DESIGN AND CALIBRATION OF APPARATUS FOR THE ALTERNATING FIELD DEMAGNETIZATION OF ROCKS.

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FOR THE ALTERNATING FIELD
DEMAGNETIZATION OF ROCKS

By

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TABLE OF CONTENTS

		Page No.
ABSTRACT		
LIST OF TABLES		(i)
CONTENTS		1 - 103
CHAPTER 1	Introduction	
1.1	Introduction to Palaeomagnetism	1
1.2	Types of Remanent Magnetization	6
1.3	Summary of Thermal Demagnetization	10
1.4	Steady-and Alternating-Field Demagnetization Techniques	13
CHAPTER 2	Description of Apparatus	
2.1	Introduction	19
2.2	The Demagnetizing Coils	19
2.3	Coil System for Steady-Field Compensation	25
2.4	Mechanism for Alternating-Field Reduction	28
2.5	The Spinner System	32
2.6	Procedure for Demagnetization	43
CHAPTER 3	APPARATUS TESTS	
3.1	Introduction	45

Page No.

CHAPTER 3 (Contd.)

3.2 Preparation of Samples 46

3.3 Single-Component Demagnetization Tests 48

3.4 Two-Component Demagnetization Tests 52

3.5 Spurious-Component Tests 56

3.6 Conclusion 73

CHAPTER 4 DIRECT-FIELD DEMAGNETIZATION WITH SPECIMEN ROTATION ABOUT THREE AXES.

4.1 Introduction 76

4.2 Single-and Double-Component Demagnetizations 80

4.3 Spurious-Component Tests 81

CHAPTER 5 SOME APPLICATIONS TO PALAEOMAGNETIC STUDIES

5.1 Introduction 86

5.2 Basalt Flows from South Coast of Labrador 86

5.3 Killary Harbour Ignimbrites 94

5.4 Virgin Rock Samples 97

CHAPTER 6 SUMMARY AND CONCLUSIONS

6.1 Summary 100

6.2 Suggestions for Further Work 102

REFERENCES 105 - 106

ABSTRACT

Apparatus for demagnetization of rocks in alternating fields up to 800 oe. (peak) has been designed, constructed and calibrated. The unit was tested in detail for effectiveness in removing "unstable" magnetization components, and to confirm the absence of all preferentially directed field components that might cause the specimens to acquire an anhysteretic magnetization. Synthetic materials consisting of one-and two-component powders of magnetite, hematite and pyrrhotite set in a plaster of Paris matrix, as well as natural, basalt, were used in these tests.

The system was shown to be especially sensitive to direct fields acting parallel to the main (N-S) rotation axis, which is perpendicular to the axis of the demagnetization coils. Spinning of the specimen about three orthogonal axes simultaneously proved superior to a two-axis spin, though alternating field demagnetization even in the highest fields of which the unit is capable, was satisfactory with two-axis spin, provided the direct field in the specimen region was insignificant.

A number of specimens from rock formations in Newfoundland and Ireland were demagnetized in alternating fields, to test their suitability for palaeomagnetic studies.

Preliminary attempts to use direct current in the demagnetizing coils showed this method to be feasible, but it requires further tests and some modification to the apparatus before it can be used to advantage.

Fig. No.		Page No.
1.1	Field Tests of Magnetic Stability Proposed by J. W. Graham (1949)	107
1.2	Hysteresis Cycle of Single-Domain Particles	108
1.3	Thermoremanent Magnetization (TRM) Acquired on Cooling from Curie Temperature to any Temperature T in a field H and from T to Ambient Temperature in Zero Field	109
1.4	Dependence of IRM and TRM on Applied Field, H, for Dispersed Magnetite	109
1.5	Steady-Field Demagnetization of the Fossil Remanence of a Sample of Varved Clay from Vermont, U.S.A.	110
1.6	Alternating-Field Demagnetization Curves for Various Types of Magnetizations of Chemically Produced Fe_3O_4	110
2.1	Dimensions of the Demagnetizing Coils	111
2.2	Electrical Circuit for the Demagnetizing Coils	111
2.3	Overall View of the Demagnetizing Unit	112
2.4	Side View of the Apparatus, showing Positioning of the Spinner System	113
2.5	Power Supply to the D.C. Coils	114
2.6	Electrolytic Resistance used to Decrease the Magnetizing Field	115
2.7	View of Spinner System with Turbine Wheel and Support	116
2.8	Closeup View of the Spinner System	117
2.9	Histogram of the Relative Efficiency of Various Speed Ratios in 2-Axis Spinner Units	118

Fig. No.		Page No.
3.1	Remanent Intensity vs. Peak Demagnetizing Field for Single-Component Synthetic Specimens	119
3.2	Remanent Intensity After Alternating-Field Demagnetization of "Mixed" Synthetic Specimens	120
3.3	Variation of Direction of Remanence of "Mixed" Specimen 1, after Alternating-Field Demagnetization in Progressively Higher Fields. Polar Equal Area Net.	121
3.4	Variation of Direction of Remanence of "Mixed" Specimen 2, after Alternating-Field Demagnetization in Progressively Higher Fields	122
3.5	Variation of Direction of Remanence of "Mixed" Speciment 3, after Alternating-Field Demagnetization in Progressively Higher Fields	123
3.6	Specimen Orientations Relative to the Holder Axes, for Spurious-Magnetization Tests	124
3.7	Components of Spurious Remanent Magnetization in Terms of Holder Co-ordinates for Magnetite Specimen, after Demagnetization at 675 oe. Peak Fields, in 8 Successive Positions	125
3.8	Components of Spurious Remanent Magnetization in Terms of Co-ordinates, for Basalt Specimen HH21A4, after Demagnetization at 675 oe. Peak Field in 8 Successive Positions	126
3.9	Non-Random Effect of a Direct Field in the N-S Direction in a Demagnetization about 2 Orthogonal Spin Axes	127
4.1	Remanent Intensity After Steady-Field Demagnetization of Synthetic Specimens	128

Fig. No.		Page No.
4.2	Remanent Intensity After Steady-Field Demagnetization of "Mixed" Synthetic Specimens	129
4.3	Variation of Direction of Remanance of "Mixed" Specimen 1, after Successive Steady-Field Demagnetizations	130
4.4	Variation of Direction of Remanence of "Mixed Specimen 2, after Successive Steady-Field Demagnetizations	131
5.1	Mean Directions of Magnetization of Basalt Flows from Labrador	132
5.2	Variation of Intensity of Magnetization with the Demagnetizing Field for Certain Selected Basalt Specimens from Henley Harbour and Table Head, Labrador	133
5.3	Variation of I/I_0 with the Demagnetizing Field for Certain Ignimbrite Specimens from Killary Harbour, Mayo County, Ireland	134

CHAPTER 1

INTRODUCTION

1. 1 Introduction to Palaeomagnetism

Palaeomagnetism, the study of the history of the earth's magnetic field, has found increasingly wide application in geology and geophysics. The geological subject, stratigraphy, which is specifically concerned with the arrangement of stratified rocks, has been furthered by the use of palaeomagnetic results, which may give clues to the original arrangement of complex geological structures, where it is difficult to apply traditional geological methods. Palaeomagnetism may provide important tests for such geological and geophysical hypotheses as continental drift and polar wandering, or in distinguishing between these mechanisms. Reversed magnetization, which has been discovered in many rock formations, is interpreted by most authors as being most frequently due to reversal of the polarity of the geomagnetic field, though in some cases it has been shown that the reversals resulted from physical and chemical change in the rocks themselves. The discovery of reversals, in turn, has contributed to the knowledge of the nature and history of the geomagnetic field, and, on the other hand, stimulated further studies of magnetization processes in rocks, a subject belonging to the field of solid state physics.

Palaeomagnetic information is obtained from rocks possessing ferromagnetic properties due to certain minerals in their constitution. The most important of these magnetic minerals include:

magnetite ($Fe_3 0_4$), hematite (α-$Fe_2 0_3$), maghemite (γ-$Fe_2 0_3$), ilmenite ($FeTi0_3$), the solid solution series, titanomagnetite ($Fe_3 0_4$ - $Fe_2 Ti0_4$ series), and hematite-ilmenite (α- $Fe_2 0_3$-$FeTi0_3$ series), and the variable-composition iron sulphide, pyrrhotite (FeS_{1+x}). The essential property for palaeomagnetic application is that the rocks are capable of retaining, and have retained, some remanent magnetization acquired in the geological past. Thus it is required to establish some relationship between the direction of this magnetization and that of the earth's field at the time the rocks were laid down. It has indeed been found that the magnetization direction for different specimens in the same locality often deviate significantly from the present field direction for the earth and, most important, they are often consistent in direction over a wide area and are not easily destroyed, except by the application of large adverse magnetic fields or by heating to high temperatures. To obtain useful evidence on the ancient field direction, it is not only necessary that the age of the rocks be known (by fossil, radiometric or other method of dating), but also the "stability" of the remanence must be determined.

The question of the "stability" of the remanence is meant in the sense of whether the magnetic components in the rocks have preserved the earth's field direction prevailing at the time of their origin. The physical meaning of the concept "stability of magnetization" can be more clearly shown by describing some of the methods of testing for it. If, in the same locality, dissimilar rocks of approximately the same age have a consistent direction of magnetization differing from that of the present field, then the magnetization is probably stable and, in that case, it is permissible to draw palaeomagnetic conclusions from the data.

Rocks commonly are deformed by such processes as folding and faulting, often after a geologically long time has elapsed since they were laid down. A "field test" of stability consists of "re-orienting" the rocks in their presumed ancient attitudes and comparing the directions of magnetization of the remanence vectors with the direction actually found in the deformed rocks. If the "re-orientation" of the strata produces a closer alignment of vectors than is presently the case, the rocks may very likely be stable in the sense that their magnetization reflects the direction of the earth's field before geological deformation took place. A similar test relates the magnetic orientations of the pebbles comprising a conglomerate. These tests are due to Graham (1949) and are illustrated in fig. 1.1 They are discussed by various authors including Cox and Doell (1960) and Irving (1964).

Stability of remanence depends on many factors. Thus the number and kind of ferromagnetic constituents and the particle size distribution determine the coercivities of the magnetization components and, hence, the stability. There is also a strong dependence upon the magnetization process involved, a factor which will be discussed more fully in Section 1.2 below.

Essentially, then, one is concerned with a coercivity spectrum, with the contributions in the low-coercivity range constituting "soft" or "unstable" magnetization components, some with time-constants as low as a few days or hours (see VRM, below). Unstable components are often added long after the rock was laid down, by metamorphism or chemical action, though this can also result in "hard" components being added (e.g. CRM, see below), and a difficulty in stability testing lies in recognizing a "hard" component that is "unstable" in the sense that it was acquired a significant time after the rock was formed.

A better understanding of these aspects of stability can be achieved if something is known concerning the magnetization processes in rocks. There are two complementary theories available for the explanation of rock magnetism: the single domain theory of Néel (1955) and the multidomain theory of Stacey (1961). However, the single-domain theory is the most frequently used and most highly developed as it adequately explains the ferromagnetic behavior of rocks, as long as the grains are not much greater in size than 1-2 microns. A good summary of this theory and of many other aspects of palaeomagnetism will be found in Nagata (1961). According to Néel, each grain of magnetic material in a rock consists of a single, fine spheroidal magnetic domain with uniaxial symmetry. Thus, in the absence of a magnetic field, the moment of a single grain will take either of two antiparallel orientations which are separated by a potential barrier, E. The magnetization present in each grain is the spontaneous magnetization, J_s, which for any grain depends only on temperature and vanishes at the Curie temperature, T_c, above which the grain has only paramagnetic properties. In a rock possessing no remanence, J_r, the orientations of the individual grain symmetry axes are such that their contributions to J_r cancel each other, and application of a field leads to the usual magnetization curve and hysteresis loop as shown in fig. 1.2. Fig. 1.2 also shows the two extreme cases, in which all domains are parallel and perpendicular, respectively, to the applied field. The coercivity, H_c, as has been said above, depends on the size and shape of the grains and their spontaneous magnetizations. The higher the value of H_c, the more stable or "harder" the remanence will tend to be. In typical rocks a "hard" component will have a coercivity of several tens to several hundred oersteds, as in some titanomagnetite-bearing basalts and hematite-bearing red sandstone, though in the latter case, coercivities exceeding several thousand oe. are sometimes encountered. Thus coercivities two or three orders of magnitude greater than the value of the geomagnetic field (0.5 oe.) are quite common.

Most rocks contain a random selection of grains of various coercivities, and so a given field may have much greater effect upon the directions of magnetization in some of the grains than in others. Thus natural phenomena, such as lightning, can change the magnitude and direction of natural remanent magnetization (NRM) of the rocks by adding a relatively stable secondary component that is not usually in the direction of the primary stable component. While some of the domains in the primary component may be relatively unaffected by this process, it can be masked by the secondary component if the magnitude of the latter is of the same order or greater. These secondary components can frequently be removed by a demagnetization process without affecting the primary component. A more difficult secondary component to remove is CRM (see below), where the physical and chemical composition of the rock may be changed. This component may be of the same order of "hardness" as a primary component, say, of thermoremanent origin.

Some of the more important processes by which rocks may acquire a remanent magnetization are described below:

1.2 Types of Remanent Magnetization

(a) Thermoremanent Magnetization (TRM) is the most useful form for palaeomagnetic research. TRM is acquired when the rock cools from above the highest Curie point, T_c, among its ferromagnetic constituents, to temperature T_o in a field H. The resulting thermoremanence at T_o can exist in the absence of the field H.

The probability that the direction of magnetization of a single grain will reverse due to thermal agitation in the absence of an external field is determined by the "relaxation time" which is in turn a function of the coercivity and temperature. Because of large thermal agitation just below the Curie point, TRM is then small, but it reaches saturation value at $0^{o}K$ and may approach closely to saturation at atmospheric temperature (see fig. 1.3). Hence in a cooling lava the magnetization is quickly aligned with the earth's field just below the Curie point and it becomes "fixed" as the temperature falls lower. Figs. 1. 3 and 1. 4 show the idealized curves for the cumulative acquisition of TRM with ~~the~~ respect to temperature and external field, respectively. Magnetic fields of the order of the coercivity of the rocks are required to demagnetize the specimen at atmospheric temperature, and since lavas after cooling commonly have components with coercivities of the order of 10^2-10^3 oe., TRM tends to be a "hard" magnetization. Its usefulness for palaeomagnetic application depends largely upon the fact that TRM is generally acquired when the rocks originally cooled and that they are not often significantly reheated.

(b) Partial Thermoremanence (PTRM) is acquired, if, during cooling, the field is applied only between the temperature interval T_i to T_{i-1}, where $T_{i-1} < T_i < T_c$, and i=0,1,...n designates the number of temperature intervals. An addition law (Nagata, 1961) exists for PTRM's. Thus:

$$(T_o,h,T_c) = (T_o,h,T_1) + (T_1,h,T_2) + \ldots + (T_n,h,T_c) \ldots \quad (1.1)$$

where (T_o,h,T_c) is the total TRM at T_o and $T_o < T_1 < T_2$ .... $< T_n < T_c$. h is the field present during cooling. Also it has been established that, for a particular temperature range, the PTRM picked up is independent of the previous magnetic history. Thus a rock reheated to 200^oC subsequent to its formation (if $T_c = 600^oC$) will retain much more of the original TRM than one reheated to 500^oC, as most of the remanence is acquired within 100^o - 200^oC below the Curie point, (see fig. 1.3). Since reheating to, say 500^oC is usually unlikely after the original cycle of volcanic activity has subsided, we find that igneous rocks which have not been unduly metamorphosed tend to be stably magnetized.

(c) Isothermal Remanent Magnetization (IRM) is a process whose occurrence in nature is exemplified by the subjection of rocks to a sudden stronge magnetic field, say due to lightning, or, alternatively, by the simple magnetization at atmospheric temperature in the existing earth's field. Thus the process is one in which domains with coercivities equal to or less than the applied field tend to align their magnetic moments with the field. The curves of fig.1.4 show the acquisition of IRM and TRM in a typical mineral for different values of the applied field. Thus, to obtain a magnetization of equivalent hardness to a TRM component, the IRM would have to be acquired in a field greatly in excess of the earth's field. Hence IRM is unlikely to have large coercivity (except when produced by lightning) and will often produce "soft" components.

