CONSTRUCTION OF A THERMAL DEMAGNETIZATION

OVEN, AND INVESTIGATIONS ON

THE MATAHINA IGNIMBRITE

by

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A non-magnetic oven, and its ancillary equipment have been constructed and used to study magnetic properties of the Matahina ignimbrite, for which the following results have been established:

1. The directions of magnetization do not alter on heating in the oven.

2. The ignimbrite may be divided into sheets on the basis of magnetic properties.

3. Geological faulting has been revealed by divergent magnetization directions.

4. The T.R.M. acquired in the present earth's field is much greater than the N.R.M. This is possibly due to changes in minerals in the rock, either in the field since the rock was deposited, or on heating in the laboratory.

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INTRODUCTION

It has been known for a long time (R. Chevallier, 1925) that
igneous rocks may become strongly magnetized in the direction
of the weak magnetic field in which they cool.   The remanent
magnetization they acquire in this way is from a few to a
hundred times as great as the magnetization induced at normal
temperatures by the same field.   It has also been demonstrated
(Thellier & Thellier, 1959, Graham, 1949, Shimizu, 1960) that
such magnetization can be stable over very long periods of time
in fields which are in different directions from the remanent
magnetization.   These facts form the basis of the study of
palaeomagnetism, which tries to determine the variation in the
earth's magnetic field during geological time by studies on the
present magnetization of rocks.

It has been shown (J. Graham, 1953, Brynjolfsson, 1957) that
the magnetization of some rocks may differ from their original
direction of magnetization.   Often the difference is due to
the presence of two components of magnetization - a "hard"
component residing in grains having high coercive force, and
hence being resistant to changes in direction, and a "soft"
component residing in grains of lower coercive force, which
easily take up new directions of magnetization.   The techniques
of alternating field demagnetization and thermal washing rely on
the removal of soft components by randomizing their directions,
either by a steadily decreasing randomly changing alternating

magnetic field, or by moderate heating followed by cooling in
zero magnetic field, or a simultaneous combination of both
(As & Zijderveld, 1958, Irving, Stott & Ward 1961, Irving,
Robertson, Stott, Tarling & Ward, 1961).
When the original magnetization of an unstably magnetized rock
is not parallel to the present earth's field, it is usually
found that with treatment at successively higher peak fields
or temperatures, the direction of magnetization rotates away
from its original direction towards a new one.   If the direction
reaches a constant direction which is then maintained until the
sample is completely demagnetized, it is usually assumed that this
final direction is that of the field which originally magnetized
the rock.

The purpose of this thesis is to describe the construction and use
of a furnace in which thermal demagnetization experiments may be
carried out.

It is not proposed to discuss the results of the large amount of
work on palaeomagnetism which has been done.   A good review
article has been written by Cox & Doell (1960).

The theory of thermoremanent magnetization (T.R.M.) will be discussed
in some detail, because of its relevance to some stability tests
which have been devised, and its use in interpreting the results of
demagnetization studies.

The design of apparatus is discussed in the main body of the thesis,
while detailed instructions on its use are included as appendices.

To illustrate the purpose of the oven, a set of samples from an
ignimbrite sheet has been investigated, and conclusions regarding

the structure of the sheet, and past behaviour of the earth's magnetic field have been drawn.

MAGNETIZATION OF ROCKS

2.1　SOURCE OF MAGNETISM

The remanent magnetization of rocks resides in certain
ferromagnetic minerals which usually occupy a small
fraction (up to, but usually much less than, 10%) of the
volume of the rock.　These minerals are spontaneously
magnetized at all temperatures below their Curie points,
by the mutual alignment of the magnetic moments of the
iron atoms in their crystal lattice.　In the absence of
an external field this alignment is along one of several
"easy" directions within the lattice, which correspond to
a local minimum in the graph of energy of the crystal
versus magnetization direction.　According to Weiss'
theory of ferromagnetism, it is possible for several
domains to form within a crystal, in each of which the
magnetization is uniform and equal in intensity to the
spontaneous magnetization, σ per unit volume, the directions
in each domain being such that they form closed or partly
closed magnetic paths, and reduce the self-demagnetizing
field of the crystal.

The spontaneous magnetization generally decreases with
increasing temperature, in a manner which depends on the
particular mineral, and reaches zero at a temperature called
the Curie temperature.　Above this temperature the minerals
are paramagnetic.

It is found that increasing an applied magnetic field
increases the induced magnetic moment, until above a
certain field no further increase is observed.   This
is explained by supposing that below this maximum
field not all of the spontaneous moments are aligned
with the applied field, so that an increased field will
cause alignment of further domains, and increase the
magnetic moment.   The maximum moment (per unit volume)
which may be induced is called the saturation magnetic
moment, J_S.   If J_S refers to a pure magnetic mineral,
it is clear that $J_S = \sigma$.   If J_S refers to a rock, then
it will be lower than σ because the magnetic fraction
is only a small part of the volume of the rock.   When
studies are made of the variation in σ with temperature,
it is usually J_S which is measured, and the shape of the
graph of J_S versus temperature is the same as the shape
of the $\sigma - T$ graph.   Other magnetic properties of a rock
depend greatly on the size and shape of the crystals of
magnetic minerals, and will be referred to later.

2.2   MAGNETIC MINERALS

2.2.1 Detailed studies of the minerals involved in rock magnetism
have been described by Akimoto (1955) and Nicholls (1955),
while a large amount of work has been summarised by Nagata
(1953).

Although there are only three common types of ferromagnetic
minerals, and all contain iron, the situation is complicated
by the various solid solution series and compositional
changes which occur.

2.2.2 <u>Magnetite-ulvospinel Series</u> (Titanomagnetites)

Magnetite (Fe_3O_4) is the most important mineral in rock magnetism. It is a typical ferrimagnetic, and its crystal has the inverse spinel structure. It has a saturation magnetization of 92 - 93 e.m.u./gram at room temperature, and a Curie point of about $578^{\circ}C$. It is completely mutually soluble with ulvospinel ($TiFe_2O_4$) which is not ferromagnetic. The solid solutions have Curie points which range continuously from $578^{\circ}C$ to $0^{\circ}K$, depending on the proportion of magnetite present.

2.2.3 <u>Hematite-ilmenite Series</u>

Hematite (αFe_2O_3) is thought to be anti-ferromagnetic, but some workers have reported a "parasitic" ferromagnetism (Stacey 1963). It has a rhombohedral crystal structure and a low saturation magnetization (J_s about .5 e.m.u./gram), but a high coercive force, so that it is generally stably magnetized.

Fe_2O_3 occurs also as a cubic form, maghemite (γFe_2O_3), with the inverse spinel structure very similar to magnetite (γFe_2O_3 has a lattice defect, compared with Fe_3O_4). Maghemite is unstable, reverting to hematite at a temperature ranging from 300 to $800^{\circ}C$, depending to some extent on impurities (especially aluminium). Its saturation magnetization is 83.5 e.m.u./gm and its Curie temperature, obtained indirectly, is $675^{\circ}C$.

Hematite dissolves to a limited extent in Ilmenite ($TiFeO_3$), giving rise to ferrimagnetic mixtures at certain concentrations. Some of these solutions show the phenomenen of self-reversal of

magnetization, that is, they become magnetized in a
direction opposite to the applied field, when cooled
in a field from above their Curie point.

2.2.4 Pyrrhotite (FeS_{1+x}) $(x < 1)$

For some values of x the minerals in this series are
ferrimagnetic, having a hexagonal structure.   They have
a fairly strong J_s of 15 e.m.u./gm, and a Curie temperature
of about 300 – 325°C.   They seem to be stable to thermal
treatment, but in view of their low coercive force and
usually metamorphic origin, should be treated with some
caution.   Kang (1962) has studied the usefulness of these
minerals to papaeomagnetism.

2.2.5   It will usually be assumed in general discussions that the
minerals have properties similar to magnetite, with possible
variation in   being caused by the solution of $TiFe_2O_4$.

2.3   THERMOREMANENT MAGNETIZATION

2.3.1 Definition

When a rock is heated above the Curie point, θ, of its
magnetic minerals and allowed to cool in a weak magnetic
field, H, (about 1 oe.), it becomes magnetized parallel to
the field, with an intensity, $J_{\theta,H}$, which is usually much
greater than the magnetization induced at constant
temperature.   That is

$$Q_\theta = \frac{J_{\theta,H}}{\chi H} \gg 1$$

The ratio, Q, is a useful parameter to describe magnetizations.

Q_θ indicates the Q ratio of a T.R.M. Q_n will later be used to specify the ratio of the natural remanent magnetization (N.R.M.), (that is the magnetization before the rock is treated in any way), to the product of susceptibility and the earth's field.

2.3.2 Partial T.R.M.

The volume intensity of magnetization acquired in cooling from a temperature T, to room temperature, in a field H, is noted by

$$J_{T,H} .$$

If the magnetic field, H, is only applied between temperatures T_1 & T_2, $T_1 > T_2$, the rock acquires a partial T.R.M., denoted by

$$J\,{}^{T_1}_{T_2,\ H}$$

In general $J_{T,H}$ increases with T increasing, slowly at first, then rapidly over a range of temperatures from 200°C. below, up to the Curie temperature, above which $J_{T,H}$ is constant at a value called the total T.R.M., and denoted by $J_{\theta,H}$.

It is found that in fields less than 10 oe, $J_{T,H}$ is proportional to H, and over a wider range of fields

$$J_{T,H} = \frac{J_{T,1}}{k} \quad \tanh kH$$

2.3.3 The Addition Law of P.T.R.M.

If a rock is given a set of partial thermoremanences in a constant weak field, between, say, the temperatures T_1 & T_2, T_2 & T_3, T_3 & T_4 ...... T_{n-1} & T_n; $T_n > T_{n-1} > ...... > T_1$, then it is found that

$$\sum_{i=2}^{n} J\,{}^{T_{i-1}}_{T_i,H} = J\,{}^{T_1}_{T_n,H}.$$

That is, the total T.R.M. between any two temperatures
is the sum of any complete set of P.T.R.M.'s between
these temperatures.   If this is assumed to hold for very
small temperature intervals, then we may define a
characteristic function of T.R.M.

$$P(T) = \lim_{\Delta T \to o} \frac{1}{H} \frac{J_{T,H}^{T-\Delta T}}{\Delta T}$$

so that

$$J_{T,H} = H \int_{o}^{T} P(T)dT$$

The peak of the graph of $P(T)$ versus T corresponds to the
maximum rate of acquisition of T.R.M. with temperature
change, and usually occurs at a temperature $50 - 100^{o}C$.
below the Curie temperature.

$J_{T_2,H}^{T_1}$ depends on the temperature at which it is measured.
As long as the temperature does not rise above T_1, $J_{T_2,H}^{T_1}(T)$
changes reversibly with temperature, corresponding to
changes in the spontaneous magnetization of the grains.

The additivity law can be expressed by saying that the
magnetization acquired in any temperature interval is
independent of magnetization acquired at temperatures outside
this interval.   The explanation for this behaviour is that
each grain has a temperature, above which it may alter its
direction of magnetization, with the assistance of thermal
agitation, but below which it is fixed in direction.   The
form of the distribution of the so-called "blocking
temperatures" determines the shape of the P.T.R.M. versus
temperature curve.

2.3.4 Time Dependence of T.R.M.

It is found that the velocity of cooling has little effect on laboratory measurements of T.R.M. (Nagata, 1953).

THEORY OF ROCK MAGNETISM

This chapter summarizes the work on this subject by Néel (1955), Everitt (1961, '62) and Stacey (1963).

3.1 DOMAINS

The formation of domains, which reduce the net magnetic moment of a grain of crystalline ferromagnetic material is a way of minimizing the total magnetic energy of the grain. The sources of energy, the sum of which is minimised, are (Stacey, 1963)

i. Exchange energy, which is due to the fundamental interaction between electron spins, and which is minimised when all spins are parallel.

ii. Anisotropy energy, which arises through a weak coupling of the spins to the orbital moments, and hence to the crystal structure, so that there is a minimum in the energy of the atoms when their moments point along certain crystallographic axes, called the "easy" directions.

iii. Wall energy is the energy due to the above two effects when the spin directions are changing with position, as they must in the boundary region between two domains with different magnetization directions. The exchange energy is less in a thick wall, and the anisotropy energy less in a thin one, so there is an optimum wall thickness.

iv. Magnetostrictive strain energy occurs where adjacent domains have non-parallel directions, e.g. at closure domains.

v. Magnetostatic energy arises when the magnetization produces an external field, and therefore self-demagnetizing effects, and depends, among other things, on the shape of the grain.

vi. Energy due to an external field, the effect of which is usually treated as a perturbation of the structure calculated for zero external field.

3.2   SINGLE DOMAIN GRAIN THEORY

3.2.1   Hysteresis of a Single Domain Grain

There is a critical size of magnetic grain, below which the energy required to form a wall is greater than the decrease in magnetostatic energy which would occur, so that grains smaller than this consist of a single domain.   For magnetite this size is probably about 0.03μ and certainly less than 1μ, which is much smaller than the observed sizes of grains in rocks, (which are usually larger than 1μ). Hematite grains have much lower spontaneous magnetization than magnetite, which means their critical size is about 1mm, so that single domain theory should be appropriate to their magnetization.

Néel (1955) has developed a theory of T.R.M. based on single domains which gives a qualitative picture of the actual behaviour of rocks, and which has served as a basis for more refined models.   In single domain grains the magnetization may change in magnitude by changes in σ (with temperature), and   in direction by rotation of σ within the domain, against the anisotropy   and self-demagnetizing forces.

We may suppose the typical grain to be approximately spheroidal with demagnetizing factors N and M along the major and minor axes respectively $(M > N)$. Suppose σ makes an angle θ with the major axis, and consider the component of external field, H, parallel to the major axis. Neglecting magneto-crystalline anisotropy effects, the magnetic potential energy of the grain is $-H\sigma\cos\theta$, while the demagnetization energy of the grain is $\frac{1}{2}\sigma^2(N\cos^2\theta + M\sin^2\theta)$. The sum of these energies is the total energy, and from the minimum of this total we find (Nagata, 1953, p. 23) that the grain has a rectangular hysteresis loop with coercive force
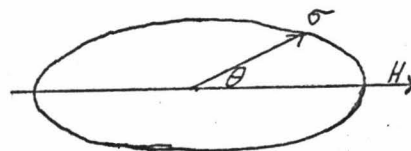
$$H_c = \sigma(M-N)$$
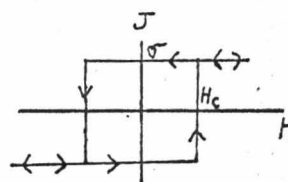
If the field is parallel to the minor axis of an oblate spheroid there is no hysteresis, so no remanent magnetization.
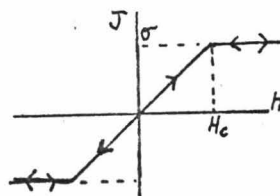
An assembly of randomly oriented grains without interactions will show a smoothed hysteresis curve (Néel, 1955) with remanent magnetization $J_R = \frac{1}{2}\sigma$, and coercive force about $\frac{1}{2}\sigma(M-N)$. This hysteresis makes possible the acquisition of remanent magnetization.

3.2.2 <u>T.R.M. and Isothermal Remanent Magnetization (I.R.M.)</u>

Consider an assemblage of the above grains with coercive forces ranging from zero to a large value H_c. Any isothermal remanent magnetization, which is produced by applying a field

$H_{,}> H_c$, for a short while, will be due only to the remanence of those grains with coercive force less than H. If the grains are heated, their spontaneous magnetization, and consequently their coercive force, decreases, so that more grains will be aligned parallel to the field, until just below the Curie temperature all grains are magnetized in this direction. On cooling in the field the directions remain parallel to the field while the spontaneous magnetization increases. Grains with axes inclined to the field will obviously contribute a component of their T.R.M. to the final T.R.M.

This gives a reason for the much greater strength and stability of T.R.M. compared with I.R.M., but is obviously oversimplified, and does not explain the dependence of T.R.M. on the magnitude of the applied field.

3.2.3 Blocking Temperature

To change from one to the other of its two stable magnetization directions, a single domain grain must cross a potential energy barrier of finite height. The energy of thermal vibrations of the crystal lattice is available to change magnetization directions by means of magnetostrictive and anisotropy effects. In an assemblage of identical non-interacting grains affected by thermal agitation in zero magnetic field, the remanent magnetic moment will decrease exponentially with time, so that

$$M = M_O \exp\left(- \frac{t}{\tau} \right) \qquad\qquad 3.1$$

where τ is the relaxation time.

Neel showed that

$$\frac{1}{\tau} = C \exp\left(- \frac{E}{kT} \right) \qquad\qquad 3.2$$

where E is the height of the potential barrier, and C is a function of the elastic constants, size, shape and temperature of the grains. Stacey (1963) summarises the various estimates of C, which range from 10^9 to 10^{13} sec^{-1}, but the absolute value is not critical. Since τ is strongly dependent on $\frac{E}{T}$, small increases in temperature will cause large decreases in the time constant, assuming the potential barrier height does not change to compensate (i.e., assuming $\frac{dE}{dT} \ll \frac{E}{T}$). The blocking temperature, T_B, is that temperature above which τ is much less than the duration of laboratory experiments, and below which τ is much greater than experimental times. This arbitrarily chosen experimental time is denoted by τ_g.

At temperatures greater than T_B and in zero field, the potential barriers may be freely crossed so that the average magnetic moment of the assemblage of grains is zero. The application of a magnetic field at these temperatures induces a magnetization which is found by assuming a Boltzman energy distribution, and a potential barrier $v\sigma H$ between direction parallel and anti-parallel to the applied field. For an assembly of identical grains the mean magnetization per grain turns out to be, (Néel, 1955),

$$M(T) = v\sigma(T) \tanh \frac{v\sigma(T) \ H(T)}{kT}, \quad (T > T_B). \qquad (3.3)$$

If the assembly of grains is cooled in the field $H(T)$, this equation holds until $T = T_B$, below which temperature further crossing of potential barriers of any sort stops, and the only change is in σ. Thus

$$M(T) = v\sigma(T) \tanh \frac{v\sigma(T_B) \ H(T_B)}{kT_B}, \quad (T < T_B). \qquad (3.4)$$

Thus $M(T)$ depends on the magnetic field at $T = T_B$ and nowhere else. The qualitative properties of T.R.M. are explained

directly, by assuming a suitable distribution of
blocking temperatures of the grains in a rock.

3.2.4 Comparison With Experiment

Everitt (1961) has performed a set of combined P.T.R.M.
and alternating field demagnetization experiments on
known single domain grains to compare the above results
with experiment.   His experiments compare coercive
force and blocking temperature of grains.   From equation
3.2,

$$\mathcal{L}_\theta = \frac{1}{C} \exp \frac{E}{kT_B}$$

so the blocking temperature depends on barrier height.
For single domain grains

$$E = \tfrac{1}{2}v\sigma H_c$$

so
$$T_B = \text{const. } v\sigma(T_B)H_c(T_B) \qquad\qquad 3.5$$

Everitt showed that for hematite grains T_B is proportional
to H_c at room temperature, and also to another factor which
could be the grain volume.

Néel (1955) showed that the addition of an external field,
H, alters the potential barrier height to

$$E = \tfrac{1}{2}v\sigma \frac{(Hc \pm H)^2}{H_c} \qquad\qquad 3.6$$

so that blocking temperature should depend on the ambient
magnetic field, but Everitt's experiments showed this
effect to be much smaller than predicted.

Everitt also showed that the intensity of T.R.M. is
proportional to tanh aH as predicted from equation 3.4,
but the dependence of intensity on the coercive force of
the grains was much less than expected from 3.4 and 3.5.

This theory appears to give reasonable agreement with experiment, and the deviations from it are probably due to the interactions between grains in experimental samples.

3.3 MULTI-DOMAIN GRAINS

3.3.1 General Principles of Multi-Domain Grain Theory

Any detailed theory of rock magnetism will attempt to correlate changes in magnetization of minerals with changes in domain structure, which modify the external field of the spontaneous magnetization. The magnitude of the spontaneous magnetization is a function only of the chemical and crystalline nature of the mineral, and the temperature.

It is necessary to study or hypothesise properties of the potential barriers impeding changes in domain structure. Néel's single domain theory assumed that the barrier is caused by the self-demagnetizing field, and gives some agreement with experiment.   Theories which consider multi-domain grains have to allow for changes in total magnetization of the grain caused by the growth of some domains at the expense of others.   The potential barriers in this case are those opposing movements of the domain walls, and depend on unknown factors such as crystal defects and the area and number of domain walls.

Everitt (1962) and Stacey (1963) have given theories of multi-domain grains based on simplified models of the potential barriers.   Their approaches are somewhat different, but their general conclusions similar, except in minor details.

Everitt obtains information about the potential barriers opposing domain wall motion from experimental relationships

between σ and T, and between H_C and T.   From this he derives a relationship between blocking temperature and coercive force, and an expression for the variation in total T.R.M. with magnetizing field.   Much stress is placed on deriving relationships which may be experimentally verified, and reasonable agreement is generally found.   The conclusion of most interest in the present work is that grains with high blocking temperature have high coercive force, although there is also a dependence on other properties of the minerals.   This supports the experimental observation that heating a mineral and cooling it in zero field will remove unstable components before the stable ones.

Stacey has developed a detailed picture of domain structure and its dependence on grain size, and used this to derive relationships between the observable magnetic properties. The only aspects considered here are those referring to the question of magnetic viscosity and its effects on the stability of palaeomagnetism.

3.3.2   Magnetic Viscosity

Magnetic viscosity is the term used to describe the change with time of an induced or remanent magnetization after changes in the ambient magnetic field have ceased (Street & Woolley, 1949, Shimizu, 1960).   These authors, working with alnico and magnetite respectively, have shown that over a wide range of temperatures

$$\delta J \ = \ \text{constant} + S \log t \qquad\qquad 3.7$$

where δJ is the change in intensity at a time t after changing the ambient magnetic field.   The viscosity coefficient, S, is proportional to absolute temperature.

Logarithmic change is not a characteristic of independent single domain grains, (Stacey, 1963), and is best explained on the basis of strong interactions between grains, for example, by the effect of the overall magnetization of the assembly of grains.

When dealing with multidomain grains, the force on a domain wall depends on the overall intensity of magnetization, J, of the grain, for there is a self demagnetizing field, NJ, within the grain, which acts on the wall. Stacey derives an expression for the change in magnetization with time, which reduces to the logarithmic equation for times common experimentally, but which tends to infinity as the time tends to infinity. His viscosity coefficient, S, is proportional to $\frac{T}{\sigma}$, and since σ is a function of temperature, is not directly proportional to T. However, changes in σ for magnetite are greatest about 150°C. below the Curie temperature, which is just where the linear dependence of S on T ceases in Shimizu's paper. Shimizu attempted to relate this lack of linearity to changes in coercive force in a single-domain model, but Stacey's theory provides a more satisfactory explanation.

Experimental work on time effects has largely been confined to induced magnetization or I.R.M. The only reference to time changes of T.R.M. seen by the author is that by Nagata (1953), where the change in $J_{T_2,H}^{T_1}$ of magnetite with time was measured at temperature T_1. In this case there is a wide range of potential barrier heights, ranging from nearly zero for those grains with blocking temperatures near T_1, to some larger, but finite height for those grains with $T_B = T_2$. The logarithmic law would not be expected to hold under these circumstances.

If the T.R.M., of a mineral with most of its magnetization residing in grains of high blocking temperature, were measured at room temperature, one would expect that a logarithmic decay would be observed, for the principle of thermal agitation still applies, and the potential energy barriers are approximately equal, as assumed by Stacey.   In Stacey's theory it is assumed that

$$H = H_e - NJ \ll H_c \qquad\qquad 3.8$$

where H is the field at a wall of coercive force H_c, when the external field is H_e.   For decay of remanence, $H_e = 0$, so

$$NJ \ll H_c$$

is a necessary approximation.   The intensity of T.R.M. is generally much higher than that of similar I.R.M.'s so it is necessary to see whether this approximation is still valid. The coercive force of the barriers opposing change in T.R.M. is known to be higher than those opposing change in I.R.M., by a factor about equal to or greater than the ratio of T.R.M. to induced magnetization in weak fields, so that the approximation will probably be valid.

If one could show that T.R.M. decayed logarithmically with time, for periods up to several million years, then a test of the usefulness of a rock for determination of the intensity of the past earth's magnetic field is obviously possible.   A form of the test is used by Thellier (quoted by Doell & Cox, 1961) who measures viscous changes in magnetization intensity at room temperature over a period of weeks in the earth's field, and rejects samples which, on the basis of logarithmic decay, would have a significant change in intensity over the 2000 years or so of their age.

A method used in this thesis is to measure directly the decay of T.R.M. with time as soon as possible after cooling to room temperature. Extrapolation allows an estimate of the upper limit of the changes in intensity of the N.R.M. In the absence of detailed testing of the hypothesis that the extrapolation is valid, the results are treated with reserve.

3.3.3 Temperature and Viscous Magnetization

If the temperature of a magnetic mineral is increased, thermal activation processes are speeded up, so it might be possible to reproduce in the laboratory at elevated temperatures, effects on the magnetization of rocks which have occurred over geological time at normal temperatures. In order to investigate this possibility, Stacey (1963) considers the effects of increased temperature on the time constants for crossing of potential barriers opposing individual domain walls. He expresses the height of the potential barriers in terms of the logarithmic viscosity coefficient, S, which he has previously related to various parameters of the domain walls, and which he knows is proportional to T, up to within 150° of the Curie temperature. The time constant for a single wall crossing the barrier of height E is

$$\ln c \mathcal{T} = \frac{E}{kT} \qquad 3.9$$

where c is the constant mentioned in paragraph 3.2.3 (c about 10^{10} sec^{-1}), and

$$E = \frac{kT}{NS} \left(\frac{2}{\pi} H_c' - H \right). \qquad 3.10$$

H_c' is a "microscopic" coercive force, proportional to σ^2 and independent of grain size or shape.

If $H \ll H_c$, these equations imply

$$\frac{\ln c \tau_1}{\ln c \tau_2} = \frac{S_2 \sigma_1{}^2}{S_1 \sigma_2{}^2} = \frac{T_2}{T_1}(\frac{\sigma_1}{\sigma_2})^2 \qquad 3.11$$

Processes with time constant τ_1 at temperature T_1 would take place with time constant τ_2 at temperature T_2. Processes may be supposed to be sufficiently complete to measure in a time equal to their time constant.

There are two time dependent effects to study. One is the decay of intensity of an original T.R.M. over geological time, without the simultaneous acquisition of a new direction of magnetization. The other is the acquisition of an I.R.M., when the rock has been situated for a long time in a weak magnetic field.

Stacey implies in his brief description of the uses of equation 3.11 that by heating at a constant temperature T_2 for a time $\overline{\tau}_2$, a magnetization may be produced in the laboratory which is equivalent to the I.R.M. acquired over geological time τ_1, at temperature T_1. The act of heating the rock to T_2 will destroy any T.R.M. acquired below this temperature, but the test can be used to find whether any I.R.M. may be expected to be possessed by grains having blocking temperatures greater than T_2.

To estimate a value for the temperature T_2, it is necessary to decide on T_1, τ_1 & τ_2, and estimate the variation of σ with T. In his 1962 paper Everitt publishes some experimental results for magnetite, which show that

$$= A (1300 - T) \qquad 3.12$$

(T in ^oK) for $300 < T < 700^oK$. Taking $\tau_1 = 10^{14}$ sec., $\tau_2 = 10^3$ sec., $c = 10^{10}$ sec.$^{-1}$ gives

$$\frac{T_2}{T_2} \left(\frac{1300 - T_1}{1300 - T_2}\right)^2 = 2 \qquad\qquad 3.13$$

Substituting $T_1 = 300^\circ K$ gives

$$T_2 = 550^\circ K \doteqdot 300^\circ C \qquad\qquad 3.14$$

The accuracy of this figure has been estimated, assuming that the theoretical assumptions are justified, and considering only changes in the assumed values for parameters. Equation 3.12 is written as $\sigma = A(B - T)$ $\qquad\qquad 3.15$

which leads to

$$\frac{T_2}{T_1} \left(\frac{B - T_1}{B - T_2}\right)^2 = R \qquad\qquad 3.16$$

$$dT_2 = \frac{\partial T_2}{\partial B} dB + \frac{\partial T_2}{\partial T_1} dT + \frac{\partial T_2}{\partial R} dR$$

The partial differentials have been calculated from 3.12, 3.14 and 3.16, giving

$$dT_2 = 0.6dB + 0.6dT_1 + 300dR$$

δT_2 may be supposed to be $\pm 20^\circ C$.

δR is about ± 0.2 for extreme values of c.

δB is about ± 100, estimated from errors in calculation from the graph (not allowing for possible variation between samples.) Thus δT_2 is about $\pm 100^\circ C$.

This theory indicates that if a rock does not acquire any I.R.M. after heating for about 20 minutes at $400^\circ C$. in the earth's magnetic field, then the N.R.M. remaining after heating to this temperature is probably in the direction of the original magnetization.

This test is more general than the usual methods, which rely on removing I.R.M. at lower temperatures than T.R.M., with a consequent change in direction of magnetization of the sample, unless the two happen to be parallel.

This test could be used to test the stability of the intensity of a T.R.M. produced in the laboratory, for changes in intensity of

the P.T.R.M. above 400°C., after heating to this temperature in zero field, might indicate the possible decay over geological time.   The results would not be valid if a large proportion of the blocking temperatures was near 400°C.

PARTIAL DEMAGNETIZATION OF ROCK MAGNETISM

4.1 ALTERNATING FIELD DEMAGNETIZATION

After the discovery of viscous magnetization of rocks it was
natural to attempt to demagnetize them by means of an
alternating field of peak intensity about the magnitude of
the coercive force of the viscous component.   It was found
by Thellier & Rimbert (1954, '55) that providing suitable
precautions are taken, such as a smooth reduction of the
peak field intensity to zero and the cancellation of the
ambient magnetic field, it is possible to remove I.R.M.s
acquired in fields up to several tens of oersted without
affecting a T.R.M. acquired in fields of about 0.2 oe.   The
method of alternating field (A.F.) demagnetization was used
by Brynjolfsson (1957) on some reversely magnetized samples,
which showed at first an increase of intensity on demagnetizing.
This increase could only have been caused by the removal of an
unstable component parallel to the present earth's field.   A
viscous magnetization acquired in the laboratory was able to
be demagnetized without affecting the direction of the stable
component.   The following year As & Zijderveld (1958) showed
that the direction of magnetization of some samples changed
progressively in the plane defined by the present earth's
field direction, and that of the previously determined
palaeomagnetic pole for that age of rocks, the change being
away from the present direction.   The effect of demagnetizing
a set of specimens was to reduce the scatter of their directions
of magnetization.   Their A.F. demagnetizations were performed
at up to 150°C. but they give no clear statement on what were
the separate effects of heating and of the alternating field.

