &= -\tau \cos 2\theta \\ \text{and } p &= -\tau \sin 2\theta \end{aligned} \quad (3)$$

and σ will be zero for $\theta = \pm 45^\circ$. For this value of θ

$$p = \pm \tau$$

Thus the system of shearing couples shown in fig. 19 may be replaced by a system of normal stresses acting parallel to the planes of the x - y diagonals of the specimens, as shown in Fig. 21.

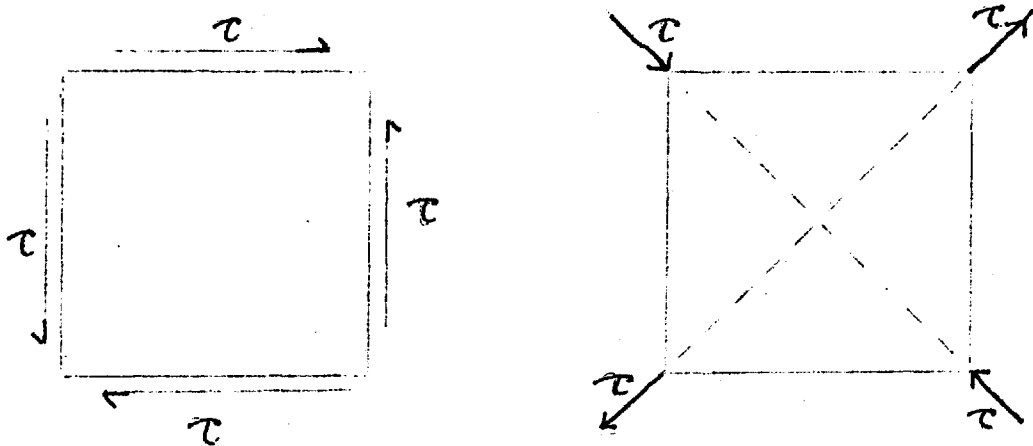


Fig 21

This relationship may be used to predict the form and magnitude of the shear stress effects to be expected.

4.1.2 Estimation of the form of the shear stress effect.

It has been shown that the magnitude of the angular stress effect for conditions of normal stress is directly proportional to the stress (14).

If it is assumed that a tensional normal stress produced an effect which is equal in magnitude but opposite in sense from an equal compressional normal stress, it is evident that maximum rotations of moment will occur when the magnetising field is exactly aligned along the intersection of the maximum and minimum normal stresses, that is, parallel to the cube faces. In addition it may be seen

that zero effects will be observed for field directions inclined in the planes bisecting the angles between the cube faces.

Accordingly a relationship between the inclination of field relative to the cube axes indicated in Fig. 22 and the magnitude of the rotation of the moment of the form

$$\Delta\theta = k \cos 2\theta$$

may be expected, where $\Delta\theta$ is the rotation of moment and k some constant.

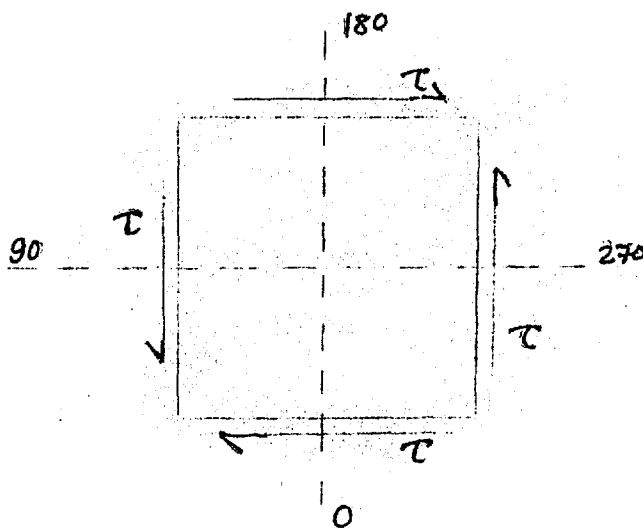


Fig 22

4.1.3 Estimation of the magnitude of the shear stress effect.

The relationship between the shear stress system and equivalent normal stress system derived in 4.1.1, in conjunction with measurements made by Neale and others to be described in this thesis (5.3.3.) may be used to estimate the magnitude of the shear stress effect.

It is well known that the ultimate tensile strength of rocks is much lower than their ultimate compressive strengths, a ratio of 1 : 30 not being uncommon (22). An ultimate tensile strength of 50 kg/cm^2 may be taken as representative of igneous rocks of the type used in this investigation, and this figure will be used in the following calculations. In practice, of course, a slightly lower tensile stress would have to be used to prevent fracture.

If a 2 cm. cube of rock material is subjected to the shear stress system shown in Fig. 19 the equivalent normal stress system can contain a tensional component of maximum intensity 50 kg/cm^2 , and, from section 4.1.1, it is clear that the compressional component will have an identical magnitude, i.e. $|\tau_{\text{Tensional}}| = |\tau_{\text{Compressional}}| = 50 \text{ kg/cm}^2$

If the rock is of the type described in 4.1.1 two properties of the thermoremanent moment acquired under uniaxial stress

are known:

- (i) The moment acquired under stress shows a rotation away from the stress axis for compressive stress.
- (ii) The intensity of the stress acquired moment is less than that of the stress free moment.

It is reasonable to consider these together as manifestations of one basic mechanism and to calculate changes in the vertical and horizontal components of the thermoremanent moment necessary to cause the observed angular rotations. In general, the magnetite/maghemite Ob Lusa dolerite used by Neale, and in this investigation, shows that an angular change can be interpreted as a reduction in the vertical component of the moment together with a smaller increase in the horizontal component (see 5.3.3).

The method of analysis to be used is as follows:

If the cube shown in Fig. 26 is subjected to the sequence of uniaxial pressure experiments described in 2.8 the following results might be expected.

	θ	$\underline{J}$
<u>Experiment 1</u> (without pressure)	45°	J_1 emu/cc.
<u>Experiment 2</u> (with compressive pressure)	$(45^\circ + \Delta\theta)$	$(J_1 - \Delta J)$
(where θ is $\angle$ measured inclination and J the measured intensity)		

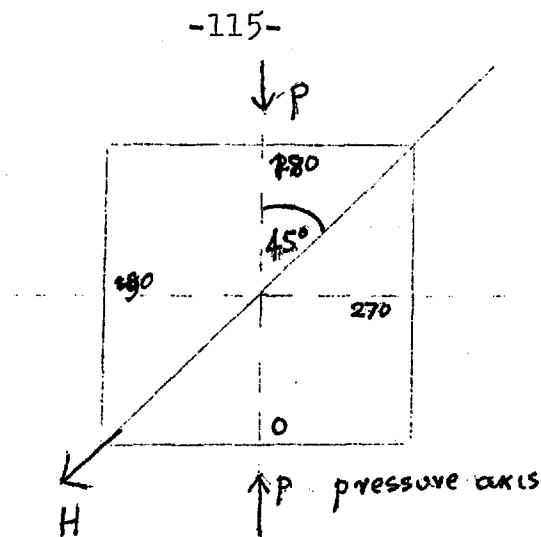


Fig 26

These figures may be used to calculate the changes in the vertical and horizontal components of the moment necessary to produce the observed angular change.

	<u>Vertical Component</u>	<u>Horizontal Component</u>
<u>Experiment 1</u> (without pressure)	$J_1 \cos 45$	$J_1 \sin 45$ (= $J_1 \cos 45$)
<u>Experiment 2</u> (with pressure)	$(J_1 - \Delta J) \cos (45 + \Delta \theta)$	$(J_1 - \Delta J) \sin (45 + \Delta \theta)$ = $(J_1 - \Delta J) \cos (45 - \Delta \theta)$

This gives the decrease in the vertical component as

$J_1 \cos 45 - (J_1 - \Delta J) \cos (45 + \Delta \theta)$ and the increase in

the horizontal component as $(J_1 - \Delta J) \cos (45 - \Delta \theta) - J_1 \cos 45$

For the purpose of the discussion the ratio

(decrease in vertical component)
(increase in horizontal component)

will be taken as 2.

This method of analysis can be applied in a similar way to a rock subjected to shear stress. Fig. 27 shows a cube subjected to shear stress with the magnetising field in a vertical direction (a direction of maximum angular shear effect as shown in 4.1.1). The two components of the equivalent normal stress system will be treated separately.

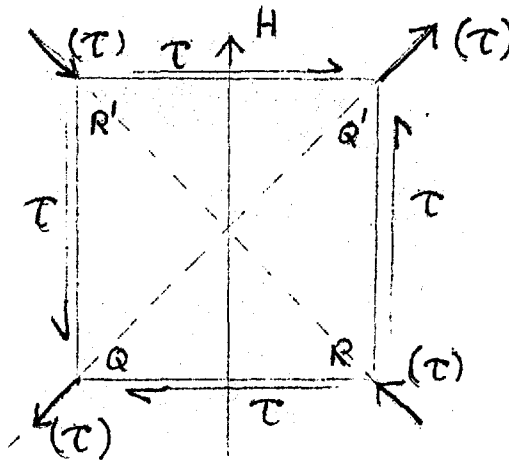


Fig 27

(i) Compressive Component: Reference to Fig. 27 shows that the same orientation exists between the pressures and magnetic axes in both this case and the uniaxial pressure case shown in Fig. 26. On magnetising under pressure a decrease in the component of the moment parallel to the $R - R'$ diagonal together with an increase of ~~magnitude~~^{moment} parallel to the $Q - Q'$ diagonal equal^{in magnitude} to half this decrease will occur.

(ii) Tensional Component: To estimate the effect of this component it has been assumed that the effect of this component is equal in magnitude but opposite in sense to the compressive component. On magnetising under pressure, an increase of the moment along the $Q - Q'$ diagonal together with a decrease along the $R - R'$ diagonal equal in magnitude to half this increase will occur. These small changes in the two components of the moment are shown in Fig. 28 as small arrows along the diagonals proportional in lengths to the changes in the components of the moment. It is clear from this figure that the angular rotation of the moment in this instance will result from a decrease in the moment along the $R - R'$ diagonal and an equal increase in the moment along the $Q - Q'$ diagonal.

Fig. 29 shows the effect on the total moment of these

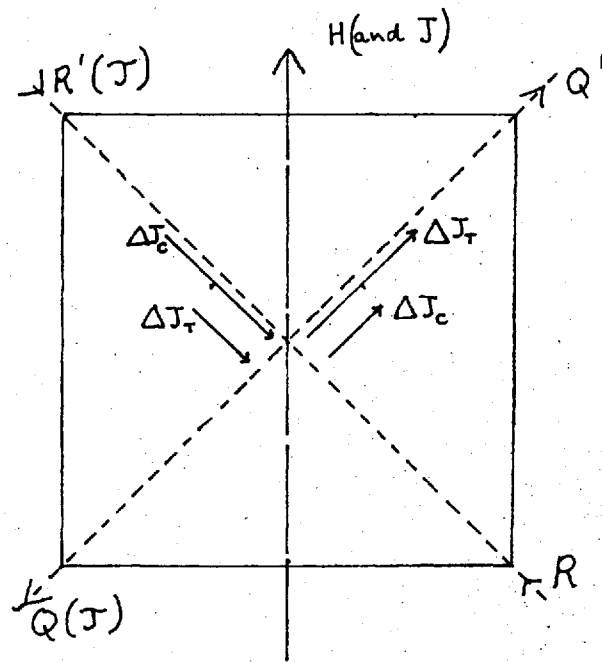


Figure 28

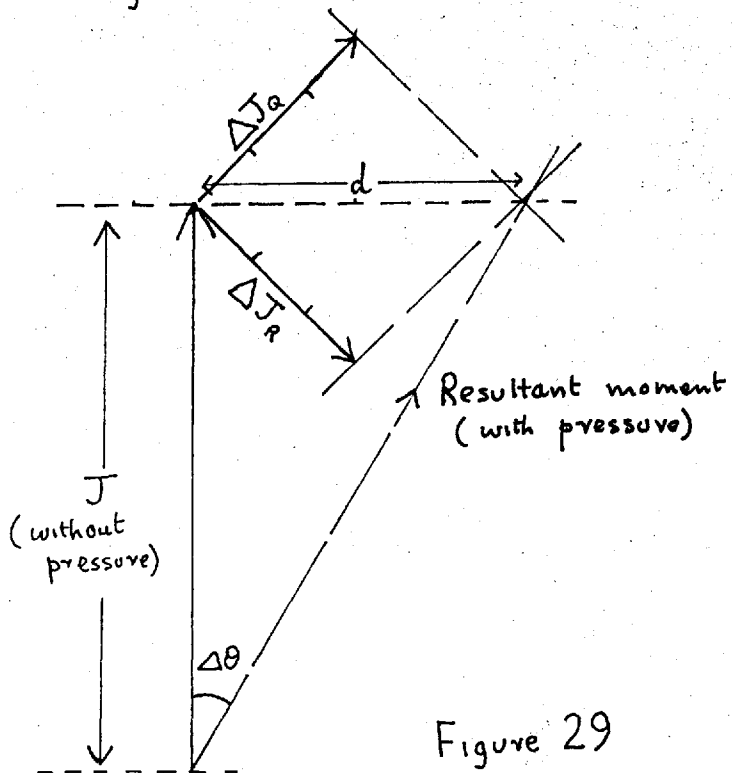


Figure 29

small changes in moment and indicates the means by which the rotation of the angular moment may be calculated.

$$\text{Thus } \Delta\theta = \tan^{-1}\left(\frac{d}{J}\right)$$

where $\Delta\theta$ is the angular rotation of the moment and

$$d = \sqrt{\{(\Delta J_Q)^2 + (\Delta J_P)^2\}} \text{ and } \Delta J_Q = \Delta J_R = (\Delta J_c + \Delta J_r)$$

for one diagonal and J is the intensity of the moment acquired without pressure.

The calculation of actual values of $\Delta\theta$ requires a knowledge of the magnitudes of the angular rotations and intensity decreases to be expected for tensional and compressive stresses of 50 kg/cm². Fortunately experiments with the linear pressure vessel allow these quantities to be calculated. No experiments with the linear pressure vessel have been made at such low pressures but graphs of the variation of these functions with pressure are available (see Figs. 30, 31 and 32). It should be noted that the values of pressures indicated in these graphs have been corrected for friction in the linear pressure vessel, resulting in a 20% reduction of the theoretical pressure.

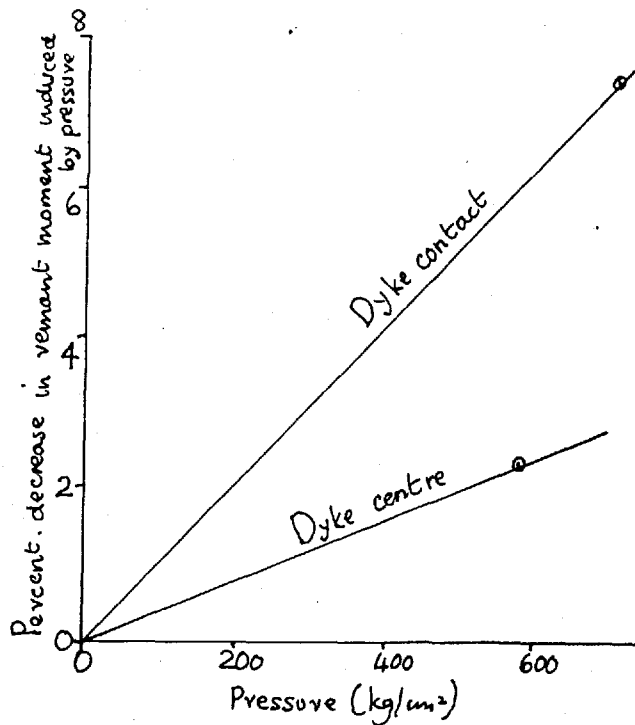
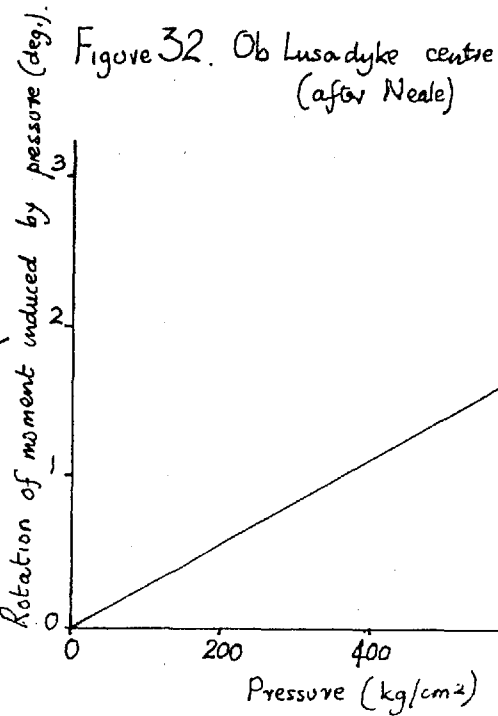
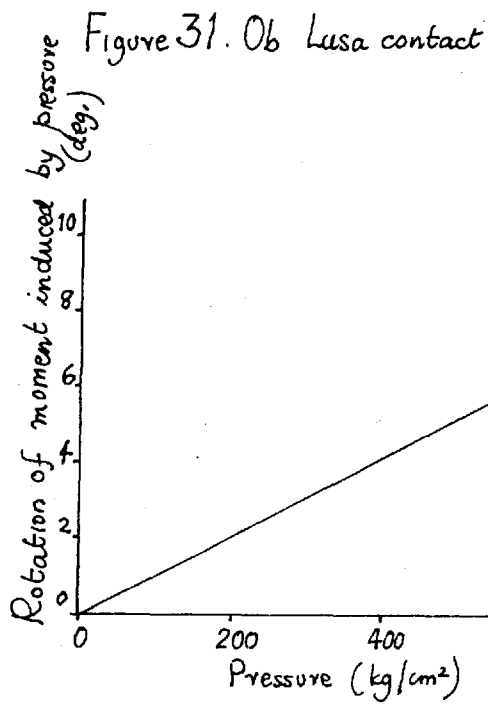


Figure 30. Ob Lusa dyke contact and centre

Ob Lusa dyke centre: decrease in the moment on magnetising under 50 kg/cm^2 compressive stress : 0.2%
angular rotation on magnetising under 50 kg/cm^2 compressive stress: 0.12° .

(Rationalised moments will be used throughout the calculations).

(i) Compressive component:

	Component along (R-R') diagonal	Component along (Q-Q') diagonal
<u>Experiment 1</u> without pressure	$1.0000 \cos 45^\circ$	$1.0000 \cos 45$
<u>Experiment 2</u> with pressure	$0.998 \cos 45.12$	$0.998 \cos 44.88$

Therefore the decrease in the component along the (R-R') diagonal is given by

$$1.000 \cos 45 - 0.998 \cos 45.12 = 0.0029$$

and the increase in the component along the (Q-Q') diagonal is given by

$$0.998 \cos 44.88 - 1.0000 \cos 45 = 0.0002$$

(ii) Tensional component: this will produce the same numerical changes but in the reverse sense.

Now, from Fig. 29 it can be seen that $\Delta J_R = \Delta J_Q = (\Delta J_L + \Delta J_T)$ for one diagonal. Thus, for the Ob lusa dyke centre

$$\Delta J_R = \Delta J_Q = (0.0029 + 0.0002) = 0.0031 \text{ and}$$

$$\Delta \theta = \tan^{-1} \left(\frac{d}{J} \right) = \frac{\tan^{-1} \sqrt{\{(0.0031)^2 + (0.0031)^2\}}}{1.0000}$$

$$\text{i.e. } \Delta \theta = 0.25^\circ$$

Ob lusa dyke contact: decrease in moment on magnetising
under 50 kg/cm^2 compressive stress: 0.6%
angular rotation on magnetising under 50 kg/cm^2 compressive
stress: 0.5°

(i) Compressive Component

	Component along (R-R) diagonal	Component along (Q-Q) diagonal
<u>Experiment 1</u> without pressure	$1.000 \cos 45$	$1.000 \cos 45$
<u>Experiment 2</u> with pressure	$0.994 \cos 45.5$	$0.994 \cos 44.5$

Therefore the decrease in the component along the (R-R)
diagonal is given by

$$1.000 \cos 45 - 0.994 \cos 45.5 = 0.0103$$

and the increase in the component along the (Q-Q) diagonal by

$$0.994 \cos 44.5 - 1.000 \cos 45 = 0.0018$$

(ii) Tensional Component: (as for Ob lusa dyke centre).

$$\text{Thus } \Delta J_R = \Delta J_Q = (0.0103 + 0.0018) = 0.0121$$

$$\text{and } \Delta\theta = \tan^{-1}\left(\frac{d}{J}\right) = \tan^{-1} \frac{\sqrt{(0.0121)^2 + (0.0121)^2}}{1.0000}$$

$$\text{i.e. } \Delta\theta = 1.0^\circ$$

It is evident that the angular rotation to be expected are of the same order of magnitude as experienced in the uniaxial stress experiments. In contrast with the uniaxial pressure experiments Fig. 29 shows that for small angular rotations of the order predicted there will be no intensity change at the position of maximum angular rotation. The application of uniaxial stress results in there being a considerable intensity decrease at the position of maximum angular rotation. In the shear stress case a maximum change (either decrease or increase) of moment will take place when the magnetising field is aligned along one of the cube diagonals.

4.1.4 Design of the apparatus for producing shear stress in cubic specimens

The design of the apparatus used has been fully described in 2.3. The success of the apparatus in producing a shear stress was demonstrated by the ease with which cubes could be broken across the $(R - R^1)$ diagonal plane, which is normal to the tensional component of the shear stress.

To facilitate the fitting of cubes into the shearing system the free links were split horizontally between the pivots and vertical nimonic bolts fitted with which the severed halves of the links could be pulled together when the cube had been fitted into its recesses.

4.2 Consistency attained with the shear stress apparatus

Although it was thought that the Ob Lusa dyke central material would show an angular pressure effect close to the detectable limit, pressure experiments on both centre and contact material were carried out in order to test the theory developed in 4.1.1 and 4.1.2.

The consistency attained with the apparatus was measured using a series of dyke centre specimens. Initially three difficulties were encountered which presented the realisation of the required consistency. These were a slow drift in the magnetising field due to the potentiometer battery running down, a more rapid drift on starting the generator, and the inexact measurement of the orientation of the linked shearing jaws during each experiment. Both the drifts in the magnetising field were quickly removed, the slow drift by supplying the potentiometer from two batteries in

parallel and the more rapid drift by leaving the generator running for periods of up to 14 days. The measurement of the movement of the linked jaws was made more precise by means of a needle fixed to the lower jaw which acted as a pointer for a scale marked in intervals of 0.01 inches attached to the rigid frame of the instrument. This device allowed angular changes between experiments of 0.1° to be detected.

With these refinements the required consistency was obtained. A number of consistency measurements were made during the use of the apparatus, and Table 12 shows the results of a test in which two field directions were utilised. From this table it can be seen that the inclinations of thermoremanent moments can be repeated to 0.2° , a consistency better than that originally expected. Measurements of the intensity are less consistent. This is due both to the uncorrected drift of the spinning magnetometer and to the tendency for the intensity of the Ob Lusa dyke central material to increase with successive heatings.

TABLE 12

Consistency of Shear Stress Apparatus

Pressure: none

Ob Lusa dyke centre material

Intensity x 10^3 emu/cc

Specimen	J ₁	H1 θ_1	J ₂	H2 θ_2	J ₃	H3 θ_3	J ₄	H4 θ_4
043	42.8	183.40	44.9	164.80	44.2	183.58 (+0.18)	44.8	164.53 (-0.27)
055	56.7	186.63	60.8	167.20	59.7	186.48 (-0.15)	59.7	166.83 (-0.37)
058	49.5	186.35	50.3	166.65	50.5	186.38 (+0.03)	49.4	166.40 (-0.25)
059	53.6	187.20	55.1	168.48	54.7	186.98 (-0.22)	56.6	168.38 (-0.10)

Average angular change from first value: 0.20°

Maximum angular change from first value: 0.37°

4.3 Experimental Results

4.3.1 Ob Lusa Dyke Centre Material

A great number of experiments were carried out on this rock with various magnetizing field directions. No consistent pressure dependent angular rotation of the remanent moment could be detected.