(d) Related to IRM is another important natural magnetization process called Viscous Remanent Magnetization (VRM). All ferromagnetic substances change their remanence gradually with time. Magnetic viscosity affects the NRM of rocks in two ways: (i) they acquire a VRM and (ii) the remanence already present decays with time. Although this VRM will be weak and soft if acquired in a short time, it can be quite hard if acquired over a geologically long period of time and may then form a considerable proportion of the NRM of the rock.

(e) Chemical Remanent Magnetization (CRM) is normally associated with sedimentary rocks and involves chemical changes in the rocks occurring after they have been deposited or consolidated. A remanent magnetization can be acquired by a magnetic material while it is undergoing a chemical change, such as reduction of hematite to magnetite, at constant temperature in a weak field. The stability of CRM tends to be as high as that of TRM. The chemical changes involved in CRM are in turn associated with physical effects due to changes in the size of the magnetic grains or in their spontaneous magnetization.

(f) Depositional Remanent Magnetization (DRM) occurs in sediments including such rocks as red sandstones which have proved to be important in palaeomagnetism. Previously magnetized magnetic grains are deposited (usually in water) with a preferential alignment of their magnetizations in the direction of the prevailing field, and they maintain this alignment after the consolidation of the rock. The magnetic hardness of DRM depends largely on that of the deposited grains.

1.3 Summary of Thermal Demagnetization Techniques

As has been mentioned previously, the NRM of a ferromagnetic rock usually consists of several components with magnetizations that differ in intensity, direction, and degree of hardness. There are two commonly used methods which can distinguish between these various components, both of which separate the components according to hardness by selectively destroying the softer components while leaving the harder components essentially intact. These methods are "thermal demagnetization" and "alternating - field demagnetization". (The latter method is commonly called "AC demagnetization"). The thermal technique, which was originated by Thellier (1938), will be discussed now and the alternating-field technique later.

The basic principle of thermal demagnetization is the addition law of PTRM's. Thus if the rock sample is heated above the highest temperature of the range in which the PTRM was obtained, and then allowed to cool to room temperature in a magnetic field-free space, the PTRM will be removed along with any component obtained at lower temperatures. However, (i) components obtained at high temperatures, and (ii) any low-temperature, high-coercivity component (e.g. a CRM or a high field IRM), that might be present, are left intact, provided that the heating process introduces no chemical changes which affect the Curie points of the minerals involved.

The field-free space is usually established by a system of two or three mutually perpendicular coils which compensate for the components of the local geomagnetic field. The heating is done in an oven with non-inductive heating elements. The remanence is measured by a suitable astatic or spinner magnetometer. The measurements may be made while the specimen is heating or cooling in the oven, or separately when it has cooled to room temperature and removed from the oven. The former method will provide a complete curve for the demagnetization of a specimen, and also has the advantage of demonstrating the occurence of significant chemical changes due to the heating process, which would be revealed by serious discrepancies between the heating and cooling curve for the same specimen. The disadvantages of the procedure of taking continuous measurements are

(1) more difficult instrumentation, (2) the fact that only a single specimen may be thermally treated at one time. While the second procedure only gives information about one temperature level at one time, it permits the simultaneous heat treatment of many specimens and involves less difficult instrumentation; for this reason the second procedure is commonly used. To determine the spectrum of the magnetization components present in a rock sample, using the second (room temperature measurement) method, the components are removed one by one, by using the thermal technique successively with increasing maximum temperatures. A stable component may be inferred when the direction of the remanent magnetization remains constant through several steps of thermal demagnetization at successively higher peak temperature.

Thermal demagnetization techniques have been found quite successful (see Wilson and Everitt, 1963), especially for the separation of several hard components with different Curie points which may be present. CRM and IRM components are treated by the techniques as equivalent to PTRM's of the same coercivity. Thus CRM and PTRM components with coercivities or acquisition temperatures respectively quite close to that of the primary TRM can be differentiated from the primary component. The thermal technique can often be used to differentiate components with Curie temperatures differing by as little as $10^{o}C$.

Brief mention has already been made of an important drawback to the thermal demagnetization method with some rocks.

These rocks contain minerals that undergo chemical changes, such as oxidation, or physical changes such as the inversion of γ- Fe_2O_3 to α-Fe_2O_3, when they are heated as required in this method. With rocks of this nature, the method cannot be used and another method of stability testing, such as alternating-field demagnetization, must be used.

A thermal demagnetization unit of the second type (requiring measurements after the specimen has cooled) has been built at Memorial University and is at present undergoing preliminary tests by Dr. P. S. Rao of the Physics Department.

1. 4 Steady - and Alternating-Field Demagnetization Techniques

These represent the other commonly used procedures for testing stability and for obtaining magnetization spectra. The basic procedure is to subject the specimen to a steady or alternating magnetic field for a certain length of time, after which the specimen is removed and its remanent magnetization remeasured.

The direct-field methods were introduced into palaeomagnetic work by Johnson, Murphy, and Torreson (1948) and used most extensively by Russian workers (Petrova and Koroleva, 1959); Petrova, 1961; Lin'kova, 1961; Brodskaya, 1961). After the direction and intensity of magnetization of a specimen have been measured, it is placed in a small magnetic field (say 10 oe.), with the direction opposite to that of the field. The specimen is then removed from the field and its magnetization remeasured. This process is repeated in successively higher fields until the intensity is reduced to zero. Figure 1.5 shows an example of the results. The field required to accomplish this is the "disruptive" or "destructive" field, and is equal to the coercivity of the NRM of the specimen (H'_{cr}). The magnitude of H'_{cr} depends partly on the concentrations and separate coercivities of the ferromagnetic components in the rock, and partly on the proportion of domains with coercivities below H'_{cr}. Thus zero remanence indicates that the proportion of domains present whose coercivity is less than H'_{cr} is sufficient to counterbalance the magnetization arising from the domains carrying the initial magnetization, which possess a coercive force exceeding H'_{cr}.

A high H'_{cr} generally indicates high stability, but although a low value for H'_{cr} means that a large proportion of low-coercive-force domains are present, it does not necessarily mean that small proportions of stable components are absent. Thus the destructive field is only a general guide to stability and tends to give a somewhat confused picture of the magnetization spectrum.

Related to the above method is that of leaving the specimen in a specified position and orientation in either the earth's field, an artificial field of low intensity (say, 10 oe.), or in a field-free space, for a considerable period of time (say, a month or even several years), and remeasuring the remanence after this treatment and possibly at various times in the course of it. This procedure can provide qualitative information on the ease with which a specimen will gain or lose a VRM component, but it will not give much information concerning the harder components. Creer (1959) used a field-free space to remove possible temporary components from his specimens.

Alternating-field techniques were first used for palaeomagnetism by Thellier and Rimbert (1955) and have since been employed successfully by many workers including Brynjólfsson (1957), As and Zijderveld (1958), Creer (1959), and Irving, Stott, and Ward (1961). In these procedures the specimen (in the presence of zero ambient steady fields) is subjected to an alternating magnetic field which is smoothly reduced to zero. During the process all domains with coercivities less than the peak value of the applied field will follow the field as it alternates, describing a series of hysteresis loops. As the magnitude of the peak field is then reduced, domains of progressively lower coercivities assume a fixed orientation with either polarity parallel to the ambient field. Since these two orientations are of equal probability if the field is symmetrical (i.e., it includes no even harmonics or "noise"), the net effect on the specimen as a whole is to remove the resultant magnetization due to the domains having coercivities below the highest applied field, by randomizing their direction.

If a steady field, such as the earth's field, or a field asymmetry due to even harmonics in the power supply for the alternating-field coils, is present during the demagnetization process, an anhysteretic remanent magnetization (ARM) will develop which may mask the remaining "hard" components. A ferromagnetic material acquires an ARM when subjected to a low steady field superimposed on an alternating field. The resultant magnetization is much more intense and stable than if the alternating field had been absent. Patton and Fitch (1962) and Nagata (1961) discuss ARM at some length. Removal or reduction of ARM may be effected by tumbling the specimen about several axes during the demagnetization procedure. This process is discussed more fully below.

Kobayashi (1959) performed experiments on synthetic specimens containing chemically prepared magnetite, so that a magnetization of known origin could be acquired (many of the magnetization processes can be reproduced in the laboratory). They were then demagnetized by the alternating field method. Fig. 1.6 shows the results obtained with TRM and CRM produced in weak fields and an IRM in a relatively high field. The IRM produced in a 30 oe. field at room temperature is effectively destroyed in an alternating field with a peak value of 100 oe.; however the TRM acquired in a field of 0.5 oe. has decreased only slightly in the 100 oe. field and a significant amount remains after 500 oe. CRM has a stability comparable to that of TRM. Thus it is relatively easy to distinguish IRM in rocks from TRM and CRM but it may prove difficult to distinguish between CRM and TRM.

As alternating field demagnetization is a directional process removing ordinarily one component of a magnetization at a time, various means have been used to make sure that each "soft" component is completely removed by randomization of the directions of magnetization vectors and to minimize effects due to ARM. The slowest and simplest method is to demagnetize successively in three orthogonal directions (As and Zijderveld, 1958; Russinov and Sholpo, 1962; Lui Ch'un and Feng Hao, 1965). To minimize spurious ARM's due to imperfect compensation of the earth's field or to power supply "noise", Creer, (1958) suggested demagnetizing in both directions along each of the three orthogonal axes.

The most popular method is to spin the specimen about two or three orthogonal axes in the alternating field region during the demagnetization period. Thus, if the range of rotation speeds for the spin axes is properly chosen, all magnetization vectors in the specimen corresponding to coercivities less than the magnitude of the peak field are demagnetized during a period that is short compared with the time during which the peak field decreases significantly. When properly used, this method can be successful even if a considerable steady field is present (Doell and Cox, 1964). This procedure, introduced by Creer

(1959), has been adopted, with differences only in details, by most workers, e.g.: Khan (1960), Irving, Stott, and Ward (1961), Doell and Cox (1964), McElhinny (1966).

CHAPTER 2

DESCRIPTION OF APPARATUS

2.1 Introduction

The present study involves the design and construction of an alternating-field demagnetization unit at Memorial University, and some tests and treatments performed with it. In this chapter some of the design features of this apparatus are described in terms of the components: demagnetizing coils, compensatory coils, field reduction mechanism, and specimen system.

In association with any demagnetizing apparatus, it is necessary to use a magnetometer to measure the remanent magnetization of the specimen before and after treatment. An astatic magnetometer built at Memorial University is in operation at the Physics Department (see Murthy, 1966), and has been used for all remanence measurements. The instrument has a reciprocal sensitivity of 4×10^{-7} oe./mm scale deflection, which permits the measurements of directions of magnetization to a few degrees in specimens with intensities as low as 4×10^{-6} emu/cc.

2.2 The Demagnetizing Coils

The basic equipment of the alternating-field method is the system for producing the alternating field, which is in practice a coil arrangement. This must fulfill two main requirements: (1) It must be capable of producing a peak field, over some minimum time span, sufficient for typical applications in rock magnetism. Experience has shown that peak fields of, say, 750-1000 oe. may be required to remove the "hard" magnetization in some typical rocks. (2) This field must be uniform in both direction and magnitude over the region occupied by the specimen, so that all parts of the specimen receive the same field at a given time; this is to insure that at the end of a demagnetization run, no residual magnetization components due to field inhomogeneity are left in the specimen.

The most common system used is a short solenoid of length and inside diameter typically about 15 cm. each (e.g. Creer, 1959). Such coils are usually capable of producing between 100 and 250 oe./amp and maximum fields of 1000 to 2000 oe. (peak). However, for a solenoid of these dimensions there is a possibility of significant variation of field direction and magnitude at points within the specimen region, but lying off the coil axis.

A Helmholtz coil arrangement that will give a more uniform field has been used by some authors (e.g. by Doell and Cox, 1964). The main disadvantage of the Helmholtz coils is that in order to produce high fields with moderate currents, one requires many turns of wire. This entails a partial sacrifice of field uniformity in the design, which will depart somewhat from that of an ideal Helmholtz coil to be consistent with practical dimensions.

The system built at Memorial University is a compromise between the solenoid and Helmholtz coil arrangements. Moreover, the geometrical design of the spinner system (described below) made it advantageous to build coils of square instead of circular shape, as this enables one to reduce the cross-section of the coils to produce a given field at the centre for the same current and number of turns, compared with circular coils. For the square shape the Helmholtz dimensions differ from those of the usual circular design for which the separation between the individual coil is equal to the coil diameter. In the present case, with square coils, the separation between average turns in each coil must be 0.5445 times the side length of a turn.

The ideal circular Helmholtz coil design ensures that the radius of each turn is twice the distance between the centre of the plane of that turn and the centre of the coil system. This means that the turns must be wound on a double cone coaxial with the coil axis and subtending a semiangle of 63.4^{o} at the vertex (for a square design, a corner semiangle of 61.4^{o} and a middle-of-side semiangle of 68.9^{o} respectively are subtended at the centre of the system). With any multi-layered coil one can, of course, only approximate this ideal, by assuring that an average (usually centrally located) turn will conform to the ideal design, and that any other turn will differ from it as little as possible in the presence of practical factors such as (i) necessity of producing the maximum possible field for a given current; (ii) need for a large wiring section, resulting in bulky coils, and (iii) a minimum space required in the middle for the spinner system.

Several design criteria were thus formulated: (a) the field strength in a space that can be occupied by the specimen (a sphere of about 3 cm. diameter) should vary by no more than 1%; (b) the spinner apparatus demands a minimum cylindrical space of about 12.2 cm. diameter and 12.2 cm. length at the centre of the coil system and a minimum separation of 4.0 cm. between the two coils to accomodate the shaft (see Section 2.5); (c) a field of 175 oe./amp. (r.m.s.) or 250 oe. (peak)/amp (r.m.s.) is required; and (d) size 14 SWG varnished copper wire should be used to permit the coils to carry a sufficiently high current (10 amps. or less) and to keep the resistance low so that the voltage required in the case of large fields would not be prohibitively high.

With these criteria in mind, an optimum shape for the wiring cross-section was found using the following procedure: The central field and the field at various off-centre points in the central region of the double coil was calculated for various wiring cross-sections of different shape, but approximately constant area. The procedure was to divide each configuration into about 80 square grids of unit area, with a single turn in the centre of the grid representing all the wiring in the grid. The individual grid contributions were summed to give the field strengths at the different points corresponding to each configuration. The IBM 1620 computer at the university was used to make the calculations.

The optimum shape found in this way was a rectangle 7 units high and 11 units wide, though the variation in properties was not critical near the optimum shape. Taking in consideration the other design criteria, a wiring section 7.0 cm. x 11.0 cm. and containing about 2500 turns of 14 SWG wire was derived. However, in actual construction the wiring was tighter than had been indicated in standard wire tables, and so the required number of turns gave an average height of only about 6.6 cm. (Fig. 2.1). This, however, does not significantly affect the uniformity of the field, for the difference between its value at the centre of the system and at off-centre points was found to be 0.5% or less in the case of points within 2.0 cm. from the centre and lying on the coil axis, and 1.0% or less for points within 1.6 cm. from the centre and along a line perpendicular to the axis.

After winding, each coil was dipped in a varnish vat, removed and then baked at 350°C for 18 hours, to give the coil rigidity and to increase the insulation of the wire.

Table 2.1 Parameters of the Demagnetizing Coils

Parameter	Coil #1	Coils in Series	Coil #2
Dimensions of wiring cross-section (width x height) (cm. x cm.)	11.0 x 6.7	--	11.0 x 6.5
No. of turns	2550		2539
Resistance (Ω)	16.35	32.60	16.25
Self-inductance (h.)	1.27	--	,1.24
Total inductance (h.)	--	2.90	--
Capacitance for 60-Hz resonance (μf)	--	2.24	--
Specific field $\left[\frac{oe./(peak)}{amp\ (rms)}\right]$	--	257	--

The dimensions of the coils are shown in Fig. 2.1, and Figs. 2.3 and 2.4 are photographs of the coils and other components of the demagnetizing unit assembled for operation. The coils are supported on a track, resting upon strips of teflon to facilitate sliding. A double screw (similar to that of a turnbuckle) is used to change the separation of the coils, which are moved apart to permit specimens to be inserted into the holder or removed from it. Table 2.1 gives the important parameters of the system.