Creer in 1959 improved the method of A.F. demagnetization
by spinning the sample about two perpendicular axes while
applying the field. This ensured equal demagnetization
in all directions and also reduced the effect of the ambient
stationary field. He found fields of several thousand
oersted necessary to completely demagnetize the sedimentary
rocks used.

Up till now people had considered the detailed effect on
each sample, but in 1961 Irving, Stott & Ward suggested
selecting a set of specimens from a collection, treating them
in increasing magnetic fields, and then treating all the
samples in that field which gave the greatest value for
Fisher's precision, "k", calculated from the selected specimens.
This is a convenient procedure when dealing with a large
number of specimens. These authors also noted that the
magnetization of the rocks never reached zero intensity, but
instead became random in direction after successive treatments
in very high fields. This effect was pointed out by Mumme
(1962) as a limitation to the technique, for, by correlating
changes in intensity and changes in direction, he showed that
there was a component present after demagnetization in strong
fields, which was stable in direction, but masked by the random
changes of the unstable component.

4.2 THERMAL DEMAGNETIZATION

In view of the connection described fully by Nagata (1953) and
others, between coercive force and blocking temperature, it
seemed reasonable to attempt to remove components of
magnetization residing in grains with low coercive force by

heating the rock and cooling it in zero magnetic field.
Cox (1957) reported a reduction in scatter of some basalt
samples on heating them and cooling in zero field.   Irving
and others (1961) constructed a furnace for heating
sedimentary rocks in order to demagnetize them, with the
particular view to cleaning magnetically some sedimentary
rocks with high coercive force which otherwise would require
several thousand oested for A.F. demagnetization.   As in
their work on A.F. demagnetization, they selected a temperature
of reheating which gave the least scatter in a trial selection
of samples.

The great potential of thermal treatment in the separation of
all the information contained in T.R.M.s has been fully
exploited by R. L. Wilson (1961, '62a).   He was working on some
laterites which had been baked by lavas and dykes, and which
contained two magnetic minerals, maghemite and hematite.   He
had constructed a furnace mounted beneath an astatic
magnetometer, so that measurements of magnetization were made
at elevated temperatures.   The maghemite was unstable
magnetically so that as the temperature was increased the
magnetization direction changed, until the temperature reached
about $350^{\circ}C.$, after which the intensity continued decreasing,
while the direction was constant.   These high temperature
directions were highly consistent between samples.
Demagnetization in increasing alternating fields was found not
to lead to a constant direction for each sample.   The hematite
was found to have no blocking temperatures below $400^{\circ}C.$, and
the maghemite none above this.   No changes in direction were
found above this temperature, so the magnetization of the
hematite appeared completely stable.   The hematite appeared

to have a total T.R.M. (i.e., it had been heated above its Curie point), so that an estimate of past field intensity was made by comparing the demagnetization curve for the N.R.M. above 400°C. with that of T.R.M.s in various fields. The T.R.M. in 0.43 oe proved similar to the N.R.M., so this field was taken to be the past field strength.

Wilson infers from the figure of 670°C. for the Curie temperature of hematite, and a range from 700°C. to 850°C. for the decomposition of maghemite, that the laterite must have been heated to between these temperatures to impose the observed T.R.M. The maximum temperature the country rock is heated to when covered by a non-convecting lava at temperature T is $\frac{T}{2}$, (Hatherton, 1954a). This would imply temperatures around 1500°C. for the lava, which is surprisingly high.

In the 1962a paper, thermal demagnetization studies on a laterite baked by two successive intrusions show two separate directions of magnetization. The maximum temperature of heating in this case was about 550°C., which was surprising to Wilson, who had apparently assumed the temperature of the country rock would reach nearly that of the dyke.

4.3 COMPARISON OF ALTERNATING FIELD AND THERMAL DEMAGNETIZATION

Mumme (1962) has compared A.F. and thermal demagnetization on some reversely magnetized basalts, and showed that those rocks with a predominantly high Curie point magnetization were little affected by low peak alternating fields, and vice versa. (Agreeing with Everitt, (1962) and confirming the principle of thermal demagnetization).

Irving & Parry, (1963) also report reduction of scatter of magnetization directions which are similar when either A.F. or thermal demagnetization is used.   Robertson, (1963), reports slightly better improvements in scatter on treating dyke and contact rocks thermally, and on treating plutonics with alternating field.

The decrease of scatter which can be gained from thermal treatment is similar to that gained by alternating field treatment.   The equipment used for thermal cleaning may be used to give such a variety of extra information that it is the most generally useful, although A.F. demagnetization is simpler and quicker to perform.

DESIGN AND CONSTRUCTION OF AN OVEN
FOR THERMAL DEMAGNETIZATION

5.1 INTRODUCTION

It is possible to mount an oven directly beneath an astatic
magnetometer, which enables measurements of magnetization to
be made while the specimen is hot, (Wilson, 1962b, Mumme,
1963). The alternative is to cool the specimen in zero
field after heating, and measure its magnetization at room
temperatures. Both methods lead to similar information
about the N.R.M. of the specimens.

If an oven is to be placed near a magnetometer, it must be
free from all ferromagnetic impurities, which would give
changing stray magnetic fields with changing temperatures.
It is necessary to ensure that the oven does not cause any
heating of the magnetometer, for this could lead to convection
currents, and possible drift in the zero reading.

The apparently more straightforward method of measuring the
magnetization at room temperature, after subjecting it to
thermal treatment, was chosen for this work.

5.2 GENERAL DESCRIPTION OF OVEN

The design was based on that of Irving, Robertson, Stott, Tarling &
Ward (1961). This oven allows twelve cylindrical specimens
to be heated up to 650°C. in an atmosphere of nitrogen, and
zero magnetic field. It consists of a heating element wound

on a copper "pot", (Fig. 5.3), which rests on an insulating
base and is surrounded by an insulating jacket, (Fig. 5.1),
made up of a set of concentric metal cylinders, separated
by a 1.2 cm air gap.   Specimens are mounted on a pottery
stand, (Fig. 5.2), supported on a ceramic shaft passing
through the base, where it is supported by a brass shaft
which may rotate about its axis (Fig. 5.5).   The oven is
made from non-magnetic materials, and is situated at the
centre of a set of Parry coils, which are used to cancel the
ambient magnetic field, (Fig. 5.4).   The following sections
present detailed description and design considerations.

5.3   SIZE OF OVEN

The larger the oven is, the shorter the average time for
treatment of each specimen, for the time for a heating cycle
increases at a slower rate than the number of specimens
which may be contained in it.   A practical limit is set by
the need to cancel the ambient magnetic field over the volume
of the oven.   The oven size was decided by first choosing
the arrangement of specimens within the oven (Fig. 5.2), and
then calculating the separation between specimens necessary
to prevent interaction of their magnetic fields.   The
criterion assumed was that a cylindrical specimen 35 mm in
diameter and 35 mm high, with an intensity of magnetization of
10^{-3} e.m.u./cc should produce a field less than 20γ at its
nearest neighbour.   This gave a spacing of 9 cm between the
centres of specimens, which led to the choice of a diameter
of 24.5 cm and a height of 20.5 cm. as the internal dimensions
of the pot surrounding the specimens.

5.4 HEATING ELEMENT

The heating element is wound on to a $\frac{1}{8}$" thick copper pot
surrounding the specimens.   This copper pot assists in the
attainment of a uniform temperature distribution within the
oven.   Seventy feet of 17 B. & S. gauge nichrome wire,
insulated with $\frac{1}{8}$" ceramic "fish-spine" beads, are non-
inductively wound in a double spiral groove machined in the
pot (see Fig. 5.3).   The tension is adjustable and is
sufficient to hold the wire in the groove without other
support.   The resistance of the wire is 26 ohms, which
allows 2KW to be dissipated at 230 volts.   The beads and
wire do not contribute significantly to magnetic fields
within the oven.

Electrical connections to the element proved troublesome at
first.   Sindanyo, which is an asbestos-based electrical
insulator intended for moderately high temperature use, lost
its mechanical strength after several heating cycles to 600°C.
Steatite, a form of talc, is a soft material, easily worked
with hand tools in its natural state, which becomes a hard
ceramic very suitable as a high temperature insulator, after
heating to 1100°C.   This material was used to insulate the
ends of the element, and has proved completely successful.
The lower terminal block (Fig. 5.3) is in two parts, held
together by a brass nut and bolt.   Brass connection strips
are hard soldered to the nichrome wire, and are clamped into
recesses between the two parts of the block when they are
assembled.   These strips fit over terminals permanently
fixed to the base of the oven, when the pot is placed over
the specimens.   The block itself fits into a slot cut in the
pot, in order to hold it.

The upper terminal block is a brass wedge which fits into
a matching wedge welded to the pot, with a steatite
insulator between the two.   The wires pass through the
block and are held in position by screws, in order to be
able to adjust the tension in the wire.   The tension holds
the wedge in position.   Because some oxidation of the wire
occurs, the two wires are twisted and hard soldered, to make
electrical connection.

5.5   INSULATION OF OVEN

This follows the design used by Irving and others.   A
removable jacket consists of an aluminium frame bolted to a
sindanyo plate, on which sit two copper and three aluminium
cylinders, separated by air gaps of 1.2 cm.   This insulation
is light and efficient, and does not require a water supply,
which in the present case was an important consideration.
The inner, copper, cylinders, were initially chromium plated,
but owing to its ferromagnetism the usual base coating of
nickel had to be omitted.   The copper quickly oxidized beneath
the chromium, which peeled off, but this has not seriously
affected the performance of the oven.   A counterweight
arrangement allows the jacket to be easily lifted to give
access to the oven.

The base is a hollow sindanyo box, with two copper and two
aluminium plates forming horizontal divisions which reduce
heat transfer, both by convection and radiation.

5.6   SAMPLE HOLDER

It was suggested by Mr Gellen at the start of this work that
the effect of stray fields remaining after cancelling the main

part of the ambient field might be reduced by rotating the specimens about a vertical axis, which would randomize the effective direction of any horizontal component present. The effect of vertical components might be detected by using two specimens from the same core from a sample, which ought both to be magnetized in the same direction. If they were placed above each other, but one upside down with respect to the other, then effects of the vertical field should be able to be distinguished from changes in the magnetization due to instability.

It was envisaged that the holder might sometimes be required to rotate while a vertical field is applied. A metal sample holder in these circumstances might have magnetic fields near it due to eddy currents, so the present sample holder was designed and constructed by Mr Roy Cowan from pottery clay, (Fig. 5.2). The ceramic shaft which supports the holder withstands great thermal stresses, and is a former from a large wire wound resistor. It is attached to the pottery by cold setting cement, and to a cup in a brass fitting at its lower end by type metal, which was poured in while molten, and expanded on freezing to give a very tight joint. This brass fitting screws on to a shaft which is rotated on "tufnol" bearings, (Fig. 5.5), by a pulley and cord drive from a 70 r.p.m. induction motor, placed six feet away from the oven to reduce its effect on magnetic fields at the specimens.

5.7 INERT ATMOSPHERE

To prevent oxidation of the specimens, and especially of the copper parts of the oven, nitrogen gas is passed into the oven while it is hot. Commercial nitrogen is passed through

an ordinary flow regulator, a needle valve to provide
sufficient back pressure to ensure correct operation of
the regulator, and a differential mercury manometer which
allows comparison of flow rates.   It has been found
necessary to remove traces of oxygen by bubbling the gas
through alkaline pyrogallol solution (Thorpe, 1937), and to
dry it with concentrated sulphuric acid.   An "oxygen-free"
grade of nitrogen has recently become available, but has
not been used.   The nitrogen enters the oven through a
copper pipe which extends to near the top of the oven.

5.8   POWER SUPPLY

At present control of temperature is achieved by regulating
the supply voltage with a variable transformer.   Automatic
control (available commercially) would be convenient, but
expensive.   With the present system temperatures can be
adjusted to within 20°C. of the desired temperature.

An isolating transformer is incorporated between the oven and
the Variac, in order to reduce voltage stresses on the
insulating beads of the element.   (It is also a safety
precaution).   The original arrangement enabled the full
mains voltage, of up to 350v. peak, to be applied across
one thickness of beads, between the wire and the earthed pot.
At high temperatures this was sufficient to cause electrolytic
conduction to occur in the porcelain (Riddle, 1927), and
resulted in complete breakdown and fusion of the element.
The breakdown temperature was found to be highly voltage-
dependent, so that the isolating transformer, by ensuring
that the maximum voltage can occur only across two bead
thicknesses, prevents breakdown at temperatures below at
least 650°C.

5.9 TEMPERATURE MEASUREMENT

It is convenient to use thermocouples to measure temperatures because as many as are needed can be easily and cheaply made, connected to a millivolt recorder, and recorded along with information such as changes in the current used to cancel the earth's field. Chromel-alumel and platinum thermocouples are the most resistant to oxidation at the temperatures used, but platinum ones require the provision of a cold junction near the oven, in order to keep leads short (and therefore less expensive). Chromel-alumel ones are used here despite their ability to become permanently magnetized (this is the most serious source of field gradients in the oven).

Junctions are made by cleaning and twisting the wires, and then hard soldering them. When the solder melts (at about $620^{\circ}C$.) there is a lag in temperature of the junction, owing to the latent heat absorbed, but this is not serious in this application. The wires are insulated by 3" long two-hole ceramic insulators in the high temperature regions.

Connection to the thermocouples on the rotating sample holder are made via mercury trough slip rings mounted on the drive shaft, (Fig. 5.5). No noise or stray D.C. voltages were detected here.

The E.M.F. of the thermocouples used was measured at the freezing points of tin, lead, and zinc, and found to lie on the calibration curve given by Roeser (1941). For the purposes of these measurements it can be assumed that the E.M.F. varies linearly with temperature, with coefficient $41.7 \mu v/^{\circ}C$.

5.10 UNIFORMITY OF TEMPERATURES IN OVEN

Specimen temperatures were measured by means of thermocouples inserted in holes drilled in some dummy specimens. With the heating rates used the inside of a specimen could be about $10^{\circ}C$. cooler than the outside, but this became practically zero five minutes after holding the oven temperature constant.

The temperature of the pot at its bottom was about $25^{\circ}C$. lower than that at its top at $300^{\circ}C$., with very little change with time. This is presumably due to thermal conduction through the base being greater than that through the jacket, and leads to a difference in temperature between specimens on the top and bottom of the sample holder. The temperature difference is about 25° to 50° at low temperature ($< 200^{\circ}C$.) but decreases with increasing oven temperature, so that separate measurements of top and bottom layer temperatures are usually required. There is no difference in temperature greater than $1^{\circ}C$. between similar specimens on the same layer.

An attempt to supply extra heat to the bottom of the oven, with a flat heating coil, resulted in cracks forming in the sindanyo of the base, and was not repeated. A heavy copper plate on the base might assist in attaining uniform temperatures, but the oven is useful as it stands, so further work has been directed towards getting results from the present design.
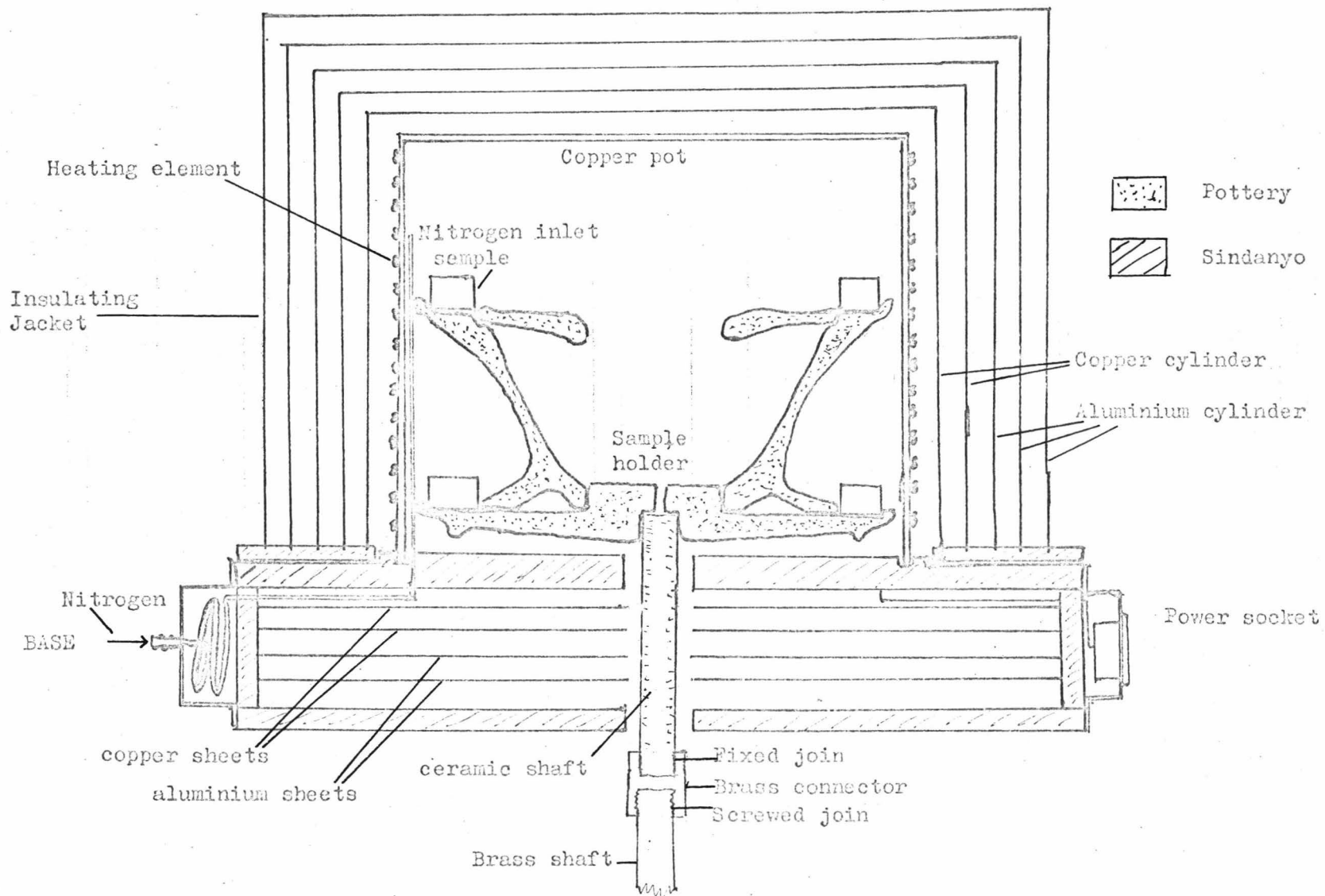
Fig. 5.1 Cross Section of Oven

Heating element

Insulating Jacket

Nitrogen inlet
sample

Copper pot

Sample holder

Pottery

Sindanyo

Copper cylinder

Aluminium cylinder

Power socket

Nitrogen

BASE

copper sheets

aluminium sheets

ceramic shaft

Fixed join

Brass connector

Screwed join

Brass shaft

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Fig. 5.2 Sample Holder
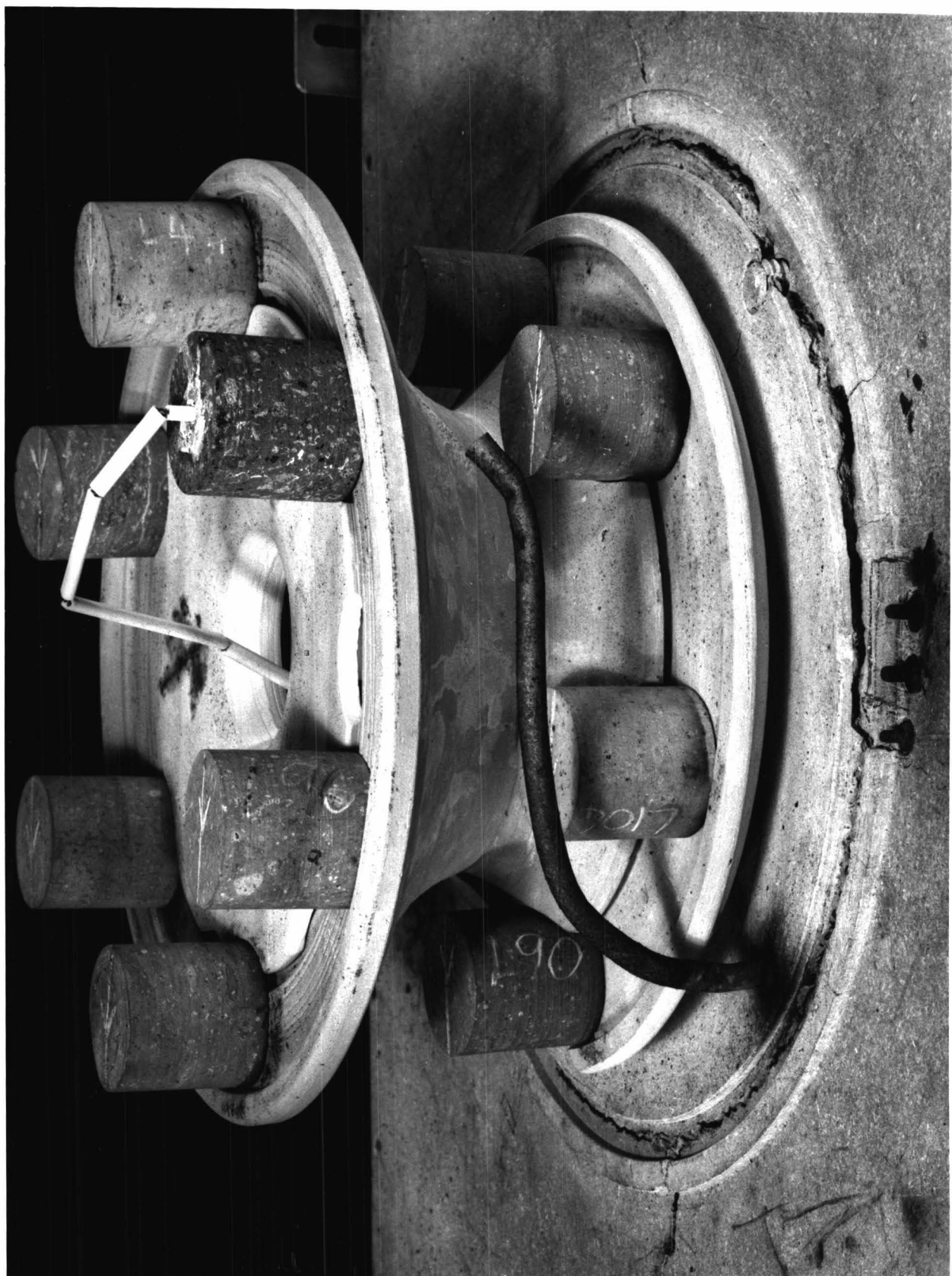
Fig. 5.3 Heating Element
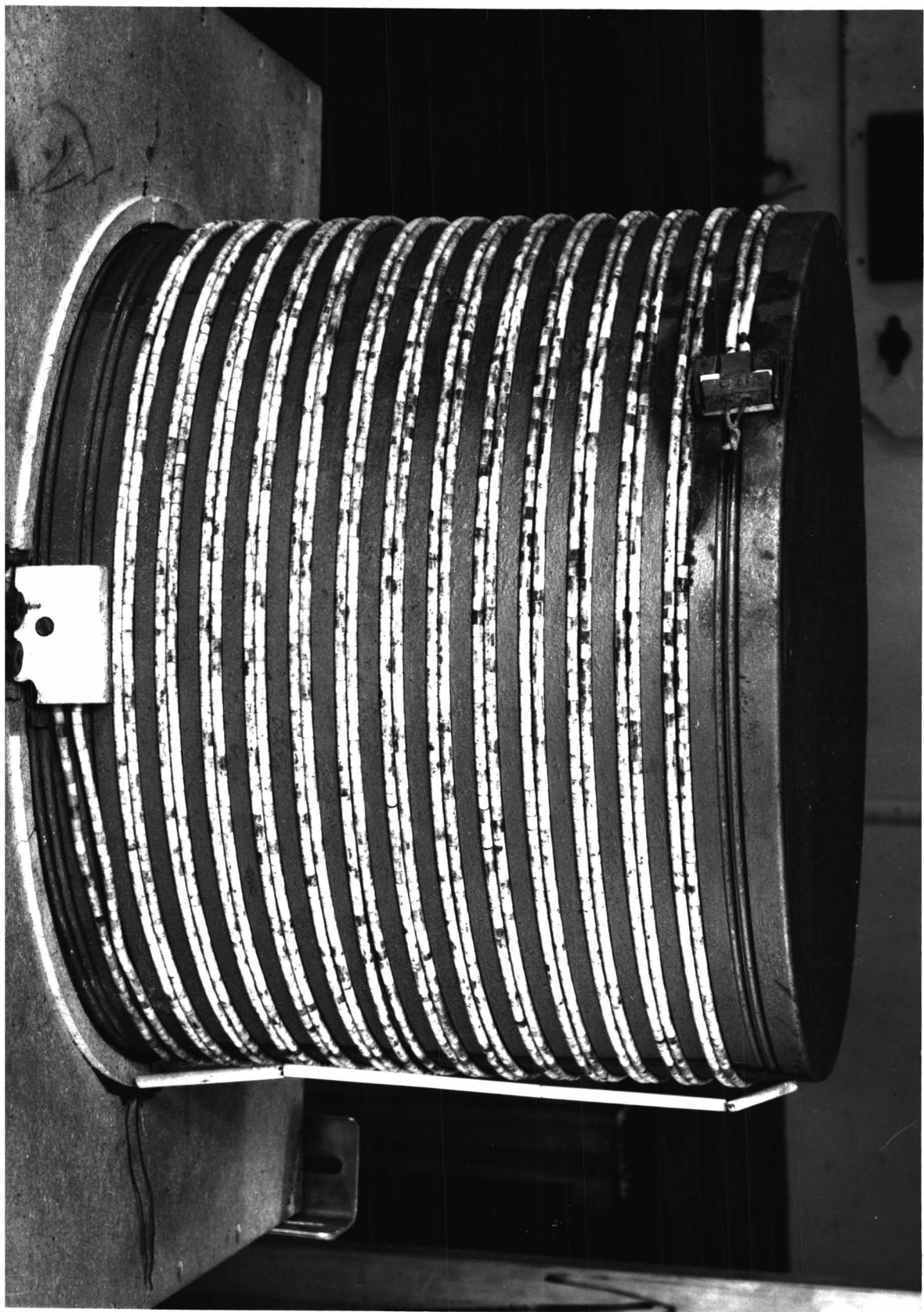
Fig. 5.4 Oven and Field Cancellation Coils

Screw to allow attachment of
ceramic shaft

Tufnol bearing

Mercury slip rings

Drive
belt

Brass
shaft

Tufnol
bearing
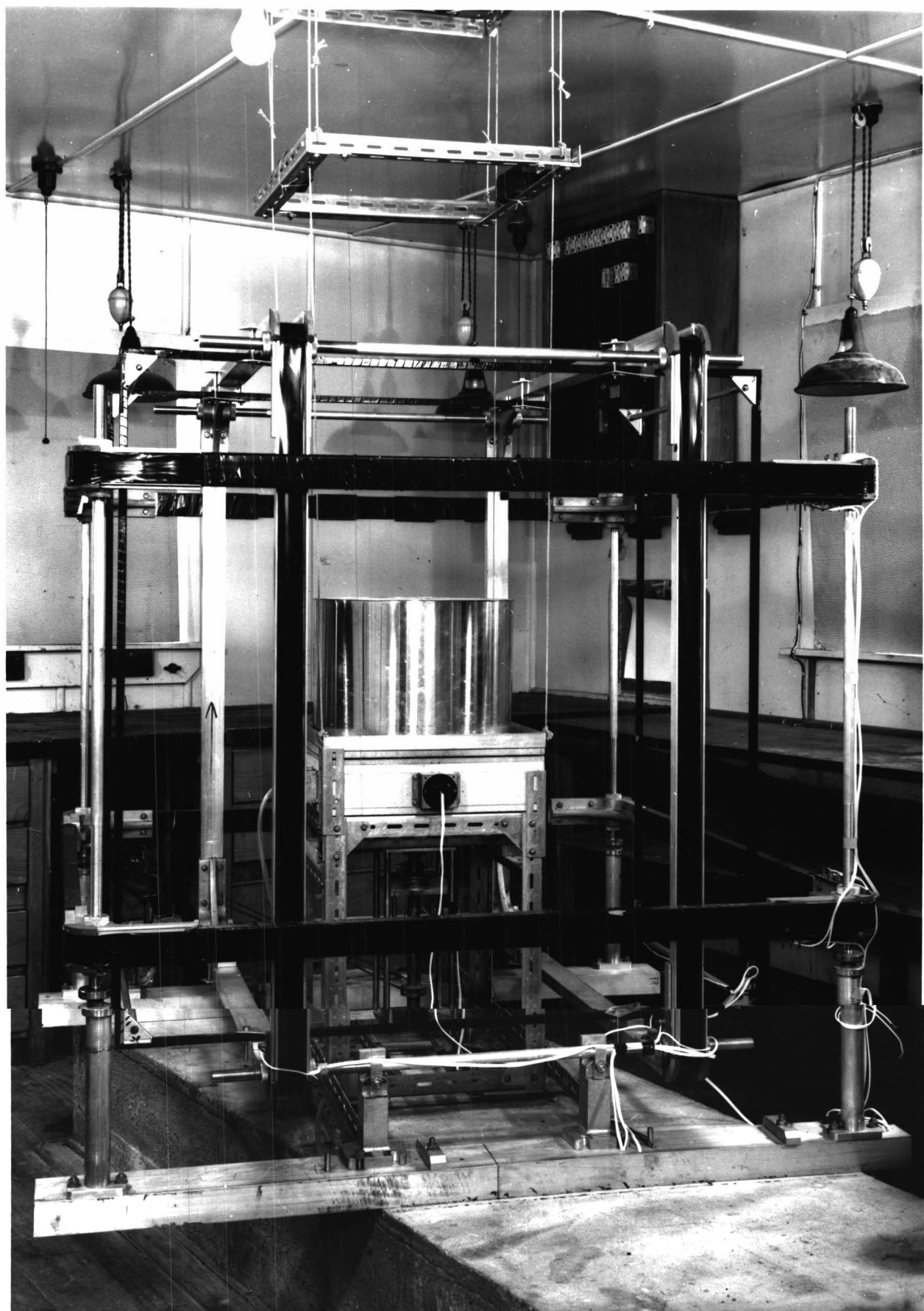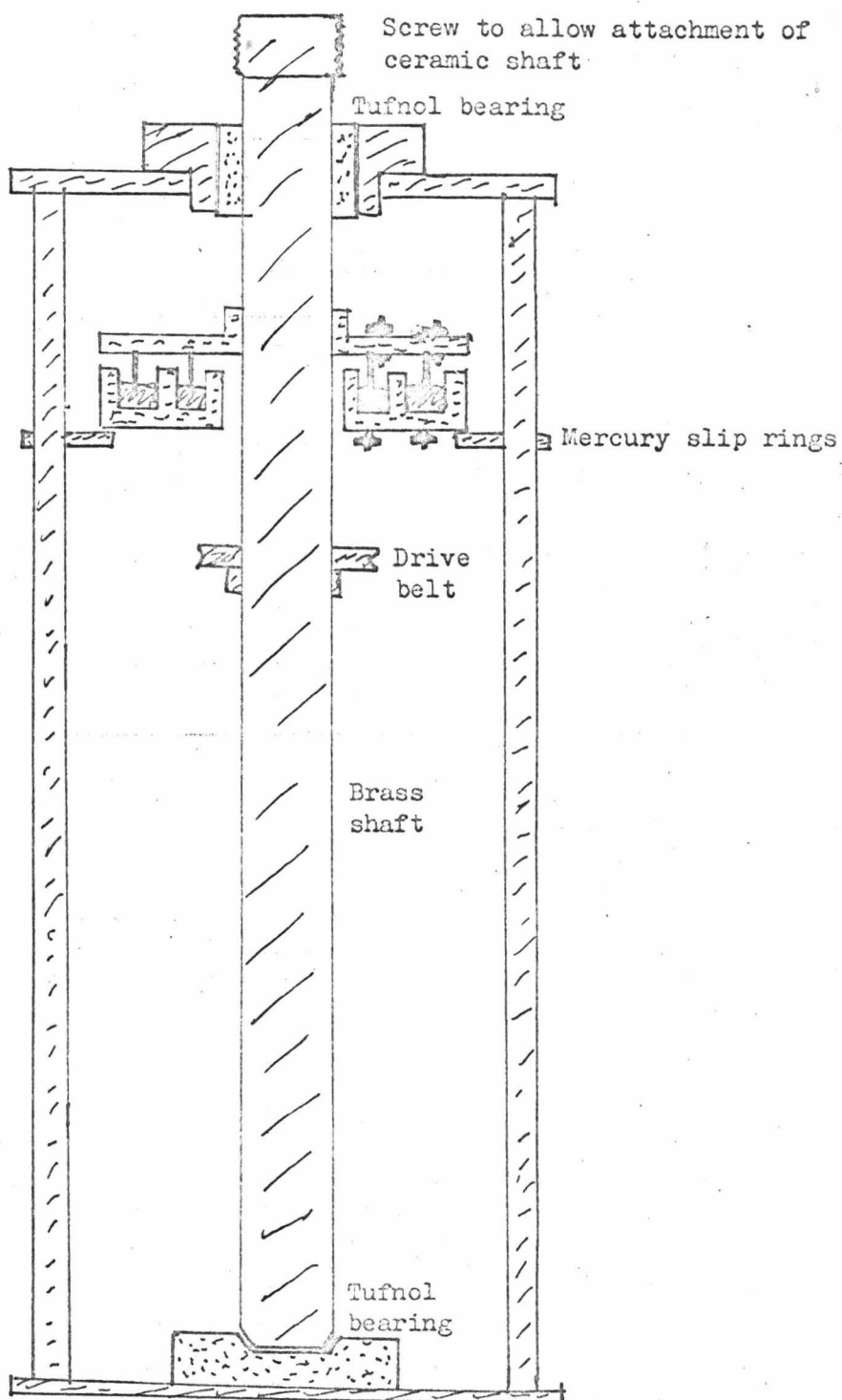
Fig. 5.5   Rotating Support for Sample Holder

FIELD CANCELLATION COILS

6.1 GENERAL

It is necessary to cancel the earth's magnetic field over the useful volume of the oven. One method is to surround it with mu-metal, but a simpler and more common method is to cancel the field with another produced by the currents in a set of coils. It is usual to have three sets of coils and cancel the components of the earth's field in the three directions parallel to their axes. To ensure that the field produced in each direction is sufficiently uniform it is necessary in this case to use either a very large single coil or a pair of smaller coils spaced in such a way that the first three differentials of the field at the centre of the pair are all zero. Even smaller coils could be used by using three or four coils, but this restricts access to the oven.