It was found that a permanent deformation of the cube took place during experiments with the shear pressure apparatus. Fortunately, even after four heatings this deformation was not large enough to invalidate the further use of the cube. Some figures for this deformation are shown in Table 13. However, the deformation did result in the rotation of the shearing jaws between successive experiments, and this influence had to be corrected by the use of the turn indicator. A further difficulty encountered was the universal tendency for the shearing jaws to turn spontaneously through a small angle during the cooling part of a pressure experiment. No attempt was made during the pressure experiments to interpret the effect of this turn, angular rotations for both the beginning and the end of the rotation being calculated.

TABLE 13

Permanent Deformation of Cubes Heated in the
Shear Apparatus

(The Ob Lusa contact rocks described in this table were more fully documented than the dyke centre rocks, although, as far as can be seen, no differences between the behaviour of the two rocks types existed).

All measurements are in thousandths of an inch.

Speci- men		Before H1	Before H2 (15 lb load)	Before H3	Before H4
024	<u>Top-Bottom</u>				
	Front(L)	795.8	794.4	(793.6	(793.0
	Back(R)	(centre)	(centre)	(794.3	(794.1
	<u>Front-Backends</u>				
	Centre:	788.0	790.2	789.9	789.9
	Sides: centre:	786.1	791.2	791.2	791.1
027	<u>Top-Bottom</u>				
	Front(L)	795.8	(794.6	(794.4	(794.7
	Back(R)	(centre)	(795.4	(795.5	(795.4
	<u>Front-Backends</u>				
	Centre:	789.7	791.9	791.9	791.6
	Sides: centre:	786.3	788.4	788.4	788.7

The measurements show that most of the deformation took place during the first heating, the effect of the application of pressure being negligible compared with this. This relatively large change during the first heating must be related to the reddening of the outer layer of the cube and other invisible chemical and structural changes which take place when the specimen is first heated to 600°C .

The form of the deformation is seen to be a shortening of the vertical axis of the cube together with an increase in both the horizontal axes. The initial deformation results in an increase in the volume of the specimen of about 0.5%. Table 14 shows the results of an unsuccessful series of pressure experiments carried out on the dyke centre material at two field directions estimated to give a maximum angular effect.

The random scatter of the measured deflections is of such a magnitude that no regular pressure induced rotation of the thermoremanent moment can be detected from the results of either of these experiments. At this stage in the investigation the experimental technique was still being developed and this factor accounts for the rather wide scatter of results obtained in the dyke centre material experiment.

TABLE 14

Ob Lusa Dyke Centre Material

Pressure: 20 lb on lever arm (equivalent theoretically to a tensional component of 58 kg/cm²)

Field direction: 039/40/2/4 92°
045/6/7/8 356°

(No intensity values were recorded at the time when these measurements were made)

Specimen	H1 no (pressure) θ ₁	H2 (pressure) θ ₂	H3 no (pressure) θ ₃	H4 (pressure) θ ₄
039	93.20	cs: 92.95 (-0.25) cf: 92.63 (-0.57)	92.70	cs: 93.03 (+0.33) cf: 92.90 (+0.20)
040	93.90	cs: 93.73 (-0.17) cf: 93.38 (-0.52)	93.98	cs: 94.18 (+0.20) cf: 93.78 (-0.20)
042	91.78	cs: 92.18 (+0.40) cf: 91.73 (-0.05)	92.13	cs: 92.35 (+0.22) cf: 91.98 (-0.15)
044	92.10	cs: 92.55 (+0.45) cf: 91.90 (-0.20)	92.38	cs: 92.03 (-0.35) cf: 91.13 (-1.15)
045	355.35	cs: 355.95 (+0.60) cf: 355.40 (+0.05)	355.75	cs: 355.75 (0.00) cf: 355.15 (-0.60)
046	355.30	cs: 355.35 (+0.05) cf: 354.88 (-0.42)	355.40	cs: 355.68 (+0.28) cf: 355.48 (+0.08)

TABLE 14 contd.

	H1	H2	H3	H4
Spec- imen	no (pressure) θ_1	(pressure) θ_2	no (pressure) θ_3	(pressure) θ_4
047	357.48	cs:357.15 (-0.33) cf:356.95 (-0.53)	357.15	cs:356.80 (-0.35) cf:356.15 (-1.00)
048	357.18	cs:357.20 (+0.02) cf:357.00	356.63	cs:357.10 (+0.47) cf:357.00 (+0.37)

4.3.2 Ob Lusa dyke contact material

During the negative experiments with the dyke centre material, tests carried out with the uniaxial pressure vessel had shown the moment of the contact rock to be more pressure dependent by a factor of four than the moment of the dyke centre material. In this knowledge a series of successful pressure experiments using this material were made with the shear pressure apparatus. Four different field directions were used allowing the variation of angular pressure effect with the angle between the plane of the shear stress and the magnetising field to be completely studied. Drift correction is made on the assumption that a difference in the inclinations recorded after H1 and H3 represents a change in field direction. It is also assumed that this change may be taken as varying linearly with respect to time for the duration of the experiment and, to make this assumption more reasonable experiments on individual specimens were carried out at the same time on successive days. The justification of this correction is that it brings greater consistency to the interpretation of the measurements.

The pressure induced angular rotations of moment derived from Tables 15 - 18 are shown graphically in Fig. 33.

TABLE 15

Ob Lusa Dyke Contact Material

Pressure: 15 lb on lever arm (equivalent theoretically to a tensional component of 45 kg/cm²)

Field direction: 165°

Intensity x 10³ emu/cc

	H1		H2		H3		H4	
Speci- men	J ₁	θ ₁	J ₂	θ ₂	J ₃	θ ₃	J ₄	θ ₄
023	53.5	162.78	52.1	cs: 163.85 cf: 163.65	52.9	162.05	52.3	cs: 164.00 cf: 163.90
024	55.8	164.15	53.3	cs: 165.73 cf: 165.53	55.3	163.38	51.5	cs: 165.15 cf: 165.05
027	109.0	165.43	102.4	cs: 166.15 cf: 165.95	103.8	165.43	101.0	cs: 166.58 cf: 166.38
028	152.2	166.13	142.1	cs: 167.33 cf: 167.23	148.0	166.30	147.6	cs: 167.23 cf: 167.13

Mean drift corrected angular rotation of Moment:
calculated for cooling started position of shearing jaws:
+1.44°
Cooling finished position of shearing jaws: +1.29°

TABLE 16

Ob Lusa Dyke Contact Material

Pressure: 15 lb. on lever arm

Field direction: 186°

	H1		H2		H3		H4	
Speci- men	J ₁	θ_1	J ₂	θ_2	J ₃	θ_3	J ₄	θ_4
029	145.0	185.93	143.3	cs: 188.03 cf: 187.93	140.6	186.50	140.8	cs: 188.00 cf: 187.90
030	110.1	185.90	108.0	cs: 187.23 cf: 187.03	107.8	185.90	109.7	cs: 187.35 cf: 187.25

Mean drift corrected angular rotation of moment:

Cooling started: $+1.47^{\circ}$

Cooling finished: $+1.36^{\circ}$

TABLE 17

Ob lusa Dyke Contact Material

Pressure: 151b on lever arm

Field direction: 138°

Spec- imen	H1		H2		H3		H4	
	J_1	θ_1	J_2	θ_2	J_3	θ_3	J_4	θ_4
031	298.0	138.58	279.2	cs: 138.28 cf: 137.98	290.7	138.23	288.7	cs: 138.00 cf: 137.70
032	211.2	138.05	204.5	cs: 137.55 cf: 137.45	212.0	138.15	209.8	cs: 138.10 cf: 138.00

Mean drift corrected angular rotation of moment:

cooling started: -0.21°

cooling finished: -0.36°

TABLE 18

Ob lusa Dyke Contact Material

Pressure: 15 lb. on lever arm.

Field direction 91°

Speci- men	J_1	H_1 θ_1	J_2	H_2 θ_2	J_3	H_3 θ_3	J_4	H_4 θ_4
033	99.5	91.03	100.0	cs: 88.70 cf: 88.60	102.8	90.40	101.9	cs: 88.95 cf: 88.75
034	270.0	91.30	258.2	cs: 89.70 cf: 89.50	258.7	91.78	252.2	cs: 89.50 cf: 89.30

Mean drift corrected angular rotation of moment:

cooling started: -1.88°

cooling finished: -2.11°

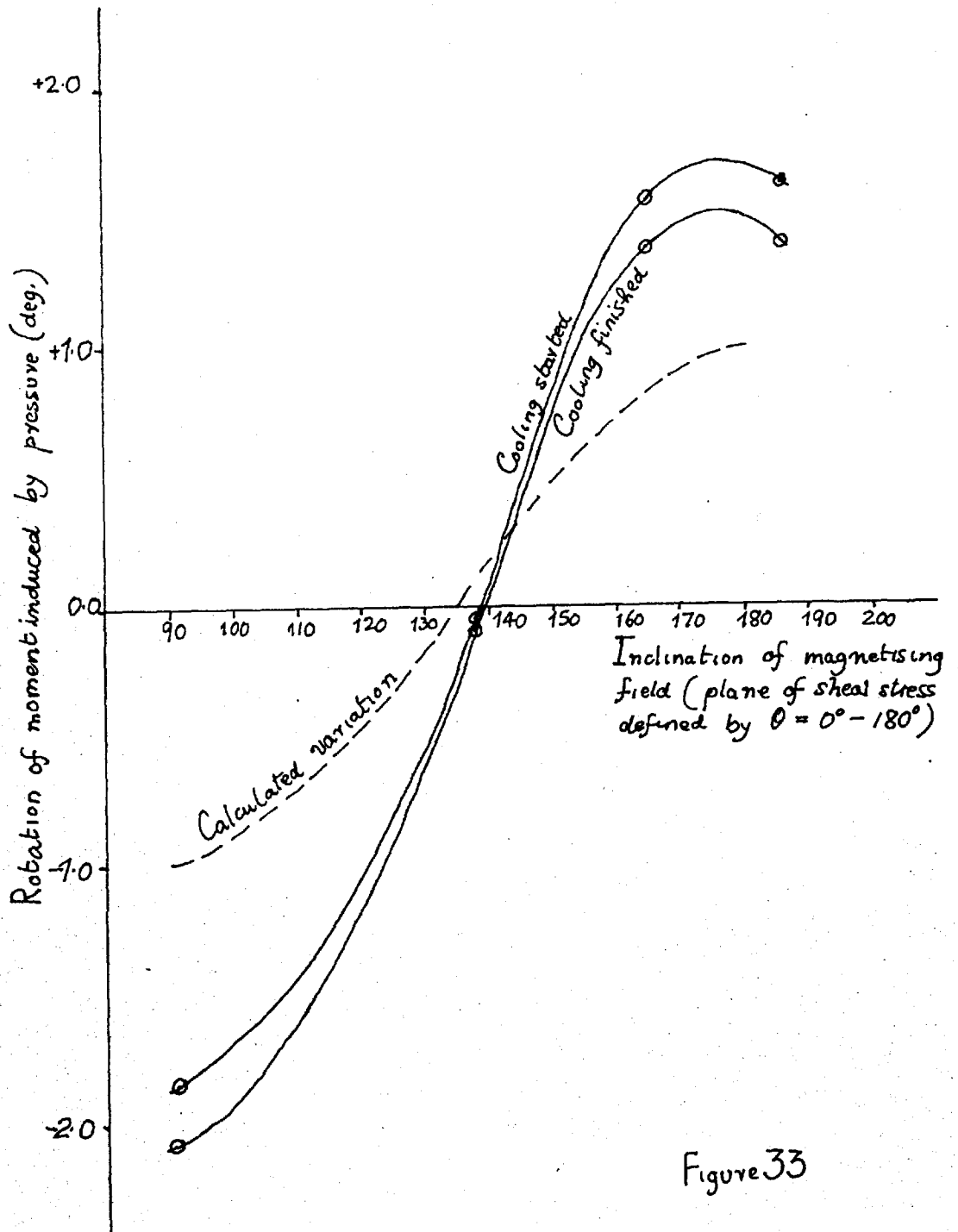


Figure 33

This graph shows that there is good agreement between the observed values of angular rotation of the moment and the predicted form of the variation of angular pressure effect with direction of magnetising field. However, the quantitative agreement between the values of maxima and minima measured and those calculated is poor. The reason for this poor agreement is thought to lie in the value of the reduction in intensity with pressure chosen for the calculation in 4.1.2. The variation of this pressure induced reduction in intensity is not so well known as the variation of angular rotation as no correction for drift could be applied to the intensity measurements made with the spinning magnetometer.

When the variation of intensity with pressure observed in the shear pressure experiments has been discussed an attempt to relate directly these changes with the observed angular changes will be made using the method developed in 4.1.2 together with information derived from this series of experiments.

The graphs for field directions of 165° and 138° (Figs. 34, 36) show clearly the dependence of remanent intensity on pressure while the graphs for field directions of 184° and 91° (Figs. 35, 37) show no indication of such dependence. Although the scatter of values in Fig. 37 is

large it is fair to say that, within the limitations imposed by the spinning magnetometer drift on intensity measurements, Figs. 35 and 37 support the conclusion of 4.1.2 that, for shear pressure applied in the present manner, there should be no intensity change with pressure at the position of maximum angular rotation.

Using these graphs an attempt may be made to relate directly the reduction of moment and the angular rotation of moment for the Ob Lusa contact material using the method developed in 4.1.2. Reference to 4.1.2 indicates that the angular rotation of moment is given by by the expression

$$\Delta\theta = \tan^{-1} \left(\frac{d}{J} \right)$$

where $d = \sqrt{(\Delta J_R)^2 + (\Delta J_Q)^2}$

and $\Delta J_R = \Delta J_Q = (\Delta J_C + \Delta J_T)$ for one diagonal

(J is the pressure-free moment).

It is possible to make a direct measurement of $(\Delta J_C + \Delta J_T)$ for one diagonal from the shear pressure experiment carried out with a magnetising field direction of 138° . Fig. 38 demonstrates that such a direct measurement is possible. In this figure the small arrows show the reduction in the total moment due to magnetising under pressure, the arrow two units long indicating the compressive effect and the

Figure 34
 $\theta = 165^\circ$

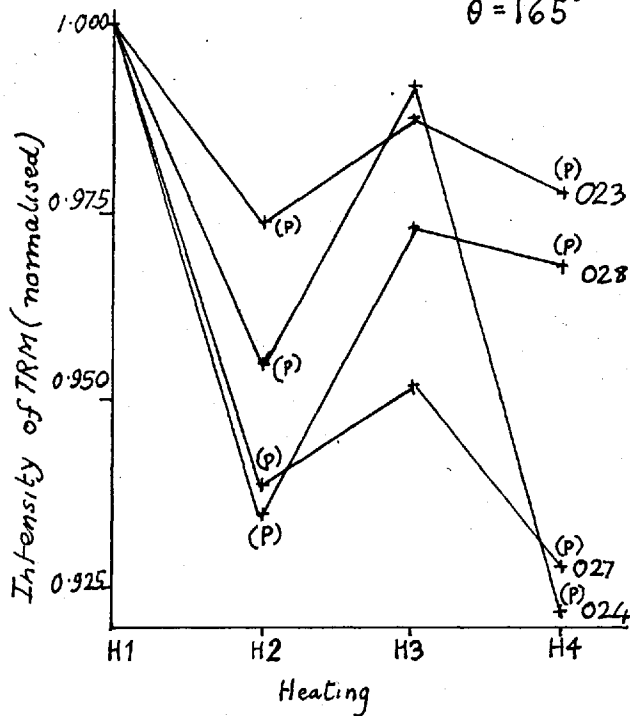


Figure 35
 $\theta = 184^\circ$

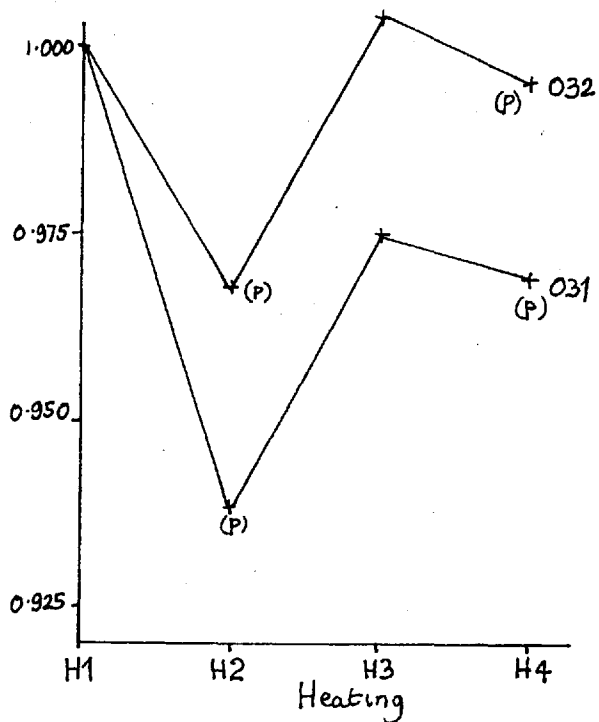
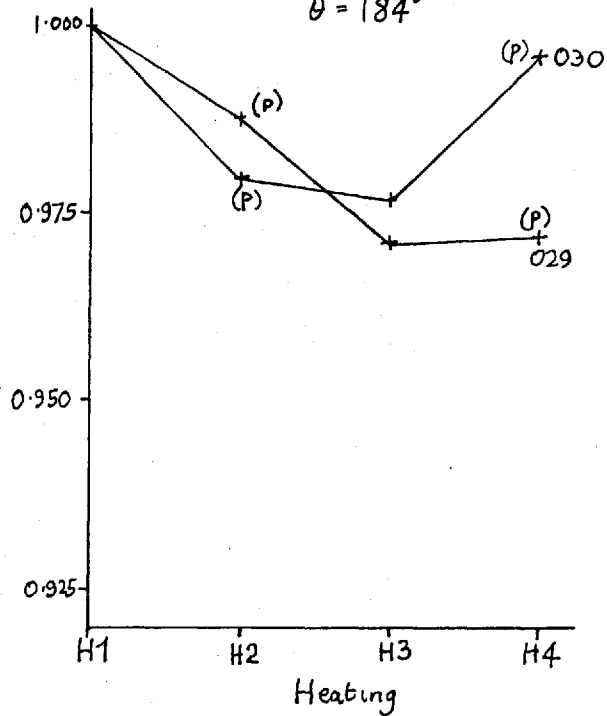


Figure 36
 $\theta = 138^\circ$

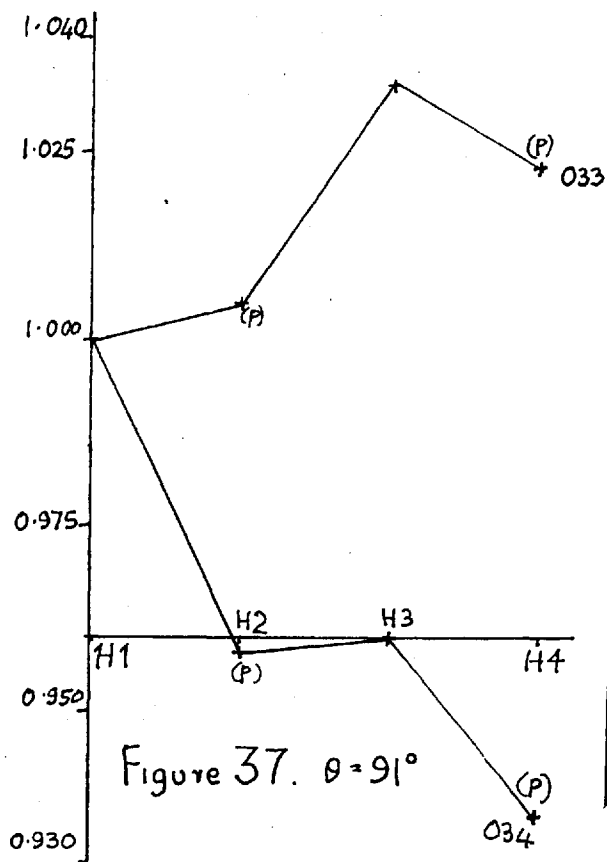


Figure 37.
 $\theta = 91^\circ$

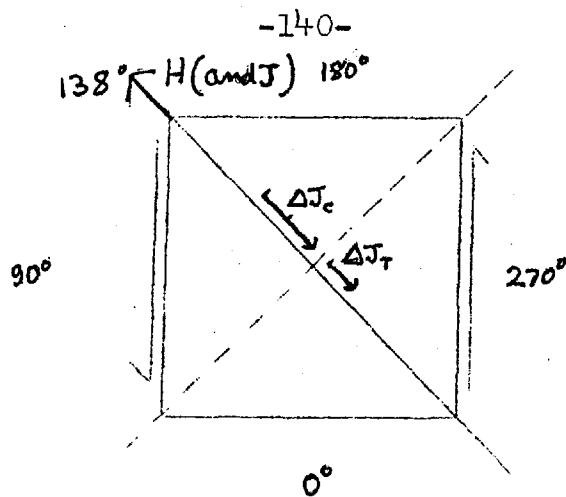


Fig 38

arrow one unit long indicating the tensional effect.

From 4.1.2 it is seen that the sum of these effects is

($\Delta J_C + \Delta J_T$) for one diagonal. From Fig. 36 an estimate of this quantity may be made if allowance is made for overall drift in the two curves. A reasonable figure is 0.02 rationalised units decrease in moment. Substituting this value in the relationship for $\Delta\theta$ we have

$$\Delta\theta = \tan^{-1} \left(\frac{d}{J} \right) = \tan^{-1} \left(\frac{\sqrt{(0.02)^2 + (0.02)^2}}{1.0000} \right)$$

i.e. $\Delta\theta = \tan^{-1} 0.0283 = 1.6^\circ$

This value of $\Delta\theta$ (maximum angular rotation of moment) of 1.6° agrees very closely with the observed value of 1.7° determined as the mean value of the results of the experiments at field directions of 184° and 91° (cooling started and cooling finished values giving the same mean). The close agreement of these figures, together with the agreement

of the form of the variation of pressure effect with field direction and of the pressure induced variation of remanent intensity with field direction, support the validity of the theory developed in 4.1.1 and 4.1.2.

4.4 Summary of the Results of the Shear Stress Investigation.

The results of the experiments carried out indicate that if the variation with pressure of two magnetic parameters for uniaxial stress conditions are known, the variation of these parameters with shear stress may be calculated.

The relevant parameters are:

- i. the variation of the rotation of the thermoremanent moment with stress, and
- ii. the variation of the intensity of this moment with stress.

If these parameters are known it is possible to show that the effect of shear stress on the remanent moment will have the following properties, all of which may be verified experimentally.

1. There will be an angular rotation of the thermoremanent moment which will vary with the direction of the magnetising field. There will be a maximum and minimum

value of the angular rotation, occurring at different positions when the magnetising field is parallel to the cube faces. An angular rotation of zero value will occur when the magnetising field is aligned parallel to the cube diagonals.

2. There will be a change in the intensity of the thermoremanent moment which will vary in magnitude depending on the direction of the magnetising field. In contrast with the effect of uniaxial stress this variation will be zero at the field direction required to cause maximum or minimum angular rotation of the thermoremanent moment. There will be a maximum change of moment in the direction where no angular rotation takes place, a reduction if the field is parallel to the direction of the compressional diagonal and an increase if it is in the direction of the tensional diagonal.
3. The magnitude of the maximum angular pressure effect may be calculated from either a knowledge of the variation of the two uniaxial pressure parameters described above or from a knowledge of the magnitude of the maximum increase or decrease of intensity for shear conditions.