Fig. 2.2 shows the circuit for the coils; the 2.24 μf. capacitor is required to reduce the impedance of the coils at 60 hertz to a minimum. Some workers (Larochelle and Black, 1965) connect a series-resonant circuit, tuned to 120 hertz, across the coil circuit to reduce the amplitude of any second-harmonic component in the supply. However, McElhinny (1966) argues that this is probably not necessary, since a transformer tends to suppress asymmetric waveforms and the 60 hertz tuned circuit will also attenuate second-harmonic components if the Q is moderately high. For example for the present coils; Q is about 34 ($R = 33\Omega$; $L = 2.9$h), so that while the impedance of the tuned circuit is about 33 ohms at 60 hertz, it is about 1600 ohms at 120 hz., which means considerable attenuation of the second harmonic compared to the first.

2.3 Coil System for Steady-Field Compensation

In any ordinary place the main contribution to the total magnetic field present at any time is the earth's magnetic field. Thus the compensatory coil system must be designed for the elimination specifically of this component, and be flexible enough to remove local or stray fields, which may be caused by ferromagnetic materials or electrical equipment in the vicinity of the demagnetizing unit. It is usually difficult to compensate for local fields having a significant gradient or an irregular variation with time. If significant fluctuating fields are present, for example those due to time-varying d.c. currents in heavy cables, it would be better to move the apparatus elsewhere.

The usual method for obtaining a region of zero field is with a set of either two or three orthogonal pairs of Helmholtz coils to compensate for separate field components or a single pair coaxial with the field direction, for total compensation. The shape of the coils may be either circular or square (the latter are "Parry" coils, after Parry (1957) who first used the square shape). The present system uses three pairs of circular Helmholtz coils (see Figs. 2.3, 2.4). These must eliminate magnetic fields (in St. John's) of approximately 0.5 oe. in the vertical direction and 0.2 oe. in the main (N-S) horizontal direction. For convenience in regulating the current supply, the two pairs with horizontal axes are usually set up so that their axes make small angles (say 2°) with the magnetic north-south and east-west directions, respectively. The corresponding horizontal

Table 2.2 Parameters of the D.C. Compensatory Coils

Parameter	Vert. pair	N-S Pair	E-W Pair
Mean radius (cm)	45.0	50.0	55.0
Mean separation (cm)	45.[illegible]	50.3	55.5
No. of turns	50	50	15
Specific field (oe./amp)	0.994	0.894	0.244
Required current (amps)	0.440	0.247	0.031
Compensatory field ($=10^{-5}$ oe.)	4.37×10^{4}	2.21×10^{4}	7.6×10^{2}

field components which are to eliminated are about 0.2 oe. and 0.01 oe., respectively.

Table 2.2 shows the dimensions and characteristics of these coils. The diameters were staggered so that the coils can fit together as shown in the photographs (Figs. 2.3, 2.4). They provide a nearly spherical region of approximately 10 cm. diameter where the field is uniform to within 0.1%.

These coils require highly stabilized d.c. power supplies that provide a fine control of voltage. The electrical circuits used for supplying power are shown schematically in Fig. 2.5. The power supplies used were Power Designs Model 2005, which gives up to 20V d.c. at 500 ma. max . Regulation is to 0.0005% or 100 microvolts (whichever is greater), ripple and noise are less than 100 μv peak-to-peak, and the voltage can be set for a resolution of 10 μv with an absolute accuracy of 0.1% ± 1 mv. over the range 0-10V.

2.4 Mechanism for Alternating-Field Reduction

The alternating field acting on the specimen can be decreased in several ways. One common method is the removal of the field coils from the vicinity of the specimen by a mechanical means. The specimen should remain in the zero field region, and so the field coils themselves, or the compensatory coil system along with the specimen, must be moved. In both cases the devices to be moved are necessarily massive, so that the mechanical system would have to be elaborate in size and construction

Usually the field coil is moved.

Alternating-field reduction by this method can be made quite smooth, though it is difficult to make it linear with time, as this would require an accelerating motion during withdrawal of the coils from the specimen region. The separation of the coil from specimen must usually amount to 1-2 meters, so that the field may be reduced to negligible proportions. The maximum field obtainable is limited only by the capability of the coil to carry the necessary current for the required length of time without overheating. However, it has several disadvantages. The distance the coil must be moved to gain sufficient reduction of the field causes the apparatus to become unwieldy. Also smooth movement of the coils may be difficult to obtain due to frictional jerking. The a.c. current, and so the mean r.m.s. field, must be kept relatively constant throughout the withdrawal period. The method has been employed by Russinov and Sholpo (1962) and Lin Ch'un and Feng Hao (1965), using in both cases a track on which the alternating-field coil was moved, and by Creer (1959) who lifted the coil vertically in a cradle suspended from the ceiling.

The other and more commonly used method is electrical rather than mechanical in principle, as it involves the smooth and slow reduction of the current to the demagnetizing coils. Three alternative types of instruments have been used for this purpose: (i) the autotransformer; (ii) a transformer with continuously-variable output; and (iii) the electrolytic resistance. The autotransformer is set up to reduce smoothly the voltage applied to the demagnetizing coils, and perfectly smooth reduction can be approximated by use of a stepped-down synchronous motor to drive the rotating contact of the autotransformer. This method is especially useful in cases where high initial currents are to be reduced to zero. However, its main disadvantage is that, because of the finite number of turns in the winding of an autotransformer, the voltage is reduced in steps even when the driving mechanism is perfectly smooth. Thus, to obtain an autotransformer with sufficiently smooth reduction (i.e., operable through a large number of very small steps) and also high current capability, a bulky and costly instrument is required. McElhinny (1966) described a special transformer which produces an output voltage continuously variable from line value to within 0.1% of zero.

The device used in the present apparatus is the electrolytic resistance, shown schematically in Fig. 2.6. The resistance unit is connected in series with the coil and power supply, and its resistance is increased when the electrolyte is drained through the output tube at the bottom, thus decreasing the area of contact between the electrodes and the solution; this results in a smooth decrease of the a.c. supply to the demagnetizing coils. The resistor constructed for use with the present apparatus consists of two copper tubes 3.8 and 1.1 cm. in diameter and 152 and 168 cm. in height, respectively. These are set concentrically and plugged at both ends by rubber stoppers, such that the enclosed annular region constitutes a closed vessel, except for inlet and outlet tubes inserted in the stoppers to allow passage of the liquid, as shown in Fig. 2.6.

In operation, the tubes represent the two terminals of the resistor. The annular region of the concentric system is filled with electrolyte, which in the present case is 0.5% solution of copper sulphate, giving a resistance of about 20 ohms when the resistance unit is filled. The desired maximum current is then applied, and is continuously decreased as the electrolyte runs out through the bottom hole. A very smooth change in current is thereby obtained, and the final resistance will be of the order of one megohm, giving a ratio of initial to final field of at least 1×10^4 which is sufficient. The runout rate can be controlled by the size of the outflow hole or by a stopcock applied to flexible tubing at the exit. The effect of changes of rate of outflow is discussed in the next section.

One difficulty in this component of the apparatus is the large extent to which the resistance at a given electrolyte level depends upon the temperature of the liquid and the chemical condition of the electrode surfaces. Thus with high current especially, the resistivity of the liquid changes with time during the demagnetization. Apart from this cause the resistance is not a constant for a given current, i.e. the current does not vary linearly with voltage. However, the variations do not introduce discontinuities into the process of current reduction, which is quite smooth as long as the rate of outflow of electrolyte varies smoothly with time. The rate of outflow was found to be fairly constant during a demagnetizing run, being modified only by the effect of the decreasing head, which is relatively moderate for the rates used (2-4 minutes to drain).

Electroplating on the copper surface of the resistance might be expected to be a second difficulty. However, while a deposit of finely divided copper sulphate precipitate has been found to accumulate on both surfaces of contact with the electrolyte, this build-up is very slow when a.c. is used; moreover, the withdrawal of electrolyte has a washing action on any loose deposit. Thus an occasional cleaning will keep this from affecting the performance of the apparatus.

2.5 The Spinner Unit

Most workers use a two-axis spinner system, either gear— or belt — driven, with motive power supplied by an air turbine or an electric motor operating from a distance through a system of rods. (Creer, 1959: Khan, 1960; Cox, 1961; Irving, Stott and Ward, 1961; Larochelle and Black, 1965). However, it has been found by some authors that ARM components may be introduced into the specimens when the systems are used, particularly at high peak fields; hence Doell and Cox (1964) recommend a system with three or even four axes of spin to eliminate this tendency. Thus, although Larochelle and Black (1965) obtain good results with their two-axis system (with accurate nulling of the earth's field), a three-axis system was designed and built for the present apparatus.

The two inner rotation frames are driven, with negligible slippage, by plastic belts connected to their immediate outer neighbours. The outermost frame is driven by an air turbine which produces a rotation speed of about 5 r.p.s. with an air pressure of 12 lb./sq.in. The turbine consists of a large (~30.5 cm. diameter) wheel made of a varnish laminate with ~ 50 small paddles (Figure 2.7). A secondary function of the wheel is to act as a flywheel to regulate the speed of rotation to some extent (stroboscopic measurement showed that, about one minute after being set in motion, the turbine assumed a steady rotation at a rate of 300 r.m.p. or so, and with fluctuations within ± 2 r.p.m.)

In the usual demagnetization run the time required to reduce the field nearly to zero will be 2-4 minutes, depending upon the chosen outflow rate for the electrolyte, and so the average rate of reduction is 0.4 - 0.8% of the peak field per second. Thus, while the field decreases by about 1% of its value, the outermost frame of the system completes on the average 6-12 revolutions, assuming its speed to be 5 r.p.s.

However, the effectiveness of the demagnetization depends not so much upon a large rotation rate of the spinner frames, as upon the achievement of maximum coverage of specimen positions during a time in which the applied field decreases negligibly. "Positions" in this case are usefully defined in terms of unit position vectors (or magnetic dipoles) centered at the specimen centre and rotating about the spinner axes. The tips of the vectors may be considered as points on the surface of a sphere, where they trace circles when the rotation is about one axis only and spirals in the case of rotations about two or more axes with more than 1:1 angular speed ratios. "Maximum coverage" can then be looked upon from two different aspects:

(1) If a single vector is considered, the angle between this vector and some non-rotating coordinate should cover uniformly all values between 0 and 90^{o} degrees; in practice, this means for example that equal times are spent in the ranges $0\text{-}5^{o}$, $5\text{-}10^{o}$ --- $85\text{-}90^{o}$ respectively. A useful choice for the fixed coordinate is the axis of the demagnetizing coils, in which case the maximum torque is acting when the vector (here considered to represent a dipole moment) makes a 90^{o} angle with the field axis. If the dipole vector is initially aligned with the axis of the demagnetizing coils, and rotates only about an axis perpendicular to the field direction (i.e. only the main frame rotates), it will experience a sinusoidally varying torque (of 5 Hz. frequency) if the field is direct, and a torque varying in accordance with two superimposed sine waves (from the 60 - Hz. field

and the 5 - Hz. spinner rotation, respectively), when an alternating field is used. In both cases there is complete coverage of directions (in the rotation plane) on the part of the rotating vector during the 6–12 revolutions in which the peak field is reduced by 1%.

(2) However, consideration of a single vector is unrealistic, as the problem here is to randomize the vectors in a given distribution. For example, a magnetic dipole aligned with the axis of the main spinner frame would make a 90° angle with the field axis at all times, and hence experience the maximum torque continuously in the case of a direct field, and a sinusoidally varying torque (of 60-Hz. frequency) in the case of an alternating field. Hence, if both vectors (parallel and perpendicular to the field, respectively) were present in the specimen, comparison with the example under (1) shows that they would experience torques with different time variation, whether direct or alternating fields are applied.

A better approach is to consider a distribution of regularly-spaced position vectors (or "poles" on the sphere), say with an angular separation of 20°, and to determine optimum rotating ratios in such a way that each vector experiences a particular range of torque for the same length of time, the whole range being covered during a period in which the peak field decreases insignificantly; this means in practice that at any time some vectors will be nearly perpendicular to the field direction and others nearly parallel, so that the full range of torques is experienced at one time or another by all vectors. Such uniformity is not easy to achieve. For example in a 2-axis spinner with 5:1 rotation ratio, (say 5 hz. and 1 hz. for the main and second frames, respectively), a single point vector on the sphere will trace during one second 5 twisted "meridians", spaced evenly with respect to any latitude circle on the sphere so that the maximum angle between the vector and the field axis would be 18°. The spiral traced by a single point is at the same time indicative of the coverage of points on the sphere, which is here certainly non-uniform. The main flaw in this design is that the spiral is retraced during every subsequent second, and for this reason simple rotation ratios should be avoided in spinner systems. More uniform coverage is, then, achievable through proper choice of rotation ratios that are not simple multiples of one another, whether two or more than two rotation axes are used.

Apart from considering the rotation ratios between different axes, and the rotation speeds relative to the rate of decrease of the applied field, one must pay careful attention to the ratio between the frequency of the field and that of the most rapidly spinning frame. Actually the field, being sinusoidal, is at 90% or more of its maximum intensity (considering both polarities) for only 28% of the time. With a rotation speed of 5 r.p.s. about the axis of the outer frame, a line-frequency cycle is one-twelfth of a cycle of the outer frame, so that the specimen is affected by the full amplitude of the field about every 15^{o} of rotation. It is here assumed that the motion of a position vector is not greatly distorted by the rotation of the second (inner) frame, i.e., a large speed ratio between the outer and inner frames is assumed.

Then the 15^{o} value represents a maximum distance between field direction and specimen direction, which is less than that produced by the rotation alone, with say, 5:1 speed ratios (18^{o}). This indicates that in the present apparatus the ratio between the alternating-field and maximum spinner frequencies (12:1) permits effective coverage of specimen directions, though this is arather rough estimate based on the (unsuitable) 5:1 speed ratio. It is easily seen that this coverage would become less efficient as the rotation speeds are increased, so that such a measure should be avoided. On the other hand a decrease in the rotation speeds could result in a loss of efficiency, unless the rate of decrease of the peak field were correspondingly lowered; this is because the existing rate may then be too large to permit complete coverage of specimen directions during the time of an insignificant decrease of the field.

Apart from the criteria discussed above, the rotation speeds about the respective specimen axes must fulfill two further conditions to result in maximum demagnetization of the unwanted components. First, complete randomization of pole directions;

that is, the projection of each vector upon the axis of the magnetizing field must be parallel with the field during half of the time taken by the demagnetizing process, and anti-parallel during the other half. This will reduce anyhysteretic effects. Secondly to insure that the various directions are covered with as close an approach to randomness as possible, it is not only necessary to avoid introducing simple multiples into the speed ratios between different frames, but also to exclude subharmonics of the field frequency (60 hz.) in selecting spin frequencies about any axis.

An optimum ratio of speeds would involve a set of rotation speeds requiring the shortest time to carry out the experiment, while keeping to a minimum any preferential exposure on the part of certain magnetization vectors to the peak demagnetization field. For example, if in a two-axis system, one rotation speed were much greater than the other, say in the ratio of 10:1, the approach to complete coverage would be good, but this ratio would be inefficient as it would have to meet the requirement that both rotations and hence, in particular, the faster of the two, be much less than 60 hz. The slower rotation would then have to be so slow as to make the required field reduction time impractically long. The most efficient ratio will be between 1:1 and 1:2 (but, of course, not equal to either), since both speeds could then be quite large. For this reason most workers use ratios in that neighbourhood. Thus Creer (1959) used 1.0:1.1, Irving, Stott and Ward (1961) 15:16, and Doell and Cox (1964) used 1.61:1.21:1.00 for their three-axis system.