Preliminary calculations for circular (Helmholtze) coils showed that a diameter of about four feet would be necessary. This is too large to be machined in the college workshop, and such coils would cost about £300 if cast and machined commercially.

The method of construction used was to make the coils square, the sides being cut from 2" x 1" outside dimensions U-section extruded aluminium channelling. These were joined at the corners by screwing them to machined aluminium castings. The coils have uniformity comparable to circular coils, are simpler to construct, and provide good access to the central space. The finished coils are visible in Fig. 5.4.

The calculations which follow, on the properties of square coils, were carried out with greater accuracy than needed for the coils associated with the oven, for it was expected that a similar set of coils would be required for the magnetometer at some future date.   The requirement in this case would be that field gradients at the centre of the coils should be very small over a relatively small volume.

6.2   FIELD OF PARRY COIL SET

6.2.1   Introduction

Previous calculations of the field of square coils have been made by Parry (1957), but have not been published. Accordingly, Mr I. D. Cave started in 1962 the task of calculating the field at off centre points between a pair of coils spaced so the first three differentials of the field at the centre are zero, (Parry spacing).

6.2.2   Parry Spacing

The field at a point P on the axis of a square coil of side 2a, and distant z from the centre of the coil, is along the axis and is given by Robertson (1960), as

$$H \quad = \quad \frac{8ia^2}{(a^2 + z^2)(2a^2 + z^2)^{\frac{1}{2}}}$$

$$= \quad \frac{8i}{a} \quad \frac{1}{(1 + s^2)(2 + s^2)^{\frac{1}{2}}}$$

where $s = \frac{z}{a}$, i is measured in abamps, and a and z are in cm.   This is an even function of s, so that if P is at the centre of a pair of similar coils the odd differentials will cancel.   The Parry condition is that

$$\frac{\partial^2 H}{\partial z^2} \quad = \quad 0$$

and the only real value of s for which this occurs is

$$s = \frac{z}{a} = 0.5445$$

The corresponding coil spacing is

$$d = 1.089 \, a$$

and is called the Parry spacing.

The field at the central point P corresponding to this spacing is

$$H = \frac{8Ni}{a} \text{ x } 1.018$$

where Ni is the number of abamp turns per coil.

6.2.3 FIELD AT OFF-CENTRE POINTS

These equations were derived by Mr Cave and checked by the author, and are given here for reference.

Consider a single square coil of side 2a.   A coordinate system (x, y, z) has as its z axis the axis of the coil, and x & y axes parallel to the coil sides.   The origin is distant b from the centre of the coil, (see diagram   ).
P is a general point between the coil and the x-y plane.   The current circulates in a left handed sense about the z axis.

Hy is the component of H in the y direction at P, Hx that in the x direction and Hz in the z direction, due to one coil at z = +b.
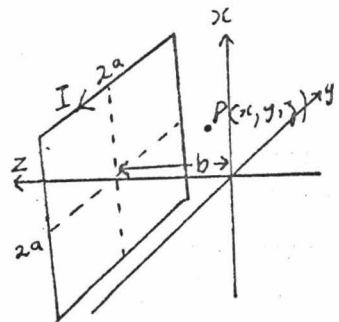
Writing $u = x-a$, $v = y-a$, $w = z-b$, then:

$$Hx = \frac{wi}{w^2 + u^2}\left[\frac{v}{(u^2 + v^2 + w^2)^{\frac{1}{2}}} - \frac{v + 2a}{(u^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right]$$

$$+ \frac{wi}{w^2 + (u + 2a)^2}\left[\frac{-v}{((u + 2a)^2 + v^2 + w^2)^{\frac{1}{2}}}\right.$$

$$\left. + \frac{v + 2a}{((u + 2a)^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right]$$

$$Hy = \frac{wi}{(w^2 + v^2)}\left[\frac{u + 2a}{((u + 2a)^2 + v^2 + w^2)^{\frac{1}{2}}} - \frac{u}{(u^2 + v^2 + w^2)^{\frac{1}{2}}}\right]$$

$$+ \frac{wi}{(w^2 + (v + 2a)^2)}\left[\frac{u}{u^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right.$$

$$\left. - \frac{u + 2a}{((u + 2a)^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right]$$

$$Hz = \frac{vi}{v^2 + w^2}\left[\frac{u}{(u^2 + v^2 + w^2)^{\frac{1}{2}}} - \frac{u + 2a}{((u + 2a)^2 + v^2 + w^2)^{\frac{1}{2}}}\right]$$

$$+ \frac{(v + 2a)i}{(v + 2a)^2 + w^2}\left[\frac{-u}{(u^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right.$$

$$\left. + \frac{u + 2a}{((u + 2a)^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right]$$

$$+ \frac{(u + 2a)i}{(u + 2a)^2 + w^2}\left[\frac{-v}{(u + 2a)^2 + v^2 + w^2}\right.$$

$$\left. + \frac{v + 2a}{((u + 2a)^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right]$$

$$+ \frac{ui}{u^2 + w^2}\left[\frac{v}{u^2 + v^2 + w^2} - \frac{v + 2a}{(u^2 + (v + 2a)^2 + w^2)^{\frac{1}{2}}}\right]$$

The field of the other one of a pair whose centre is at the origin
is found by substituting $(z + b)$ for $(z - b)$, that is $w' = w + 2b$
is substituted for w.   The x or y component for one coil is
subtracted from the x or y component for the other, and the z
components are added.

From these equations the field was calculated for points with coordinates of the form $(0,0,1)$, $(1,0,0)$ and $(1,1,1)$, with 1 taking various values, and the results expressed as $\frac{Ho - H}{Ho}$, where Ho is the field at the centre of the coils. The results are graphed in Fig. 6.1.

A maximum change of 50 γ from the centre of the coils to the point $(1,1,1)$ requires $\frac{Ho - H}{H}$ to be less than 10^{-3}, which corresponds to $\frac{1}{a}$ less than 0.13. Since in this case 1 is about 10 cm, a must be about 80 cm, which means the side of the coils is about five feet.

6.2.4 Effect of Construction Accuracy

It was decided that accuracy of $\pm$ 1mm in major distances was a reasonable requirement for coils of this size made from available extruded u-section aluminium channel. Gellen (1959) showed that when considering the effect of errors in construction of circular coils, a fair estimate is obtained by treating the area, A, between the theoretical and the actual position, as a magnetic shell of moment nIA, which for points near the centre of the coil acts as a dipole with its axis normal to the area. This approximation was checked for the case of a straight line filament with dimensions about those of the coil set, and found to give an over-estimate by a factor of about two. The effect of a displacement of the nearest coil side on the field at an extremity of the oven is estimated below, and it is assumed that the total error field will be less than four times this for the x component (or y component) and no more than eight times this for the z component. This will give a large overestimate of the effect of constructional inaccuracy.

Consider the change in field produced at a point P distant $r = (x^2 + z^2)^{\frac{1}{2}}$ from a line current of length 2a, due to small displacements of that current. The displacements x and z parallel to the x and z axes produce the magnetic moments m_1 and m_2 parallel to the z and x axes respectively.
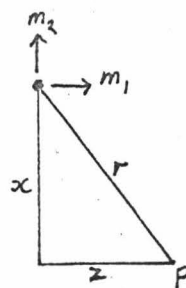
$$m_1 = 2nIadz$$
$$m_2 = 2nIadx$$

where I abamps flow through each of n turns, and distances are measured in centimeters. The x component of field at P due to m_1 is denoted by $H_x)_1$ and similar definitions hold for other components. It is easily shown that

$$H_z)_2 = - \frac{3m_2xz}{r^5}$$

$$H_z)_1 = \frac{m_1}{r^5}(2z^2 - x^2)$$

$$H_x)_1 = \frac{3m_1xz}{r^5}$$

$$H_x)_2 = \frac{-m_2}{r^5}(2x^2 - z^2)$$

For the worst possible case the total field H_x is

$$H_x = \frac{m_1}{r^5}(2x^2 - z^2 + 3xz)$$

With a = 80cm, x = 70cm, z = 35cm and nI = 2.5 abamp turns

$$H_x = 5 \times 10^{-5} \text{ oe}$$

so $4H_x = 20\gamma$.

Similarly

$$H_z = 2.5 \times 10^{-5} \text{ oe}$$

$$8H_z = 20\gamma$$

so a constructional accuracy of $\pm$ 1mm with this size of coil will give sufficiently uniform fields.

6.3 Construction of Coils

The design and drawing of the castings forming the corner pieces of the coils was done by Mr Gellen, and the coils were made in the College workshop.

The windings of the vertical component coils (called the "V" coils) were as follows -

a) In the bottom of the channel, and insulated from it by 0.005" polythene, was a single layer coil of 64 turns of 23 B.S.G. enamel insulated copper wire.

b) The next coil, insulated from the first by 0.010" "Paxolin" sheet, contained another four layers of the same wire, each layer being separated by 0.005" thick insulating paper from its neighbours. Each layer was varnished before winding the next.

c) Four further sections of four layers each followed these, each section being insulated from the others by "Paxolin" sheet.

d) The coils were finished by being pressed firmly into the channel, and binding with PVC insulating tape.

Each section was tested at 600v. D.C. for insulation to the frame. To test for shorted turns the coil was made the secondary winding of a transformer, the primary of which was supplied with 230v. A.C. The voltages induced in all the sections were compared, and were found to be equal to within 0.2% when the number of turns in each section was equal, which indicated that no shorted turns were present.

The extra sections on the V coils were to allow the application of fields up to 10 oe if required.

The North-South component coils ("N-S" coils) are of the same design as the vertical component coils, except that the sides are short enough that they may fit inside the V coils, and they have only one layer of 64 turns.

The sides of the V coil are 128.2cm long and those of the N-S coils are 120.0cm long. The spacing has been set without allowing for the finite width of the coils.

6.4   The East-West Component Coils

These, the "E-W" coils, are of different construction because it was proposed to line up the other coils so that the residual field, after cancelling that component of the earth's field in the plane defined by their axes, would be very small. The field of these coils is small, so the accuracy of their construction and their rigidity is not as important as in the others.   The former for these coils is made from lengths of $\frac{1}{2}$" x $\frac{1}{2}$" outside dimensions extruded u-section aluminium, which are joined at the corners by screwing them into a triangular section of $\frac{1}{2}$" aluminium plate.   The coils have sides 115.0cm long, to fit inside the N-S coils, and are wound with 20 turns of 23 B.S.G. wire.

6.5   Installation of the Coils

The magnetometer was to be erected at the D.P.L. field station at Moore's Valley, so for convenience of measurement the oven was installed in another hut on the site.   This hut already contained a concrete instrument pillar 8' long and 2' 6" wide with its short side pointing geographic North-South.   The coils were mounted on 4" x 2" u-section aluminium beams, 4' 8" long, with their long axes magnetic North-South.

The V and N-S coils were mounted on aluminium supports bolted to the beams, and the E-W coils were clamped to the N-S coils. These coils were sufficiently rigid not to need extra bracing.

The coils were adjusted on the spacer rods so the four corners of each coil lay in a plane, and that these planes were parallel. The planarity of one coil was measured by defining the diagonals of the coils by string clamped between the collars and castings of each corner. Their intersection could easily be ensured to within $\pm$ 1mm. The spacing of the other coil in the pair was set at each corner to the length of a rod 59.06 $\pm$ 0.03cm long in the case of the N-S coils, and to the length of this rod, plus one 4.60 $\pm$ 0.01cm long, for the V coils. These distances make the centre of the coils' sides a distance apart equal to the Parry spacing. No correction has been made for the finite width of the coils.

It is necessary that the axes of the coils coincide, but this was not checked geometrically. However, the accuracy of construction, particularly the machining of the holes and collars at the corners, should be accurate enough to ensure this.

The centres of the V and N-S coil pairs were made as coincident as possible, testing being performed with diagonal strings, but because there is insufficient screwed length on the V coil supports, the N-S coil centre is $\frac{1}{2}$" vertically above the V coil centre.

6.6   FIELD CANCELLATION PROCEDURE

6.6.1 Fluxgate Magnetometer

To detect and measure the magnetic field a portable
fluxgate magnetometer was borrowed from the Geophysics
Division of D.S.I.R.   The detecting head of this
instrument contains two parallel mu-metal wires $3\frac{1}{2}$" long
and 1/16" wide, each inside a solenoid 3/16" diameter.
These solenoids are in two arms of a bridge circuit, the
other arms of which are two 100 ohm resistors.   A 200c/s
alternating voltage is applied as
shown, and a detector tuned to the
first harmonic is placed across
the other two corners of the bridge.
The coils are arranged so that in
the presence of a steady magnetic
field, saturation of the core occurs
in one solenoid before the other.   This gives rise to a
first harmonic signal, which is detected, and is a minimum
when no direct field is present.   It is possible to
measure fields by passing a direct current through the
coils to produce a steady field which cancels the ambient
one, the magnitude of this current being proportional to
the field.
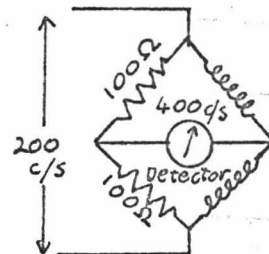
Some trouble was experienced with the instrument, it giving
apparently different strengths for the field when pointing
parallel or antiparallel to the field.   It was suspected
that the cores had a permanent magnetization or too high a
coercive force, so they were sent to the firm of Telcon,
England, for demagnetization and annealing.   The effect

persisted, though to a lesser degree, and the explanation may lie in a difference between the solenoids or resistor arms of the bridge. The difficulty was avoided by adjusting the direct current through the solenoids to about 13μA. When the external field is then adjusted for minimum signal with the Parry coils, the fluxgate will give the same signal independently of its orientation. Under these conditions the field can be cancelled to about 10γ.

6.6.2 Alignment of Coil Axes

In order that most of the cancellation can be carried out with the V and N-S coils, it is necessary that the axes of these coils and the earth's magnetic field vector at the oven all lie nearly in a plane. Preliminary adjustments were to level the sides of the V coils and align the separating rods of the N-S coils parallel to a compass needle. With the aid of the magnetometer the axis of the V coils was brought into the plane defined by the earth's field and the N-S coil axis, using the following method.

If the magnetometer axis is perpendicular to each of two different field vectors, then any third vector perpendicular to the magnetometer lies in the plane of the other two. A holder for the magnetometer was devised which enabled it to be rotated about an axis, A, perpendicular to the magnetometer axis, the orientation of A being adjustable so it could be made parallel to the earth's magnetic field vector. A was set approximately in this direction by eye, and then adjusted
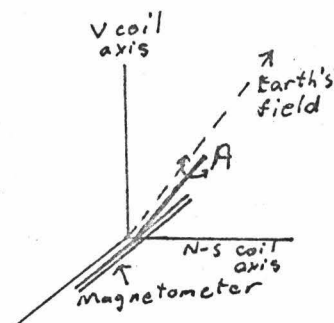
till the signal was a minimum and did not change on
rotating the magnetometer about A.

An approximately horizontal field was applied by the
N-S coils, in the same direction as the earth's field
component, and the magnetometer rotated about A until
minimum signal was again obtained.   The direction of
the magnetometer was then perpendicular to the N-S coils
and the earth's fields, and was almost horizontal and
East-West.

Application of the V field gave a signal, which was
minimised by raising the eastern side of the V coils a
few millimeters.

6.6.3 Cancellation

To cancel the field the magnetometer is set approximately
parallel to the axis of one coil-pair, say the vertical
one.   The current is adjusted to give minimum signal,
and then the magnetometer is set approximately horizontal.
With the vertical field nearly cancelled from the previous
adjustment, the horizontal component may now be almost
exactly cancelled, even though the magnetometer is not
parallel to the coil axis.   Having done this the vertical
field may now be exactly cancelled.   The coil axes are
near enough to perpendicular that the component of field
of one along the other is negligible.   There may be a
small East-West component of field remaining, which is
cancelled by placing the magnetometer parallel to the
E-W coil axis.   Because of the small fields in this
direction, it has not proved necessary to align these

coils perpendicular to the others, or to adjust the field produced by the main coils after altering the E-W current.

Cancellation to about $\pm$ 20γ has been easily achieved over the volume of the oven, although once set up to this accuracy, magnetic objects in or near the hut, such as motor vehicles and portable meters should not be moved.

$\frac{H_o - H}{H_o}$

○ H_z at points (l, l, l)

× H_z $(l, 0, 0)$

＋ H_z $(0, 0, l)$

○ H_x (l, l, l)

FIG. 6.1 FIELD OF PARRY COILS

$\frac{l}{a}$
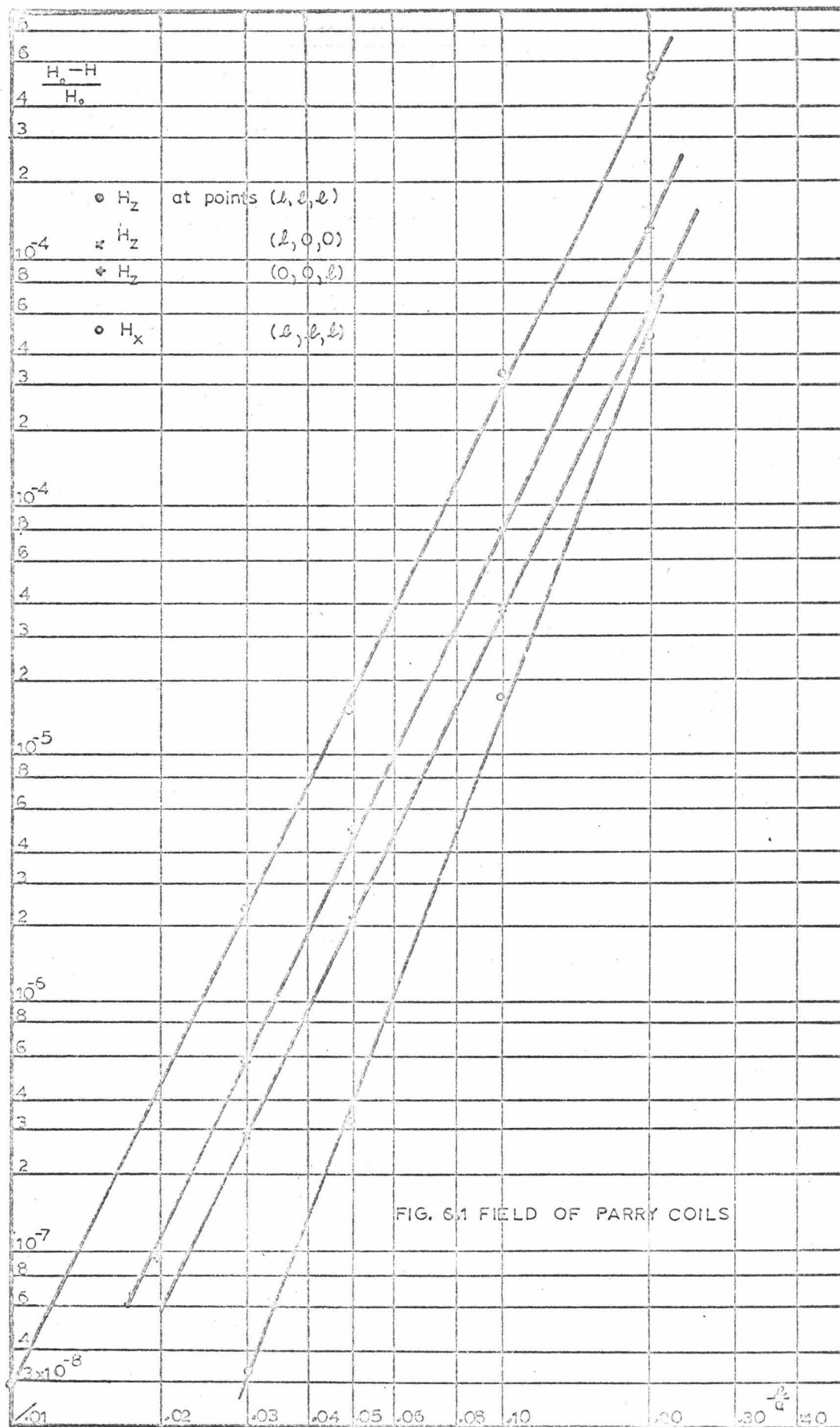
CONSTANT CURRENT POWER SUPPLY

7.1 SPECIFICATIONS

The field cancellation coils require a current of up to
one ampere, and a voltage of about 25 volts.   To keep
field fluctuations within $\pm$ 25γ of the mean field, the
current must vary by less than $\pm$ 0.05%.   An important
source of current fluctuations without regulation is the
change in load resistance with temperature, which is
about 0.4% per ^{o}C.   Supply voltage variations will also
be important.

To reduce the engineering problems, lead-acid accumulators
are used as the voltage source, instead of a transformer
and rectifier system.   These have the advantage of almost
constant voltage, over the time taken for each cycle of
the oven.

7.2 SIMPLE REGULATOR

A simple transistor series current regulator circuit,
published by Schwartz (1960), appears, at first sight, to
have sufficient stability for this purpose.   A slightly
modified version of this was constructed, according to
the circuit shown in Fig. 7.1.   The current from the
supply passes through the resistance R_s and transistors
Tr 1 and Tr 2.   The OAZ202 is a zener diode, the voltage
across which is almost independent of the current through
it.   The voltage V_s is equal to this voltage, less the

base-emitter voltage drops of transistors Tr 1 and Tr 2.
The base-emitter voltage of the transistors used is about
half a volt and is not strongly dependent on collector-
emitter voltage, while the zener voltage is about 6v., so
V_S is almost independent of the voltage across the regulator.
If R_S is constant, this means the current passing through
the load is almost independent of the magnitude of the load,
within obvious limits.

The particular diode chosen has the property that at a
certain current its temperature coefficient of voltage, which
is otherwise considerable, is zero. A variable resistor was
provided to enable the diode to be operated at this current.

The arrangement used to test the stability of the regulated
supply is shown in Fig. 7.2(a). The current, i, from the
supply is passed through a 2 ohm constantan resistor, and
adjusted to develop just over one volt across it. This
voltage is compared with the E.M.F. of a Weston cell and the
difference measured on a Philips recording potentiometer
operated at 1mV full scale deflection. Changes in current
as small as 0.001% could be detected with this arrangement.

Although the regulator prevented significant changes in
current due to load changes, it was very sensitive to ambient
temperature fluctuations. The temperature effects proved
to be due to variation with temperature of the base-emitter
voltage of the regulating transistors. It has been mentioned
that this voltage is in series with the comparison voltage,
and will directly affect the current. In fact the specified
value for $\frac{\partial V_{be}}{\partial T}$ led to precisely the observed value for change
in current with temperature (0.1% 1°C.)

7.3   SATISFACTORY REGULATOR

7.3.1 Basic Circuit

Just after this effect was recognised, two successive
issues of "Electronic Engineering" carried articles on
current stabilized transistor power supplies (Walker,
1962, and Lovick, 1962).   These stabilizers avoid
temperature effects by using a differential "long
tailed pair" amplifier, in which the change in V_{be}
affects two transistors equally, which means there is
no change in current.   A regulator based on Walker's
circuit was designed to the above specifications,
(Fig. 7.3).

In this circuit transistors Tr 4 and Tr 5 correspond to
Tr 1 and Tr 2 in Fig. 7.1.   Tr 4 is driven by Tr 3
from the differential amplifier transistors Tr 1 and
Tr 2.   The base potentials of Tr 1 and Tr 2 will be
nearly equal, because of the equal base-emitter voltages,
so that the voltage across R_s is the same as the centre
tap voltage of the helipot.   This voltage is stabilized
by means of a zener diode, and its range is altered when
changing current ranges.   Adjustment of current is in
six equal ranges from 200mA to 800mA, the calibration of
the helipot being linear within each range.

7.3.2 Temperature Regulation

The problem of temperature variations affecting the zener
diode voltage will be encountered unless the current
through it is about $\frac{1}{2}$mA (cf Section 7.2).   It can be
seen from the part of the circuit shown in Fig. 7.4 that
such low currents are not possible.   For linear variation
of current with helipot position, the transistor base

current must be much less than the current in the helipot. The maximum base current is 40μA, so the minimum helipot current may be 400μA. This occurs when R_a is maximum, so when Ra is a minimum, the helipot current will be $\frac{9 \times 0.4}{3} = 1.2$mA. As this change in current must be supplied by the zener diode, its operating current should be much greater than 1mA. This means it is not possible to operate the diode near the current required for zero temperature coefficient. The operating current was chosen as 20mA to give low dynamic impedance.

The temperature of the reference diodes and differential amplifier transistors are regulated (using the method described by Kemhadjian, 1958,) for two reasons:

1. To prevent changes in zener diode voltage.
2. To eliminate possible troubles arising from imperfect balancing of the differential amplifier.

The circuit is shown in Fig. 7.5.

The transistors OC71 and OC72 are mounted in holes drilled in a cylindrical copper block $1\frac{1}{4}$" in diameter and $\frac{3}{4}$" high, (see centre of Fig. 7.7). Three strands of resistance wire wound around the outside and connected in parallel form a heater of 12 ohms resistance, which is supplied with current at a rate controlled by Tr 4. Tr 1 has its base open circuited, and is connected to Tr 2 in such a way that its I_{ceo} controls the base current of Tr 2 and hence the heater current. The value of I_{ceo} is very temperature dependent, so that Tr 1 acts as a thermometer and regulates the temperature of the block. The devices whose temperatures are to be regulated are mounted in other holes drilled in the block.

The resistance of 12 ohms for the heater in the present device is higher than the 8 ohms quoted by Kemhadjian, but

at first sight this appears immaterial, as, although it increases the time to heat up, it reduces thermal overshoot. However, there turned out to be a somewhat subtle effect of this change.   If V_{ce1} represents the collector-emitter voltage of transistor Tr 1, and so on for the other voltages possible, then

$$V_{ce1} = V_{be3} + V_{be4} - V_{be2}$$

V_{be4} decreases as I_{c4} decreases, so a decrease in I_{c4} decreases V_{ce1}.

Suppose the temperature of the block increases slightly above the equilibrium temperature. I_{ce1} increases, which decreases I_{ce4} and hence the heater current.   It also decreases V_{be4} and hence V_{ce1} decreases, which lowers I_{ce1} electrically, allowing the temperature of the block to rise slightly above its previous value.   With an 8 ohm heater the current required at equilibrium is such that V_{ce1} is greater than $\frac{1}{2}$v.   In this case $\frac{\partial I_{ce}}{\partial V_{ce}} = 0$ so the electronic feedback is negligible.   With the 12 ohm heater V_{ce1} is low enough that the feedback considerably reduced the thermal regulation.