Owing to the movement of the linked shearing jaws during the cooling part of an experiment two values of the angular rotation of the thermoremanent moment may be calculated, one corresponding to the inclination of the jaws at the commencement of cooling and the other to the inclination at the end of cooling. This rotation must be related to the contraction along the vertical axis of the cube and will probably vary linearly with temperature. Since the greatest part of the moment is acquired during the first part of the cooling interval ($600^{\circ}\text{C} - 300^{\circ}\text{C}$) it is reasonable to assume that the first calculated value, for the commencement of cooling, is closest to the real mean angular rotation of moment. Experimental evidence appears to support this theory since the curve obtained for the commencement of cooling agrees most closely in shape with the theoretical curve.

The importance of the effect of shear pressure in the interpretation of palaeomagnetic measurements cannot be wholly judged from these experiments. In the unsupported state the rocks used failed when the calculated tensional stress amounted to only 70 kg/cm^2 . At this low stress the maximum angular rotations of the thermoremanent moment observed was only of the order of 2° , which is negligible when

compared with the usual errors introduced in a palaeomagnetic survey. It is certain that the ultimate tensile strength of rocks increases when a hydrostatic supporting pressure is added to the shear stress, but the relationship between the two factors is only poorly known and estimates of the ultimate tensile strength of rocks of this type at considerable depths in the Earth's crust have not been assessed.

CHAPTER 5

THE EFFECT OF GRAIN SIZE ON THE MAGNITUDE OF THE UNIAXIAL PRESSURE EFFECT

5.1 Introduction

The results of the first experiments, carried out by Neale⁽¹⁴⁾, with the linear pressure vessel, demonstrated that a group of four specimens, subjected to the same pressure and magnetising conditions, generally showed a scatter of angular rotations of moment many times larger than the error of the experiment. An example of this scatter is shown in Table 19. This batch of cubes together with other batches showing large scatters, were examined for material differences between the specimens. It was immediately obvious that the specimens showing the larger angular deflections were considerably finer grained than the other specimens. It was apparent that this grain size difference was in some way related to the pressure effect. Three relationships were possible.

TABLE 19 (after Neale)

Linear pressure vessel. Pressure: 660 kg/cm² calculated
Field direction: 45° between pressure axis and field
direction.

<u>Specimen</u>	<u>Mean angular rotation</u>
128	1.40°
129	2.65
131	0.55
132	1.53

- (i) The pressure effect was simply proportional to grain size.
- (ii) A compositional change might occur with the grain size change, the change in pressure effect being related to the change in composition.
- (iii) The pressure effect might be related to both grain size and composition changes.

A series of experiments was devised to study this apparent grain size effect over a wider range of grain sizes than that occurring in the material studied by Neale.

5.2 Experimental Determination of the Grain Size Effect

It was necessary to eliminate some of the possible causes of the apparent grain size effect, in particular, that of compositional change accompanying grain size change. The Ob Lusa dolerite proved an ideal rock for this purpose. Determination of the composition of the magnetic constituents, as described in Chapter 3, showed that there was little change in the composition of these constituents from the dyke centre to the dyke contact. Material from both locations, after being heated to 600°C, contained two magnetic constituents, a nearly pure magnetite and an impure maghemite. The ratio of grain sizes from contact to centre was 1 : 4 (principal axes) and 1 : 150 (areas). The apparent discrepancy between these ratios is explained by the skeletal forms of the major generation of magnetite in the contact material. Unfortunately, owing to the presence of two magnetic constituents in the rock, the observed pressure effect could not be ascribed to any particular mineral.

The experimental technique~~s~~ employed was identical to that used by Neale, this being done to facilitate comparison with his work. Briefly, cubical specimens were cut from successive 2 cm. slices of rock from the dyke contact inwards towards the dyke centre. It was always attempted

to cut at least two cubes from each slice, the slice itself being cut parallel to the contact. The results of experiments carried out on a group of specimens showing a grain size variation from the minimum to the maximum available in the Ob Lusa dyke are shown in Table 20. (No accurate record of intensity changes was kept at the time of this experiment.) The drift correction is the same as that described on page ~~147~~¹³¹. Comparison of the values of angular rotation of moment with the respective grain size measurements is made in Table 21.

The measurements shown in Table 21 are presented graphically in Figs. 39, 40 and 41. Graphs of variations in the grain size parameters have been plotted against pressure effect. i.e.

angular pressure effect	vs	area of dominant ⁹ penetration grains (Fig. 39).
angular pressure effect	vs	square root of area of dominant generation grains (Fig. 40)
angular pressure effect	vs	log of area of dominant generation grains (Fig. 41)
log of angular pressure effect	vs	log of area of dominant generation grains (Fig. 41A).

These graphs show that there is a regular change of angular pressure effect with the grain size of the dominant magnetic

TABLE 20

Ob lusa Dyke Material

Pressure: Uniaxial pressure, 705 kg/cm² calculated

Field: 45° between pressure axis and magnetising field.

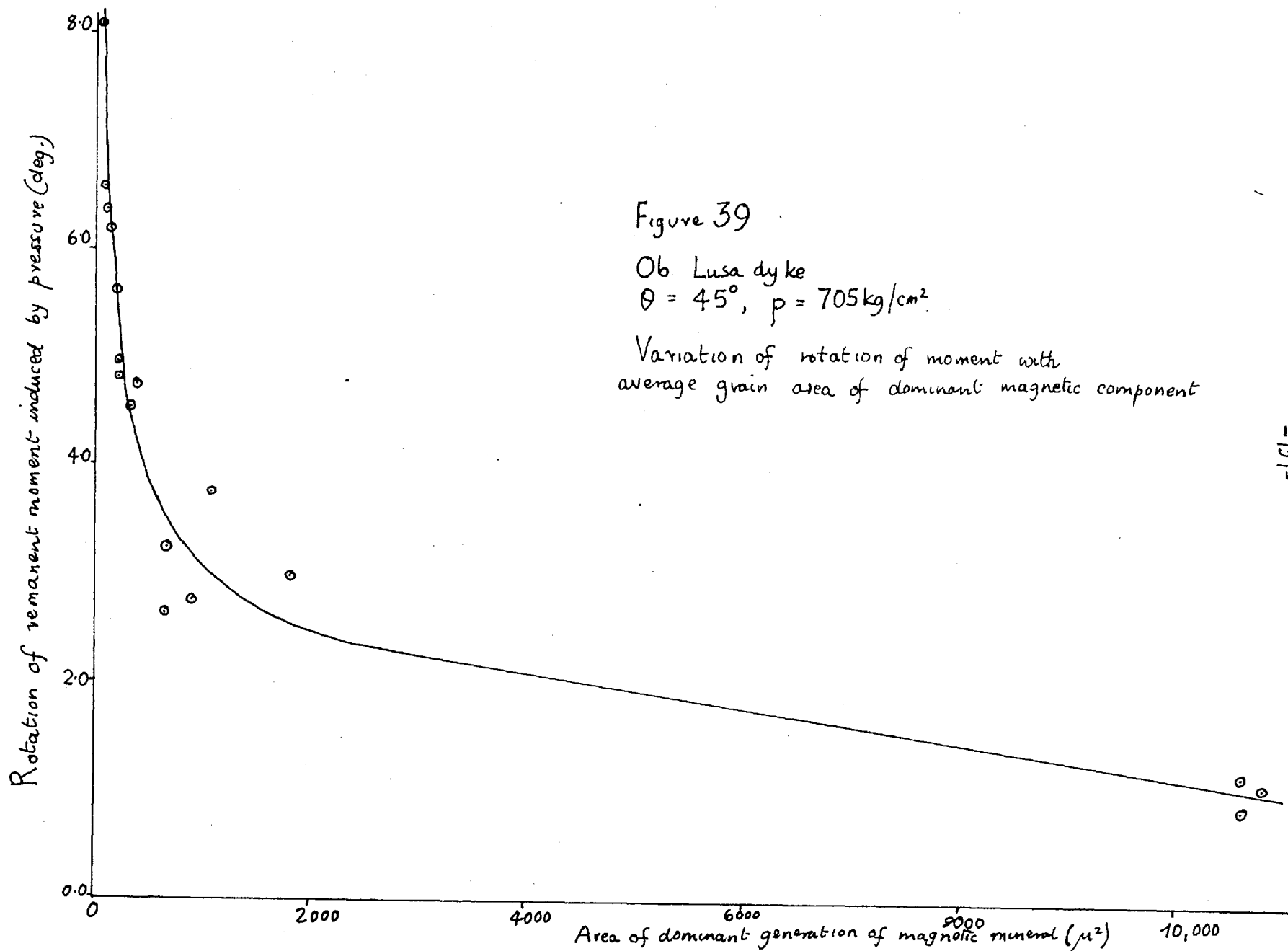
Spec-	Dist. from imen Contact	θ_1	$\theta_2(p)$	θ_3	$\theta_4(p)$	Mean drift corrected angular rotation
01	$\frac{1}{2}''$	231.00	238.03	230.73	236.70	+6.37° #
02	"	228.58	236.40	228.00	236.00	+8.12
04	"	229.18	233.88	228.75	233.35	+4.81
05	"	229.65	236.08	229.45	235.15	+6.17
07	"	315.75	308.83	315.15	308.33	+6.57
03	$1\frac{1}{2}''$	230.33	235.93	229.93	235.13	+5.60
08	"	315.73	310.30	(cube broke)		(+5.43)
09	"	315.75	310.90	316.25	311.70	+4.95
013	$2\frac{1}{2}''$	314.78	309.75	314.53	310.05	+4.53
014	"	315.45	310.63	315.35	310.60	+4.74
015	$3\frac{1}{2}''$	315.00	312.60	315.20	312.53	+2.64
016	"	315.95	312.35	315.70	312.58	+3.24
017	$4\frac{1}{2}''$	314.25	312.43	315.68	313.43	+2.76
018	"	316.53	312.78	317.00	313.70	+3.77
019	$5\frac{1}{2}''$	316.85	313.53	316.35	313.20	+2.99
010	Dyke centre	315.45	314.15	314.85	313.65	+0.90
011	"	317.75	316.65	317.85	316.78	+1.13
012	"	315.85	314.65	316.00	314.90	+1.22

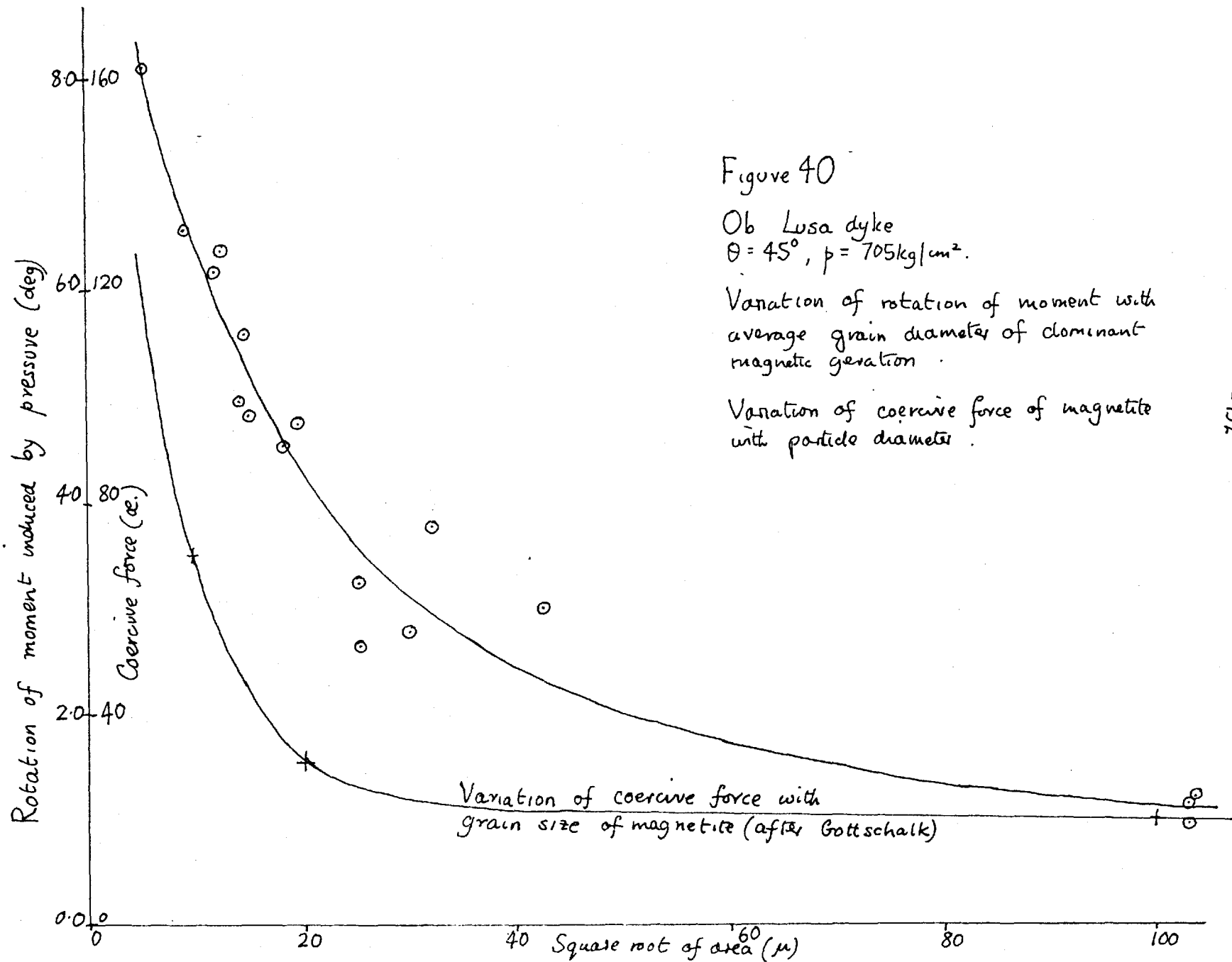
#The positive sign in uniaxial pressure experiments indicates a rotation of the moment away from the stress axis.

TABLE 21

Specimen	Angular Pres. effect	Acicular generation		Equidimensional gener.		Ratio of gener. (total areas)
		p axes	areas ($\bar{a}$ area)	p axes	areas	
01	+6.37	28.5x3.7 μ	105 μ^2 (10.25 μ)	34 μ	1160 μ^2	90A:10E
02	+8.12	22 x 2.6	57 (7.55)	33	1090	90A:10E
04	+4.81	34 x 6.5	224 (15.0)	27	730	90A:10E
05	+6.17	33 x 4.3	142 (11.8)	25	625	90A:10E
07	+6.57	24 x 3.5	84 (9.15)	29	840	85A:15E
03	+5.60	41.5x5.1	212 (14.6)	29	840	85A:15E
08	(+5.43)	-	-	-	-	-
09	+4.95	40.5x5.0	202 (14.2)	37	1370	85A:15E
013	+4.53	52x6.5	338 (18.4)	33	1090	75A:25E
014	+4.74	54x7.3	394 (19.8)	29	840	70A:30E
015	+2.64	64x10	640 (25.2)	39	1520	85A:15E
016	+3.24	65x10	650 (25.3)	36	1300	75A:25E
017	+2.76	84.5x10.6	899 (30.0)	37	1370	65A:35E
018	+3.77	84.5x12.5	1060 (32.3)	35	1220	65A:35E
019	+2.99	106x17	1800 (42.5)	46.5	1820	70A:30E
010	+0.90	no acicular generation		103	10600 (103) μ^2	---
011	+1.13	"	"	104	10800 (104) μ^2	---
012	+1.22	"	"	103	10600 (103) μ^2	---

constituent, and that the rate of change with grain size becomes rapid for grain areas of less than 2000 μ^2 . The interpretation of the experimental results is complicated by the occurrence of two generations of magnetic constituents in the contact region. The distinguishing characters of the generations are as follows:





Rotation of moment induced by pressure (deg)

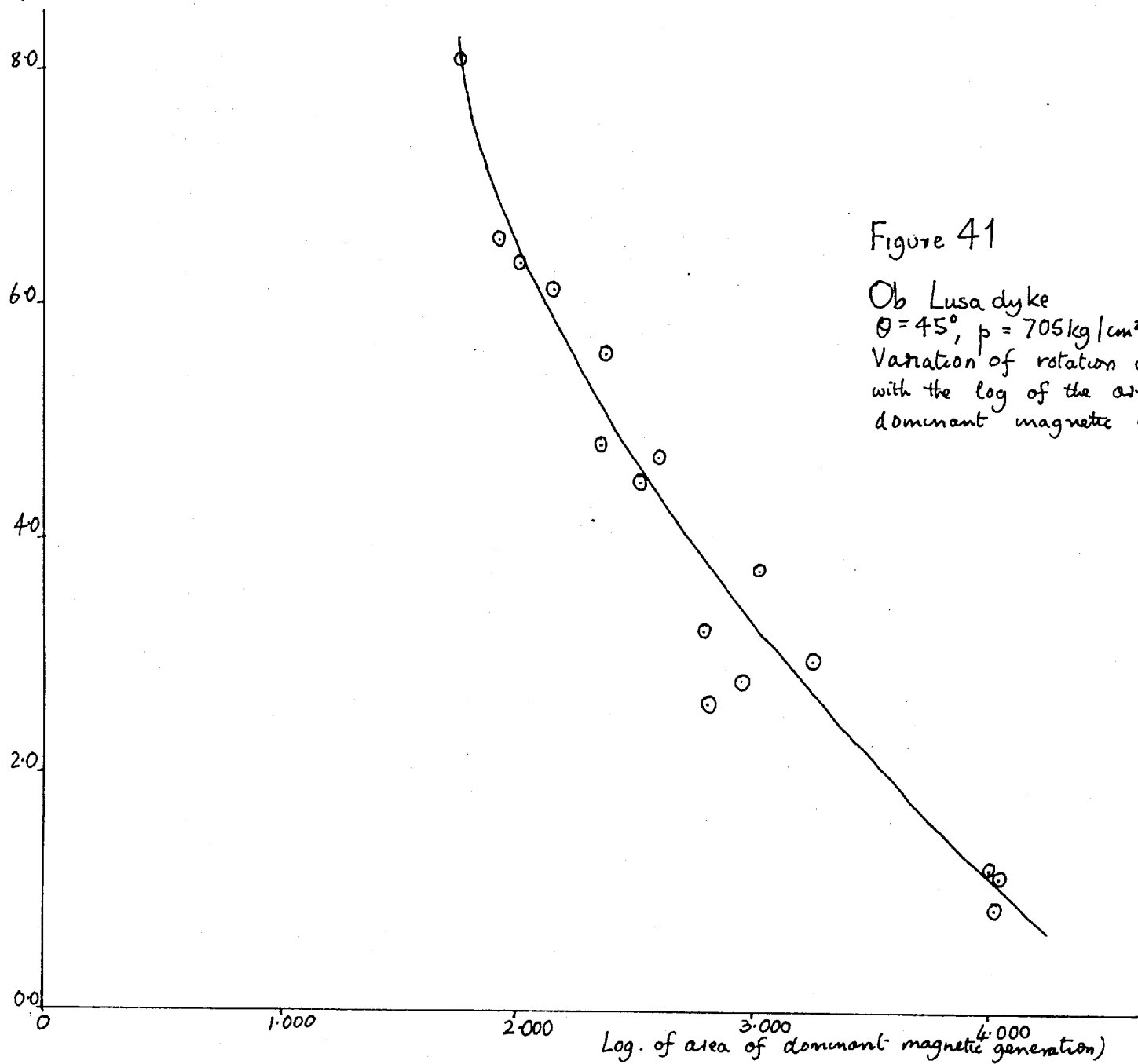
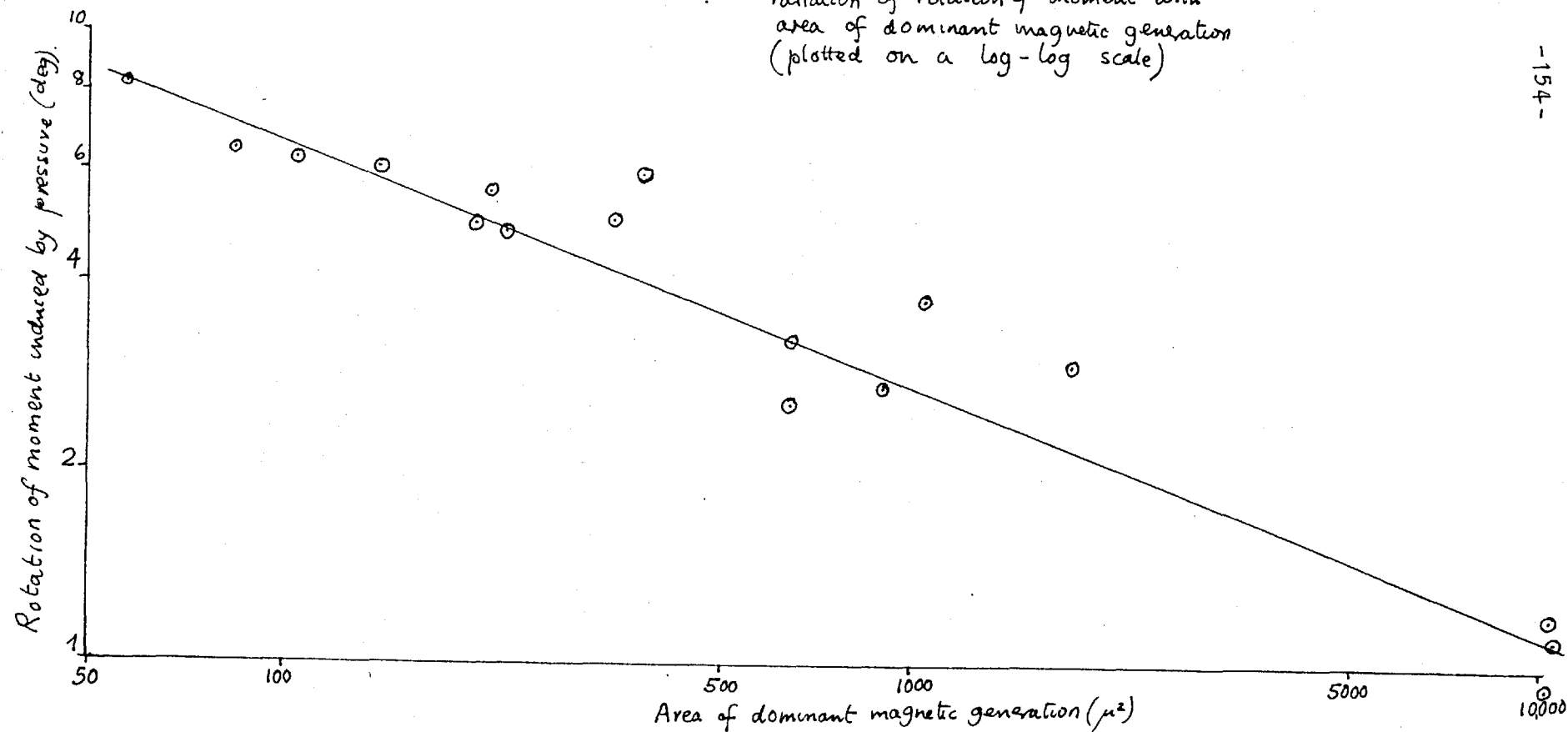


Figure 41(A)

Ob Lusa dyke

$\theta = 45^\circ$, $p = 705 \text{ kg/cm}^2$

Variation of rotation of moment with
area of dominant magnetic generation
(plotted on a log-log scale)



Acicular generation: Fine skeletal crystals of magnetite (pseudomorphed by maghemite in the reddened region) lying in the cleavage planes of the silicate members of the rock. It is this generation which shows a regular grain size variation from the contact inwards towards the centre of the dyke. The acicular generation is predominant in bulk in the contact region, ratios of 10 : 1 with the equidimensional generation being common. Crystals of this form are entirely absent from the central region of the dyke.

Equidimensional generation: Equidimensional sections of magnetite and maghemite pseudomorphs, indicating the normal cubic form of magnetite. This generation shows only a very slow increase in grain size in the contact region, which does not appear to be related to the angular changes in the moment obtained on applying pressure during cooling. Accordingly, the acicular generation is thought to be responsible for the angular rotations observed. It is likely that the second generation indicates that the dolerite magma was already partially crystallised when emplaced, the equidimensional grains belonging to the crystallised fraction. The acicular grains would then represent the embryonic crystals formed from the liquid fraction on its rapid cooling.