An analysis of the most efficient system was attempted. The method mentioned above was used, and consisted of choosing a set of points uniformly distributed over the surface of an imaginary sphere, with its centre at the specimen centre. The magnetization vectors were taken to be parallel to the lines joining such points to the centre of the sphere. For a given number of revolutions (100 were used) about one of the axes it was determined how many times each ideal magnetization vector, as defined above, would be perpendicular to the magnetizing field and whether the field would be at a maximum at this time. Thus it was ascertained whether the vector is subjected to the full torque of the peak field. In the actual calculation, points on the surface were replaced by circular regions subtending an angle of 0.3 radians (17.2^{o}) at the centre of the sphere (within this region the torque acting on any vector is never less than 95% of the maximum torque experienced by a vector piercing the centre of the region, so that each magnetisation vector could be located anywhere within the region of a cone having its vertex at the centre of the sphere). A perfectly efficient set of spinner speeds will cause each magnetization "vector" (as defined above by the region surrounding it) to be affected in this way an equal number of times; hence the aim will be to determine a system having as small a deviation as possible from this ideal. The IBM computer at the University was used to make the calculations. The analysis has been discussed elsewhere in some detail (Pearce, 1965), but the results will be summarized below:

As the analysis was somewhat limited to only five speed ratios between 1:1 and 1:2 (1.00:1.05, 1:00:1.10, 1.00:1.20, 1.00:1.34, 1.00:1.88) the results are preliminary and only directly applicable to two-axis systems. However, some general conclusions can be drawn from the results, which are shown in histogram form in Fig. 2.9 for three of the speed ratios. This shows the number (N_{100}) of "points" (or "vectors", as defined above), out of a total of 100 points uniformly distributed over the sphere, which are subjected to the full torque of the demagnetizing field for a given number (N_c) of times during 100 rotations of the slower frame. In assuming here that a given specimen vector perpendicular to the field experiences the full torque, one neglects the sinusoidal character of the field; however the assumption is not unjustified, as the diameter of the circular region defining the vector (17.2°) is larger than the angular distance covered by the fastest rotation component in Fig. 2.9 (about 13° for 4.33 r.p.s.) during a half-period of the 60-hz. field.

For 4 out of 5 speed ratios (1.00:1.20 being the exception), the results are quite similar in character, as typified by Figs.

2.9a, c. Here the large spread of N_c for any given ratio is probably a consequence of the sinusoidal character of the field. Fig. 2.9b, for a 1.00:1.20 (or 5:6) ratio, shows more than twice as many occurrences of $N_c = 0$ (i.e., points which never experience the full torque) than is the case with the other two speed ratios shown. This seems to confirm the point previously raised, that simpler ratios [in this case 5:6, which is equivalent to (1/12):(1/10) of the line frequency] are not as efficient as the others.

In the case of all ratios it was found (Pearce, 1965, but not shown here), that the torques are symmetrically distributed with respect to a plane perpendicular to the field axis; i.e., even in a direct field the mean torque experienced by any vector during, say, 100 spinner rotations should be algebraically zero for a field perpendicular to the outermost spinner axis. This is important in later application (Chapter 4) where an attempt to substitute direct for alternating fields is described.

McElhinny (1965) performed a similar analysis by plotting on a stereographic projection for various 2--axis ratios the directions in the rock which are successively brought into coincidence with the field direction. On the basis of these he concluded that by setting the tumbler (i.e. spinner) ratios close to, but not exactly at values of 1:2 or 2:3, maximum efficiency would be obtained. Such close ratios cause the entire pattern of magnetization vector paths to be exactly repeated only after a large number of rotations (e.g. for 1:00:1.21, 100 rotations are necessary), but by this time the field may have decreased significantly, say by 10%. If the ratios are too close to the simple ratios the spinning action will resemble that obtained for the simple ratios with the main disadvantage of a pattern that is too repetitive to permit efficient randomization as discussed above. McElhinny's analysis also lacked completeness, since he did not consider the effect of the sinusoidal variation of field intensity upon the vector directions in the specimen.

For the present apparatus the ratios of the angular velocities can be varied quite easily by changing the diameters of the main wheels. The ratio for the inner frames is 3.00:4.00 and that for the outer frames 1.00:1.21, to give 1.61:1.21;1.00 for spinning about the inner, middle and outer axes respectively. This set of ratios has been used successfully by Doell and Cox (1964).

The whole system was made of non-magnetic and electrically non-conducting materials to eliminate spurious effects due to eddy currents. The three frames (illustrated in Figs. 2.7 and 2.8) are made of vulcanized fiber laminate, 1.9 cm. thick, while the material of the large wheels (for determining speed ratios) is a paper-varnish laminate. The small wheels and bushings are teflon; and shafts, screws, and nuts are nylon. Excepting the nylon, these materials do not normally collect strong charges of static electricity, and this has not given trouble in the present apparatus. The dimensions of the system were designed so that it would occupy the minimum space in the alternating field coils, while retaining adequate thickness for the frame material (1.3 cm. for outer frame, 1.1 cm. for inner two). The resulting outer dimension for sides of the outer frame is 10.2 cm., the turning diameter of this being 11.4 cm. when the attached wheel is considered.

The inner frame acts as the sample holder. It takes samples in the form of cylinders of up to 2.2 cm. diameter, or cubes of 2.0 cm. side length. These are held securely in place by four nylon screws at the four corners of the cubes (see Fig. 2.8).

2.6 Procedure for Demagnetization

Over a period of time a fairly standardized procedure for demagnetization runs has been developed. This can be described in the following steps:

1. The d.c. currents for the compensatory fields are turned on at the beginning of the session and allowed 20 minutes or more to stabilize.

2. Following measurement of its remanent magnetization with the magnetometer, the specimen is placed in the specimen

holder, and the coils are brought together at the optimum separation. The pump supplying air to the turbine is turned on, thereby starting the spinner rotation.

3. The variac is set at the voltage corresponding to the required maximum field, on the assumption that the minimum impedance of the circuit is 55 ohms. The power is switched on.

4. The resistor is filled with electrolyte until the required maximum current has been reached. The time for filling averages 20-30 seconds.

5. The specimen is allowed to spin in the maximum field for about 10 sec. after which the electrolyte is drained out. For most specimens the drainage time is set for 150±15 sec. but in a set of demagnetizations requiring many high-field runs it has been usual to change the rate to give a 240 sec. drainage time.

CHAPTER 3

APPARATUS TESTS

3.1 Introduction

Alternating-field demagnetization apparatus has been used by many workers, commonly with a two-axis spinner system (As and Zijderveld, 1958; Creer, 1959; Irving, Stott and Ward, 1961; Khan, 1960; Cox, 1961). However, several workers report obtaining a "scattering" of remanence directions between different rock specimens in a set after demagnetization in high peak fields, compared with closer alignment of direction when lower fields were applied. Doell and Cox (1964) have shown that apparatus design can be responsible in large measure for this phenomenon, in the form of spurious ARM components introduced by the apparatus due to the presence of imperfectly nulled magnetic fields and to "noise" in the power supply to the demagnetizing coils. They recommend that a system with three or even four spin axes might be used to eliminate this difficulty. Larochelle and Black (1965), however, found that a two-axis system is adequate if the steady field in the region of the specimen is kept quite low during the demagnetization process. (They concluded in particular that a field of only 1800γ produced troublesome ARM components if it were applied along the axis of the demagnetizing coil.

Thus there is still disagreement about the relative effectiveness of various procedures in alternating-field demagnetization. Because of this, and the need to calibrate the present equipment, a series of tests have been carried out with the double objective of investigating (i) the degree of randomness achievable in the demagnetization under various experimental conditions and (ii) the effectiveness of the unit in destroying remanent magnetizations of various origins residing either in a single ferromagnetic component or in a combination of components.

Since the ferromagnetic mineralogy of natural rocks is frequently quite complicated, artificial specimens were prepared by combining the powder of a pure magnetic mineral, or minerals, with plaster of Paris, and setting the mixture with water. The behaviour of such synthetic materials, which were used in most of the following tests, could be expected to be more reliable than that of natural specimens and the measurements more reproducible; hence their use in calibrations of this type is preferable to that of natural rocks.

3.2 Preparation of Specimens

Three different minerals were used in the tests--pyrrhotite, a sulphide; and hematite and magnetite, both oxides.

The pyrrhotite was obtained from sulphide ore from Notre Dame Bay, Newfoundland; it contained besides the pyrrhotite pyrite and chalcopyrite, and small quantities of various gangue minerals, but examinations of the sample in polished section prior to crushing and powdering revealed no trace of other ferromagnetic minerals. The pyrrhotite was ground finely enough to pass through a 250-mesh sieve (about 80μ), but not through a 350-mesh sieve (about 40μ). It was purified by magnetic separation to eliminate most of the non-magnetic materials.

The hematite used was a chemical reagent in the form of a fine powder of α-Fe_2O_3 (less than 1μ). The magnetite was obtained from an ore sample (from Visakhapatnam, India) which was almost pure magnetite but contained a small amount of gangue minerals and maybe a trace of hematite. It was ground to an 80-mesh sieve (210μ), but not a 120-mesh sieve (125μ), and magnetically refined.

The magnetic powder to be used was, in each case, mixed thoroughly with plaster of Paris, then mixed with water and set in a mold of the same cylindrical dimensions (height = diameter=2.2 cm.) as those of the natural specimens prepared for palaeomagnetic measurements in the laboratory.

An arbitrary azimuth line was drawn on the top surface of each specimen after hardening.

The pyrrhotite and hematite were also used together to provide some specimens with two possible magnetic components, the pyrrhotite yielding a "softer" magnetization than the hematite, as explained in Chapter 1. In this, care must be taken while preparing the specimens to avoid the possibility that particles of the two minerals may cling together, causing one to interfere magnetically with each other. Study of a thin-section of one of the completed specimens under the microscope showed that, while there was some tendency for hematite particles to cohere to each other, few associations of hematite with pyrrhotite particles, or of pyrrhotite particles with each other, were observed.

The concentrations (in terms of weights of dry powder mixture) of the magnetic minerals are shown in Table 3.1:

Table 3.1 Magnetic Mineral Concentration in Synthetic Specimens.

Specimen	Weight Percentage of Magnetite	Weight Percentage of Hematite	Weight Percentage of Pyrrhotite
"Pyrrhotite"	-	-	0.18
"Magnetite"	7.3	-	-
"Hematite"	-	0.60	-
"Mixed"	-	0.35	0.14

3.3 Single-Component Demagnetization Tests

In each of the following tests a synthetic specimen was given a TRM component by heating it above its Curie point and cooling in a suitable uniform and steady magnetic field. The specimens were then demagnetized stepwise up to a maximum peak field of at least 675 oe. For the three specimens used the results are given in Table 3.2 and the remanent intensity is plotted against peak demagnetizing field in Fig. 3.1.

A. Pyrrhotite A TRM, with an intensity of about $2x10^{-3}$ emu/cc and an arbitrary direction, was induced in a synthetic pyrrhotite specimen by cooling in a 10 oe. steady field. The results show that the intensity of the remanence is reduced to 10% of its initial value at about 400 oe., but that the direction of the remanence remains essentially unchanged throughout the demagnetization. However, slightly more fluctuation is evident at higher fields, when the remanent intensity is reduced to lower values, so that the precision of the magnetometer measurements becomes more critical. A second cause of fluctuations in the direction of remanence may be the presence of a VRM component that becomes relatively more prominent after a high degree of demagnetization has been achieved.

B. Hematite As with the pyrrhotite, a field of about 10 oe. was required to give the hematite specimen a TRM of about $2x10^{-3}$ emu/cc. Table 3.2 and Fig. 3.1 show that the demagnetization to 810 oe. had little effect on the hematite TRM, reducing the intensity only by about 20% of the initial

Table 3.2 Results of Alternating-Field Demagnetization for Single-Component Synthetic Specimens

(Azimuths are quoted in degrees east of an arbitrary "north" direction marked on the upper cylinder surface. Dips are positive when the north direction of the remanence is downward.)

Specimen	Peak Demagnetizing Field (oe.)	Remanent Magnetization		
		Azimuth	Dip	Intensity (emu/cc)
A. PYRRHOTITE	before treatment	186.4	0.6	195×10^{-5}
	54	186.9	2.5	162
	108	185.3	0.8	108
	243	187.0	1.8	51
	405	184.9	2.7	19.0
	540	185.4	6.3	10.3
	675	188.8	3.7	8.3
B. HEMATITE	before treatment	187.5	-13.9	159×10^{-5}
	270	187.8	-13.9	133
	405	187.0	-13.8	131
	540	187.6	-14.0	131
	675	187.8	-13.6	130
	810	187.1	-10.9	127

Table 3.2 (Continued)

Specimen	Peak Demagnetizing Field (oe.)	Remanent Magnetization Azimuth	Dip	Intensity (emu/cc)
C.	before treatment	286.2	72.6	197×10^{-5}
MAGNETITE	54	288.0	73.4	175
	108	285.4	72.6	116
	243	280.9	74.7	28.5
	324	284.5	72.9	14.6
	540	320.1	73.1	3.8
	675	272.3	75.8	3.4

value. Then the hematite retained a very hard TRM component compared to the pyrrhotite.

C. Magnetite Only the earth's field was required to give to the magnetite specimen a TRM as intense as that imparted to the other minerals. Fig. 3.2 shows that the magnetite TRM is reduced to 10% of its initial intensity at about 270 oe. and is essentially demagnetized at about 500 oe. It is thus softer than the pyrrhotite TRM. The remanence is also less stable in direction at higher fields than that of the pyrrhotite. However, there is some uncertainty in these high field values for magnetite, as these were taken quite close to the lower limit of measurement of the magnetometer, and again the scatter may be at least partly due to VRM contribution.

3.4 Two-Component Demagnetization Tests

Three mixed specimens were used in these tests. They were each given a TRM initially by heating above the Curie point of hematite (675°C) and cooling in a 2.0 oe. steady field. Since the pyrrhotite Curie point ($\sim 300^\circ$ C) is below that of hematite, both minerals gained TRM's in the same direction. The pyrrhotite was now given a secondary component by application of a high field with its direction along a different axis than the primary component. One specimen was subjected to a 200 oe. field perpendicular to the primary direction, producing a secondary component with an intensity of about 0.7 times that of the primary component. (The intensity of the secondary component was in each case computed from the resultant change in direction of the NRM). Similarly, in the second specimen, a 400 oe. field opposite in direction to the primary component produced a secondary component three times as intense as the primary one, and in the third specimen, a 1,000 oe. field produced a secondary component about 15 times as intense as the primary one and perpendicular to it.

The specimens were then subjected to progressive demagnetization until the secondary component was removed, i.e. until the direction of the remanence returned to the initial or primary - component direction. The results are shown in Table 3.3 and in Figures 3.2 - 3.5, where Figure 3.2 shows the intensity variation of the remanence with peak demagnetizing field and Figures 3.3 - 3.5 show the corresponding variation in direction. In each case the demagnetization was successful but as would be expected, this becomes more difficult as the intensity of the IRM of the secondary component increases. Again as expected, the change in direction with demagnetization in each case progressed approximately along a great circle.

Table 3.3 Remanent Magnetism of Two-Component Synthetic Specimens after Alternating-Field Demagnetization

(Azimuth and dip are defined in Table 3.2. Composition of the specimens is shown in Table 3.1. All fields are peak fields, in oe.)

Table 3.3 (a)

Specimen	Applied Field to Establish Second-Component IRM
1	200 oe.
2	400 oe.
3	1000 oe.

Table 3.3 (b)

Specimen	Peak Demagnetizing Field (oe.)	Remanent Magnetization Azimuth	Dip	Intensity (emu/cc)
1	before treatment	359	2	1.36×10^{-3}
	second component added	348	35	1.47×10^{-3} (I_o)
	108	351	25	1.22
	243	357	9	1.01
	324	358	5	0.90
	405	359	4	0.85
	675	358	4	0.75

Table 3.3 (b) (Continued)

Specimen	Peak Demagnetizing Field (oe.)	Remanent Magnetization Azimuth	Dip	Intensity (emu/cc)
2	before treatment	359	2	1,16 x 10^{-3}
	second component added	182	22	2.21 x 10^{-3} (I_o)
	108	184	31	1.23
	242	352	47	0.40
	324	359	11	0.75
	405	358	6	0.92
	540	359	3	1.00
3	before treatment	353	+3	1.43 x10^{-3}
	second component added	202	-88	22.3 x 10^{-3} (I_o)
	108	264	-89	19.3
	243	321	-83	4.0
	405	345	-73	1.07
	540	349	-54	0.56
	675	355	-22	0.35
	810	354	+3	0.33

3.5 Spurious-Component Tests

Both Doell and Cox (1964) and Larochelle and Black (1965) analysed their apparatus for spurious components by repeated experiments under identical conditions, where only the specimen orientation relative to the sample holder was different for each treatment. The authors in both cases used two different types of natural specimens; those having a coercivity (H_c) spectrum with relatively high values of H_c, and those with relatively low H_c, i.e. a "hard" and a "soft" specimen were used. In each case the authors found that the "soft" specimen picked up any spurious components more easily than the "hard" ones, and so they based their conclusions largely on the former.