Rather than rewind the heater, a 2 ohm emitter resistor, consisting of 3" of resistance wire instead of a copper connecting wire, was inserted in the emitter circuit of Tr 4.   After this modification a change in ambient temperature of 5°C. produced 1/40°C. change in temperature of the copper block.   This degree of regulation was considered very satisfactory.

7.3.3 Final Design

Two independent regulated supplies are required, one for each pair of field cancellation coils.   These are both

constructed on a single panel of $\frac{1}{4}$" aluminium, which
also serves as a heat sink for the OC26 transistors.
The GET114's and the OAZ202's are mounted in the
temperature regulated copper block.   The two regulators
shared a 24v. and 12v. zener regulated supply, the
OAZ213's of which are mounted in holes drilled in a $\frac{1}{2}$"
diameter brass supporting rod, which acts as a heat sink.

Meters are provided to measure the supply voltage, and
the current in both outputs.   Terminals are provided on
the front of the panel for insertion of a shunt and
potentiometer, for accurate current measurements.   A
rear view of the instrument is shown in Fig. 7.7, and it
is visible in the rack in Fig. 7.8.

7.4   TESTING AND MODIFICATION OF REGULATOR

7.4.1   Effect of Load Changes

The current changes by 0.01% for a 10% change in load
resistance.

7.4.2   Ambient Temperature Effects

The temperature coefficient was initially about 0.1% per
^{o}C. change in ambient temperature, part of which was due
to the use of a common positive lead to the Tr 4 of the
temperature regulator and the helipots of the current
regulator.   Although very small, the resistance of the
wire was sufficient that the varying current in the
thermostat with ambient temperature produced a
significantly variable voltage drop in the leads to the

differential amplifier, which caused changes in current with the temperature. A separate lead corrected this problem.

A temperature coefficient of $0.02\%/^{\circ}$C. remained. It was suspected that this was due to the different temperature coefficients of the helipots and the resistors in series with them. The temperature coefficients of commercially available resistors were measured using the circuit shown in Fig. 7.2(b). One of the two similar resistors to be tested, R_1 and R_2, was cooled in a test tube immersed in ice and water. The change in reading of the potentiometer when the resistors were brought to the same temperature gives the resistance change, since

$$\frac{dV_1}{V_1} = \frac{1}{2}\frac{dR_1}{R_1}$$

The best resistors available had a coefficient of $0.002\%/^{\circ}$C. which is similar to that of the helipots, but substitution of these for the previously used ones did not significantly alter the temperature coefficient of the regulator.

A possible source of the temperature effect is the variation in the characteristics of transistors Tr 4 and Tr 5, in Fig. 7.3, with temperature, for the base current of Tr 4 passes through the current sensing resistor, but not the load. The effect of variations in gain was calculated to be $0.003\%/^{\circ}$C., and in I_{ceo} $4 \times 10^{-4}\%/^{\circ}$C., which are too small to matter at the present level of stability. Despite this calculation the effect seems to be connected with the temperature of these transistors, as shown by local heating of the heat sink with a soldering iron.

It is possible to insert a temperature dependent resistance, R_X, in series with the current sensing resistor, R_S, to compensate for temperature changes in these transistors.

Let $\quad R = R_S + R_X$

$$\frac{1}{V}\frac{dV}{dt} = \frac{1}{I}\frac{dI}{dt} + \frac{1}{R}\frac{dR}{dt}$$

$(t = \text{temperature})$

The voltage V may be supposed to be held constant by the feedback system, and it is desired to alter the current I with temperature changes, in order to compensate for changes in the base current of Tr 4, which does not flow through the load. The measured change in load current is $+ 0.02\%/^{\circ}C.$, so

$$\frac{1}{V}\frac{dV}{dt} = 0 \text{ and } \frac{1}{I}\frac{dI}{dt} = -0.02\%/^{\circ}C.$$

so $\quad \frac{1}{R}\frac{dR}{dt} = + 0.02\%/^{\circ}C.$

If copper wire is used for R_X, $\frac{dR_X}{R_X dt} = 0.4\%/^{\circ}C.$

$$\frac{dR}{Rdt} = \frac{dR_X}{(R_X + R_S)dt} = 2 \times 10^{-4}$$

so $\frac{R_X + R_S}{R_S} = 20,$

i.e. $R_S = 19R_X$

Thus the value of the stabilizing resistor depends on the range used. For the vertical component power supply $R_S = 10$ ohms, so $R_X = \frac{1}{2}$ ohm.

The resistor was constructed from 6" of 40g copper wire, which was wound on the surface of a 1" square x $\frac{1}{8}$" thick copper plate, and insulated from it by paper glued over its
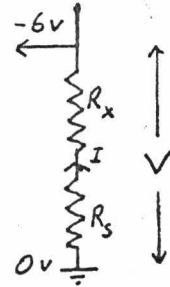
surface (Fig. 7.2(c) and (d)).   The plate was then
screwed on to the heat sink with the wire between the
two.

With this modification the temperature coefficient was
+ 0.003%/$^{\circ}$C., which was expected to be sufficiently low.

7.4.3   Supply Voltage Variations

The regulator was powered from a DC supply with a 2 volt
(7%) peak to peak 50c/s ripple voltage superimposed.
This resulted in a 0.1% ripple current in the output, so
that current stability better than 0.01% requires input
voltage stability about 1%.   At a 1 amp discharge rate a
typical change in voltage is 0.1% per hour for heavy duty
lead acid accumulators, which gives the required degree of
current stability over a 10 hour day.   The temperature
coefficient of voltage, being 0.015%/$^{\circ}$C., is negligible.

7.5   LOAD IMPEDANCE RESTRICTIONS

7.5.1   Open Circuit Conditions

Current regulators in general are susceptible to damage
under these conditions, so an analysis was performed to
determine what factors were involved.

As the load increases, the voltage drop across Tr 5
(Fig. 7.3) drops, regulation ceasing when V_{ce5} = V_{knee}.
As the load continues increasing, Tr 2 becomes cut off
because its base voltage becomes more positive while its
emitter is held at constant voltage by Tr 1.   The lowered
current in its 8.2k collector resistor makes the base of

Tr 3 become more negative, so more current flows through
the circuit: Tr 3 collector-emitter, Tr 4 base-emitter
diode, Tr 5 base-emitter diode, R_S, to ground. Assuming
Tr 2 completely cut off, the maximum base current in Tr 3
is 3mA, corresponding to an emitter current of 100mA, which
flows through the two base-emitter diodes. This does not
exceed the rating of the transistors, but the current would
have to pass through the zener diode Z3, which is rated at
50mA maximum. By putting a 1K collector resistor on Tr 3
the maximum current is limited to 10mA, which when combined
with the normal current in Z3 of 30mA, is a safe rating.
Normal operation is not affected by the presence of this
resistor because the usual current of 3mA produces a drop
of 3v. and leaves the V_{ce} of Tr 3 at at least $2\frac{1}{2}$v., which
is ample to run it. Because of the small value of $\frac{\partial(I_{ce})}{\partial(V_{ce})}$
this resistor introduces negligible feedback.
This modification successfully protected the circuits, but
a 25 ohm dummy load, which was previously connected across
the output when the polarity switch was in the off position,
has been left connected.

7.5.2   Short Circuit

The maximum allowable collector emitter voltage on the
OC26 is -40 volts, so voltage ratings cannot be exceeded
with supply voltages less than this. The power dissipation
in the transistor should be limited to 12.5 watts. Under
short circuit conditions, therefore,

$$(V_{cc} - 6)I = 12.5$$

$$\text{so} \quad I = \frac{12.5}{32} = 0.4 \text{ amps}$$

Thus the supply will not be damaged on short circuit if it
is operating on the 0.4 amp range or lower. To protect it

on higher current ranges it is necessary to use a lower supply voltage, or insert another OC26 in parallel with Tr 5.   The maximum current, I_{max}, with a given load impedance, R_L, or minimum load with a given current, is found from

$$I_{max}^2 R_L - (V_{cc} - 6) I_{max} + 12.5 = 0$$

where V_{cc} is the supply voltage.   Any alterations in supply voltage will require adjustment of the load resistors of zener diodes Z2 and Z3 to keep their current at 20 - 30mA.

7.6   TRANSIENTS

It is necessary that no destructive transients are produced when switching currents or loads.   This was checked on the final installation at Moore's Valley, the greatest transients found being only 15v. peak for about 1m s, and across collector emitter junctions.

7.7   FINAL CIRCUIT

The final circuit is as shown in Fig. 7.6.   Any future modifications should be recorded in the book for circuits at Moore's Valley.
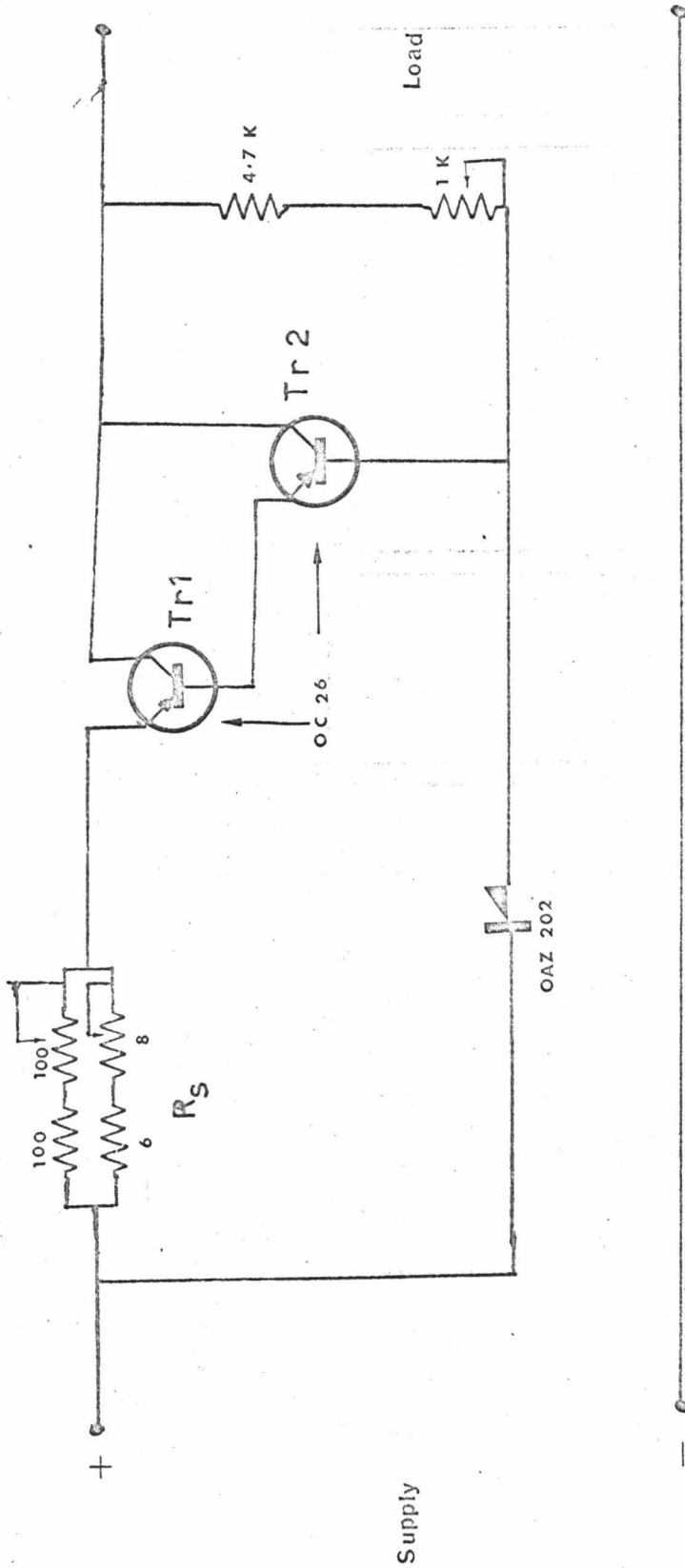
Fig. 7.1   Simple Regulator
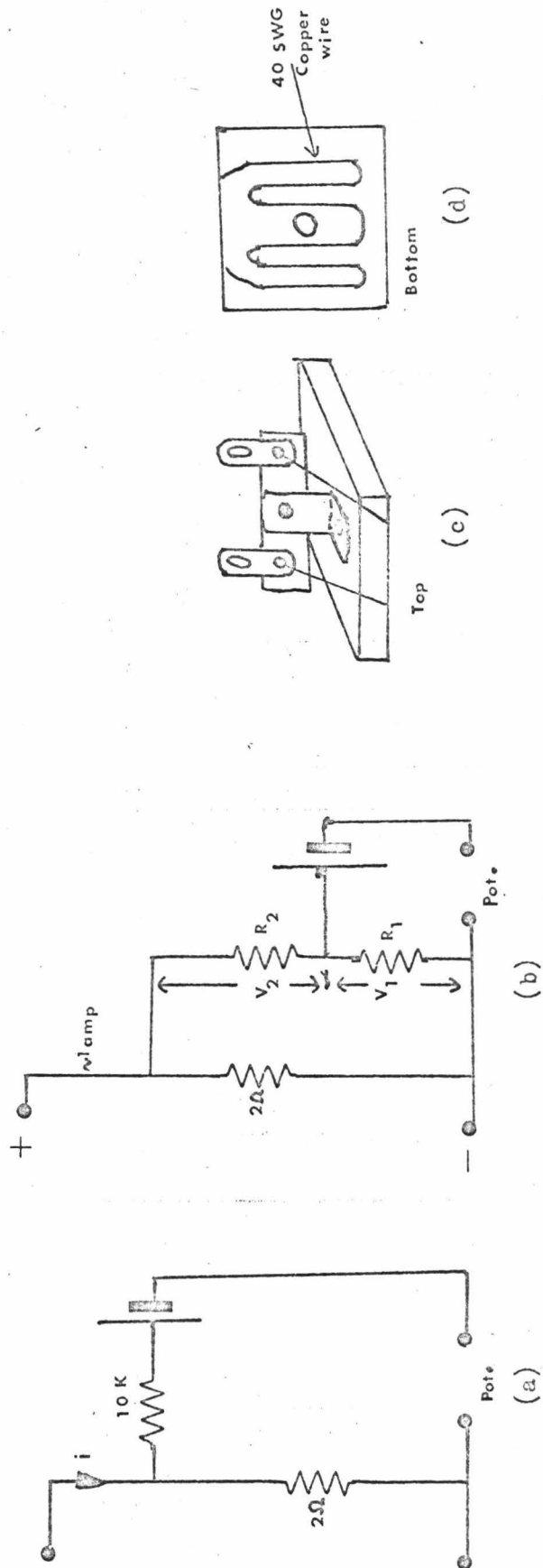
Fig. 7.2
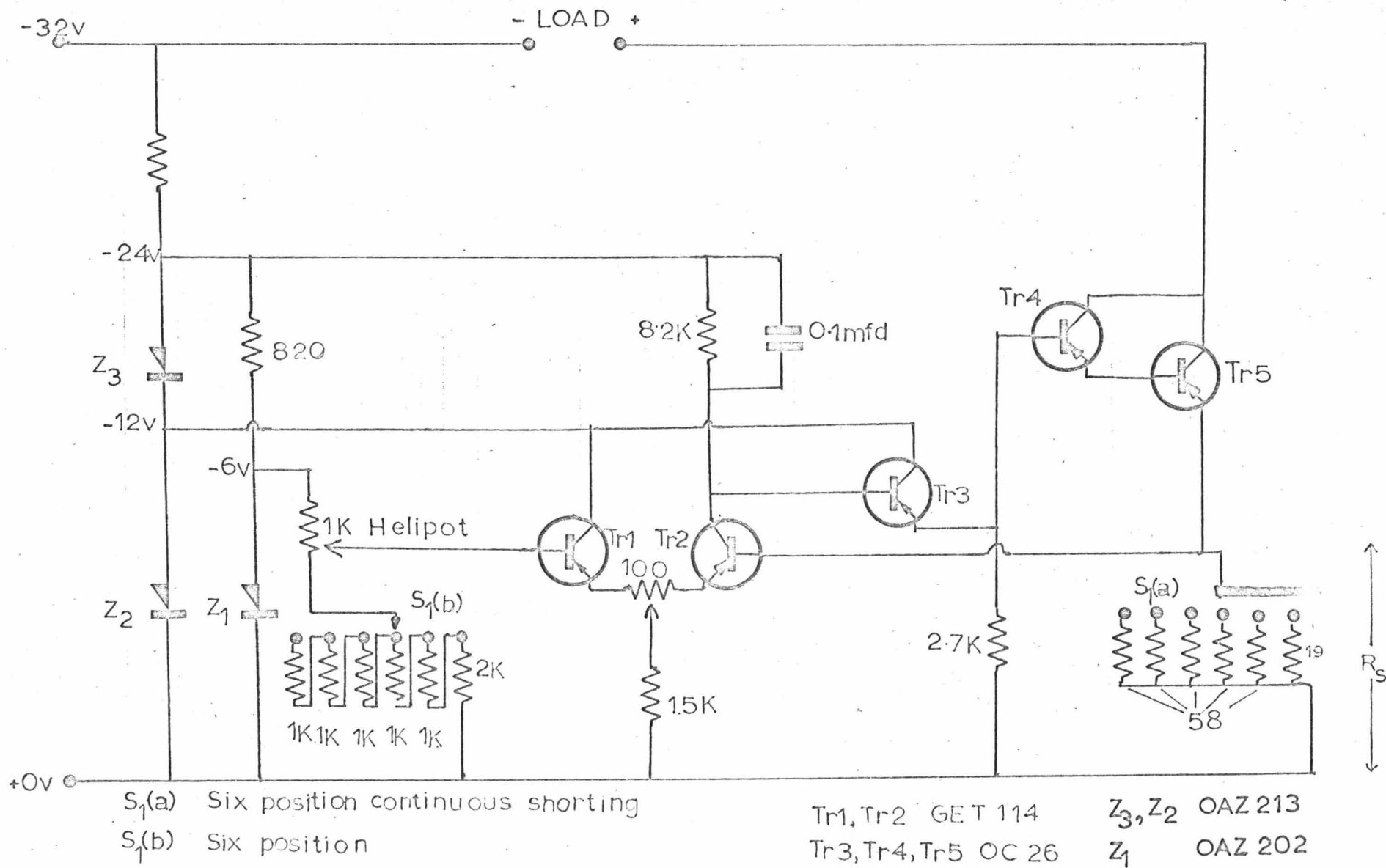
Fig. 7.3   Basic Circuit of Current Regulator

Fig. 7.4   Part of Fig. 7.3

Tr1, Tr2   OC 71
Tr3   OC 72
Tr 4   OC 26

Fig. 7.5   Temperature Regulator

81

Fig. 7.6   Final Regulator Circuit
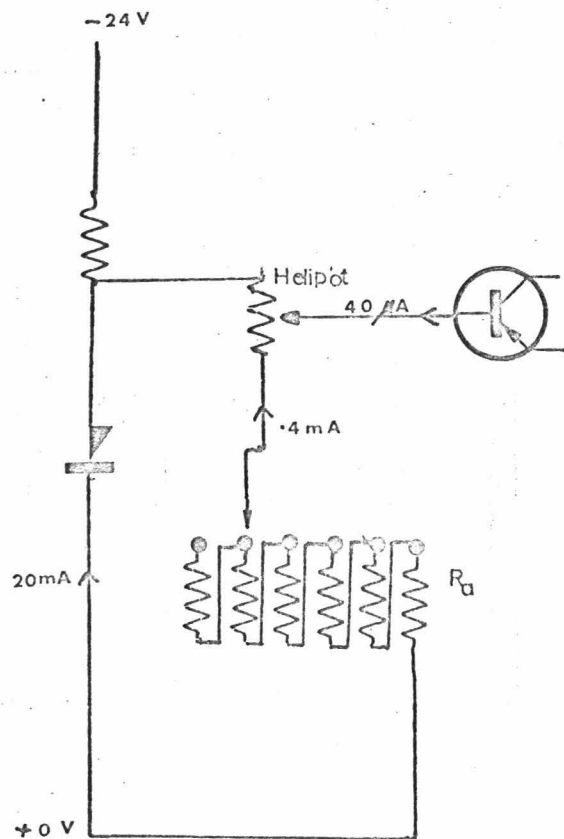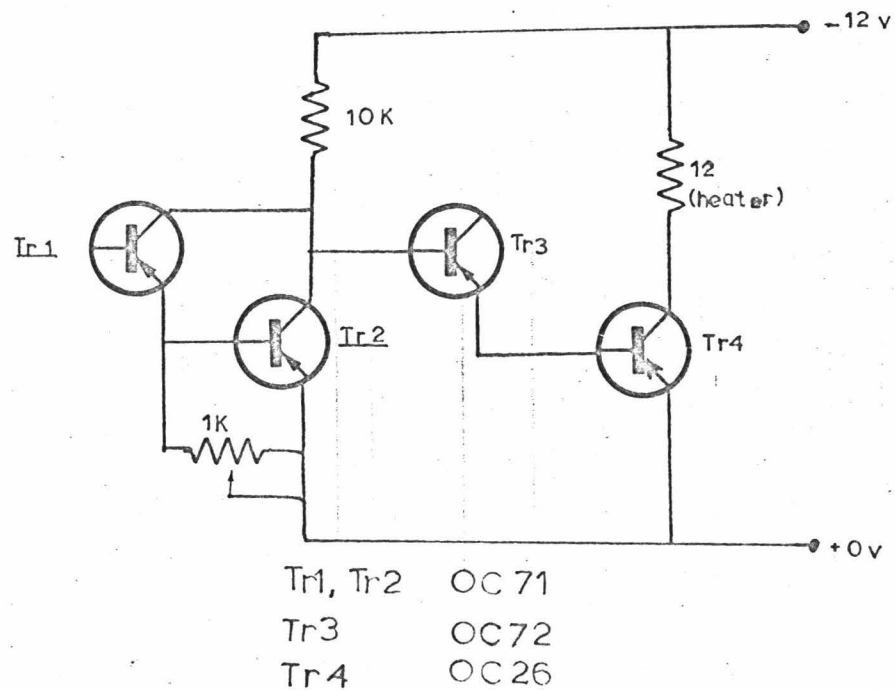
Fig. 7.7 Rear View of Current Regulator

telephone

E-W control

Recorder terminals

battery

Current regulator

charger

nitrogen

cylinder

battery distribution

magnetic

valve

oxygen

Recorder

Variac

removal
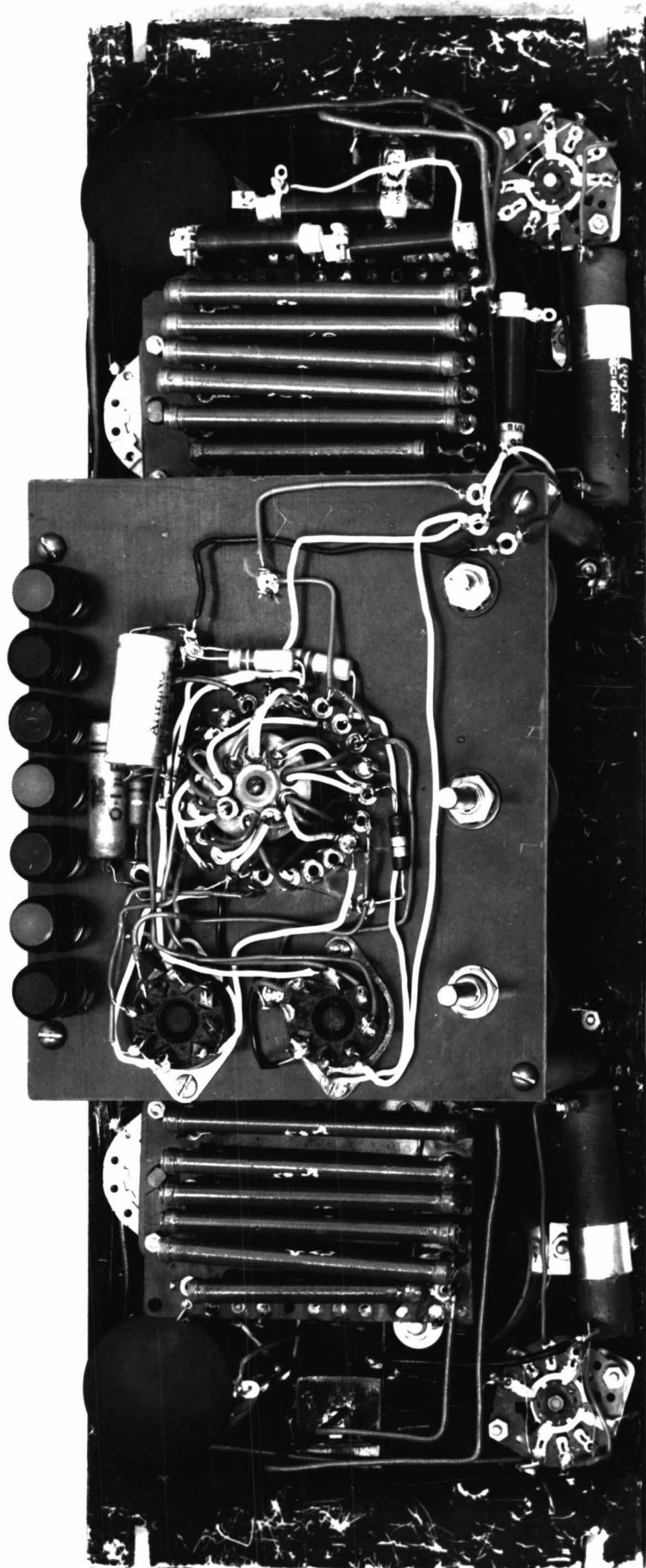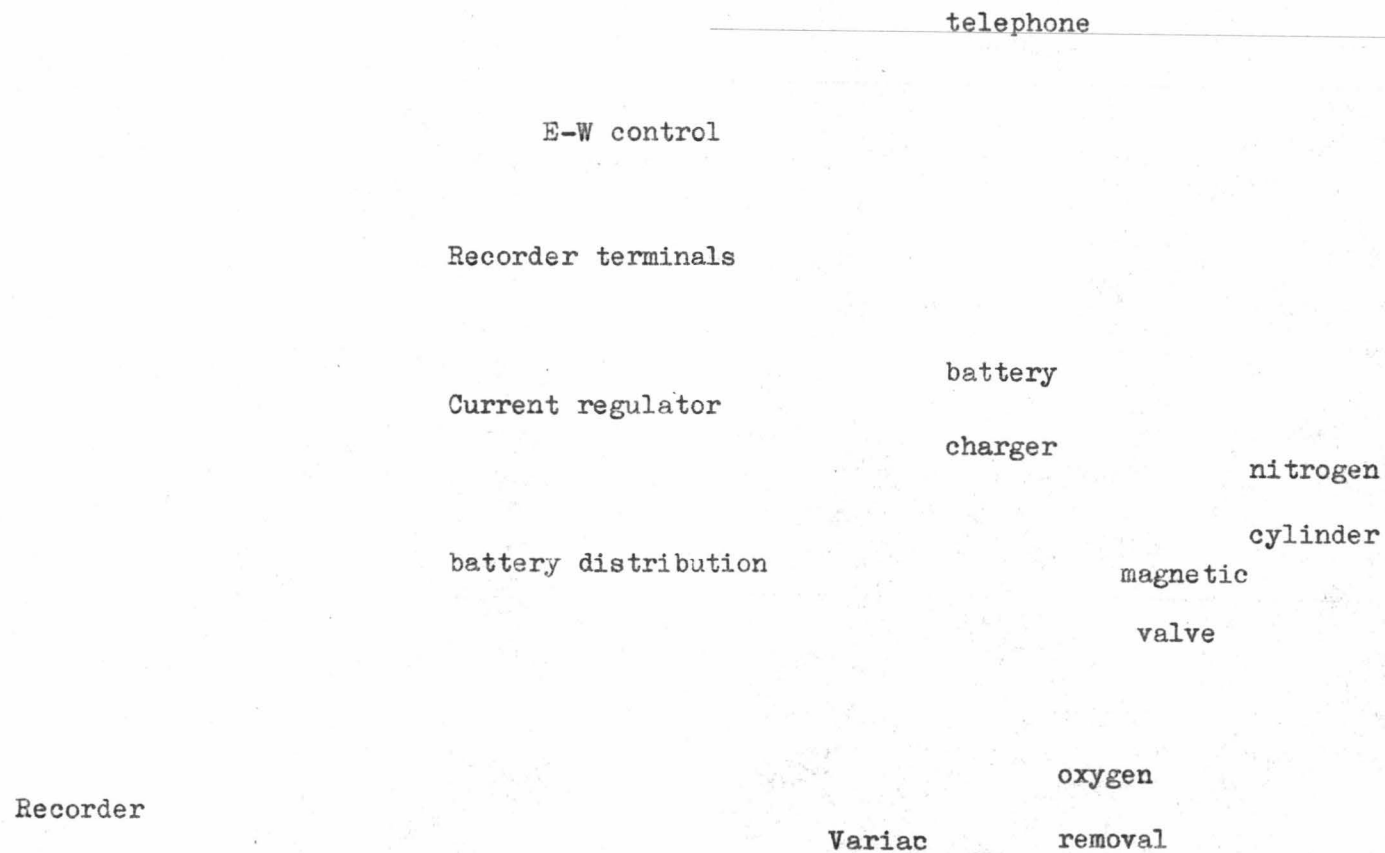
Fig. 7.8 Control Equipment
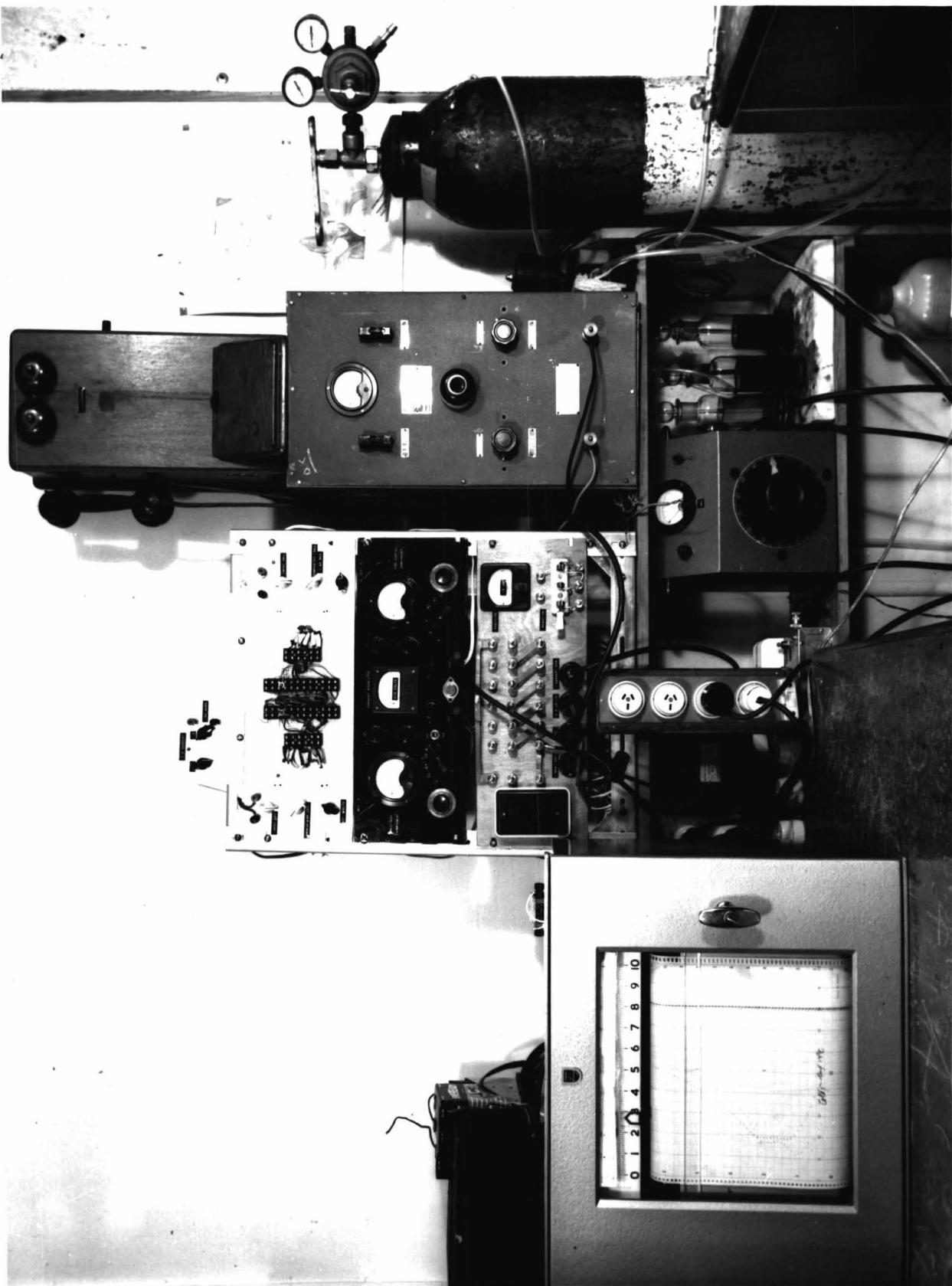
THE MAGNETOMETER

8.1 GENERAL DESCRIPTION

This astatic magnetometer is a modification, designed by
Clegg, of Blackett's instrument (Blackett, 1952). It
was originally installed at V.U.W. by Mr Gellen (1959),
who performed most of the work involved in setting it up
at a more magnetically quiet site at Moore's Valley.
It remained for the author to level and centre the sample
holder before using it in the investigation in this thesis.
A method of cancelling the ambient magnetic field was
devised by the author.