The graphs in Figs. 39, 40, ⁴¹and 41A have all been plotted using grain area, or some function of area, as the criterion of grain size. This has been done to allow the comparison of the different shaped dominant generations of the dyke centre and contact rocks.

Grain size measurements were made in the manner described in 3.3. The thin sections used were cut from the central region of each cube in a plane parallel to the dyke contact. This system is not completely justifiable since the specimens from the 18" wide contact region have a grain size gradient crossing them. However, the error introduced by this factor is probably less than the error in the actual grain size measurements and can be neglected except for the finest specimens $\frac{1}{2}$ " from contact. Here the gradient is very high as is indicated by the various grain sizes and pressure effects measured for the different specimens in this group.

5.3 Additional Experimental Results Related to the Grain-Size Uniaxial Pressure Effect Investigation

In the course of the experiments described in Chapter 4 and in this chapter measurements of a number of

other grain size dependent magnetic parameters were made, in particular:

Initial susceptibility in a 0.5 oe. field

Intensity of thermoremanent magnetisation acquired in a 1.5 oe field.

Values of the Q-ratio

A.C. (alternating current) demagnetisation behaviour

Change in the intensity of the thermoremanent moment when acquired under pressure

Consistency of the pressure effect in successive cycles for contact specimens.

5.3.1 The variation of initial susceptibility, thermoremanent moment and Q-ratio with grain size.

Table 22 shows the variation of these parameters with grain size for a number of specimens used in the shear stress experiments described in Chapter 4, together with one specimen, 06, which was used in the grain size - pressure effect determination.

From Table 22 it is evident that

- (i) there is an increase in initial susceptibility with increasing grain size,

TABLE 22

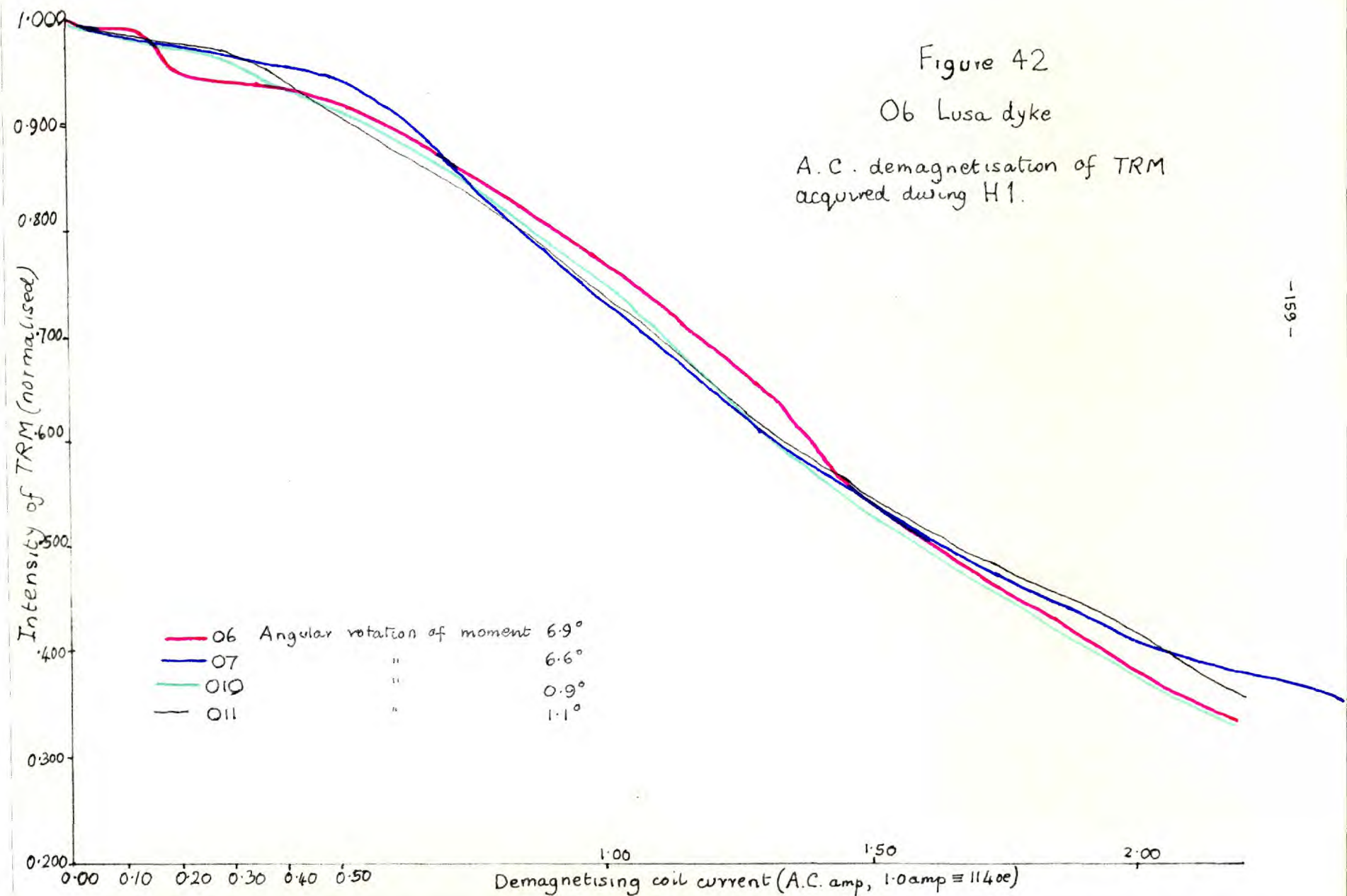
Specimen	Location	Initial Suscept. ($\times 10^{-3}$ emu/cc) (in 0.5 oe. field)	Remanent Intensity ($\times 10^{-3}$ emu/cc) (in 1.5 oe field)	Q-ratio: ($\frac{J_R}{KH}$)
06	$\frac{1}{2}$ " from contact to cube centre	4.32	175.5	27.0
023	"	2.93	53.5	12.2
024	"	2.99	55.8	12.4
028	"	4.22	152.2	24.0
029	"	4.48	145.0	21.6
030	"	4.95	110.1	14.8
031	"	4.82	223.3	30.8
032	"	4.65	158.4	22.6
050	Dyke	7.00	56.3	5.35
051	centre	7.12	58.6	5.5
052	"	7.30	48.0	4.4
053	"	8.10	71.0	5.85
054	"	6.68	49.5	4.95
056	"	6.74	49.8	4.9

- (ii) there is a decrease in remanent moment with increasing grain size, and
- (iii) there is a decrease in the Q-ratio with increasing grain size, together with some dependence on remanent intensity.

Figure 42

Ob Lusa dyke

A.C. demagnetisation of TRM
acquired during H1.



If it is assumed that there is little change in the overall bulk of magnetite plus maghemite from the contact to the dyke centre, and that the ratio between these minerals remains approximately constant over the same region, the variations described above agree perfectly with those described by Roguet⁽²⁴⁾ for an investigation of the variation of various magnetic parameters with grain size.

5.3.2 A.C. Demagnetisation of Ob Lusa rocks.

Neale was able to demonstrate a relationship between the order of the A.C. demagnetisation curves for a batch of four specimens, and the order of the angular pressure effects. A.C. Demagnetisation of both contact and dyke centre rocks was carried out during this present investigation and, surprisingly, at no demagnetising field was satisfactory correlation found to exist. No explanation of this discrepancy with Neale's results can be suggested. Demagnetisation curves for contact and dyke centre rocks are shown in Fig. 42. There is little difference between these curves although the grain sizes, and angular pressure effects, are very different.

5.3.3 Change of remanent moment with pressure and consistency of angular pressure effect.

A considerable decrease in intensity was found to accompany the large angular pressure effects obtained with the contact rocks, and a study of previous experiments showed that a smaller change accompanied the smaller angular pressure effects of the dyke centre rocks. This variation in the decrease in moment, when magnetising under pressure, with the angular pressure effect suggests that both phenomena are manifestations of the same underlying process. The situation was complicated by another effect, the general change of moment with successive heatings. It was found that, for the dyke centre rock, the moment increased on successive heatings while for the dyke contact rock, the moment decreased.

An especially careful experiment was carried out with two specimens cut from $\frac{1}{2}$ " from the dyke contact (035, 036). Seven heating were carried out on 035, utilising a calculated pressure of 1220 kg/cm^2 , while nine heatings were carried out on 036, utilising a calculated pressure of 705 kg/cm^2 . The results of these experiments are shown in Table 23. It is immediately evident that, allowing for the gradual decrease in the moment which is independent of pressure,

TABLE 23

Ob Lusa Dyke Material

Pressure: 035 - 1220 kg/cm² calculated

036 - 705 kg/cm² calculated.

Field direction: 45° between pressure axis and magnetising field.

Speci- men		H1	H2	H3	H4	H5
035	J	1.0000	0.8750	0.9155	0.8541	0.9111
	Ø	314.05	304.45 (+9.60)	314.98	302.2 (+12.78)	315.005
036	J	1.0000	0.9356	0.9779	0.8790	0.9185
	Ø	318.33	310.35 (+7.98)	317.73	310.33 (+7.40)	318.65
Speci- men		H6	H7	H8	H9	
035	J	0.8145	0.8010			
	Ø	315.6	305.03 (+10.58)			
036	J	0.8440	0.8551	0.8660	0.8269	
	Ø	310.98 (+7.68)	318.2	318.3	311.35 (+6.95)	

the specimen subjected to 1220 kg/cm^2 shows a larger pressure induced decrease in moment than the specimen subjected to 705 kg/cm^2 .

Intensity values in Table 23 are given in rationalised form. The scatter of pressure results obtained for 035 are explained by the difficulty in maintaining a consistent pressure of 1220 kg/cm^2 owing to continued oil leakage in the hydraulic pressure system at this pressure. The values of moment shown in these tables are plotted graphically in Figs. 43 and 44.

Using the method described in 4.1.2 it is possible to analyse the more consistent of these results (for specimen 036) to examine the changes in vertical and horizontal components of the moment needed to cause the observed angular change. If heating one and two of this specimen are compared, making an allowance from Fig. 44 for the overall decrease of moment with successive heating the following values of J and θ are obtained:

H1 (without pressure)		H2 (with pressure)	
J_1	θ_1	J_2	θ_2
0.9900		0.9356	
	318.33		310.35 (+7.98°)

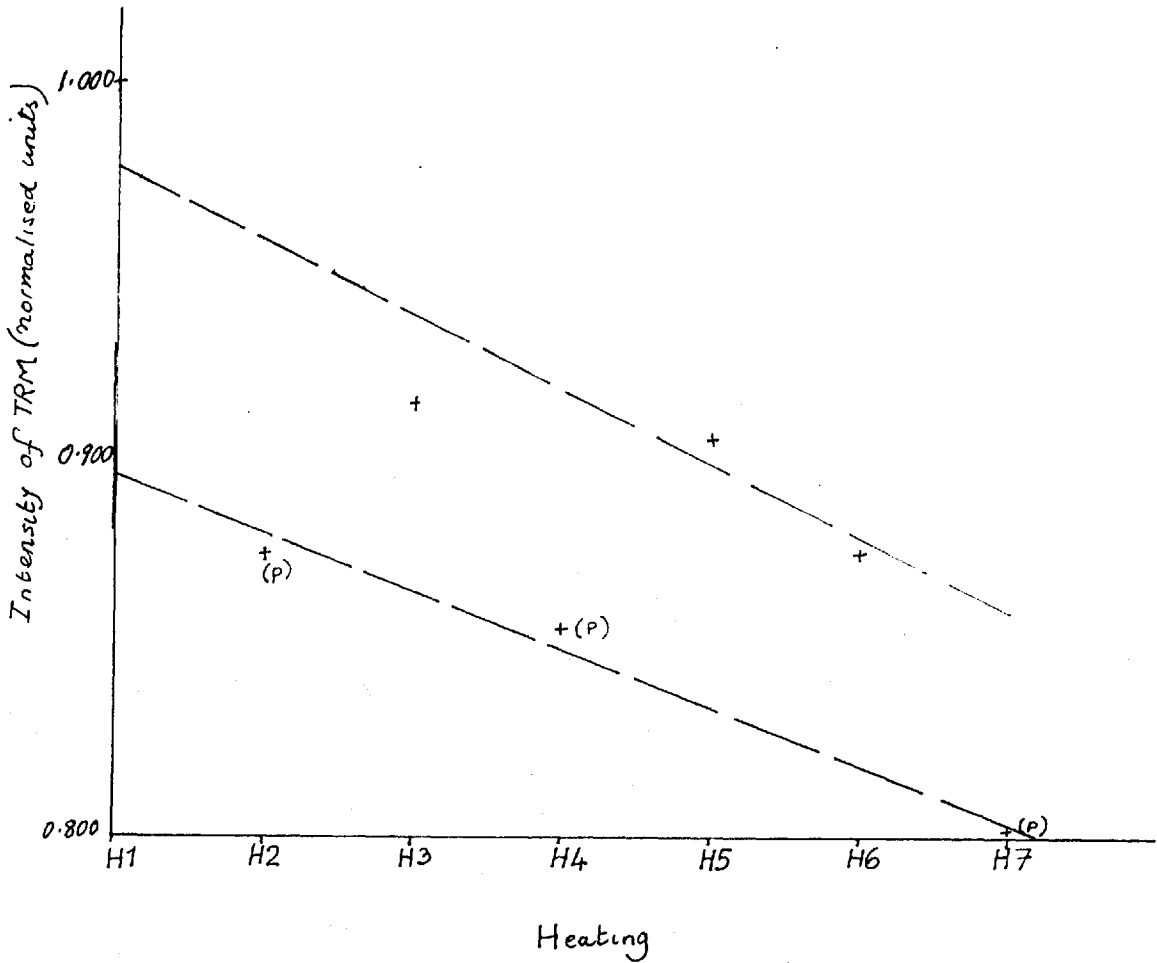


Figure 43

Ob Lusa dyke contact material
Pressure induced reduction of remanent moment

$\theta = 45^\circ$, $P = 1220 \text{ kg/cm}^2$

+ moment for pressure free heating

+ (P) moment for heating with pressure applied

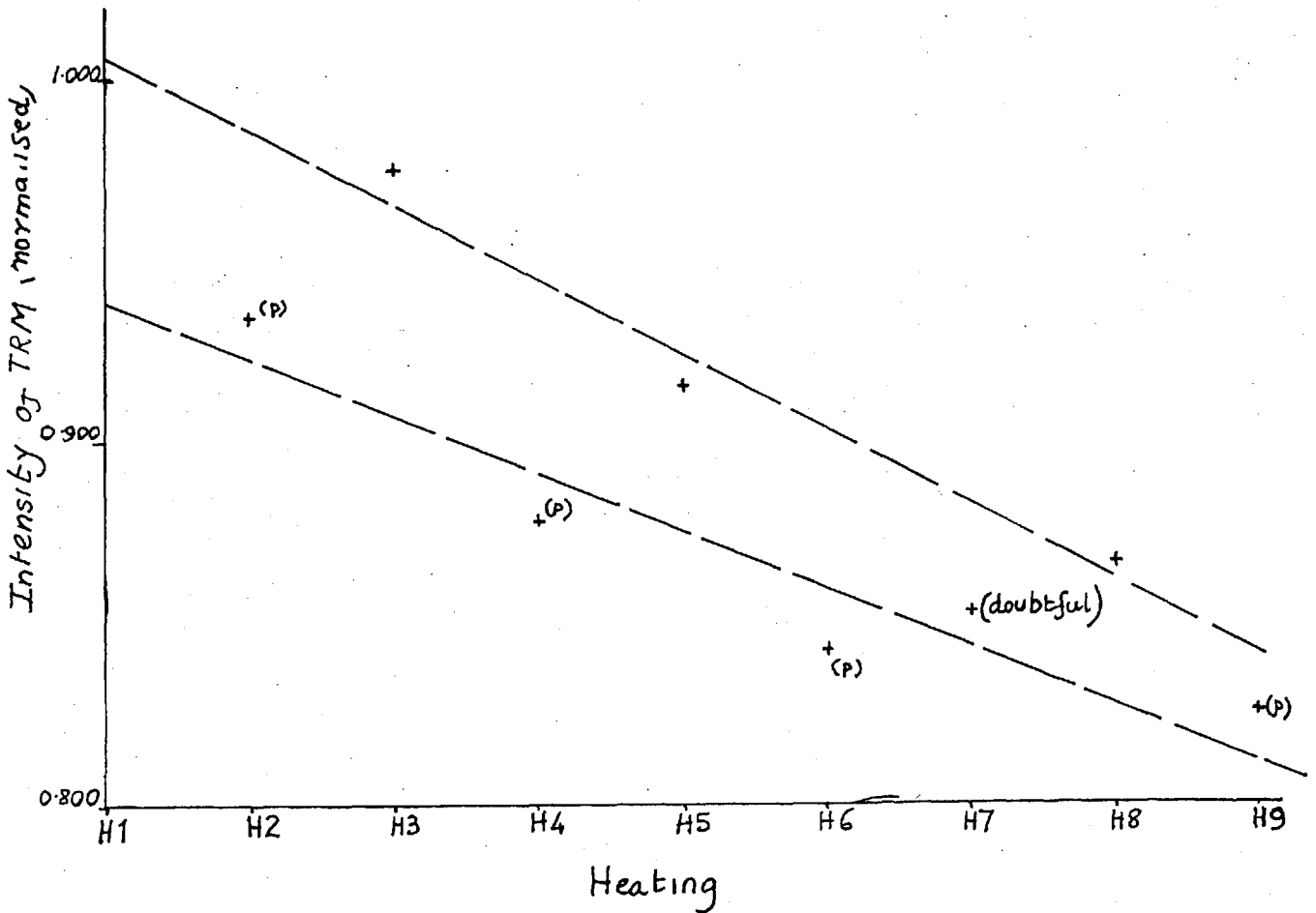


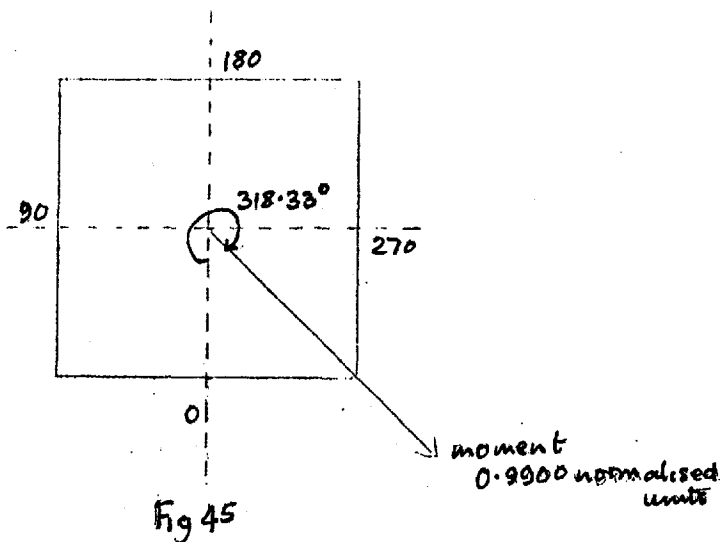
Figure 44

Ob Lusa dyke contact material
 Pressure induced reduction of remanent moment
 $\theta = 45^\circ$, $P = 705 \text{ kg/cm}^2$

+ moment for pressure free heating

+ (P) moment for heating with pressure applied

First, consider the magnetisation acquired without pressure (Fig. 45).



Resolving the moment into vertical and horizontal components we have:

$$\begin{aligned} J_{1V} &= 0.9900 \sin (318.33 - 270) \\ &= 0.7395 \end{aligned}$$

$$\begin{aligned} J_{1H} &= 0.9900 \cos (318.33 - 270) \\ &= 0.6590. \end{aligned}$$

Secondly, consider the magnetisation acquired under pressure (Fig. 46).

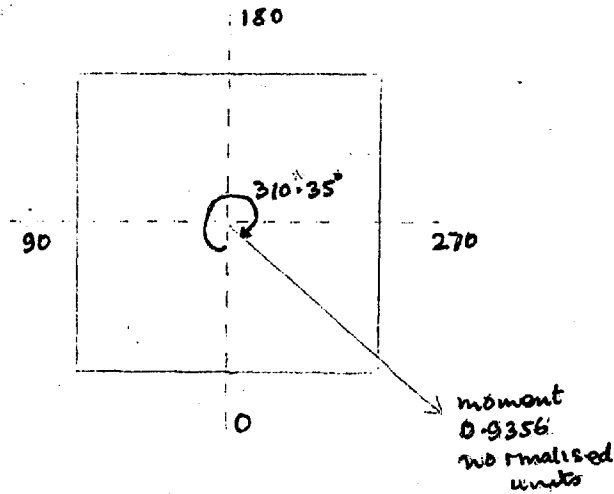


Fig 46

Resolving as before we have:

$$\begin{aligned} J_{2V} &= 0.9356 \sin (310.35 - 270) \\ &= 0.6058 \end{aligned}$$

$$\begin{aligned} J_{2H} &= 0.9356 \cos (310.35 - 270) \\ &= 0.7140 \end{aligned}$$

Thus it appears that a decrease in the vertical component will not account for the rotation of the moment. Instead the rotation of the moment must be related to a

decrease in the vertical component together with an increase in the horizontal component of about half the magnitude of the decrease in the vertical component (Ratio $\frac{0.1337}{0.0550} = 2.49$).

Similarly, for heatings eight and nine of specimen 036 we have:

H8 (without pressure)		H9 (with pressure)	
J_8	θ_8	J_9	θ_9
0.8590		0.8269	
	318.30		311.35 (+6.95°)

Resolving the moments as before we have:

$$J_{8V} = 0.8590 \sin (318.30 - 270) = 0.6412$$

$$J_{8H} = 0.8590 \cos (318.30 - 270) = 0.5715$$

$$J_{9V} = 0.8269 \sin (311.35 - 270) = 0.5462$$

$$J_{9H} = 0.8269 \cos (311.35 - 270) = 0.6217$$

This gives a ratio of $\frac{(\text{decrease in vertical component})}{(\text{increase in horizontal component})}$

of 1.90. The value of this ratio may be used to derive a quantitative relationship between $\Delta\theta$, the angular rotation of moment and ΔJ the pressure induced decrease in moment. The ratio of decrease in vertical component of moment to increase in horizontal component of moment may be written as follows:

$$\frac{J \sin \theta - (J - \Delta J) \sin (\theta - \Delta\theta)}{(J - \Delta J) \cos (\theta - \Delta\theta) - J \cos \theta}$$

the terms in the expression relating to the diagrams in 4.1.2.

If this expression is expanded and $\cos \Delta\theta$ taken as unity, $\sin \Delta\theta$ as equalling $\Delta\theta$ and terms involving the product of ΔJ and $\Delta\theta$ ignored the expression becomes

$$\frac{J \cos \theta \Delta\theta}{J \sin \theta \Delta\theta} + \frac{\Delta J \sin \theta}{\Delta J \cos \theta}$$

which reduces to $\frac{J \Delta\theta}{J \Delta\theta} + \frac{\Delta J}{-\Delta J}$ since $\sin \theta = \cos \theta$ ($\theta = 45^\circ$)

and using the numerical value of 2 for the ratio we obtain

$$\Delta\theta = 3 \frac{\Delta J}{J} \text{ and expression which is closely followed by the}$$

experimental results.

The consistency of the angular change with pressure can be estimated from this experiment. Four successive pressure experiments produce a random scatter of pressure induced rotations of moment with a range of $\pm 0.5^\circ$ ($\pm 7\%$) about the mean value. The greater inconsistency of the results for specimen 035 has already been explained as being due to failure of the apparatus to maintain the required pressure.

5.4 Conclusions and Possible Mechanisms Involved in the Grain Size - Uniaxial Pressure Effect Variation.

The results of the experiment carried out with specimens 01 - 019 show that there is a regular increase in the rotation of the thermoremanent moment with pressure as the grain size of the dominant generation of magnetic component decreases.