For the present study the hematite specimens are nearly useless since any spuriously induced component would be difficult to distinguish; this is due to the masking effect of the primary remanence which is quite large, even at the highest demagnetizing fields employed (Table 3.2). From the pyrrhotite and magnetite, the latter, having the lower observed coercive force, was chosen for this work.

There are 24 possible orientations for a specimen aligned axially in various directions relative to a system of axes fixed to the specimen holder. For a cylindrical specimen only eight of these as illustrated in Fig. 3.6 and Table 3.4 are sufficient for a conclusive test to detect spurious components;

in the other sixteen positions, the Z direction of the specimen (i.e. a direction along the cylinder axis) is horizontal and parallel to the N-S or E-W direction of the holder (the directions were marked on the holder in such a way that, when the three frames are horizontal, the E and N directions are parallel and perpendicular to the axis of the inner frame, respectively). Since the inner rotation axis essentially sees specimens in only two basic orientations[i.e. a vector can be perpendicular or parallel to the axis (see Chapter 2, pp 34-35)], eight orientations are sufficient; these will include all possible orientations for which any two perpendicular directions (in this case the X and Y axes) in the specimen coordinate are perpendicular to the axis.

Thus for the magnetite specimen a set of treatments consisted of demagnetizations performed with the specimen in each of the eight placements. The numbers shown in Table 3.4 will be used to identify the same positioning in later tables. The magnetite specimen which had been previously demagnetized (see Fig. 3.1 and Table 3.2) was used, as its remanence is quite small and any added component becomes relatively much more prominent and hence easier to distinguish as such in the measurements. Thus this specimen was repeatedly demagnetized, and its remanence measured for the various orientation in each of the tests described below.

Table 3.4 Specimen Orientations Relative to the Holder Axes, for Spurious-Magnetization Tests

(N,E, and U refer to the north, east, and upward directions along the three holder axes, respectively).

Designation	Position No.	N	E	$V_{up} = U$
(+Z,+Y)	1	+Y	+X	+Z
(+Z,+X)	2	+X	-Y	+Z
(+Z,-Y)	3	-Y	-X	+Z
(+Z,-X)	4	-X	+Y	+Z
(-Z,+Y)	5	+Y	-X	-Z
(-Z,+X)	6	+X	+Y	-Z
(-Z,-Y)	7	-Y	+X	-Z
(-Z,-X)	8	-X	-Y	-Z

Besides testing whether the apparatus would introduce ARM components into specimens under normal conditions, it is of use to find whether the presence of the earth's field or the use of only two spin axes, instead of the usual three, would affect the results. Therefore the following sets of treatments were applied.

1. The remanence of the magnetite specimen was measured on the astatic magnetometer. The specimen was then demagnetized in Orientation No. 1 at 675 oe. peak alternating field, and with full compensation for the earth's field. The remanence was remeasured and the process repeated for Orientations 2-8

2. The specimen was treated as in Set 1 but without the earth's field compensation, i.e., the d.c. supply to the Helmholtz coils for field nulling was disconnected.

3. The inner spin axis was disabled; the air pressure for the turbine adjusted to give the same speed for the outer axis (about 5 r.p.m.) as when three axes were used. With the resulting two-axis system the specimen was treated as in Set 1 (i.e., earth's field compensation restored.)

4. With the two-axis system the specimen was treated as in Set 2. (i.e. the earth's field compensation was removed).

5. As a consequence of the results obtained in Set 4, the procedure was repeated as in Set 4 but with 405 oe. peak field substituted for 675 oe.

The results of these tests were first corrected for a small remanence that remained in the specimen after these treatments. The components of this primary remanence, which is probably due to the small amount of hematite in the specimen, were (all in emu/cc x 10^5): X = +0.3, Y = -1.6, Z = -4.6. This direction of the primary remanence was obtained by averaging algebraically the resultant directions of remanence measured after each demagnetization in all five experiments; i.e. 40 directions or 120 components in all were averaged. Then for the eight specimen orientations in each single experiment, the average remanence should be zero in the absence of a primary remanence. The correction consisted of subtracting the same (mean) components of the primary remanence (i.e. the above values of X,Y,Z) from the components of the total remanence measured after each step. Ideally, as long as the value obtained for the primary remanence is correct, the resulting differences $\Delta X, \Delta Y, \Delta Z$, respectively, should sum algebraically to zero within a set of treatments as outlined above. These differences, $\Delta X, \Delta Y, \Delta Z$, respectively, have been expressed also in terms of the axial directions N,E,U of the apparatus as shown in Table 3.4. The results, both in terms of specimen and apparatus axes are tabulated in Table 3.5 - 3.11. The N,E and U components are also shown in the form of a bar graph in Fig. 3.7.

The results indicate the presence of a small random spurious component affecting all of the results. This can at least partially be explained by the limit of accuracy of the magnetometer as has been noted previously. It may be noted from Tables 3.5 - 3.11 that the values of ΔX, ΔY, and ΔZ, which are corrected for the primary remanence, appear to be randomly distributed with respect to sign. The r.m.s. value of the observed deviations (a standard deviation) gives an estimate of the accuracy that can be assigned to the value for the primary remanence: thus this can be written (in emu/cc x 10^{-5}); $X=+0.3\pm0.3$ $Y = -1.6\pm0.3$; $Z = 4.6 \pm 0.3$.

The bar graph clearly indicates the significant addition of a spurious component with a definite orientation relative to the spinner system in the presence of the earth's field. (Set 4 demagnetizations; Table 3.8, Figure 3.7). The other results show that changing to a three-axis system (Set 2, Table 3.6) or restoring the compensation of the earth's field (Set 3, Table 3.7) would suffice to remove this directed component. Reducing the peak field to 405 oe. but leaving the earth's field uncompensated (Set 5, Table 3.9) would remove most, though not all, of this non-random component.

A basalt specimen (HH21A4) obtained from Henley Harbour, Labrador, was subjected to a series of demagnetization experiments similar to those described above, so that the possible introduction of a spurious magnetization into a natural rock could be studied. The specimen was first demagnetized in steps to yield information on the nature of its remanence. This was

Table 3.5 Intensity Components of Spurious Magnetizations Acquired by Magnetite Specimen during Set 1 Demagnetizations.

(X, Y, Z, are components of the intensity of magnetization along specimen axes X, Y, and Z: they represent the difference between the primary remanence after demagnetization in 675 oe. peak fields under N, E, and U, these components have been referred to the specimen holder axes. All intensities are in emu/cc x 10^{-5}. (See also Table 3,4 and Figure 3.6)

Specimen Position	ΔX	ΔY	ΔZ	N	E	U
1	-0.6	-0.2	0.0	-0.2	-0.6	0.0
2	0.0	+0.4	+0.2	+0.0	-0.4	-0.2
3	-0.8	+1.0	+1.7	-1.0	+0.8	+1.7
4	-0.8	-0.4	0.0	+0.8	-0.4	0.0
5	-0.3	-1.6	-0.6	-1.6	+0.3	+0.6
6	+0.2	-0.9	-0.5	+0.2	-0.9	+0.5
7	+2.0	+1.0	+0.4	-1.0	+2.0	-0.4
8	+0.1	-0.1	+0.2	-0.1	+0.1	-0.2
Arithmetic mean and standard deviation	-0.0	-0.1	+0.1	-0.4 ± 0.8	+0.1 ± 0.9	+0.2 ± 0.7

Table 3.6 Intensity Components of Spurious Magnetizations Acquired by Magnetite Specimen during Set 2 Demagnetizations

Intensities in emu/cc x 10^{-5}. All symbols as in Table 3.5.

Specimen Position	ΔX	ΔY	ΔZ	N	F	U
1	-1.0	-1.2	+0.4	-1.2	-1.0	+0.4
2	+2.8	+1.8	-1.6	+2.8	-1.8	-1.6
3	0.0	+1.0	-0.9	-1.0	0.0	-0.9
4	+1.3	+1.7	+0.2	-1.3	+1.7	+0.2
5	-1.2	+0.4	+1.1	+0.4	+1.2	-1.1
6	-0.1	+1.0	-0.3	-0.1	+1.0	+0.3
7	+1.6	-3.0	+0.2	+3.0	+1.6	-0.2
8	-2.0	+1.8	-2.1	+2.0	-1.8	+2.1
Arithmetic mean and standard deviation	+0.2	+0.4	-0.4	+0.6 ± 1.8	+0.1 ± 1.5	-0.1 ± 1.1

Table 3.7 Intensity Components of Spurious Magnetizations Acquired by Magnetite Specimen during Set 3 Demagnetizations

Intensities in emu/cc x 10^{-5} . All symbols as in Table 3.5.

Specimen Position	ΔX	ΔY	ΔZ	N	F	U
1	-0.6	+0.4	+0.2	+0.4	-0.6	+0.2
2	-0.7	+0.8	-1.0	-0.7	-0.8	-1.0
3	+1.4	+0.7	+0.6	-0.7	-1.4	+0.6
4	+0.7	-0.7	-0.7	-0.7	-0.7	-0.7
5	-1.2	-1.7	-0.9	-1.7	+1.2	+0.9
6	+2.6	+0.0	+0.2	+2.6	+0.0	+0.2
7	-0.6	-0.2	0.0	+0.2	-0.6	0.0
8	-1.9	+0.2	+0.2	+1.9	-0.2	-0.2
Arithmetic mean and standard deviation	0.0	-0.1	-0.2	+0.2 ± 1.4	-0.4 ± 0.9	-0.1 ± 0.6

Table 3.8 Intensity Components of Spurious Magnetizations Acquired by Magnetite Specimen during Set 4 Demagnetizations

Intensities in emu/cc x 10^{-5}. All symbols as in Table 3.5.

Specimen Position	ΔX	ΔY	ΔZ	N	F	U
1	+0.6	+5.6	-0.5	+5.6	+0.6	-0.5
2	+6.0	+1.4	-0.5	+6.0	-1.4	-0.5
3	+0.1	-4.5	-0.7	+4.5	+0.1	-0.7
4	-3.1	+0.2	+1.1	+3.1	+0.2	+1.1
5	-1.8	+2.1	+1.5	+2.1	+1.8	-1.5
6	+3.0	+0.2	+0.5	+3.0	+0.2	-0.5
7	-2.2	-8.4	+0.2	+8.4	-2.2	-0.2
8	-1.8	+1.7	+1.3	+1.8	-1.7	-1.3
Arithmetic mean and standard deviation	+0.1	-0.2	+0.4	+4.3 ± 2.3	-0.3 ± 1.3	-0.5 ± 0.8

Table 3.9 Intensity Components of Spurious Magnetizations Acquired by Magnetite Specimen during Set 5 Demagnetizations

Intensities in emu/cc x 10^{-5}. All symbols as in Table 3.5.

Specimen Position	ΔX	ΔY	ΔZ	N	E	H
1	-0.5	+1.8	-0.5	+1.8	-0.5	-0.5
2	+1.3	+0.9	-0.7	+1.3	-0.9	-0.7
3	+1.0	-1.7	-1.0	+1.7	-1.0	-1.0
4	-2.1	+0.4	+1.4	+2.1	+0.4	+1.4
5	-0.1	-1.7	+0.0	-1.7	+0.1	-0.0
6	+1.7	+0.7	+0.1	+1.7	+0.7	-0.1
7	-0.9	+1.6	+0.3	-1.6	-0.9	-0.3
8	-0.8	-1.0	+0.4	+1.8	+1.0	-0.4
Arithmetic mean and standard deviation	-0.1	+0.1	0.0	+0.9 ± 1.6	-0.1 ± 0.8	-0.2 ± 0.7

Table 3.10 Intensity Components of Spurious Magnetizations Acquired by Basalt Specimen HH21A4, with the Earth's Field Fully Compensated. Intensities in emu/cc x 10^{-5}. All symbols as in Table 3.5

Specimen Position	ΔX	ΔY	ΔZ	N	E	U
1	+0.1	+0.8	-0.2	+0.8	+0.1	-0.2
2	+2.8	0.0	-1.3	+2.8	0.0	-1.3
3	+1.2	-1.0	+0.2	+1.0	-1.2	+0.2
4	-1.8	+0.4	+1.2	+1.8	+0.4	+1.2
Arithmetic mean and standard deviation	+0.6	+0.1	0.0	+1.6±0.9	-0.2±0.7	0.0±1.0

Table 3.11 Intensity Components of Spurious Magnetizations Acquired by HH21A4 with Earth's Field uncompensated.

Intensities in emu/cc x 10^{-5}. Symbols as in Table 3.5.

Specimen Position	ΔX	ΔY	ΔZ	N	E	U
1	+2.0	+10.4	-4.4	+10.4	+2.0	-4.4
2	+12.2	+1.7	+1.1	+12.2	-1.7	+1.1
3	-1.4	-13.8	+2.5	+13.8	+1.4	+2.5
4	-13.1	+1.6	+0.8	+13.1	+1.6	+0.8
Arithmetic mean and standard deviation	-0.1	0.0	0.0	+12.4±1.5	+0.8±1.7	0.0±3.0

discovered to be very soft, causing the demagnetized specimen to regain a small remanence if left in the earth's field for a few days. Further data concerning this specimen are given in Chapter 5.

The tests carried out on this specimen were abbreviated to include only Orientations 1-4 (Figure 3.6) with the specimen upright (Z positive), instead of the full eight orientations. The tests were otherwise equivalent to Sets 3 and 4 (2 spinner axes, peak demagnetization field 675 oe., with and without earth's field), as performed on the magnetite specimen. The results are given in Table 3.10 and 3.11 and in Figure 3.8, and show a similar behaviour to that of the magnetite specimen i.e., a weak random component and a strong oriented component in the N direction was observed after the treatments without earth's field compensation. However, the magnitude of the preferential directed component is here approximately twice as large as that produced in the magnetite specimen, while the random components, whose magnitude can be expressed by the standard deviations of the arithmetic means for the four specimen positions, show no such increase, but possibly a slight decrease.

Although it appears reasonable to assume that the presence of the non-random N-axis component is due to the action of the north component of the earth's field, experimental confirmation was lacking. To test this, the natural specimen (HH21A4) was used (since it produced a larger component, and hence, more conclusive evidence), and abbreviated tests, with four specimen orientations were performed as before, first with the east-west and vertical components of the earth's field both compensated, and secondly, with only the north-south component compensated. Tables 3,12 and 3.13 and Figure 3.8, lower half, illustrate the results of these tests. They clearly show that the N-S component is largely responsible for the observed spurious non-random component which, because of its conditions of formation, can be expected to be an ARM.

Tables 3.10, 3.13 and Figure 3.8 show that even when the N-S field is compensated, a small ARM remains in the N-direction in this case when only two spin axes are operative. A "t" test for significance of the difference from zero of the mean, 1.6×10^{-5} emu/cc, for the results of Table 3.10 (complete compensation, 2 spin axes) gave a probability of about 0.04 ($t = 3.56$, $N = 3$) that this mean could occur, which is to be considered mild significance, However, when these results are considered together it is quite evident that there still exists some preferentially directed components, leading to an ARM. However this is small and does not show up at all in the magnetite samples and will normally not be of any significance, being similar in intensity to the VRM component the specimen may acquire.

Table 3.12 Intensity Components of Spurious Magnetizations Acquired by PW21A4 with the E-W and Vertical Components of Earth's Field Compensated and the N-S Component Acting.

Intensities in emu/cc x 10^{-5}. Symbols as in Table 3.5

Specimen Position	ΔX	ΔY	ΔZ	N	E	U
1	+1.6	+7.7	+2.6	+7.7	+1.6	+2.6
2	+8.1	+0.1	-1.7	+8.1	-0.1	-1.7
3	-1.4	-7.1	-0.6	+7.1	+1.4	--.6
4	-8.4	-0.7	-0.4	+8.4	-0.7	-0.4
Arithmetic mean and standard deviation	0.0	0.0	0.0	+7.8±0.6	-0.5±1.1	0.0±1.8

Table 3.13 Intensity Component of Spurious Magnetizations Acquired by HU21A4 with the N-S Component of the Earth's Field Compensated, and the E-W Component and Vertical Component Acting.

Intensities in emu/cc x 10^{-5}. Symbols as in Table 3.5.