The astatic magnetometer consists of a pair of magnets
P_1 and P_2 (Fig. 8.1) rigidly fixed to a beam, and magnetized
equally in opposite directions. The beam is suspended
from a fine fibre, and rotation of it is detected by the
deflection of a light spot reflected from a mirror attached
to the beam (not shown in Fig. 8.1). When P_1 and P_2 are
equal no torque is exerted on the beam by a uniform
magnetic field. The earth's field is cancelled with
Helmholtze coils. If a magnetized body is placed beneath
the lower magnet, the field produced at P_1 is greater than
that at P_2 so a torque proportional to the field difference
is exerted on the beam, and the deflection produced by it
is a measure of the difference in horizontal field, in the
direction perpendicular to the magnetization directions,
between P_1 and P_2.

To measure the vertical component of the magnetization of the specimen, it may be offset from the central position a distance x_0, which results in a horizontal component of field at the magnets, due to this vertical component of magnetization.   The sample is rotated about a vertical axis to find the two horizontal components.

8.2   CENTRING AND LEVELLING

This was accomplished with the aid of a spirit level, and measurements on the field of a small coil mounted on the sample holder.   The coil is supposed to act as a dipole of moment H, which makes a small

Fig 8.2

angle θ with the vertical.   The centre of this dipole is a distance z_0 below the lower magnet, which is assumed to be the only one affected by the field, and is offset distances $\mathcal{X}$ and $\mathcal{Y}$ in the x and y directions (see Fig. 8.2). The dipole may be rotated in the sample holder about an axis which it is desired to make vertical, and which is nearly parallel to the direction of H.
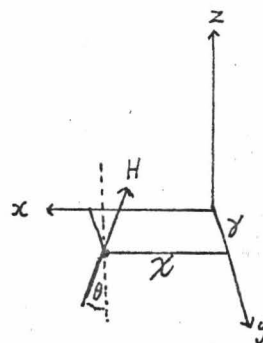
It is of interest to consider the sum of the deflections produced with the dipole in two positions, one of which is that attained by rotating 180° about the above axis from the other position.   Call the components of H along the x, y, and z axes L, M, and N respectively where N is very much greater than M or L.   Cave (1961) showed that the horizontal component of the field, in the x direction, at the lower magnet is approximately given by

$$X = - \frac{L}{z_0^3} - \frac{3\mathcal{X}N}{z_0^4} - \frac{3\mathcal{X}\mathcal{Y}M}{z_0^5}$$

Write

$$L = p_x + q_x + r_x$$

$$M = p_y + q_y + r_y$$

$$N = p_z + q_z + r_z$$

where p, q and r are the components of H along coordinate axes P, Q, R, where R is parallel to the rotation axis, and p_x, p_y, etc. are components of these components, along the x, y, and z axes. On rotating the dipole 180° about R, p and q change sign, so that

$$X_0 + X_{180} = -2\left(\frac{r_x}{z_o^3} + \frac{3\chi r_z}{z_o^4} + \frac{3\chi r_y}{z_o^5}\right)$$

In practice, the centre of the dipole will not be exactly on the rotation axis, but this merely alters χ slightly, and does not affect the argument.

If the dipole is almost parallel to the rotation axis, then $r_y \ll r_z$. Since also $\frac{\chi}{z_o}$ 1

$$X_0 + X_{180} = -2\left(\frac{r_x}{z_o^3} + \frac{3\chi r_z}{z_o^4}\right)$$

$$= A(z_o r_x + 3\chi r_z)$$

If χ is adjusted until $X_0 + X_{180} = 0$,   (8.1)

then

$$\frac{r_x}{r_z} = -\frac{3\chi}{z_o} \tag{8.2}$$

$\frac{r_x}{r_z}$ is the tangent of the angle between the rotation axis and the vertical, and the magnetometer is said to be levelled when this angle is zero. The condition $X_0 + X_{180} = 0$ is the condition that the relationship 8.2 between centring and levelling holds.

Levelling was achieved to $\pm$ 0.02° with a spirit level.
With this degree of levelling, the criterion (8.1) would
give

$$\mathcal{X} < \frac{8}{3} \times \frac{0.02 \times \pi}{180} \text{ cm} \ (z_0 \doteqdot 8\text{cm})$$

$$= \ 0.001\text{cm}.$$

This is better than the accuracy of setting samples in the
holder, and is quite sufficient.

Centring in the x direction was limited to $\pm$ 0.02cm by
random movements of the sample holder.

Centring in the y direction was accomplished to $\pm$ 0.1cm by
a no parallax method.

8.3 CANCELLATION OF EARTH'S MAGNETIC FIELD

This was initially done using a single magnet suspended in
the magnetometer, for the horizontal components, and using
a fluxgate for the vertical component.   When the Avo used
to record the currents became faulty it became necessary to
set the currents up again, for the meter had been used
across an external shunt, on low current ranges to obtain
sufficient sensitivity as a voltmeter.   The readings
depended on the unknown internal resistance of the meter.
Rather than risk damage to the magnetometer suspension, on
removing it to use the single magnet, a cubical box of
$MnSO_4.4H_2O$ was placed in the sample position, and the currents
in the Helmholtze coils altered so that it had no detectable
induced magnetic moment.   The procedure is simple and fairly
obvious.   The x component is cancelled with zero offset, and
then the z component with about 1cm offset.   The y component
Helmholtze current was set to be the same as the previous

reading on the meter incorporated in the control panel, which ought to be accurate enough for this component. The x and z component currents could be set to 1% with this salt, the main difficulty being the smallness of the induced moment. Greater accuracy could be attained with a more strongly paramagnetic salt.
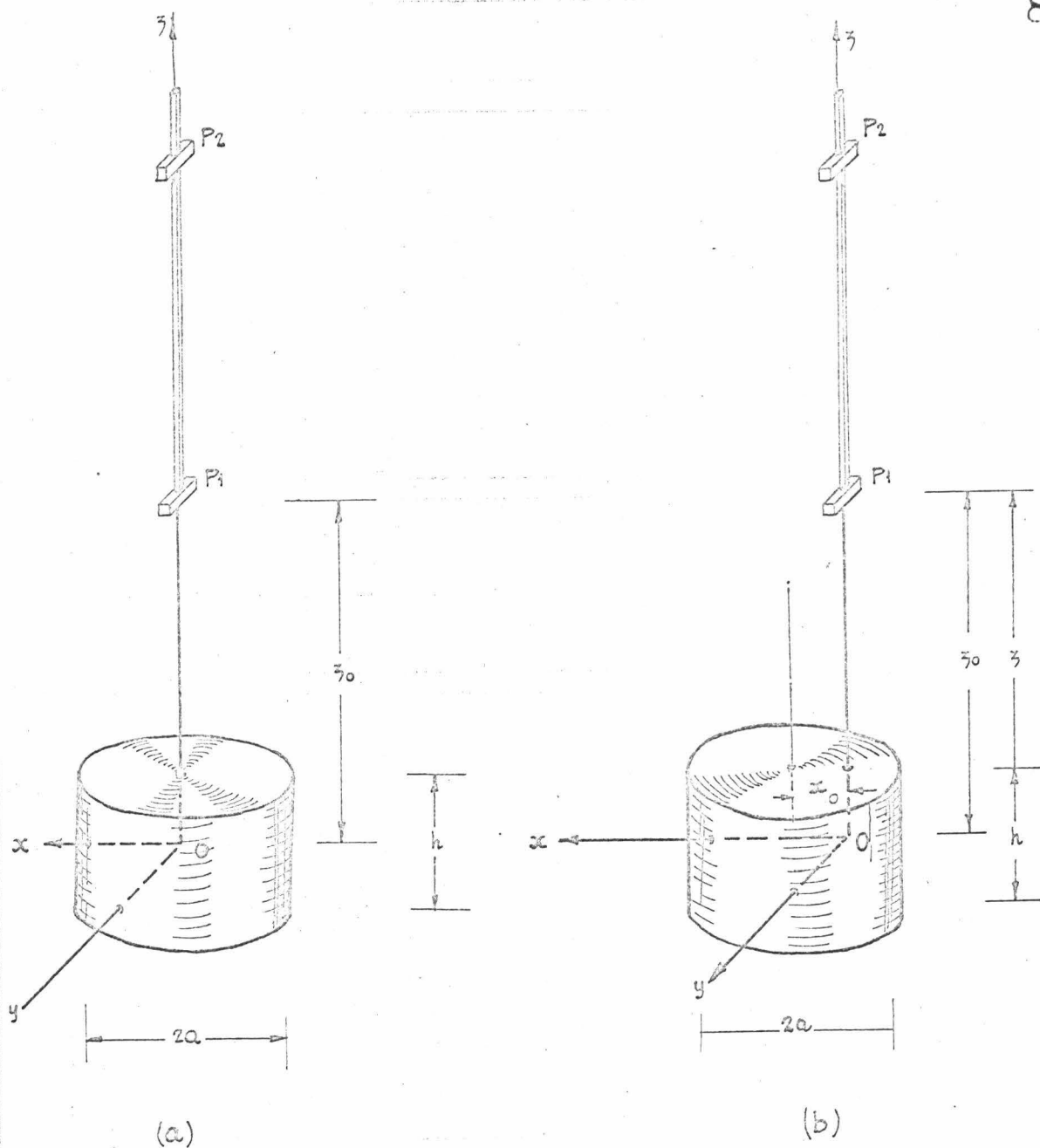
CYLINDRICAL SPECIMEN NEAR LOWER
MAGNET OF MAGNETOMETER.

(a) CENTRAL POSITION

(b) OFF-SET

FIG. 8.1

I G N I M B R I T E S

9.1 GENERAL GEOLOGICAL DESCRIPTION

Ignimbrites (also called welded tuffs and other names) are
an igneous rock, usually characterised by their occurrence
in extensive, flat-lying sheets up to several hundred feet
in thickness.   They were first recognised as a distinct
class of rock by Marshall (1932, '35) and have since been
frequently described in many parts of the world.   They
occur in large volume in the central part of the North
Island, where Martin (1959, '61, '64) has described several
tens of different examples, whose ages probably span a
large proportion of the Pleistocene.

The flatness of the surface of the flows over distances up
to thirty miles indicates extreme fluidity of the original
flow, which is usually explained by supposing that the
incandescent particles were still emitting gas as the sheet
moved, the turbulence produced being sufficient to allow a
large amount of solid material to be transported with low
viscosity, in much the same way as modern methods for
transporting powders through pipelines.

Alternative theories of the mode of emplacement of
ignimbrites have been proposed by Grange (1937) and Steiner
(1960), but neither of these have much support.   The
properties and theories of origin of ignimbrites in general
have been extensively discussed by Smith (1960).

The ignimbrite sheets show variations in texture from
bottom to top which give some indications as to their
mode of formation.   Near the bottom they are generally
very soft and friable, with many easily visible pumice
fragments.   Further up they become more closely compacted,
and the pumice becomes crushed into "lenticles".   Welding
of particles becomes progressively more pronounced, until
in the centre of the sheet the rock is hard, non-porous,
and completely welded.   Near the top the welding becomes
less pronounced and the density decreases again.   Vertical
jointing, which often occurs in the central region, indicates
that the rocks were at rest while cooling.

Glass shards were observed by Marshall (1935) to have been
distorted by flowage.   Experiments on softening temperatures
indicate that for this to occur the temperature of the fluid
rock must have been about $1000^{o}C$.

9.2   PREVIOUS PALAEOMAGNETIC WORK

Hatherton (1954a, b) has investigated various magnetic
properties of the Whakamaru ignimbrite sheets.   The main
conclusions in these papers are based on studies of the
variations in the ratio $Q = \dfrac{M}{\chi H}$, where M is the intensity of
the magnetization, χ is the susceptibility and H is the earth's
magnetic field (assumed constant, and about $\frac{1}{2}$ oe).

Hatherton found that Q varied between sheets differentiated on
petrological grounds, and that near the edge of each sheet the
value of Q greatly increased.   In addition, Q increased in a
similar manner at other positions in the ignimbrite, so he
proposed division of it into several more sheets.   He
calculated the variation in cooling rate with distance from

the surface of a horizontal cooling sheet and produced
graphs which correlated with those of the variation of
Q with distance.   This agreed nicely with the hypothesis
that the value of Q was related to physical properties of
the magnetic grains, which depend on the rate of cooling
of the rock when the grains were forming.

The direction of magnetization of the rocks is about that
of the present field, as expected for rocks of this age
(lower Pleistocene) (Torreson and others, 1949).   There
appears to be a somewhat large scatter in the inclination
directions, but the dip directions suggest secular
variation effects.

Hatherton determined the magnitude of the T.R.M. acquired
in the present earth's field for some samples, and found
that the ratio of this to the natural magnetic moment was
about 1.1.   This is usually taken to indicate that the
earth's field when the rocks were formed was about the
same intensity as now, and that the magnetization intensity
of the rocks is stable over the geological time involved.

Bailey (unpublished) of the U.S. Geological Survey, collected
some oriented samples from the Matahina ignimbrite sheet,
the magnetization directions of which were determined by
Geophysics Division, D.S.I.R.   The directions of magnetization
obtained are rather scattered, with some directions being
opposite to that expected.   There appear to be variations in
Q throughout the sheet, but no definite conclusions are
obvious.   It was thought worthwhile to investigate the same
ignimbrite again.

9.3 THE MATAHINA IGNIMBRITE

This formation covers a large area in the North East of
the central North Island (see Fig. 9.1). It is, like
many of the N.Z. ignimbrites, mostly lying horizontally,
indicating that it has not been shifted since formation.

A detailed petrographic axamination was performed by Mr
R. A. Bailey about 1956, but so far this work is not
published.

Near its eastern boundary, the ignimbrite has been
completely cut through by the Rangitaiki river, which has
a gorge with numerous rock outcrops convenient for sampling.
The Ministry of Works are currently building a hydro-electric
dam at Matahina, so many drilled cores and much geological
information are available. It appears that the Rangitaiki
gorge has been cut along the trace of a large fault. The
western side of the river is practically horizontal and
shows little evidence of movement, but the eastern side has
been raised several hundred feet. There appears also to
be some buckling of the rocks on the eastern side, as if the
fault has some transcurrent component which exerts a lateral
pressure. This information has been obtained from M.O.W.
geological reports by J. Healy, and was not available when
samples of ignimbrites were being collected, so that no
thought was given at the time to possible movements of the
ignimbrite on the eastern side of the Rangitaiki, where the
Luke's farm section was collected. In order to fully
interpret the results of the work described in the next
chapter, estimates of the movements of the outcrop will be
necessary, but are not available.

Waikato R.

Hamilton

Tauranga

Whakatane

Matahina

Matahina Ig.

Rangitaiki R.

L. Taupo

Ignimbrites

FIG. 9.1
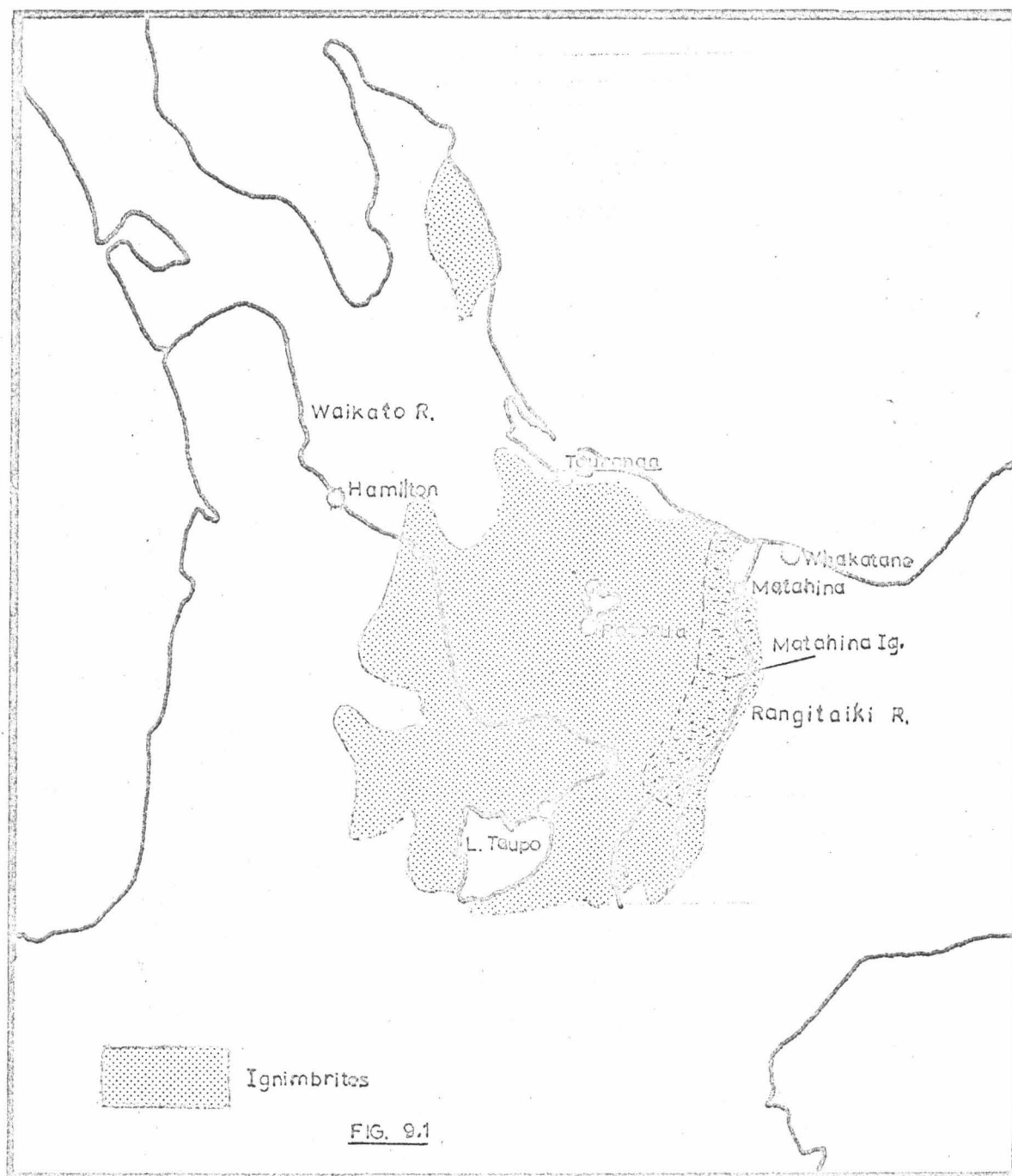
SOME MAGNETIC PROPERTIES OF THE MATAHINA IGNIMBRITE

10.1   SAMPLE COLLECTION

10.1.1 Collection Locality

During the summer of 1961-62, Mr Gellen, assisted by the author, collected a set of oriented rock samples from an exposure of the Matahina ignimbrite at Luke's Farm, near the site of the Matahina hydro-electric dam.   The exposure is in two parts.   Exposure 1 is a steep cliff face parallel to the road and river, on which apparently undisplaced rock outcrops in many places, through vegetation and rock debris.   Exposure 2 is a vertical cliff about $\frac{1}{4}$ mile from the other exposure, and separated from it by a small spur ("Sugar-loaf Spur"), (see map, Fig. 10.1).   At the time of making the collection it was believed that this exposure, like most of the ignimbrites, had not been moved more than a degree or two from its original flat-lying position.   It has since been learnt , from geological reports supplied to the Ministry of Works by Mr J. Healy, that faulting, and tilting up to 20°, is common on the eastern side of the Rangitaiki, and that less than a mile from the collection area, the Matahina ignimbrite dips 20° downwards towards the North.

Two rock samples were taken from each of twenty collection sites, nine of the sites being on exposure 1, and eleven on exposure 2.   (The samples from each site are supposed to have the same properties).   At the time of collection it

was thought that both exposures would be equivalent,
but the results indicate the desirability of treating
them separately.

All samples in this collection belong to Mr Gellen's
collection "L", that is, they are recorded in field
books and in the rock store as sample L53 etc.   The
prefix L has here been omitted.

10.1.2   Sample Altitudes

It was desired to sample the sheet at vertical intervals
of 10 to 20 feet throughout its thickness, in order to
repeat the measurements made by Bailey in 1956 (unpublished).
To this end, the altitude of each sample was determined with
a Paulin aneroid barometer.   It is necessary when using an
aneroid barometer to make an allowance for changes in air
pressure due to causes other than changes in altitude, so
each day readings were taken, every hour or half hour, of
the height indicated by another Paulin barometer at base
station, which was the M.O.W. camp about three miles from
the exposure.   This gives some indication of the trends
in barometric pressure, but no correction can be made for
the pressure changes occurring in the valleys and on the
cliffs of the exposures due to local wind and temperature
changes.   It is probable that the heights determined by
this method are in error by $\pm$ 20 feet and sometimes even
more.

Heights were corrected for the daily pressure variation
by recording the time at which each field reading was taken,
and finding the change in height indicated at base station
at that time, from a graph of pressure versus time.

This procedure initially led to some obviously wrong relative positions. Two samples, one collected on the first day, the other on the last, were known to have the same altitude, but were apparently 45 feet apart. The density of the ignimbrite was expected to increase steadily upwards through the lowest hundred feet, but the pair of samples with the lowest density were not at the bottom. It was found possible to locate most collection sites on photographs taken at the time, and from these to determine relative order within each of the exposures. Table 10.1 gives the apparent height of each sample, corrected for the diurnal variation of air pressure, and the difference in reading of the two barometers at base each day (zero correction). Table 10.2 has been derived from this information, the known relative positions of samples 43 and 44, and the information that samples 53 and 54 are the lowest ones, and shows the stratigraphic sequence (i.e. relative vertical position), of the samples. No allowance has been made for possible tilting of the ignimbrite sheet, which, if present, would mean that present altitudes alone would be insufficient to determine relative vertical positions within the original sheet.

10.1.3 Orientation Method

Samples were chosen which had one flat face, either natural or chiseled. On this face a horizontal line was drawn with a felt-tipped pen. The dip of the face was measured, being that angle through which a horizontal surface through the line must be rotated, in order to make the upper
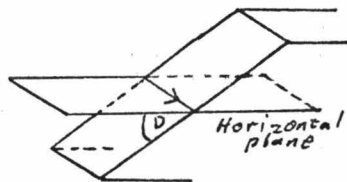
side of the surface coincident with the outer side of
the face.   The angle was measured in a right handed
sense about an arrow drawn on the orientation line.
The magnetic declination of this arrow was also
measured.   Both measurements were made to the nearest
degree with a Brunton combined compass and inclinometer.
None of the rocks were found to be sufficiently
magnetic to deflect the compass.

10.1.4   Preparation of Specimens

One cylindrical specimen was cut from each of the 40
oriented samples, using non-magnetic diamond cutting
tools.   Each specimen is 3.46 ± 0.01cm in diameter and
about 3.5cm long.   The axis of the cylinder is perpendicular
to the oriented face of the sample, and a reference line is
drawn on the end of the cylinder near the face, parallel to
the original orientation line.   A specimen coordinate system
has its x axis parallel to this line, and z axis along the
cylinder axis.   Marking of the specimens was originally
with Indian ink, but later they were re-marked with white
"Chinagraph" pencil before heating to high temperatures.

10.2   DENSITY OF SPECIMENS

Differences in texture and density between specimens were
obvious to the eye and appeared to vary in a regular manner.
Martin (1959) has described typical variations of these
properties throughout the sheet, and it is interesting to
compare the Matahina sheet with his generalized description.

Dry densities were determined to about 1% by weighing the
cylinders (after heating above 600°C.) and calculating their

volume from the dimensions.   A graph of density against altitude is shown in Fig. 10.2. and it can be seen that density decreases near the top and bottom of the sheet. Owing to the uncertainty in altitudes and the approximate (but simple) method of finding density, nothing can be said about the possibility of the existence of more than one sheet within the ignimbrite from these results (refer Section 11.2).

Samples 51 to 56 are pinkish in colour and comparatively friable, corresponding to Martin's basal zone.   Those next above them (49, 50) are very granular and contain up to 5% of black, glassy, obsidian-like material, in grains several mm in diameter, as expected from Martin's description, while further up the rock is uniformly welded and grey in colour, becoming lighter in colour over the top 30 feet.   It appears that the exposure includes only one typical ignimbrite.

10.3   NATURAL REMANENT MAGNETIZATION

10.3.1   Notation

The following symbols have been used: The angles θ and φ give the specimen magnetization direction measured in the specimen coordinate system defined by the orientation line, and the cylinder axis, as shown in the diagram.
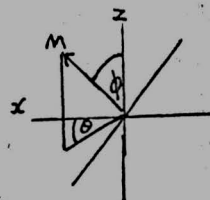
M is the intensity of magnetization, per unit volume, of the specimen, (measured in oersteds).

χ is the magnetic susceptibility of the specimens (per
unit volume). The values tabulated are 1.06 times the
actual values, but because of the large random errors
inherent in the susceptibility measurement procedure used,
this has no effect on any conclusions drawn here.

N.R.M. is an abbreviation of "natural remanent magnetization".

T.R.M. is an abbreviation of "thermoremanent magnetization".

C.R.M. is an abbreviation of "chemical remanent magnetization".

10.3.2 Measurements of Direction

The N.R.M.s of the specimens were first measured in November,
1963, with the magnetometer fitted with a phosphor bronze
suspension.   Table 10.3 gives these directions of
magnetization for all samples except 53 and 54, which were
too weakly magnetized to measure.

After measurement the specimens were stored in the earth's
field for three months, and remeasured in February 1964,
using a more sensitive quartz fibre suspension.   The
direction of the field was $\theta = 90^{\circ} \pm 5^{\circ}$ and $\phi = 26^{\circ} \pm 5^{\circ}$
in the specimen coordinate system, for all specimens.   The
new directions also appear in table 10.3

There is a small average decrease in the values of θ and ϕ,
but this is probably not significant, and is in the opposite
sense to the changes to be expected from viscous magnetization.

The directions of magnetization in local geomagnetic coordinates
(i.e. relative to the present magnetic north direction, the
magnetic east direction, and the vertical), were calculated

using a stereographic projection (see Appendix III),
and are shown in table 10.4 and Fig. 10.3. The points
have been plotted on two stereograms, one for specimens
from exposure 1, the other for specimens from exposure
2.

10.3.3 Intensity and Susceptibility of N.R.M.

Table 10.5 displays these as well as other quantities
which will be explained later. The ratio $\frac{M}{\chi}$ is a useful
parameter as it eliminates effects due only to differences
in amount of magnetite. Variation of $\frac{M}{\chi}$ can be due either
to differences in the nature (e. g. grain size) of the
magnetic fraction, or to the magnetization process and
history. This ratio is included in table 11.2. No
definite trends in the changing values of $\frac{M}{\chi}$ with position
were noted at first, partly because of difficulties in
deciding the altitudes of the samples.

10.4 THERMAL DEMAGNETIZATION OF N.R.M.

10.4.1 Choice of Specimens for Trial Demagnetization

Only nine specimens could be treated at a time because of
the need to include two dummy specimens for temperature
measurement, and the partly broken sample holder.

Because of limited time only one set of nine specimens
was fully investigated. These specimens were chosen to
fairly represent both position in the sheet and the
measured value of $\frac{M}{\chi}$. Specimens chosen were from five
sites. In four cases one specimen was treated from each
of the two samples collected at each site, and the other
site was represented by a single specimen. The purpose

of the pairs of specimens was to provide a check against errors in measurement, but it was found that such errors were sufficiently uncommon and obvious that a better procedure would be to use only one specimen from more sites.

10.4.2 Heating and Measuring Procedure

The specimens were heated to successively higher maximum temperatures, held at these temperatures for 20 - 30 minutes, and then allowed to cool, all this being in zero magnetic field.   Their magnetizations were then measured in a vertical magnetic field equal to twice the vertical component of the earth's field, which allowed measurement of susceptibility (see Appendix II).   The magnetization intensity, M, after heating to the successively higher temperatures, T, is plotted against T in Figs. 10.5 to 10.13, and corresponding changes in magnetization direction from the initial value are plotted in Figs. 10.14 and 10.15.

10.4.3 Changes in Directions of Magnetization

These are generally small, and show no trends which might be attributable to the removal of a viscous magnetization inclined to a more stable component.