The relationship between these two parameters appears to have the form

$$\log \Delta\theta = -k \log A,$$

where $\Delta\theta$ is the angular pressure effect

k a constant, and

A the average grain area of the dominant generation.

Concurrent with this angular rotation of the moment there occurs a decrease in the remanent moment. The variation in decrease in moment and that of angular pressure effect appear because of their similar form to be closely related in origin. For a pressure of 705 kg/cm² (calculated) and a grain area of the order of 100 μ ² this overall decrease in moment may be resolved into a decrease in the vertical component of the moment (parallel to the pressure axis) and an increase in the horizontal component. For these conditions the ratio of decrease in vertical component to the increase in horizontal component is approximately 2.

The form of the curve of angular pressure effect plotted against the square root of the grain area is similar in form to the variation of coercive force with grain size, as described by Roquet et.al.⁽²⁸⁾. The rapid increase in coercive force and decrease in susceptibility with decrease in grain size are usually explained by postulating a change in the mechanism of magnetisation. For grain size diameters of greater than 100μ magnetisation is thought to be mainly caused by domain wall movement while, for smaller grain sizes less than 1μ where the single domain grain state is being approached, magnetisation is thought to be caused mainly by domain rotation, which is energetically a more difficult process to accomplish than domain wall movement.

The grain size range used in the experiments described in this chapter falls in the $10\mu - 100\mu$ region for which no satisfactory theory of thermoremanent magnetisation exists. It has been suggested by Néel (Ref. 30) that until such a theory exists no quantitative theory for the effect of pressure on a rock acquiring a thermoremanent moment may be devised.

A second difference in the magnetisation processes between fine and coarse grains has recently been suggested

by Verhoogen. This new appraisal considers thermo-remanent magnetism to be complex in origin, having three main sources, i.e.

- i. A soft part, probably caused by the blocking of domain walls.
- ii. A part due to the rapid decrease in magnetocrystalline energy near to the Curie point allowing domain rotation to take place.
- iii. A hard part which resides in the stressed regions surrounding dislocations.

The high remanent moments associated with the finest Ob Lusa rocks are probably caused, in the terms of Verhoogen's suggestion, by the very great number of dislocations, with their surrounding very hard stressed-region domains, in the poorly annealed skeletal magnetic grains in the material.

A tentative explanation of the grain size - pressure effect variation, may be suggested. The application of pressure during magnetisation alters the easy direction of magnetisation of the randomly oriented grains in the specimen, causing a movement of this direction away from the stress axis. A magnetisation direction is acquired under pressure which is only partly reversible when the pressure is released at the end of the experiment. Owing to the factors described above the remanent moment of the finer grained material is

less able to move towards the pressure free direction on the release of pressure than is the coarser material. Thus the finer grained material shows a greater angular pressure effect on measurement. Unfortunately, the evidence of the A.C. demagnetisation experiment does not support this theory since there appears to be little difference in the hardness of the fine and coarse material.

To examine this theory more fully it would be necessary to measure the direction of the moment while pressure was still being applied. No method of making this measurement appeared feasible with the apparatus used in the present investigation. An important fact is that only a 20% rotation towards the pressure free direction occurred on A.C. demagnetising to 500 oe., while the moment itself was reduced by 80%. This suggests that, if Verhoogen's division of the origins of thermoremanent magnetism is correct, the angular pressure effect must be distributed amongst all the parts of the moment, it certainly does not merely represent a soft component of magnetisation superimposed on a harder moment in the ambient field direction, or vice versa. A fuller examination of the mechanism of this pressure effect and its relationship with grain size is given in 7.2.1.

The importance to palaeomagnetic interpretation of the angular pressure effects described in this chapter seems

limited. Palaeomagnetic measurements have frequently been made such that an 8° pressure induced deflection of moment would only be of the order of the error of the experiment. In addition, it seems unlikely that fine grained rocks showing such large pressure effects are common in natural conditions. A pressure of 1000 kg/cm^2 exists at a depth of about 3000 m. in the Earth's crust and it is likely that a magma being intruded at this depth would cool to form a dolerite rather than a basalt. In such a case only the contact regions of the intrusion would be fine grained and might show a measurable angular pressure effect in latitudes of about 35°N or 35°S (inclination 45°). It would be interesting to see whether a sill estimated to have been intruded under this depth of cover did show a regular change of direction of moment in its contact regions.

CHAPTER 6

THE RELATIONSHIP BETWEEN MINERAL COMPOSITION AND UNIAXIAL PRESSURE EFFECT

6.1.1 Introduction

It was thought likely that changes in the composition of the magnetic constituents of rocks, in addition to grain size change, would ^affect the observed uniaxial pressure effects. Accordingly a programme of experiments was carried out wherein a number of different rocks were subjected to the standard pressure and magnetising conditions described in 6.1.2. At the same time the composition of the magnetic constituents of these rocks were determined. Fortunately the small number of rock types sampled proved representative of all the main groups of rock forming magnetic minerals, with the exception of pure hematite.

6.1.2 Experimental conditions

Initial experimental conditions were chosen to obtain

the maximum angular deflection of moment, based on the experience gained from the Ob Lusa rocks, and also to be well within the mechanical limits of the apparatus. Thus, a 1.5 oe. field was applied at an inclination of 45° from the stress axis, and a calculated pressure of 705 kg/cm^2 imposed on each of the four specimens in one group while being cooled from the Curie point to room temperature. A greater pressure than 705 kg/cm^2 would produce a larger angular pressure effect, but it was found that the apparatus would have to be dismantled after every three experiments to replace the washers at pressures of over 1000 kg/cm^2 , making such pressures impractical.

Further experiments were carried out with different pressures and temperatures as required, and details of these conditions will be given with the relevant experiments.

6.2 Experimental Results

6.2.1 The Ob Lusa dyke

The heated dyke rock contains two magnetic constituents, a nearly pure magnetite and an impure maghemite. The angular pressure effect for this rock was found to be a

rotation of the moment away from the stress axis. Rotation in this sense, obtained with the uniaxial pressure vessel, will be known as positive rotation. For this rock the grain size of the magnetic constituents was found to be a critical factor in determining the magnitude of the angular pressure effect, and the reduction in moment on magnetising under pressure. The coarse dyke centre material showed a deflection of $+1^{\circ}$ for a grain diameter of 100μ while values as high as $+8^{\circ}$ were found for the fine grained contact material where the equivalent diameter of the grains was 10μ . A succession of non-pressure and pressure experiments showed the angular pressure effect for the contact rock to be consistent to within $\pm 7\%$ of the original value.

6.2.2 The central region of the Heast Road Sill.

The magnetic constituent of this rock was shown to be a titanohematite, that is, a solid solution of ilmenite and hematite showing magnetic properties distinct from either of these minerals.

The direction of the thermoremanent moment acquired by this rock was found to be consistent to within 0.3° of the direction acquired after the first heating (see Table 24)

TABLE 24

Consistency of Heast Road Sill
Central Region.

Pressure: none

Field direction: 45° between magnetising field and pressure axis.

Intensity $\times 10^3$ emu/cc.

Specimen	H1		H2		H3		H4	
	J ₁	θ_1	J ₂	θ_2	J ₃	θ_3	J ₄	θ_4
SS12	53.2	314.35	54.25	314.20 (+0.15)	56.4	314.43 (+0.08)	56.3	314.33 (+0.02)
SS20	53.2	319.55	53.7	319.83 (-0.28)	53.8	319.80 (-0.25)	53.2	319.75 (-0.20)
SS21	56.6	318.80	56.6	319.10 (-0.30)	55.7	319.03 (-0.23)	54.7	318.73 (+0.07)
SS22	59.8	315.58	59.8	315.40 (+0.14)	58.5	315.65 (-0.07)	56.8	315.68 (-0.10)

All angular changes for heatings 2, 3 and 4 are based on the direction for H1.

and the intensity of the moment was consistent to within 5% of its first value.

At the same time as this consistency experiment an experiment was performed with the standard pressure conditions described in 6.1.2. The result of this was the discovery that a small angular change in the opposite sense to that found for the Ob Lusa rocks occurred, that is, a rotation towards the stress axis. It was then decided to examine the variation of this deflection with pressure, and three further experiments were carried out, at 320 kg/cm^2 , at 705 kg/cm^2 as a check, and at 1220 kg/cm^2 . The results of all these pressure experiments are shown in Tables, 25, 26, 27 and 28. It may be seen from the graph (Fig. 47) that within the scatter of deflection a linear law can be fitted to the variation of angular pressure effect with pressure. All specimens apart from SS1 - 5 were A.C. demagnetised to 500 oe. before each heating to clean the specimen as far as possible from the influence of a previous experiment.

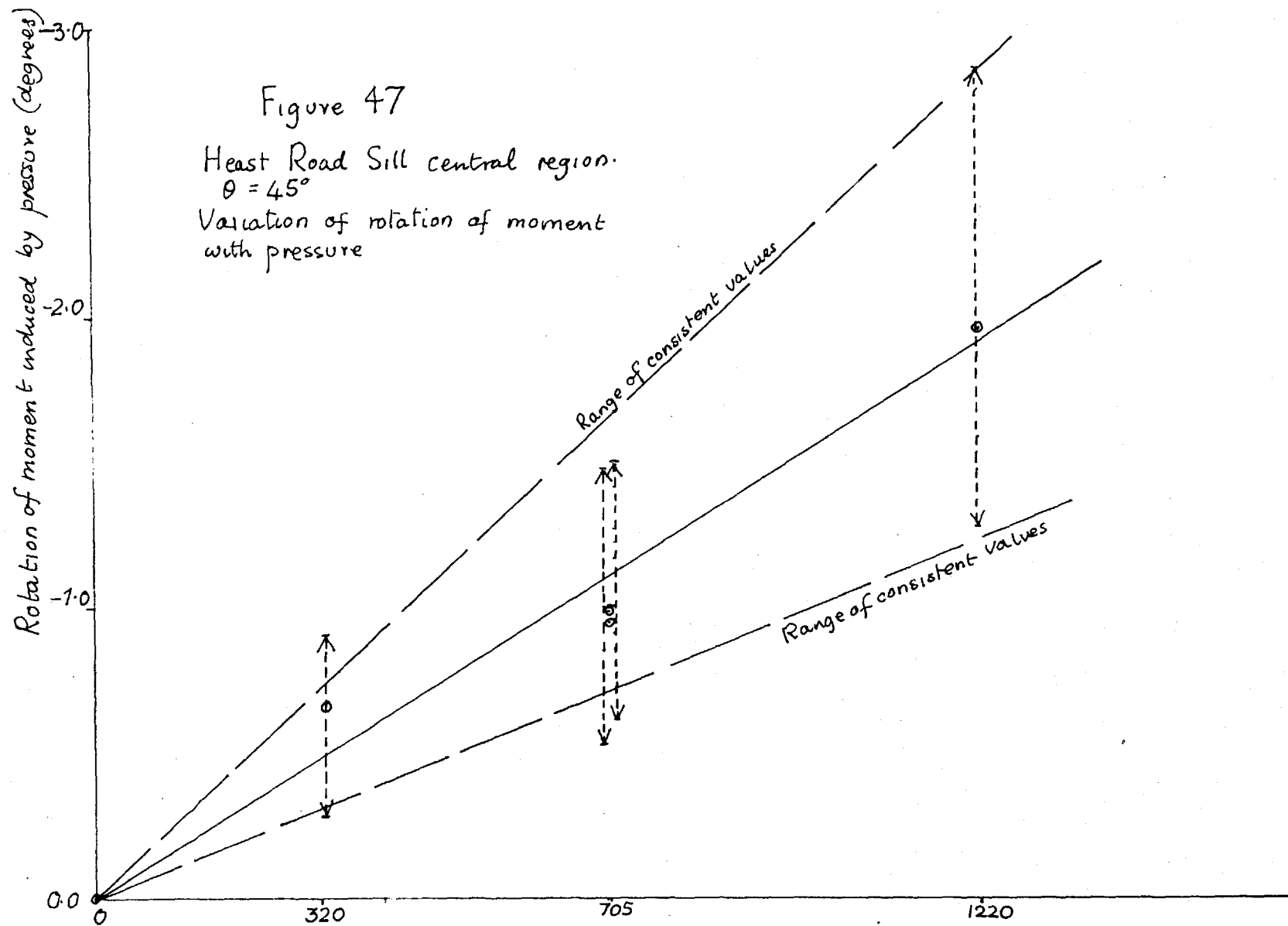


TABLE 25

Heast Road Sill Central Region

Pressure: 320 kg/cm²

Field direction: 45° between magnetising field and stress axis

Intensity x 10³ emu/cc.

Specimen	H1 J ₁	θ ₁	H2 J ₂	θ ₂	H3 J ₃	θ ₃	H4 J ₄	θ ₄	Mean drift corr. angl. pres. effect.
SS39	57.0	312.63	54.0	313.45 (-0.70)	54.6	312.88	56.2	314.10 (-1.10)	-0.90
SS40	54.4	312.65	57.2	313.33 (-0.34)	54.4	313.33	54.8	313.90 (-0.23)	-0.29
SS41	49.8	312.45	51.1	313.78 (-1.06)	49.5	313.00	49.8	313.95 (-0.68)	-0.87
SS42	57.0	315.43	55.7	317.10 (2 days interval) (-1.07)	52.4	316.33	not recorded	316.78 (-0.15)	-0.61

Mean drift corrected angular pressure effect: -0.67°

TABLE 26

Heast Road Sill Central Region

Pressure: 705 kg/cm² calculated (first experiment)

Field Direction: 45° between field and pressure axis.

No accurate intensity measurements were made at the time this experiment was performed.

Spec- imen	J ₁	H ₁ θ ₁	J ₂	H ₂ θ ₂	J ₃	H ₃ θ ₃	J ₄	H ₄ θ ₄	Mean drift corr. angl. pres. eff.
SS1		226.10		225.63 (-0.64)		226.65		226.63 (-0.39)	-0.52
SS2		225.23		224.45 (-1.09)		225.85		224.95 (-1.21)	-1.15
SS3		227.08		226.65 (-0.64)		227.50		227.28 (-0.43)	-0.54
SS4		228.30		227.08 (-1.22)		228.33		226.58 (-1.75)	-1.49
SS5		228.73		228.28 (-1.49)		229.90		228.78 (-0.84)	-1.17

Mean drift corrected angular pressure effect: -0.99°

TABLE 27

Heast Road Sill Central Region

Pressure: 705 kg/cm² (repeat of experiment described in Table 26)

Field direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

Specimen	H1 J ₁	θ ₁	H2 J ₂	θ ₂	H3 J ₃	θ ₃	H4 J ₄	θ ₄	Mean drift corr. angl. press. effect.
SS23	56.6	315.95	54.7	317.33 (-1.19)	54.9	316.33	53.4	318.33 (-1.81)	-1.50
SS24	57.8	319.48	54.0	319.75 (-0.22)	55.7	319.58	53.3	320.95 (-1.32)	-0.77
SS25	56.7	315.48	54.0	316.58 (-0.83)	53.3	316.03	51.4	317.18 (-0.88)	-0.86
SS26	58.5	315.88	55.9	316.68 (-0.54)	57.3	316.40	56.6	317.33 (-0.67)	-0.61

Mean drift corrected angular pressure effect: -0.94°

TABLE 28

Heast Road Sill Central Region

Pressure: 1220 kg/cm²

Field direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

Specimen	J ₁	H ₁ θ ₁	J ₂	H ₂ θ ₂	J ₃	H ₃ θ ₃	J ₄	H ₄ θ ₄	Mean drift corr. angl. press. effect.
SS31	49.3	313.85	50.4	316.70 (-2.96)	52.1	313.63	49.8	316.28 (-2.76)	-2.86
SS32	51.3	317.40	50.2	320.03 (-2.48)	51.0	317.70	47.7	319.55 (-1.60)	-2.04
SS33	51.3	314.70	53.6	316.00 (-1.59)	51.5	314.13	51.6	315.40 (-1.56)	-1.58
SS34	54.8	315.70	54.2	317.25 (-1.55)	57.1	315.65	55.1	316.68 (-1.03)	-1.27

Mean drift corrected angular pressure effect: -1.94°

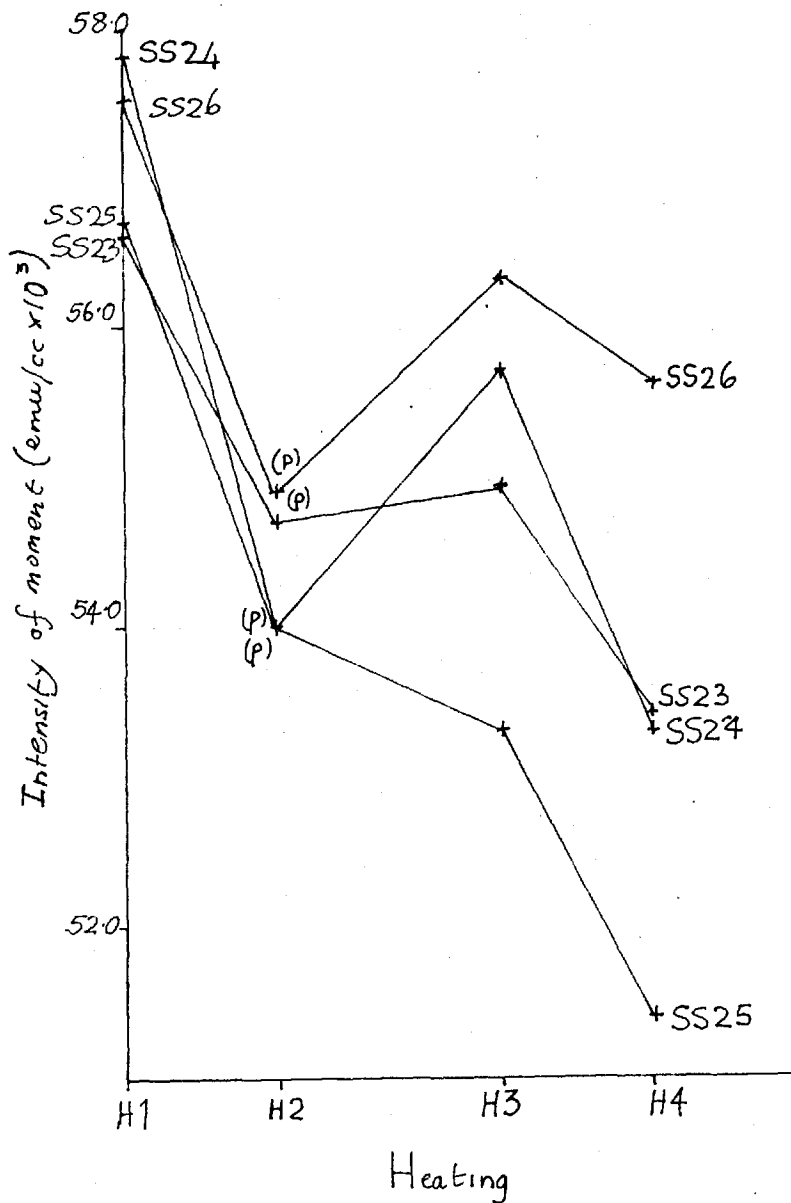


Figure 48

Heast Road Sill central region
Variation of remanent moment induced by pressure
 $\theta = 45^\circ$, $P = 705 \text{ kg/cm}^2$

Summary of Experimental Results

(i) The Central Region of the Heast Road Sill shows a suitable consistency for use in pressure experiments. Four successive heatings showed the variation of the inclination of the moment to be less than 0.3° from the first inclination and the variation of the intensity of the moment to be within 5% of its first value.

(ii) On subjecting the rock to pressure during alternate heating experiments a rotation of the moment towards the stress axis was obtained ("negative" deflection). This deflection appears to vary linearly with pressure over a range of 0 - 1200 kg/cm², with an angle of 45° between the magnetising field and the pressure axis. The rate of increase of deflection with pressure was 1.54° per 1000 kg/cm², which is close to the value of 1.23° per 1000 kg/cm² found for the Ob Lusa dyke centre, the sense of the deflections being in opposition. The grain size of the Heast Road Sill centre rock is just over half that of the Ob Lusa dyke centre.

(iii) There is a large scatter of angular deflections in each group of four specimens subjected to the same magnetising

and pressure conditions. The amplitude of this scatter (see Fig. 47) varies approximately linearly with the value of the mean angular deflection for the group. This scatter is certainly not a grain size effect as all the specimens used in this investigation were cut from a small number of 2 cm. slices taken from only three blocks of fresh rock from the central region of the sill.

(iv) There is a small decrease in the intensity of the thermoremanent moment acquired under pressure compared with the pressure free moment. This change in moment is best seen in specimens SS23 - 26 (Fig. 48) since this was the only group in which heatings did not have to be repeated owing to instrumental failures. Fig. 48 shows an overall decrease in the intensity of specimens on successive heatings together with a pressure induced decrease averaging 1.5×10^{-3} emu/cc (about $2\frac{1}{2}\%$) per heating for a calculated pressure of 705 kg/cm^2 .

Conclusions

The experiments carried out on the central region of **Heast Road** Sill make it obvious that the composition of the

magnetic constituents of a rock is a critical factor in determining the pressure induced effects of the thermo-remanent moment. The opposite sense of the deflections obtained for this rock and the Ob Lusa dyke material may be related to the different sense of the magnetostrictive coefficients of the different magnetic constituents. The mutual pressure induced decrease in moment makes the mechanism of magnetostriction difficult to fit to the results. Without definite knowledge of the magnetostrictive coefficients of titanohematites no magnetostriction mechanism can be proposed with certainty.

The scatter of deflections seen in each group of specimens is disturbing since no grain size effect is operative. The ratio of (largest deflection) for each (smallest deflection) group varies from 2.3 to 3.8 being largest for the smallest mean angular deflection. There is no doubt that this scatter is real since the values of rotation obtained for one specimen for successive pressure experiments are usually consistent. It is conceivable that this scatter indicates that some preferred direction of magnetisation, due to crystal orientation, exists in the sill, specimens cut randomly would then have this preferred direction at different positions relative to the axes of the cube. A

situation of this type would cause the pressure induced rotations to be partly dependent on the orientation of this preferred direction relative to the pressure axis. Such an orientation of crystals, if it exists, must be very slight as it could not be detected in the thin sections studied.

6.2.3 The Contact Region of the Heast Road Sill

When it was first shown that the central region of the sill had a negative pressure effect an attempt was immediately made to amplify the effect by using the finer grained material from the sill contact. However, this rock showed entirely different magnetic properties from the material from the central region and, as described in 3.2.4, the magnetic constituent was shown to be pyrrhotite, the magnetic sulphide of iron. Since this mineral is widely distributed in igneous and metamorphic rocks it was decided to carry out a separate investigation to determine the effect of pressure during the acquisition of thermoremanence by pyrrhotite. Both heated and unheated rocks show pyrrhotite as the magnetic constituent (together with some hematite in the rock heated to 600°C) even when the specimen has been raised to 600°C. However, a complete and irreversible change in the

magnetic properties of the pyrrhotite occurs when the temperature exceeds 400°C . This change is seen in both the initial susceptibility and the remanent moment. Table 29 shows the contrast between these two magnetic states. The change from the state stable below 400°C to that stable above this temperature is incomplete even after five heatings to 600°C , since the remanent intensity still shows an increase on successive heatings. However, the angular change in moment accompanying this change of magnetic state is complete after only one heating. This change of magnetic state is clearly seen from the magnetisation curves in Fig. 49. The magnetisation curves shown in Fig. 49 were obtained in the manner described in 3.2.2. Any point on the magnetisation curves represents the moment that would be acquired by the specimen in cooling from the temperature at that point to room temperature, in a field of 1.5 oe.

The magnetisation curve for SS14_{HL} shows from 200°C to 400°C the acquisition of a remanent moment by the low temperature pyrrhotite, resulting in a maximum moment of 83.5×10^{-3} emu/cc inclined at 308° . The curve from 400°C to 600°C shows the decay of this magnetic state, the change being completed at about 540°C . At this temperature the specimen had a moment of 21.2×10^{-3} emu/cc inclined at an angle of 315° , this being the ambient field direction. The

TABLE 29

Heast Road Sill Contact Region

Maximum temperature: SS16, 17 - 620°C
SS27, 28 - 375°C

Magnetising field: 1.5 oe.