Specimen position	ΔX	ΔY	ΔZ	N	E	U
1	-0.8	+2.7	+0.5	+2.7	-0.8	+0.5
2	+2.5	+0.6	-2.6	+2.5	-0.6	-2.6
3	+0.5	-3.2	+1.0	+3.2	-0.5	+1.0
4	-2.3	-0.1	+1.0	+2.3	-0.1	+1.0
Arithmetic mean and standard deviation	0.0	0.0	0.0	+2.7±0.4	-0.5±0.3	0.0±1.7

3.6 Conclusions

Several tests have been applied to determine the effectiveness of the present apparatus, with the following results:

1. The preliminary tests, designed to remove TRM and IRM components previously given to various specimens, showed that the apparatus was certainly capable of magnetically cleaning specimens if the coercivity of the material is not excessively high, i.e. as long as the components it is desired to remove, are not themselves, "harder" than a certain maximum (say, 600 oe.) Removal of a TRM of finely divided hematite, for example, would be difficult as the tests confirmed.

2. All treatments repeated at various specimen orientations showed a random induced remanence with components whose intensity can be represented by the standard deviation of the respective N, E and U average values relative to the holder coordinates. These random components varied between $0.4\text{-}1.8 \times 10^{-5}$ emu/cc for both the magnetite specimen and the natural specimen, but as the magnetometer used in the remanence measurements is accurate to about 0.3×10^{-5} emu/cc, the magnetometer measurements may account for part of the scatter. The latter will normally affect none but the weakest of specimens.

3. If the number of spin axes for the specimen is reduced to two, an ARM tends to be acquired by the specimen where

high demagnetizing fields (say, more than 400 oe.) are in use and the north-south component of the earth's field is acting. This ARM component, directed north along the N-S axis of the specimen holder had an average intensity of 4.3×10^{-5} emu/cc and 12.4×10^{-5} emu/cc in the case of the magnetite and natural specimens respectively, when the complete earth's field was acting. The use of three spin axes instead of two was found to be effective in removing this component, and it does not appear when two axes are used while compensation of the ambient field is complete.

It would seem that to obtain reliable results, one should take both these precautions (earth field compensation and use of three spin axes with suitable speed ratios), especially when it is necessary to consider in addition the possible presence of fluctuations of the ambient field in the vicinity of the apparatus, due to local disturbances.

4. It is useful to attempt an explanation for the presence of the northward-directed ARM component that is produced when demagnetizing with two spin axes in the presence of the full earth's field (Tables 3.8, 3.9; Figure 3.7). Let a magnetic dipole be centrally located in the specimen and directed along the inner rotation axis, i.e. the E-W axis (Figure 3.9). The motion of this dipole is unaffected by the inner axis and so consists of a simple rotation in a plane perpendicular to the

N-S axis. Thus a magnetic force directed along the E-W or vertical axis will affect the imaginary dipole symmetrically about the respective axis, the mean torque of a full cycle being algebraically zero in both cases. However a force directed along the N-S axis will produce a constant torque in always the same direction along the Z axis of the specimen. The effect of this torque will be to deflect the imaginary dipole towards the axis of the force (N-S axis). Thus the alternating field in the demagnetizing coils produces in the specimen a remanence which in this case will be an ARM directed along the N-S holder axis. If three spin axes are used, however, the third axis will produce a sinusoidal oscillation of the torque about the Z axis of the specimen which randomizes the effect of the northward-directed field.

CHAPTER 4

DIRECT - FIELD DEMAGNETIZATION WITH SPECIMEN ROTATION ABOUT THREE AXES

4.1 Introduction

In the earlier applications of alternating-field demagnetization reported in the literature (see Section 1.4), the specimen was not rotated, and to obtain an alternating sinusoidal field through the specimen, alternating current was required for the demagnetizing coils. An effect similar to a.c demagnetization at 60 hz. could be achieved if the specimen were rotated (at 60 r.p.s.) about an axis perpendicular to that of the demagnetizing coils, but with direct current in the coils: this case was considered briefly in Section 2.5. At constant d.c., all vectors lying in the plane perpendicular to the rotation axis, i.e., parallel to the field, experience the same sinusoidal variation of the field in the course of one rotation. However, the a.c. case differs from this in the sense that only two antiparallel directions in the specimen experience the full torque due to the a.c. field, unless the demagnetization is carried out with the specimen in different successive positions.

A more realistic mechanism would involve a two-or three-axis spinner system with direct current. Such a unit has several advantages;

1. The peak field produced by the current at a given time is always acting, compared to the case of the field produced by a.c., which attains 95% or more of the peak value during 28% of a cycle only.

2. The use of d.c. would eliminate the need of a resonating capacitor in series with the coils to reduce the impedance of the coil circuit. Thus also a source of potentially dangerous high voltage [about 1,100 volts per ampere (r.m.s.) across the two terminals in the present system] would disappear.

3. With a well-filtered and low-noise d.c. power supply, there would be no trouble with even harmonics.

In view of these advantages, it has been attempted to use the present apparatus for some demagnetization tests in direct fields. Several difficulties are involved:

(a) It is necessary to obtain a d.c. power supply of sufficient voltage and current:

(b) The electrolytic resistor, while satisfactory with a.c., is unsuitable for d.c. due to excessive electroplating, and must be replaced by a different component capable of smoothly reducing the d.c. current.

(c) In a d.c. method efficient randomization of vector directions, which is now partly the function of the 60 hz. a.c.

will have to be accomplished entirely by the spinner system. A corresponding spin rate of 60 r.p.s. for the fastest frame is mechanically unattainable with the present design, so that substitution of a fast spin would require modification in the apparatus. However, the present maximum and minimum spin rates of 8 & 5 r.p.s. respectively should allow as efficient a demagnetization as is possible with larger spin rates, provided that the spin ratios about different axes, and the ratio of the smallest spin rate to the rate of reduction of the currnnt, are carefully adjusted within some optimum range of values. Simultaneous rotation about three axes is probably a minimum for error-free demagnetization in direct fields, as indicated by the results quoted previously and below. Then, if the slowest of the three spins is again 5 r.p.s., the current will have to be reduced more slowly than at present, to allow complete coverage of a specimen directions before the current has changed significantly. This has the disadvantage of increasing the length of a demagnetization run. However, neither possibility (a fast spinning system with relatively fast current reduction, or the present system with slower reduction) presents major technical difficulties and a choice or compromise between the two procedures can be based upon results of tests with the equipment.

(d) To achieve randomness in a.c. demagnetization, a minimum requirement was that the torques be distributed symmetrically about the plane perpendicular to the applied field. (Section 2.5). With direct fields instead of a.c. this criterion will be even more important. For this reason it becomes essential in the design to place the main rotation axis perpendicular to the direction of the applied field. It was also shown previously that such a system is particularly sensitive to direct-field components parallel to the main spin axis; e.g. in the present system, where this axis is in the N-S direction, the N-S component of the earth's field (o.2 oe.) was capable of introducing a non-random magnetization with a 2-axis spin system. When d.c. is used even a 3-axis system would probably be insufficient to prevent such non-random components if the d.c. in the N-S direction were not completely compensated. This implies that the large torques due to the applied field itself (in the E-W direction) might be easier to randomize than torques due to any N-S components three to four orders of magnitude smaller than the demagnetizing field. Then if the axis of the latter is not accurately perpendicular to the main spin axis, a relatively large field component may be set up in a N-S direction; e.g. for an angle of $90^{\circ} \pm 1^{\circ}$ between the two axes, and a maximum direct field of, say, 500 oe., the N-S component would amount to 8.8 oe.

Two power supplies were available: a battery supply with voltage sufficient for about 500 oe. in the field coils, and an unfiltered three-phase rectifier supply corresponding to about 1,000 oe. maximum. For the preliminary demagnetizations made so far, a system of manually adjusted rheostats with a potentiometer was used to reduce the field. To prevent the introduction of some irregular steps in the field-reduction curve, which is unavoidable with manual operation of the rheostats, the reduction will have to be accomplished through a mechanical drive, perhaps with the aid of a synchronous motor. In any case, experimental conditions under which the present tests were carried out are open to several improvements so that the results must be regarded as entirely tentative. Still, it will be seen below that, allowing for crudeness in the procedure, some striking results were obtained, these suggest that the direct-field procedure is potentially feasible.

4.2 Single-and Double-Component Demagnetizations

Several demagnetization similar to those considered in Sections 3.3 and 3.4 were performed, as follows: TRM components were imparted to one synthetic specimen each of pyrrhotite and magnetite, which were then demagnetized. The results are shown in Table 4.1 and Fig. 4.1 Two "mixed" specimens were then demagnetized, Specimen 1 possessing a secondary magnetization perpendicular to the primary component, and Specimen 2 with secondary antiparallel to primary; both secondary components were acquired at room temperature in about 300 oe. fields.

The results (Table 4.2 and Figures 4.2 - 4.4) are encouraging, being similar to those obtained with the conventional technique in Chapter 3. However, the intensity for the magnetite specimen after demagnetization to 700 oe. is higher than that observed with a corresponding a.c. field; also the changes in the directions of remanence do not fall on as smooth a curve as in the a.c. case.

4.3 Spurious-Component Tests

With large d.c. fields, there is certainly an increased possibility of inducing ARM components into the specimens. Therefore, as described in Chapter 3, a magnetite specimen, previously demagnetized conventionally at 810 oe., was demagnetized in each of the eight orientations of Fig. (3.6), with the conditions: 700 oe. maximum direct field, 3 spin axes, and complete d.c. compensation. The results, shown in Table 4.3, are more erratic than those obtained in demagnetizations with a.c. and indicate in all cases that a relatively large component, which may be predominantly random, has been introduced. The mean intensity of the magnetization is $25 \pm 8 \times 10^{-5}$ emu/cc, as compared to components of the order of 5×10^{-5} emu/cc introduced in a magnetite specimen spinning about two axes, with 675 oe. peak a.c. field in the presence of the earth's field. Reducing the maximum direct field to

500 oe. failed to change the pattern significantly, and the mean intensity after demagnetization was still 22 x 10^{-5} emu/cc.

The above results were obtained with the same rotation speeds as in the a.c. demagnetization, though the restriction imposed by the a.c. frequency on the maximum speeds (Chapter 2) does not apply with a steady field. It was argued previously that, while speeding up of the rotation to correspond to the order of frequency of the a.c. field (60 hz.) might prevent the acquisition of ARM components, a decrease in the rate of reduction of the d.c. current in the coils would probably accomplish the same thing. One might then reconsider introducing larger ratios between the spin rates about the three axes, which would lead to a close approach to perfect vector randomization, but at the expense of requiring a lengthier demagnetization procedure.

Allowing for substitution of a better power supply and a smooth method of field reduction, the present, tentative results indicate that a steady field method, with specimen rotation about 3 axes, is feasible. Further tests, which are now in preparation at the Physics Department, should show whether the advantages of direct-field procedure will compensate for the additional measures required to overcome the shortcomings that still exist.

Table 4.1 Remanent Magnetization of Synthetic Single-Component Specimens after Successive Steady-Field Demagnetizations

All dips are positive (north direction downward).

Treatment (d.c. field, oe.)	Magnetization after Treatment: Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-3})
	PYRRHOTITE		
before demagnetization	2.4	+1.8	1.61
90	2.5	1.3	1.02
250	3.0	2.6	0.13
450	4.2	3.9	0.082
630	1.0	0.0	0.087
850	7.7	1.8	0.083
	MAGNETITE		
before demagnetization	4.4	+13.3	2.0
90	6.6	12.1	1.4
250	19.5	0.0	0.22
340	37.0	15.1	0.20

Table 4.2 Remanent Magnetization of "Mixed" Synthetic Specimen after Successive Steady-Field Demagnetizations

Positive dips have north directions downward. Specimen compositions are as in Table 3.1.

Treatment (all d.c. fields	Magnetization after Treatment: Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-3})
	SPECIMEN 1		
before treatment	342	+16	0.37
secondary component added	347	-58	1.22
after 100 oe. demag.	342	-51	0.95
" 200 " "	341	-41	0.78
" 300 " "	342	-14	0.42
" 400 " "	343	+ 8	0.31
" 500 " "	343	+15	0.28
	SPECIMEN 2		
before treatment	357	+ 4	0.66
secondary component added	74	-19	0.26
after 100 oe. demag.	41	-11	0.26
" 200 " "	21	- 3	0.33
" 300 " "	8	+ 1	0.45
" 450 " "	355	+ 5	0.42

Table 4.3 Components of Remanent Magnetization of Magnetite Specimen, after Demagnetization in 700 oe. Steady Field.

Symbols as in Table 3.5. Intensities in emu/cc x 10^{-5}.

Specimen Position	ΔX	ΔY	ΔZ	N	E	D
1	+19.4	+8.3	-5.3	+8.3	+19.4	-5.3
2	+10.1	-23.8	-5.7	+10.1	+23.8	-5.7
3	-6.0	+3.6	+12.9	-3.6	+6.0	+12.9
4	+4.5	+27.1	+0.6	-4.5	+27.1	+0.6
5	+30.4	-0.6	-0.6	-0.6	-30.4	+0.6
6	-11.0	-7.7	-9.1	+11.0	+ 7.7	+9.1
7	-34.6	-0.2	+6.7	+0.2	-34.6	-6.7
8	-16.6	-8.2	0.0	+16.6	- 8.2	0.0

CHAPTER 5

SOME APPLICATIONS TO PALAEOMAGNETIC STUDIES

5.1 Introduction

Alternating-field demagnetization with the apparatus described in the previous chapters has been applied to natural rock specimens in various palaeomagnetic studies currently being carried out at Memorial University. These studies are mostly still incomplete with regard to NRM measurements (using the astatic magnetometer) as well as the stability work; hence the results of the alternating-field demagnetizations which are presented in this chapter serve more as a practical test of the apparatus than as an exhaustive stability study of the rock formations concerned. Moreover, as will be seen from the results themselves, alternating-field demagnetization in some cases may be insufficient to demonstrate stability, so that other methods will have to be used before the magnetic history of these rock formations can be fully understood.

5.2 Basalt Flows from South Coast of Labrador

During the summer of 1965, members of the Physics Department of Memorial University collected 36 oriented samples (31 igneous, 5 sedimentary) from exposures in three locations at the Chateau Bay area of Southern Labrador: Devil's Dining

Table (Henley Island), Castle Island and Table Head. At each of the former two collection sites, which are 0.8 km. apart at Henley Harbour (designated HH), the samples from a 2-4 meter section of black basalt, containing augite and labradorite with minor alteration products set in a fine-grained opaque groundmass. The basalts rest unconformably on Precambrian gneisses, except in one locality where there is some underlying arkose. The third site, Table Head (TH samples) is on the mainland of Labrador, 14 km. north-east of Henley Harbour. The exposure consists of about 18 m. of red arkose and conglomerate, topped by 3.6 m. of basalt having no visible columnar structure, which forms the upper part of a flat-topped hill. All these beds are relatively flat-lying with E to SE (seaward) geological dips, amounting to 20° for the HH basalts and 10° for the TH sediments and basalts.

Murthy (1966) obtained 193 cylindrical specimens from 32 of the samples and measured the remanent magnetization of each specimen. Fig. 5.1 shows his results for these three basalt flows, separately and combined (the latter with a circle of 95% confidence), for comparison the figure also shows the direction of the present axial geocentric field and actual field at the sampling site. Neither of these present field directions lies far outside the 95% circle of confidence for the mean magnetization of all samples. It is thus necessary to provide some independent stability test before palaeomagnetic inferences may be drawn from these results. Thus the author performed alternating-field demagnetizations on 6 "regular" specimens (4 HH,2 TH) and 3"anomalous" specimens (all HH). "Regular" and "anomalous" are used here in the sense that the direction of NRM of a particular specimen is respectively close to, or markedly different from, the mean direction for all samples in the rock unit. This does not necessarily mean that two specimens in the same category ("regular" or "anomalous") will exhibit similar magnetic behaviour during demagnetization tests.

The results are shown in Table 5.1, 5.2, and 5.3, and in Fig. 5.2. Of the "anomalous" specimens, two (HH1C3 and HH21A4) have very soft magnetizations, probably due to short-period VRM or IRM components; the other (HH8A1) has a strong and hard "reversed" magnetization (steep upward dips) which may reside in a component due to lightning.