The large changes in direction observed in specimens 53 and 54 may be due to the removal of P.T.R.M.'s in different directions, originally acquired as the somewhat friable and vesicular lower layers compacted during the cooling period after deposition.

10.4.4 Changes in Intensity

The graphs showing the reduction in intensity of N.R.M. by heating are of several types, indicating differences between

magnetic minerals at different parts of the ignimbrite. The simplest graphs are those of specimens 49 and 50, whose intensities remain practically constant up to a temperature of about 350°C., decrease to 50 - 60% of their initial values by 500°C., and then drop rapidly to a minimum (not zero) value at about 570°C.   The graphs for both specimens from the site are almost identical in this and the other cases, which supports the view that only one specimen from each site need be investigated in detail for this purpose.

Specimens 47 and 48 behave in a similar manner to these two, except that their intensity starts to decrease at lower temperatures.   These four specimens have a relatively high $\frac{M}{\chi}$, which Hatherton (1954a) has suggested is associated with rapid cooling, and they also show the glassy black vitrophyre which Martin (1959) associates with rapid cooling on petrological grounds.

Specimens 97 and 98 are somewhat different from those above, in that the intensity decreases by about 20% between 200°C. and 300°C., and is then constant up to 400°C., above which temperature it drops uniformly to a small constant value above 590°C.   The change at 200°C. could be due to any of the following causes:

a) Removal of a P.T.R.M. acquired at temperatures below 300°C. in a field of 20% greater intensity than, but within 1° in direction of, the original magnetizing field.

b) Removal of an I.R.M. in the direction of the original field.

c) A mineral of Curie point about 250°C. was present.

d) A magnetic mineral chemically unstable above 250°C. was present.

Specimen 41 shows a gradual change in intensity right from 100°C., with an inflection at about 200°C. which might be due to any of the causes listed above.

Specimens 53 and 54 are similar to 41, but they do not show the inflection.

Before discussing these results further, it is useful to know more about the T.R.M. of the rocks.

10.4.5 Changes in Susceptibility

There is a general increase of 20 to 30% in susceptibility of the rocks as the temperature of heating increases to 600°C., although the scatter of the values is large owing to the inaccurate susceptibility measuring procedure (Figs. 10.16 - 10.20). This is almost certainly due to mineralogical changes, but the particular reaction is hard to identify. Oxidation of magnetite to hematite would lead to a lowering of susceptibility, and the reverse reaction is unlikely because of the oxidizing conditions probably present in the oven. A possible, but unrecorded, reaction involves the oxidation of a sulphide mineral to magnetite. Chlorophaeite is a mineral found sometimes as an alteration product of olivine, which changes to various ferromagnetic minerals on heating (Weaving, 1962). If present, this could lead to the observed behaviour.

After heating for about $\frac{1}{2}$ hour above 600°C. all samples showed a decrease in χ, this being especially great in

specimens 97, 98, and 41, which were those showing a
decrease in M at 200°C.

10.5   THERMAL DEMAGNETIZATION OF T.R.M.

To help decide whether the N.R.M. was in fact a T.R.M.,
the specimens whose demagnetization was described above
were all given a T.R.M. in the earth's field.   This was
then demagnetized in the same way as the N.R.M., and the
information obtained plotted on the same graphs as the
N.R.M. data.

10.6   COMPARISON OF N.R.M. AND T.R.M.

i.   The T.R.M. is in all cases 4 - 5 times greater in
      intensity than the N.R.M.

ii.   The low temperature changes in the demagnetization
      of N.R.M. of specimens 97, 98 and 41 are not present
      in the demagnetization of T.R.M.

iii. The demagnetization of T.R.M. of specimens 53 and
      54 shows a slower rate of decrease at low temperatures
      than the corresponding N.R.M. curve.

iv.   The susceptibility increases as demagnetization of the
      T.R.M. proceeds.

Whatever the cause of the differences between the T.R.M.
and N.R.M. demagnetization graphs, it seems that some of
the N.R.M. of some specimens resides in grains of low
Curie temperature, and so is to be regarded with caution.

10.7   THERMAL WASHING AT 300°C.

10.7.1 Experimental

On the basis of the experiments on demagnetization described

above, it was decided to heat all the remaining specimens
to between 300°C. and 350°C., cool in zero field, and
remeasure the magnetization.   It was expected that this
would remove any secondary or unstable components of
magnetization.   The results of this experiment are shown
in the columns headed "300°C wash" in tables 10.3 and 10.5.

10.7.2   Changes in Direction

These are generally small, with no obvious consistency in
the directions of change.   Specimens 42, 43, 44, 53, and
54 show surprisingly large changes in direction, away from
the present field direction, but although the changes are
larger for these samples than for others, they are not
larger than existing scatter between samples.   This could
be due to the samples having been moved since emplacement,
by undetected faulting or slumping, and then acquiring an
I.R.M. in the present field direction.   The I.R.M. has
been removed so the magnetization direction rotates away
from the mean direction, which is nearly parallel to the
present field direction.   Since most of the change is in
the declination, it is not possible to refer to rock
structure to find further evidence for post-depositional
movement.   No change in the dispersion of the directions
is obvious after this treatment, so it appears that over
the whole collection I.R.M. is unimportant in altering
directions.

10.7.3   Changes in Intensity of Magnetization

Table 10.5 lists the new values of intensity and
susceptibility.   It will be seen that after heating to
300°C. χ has increased by 10 - 30%, indicating that the

effect observed when studying the first selection of
specimens in detail is a general one in this ignimbrite.
Discussion of the details of the change in intensity of
magnetization is left until Chapter 11, where it is
compared with other properties of the rock.

10.8   EFFECT OF THE EARTH'S MAGNETIC FIELD AT ELEVATED TEMPERATURES

Nine specimens which had previously been demagnetized at
300°C - 350°C and measured, were reheated to just below 300°C
in zero field.   The field cancellation coils were then
switched off, and the temperature held constant or allowed to
increase slightly for 40 minutes, after which the field was
again cancelled and the specimens allowed to cool to room
temperature.   No consistent change in direction was
observed, (see tables 10.3 and 10.6), although the directions
of specimens 42 and 101 shifted slightly towards the field
direction in a horizontal plane, with no change in the
vertical direction.   In view of the uncertainties surrounding
the theory of this test (see paragraph 3.3.3), no conclusions
are drawn from it.   If work on known unstable rocks could
show some correlation between instability and changes at
elevated temperatures, this might prove a useful and simple
test.

10.9   DECAY OF T.R.M. WITH TIME

The specimens used in the previous experiment were given a
T.R.M. in the earth's field by cooling them in it after
holding them at a temperature of about 650°C for half an
hour.   This T.R.M. was measured 3 hours after the start of
the cooling operation, which was as soon as is possible
with this equipment.   Sixty hours after this first measurement

the T.R.M.s were measured again.   From the results,
which are shown in table 10.7, it appears that changes
in direction and intensity between the two measurements
are not greater than the accuracy of measurement.   Also
the random changes in χ between the two measurements give
an idea of the accuracy of measurement of χ, which is
about $\pm$ 20%.

10.10   T.R.M. OF ALL SPECIMENS

To complete the data on the samples, all specimens were
given a T.R.M. in the earth's field.   The values of M and
χ of the T.R.M. are included in table 10.5.   Implications
of these results are discussed in Chapter 11.

T A B L E   10.1

Date of Collection	Sample Number	Nominal Altitude	Correction for Pressure Variation	Zero Correction	Corrected Altitude
12/12/61	35	336	−26	0	310
"	36	334	−26	0	308
"	37	325	−36	0	289
"	38	322	−36	0	286
"	39	404	−52	0	352
"	40	400	−52	0	348
"	41	453	−85	0	368
"	42	450	−85	0	365
"	43	462	−85	0	377
18/12/61	44	242	−83	+265	424
13/12/61	45	242	5	78	325
"	46	244	5	78	327
"	47	202	−14	78	266
"	48	205	−14	78	269
"	49	192	269 −13'		256
"	50	191	269 −14'		255
"	51	191	256 −15'		241
"	52	192	256 −14'		242
"	53	185	−2	78	261
"	54	185	−2	78	261
"	55	205	−44	78	239
"	56	209	−44	78	243
18/12/61	87	20	−16	265	269
"	88	22	−16	265	271
"	89	29	−26	265	268
"	90	32	−26	265	272

T A B L E   10.1 (Cont.)

Date of Collection	Sample Number	Nominal Altitude	Correction for Pressure Variation	Zero Correction	Corrected Altitude
18/12/61	91	62	−32	265	295
"	92	63	−32	265	296
"	93	90	−40	265	315
"	94	93	−40	265	318
"	95	107	−50	265	322
"	96	107	−50	265	322
"	97	130	−54	265	341
"	98	132	−54	265	343
"	99	153	−56	265	362
"	100	151	−56	265	360
"	101	163	−60	265	368
"	102	162	−60	265	367
"	103	212	−82	265	395
"	104	213	−82	265	396

T A B L E   10.2

Sample Number	Density	Altitude
43, 44	1.76, 1.85	420
41, 42	2.04, 2.02	410
103, 104	2.02, 1.94	400
39, 40	2.24, 2.24	390
101, 102	2.25, 2.23	370
99, 100	2.24, 2.26	360
97, 98	2.25, 2.26	340
35, 36	2.29, 2.27	340
45, 46	2.31, 2.30	330
95, 96	2.24, 2.25	320
93, 94	2.26, 2.27	320
91, 92	2.32, 2.25	300
37, 38	2.27, 2.26	300
89, 90	2.32, 2.31	270
87, 88	2.28, 2.23	270
47, 48	2.29, 2.29	270
49, 50	2.17, 2.24	260
51, 52	1.86, 1.93	240
55, 56	1.78, 2.16	230
53, 54	1.35, 1.43	220

T A B L E   10.3

DIRECTIONS OF MAGNETIZATION,

in the samples' coordinate systems

Sample	Sample Orientation in situ		1st Measurement of Sample Magnetization		2nd Measurement of Sample Magnetization		Sample Magnetization after 300°C Wash	
	Dec.	Dip	θ	ϕ	θ	ϕ	θ	ϕ
35	–	–	8	$40\frac{3}{4}$	$9\frac{3}{4}$	$40\frac{3}{4}$	$9\frac{1}{4}$	$39\frac{1}{4}$
36	195	081	$132\frac{1}{2}$	$80\frac{1}{4}$	$132\frac{1}{4}$	$78\frac{3}{4}$	$133\frac{3}{4}$	$79\frac{1}{4}$
37	243	121	$102\frac{1}{4}$	$76\frac{1}{4}$	103	$76\frac{3}{4}$	$102\frac{1}{2}$	$74\frac{1}{4}$
38	224	076	$102\frac{3}{4}$	$61\frac{1}{2}$	$103\frac{1}{4}$	$62\frac{1}{2}$	$103\frac{1}{2}$	59
39	242	057	124	33	$122\frac{3}{4}$	$32\frac{1}{2}$	123	$28\frac{1}{4}$
40	215	074	131	58	131	$59\frac{1}{2}$	$130\frac{1}{2}$	$55\frac{1}{2}$
41	106	073	$105\frac{1}{2}$	127	105	127	$107\frac{1}{4}$	127
42	180	090	115	$87\frac{1}{2}$	$114\frac{3}{4}$	$90\frac{1}{2}$	$116\frac{1}{2}$	$80\frac{3}{4}$
43	215	073	$112\frac{1}{2}$	$55\frac{1}{2}$	$112\frac{1}{4}$	$56\frac{1}{4}$	$114\frac{3}{4}$	$44\frac{1}{4}$
44	262	020	$255\frac{3}{4}$	$16\frac{1}{4}$	$253\frac{1}{2}$	18	$262\frac{3}{4}$	$12\frac{1}{2}$
45	135	076	$119\frac{1}{2}$	124	$117\frac{1}{2}$	$115\frac{1}{2}$	$111\frac{1}{4}$	$117\frac{1}{2}$
46	227	067	$132\frac{1}{4}$	$51\frac{1}{2}$	132	$51\frac{1}{4}$	132	$51\frac{1}{4}$
47	126	076	123	$101\frac{1}{2}$	123	$100\frac{3}{4}$	123	$101\frac{1}{2}$
48	046	080	63	$128\frac{1}{2}$	$62\frac{1}{2}$	$127\frac{1}{4}$	$62\frac{3}{4}$	$127\frac{1}{2}$
49	124	095	123	$124\frac{1}{4}$	$123\frac{1}{4}$	$122\frac{1}{2}$	$123\frac{3}{4}$	123
50	209	071	$116\frac{3}{4}$	$80\frac{3}{4}$	$116\frac{1}{4}$	$80\frac{3}{4}$	$116\frac{1}{2}$	$79\frac{1}{4}$
51	128	078	$114\frac{1}{2}$	104	114	102	114	103
52	119	108	$123\frac{1}{2}$	141	123	$138\frac{1}{2}$	$127\frac{1}{2}$	$139\frac{3}{4}$
53	040	077	–	–	$56\frac{1}{4}$	$119\frac{3}{4}$	$52\frac{1}{2}$	$109\frac{1}{4}$
54	130	075	–	–	$114\frac{1}{4}$	$109\frac{3}{4}$	$111\frac{1}{4}$	$116\frac{1}{4}$
55	216	072	$135\frac{3}{4}$	$53\frac{1}{4}$	$132\frac{1}{2}$	$53\frac{1}{2}$	137	$50\frac{1}{2}$
56	208	111	130	$101\frac{1}{2}$	$129\frac{3}{4}$	95	$132\frac{1}{4}$	$90\frac{1}{4}$

T A B L E   10.3   (Cont)

Sample	Sample Orientation in situ		1st Measurement of Sample Magnetization		2nd Measurement of Sample Magnetization		Sample Magnetization after 300°C Wash	
	Dec.	Dip	θ	ϕ	θ	ϕ	θ	ϕ
87	282	088	$78\frac{1}{2}$	$57\frac{3}{4}$	$77\frac{1}{2}$	58	$76\frac{3}{4}$	$56\frac{1}{2}$
88	012	274	301	$75\frac{1}{4}$	301	$75\frac{1}{4}$	301	$73\frac{1}{4}$
89	256	155	89	125	$89\frac{1}{4}$	$124\frac{1}{2}$	$88\frac{3}{4}$	125
90	333	095	$58\frac{3}{4}$	$87\frac{1}{2}$	59	$86\frac{1}{2}$	$59\frac{1}{2}$	85
91	145	056	113	$69\frac{3}{4}$	113	$70\frac{3}{4}$	112	$69\frac{1}{2}$
92	044	000	$28\frac{1}{2}$	29	$28\frac{3}{4}$	29	$29\frac{1}{2}$	$27\frac{1}{2}$
93	233	099	108	$74\frac{3}{4}$	$107\frac{1}{2}$	71	$108\frac{1}{2}$	$73\frac{1}{2}$
94	204	107	$112\frac{3}{4}$	91	$112\frac{1}{4}$	$89\frac{1}{2}$	$111\frac{1}{4}$	$89\frac{1}{4}$
95	180	064	120	$67\frac{1}{2}$	119	$68\frac{1}{4}$	$118\frac{1}{4}$	67
96	185	085	122	$80\frac{1}{2}$	$121\frac{3}{4}$	$81\frac{1}{4}$	$122\frac{3}{4}$	$80\frac{1}{2}$
97	105	106	$99\frac{1}{4}$	$131\frac{1}{4}$	$101\frac{1}{2}$	$130\frac{3}{4}$	$97\frac{1}{2}$	133
98	134	088	$104\frac{1}{2}$	$102\frac{1}{2}$	$108\frac{1}{2}$	$101\frac{1}{2}$	$108\frac{1}{4}$	101
99	247	072	101	47	$100\frac{3}{4}$	$46\frac{1}{4}$	$100\frac{3}{4}$	43
100	218	095	$113\frac{3}{4}$	$80\frac{1}{2}$	$114\frac{1}{2}$	80	116	$77\frac{1}{4}$
101	033	009	48	$37\frac{1}{4}$	$48\frac{1}{4}$	38	$44\frac{3}{4}$	$35\frac{3}{4}$
102	340	004	$339\frac{3}{4}$	$28\frac{3}{4}$	$342\frac{1}{2}$	$29\frac{1}{2}$	$343\frac{1}{2}$	27
103	165	084	$117\frac{1}{4}$	101	$117\frac{1}{4}$	$100\frac{1}{2}$	119	103
104	156	088	120	$89\frac{1}{4}$	121	$89\frac{1}{2}$	125	86

T A B L E   10.4

Magnetizations in geographic coordinates (declinations from magnetic north, and inclinations from vertical).

Exposure No. 1

Sample Number	N.R.M. Declination	Inclination	N.R.M. After 300° Wash Declination	Inclination
35	–	–	–	–
36	010	41	009	43
37	350	46	350	48
38	015	18	007	21
39	003	33	358	35
40	006	40	000	41
45	010	48	019	46
46	012	40	013	38
47	341	41	342	41
48	344	54	343	54
49	350	42	350	42
50	044	26	042	27
51	352	34	352	34
52	345	40	353	43
53	347	53	359	49
54	006	42	013	46
55	000	42	358	46
56	001	46	007	46

Exposure No. 2

Sample Number	N.R.M. Declination	Inclination	N.R.M. After 300° Wash Declination	Inclination
41	002	56	000	56
42	003	25	339	27
43	352	26	336	35
44	000	38	354	33

T A B L E   10.4   (Cont.)

Sample	N.R.M.		N.R.M. After 300° Wash	
Number	Declination	Inclination	Declination	Inclination
87	350	32	351	34
88	348	33	347	33
89	345	31	344	32
90	348	31	351	32
91	354	25	353	24
92	014	29	014	28
93	353	33	359	31
94	349	26	350	26
95	002	26	002	26
96	357	31	356	33
97	356	27	003	28
98	350	22	350	24
99	353	29	351	30
100	008	28	003	30
101	354	31	359	30
102	003	31	009	25
103	017	32	019	34
104	337	31	335	34

T A B L E   10.5

Sample Number	N.R.M. $M \times 10^4$	N.R.M. $\chi \times 10^4$ *	N.R.M. After 300° Wash $M \times 10^4$	N.R.M. After 300° Wash $\chi \times 10^4$ *	T.R.M. $M \times 10^3$	T.R.M. $\chi \times 10^4$ *
35	32.3	6.0	29.5	7.3	9.6	3.8
36	28.9	5.9	25.8	7.9	11.0	4.4
37	32.5	5.5	28.2	6.7	11.0	6.4
38	30.0	6.5	27.1	7.5	10.0	8.9
39	23.5	5.6	19.5	6.3	10.4	5.7
40	20.9	6.7	16.9	7.8	9.1	5.9
41	9.4	6.7	5.7	8.5	5.9	1.4
42	9.5	6.5	6.4	8.1	6.5	5.3
43	7.5	5.6	4.3	7.1	5.7	7.2
44	13.2	7.0	9.2	8.0	6.1	9.5
45	57.6	4.4	56.8	3.9	22.5	6.9
46	55.8	4.8	56.3	4.8	21.0	6.2
47	51.7	2.0	51.4	4.8	20.8	3.3
48	54.5	4.4	49.8	4.7	17.8	2.7
49	23.8	3.2	24.8	4.7	16.1	3.7
50	27.8	4.1	27.6	4.5	12.4	5.5
51	9.9	4.0	7.1	4.8	5.4	8.7
52	13.7	3.5	11.1	5.0	6.8	10
53	1.63	2.2	0.75	2.4	0.66	2.1
54	2.30	2.0	1.72	2.1	1.02	0.42
55	10.3	3.0	8.4	4.0	2.59	4.6
56	7.6	3.1	5.5	4.0	5.1	7.3
87	31.3	5.6	28.5	6.3	10.0	5.3
88	29.4	5.5	26.6	6.9	10.6	5.0
89	34.1	6.8	30.7	7.1	10.2	7.0
90	35.8	6.0	32.1	7.3	11.2	6.3
91	33.6	5.3	30.6	6.4	10.4	5.2

T A B L E   10.5 (Cont.)

Sample Number	N.R.M.		N.R.M. After 300° Wash		T.R.M.	
	$M \times 10^4$	$\chi \times 10^4$	$M \times 10^4$	$\chi \times 10^4$	$M \times 10^3$	$\chi \times 10^4$
92	34.8	5.7	31.8	6.6	10.4	5.3
93	27.9	6.4	24.5	7.3	9.9	6.0
94	23.6	7.5	25.8	8.2	8.9	6.6
95	27.5	8.2	22.2	9.9	7.6	5.8
96	18.4	7.8	18.7	9.2	7.7	5.7
97	24.2	7.8	20.0	9.2	10.5	2.5
98	24.9	8.1	20.1	9.0	7.1	1.4
99	24.9	7.5	20.3	8.6	8.0	7.2
100	22.9	6.4	19.0	7.8	7.6	6.3
101	21.8	7.3	18.2	9.3	6.9	5.6
102	17.6	7.9	14.2	8.8	6.5	7.0
103	9.8	6.5	5.8	7.0	7.4	5.8
104	8.0	5.4	4.2	6.0	4.9	5.3

* See Chapter 10.3.1 for a note on the values of χ.

T A B L E   10.6

Magnetic Properties After Heating at 300°C. in the Earth's Field.

Sample	θ	ϕ	M	χ [*]
55	137	$49\frac{3}{4}$	8.2	4.3
45	111	$117\frac{1}{2}$	55.0	4.5
95	119	$65\frac{1}{2}$	21.9	10.3
36	134	$80\frac{1}{4}$	24.7	7.7
91	$112\frac{1}{2}$	68	30.9	6.7
87	$80\frac{1}{4}$	$56\frac{1}{2}$	28.5	6.6
100	$116\frac{1}{4}$	$78\frac{1}{2}$	19.8	8.3
42	$113\frac{1}{4}$	82	6.3	8.1
101	$49\frac{1}{4}$	$36\frac{1}{4}$	18.8	9.6

T A B L E   10.7

Decay of T.R.M. With Time.

Sample	After 3 Hours				After 60 Hours			
	θ	ϕ	M x 10^3	χ x 10^4 [*]	θ	ϕ	M x 10^3	χ x 10^4 [*]
101	354	$25\frac{1}{2}$	6.86	5.6	354	26	6.73	6.5
95	$357\frac{3}{4}$	$20\frac{1}{2}$	7.65	5.8	358	$20\frac{3}{4}$	7.58	6.0
42	$356\frac{1}{2}$	18	6.53	5.3	$355\frac{1}{2}$	18	6.61	5.9
100	$348\frac{1}{4}$	$16\frac{1}{2}$	7.61	6.3	$349\frac{3}{4}$	17	7.52	6.2
55	$357\frac{3}{4}$	21	2.59	4.6	357	$20\frac{3}{4}$	2.61	4.8
91	$355\frac{1}{2}$	$22\frac{1}{4}$	10.4	5.2	$354\frac{3}{4}$	$22\frac{1}{4}$	10.7	5.7
87	357	$28\frac{3}{4}$	10.0	5.3	358	$28\frac{1}{2}$	10.0	6.8
45	$008\frac{3}{4}$	$26\frac{1}{4}$	22.5	6.9	$008\frac{1}{2}$	$26\frac{1}{2}$	22.2	6.5
36	$005\frac{1}{2}$	24	11.0	4.4	$005\frac{3}{4}$	$23\frac{3}{4}$	11.1	4.6

[*]   See Chapter 10.3.1 for a note on the values of χ.

Te Teko, 5 miles

Matahina Dam

Exposure 2

Exposure 1
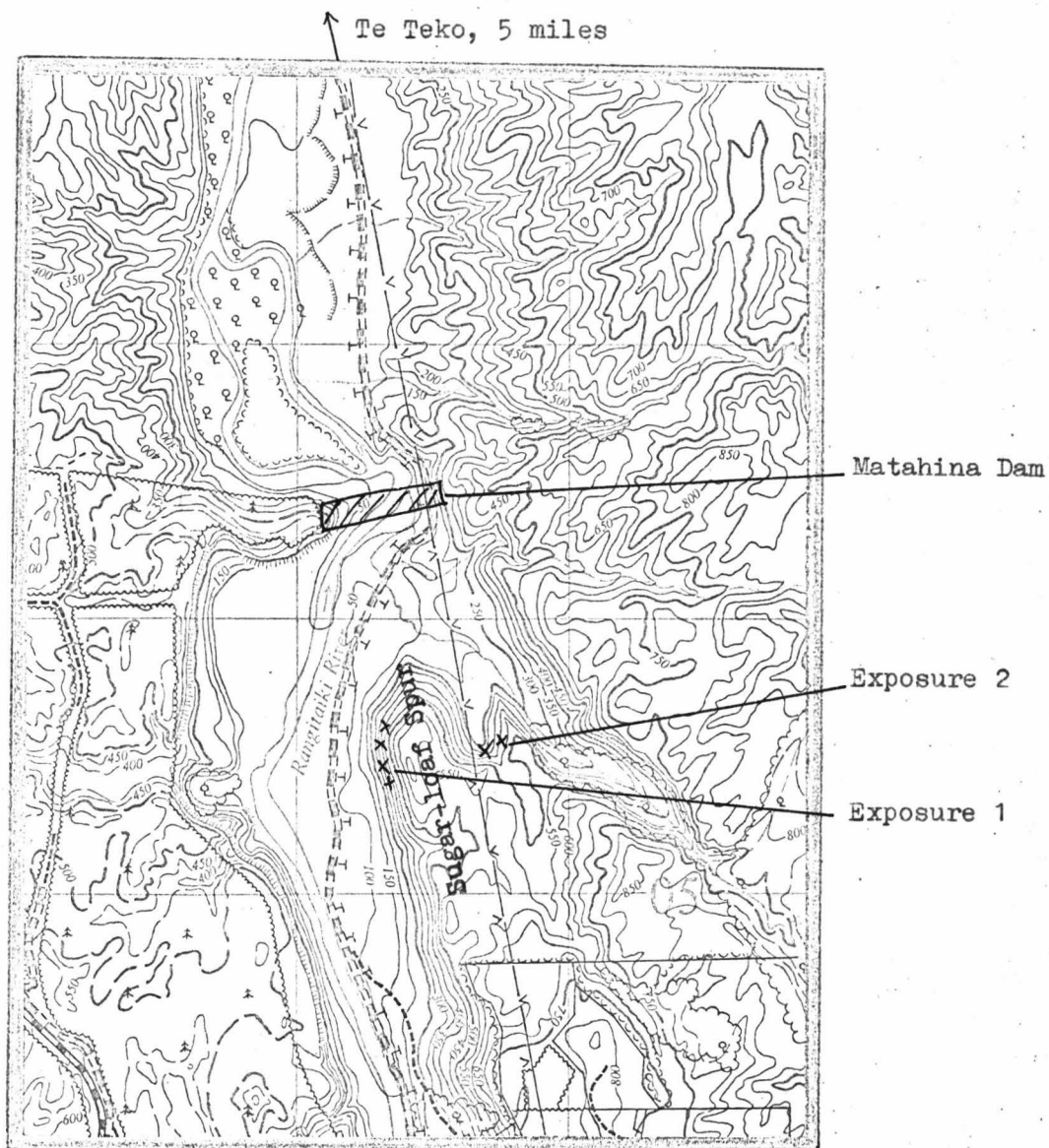
Fig. 10.1 Collection Locality

Scale 1:25,000

Fig. 10.2   Density Profile

M.N.

Exposure 1

× Present field direction

o Mean direction

M.N.