Intensity $\times 10^3$ emu/cc.

Susceptibility $\times 10^3$ emu/cc.

Specimen	Thermal History	Initial Suscept.	Remanent Moment	Q-ratio
SS16	Heated five times to 620°C	0.905 (after H5)	After H1 9.7 H5 21.4	7.2 15.8
SS17	Heated four times to 620°C	1.29 (after H4)	After H1 16.3 H4 24.3	8.4 12.5
SS27	Heated four times to 375°C	0.135 (after H4)	After H1 81.5	400
SS28	Heated four times to 375°C	0.135 (after H4)	After H1 55.6	274.

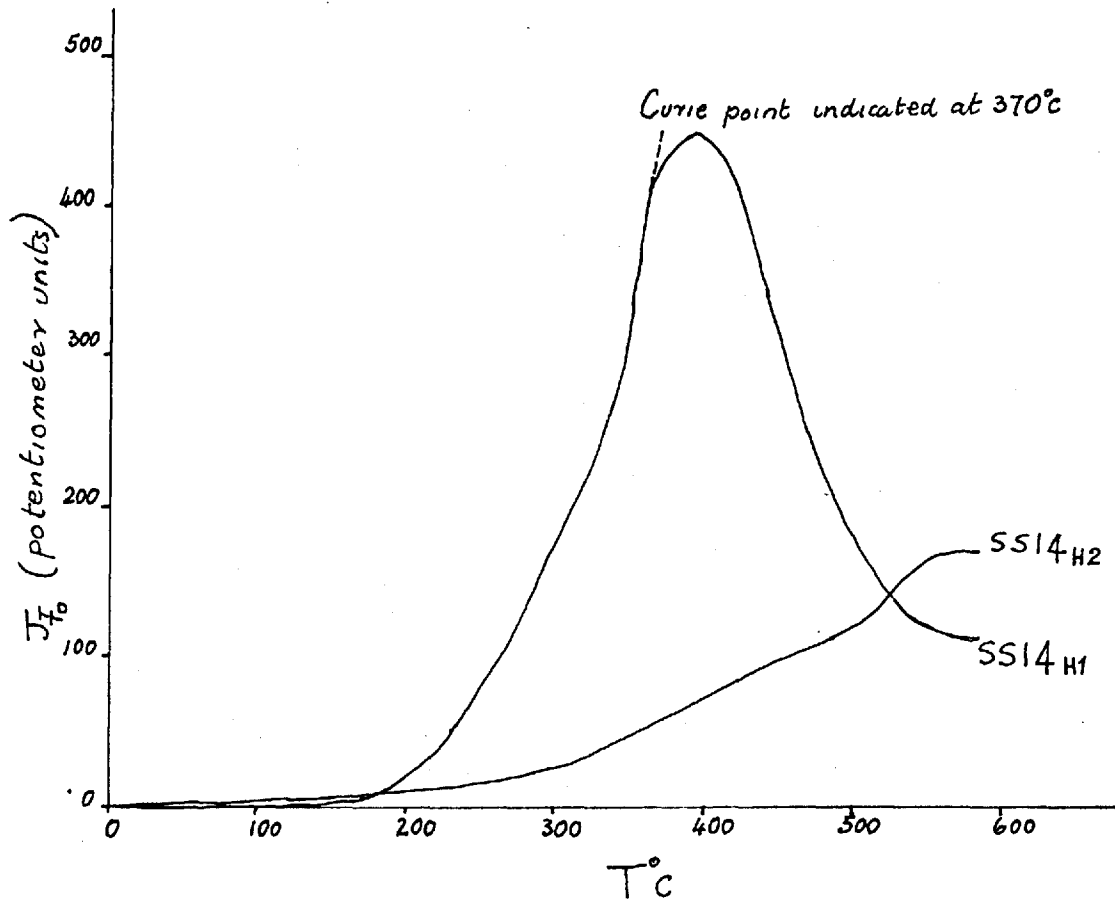


Figure 49

Heast Road Sill contact region

Thermal magnetisation using the uniaxial
pressure vessel method

curve for $SS14_{H2}$ shows that the change seen in $SS14_{H1}$ is irreversible. Owing to the complex thermal behaviour of this rock a number of experiments were carried out with inconsistent results before it was possible to isolate magnetically the pyrrhotite low temperature state. Since this state shows the magnetic properties normally assigned to pyrrhotite (remanent moment, initial susceptibility, Q-ratio and Curie point) it was used for the pressure experiments.

Consistency of the rock on successive heatings

Consistency experiments were at first of poor value since it was not realised that two magnetic states might be acquiring moments at the same time. When this fact was realised careful experiments allowed good consistency to be attained for both low and high temperature states.

The consistency of the low temperature state (hence forth to be known as pyrrhotite) was shown to be within 0.6° of the first inclination and to within 3% of the first value of intensity for four successive heatings. This consistency was achieved by applying A.C. demagnetisation to 900 oe. after each heating to remove any moment acquired by any high temperature state produced in the heating. Table 30 shows the result of a pyrrhotite consistency experiment.

TABLE 30

Heast Road Sill Contact Region

Consistency experiment. Maximum temperature: 375°C

Specimen	H1	H2	H3	H4	
	$\frac{J_1}{\text{emu/cc}}$ ($\times 10^{-3}$)	θ_1	$\frac{J_2}{\theta_2}$	$\frac{J_3}{\theta_3}$	$\frac{J_4}{\theta_4}$
SS29	51.0	49.5	50.0	49.7	
		306.05	305.75 (+0.30)	305.95 (+0.10)	306.60 (-0.55)

The high temperature state was shown to be consistent in a similar manner. Here the inclination of the moment is consistent to within 0.5° of the first value, but the intensity of the moment continues to increase with successive heatings. Apart from the great difference between the intensity of the pyrrhotite and that of the high temperature state there is a considerable difference in the inclination of the acquired moments. The direction shown by the high temperature state (315°) is close to the average direction shown by the Sill

TABLE 31

Heast Road Sill Contact Region

Consistency Experiment

Maximum temperature: 620°C.

Intensity $\times 10^3$ emu/cc.

Specimen	H1 J ₁	θ_1	H2 J ₂	θ_2	H3 J ₃	θ_3	H4 J ₄	θ_4	H5 J ₅	θ_5
SS16	9.7	314.0 (piston not up)	14.2	315.35	16.9	315.50 (-0.15)	19.8	315.10 (+0.25)	21.4	315.28 (+0.07)
SS17	16.3	316.33	21.5	316.13 (+0.20)	23.9	315.85 (+0.48)	24.3	315.85 (+0.48)	-	-
SS18	13.2	314.25	12.5	314.64 (-0.38)	14.4	314.33 (-0.08)	16.4	314.73 (+0.48)	-	-

(two heatings
necessary as
heater failed
on first
heating)

centre and Ob Lusa dyke rocks which has been taken as the ambient field direction. On the other hand with one exception the pyrrhotite shows an inclination nearer to the horizontal than this. Except SS19, all the contact specimens show a direction some 10° nearer to the horizontal. In thin section a slight orientation of the non-magnetic minerals is evident, not enough to be termed subtrachytic but possibly of a sufficient degree to cause the existence of a preferred direction of magnetisation in the rock. Pyrrhotite shows a very high degree of magnetic anisotropy and a slight orientation of crystals might produce the observed deviations. It is uncertain whether the pyrrhotite is an original mineral in the rocks, its bleb like form suggests secondary replacement, with the black shales in contact with the sill as a possible source of sulphur.

Pressure experiment results.

An experiment on the pyrrhotite bearing contact material was carried out. The experiment only differed from the standard experiment described in 6.1.2 in that one specimen was used as a control and was not subjected to pressure. The results of this experiment are shown in Table 32.

TABLE 32

Heast Road Sill Contact Region

Pressure: 705 kg/cm² calculated on SS19/27/28

Temperature: 375°C maximum

Field Direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

Spec- imen	H1 J ₁	H1 θ ₁	H2 J ₂	H2 θ ₂	H3 J ₃	H3 θ ₃	H4 J ₄	H4 θ ₄
SS19	63.5 (1.000)	314.98	59.7 (0.940)	312.13 (+2.85)	61.8 (0.974)	318.93	59.5 (0.938)	311.70 (+7.23)
SS27	81.5 (1.000)	306.20	79.6 (0.977)	301.68 (+4.53)	78.1 (0.958)	309.05	73.3 (0.900)	300.98 (+8.08)
SS28	55.5 (1.000)	304.48	53.4 (0.961)	301.78 (+2.70)	54.0 (0.973)	309.30	52.8 (0.953)	300.55 (+8.75)
SS29	51.0 (1.000)	306.05	49.5 (0.971)	305.75	50.0 (0.982)	305.95	49.7 (0.976)	306.60

The angular pressure effects shown in brackets in this table have not been drift corrected.

The changes in inclination and intensity are shown in Figs. 50 and 51. From the graphs of inclination of remanent moment and heating number (Fig. 51) it can be seen that the direction of magnetisation acquired by the pyrrhotite is very pressure dependent. The direction of rotation of the moment is positive but the situation is complicated by an entirely new factor. This factor may be described as an inconsistency of inclination during successive pressure cycles. It is certain from the behaviour of the control specimen SS29 that this inconsistency is not caused by field changes. The explanation of this behaviour would appear to be that a structural change is caused in the pyrrhotite by each pressure experiment which is not reversed by reheating the pyrrhotite to its Curie point some 24 hours later. It is not possible to say whether this is a truly irreversible effect since the interval between experiments is only one day but it is clear that the pyrrhotite, in behaving in this way, differs completely from magnetite, maghemite and titanohemite in the mode of its pressure dependence. This lasting effect on the structure of pyrrhotite causes an apparently greater pressure effect to occur during the second pressure cycle, resulting in a pressure induced inclination after the last heating further away from the ambient field than for any previous heating.

Figure 50

Heast Road Sill contact region

Change in inclination of moment
with pressure ($\theta = 45^\circ$, $P = 705 \text{ kg/cm}^2$)

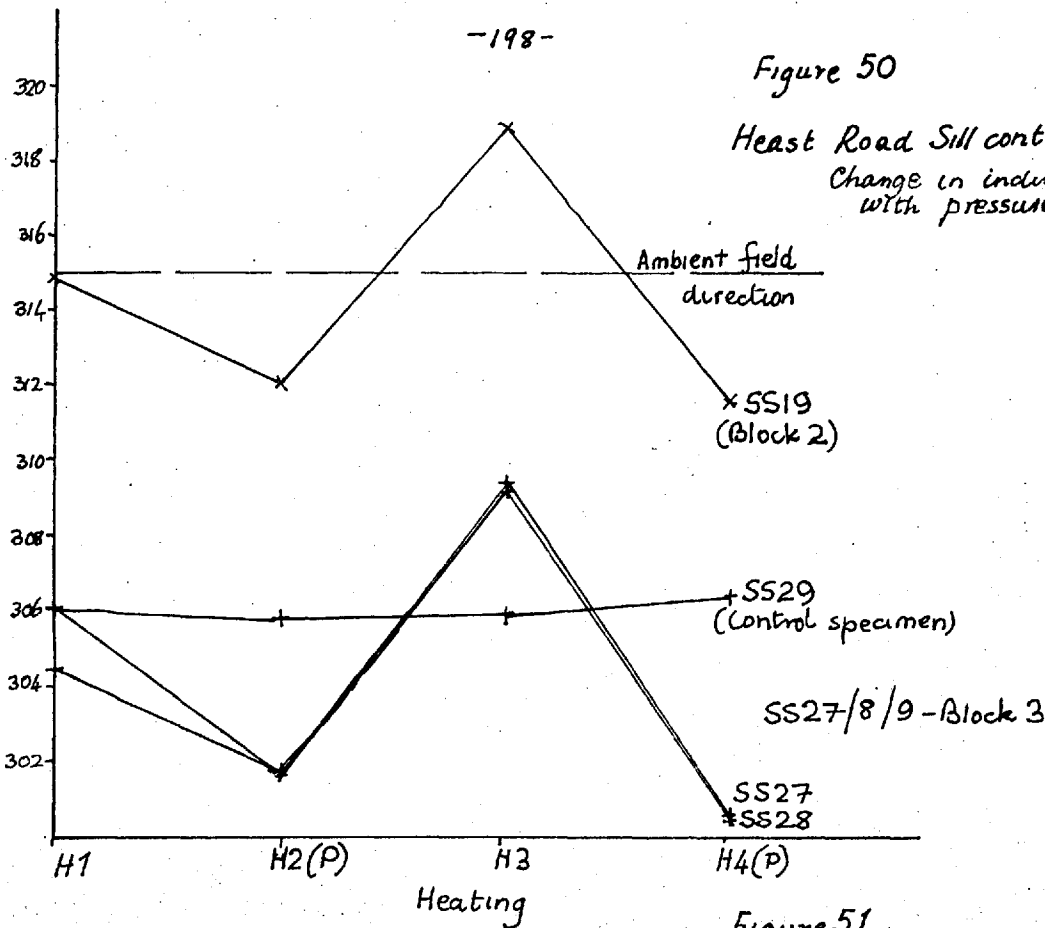
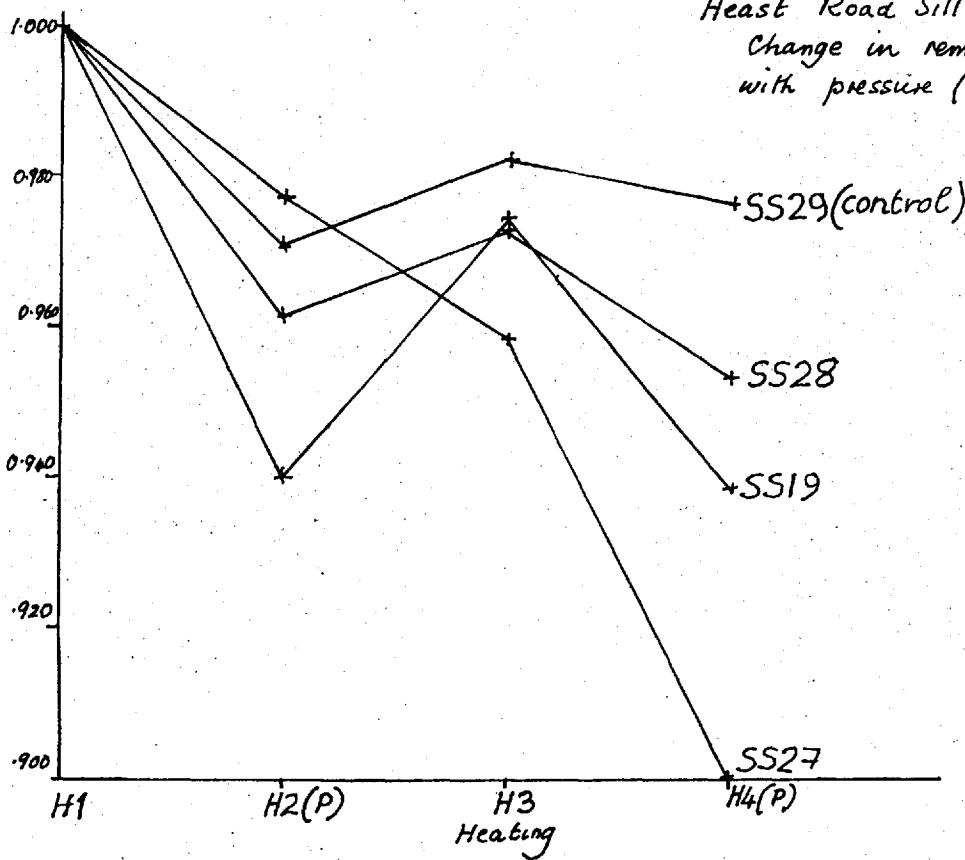


Figure 51

Heast Road Sill contact region

Change in remanent moment
with pressure ($\theta = 45^\circ$, $P = 705 \text{ kg/cm}^2$)



It is obvious that the limited number of pressure experiments carried out on pyrrhotite is not sufficient to allow the angular pressure effect to be predicted for any pressure/field conditions. A knowledge of the time of application of pressure at temperatures near to the Curie point might also be important in predicting the angular pressure effect in a particular instance.

In contrast with the experiments described for the Ob Lusa dyke and the Central Region of the Heast Road Sill it is not possible to say whether the pressure dependence of pyrrhotite will be of importance in palaeomagnetic interpretation. However, since the mineral is both highly pressure dependent and highly anisotropic it would be unlikely to show exactly the ambient field at the time of magnetisation. The graph of rationalised moment and heating number (Fig. 51) shows that there is a decrease in the moment when acquired under pressure. It is important to note that the magnetostriction of pyrrhotite is reported as being negative⁽²⁹⁾, yet the pyrrhotite bearing material shows an angular pressure effect and pressure induced reduction of moment in the same sense as the magnetite/maghemite bearing Ob Lusa dyke (magnetite has positive magnetostriction). This suggests that magnetostriction is not mainly responsible for

this type of pressure effect, or, alternatively, that pressure effects have complex origins, magnetostriction being less important than some other factor in the production of pressure effects in pyrrhotite.

6.2.4 Deccan Basalts - Samples L6 and L31

Introduction

These rocks were originally chosen for study because they were thought to contain titanomagnetites with a high titanium content as their magnetic constituents. While the investigation was in progress chemical analysis was made of the magnetic constituents which showed them to be magnetite-ilmenite solid solution compounds. The magnetic properties of this series are unknown. Table 33 shows the evidence for the composition of the magnetic constituents of these rocks. Before the results of the experiments carried out on these rocks are described it must be pointed out that both these rocks showed evidence of the effect described for pyrrhotite, that is, reheating a rock to its Curie point does not remove the effect of a previous pressure experiment.

TABLE 33

Rock Type	Curie Pt.	Cell size	Composition inferred from chemical analysis and other parameters.
L6 (type E)	300°C	8.44 Å	mg.il. solid solution with ilmenite intergrowths.
L31 (type D)	75-150°C	8.495 Å	mg.il. solid solution (Ratio of components about 1:1)

Consistency of the rocks on successive heatings

The first experiments carried out on rock types D(L31) and E(L6) were consistency experiments of the type described for the Heast Road Sill rocks. The results of these experiments were only fairly satisfactory. The low Curie points required carefully controlled heatings since it was shown by Weaving that the solid solution magnetic constituents suffered chemical alteration at a temperature only a little higher than the Curie points. It was also found that a steel screwdriver, used to screw the specimens into the cube-holder on the spinning magnetometer, was magnetising the specimens. The replacement of this tool by

a brass screwdriver eliminated this cause of error.

The results of these experiments are shown in Tables 34 and 35.

Results of Pressure Experiments

The consistency experiments were followed by a series of pressure experiments of the standard type with 24 hours interval between experiments on each cube.

The results of these experiments are shown in Tables 36 and 37.

The values in these tables are shown graphically in Figs. 52, 53, 54 and 55. These graphs indicate that rock type D behaves in a similar fashion to the Ob Lusa material. This rock shows a large angular effect, the mean angular change (not drift corrected) being 6.5° . Unfortunately, the field was accidentally changed during the experiment and the results for D2 and the first two heats of D3 and D4 show the effects of this field change. There is some indication that the behaviour of the rock is not so consistent as the Ob Lusa rock. Specimen D5 shows a considerable angular change between heatings one and three of the order that occurred in the pyrrhotite pressure experiment. Corresponding to

TABLE 34

Rock Type D

Consistency Experiment

Maximum temperature: 150°C.

Field direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

Spec- imen	H1		H2		H3		H4	
	J ₁	θ ₁	J ₂	θ ₂	J ₃	θ ₃	J ₄	θ ₄
D7	32.6	318.30	31.2	316.80 (+1.50)	31.0	315.48 (+2.82)	29.6	317.75 (+0.55)
D8	46.5	315.18	42.3	314.65 (+0.53)	40.5	315.45 (-0.27)	41.9	316.00 (-0.82)

Consistency: Maximum deviation from first inclination: 2.82°

Average deviation from first inclination: 1.1°

Maximum deviation from original intensity: 13%

Average deviation from original intensity: 7.5%

TABLE 35

Rock Type E

Consistency Experiment

Maximum temperature: 300°C

Field direction: 45° between field and pressure axis.

Intensity $\times 10^3$ emu/cc.

Spec- imen	J ₁	H1 θ_1	J ₂	H2 θ_2	J ₃	H3 θ_3	J ₄	H4 θ_4
E4	37.4	318.18	36.6	319.10 (-0.92)	34.9	317.48 (+0.70)	35.3	317.50 (+0.68)
E5	40.5	314.45	40.3	315.00 (-0.55)	39.8	315.33 (+0.88)	38.0	313.95 (+0.50)

Consistency: Maximum deviation from first inclination: 0.92°

Average deviation from first inclination: 0.72°

Maximum deviation from first intensity: 6.7%

Average deviation from first intensity: 4.3%

TABLE 36

Rock Type D

Pressure: 705 kg/cm² calculated

Maximum temperature: 150°C

Field direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

	<u>H1</u>		<u>H2</u>		<u>H3</u>		<u>H4</u>	
	<u>J₁</u>	<u>θ₁</u>	<u>J₂</u>	<u>θ₂</u>	<u>J₃</u>	<u>θ₃</u>	<u>J₄</u>	<u>θ₄</u>
D1	47.5	321.55	41.5	312.45	45.5	321.18	39.7	311.55
D2	32.8	312.65	31.0	303.85	34.6	310.98	30.4	305.10
D3	50.5	306.60	46.4	299.65	54.5	312.40	49.7	308.95
D4	29.5	312.50	27.1	306.18	34.0	317.08	26.9	310.78
D5	44.0	314.95	44.0	309.73	45.8	318.58	42.8	312.93
D6	46.5	318.43	44.2	310.78	42.3	316.70	43.8	312.93

(The values for D2, D3 and D4 enclosed in a hatchured bracket were obtained when the field direction had been accidentally changed).

TABLE 37

Rock Type E

Pressure: 705 kg/cm² calculated.

Maximum temperature: 350°C.