There is considerable variation in the magnetic hardness even among the "regular" specimens, though the changes in direction here tend to be moderate. Moreover, the six "regular" directions become more closely aligned [as shown by the increase in the precision parameter, k (Table 5.3)] as the field is raised to 324 oe. peak, though after demagnetization at 324 oe., the directions are again more scattered. These results reveal the presence of a relatively hard component which may have been

Table 5.1 Remanent Magnetization of Selected "Regular" Basalt Specimens after Successive Alternating-Field Demagnetizations

Positive dips correspond to north poles downward.

Treatment (Peak a.c. field, oe.)	Magnetization after Treatment: Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-4})
	HH11A2		
before demagnetization	18	68	6.1
108	20	53	1.4
243	28	57	0.72
324	308	54	0.34
	HH16A1		
before demagnetization	78	77	10.1
27	57	77	9.2
68	66	77	7.4
135	70	77	6.6
282	85	75	4.8
324	352	80	2.4
	HH16B1		
before demagnetization	347	60	5.5
108	74	77	3.9
243	20	78	2.5
324	59	72	2.5

Table 5.1 (Continued)

Treatment (Peak a.c. field, oe.)	Magnetization after Treatment: Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-4})
	HH20A3		
before demagnetization	27	75	14.7
108	10	71	8.8
243	4	77	8.6
324	17	70	6.0
	TH2B1		
before demagnetization	54	57	6.7
27	45	55	6.7
68	58	62	5.5
81	55	65	5.1
202	29	65	5.0
405	63	68	3.1
	TH5A4		
before demagnetization	49	71	13.0
108	59	71	6.4
243	64	73	4.3
324	77	69	2.9

Table 5.2 Remanent Magnetization of Selected "Anomalous" Basalt Specimens after Alternating-Field Demagnetization

Treatment (Peak a.c. field, oe.)	Magnetization after Treatment: Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-4})
	HH1C3		
before demagnetization	131	21	3.4
27	127	43	2.9
68	150	45	1.2
135	130	75	0.95
	HH8A1		
before demagnetization	218	-65	3.3
27	195	-63	
68	173	-72	2.5
135	141	-74	2.6
202	151	-75	2.7
	HH21A4		
before demagnetization	198	73	1.3
27	193	72	0.84
68	181	73	0.33
135	187	42	0.05
202	352	-11	0.28

Table 5.3 Mean Directions of Magnetization for 6 "Regular" Basalt Specimens from Labrador after Demagnetization in Different Fields

All dips are positive north pole downward.

Treatment (peak a.c. field, oe.)	Mean Azimuth (deg.)	Mean Dip (deg.)	Precision Parameter, k	Radius of Circle of 95% Confidence
before treatment	31.8	70.6	336	9.85°
108 (except HH16A1, 135)	42.5	70.7	404	8.98°
243 (except TH2B1, 202)	36.4	72.6	486	8.19°
324 (except TH2B1, 405)	23,8	75.9	176	13.60°

stable for a considerable time. It does not follow, however, that this must constitute the primary component due to the original magnetization. For example, if the Henley Harbour and Table Head basalts and sediments are indeed of Lower Palaeozoic age, probably Cambrian as is generally assumed (Cristie, 1952), one would expect them to be magnetized with relatively low dips, corresponding to a low-latitude pole position in the southern part of the polar wandering curves relative to North America. The actually observed NRM, however, is steeply dipping (Fig. 5.1) and has a corresponding pole position in western Europe, far removed from any part of the polar wandering curve relative to North America, which passes through eastern Asia. This discrepancy suggests that the observed NRM, though relatively "hard" in many of the Labrador rocks, may actually be due to a secondary, post-depositional component.

As indicated by initial thin-section studies, the basalts contain chlorite and hematite, perhaps both representing alteration products of augite. In the rocks from both Henley Harbour and Table Head, altered hematite seems more prominent than magnetite. One possibility is that magnetite formed the primary component and that its magnetization is masked by that of the hematite; the latter could be a low-temperature CRM. In this case thermal demagnetization of the rocks, which is still to be carried out, may be a more suitable method of demonstrating stability.

5.3 Killary Harbour Ignimbrites

Killary Harbour is an inlet on the west coast of Ireland, at the border between Mayo and Galway counties. The collection consists of 25 oriented samples from three sites north of the inlet. The rocks are exposed in 4-5 bands of well-dated Caradocian (Upper Ordovician) ignimbrites (welded tuffs), which dip 50-55^{o} in a SSE direction.

Four specimens from samples collected at one of the sites were selected for alternating-field demagnetization to provide a preliminary indication of the usefulness of these rocks for palaeomagnetic studies. Table 5.4 and Fig. 5.3 show the results of the demagnetizations in fields up to 540 oe. (peak). Even prior to the treatment, one would infer some minimum degree of stability from the direction of the NRM of the specimens, which is generally southeast with low upward dips; this is quite different from the geomagnetic field at the sampling site, which is towards the north and with a downward (positive) dip. The magnetization, while weak, is quite hard; for example after demagnetization at 405 oe. the intensity of KH2A1 has been reduced by only one-half. Also the direction of magnetization in the specimens remains fairly constant, except for a slight increase in the vertical component (i.e., an increase in dip). The behaviour of KH6A1 is slightly irregular compared to the others.

Table 5.4 Remanent Magnetization of Selected Ignimbrite Specimens from Killary Harbour, Mayo County, Ireland after Alternating-Field Demagnetizations

(Positive dips correspond to north poles downward.)

Treatment (Peak a.c. field, oe.)	Magnetization after Treatment		
	Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-5})
	KH2A1		
before demagnetization	134	-14	6.7
108	134	-11	6.5
243	138	- 9	5.7
324	135	- 8	4.5
405	139	- 3	3.4
540	136	+16	2.4
	KH5C1		
before demagnetization	147	-10	3.6
108	152	-13	3.6
243	153	-10	3.4
324	147	- 6	3.0
405	155	+ 7	2.3

Table 5.4 (Continued)

Treatment (Peak a.c. field, oe.)	Magnetization after Treatment Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-5})
	KH6A1		
before demagnetization	150	+ 1	5.9
108	161	4	7.4
243	143	22	5.7
324	145	43	5.5
405	158	30	5.0
540	207	38	4.9
	KH7A2		
before demagnetization	174	- 8	3.6
108	174	-10	2.7
243	176	- 9	2.6
324	177	0	2.0

The four specimens studied are too few in number to lend themselves to a statistically valid analysis, but they appear to have high stability and their magnetizations are quite comparable with respect to direction and intensity. Hence the complete study of these rocks should yield useful palaeomagnetic results.

5.4 Virgin Rock Samples

Several rock samples have been oriented under water and recovered by aqualung dives from high shoals nearly 200 km. SE of St. John's, on the Grand Banks of Newfoundland (Lilly and Deutsch, in the press). This collection represents a pioneering attempt to obtain for palaeomagnetic study, samples of hard rock exposed on the sea bottom. The composition and texture of these samples varies, but all rocks collected may be classified as sedimentary breccia., the remanent magnetization of which resides mainly in small irregularly scattered grains of magnetite that are found throughout.

Due to the nature of the material, the magnetization of these rocks is often inhomogeneous and variable in direction and intensity. However, in 9 out of 10 cubical specimens measured (Murthy 1966), the NRM has a low dip so that its direction makes large angles with the present field direction; this suggests at least partial stability. Five months storage in the earth's field produced little change in the magnetization of the one

Table 5.5 Effect of Exposure to Earth's Field and Alternating-Field Demagnetization upon the Remanent Magnetization of Virgin Rocks Specimen VR4(8)

Positive dips correspond to north poles downward.

Treatment	Magnetization after Treatment		
	Azimuth (deg.)	Dip (deg.)	Intensity (emu/cc x 10^{-5})
before treatment	116	-32	10.9
after 5 months in earth's field	107	-28	10.9
27 oe. (peak a.c.)	109	-32	7.2
54 oe. (peak a.c.)	105	-44	2.7
after 4 days in earth's field	233	+60	11.9

specimen [VR4(8)] that was later subjected to alternating-field demagnetization. The results are shown in Table 5.5. The magnetization was not hard (it was essentially demagnetized in 54 oe. peak field), but the direction did not change greatly. However, once this remanence had been removed, a VRM was picked up in about 4 days, resulting in major fluctuations of the direction. Demagnetization of the specimen was continued at higher fields, but failed to stabilize the magnetization so that no further useful information was obtained.

The above tests show that the magnetization of the Virgin Rocks specimens is at least partially stable. While the results of the NRM measurements, together with the stability tests on the single specimen, are necessarily inconclusive, they indicate a sufficient degree of stability to encourage further palaeomagnetic work on the Grand Banks.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

An alternating-field demagnetization apparatus has been designed, constructed, and calibrated. The central component is a pair of massive coils based on a modified Helmholtz-coil design to provide a high field per unit of current while keeping satisfactory uniformity of field. Other components are: a three-axis spinner system, three pairs of orthogonally-mounted Helmholtz coils for eliminating the ambient magnetic field, and an electrolytic resistor for attenuating the demagnetizing current. The inner frame of the spinner acts as specimen holder.

This unit has been tested for effectiveness in removing magnetization components from synthetic and natural rock specimens. The tests were designed particularly to detect the presence of preferentially directed field components relative to the rotating specimen, which might introduce an unwanted anhysteretic magnetization.

In alternating fields up to 400 oe. (peak) the demagnetization was found to be essentially random as desired, when the spin was about two axes and the direct field in the specimen region was nulled. In the absence of direct-field compensation, i.e., with a field of the order of the earth's field acting, a three-axis spin was required to achieve a similar degree of randomness. However, with one rotation frame disabled, the apparatus was somewhat susceptible to ARM when the alternating field exceeded 400 oe.(peak) and the earth's field was not fully eliminated: it was shown that nulling of d.c. components parallel to the outer (N-S) spin axis is here especially critical.

The unit was used for several tests with direct instead of alternating current in the demagnetizing coils. The use of d.c. has several advantages, but while the attempt was successful in demagnetizing one-and two-component synthetic specimens, some spurious components were acquired in high fields (500 to 700 oe. peak). Possibly these do not have a systematic origin, but are caused by irregular steps in the field reduction when this is controlled manually. However, further tests of the direct-field method are necessary to establish conclusively that no preferentially directed magnetization is acquired. This can only be done after the equipment has been further modified, particularly to enable one to reduce the field smoothly. In any case, instrumental problems do not appear to be insurmountable and further work to establish the feasibility of the method is planned by the Physics Department.

A number of specimens from rock formations in Newfoundland and Ireland were demagnetized in alternating fields, as a first step in testing the stability of these rocks; and hence their suitability for palaeomagnetic studies.

6.2 Suggestions for Further Work

As shown in Chapter 5 the apparatus as presently constructed and employed can be used quite successfully. However, several suggestions for improving the apparatus might be considered:

1. For operation in fields larger than, say, 500 oe. a specially-designed autotransformer capable of approximating a perfectly smooth current reduction would have advantages over the electrolytic resistance; if much high-field demagnetization is to be carried out, it might be useful to substitute such a transformer equipped for automatic adjustment of the current. An autotransformer, however, cannot be used with d.c., and if direct fields are to be employed some other reduction method, such as a high-current potentiometer with a precisely-driven slide mechanism, must be used.

2. The spinner system can be improved by obtaining more robust belts, particularly if the rotation speeds are to be increased. This would also require some improvements in the efficiency of the turbine, which moreover is quite noisy at present. For the reason discussed in Chapter 4, an accurate determination of the angles between the various axes in the system, and particularly between the main spin axis and that of

the demagnetizing coils, is necessary for good performance. Any departure from an exact right angle between these axes must be corrected.

3. The complicated variation of torques acting upon the remanence vectors in a rotating specimen during demagnetization must be understood in detail if one is to make the system proof against non-random components. Some insight was gained from the results reported in Chapters 2-4, which made it possible, for example, to explain the acquisition of ARM components by the synthetic magnetite and natural basalt specimens spinning about two axes in the presence of the earth's field. It will be useful to carry out a more rigorous study of the variation of torques in two- and three-axis systems, during demagnetization in direct as well as alternating fields, and in the presence of one or more direct-field components in addition to the main field.

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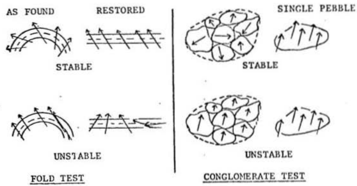
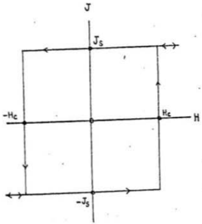
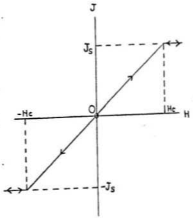


Figure 1.1 Field Tests of Magnetic Stability Proposed by J.W. Graham (1949)

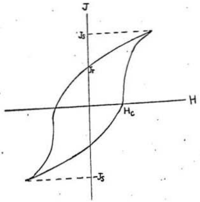
Arrows indicate the direction of natural remanent magnetism in the rocks. In the fold test it is assumed that the rock strata were originally flat-lying; the test then distinguishes between a magnetization acquired prior to folding ("stable") or after folding ("unstable"). In the conglomerate test it is assumed that the pebbles were removed by erosion from older sedimentary beds; the test distinguishes between a magnetization acquired prior to formation of the conglomerate ("stable") or since that time ("unstable"). (Figure after Deutsch, 1966).



(a) For case when all domains are parallel to applied field



(b) For case when all domains are perpendicular to applied field.



(c) For random distribution of domain directions

Figure 1.2 Hysteresis Cycle of Single-domain particles (after Néel, 1955)
H_c is coercivity, J_s is spontaneous magnetization, and J_r is the remanence.

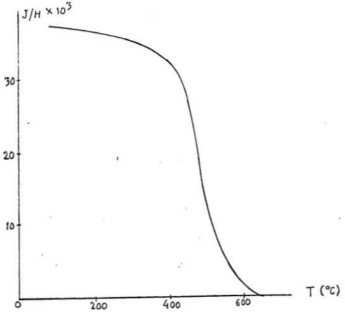


Figure 1.3 Thermoremanent Magnetization (TRM) Acquired on Cooling from Curie Temperature to any Temperature T in a field H and from T to Ambient Temperature in zero field.

J= Intensity of magnetization.

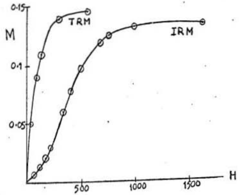


Figure 1.4 Dependence of IRM and TRM on applied field, H for Dispersed Magnetite M= Intensity of magnetization. M is in emu/g and H is in oe. (after Irving, 1964)

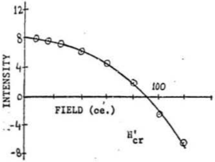


Figure 1.5 Steady Field Demagnetization of the Fossil Remanence of a Sample of Varved Clay from Vermont, U.S.A..

Intensity in emu/cc x 10^5. (after Johnson, Murphy, and Torreson, 1948)

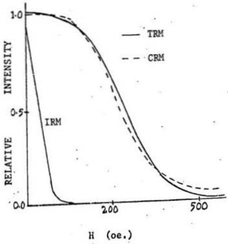


Figure 1.6 Alternating-Field Demagnetization Curves for Various Types of Magnetizations of Chemically Produced Fe_3O_4.

Normalized IRM, TRM, CRM after demagnetization, shown as a function of the peak value H of the demagnetizing field. TRM acquired in 0.5 oe. field, CRM in 10 oe. field, IRM in 30 oe. field. (after Kobayashi, 1959)

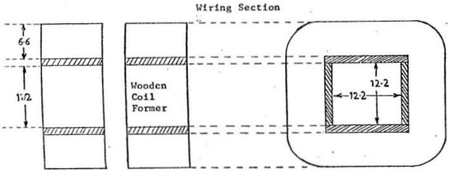


Figure 2.1

Dimensions of the

Demagnetizing Coils

(All dimensions in cm.)

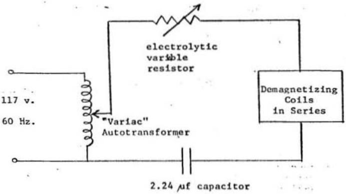


Figure 2.2

Electrical Circuit

for the

Demagnetizing Coils

Figure 2.3 Overall View of the Demagnetizing Unit.

Various components of the electrical supplies are shown at left. (The electrolytic resistor is behind the vertical shield at extreme left). The demagnetizing coils have been separated to permit free access to to the spinner system.