Exposure 2
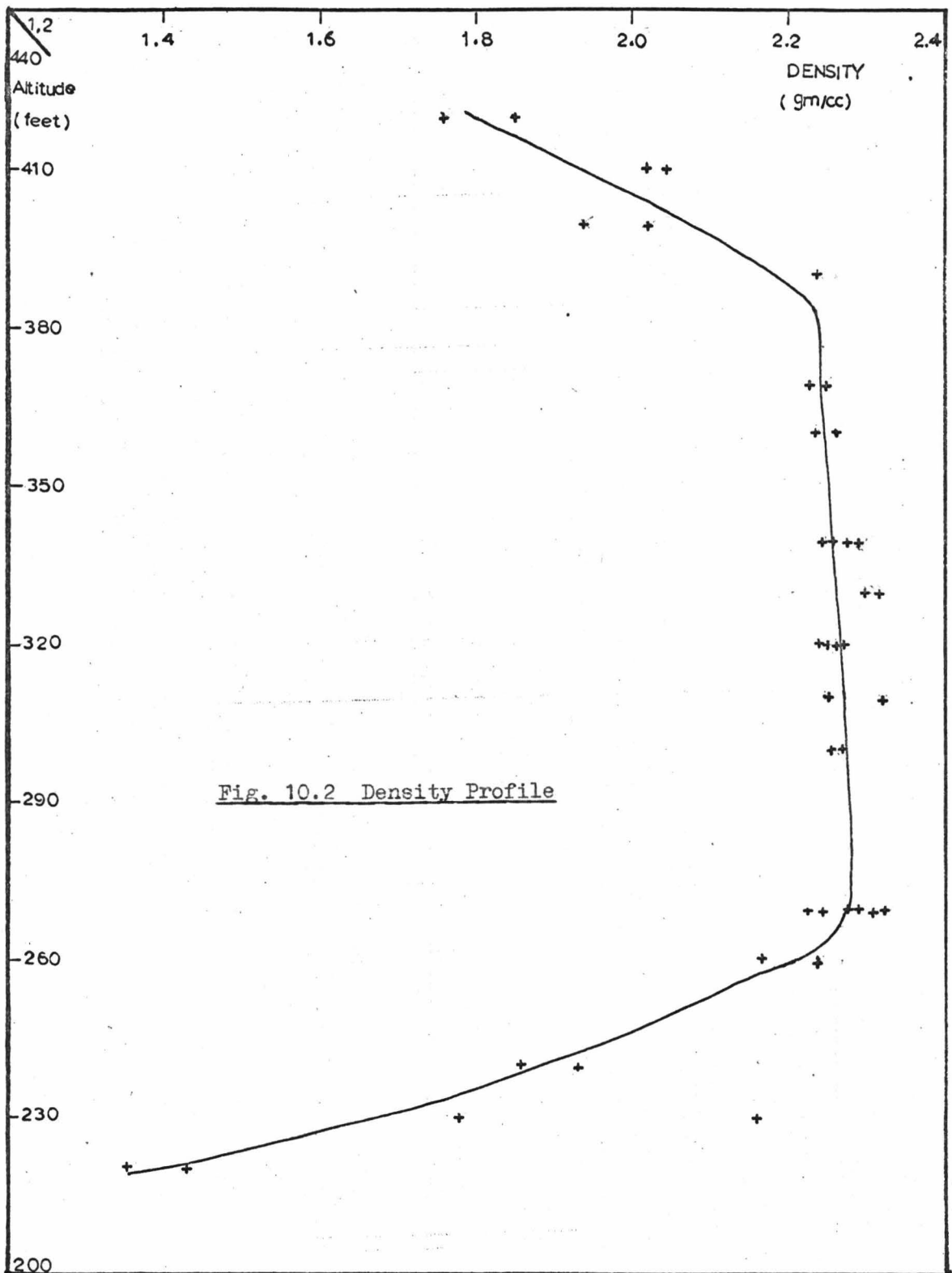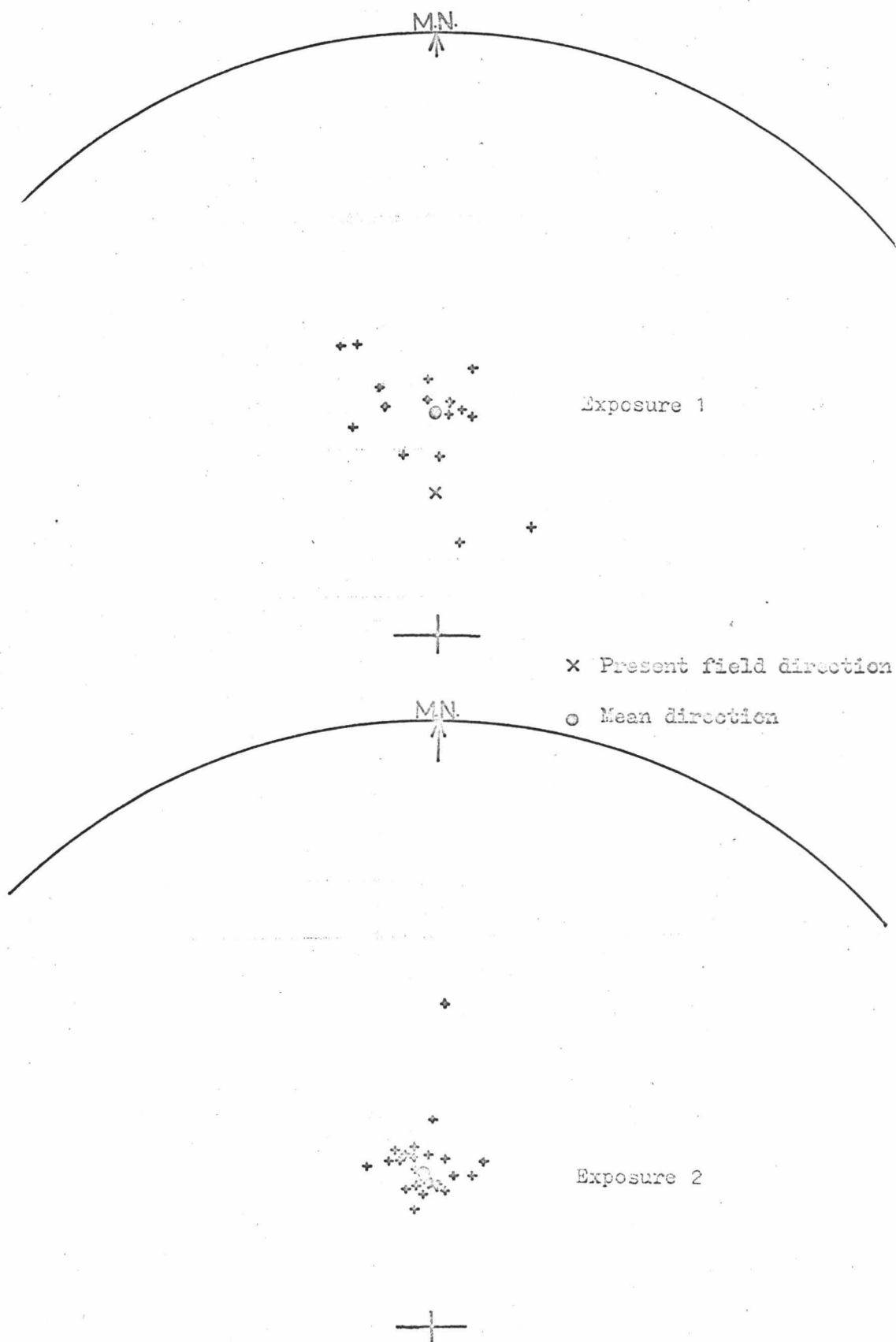
Fig. 10.3   Directions of N.R.M.

MN

Exposure 1

× Present field direction

⊙ Mean direction

MN

Exposure 2
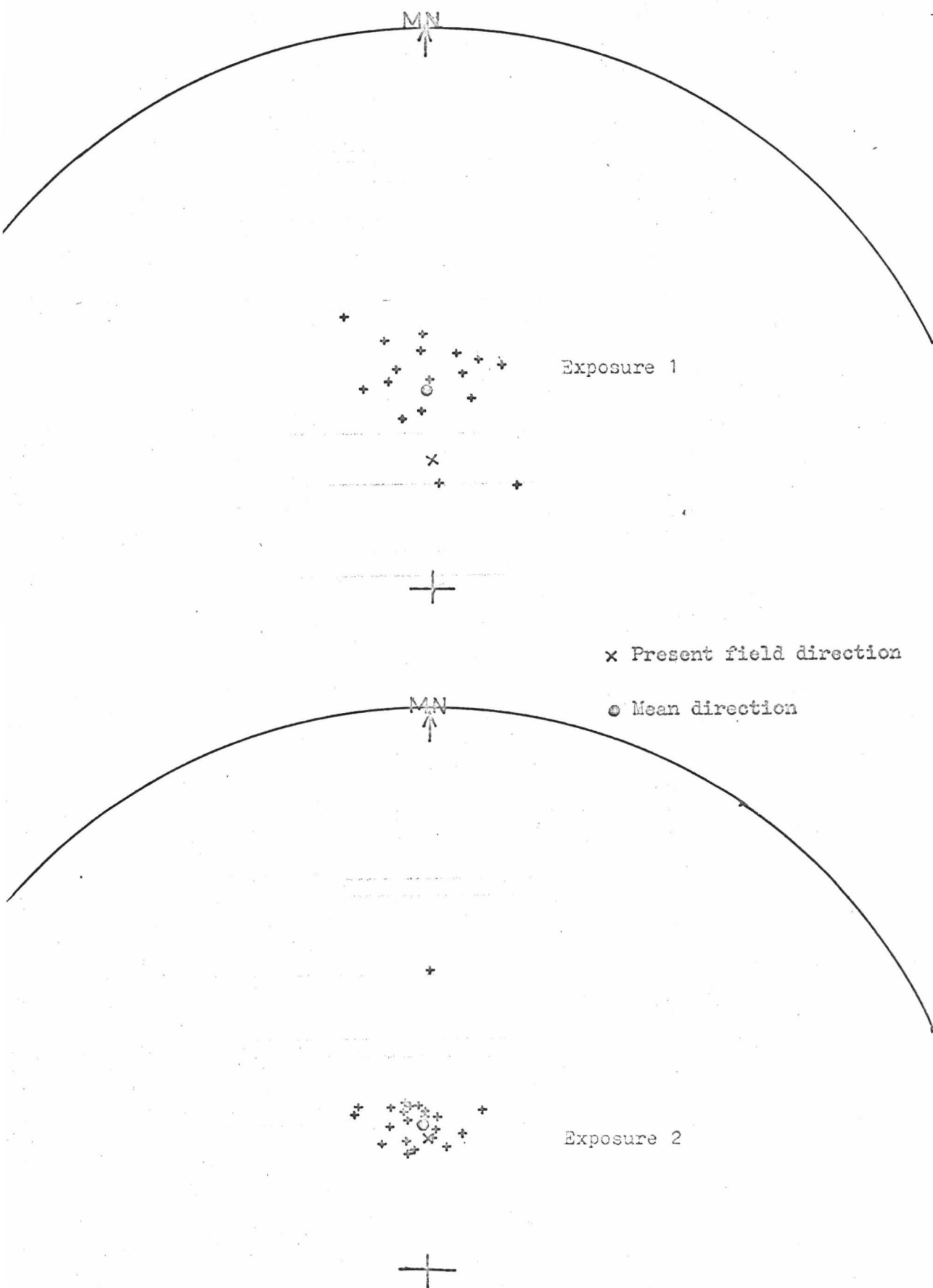
Fig. 10.4 Directions After 300°C. Thermal Wash

Demagnetization of sample 41

Fig 10.5

114

Demagnetization of sample 47

Fig 10.6

Demagnetization of sample 48

fig 10.7

Demagnetization of sample 49

fig 10.8

Demagnetization of sample 50

fig 10.9

Demagnetization of sample 53
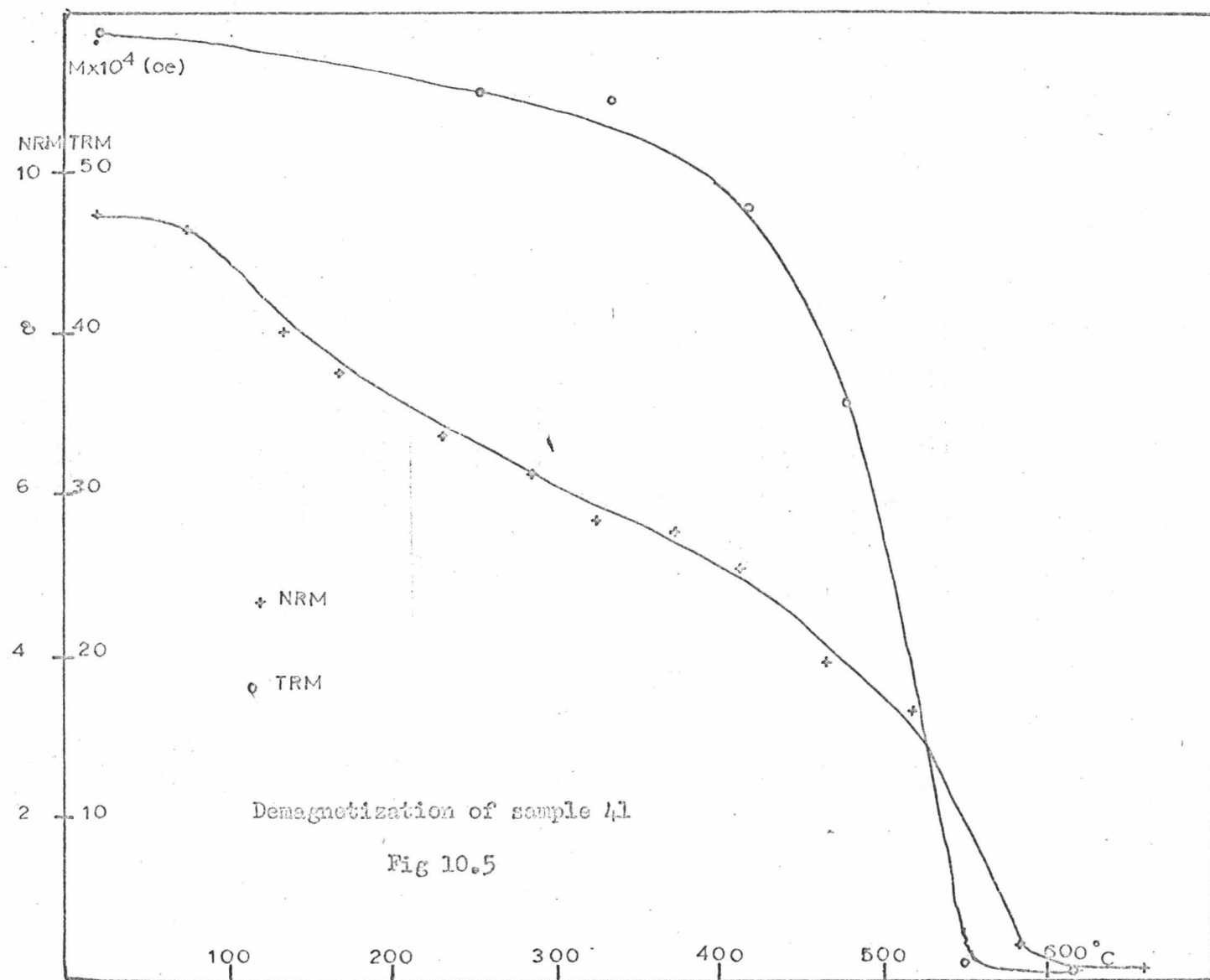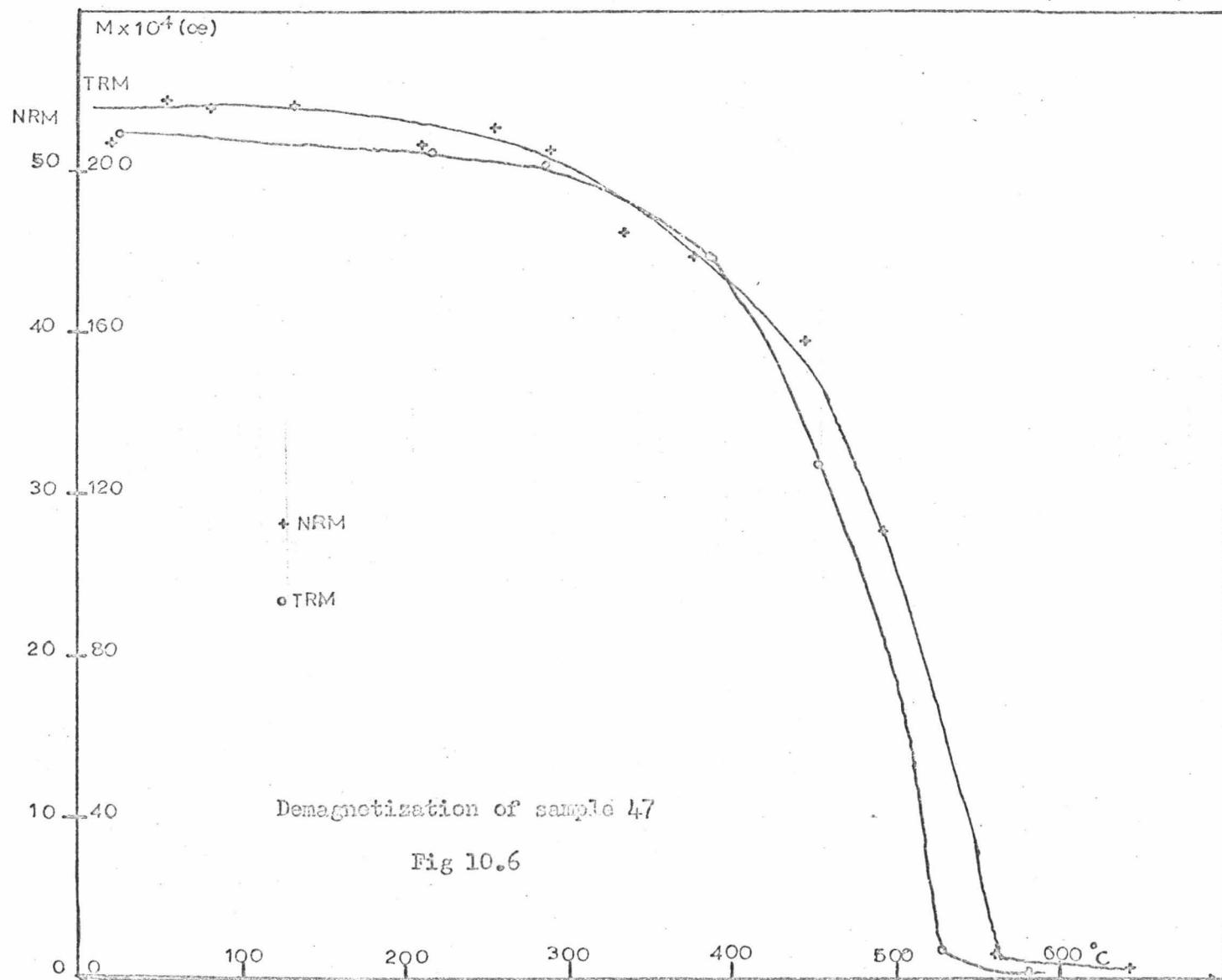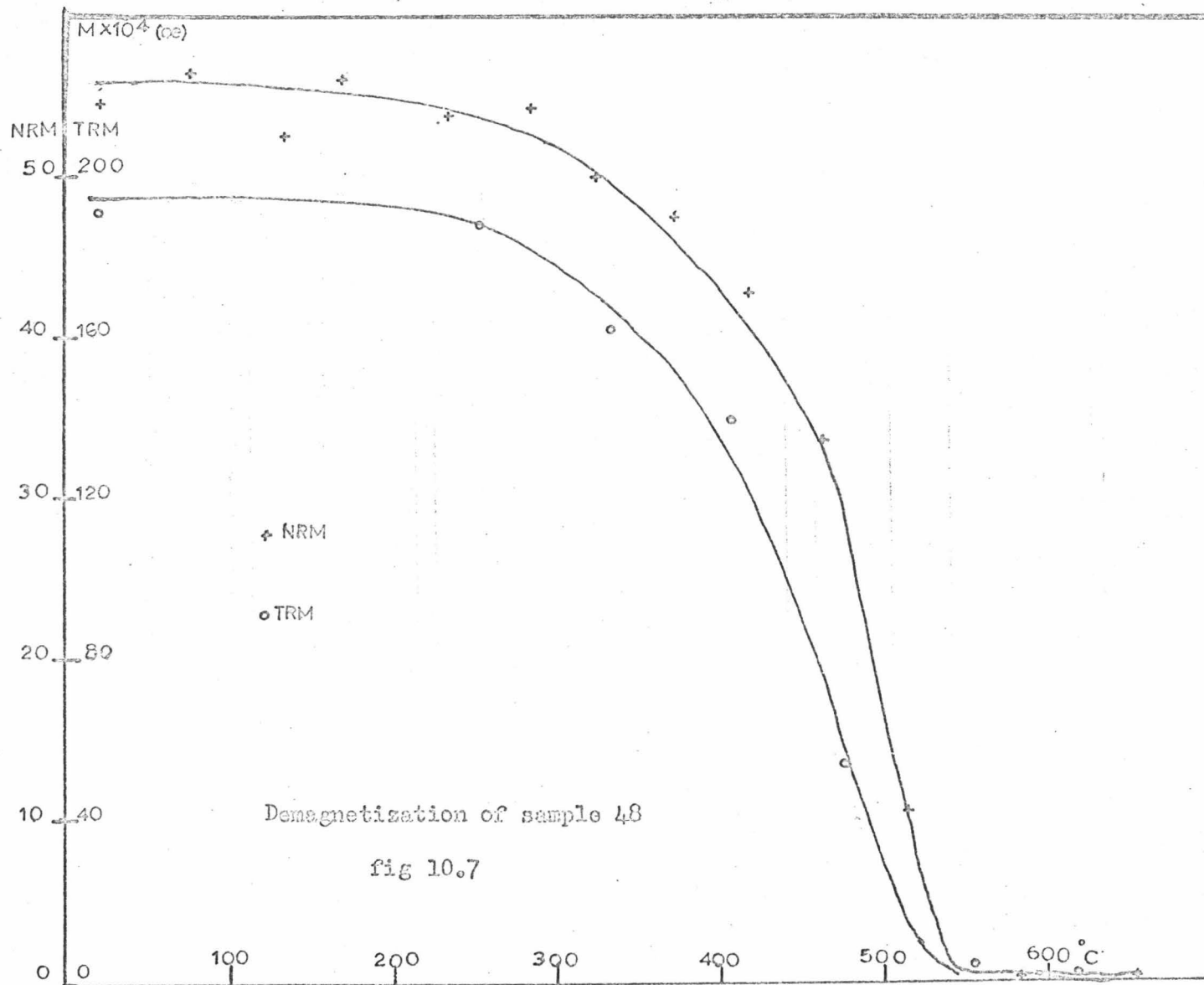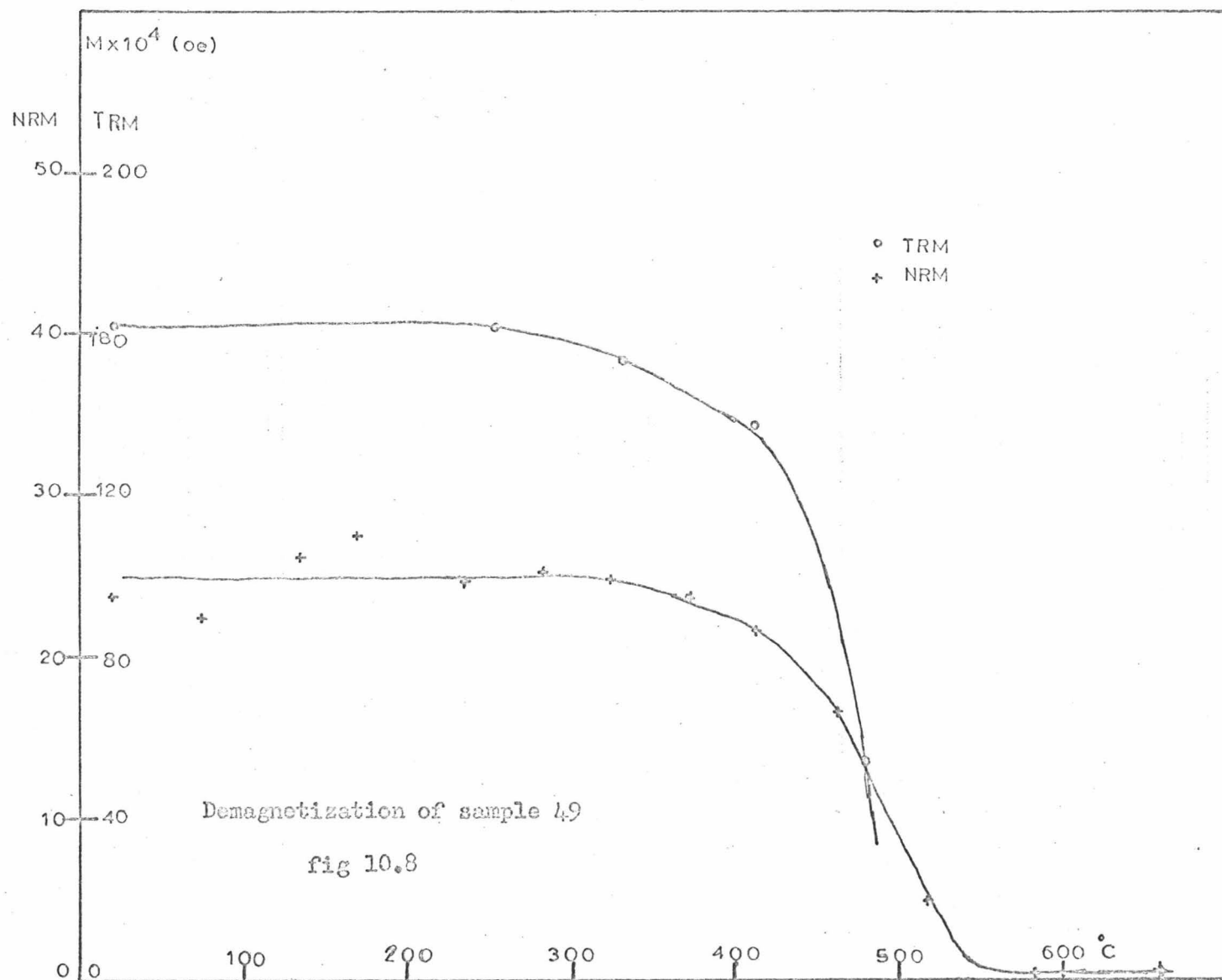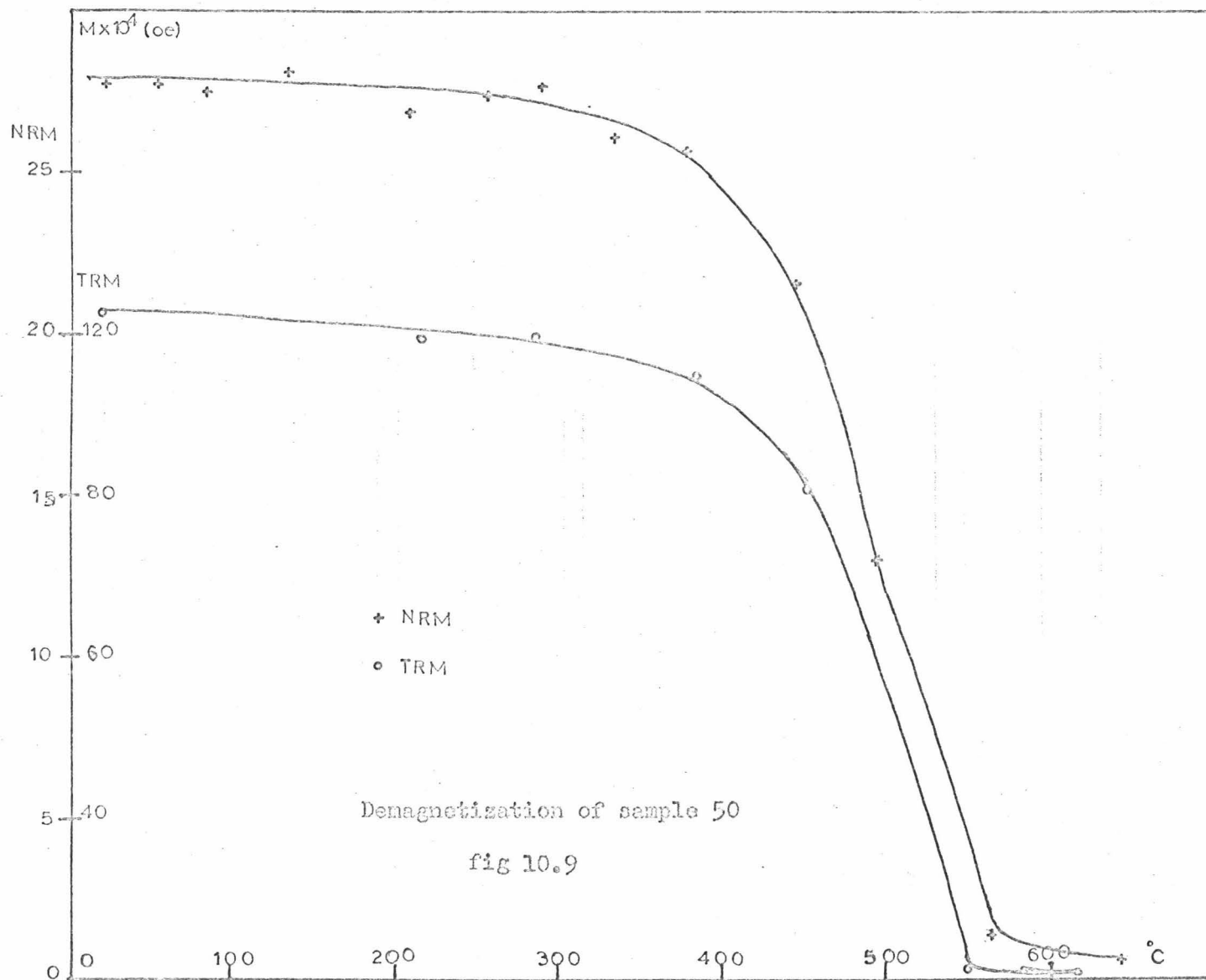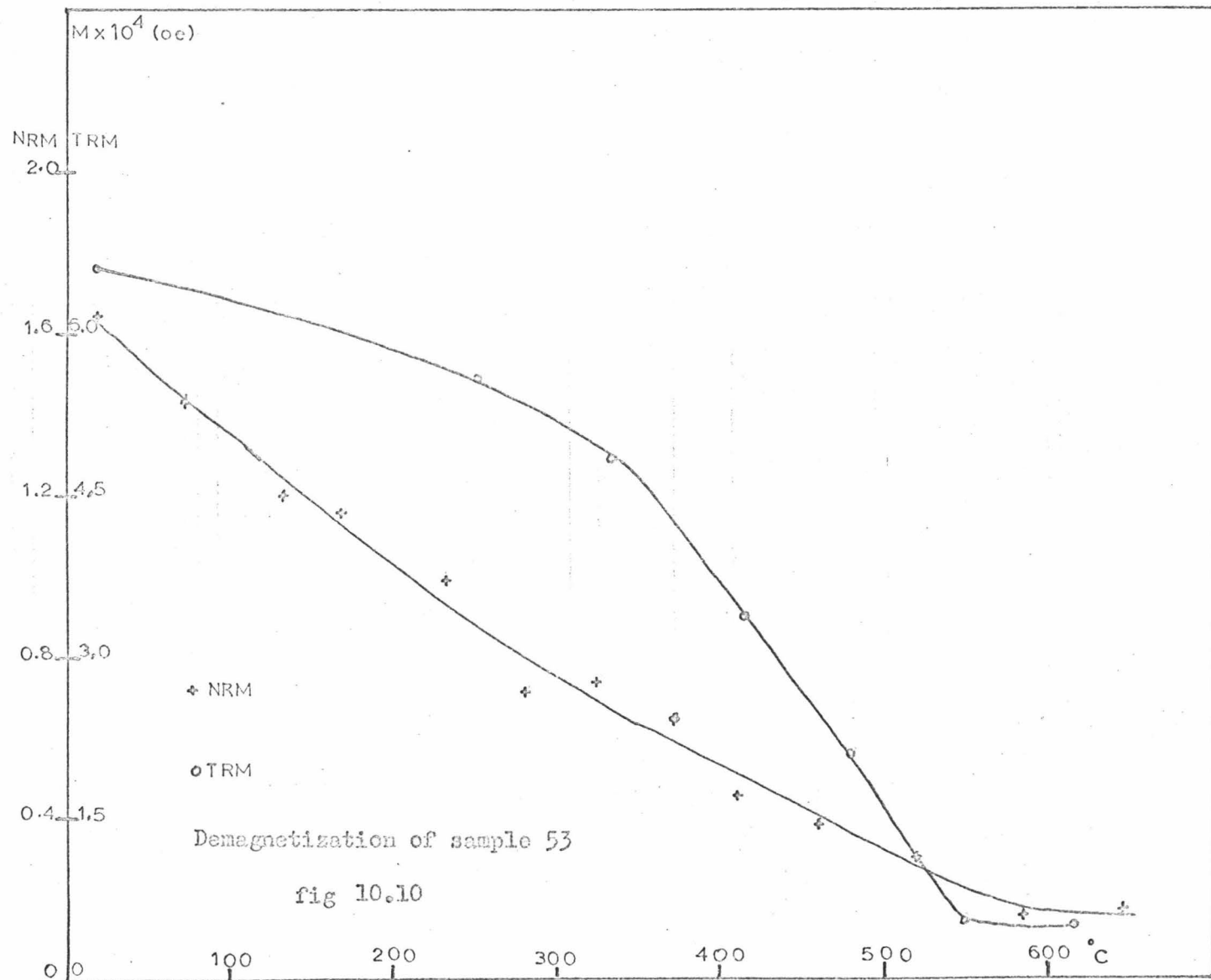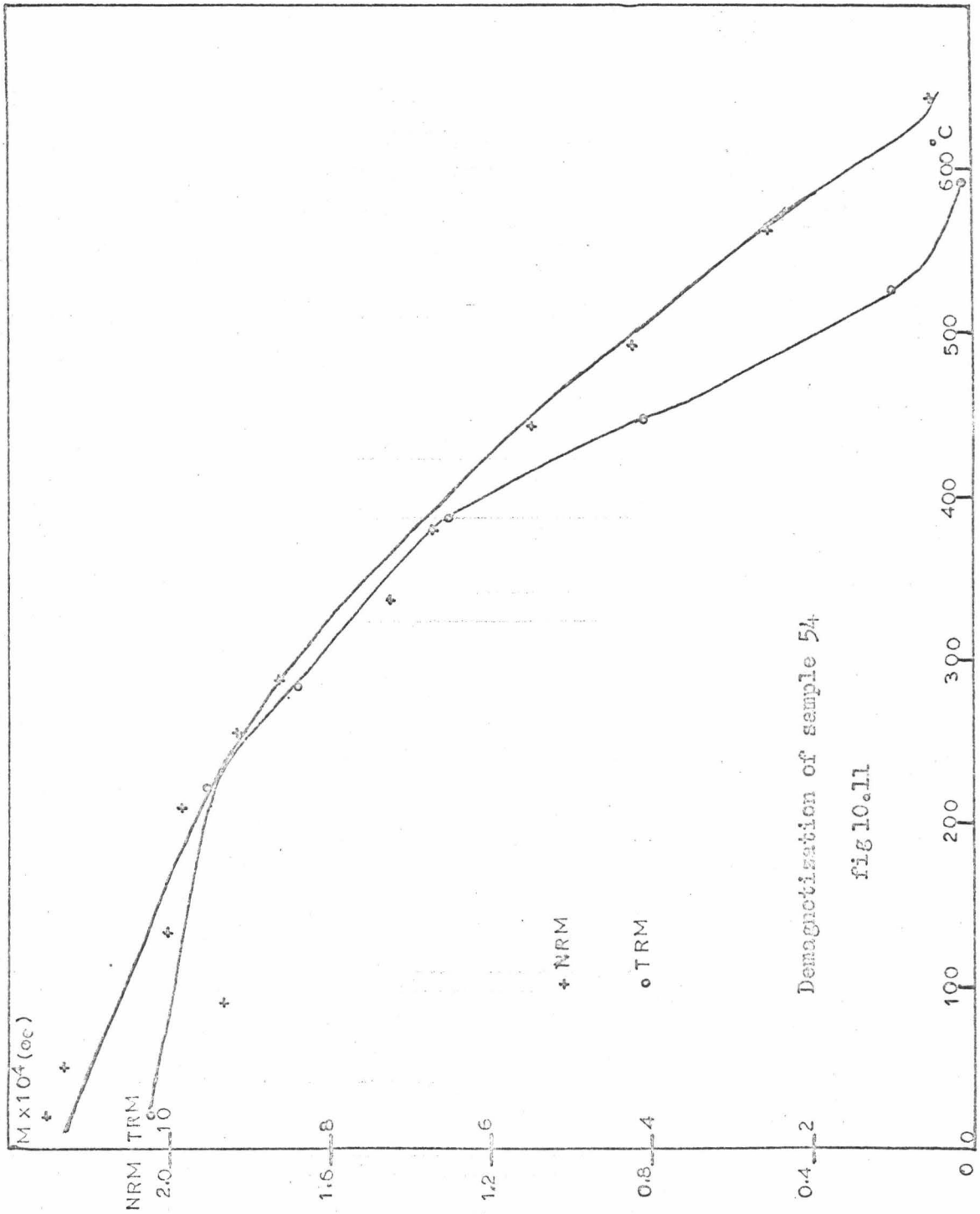
fig 10.10