Field direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

Specimen	J ₁	H ₁ θ ₁	J ₂	H ₂ θ ₂	J ₃	H ₃ θ ₃	J ₄	H ₄ θ ₄
E1	32.3	318.18	30.8	317.43	31.9	318.10	26.9	308.90
						60 hr. interval →		
E2	32.3	316.40	29.5	316.63	29.0	312.15	28.4	307.78
E3	30.8	316.30	25.4	309.83	33.2	314.4	33.2	323.38
E6	30.8	315.98	28.0	308.55	36.4	320.53	29.5	310.30

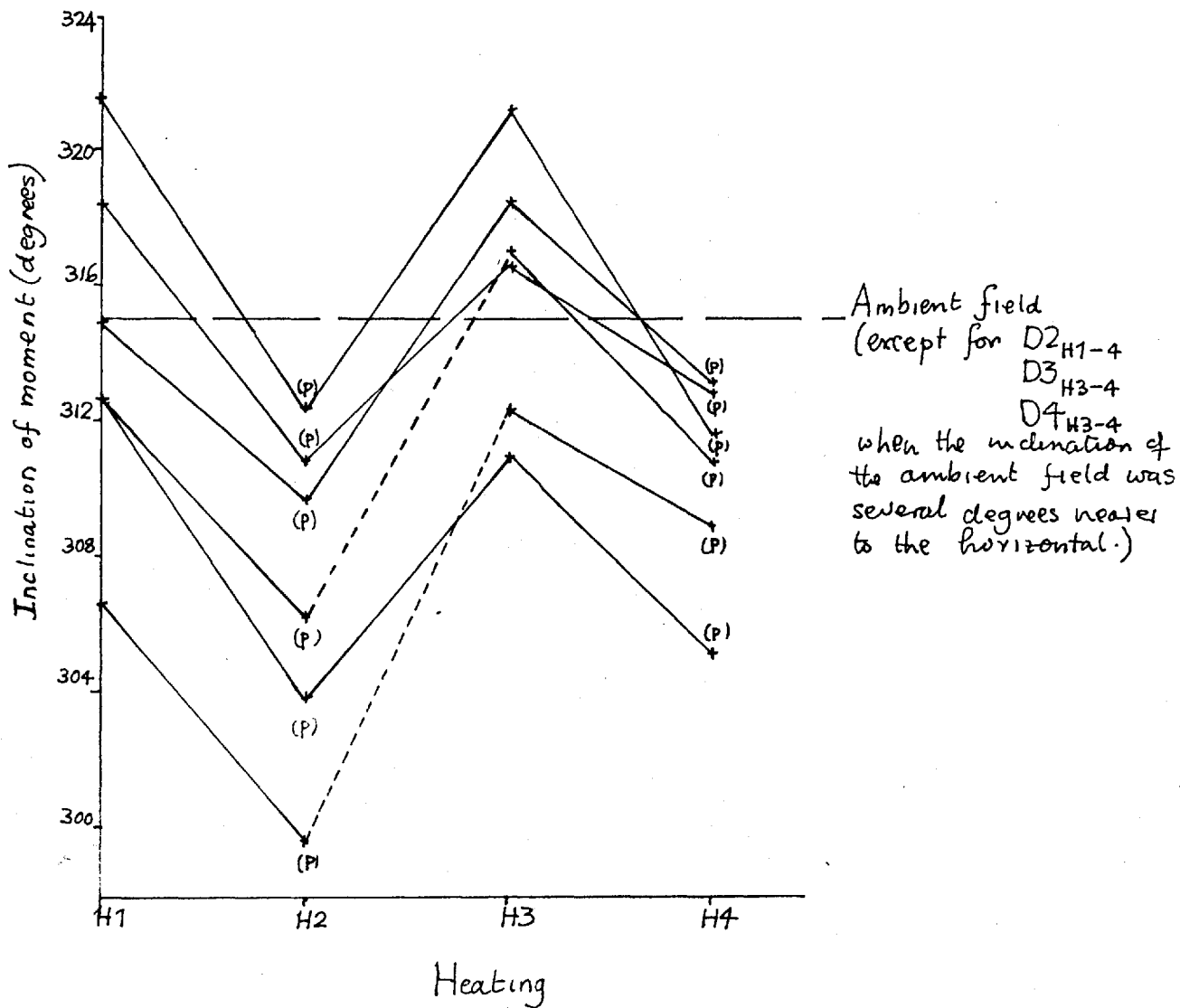


Figure 52

Deccan basalt type D

change of inclination of moment with uniaxial pressure
 $\theta = 45^\circ$, $p = 705 \text{ kg/cm}^2$

24 hr. interval before measurement

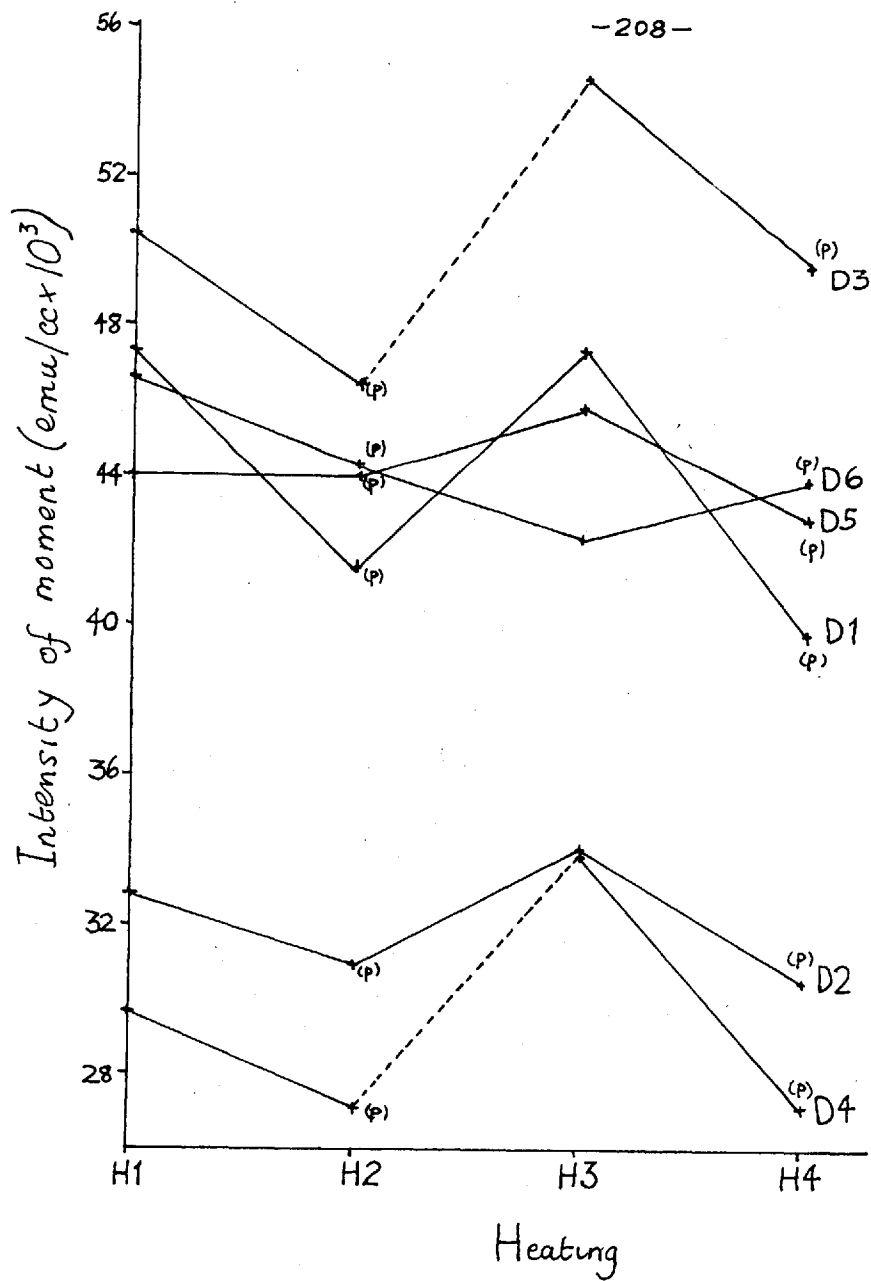
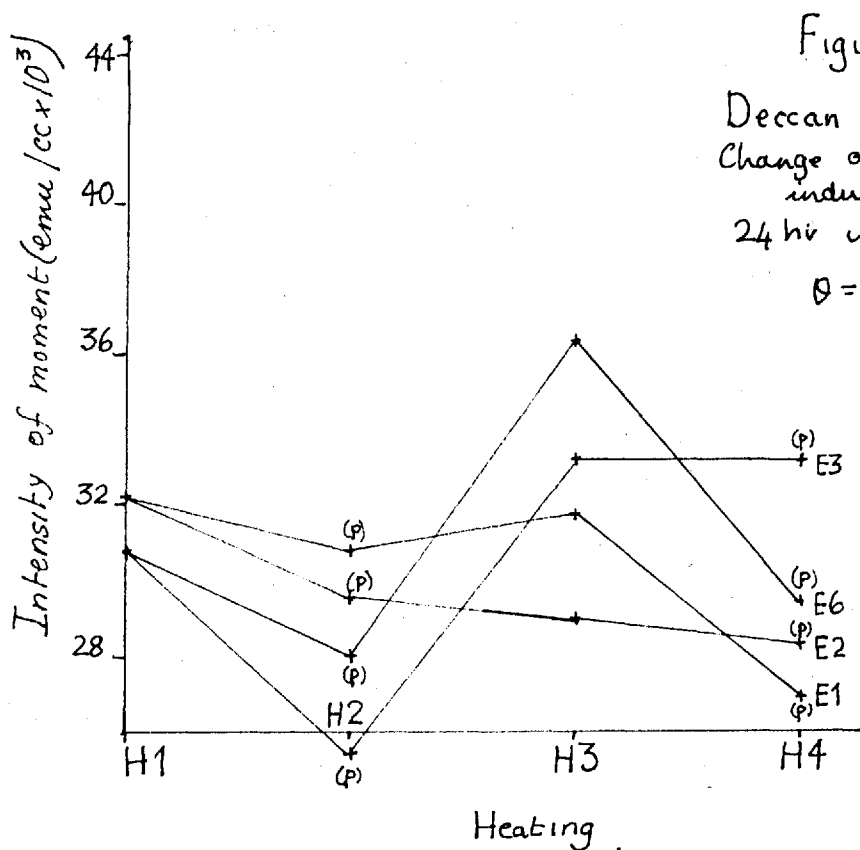
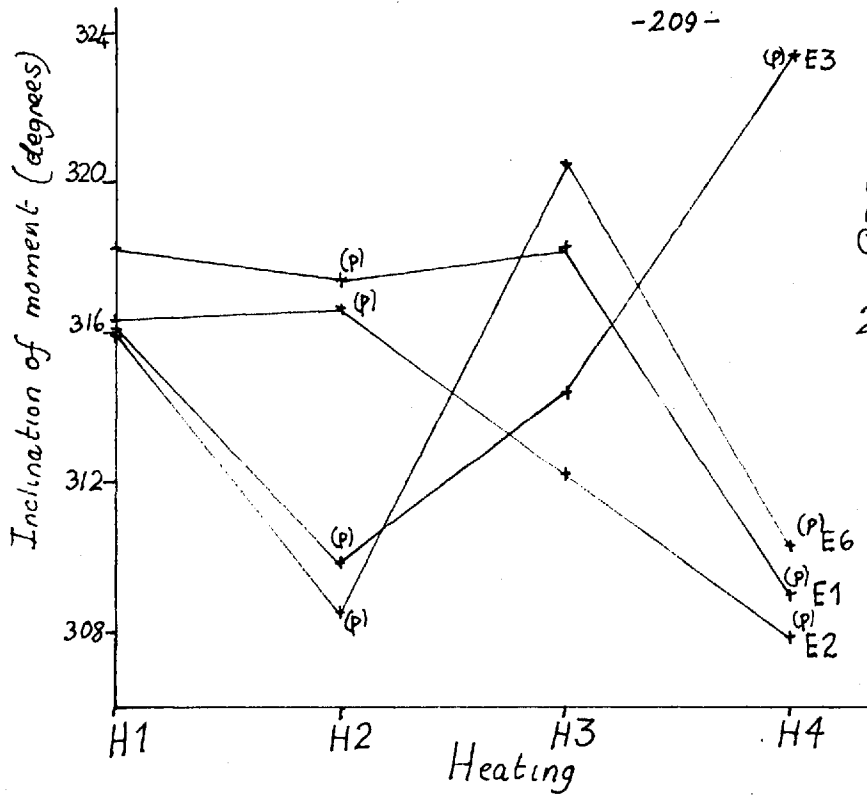


Figure 53

Deccan basalt type D
 Change of intensity of moment with
 uniaxial pressure
 $\theta = 45^\circ$, $p = 705 \text{ kg/cm}^2$
 24 hr interval before measurement.

Field change during pressure cycle for D2 and D3
 as described in Figure 52.



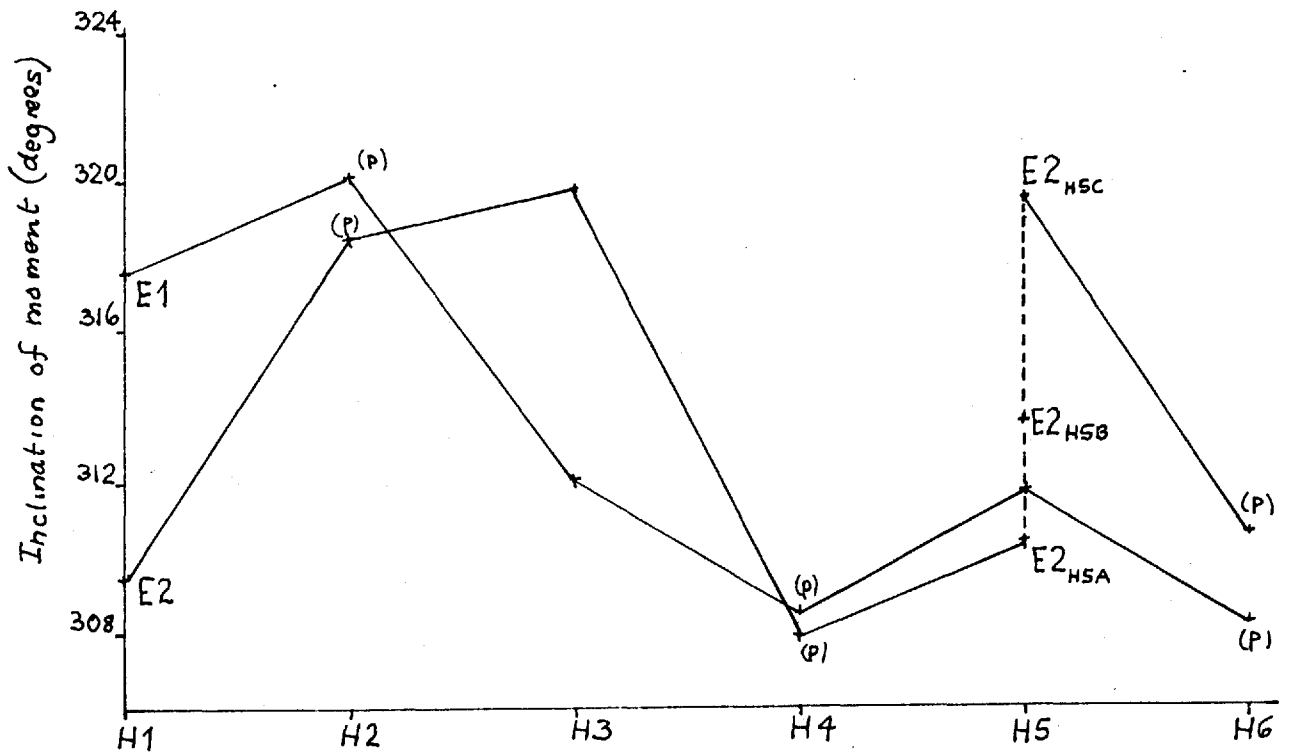


Figure 58

Deccan basalt types D and E

Change of inclination with pressure

$$\theta = 45^\circ$$

$$T_{max} = 400^\circ C$$

$$P_{E1} = 320 \text{ kg/cm}^2$$

$$P_{E2} = 705 \text{ kg/cm}^2$$

the large angular pressure effect there is a large intensity decrease in the pressure experiments, reaching a maximum of 10%.

Rock E behaves in an entirely different manner. There is only occasional correlation between pressure, angular rotation and moment. Some very large angular changes, of the order of 10° , do occur, with correspondingly large reductions in remanent moment. For rock type E reheating to above the Curie point does not remove the effect of a pressure experiment performed 24 hours previously. The behaviour of this rock is more complicated than that found for the pyrrhotite bearing rock.

These standard experiments were followed by a series of experiments where the specimens were measured directly on removal from the pressure vessel. This procedure was permissible since it was known that the angular pressure effect would be much greater than the drift in inclination found by Neale to occur in the first few hours after removal from the vessel. These experiments showed both the D and E type rocks to behave in the manner just described for the E rock. The results of these experiments are shown in Table 38. Where two heatings (a) and (b) are indicated a second heating with the same pressure conditions was performed before continuing to the next experiment of the normal sequence.

TABLE 38

Rock Types D and E

Pressure: 705 kg/cm² calculated.

Maximum temperatures: 175°C for D, 350°C for E

Field direction: 45° between field and pressure axis.

Intensity x 10³ emu/cc.

Specimens measured directly on removal from pressure vessel.

Speci- men	J ₁	H ₁ θ ₁	J ₂	H ₂ θ ₂	J ₃	H ₃ θ ₃	J ₄	H ₄ θ ₄
D1	44.2	311.03	40.6	305.38	44.0	311.80	45.0	313.25
D5	42.7	312.63	a42.8 b37.8	314.48 304.30	a38.3 b41.4	307.1 311.4	42.8	314.13
E1	36.2	321.33	27.7	308.03	36.6	320.80	28.8	308.20
E2	30.6	309.53	33.0	318.48	36.6	319.93	29.1	307.93

Figure 56

Deccan basalt
 $\theta = 45^\circ$, $P = 705 \text{ kg/cm}$

No interval before measu
 (the broken lines join successive
 heatings with the same pressure
 conditions).

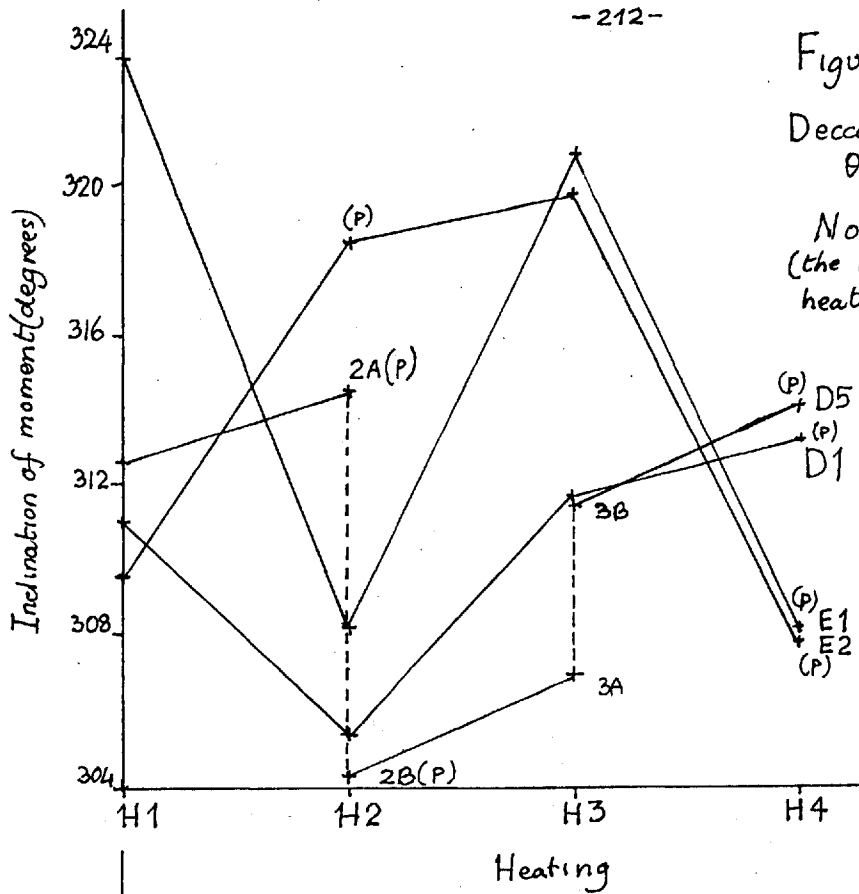
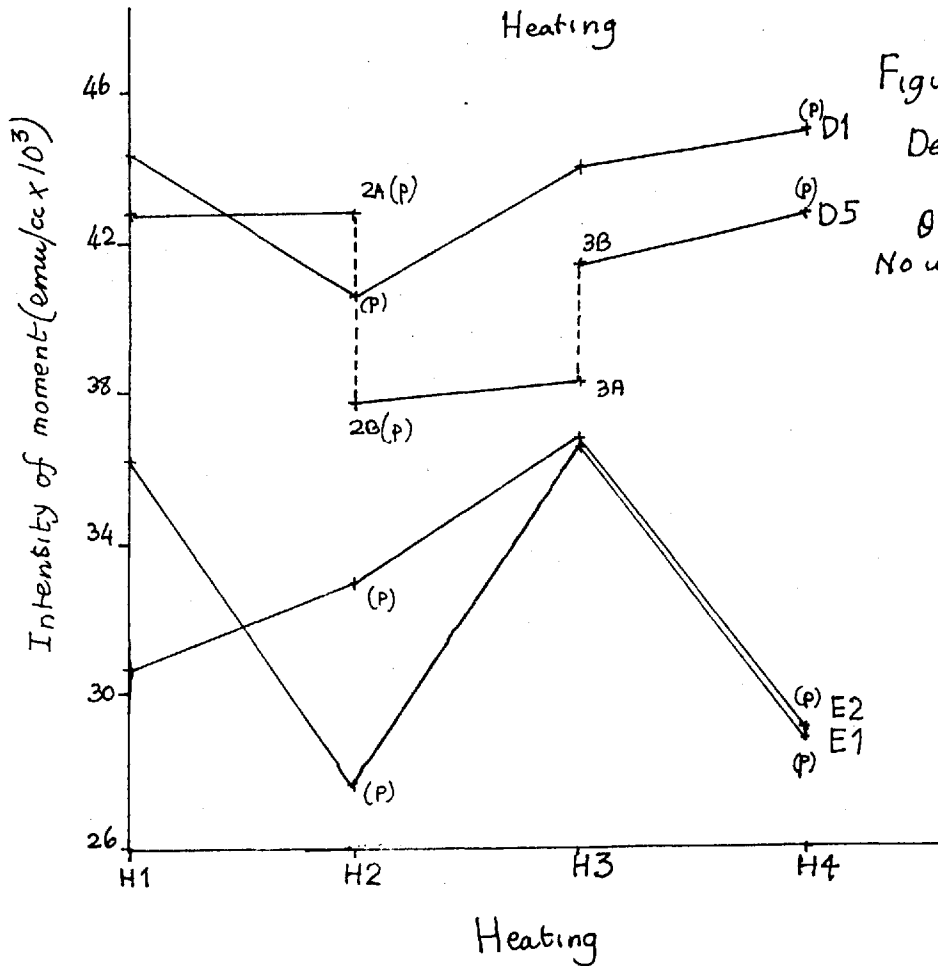


Figure 57

Deccan basalt types D and E

$\theta = 45^\circ$, $P = 705 \text{ kg/cm}^2$
 No interval before
 measuring



These results are shown graphically in Figs. 56 and 57. It is evident from these graphs that correlation between pressure and conventional angular change is rare. This shows that, for specimens measured directly after removal from the pressure vessel and immediately reheated, the effect of the previous pressure experiment is even more decisive than when a 24 hour interval was allowed to elapse between heatings. The graphs also show that when two heatings are performed successively under the same conditions (a) and (b) heatings for specimen D5, there is a tendency for the inclination and moment to move to the conventional pressure state for the particular pressure conditions. It seems certain that both rock types show a positive pressure effect and are highly pressure dependent.

An experiment was carried out on specimen E2 with the temperature raised to 500°C. At this temperature fair consistency was obtained, but, as mentioned before, a chemical change in the magnetic constituents would most certainly have occurred by the time this temperature had been achieved. The small angular pressure effect obtained at this temperature supports this suggestion.

TABLE 39

Rock Type E.

Pressure: 705 kg/cm² calculated

Maximum temperature: 500°C

Field direction: 45° between field and pressure axis

Intensities $\times 10^3$ emu/cc.

Specimen measured directly on removal from pressure vessel.

Speci-
men

	J_1	θ_1	J_2	θ_2	J_3	θ_3	J_4	θ_4
E2	43.3		42.5		44.5		43.6	
		317.98		316.90 (+1.08)		317.40		316.80 (+0.60)

Summary of Experimental Evidence

Both rock types D and E show a higher degree of pressure dependence than any other rock studied. Both have positive angular pressure effects and large decreases of remanent moment on magnetising under pressure.

The behaviour of these rocks is complicated by a time dependent effect which appears as an inability to remove the effect of a previous pressure experiment by reheating to the Curie point shortly after the experiment. This effect is more permanent for rock type E than type D. Type D behaves normally if a 24 hour interval is allowed to elapse between heatings but type E still retains the effect of a previous pressure experiment after this interval. Both rocks show this effect strongly but irregularly if measured and reheated directly after the finish of an experiment.