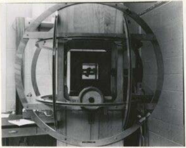


Figure 2.4 Side View of the Apparatus, showing Positioning of the Spinner System.

The coil positioning screw is in front, and the turbine wheel and air supply tubing are shown at right.

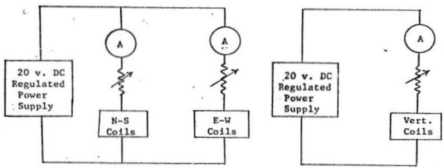


Figure 2.5 Power Supply to the D.C. Coils

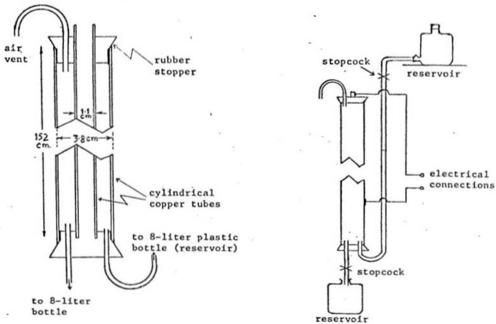


Figure 2.6 Electrolytic Resistance used to Decrease the Magnetizing Field

(a) Construction of the resistance tubes;
(b) Arrangement for filling and draining the resistance tubes with copper sulphate electrolyte; and electrical connections.

Figure 2.7 View of Spinner System with Turbine Wheel and Support.

(Unit removed from the demagnetizing setup.)

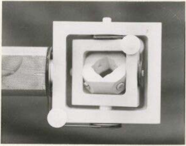


Figure 2.8 Closeup View of the Spinner System.

The three rotating frames, pulley wheels, belts, and part of the main rotating shaft are shown. Two of the four specimen retaining screws are seen on the inner frame, which can accommodate cubes as well as cylinders with a close fit.

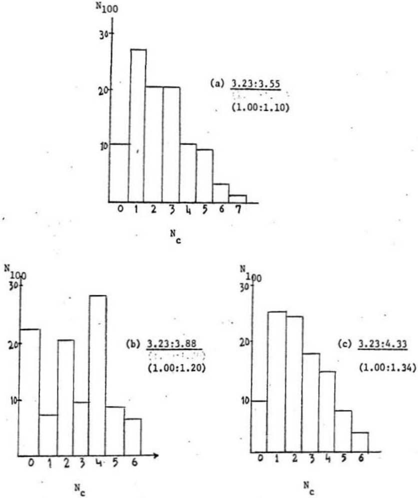


Figure 2.9 Histogram of the Relative Efficiency of Various Speed Ratios in 2-Axis Spinner Units

100 "points" or vectors, evenly distributed over an imaginary sphere centered at the specimen center, are considered, during 100 revolutions of the slower frame. N_{100} is the number of points experiencing the full torque of the 60-hz alternating field for a given number (N_c = 0,1,2, etc.) of times All speeds outside brackets are in r.p.s.

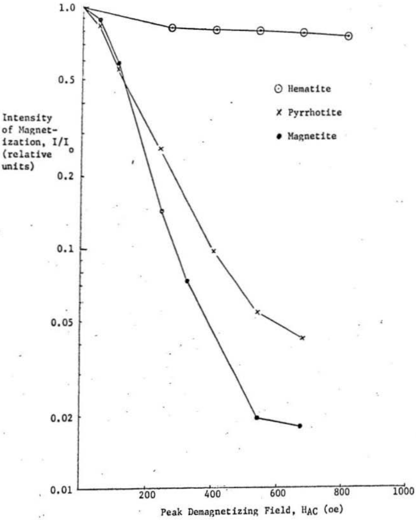


Figure 3.1 Remanent Intensity vs. Peak Demagnetizing Field for Single-Component Synthetic Specimens

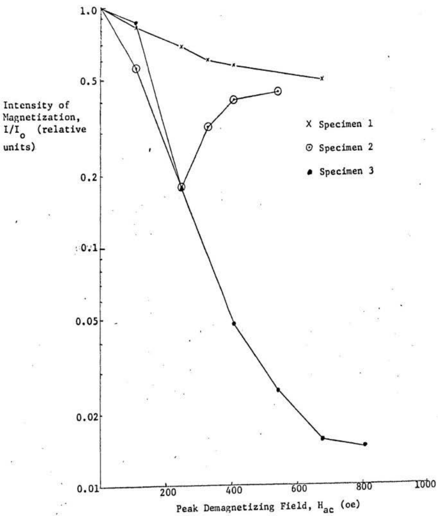


Figure 3.2 Remanent Intensity After Alternating-Field Demagnetizion of "Mixed" Synthetic Specimens

I_o = Intensity prior to demagnetization. (See also Tables 3.1,3.3)

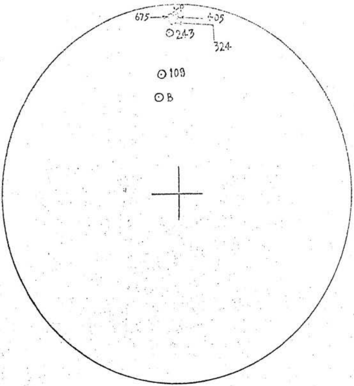


Figure 3.3 Variation of Direction of Remanence of "Mixed" Specimen, 1, after Alternating-Field Demagnetization in Progressively Higher Fields. Polar Equal Area Net.

X P- primary component; ⊙ B- both components before demagnetization; ⊙108- after demagnetization at 108 oe (peak), etc. All north poles in lower hemisphere.

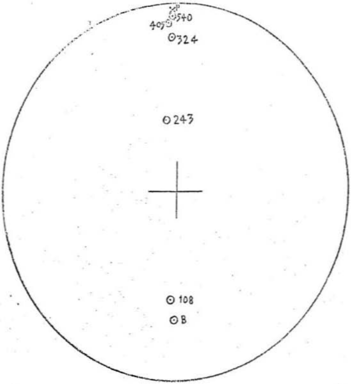


Figure 3.4 Variation of Direction of Remanence of "Mixed" Specimen 2, after Alternating-Field Demagnetization in Progressively Higher Fields.

Symbols as in Figure 3.3.

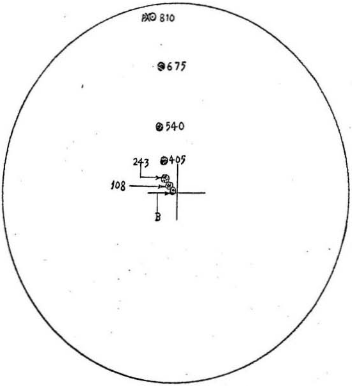


Figure 3.5 Variation of Direction of Remanence of "Mixed" Specimen 3, after Alternating-Field Demagnetization in Progressively Higher Fields.

XP- primary component; ●B- both components before demagnetization.
●108 - after demagnetization at 108 oe(peak), etc.
● - north pole in upper hemisphere; ⊙ - in lower hemisphere.

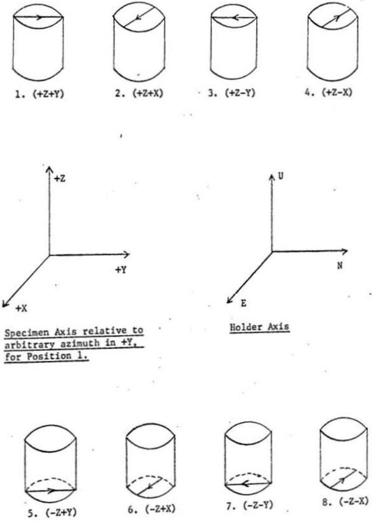


Figure 3.6 Specimen Orientations Relative to the Holder Axes, for Spurious- Magnetization Tests

(The symbols are as in Table 3.4. The arrow is an arbitrary azimuth marked on the upper cylinder surface.)

Figure 3.7 Components of Spurious Remanent Magnetization in Terms of Holder Co-ordinates for Magnetite Specimen, after Demagnetization at 675 oe Peak Fields, in 8 Successive Positions

(See Tables 3.4-3.9 and Figure 3.6.)

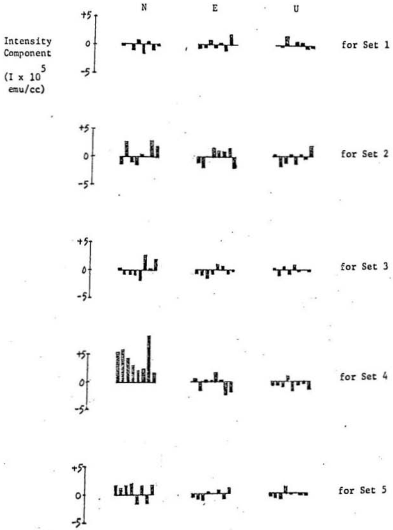
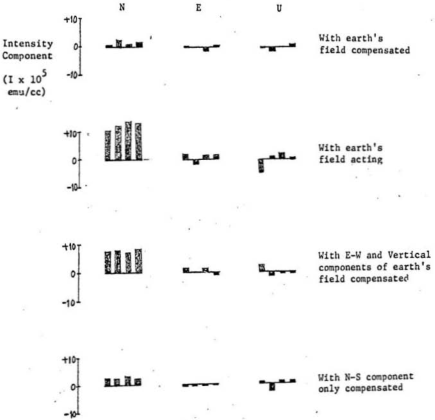


Figure 3.8 Components of Spurious Remanent Magnetization in Terms of Co-ordinates, for Basalt Specimen IIH21A4, after Demagnetization at 675 oe Peak Field in 8 Successive Positions

(Two spin axes operative, with earth's field compensation as shown. See Tables 3.4, 3.10-3.13, and Figure 3.6)



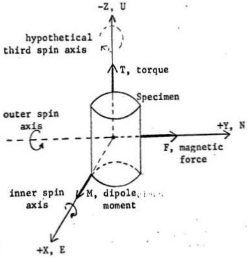


Figure 3.9 Non-Random Effect of a Direct Field in the N-S Direction in a Demagnetization about 2 Orthogonal Spin Axes

N,E,U: North, East, and Vertical upwards co-ordinates of the fixed apparatus
X,Y: Horizontal co-ordinates fixed in the specimen
Z: Vertical specimen co-ordinate
M: Moment vector in the X-direction of the specimen
F: Direct field vector fixed in the N-direction of the apparatus
T: Resultant torque in the Z-direction of the specimen

The Figure shows the specimen at the instant when its co-ordinates X,Y,Z coincide with the apparatus co-ordinates N,E,U, respectively.

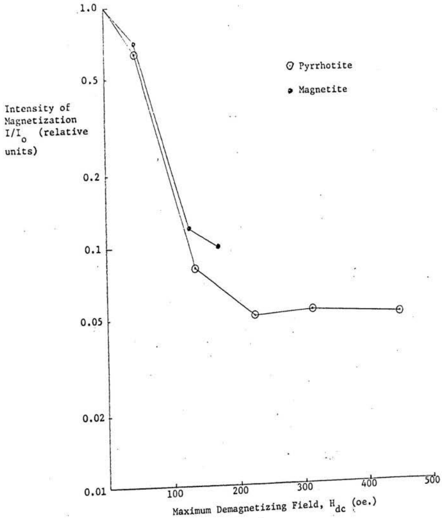


Figure 4.1 Remanent Intensity After Steady-Field Demagnetization of Synthetic Specimens

I_o = Intensity prior to demagnetization.

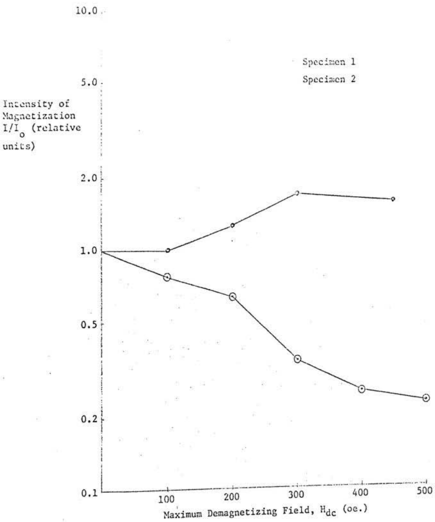


Figure 4.2 Remanent Intensity After Steady-Field Demagnetization of "Mixed" Synthetic Specimens

I_o = Intensity prior to demagnetization.

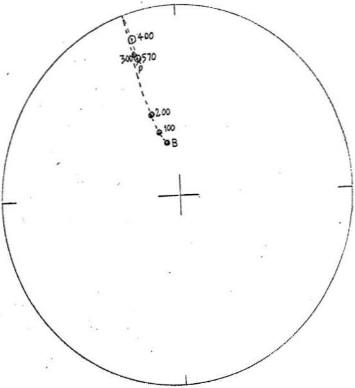


Figure 4.3 Variation of Direction of Remanence of "Mixed" Specimen 1, after Successive Steady-Field Demagnetizations

Symbols as in Figure 3.5.

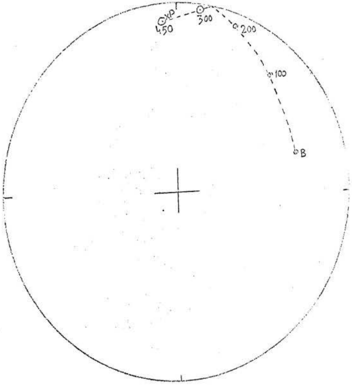
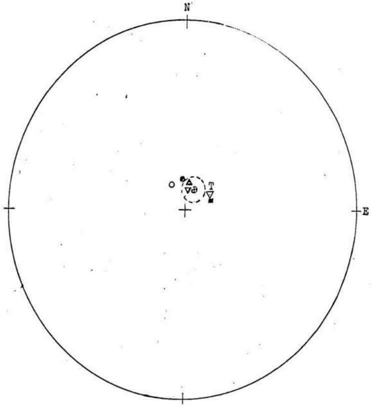


Figure 4.4 Variation of Direction of Remanence of "Mixed" Specimen 2, after Successive Steady-Field Demagnetizations
Symbols as in Figure 3.5.



<u>Figure 5.1</u> MEAN DIRECTIONS OF MAGNETIZATION OF BASALT FLOWS FROM LABRADOR

- ▽ Basalts from Henley Harbour (North poles downward)
- ▲ Basalts from Castle Island (" " ")
- ■ Basalts from Table Head (" " ")
- ⊕ Mean for the three sites
- ● Theoretical dipole field at sampling site
- ○ Direction of the present geomagnetic field at sampling site
- ▽ᵀ Henley Harbour results after tilt correction
- ( ) 95 % Circle of confidence

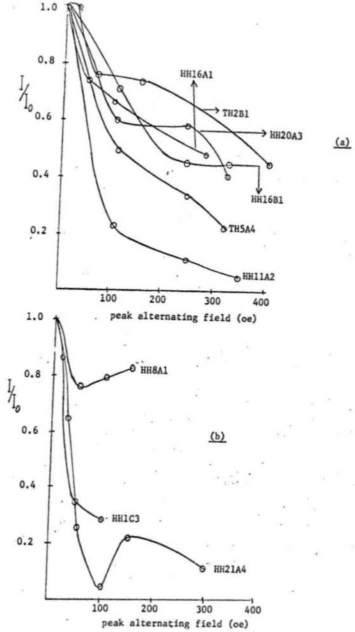


Figure 5.2 Variation of Intensity of Magnetization With the Demagnetizing Field for Certain Selected Basalt Specimens from Henley Harbour and Table Head, Labrador
(a) "Regular" Specimens; (b) "Anomalous" Specimens.
I_o = Intensity before treatment (NRM)

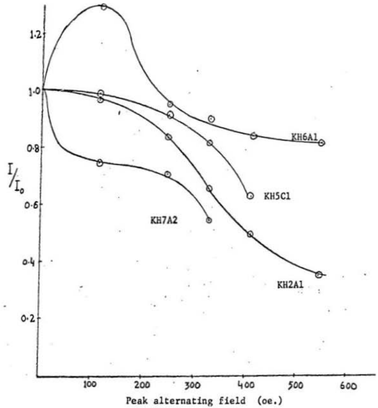


Figure 5.3 Variation of I/I_0 with the Demagnetizing Field for Certain Ignimbrite Specimens from Killary Harbour, Mayo Co., Ireland.

I_0 = Intensity before treatment (NRM)

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