The large pressure effects found for these rocks cannot be easily reconciled with the estimated magnetostrictive properties of an ilmenite-magnetite solid solution. It may be assumed, in general, that the high magnetostrictive coefficient of pure magnetite would be reduced by the substitution of ilmenite in the molecule, and a smaller pressure effect than that observed for the Ob Lusa rock would be expected if magnetostriction was the determining factor.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

The findings of this investigation may be summarised as follows:

- i. The application of pressure to a rock acquiring a thermoremanent moment invariably caused the resulting moment to differ from that acquired without pressure. This change in moment is demonstrated in two ways; as a rotation of the moment and as a change in the intensity of the moment.
- ii. From a knowledge of the behaviour of the thermoremanent moment of a certain rock under conditions of uniaxial stress it is possible to derive a theory postulating the behaviour of this moment under conditions of shear stress. All the predictions of this theory have been confirmed experimentally. The theory was based on simple elastic theory and the knowledge that, for the rock in question, under conditions

of uniaxial stress the moment was altered in the following ways:

- (a) Compressive stress caused a rotation of the moment away from the stress axis, the variation of angular rotation with pressure being known quantitatively.
- (b) Compressive stress caused a reduction of the moment, the variation of this reduction with pressure being known quantitatively.

The theory predicted the following manifestations of the effect of shear stress on a rock acquiring a thermoremanent moment

- (a) The variation of angular rotation with the angle between the field and the plane containing the shear stress would have the form $\Delta\theta = k \cos 2\theta$, where $\Delta\theta$ is the pressure induced rotation of moment, k is the constant and θ the angle between the field and the plane containing the shear stress.
- (b) The magnitude of the angular rotation attainable would be limited by the ultimate tensile strength of the rocks employed. For the rock actually used, a dolerite, estimations of 0.3° maximum rotation for the coarse dyke centre and 1.0° for the fine

contact correlate with the experimental evidence.

A later calculation for the fine grained dyke contact using the intensity reduction experienced in an actual shear experiment agrees very closely with the observed maximum rotation of moment for this rock.

- (c) The intensity change would be zero for small angular changes of the order predicted at the position of maximum rotation of moment. At the positions of zero angular rotation the intensity change would be a maximum, either an increase or decrease occurring depending on the chosen position.

iii. The magnitude of both angular rotation of moment and intensity decrease of moment, acquired under conditions of uniaxial stress, depend on the grain size of the predominant magnetic component of a particular rock. The variation of angular rotation of moment with grain size has been studied in detail and it has been shown to have the form

$\log \Delta\theta = -C \log A$, where $\Delta\theta$ is the rotation of the moment, C is a constant and A the average area of the grains of the predominant magnetic component. For the magnetite/maghemite rock studied it was shown that for a grain size (diameter of

equivalent spherical grain) of 10μ the rotation was of the order of 10^0 , while for a grain size of 100μ it was only 1^0 , the pressure in both cases being 705 kg/cm^2 .

Measurements of other magnetic parameters during the grain size investigations support the findings of Roquet, that is, remanent moment increases and initial susceptibility decreases with decreasing grain size.

The correlation, found by Neale, between the order of the A.C. demagnetisation curves and the magnitude of the angular rotation of moment was not confirmed.

iv. The magnitude and sense of the angular rotation of moment and the intensity decrease of moment acquired under uniaxial stress are dependent on the composition of the magnetic constituents of a particular rock.

Experiments were carried out on four rocks which covered a wide range of ferromagnetic rock forming minerals. Mineral compositions were inferred from three independent sources of evidence, magnetic parameters (Curie point Q-ratio etc.), X-ray crystallography, and reflection microscopy.

Rocks containing the following minerals were studied:

Magnetite	)	One rock
Maghemite	)	

Titanohematite

Pyrrhotite

Magnetite-ilmenite solid
solution (two types of rock with
the solid solution members in
different ratios).

Every rock studied showed a pressure induced reduction of thermoremanent moment.

The rocks containing magnetite/maghemite, pyrrhotite and magnetite-ilmenite solid solution all showed a positive angular rotation of thermoremanent moment (away from the stress axis). The rock containing titanohematite showed a negative angular rotation of thermoremanent moment (towards the stress axis).

v. Certain rock forming ferromagnetic minerals show a time dependent pressure induced structural alteration. It was found for the pyrrhotite and magnetite-ilmenite solid solution bearing rocks that the effect of reheating a rock to the Curie point of its magnetic constituents did not necessarily remove the effect of a previous pressure experiment. This type of behaviour could be avoided with the magnetite-ilmenite solid solution rocks by allowing a critical time interval to elapse between experiments. This interval was less than 24 hours for one type of rock

and greater for the other type.

7.2 Discussion of Experimental Evidence

7.2.1 Theoretical Considerations

It is clear that the pressure effects described in 7.1 do not have a simple origin. This will be evident when the factors influencing pressure effects are enumerated. It has not been possible to synthesise one mechanism of pressure effect production and, in general, owing to a lack of measured properties, each factor can only be discussed qualitatively.

The Importance of the Mechanism of Thermoremanent Magnetisation

It has already been pointed out that the interpretation of the observed pressure effects cannot be certain until the mechanism of thermoremanent magnetisation is more fully understood. At present, Verhoogen suggests that a complex origin is the best explanation of all the properties of thermoremanent magnetisation in the relevant grain size range from

10 μ to 100 μ each moment consisting primarily of three parts:

- i. A soft part similar to an isothermal magnetisation and probably caused by domain wall movement and blocking.
- ii. An intermediate part due to the rapid decrease in the magnetocrystalline energy near the Curie point resulting in domain rotations, and
- iii. The hardest part residing in the strained regions surrounding dislocations.

No satisfactory quantitative theory of thermoremanent magnetism in this grain size range has yet been devised.

Factors Involved in the Production of Stress Effects

Stress behaviour of rocks acquiring a thermoremanent moment under pressure may be, or has been, shown to be dependent on

magnetostriction,
magnetocrystalline anisotropy,
magnitude and direction of stress,
means of application of stress
(uniaxial or shear),
time interval between successive
applications of stress,
grain size of the predominant
magnetic constituents,

composition of the magnetic constituents, and pair ordering.

The apparent relevance of each of these factors will be described in turn.

Magnetostriction

Magnetostriction alone can satisfactorily explain the pressure behaviour of the Ob Lusa dyke material if only one grain size is considered. The mechanism invoked assumes several factors:

the maghemite has a similar magnetostrictive behaviour to magnetite and the saturation magnetostriction of magnetite λ_s , decreases steadily to zero value at the Curie point of the magnetite. At any temperature a polar diagram can be drawn showing the two relevant components of the total energy of the system (Fig. 59). Fig. 59 is a polar energy diagram and is drawn for an aggregate of magnetite grains, with positive magnetostriction, and represents the magnetic field and magneto-elastic energy conditions in the temperature interval $T \sim (T - \Delta T)$.

The magnetic field energy function has a cardioid form (Fig. 59) which is expressed by

$$E_H = HJ_T (1 - \cos \theta)$$

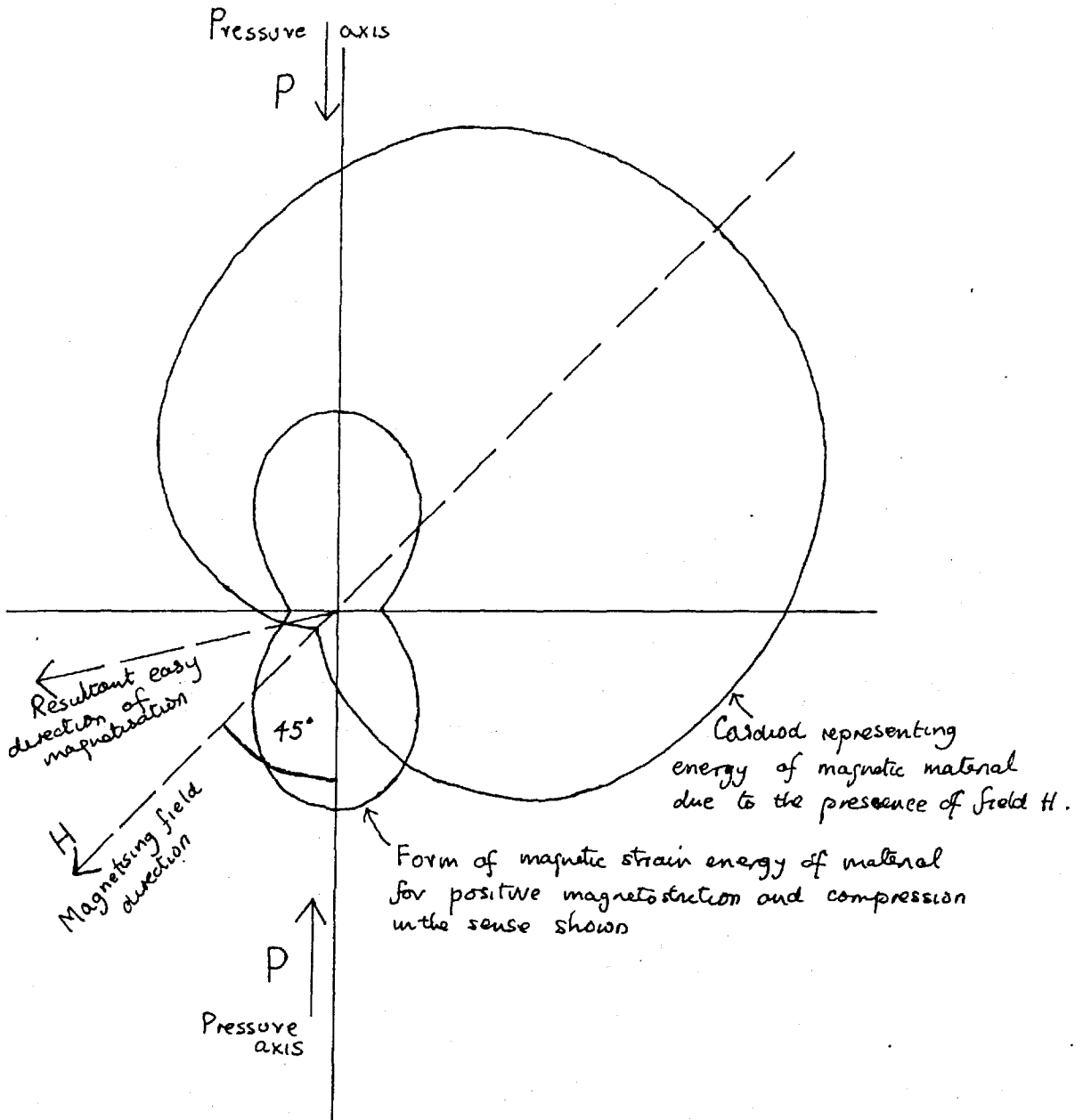


Figure 59 (not drawn to scale)

where H is the magnetising field, J_T the thermoremanance and θ the angle between J_T and H .

The magnetoelastic energy function, having the form shown in Fig. 59 is expressed by

$$E_{\sigma} = \frac{3}{2} \lambda_s \sigma \sin^2 \theta$$

where λ_s is the saturation magnetostriction, σ the compressive stress and θ the angle between the direction of compressive stress and the direction of magnetisation.

We have already assumed that both of these energy functions will expand regularly as the temperature decreases from the Curie point, where both must be zero.

Then, if the blocking temperatures of some of the grains of the assemblage fall between T and $(T - \Delta T)$, these grains will acquire a thermoremanance in the direction for which the total energy E_T has a minimum value where

$$E_T = E_H + E_{\sigma}$$

The polar energy diagram indicates that such a condition will be satisfied for an angle slightly further from the stress axis than this magnetising field direction.

Estimation of the total angular pressure effect would require a knowledge of the variation of J_T and λ_s and the distribution of blocking temperatures in the temperature interval from the Curie point of magnetite to room temperature, and

an integration of an expression involving these functions over the same temperature interval.

However, if the simple assumption mentioned above is valid the result of this integration would give a small rotation of moment in the sense found to occur experimentally (5.3).

This general approach can not be used to explain the grain size variation effect in magnetite containing rocks (5.3). It is known that J_T and the blocking temperature distribution for fine and coarse grained rocks differ. However, since the value of J_T for fine grains is higher than that for coarse grains direct application of the variation in J_T with grain size to a polar energy diagram would indicate a smaller angular change for a fine grained rock than for a coarse grained rock, which is in direct contradiction with the experimental evidence. The explanation of this apparent paradox may lie in two criteria:

- i. The observed angular rotation represents only the irreversible part of a larger effect, the fine grained rock showing a greater degree of irreversibility than the coarse grained rock.
- ii. It may not be valid to consider a specimen as a cube of weakly magnetic material showing complete isotropy.

It seems clear that the pressure effect does not reside in only part of the moment (as might have been suggested from a consideration of Verhoogen's division of thermoremanent moments into three parts). A.C. demagnetisation of up to 160 oe. causes no change in the direction of the moment acquired under pressure. That magnetostriction may not be the dominant factor in the production of a pressure effect is demonstrated by the results of the experiment on the pyrrhotite bearing rock. This rock gave a positive deflection although pyrrhotite is reported as having -ve magnetostriction.

The behaviour of the Deccan basalts is difficult to reconcile with the idea of magnetostriction as the primary cause of pressure effects. These rocks, containing ilmenite-magnetite solid solutions, would be expected to show smaller pressure effects than the magnetite bearing Ob Lusa dyke material, if magnetostriction is a decisive factor. This is suggested as the solution of ilmenite in magnetite would be expected to reduce the high positive magnetostriction of the latter mineral. This case may also be reconciled by assuming the effect to be the irreversible part of a larger effect.

Magnetocrystalline Anisotropy

It seems likely that, for one crystal of cubic symmetry,

~~that~~ distortion of the lattice by stress would cause a distortion of the normally symmetrical magnetocrystalline energy function, reducing the energy level at some easy directions and increasing it at others. The net effect of this on a specimen consisting of randomly oriented crystals disseminated in a non-magnetic matrix would appear to be zero. This supposition depends on the assumption that the pressure on individual grains is always in the same sense as the pressure applied externally to the specimen. Owing to the inhomogeneity of a crystalline matrix this condition may not exist, or even average out to cause the net effect on the moment to be zero.

Magnitude and direction of stress to the magnetising field

The linear variation of angular pressure effect with pressure demonstrated by Neale, may be explained as being an increase in a magnetostrictive or magnetocrystalline effect with increasing pressure.

The variation of effect with the angle between the stress axis and magnetising field may be interpreted as each direction of magnetising field giving a different view of the same pressure effect in the specimen.

Means of Application of Stress (uniaxial or shear)

The difference in the pressure effects for these two methods of stress application has been shown to lie entirely in the geometry of the stress application. The successful development of a theory linking the effects of the two means of applying stress depended on the assumption that tensile stress would have an equal but opposite effect to compressive stress.

Time Interval Between Successive Stress Applications

The behaviour noted for the Deccan basalts, where part of the effect of a pressure experiment was not removed on directly reheating the specimen to the Curie point of its magnetic constituents, appears to be independent of the mechanism of pressure effect production, which manifests itself separately. The isothermal effect of decrease in permeability with time recognised by Webb and Ford⁽²⁶⁾ does not appear to be relevant to these conditions. It has been suggested by Berthier (Ref. 31) that an elastic after effect is operative, possibly resulting in a redistribution of structural features or impurities after a definite time interval.

Grain size

This is a critical factor in deciding the magnitude of stress effect for a certain mineral composition. The mechanism of grain size control has been discussed under the heading of "Magnetostriction".

Composition

Composition is a critical factor in deciding both the magnitude and sense of angular pressure effects while it appears to control the magnitude only of the change in moment, found to occur for all the mineral studied.

Unfortunately, the magnetostrictive properties of the minerals studied are not known in enough detail to allow the comparison of pressure effects and magnetostriction coefficients.

If it is supposed that the different magnetostrictive properties of different minerals has resulted in the pressure effects observed, then it is difficult to explain the pressure effect found for the Central Region of the Heast Road Sill. The sense of the rotation of moment for this rock is such that a negative magnetostriction coefficient might be suggested for its ilmenite-hematite solid solution magnetic

constituent. However, if this is the case it is difficult to explain the decrease in moment acquired under pressure observed for this rock.

A similar difficulty is seen in the case of pyrrhotite, reported to have a negative magnetostrictive coefficient at room temperature, which shows a rotation of moment in the same sense as the magnetite/maghemite Ob Lusa dolerite, magnetite having positive magnetostriction at room temperature. Little more can be said without a knowledge of the variation of magnetostriction with temperature but it seems likely from the evidence of the Heast Road Sill Central region that pressure effects are not always caused primarily by the action of magnetostriction.

It is clear that two investigations would aid the correlation of the observed pressure effects with the intrinsic properties of the magnetic constituents of the rocks studied.

1. Determination of the magnetostrictive coefficients of the minerals in the rocks studied over a range of temperatures from room temperature to the Curie point of the minerals.
2. Measurement of pressure effect while the specimen is still being subjected to pressure.

Pair Ordering

It has been suggested by Néel (Ref. 30) that the ionic diffusion process known as pair-ordering may be operative in the experimental conditions used in this investigation.

In ordered alloys, and presumably ordered solid solution ferrites, a reduction in the degree of ordering may be caused by moderate temperatures (up to 600°C) and directed pressures (up to 500 kg/cm²). This is a purely elastic effect distinct from magnetostriction. Néel has found that reductions in the saturation magnetisation of about 10% may result from this mechanism and it is possible that this mechanism may explain the reduction of moment observed for the ilmenite-hematite solid solution rock and the large positive pressure effect observed for the ilmenite-magnetite solid solution rock. A combination of magnetostriction and this mechanism might be considered the basic cause of pressure effects.

Additionally, the difficulty of reconciling the positive pressure effect obtained for the pyrrhotite rock with the reported negative magnetostriction of pyrrhotite may be overcome by invoking this latter mechanism. In this instance, the ordering of the lattice defects responsible for the ferromagnetism of pyrrhotite would be reduced, so

reducing the moment in the direction of the pressure.

Comparison of thermal and cyclic isothermal pressure experiments

Several specimens (07, 012) which had been already examined for the effect of uniaxial stress on their acquisition of thermoremanent moments were tested in a cyclic isothermal pressure apparatus by Mussett. The specimens were subjected to the following treatment:

- i. Saturation followed by A.C. demagnetisation in steps to a maximum field of 200 oe.
- ii. Resaturation and cyclic compression in a field free space (10 one minute cycles with the pressure at 350 kg/cm^2)
- iii. A.C. demagnetisation as described in i.

The A.C. demagnetisation curves before and after cyclic compression (Fig. 60) were compared, and, in contrast with the results of the thermal experiments, showed the coarse grained specimen 012 to have the largest pressure effect (a 41% demagnetisation compared with only 16% for the fine grained specimen, 07).

It was concluded from these experiments that a different mechanism was operative in each of the means of pressure application. Reconciliation of the differences

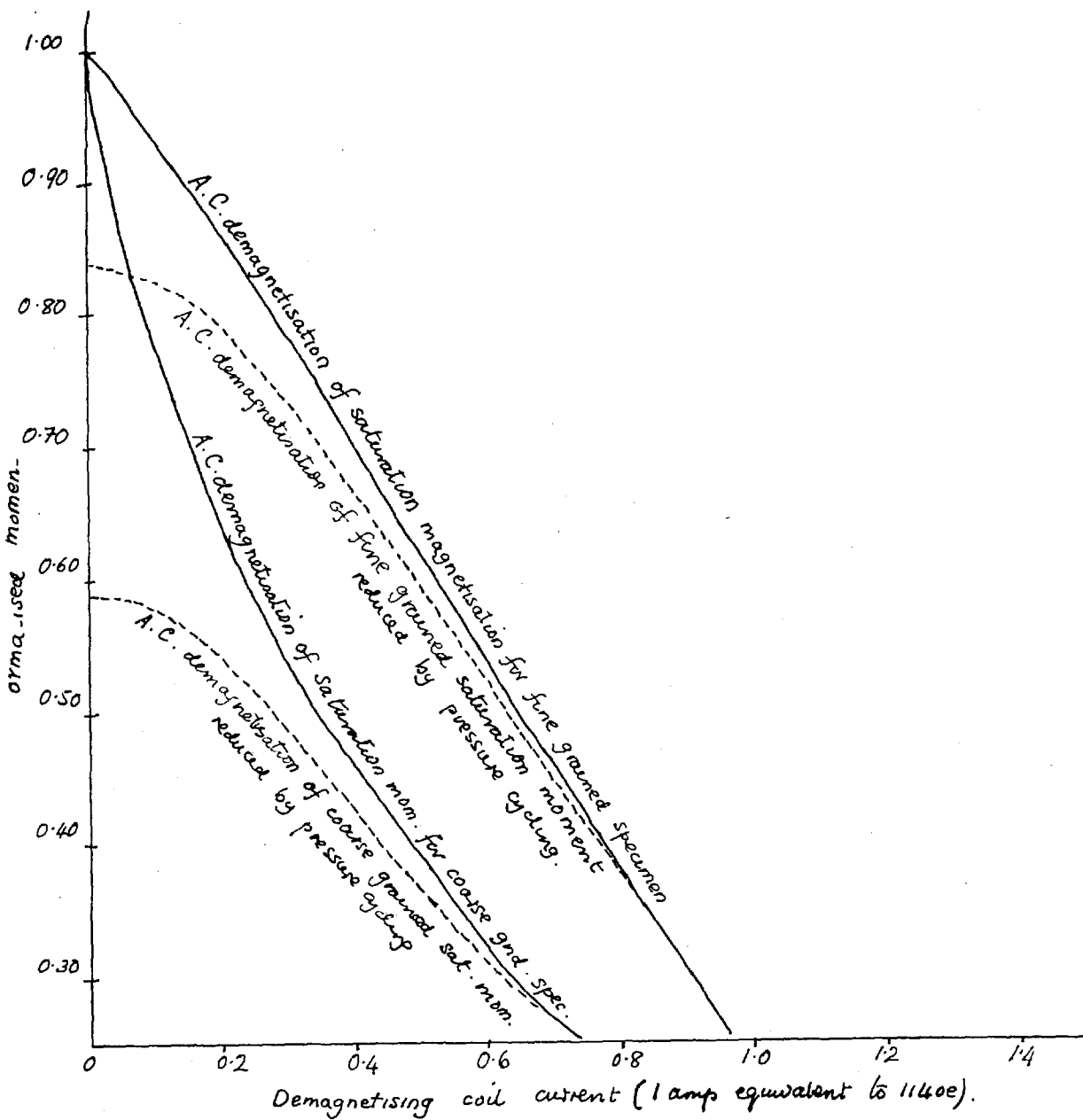


Figure 60

Results of Isothermal Cyclic Compression Experiment

in behaviour of the fine and coarse specimens under cyclic isothermal and thermal conditions is only possible if the thermal effect is considered as the irreversible part of a larger effect.

7.2.2 Palaeomagnetic significance of the observed pressure effects

If it is assumed that the pressure effects obtained in the laboratory are similar in magnitude to those produced naturally then it is clear that the majority of the values obtained experimentally would have little significance in palaeomagnetic interpretations. The precision of such investigations is usually low compared with the precision of the present work. Collection and cutting errors often amounting to 5° before measurement is attempted, this being of the order of twice the angular rotations observed for the commonplace Ob Lusa dyke centre and Heast Road Sill Centre.

The larger 8° deflection obtained for the finest Ob Lusa dyke contact specimen might be detected if especially searched for but would almost certainly be considered as random error in routine palaeomagnetic measurements.

The even larger rotations obtained for the Deccan basalts may be of some importance, but it would be unwise for any palaeomagnetic significance to be given to directions of moments from rocks with Curie points low enough for the sun's heat to impart a partial thermoremanence.

It seems probable that pressure effects such as those observed in the laboratory could occur in natural conditions. The standard pressure of 705 kg/cm^2 calculated (corrected for friction) used in the uniaxial pressure vessel is equivalent to about 10,000 ft. of average crustal rocks. In areas of volcanic activity the intrusion of sills and dykes at such depths is likely and chilled contact regions formed at the margins of these igneous bodies would show pressure induced rotations of moment of the order produced in the laboratory. Intrusions at ~~greater~~ depths would be subjected to higher pressures during the acquisition of a magnetic moment, but, the slower cooling to be expected at great depths in the crust would preclude the formation of very fine contact regions ~~at~~ the margins of igneous bodies.

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