Demagnetization of sample 54

fig 10.11

Demagnetization of sample 97
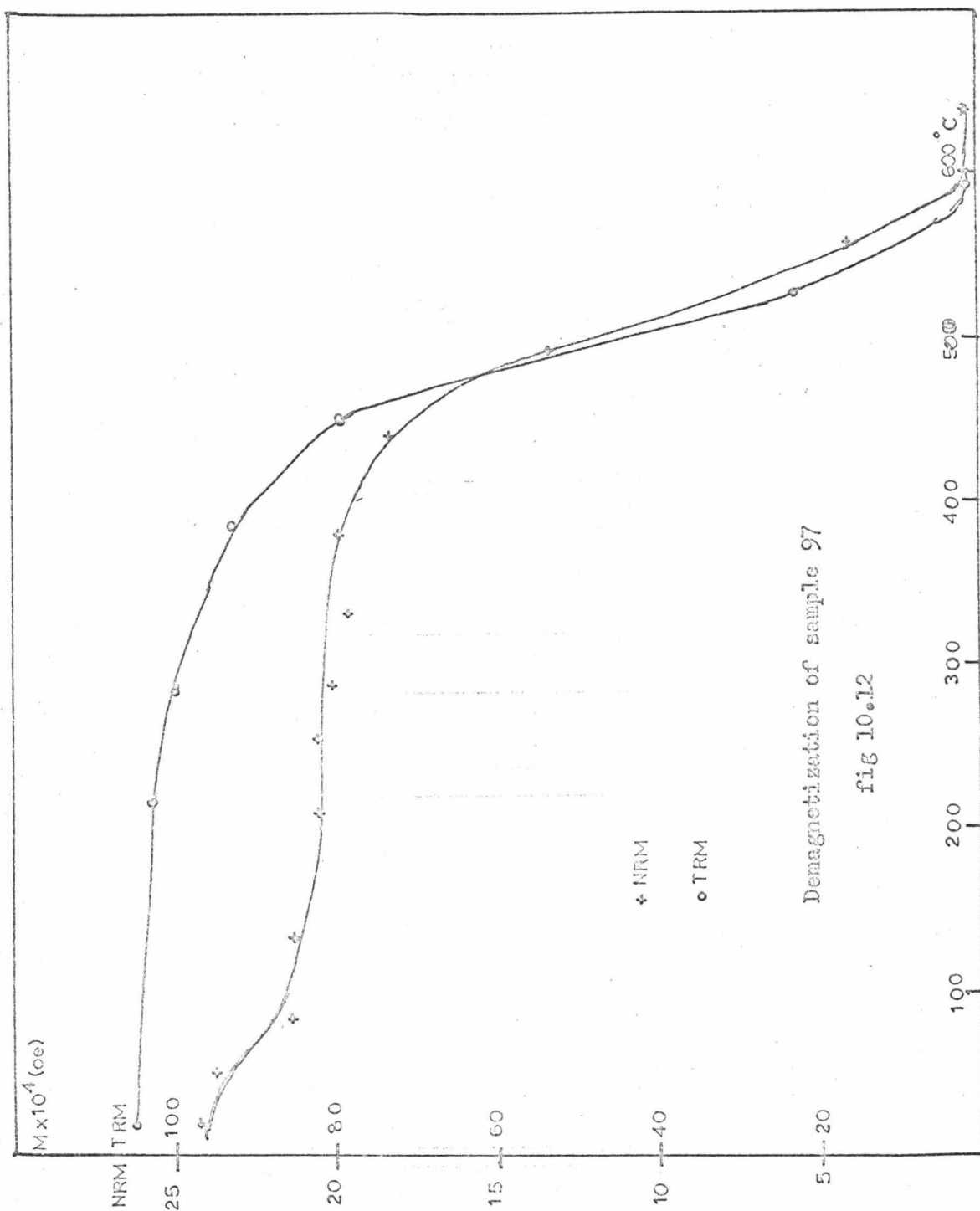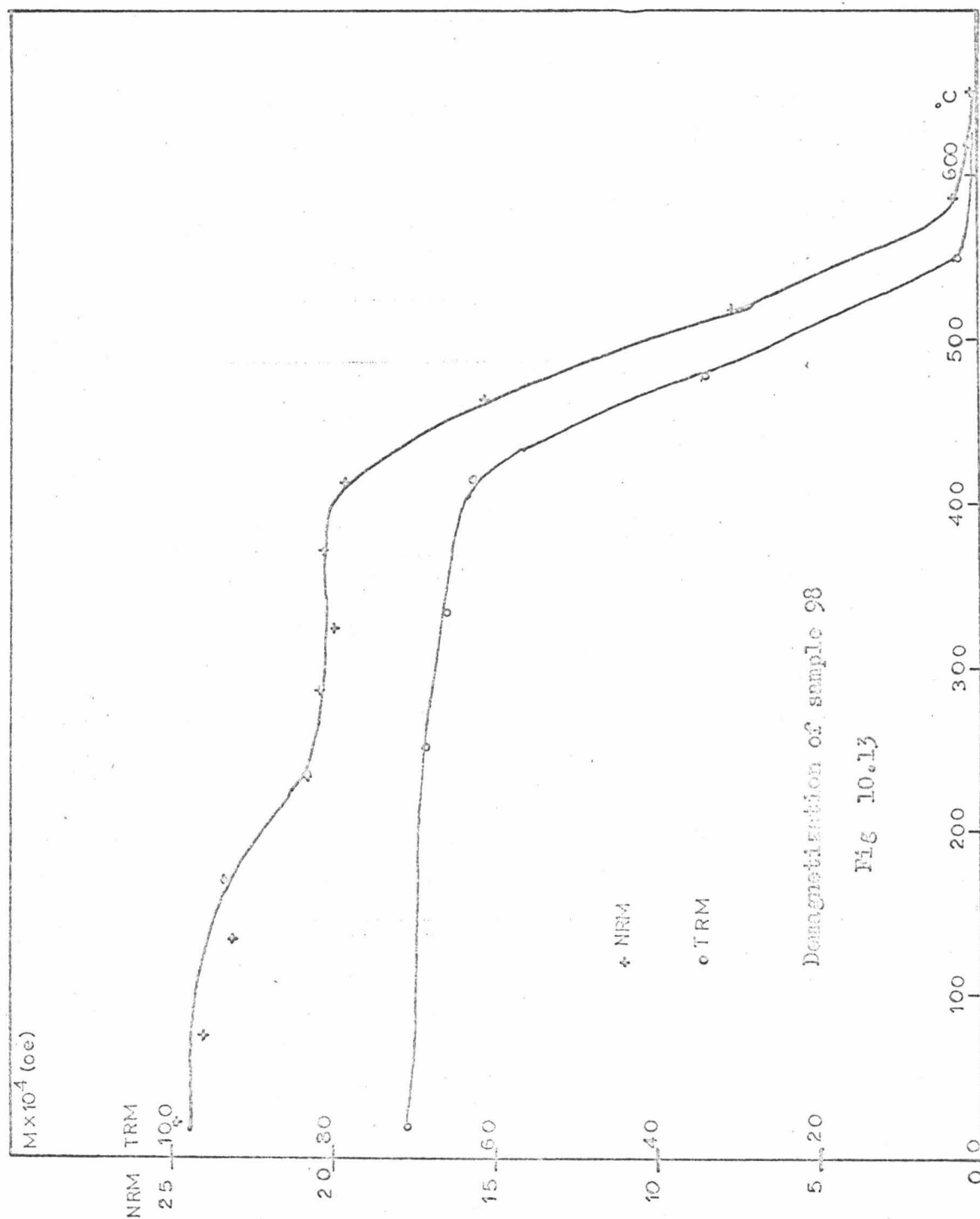
fig 10.12

Demagnetization of sample 98

Fig 10.13

+ NRM

o TRM
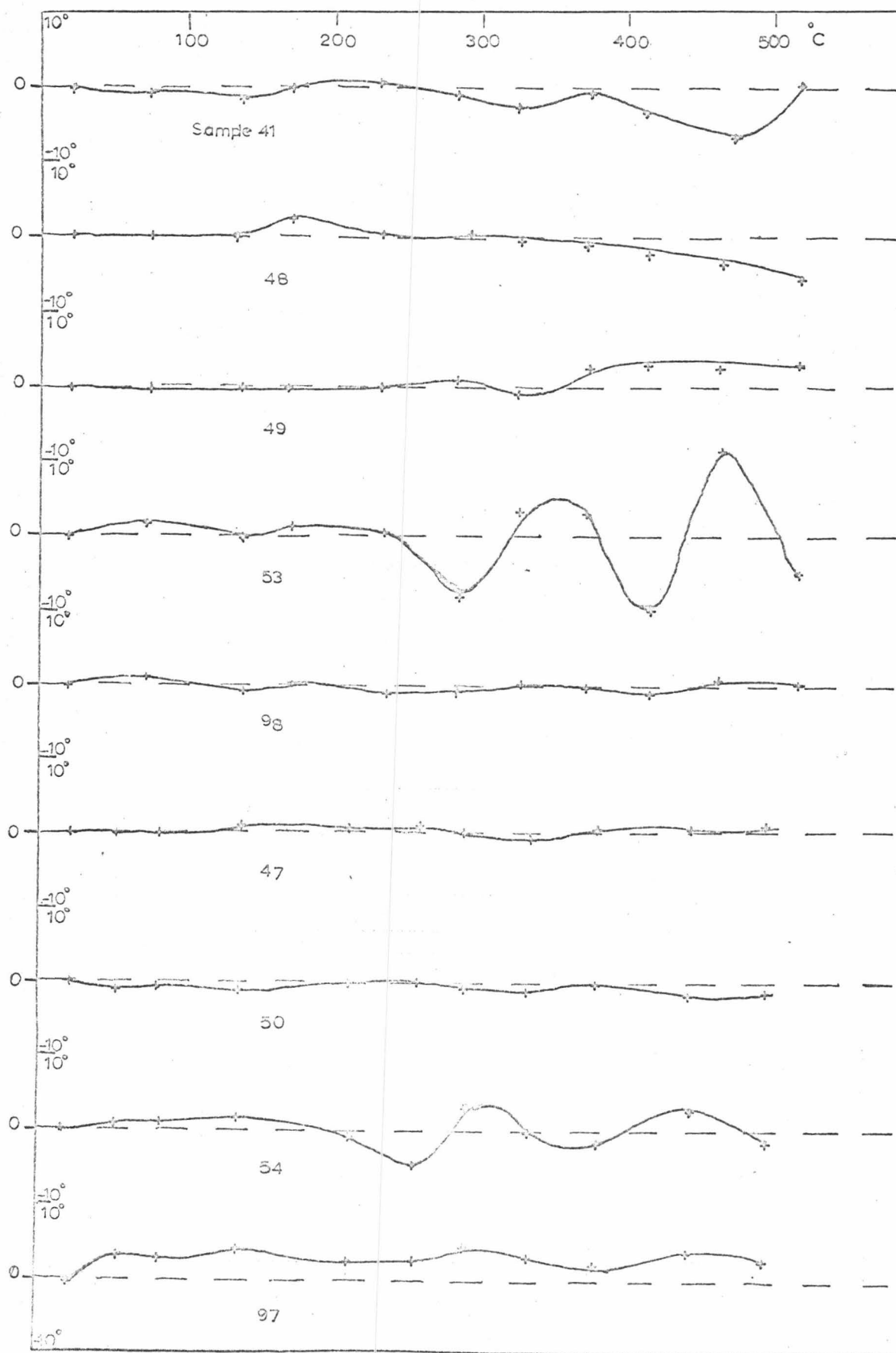
Fig 10.14. Changes in angle θ with successive reheating cycles.
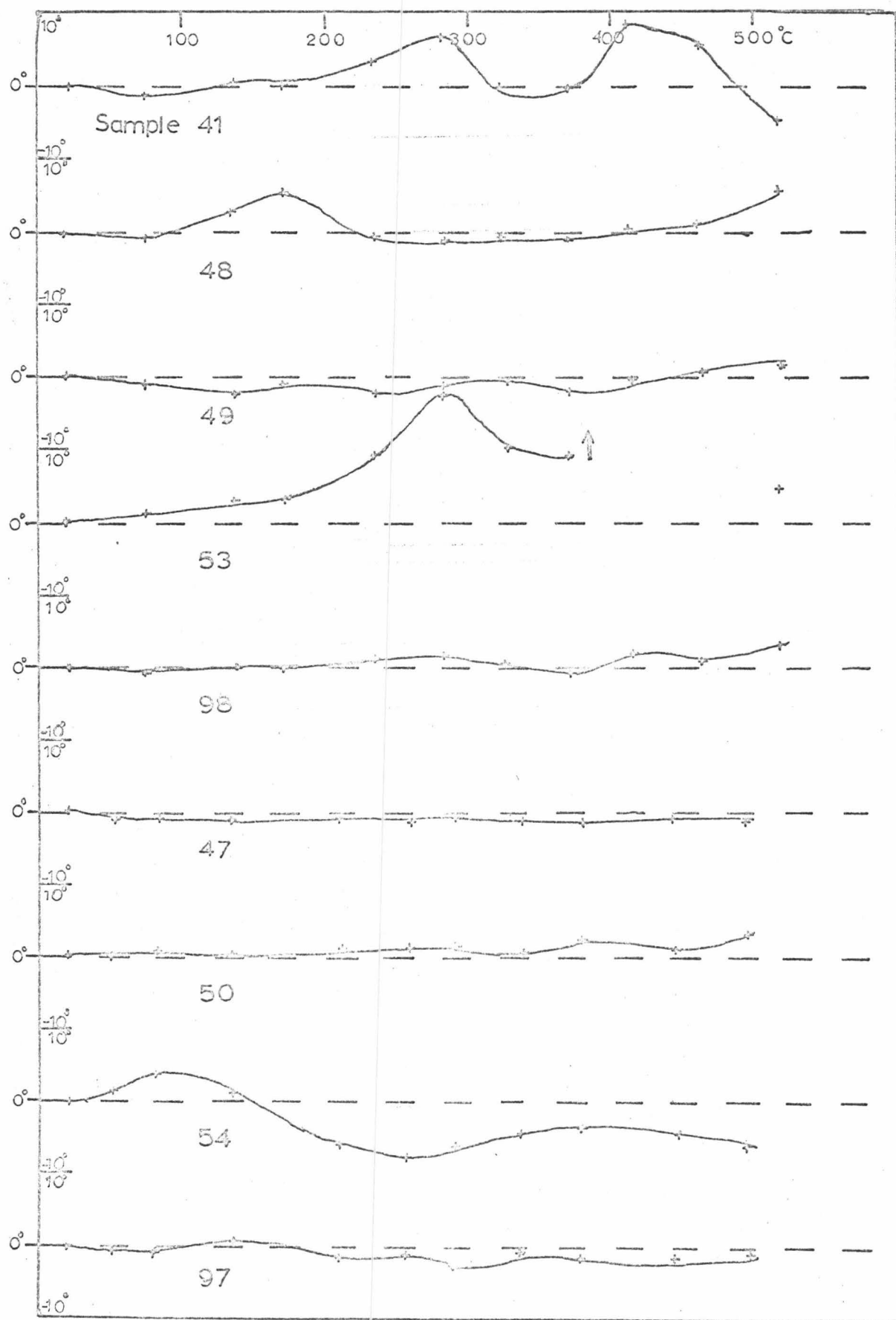
Fig 10.15 Changes in angle ϕ with successive reheating cycles.

Fig 10.16 Changes in χ on heating

Demagnetization of TRM

Reproduction of TRM

$\chi \times 10^4/cc$

o Sample 47

+ Sample 48

Fig 10.17 Changes in χ on heating

$\chi \times 10^{6}/cc$

∘ Sample 49

+ Sample 50

Demagnetisation of NRM

Demagnetization of TRM
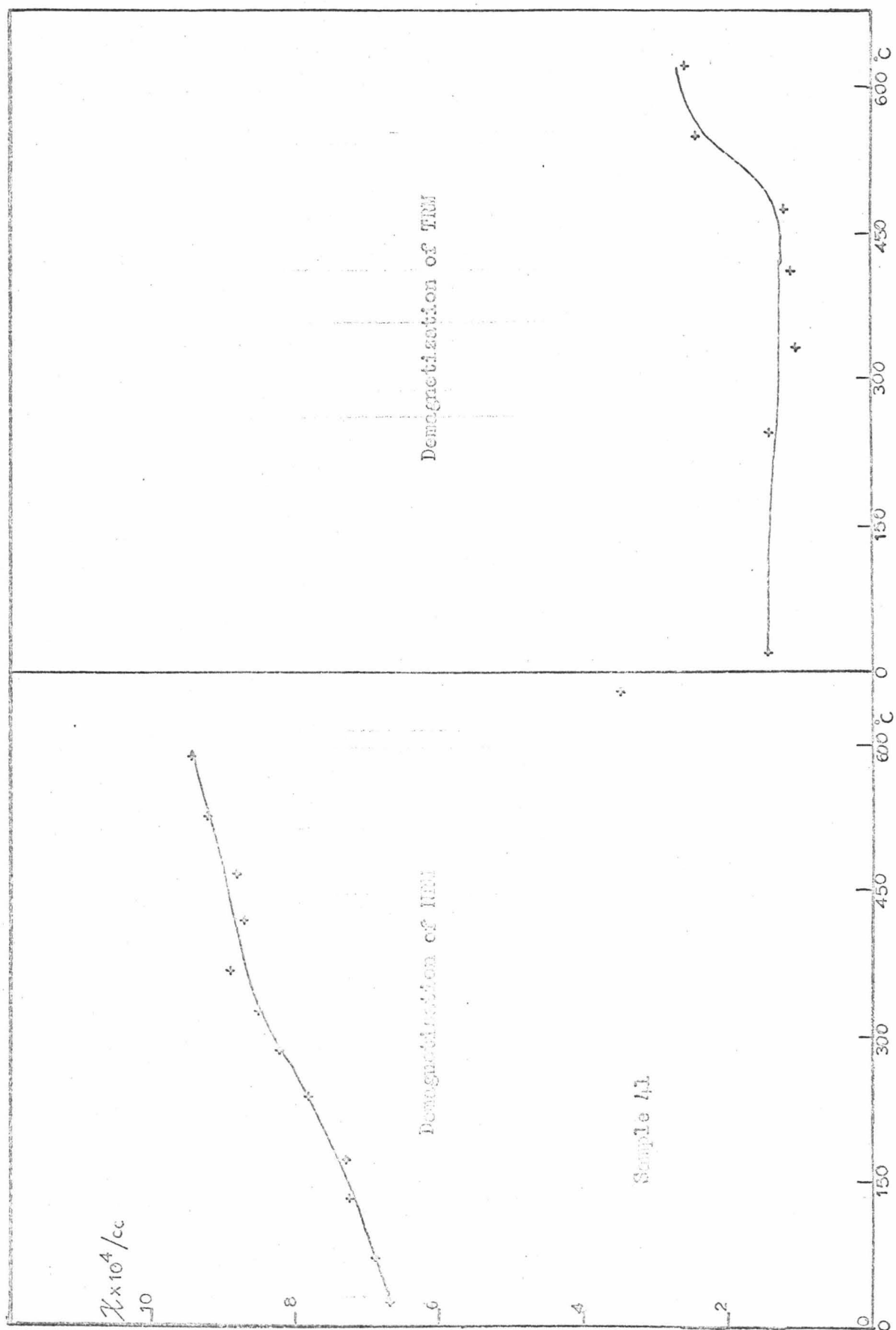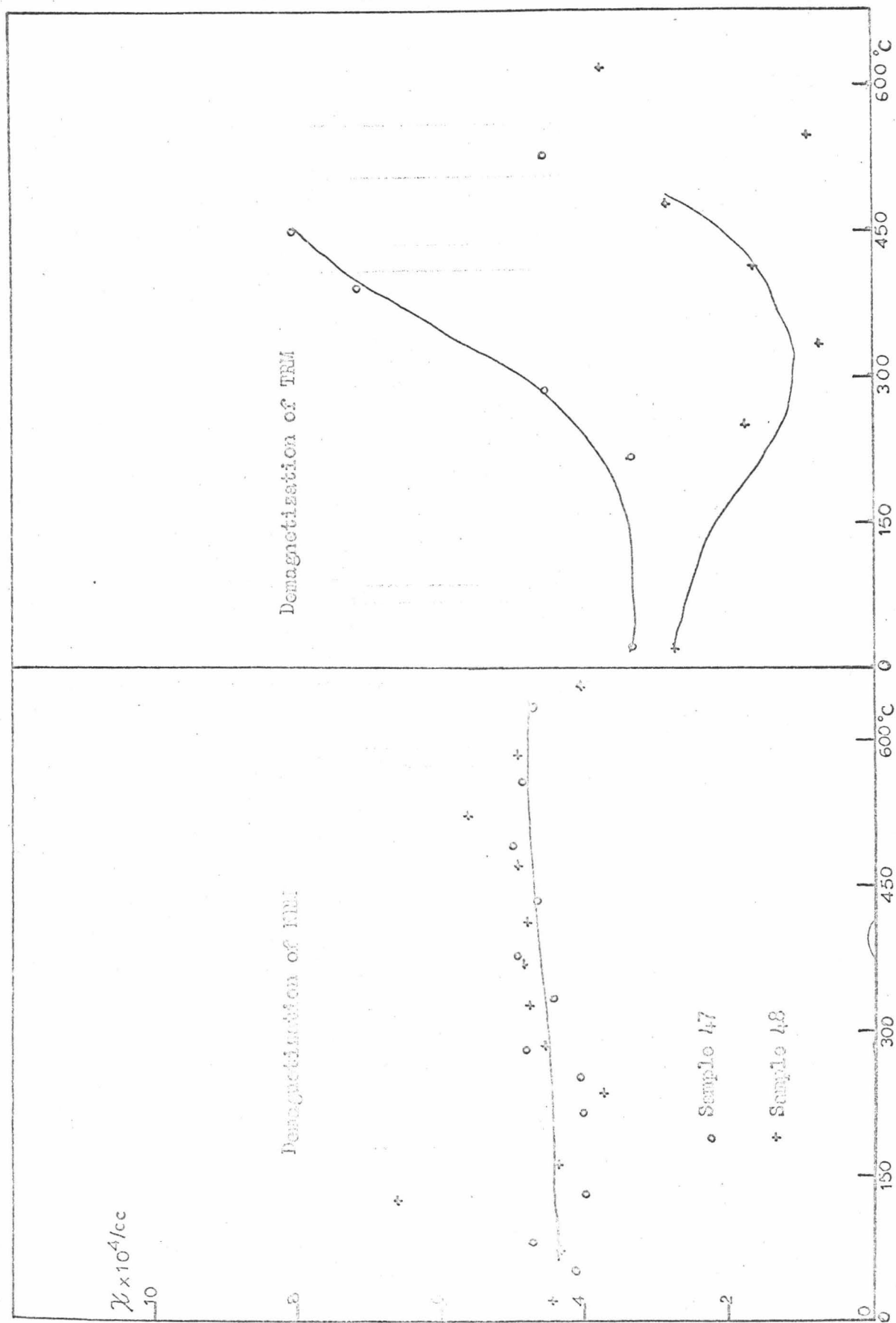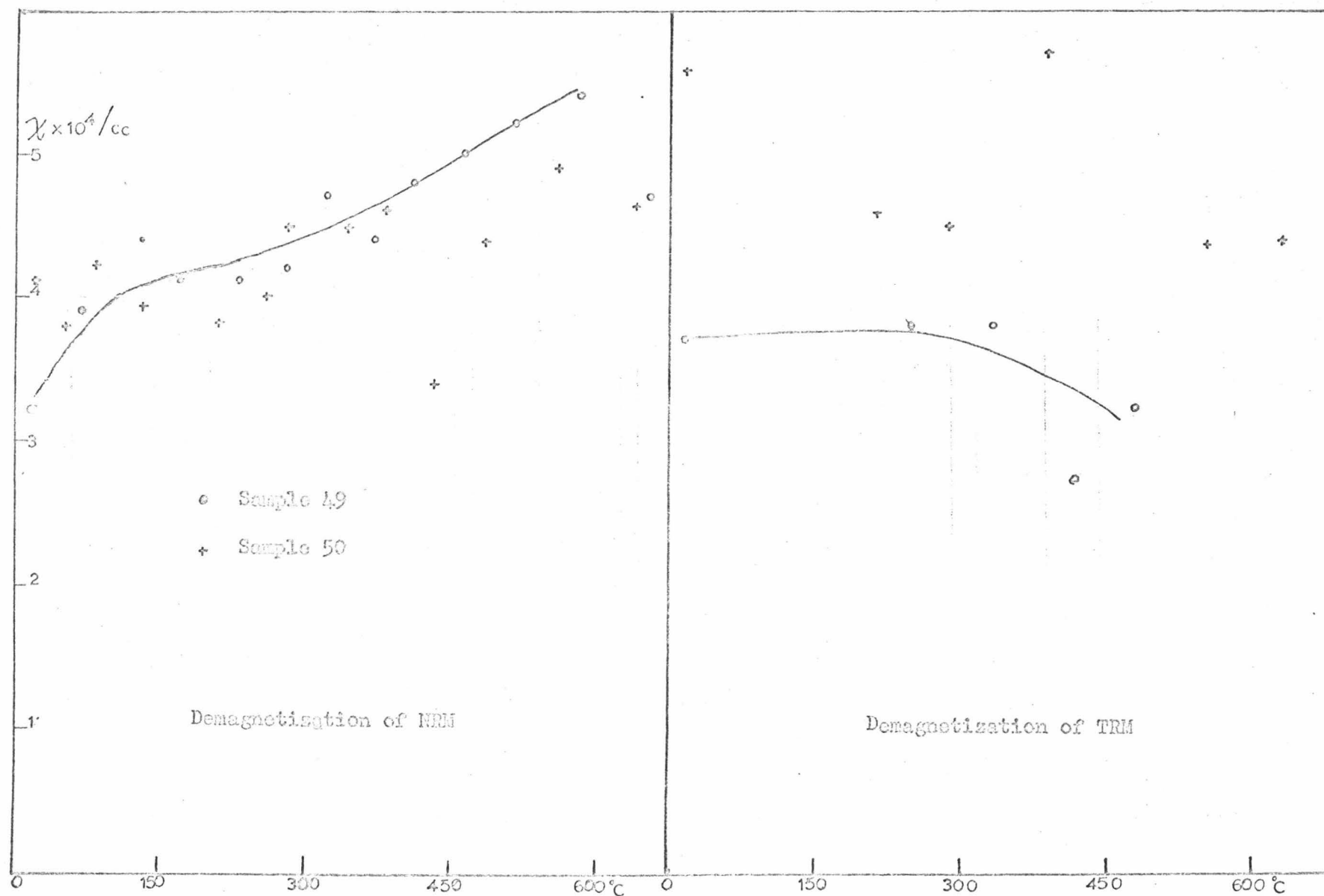
Fig. 10.18 Changes in χ on heating

Fig. 10.19 Changes in χ on heating

$\chi \times 10^4$/cc

Demagnetization of TRM

Demagnetization of IRM

o Sample 53
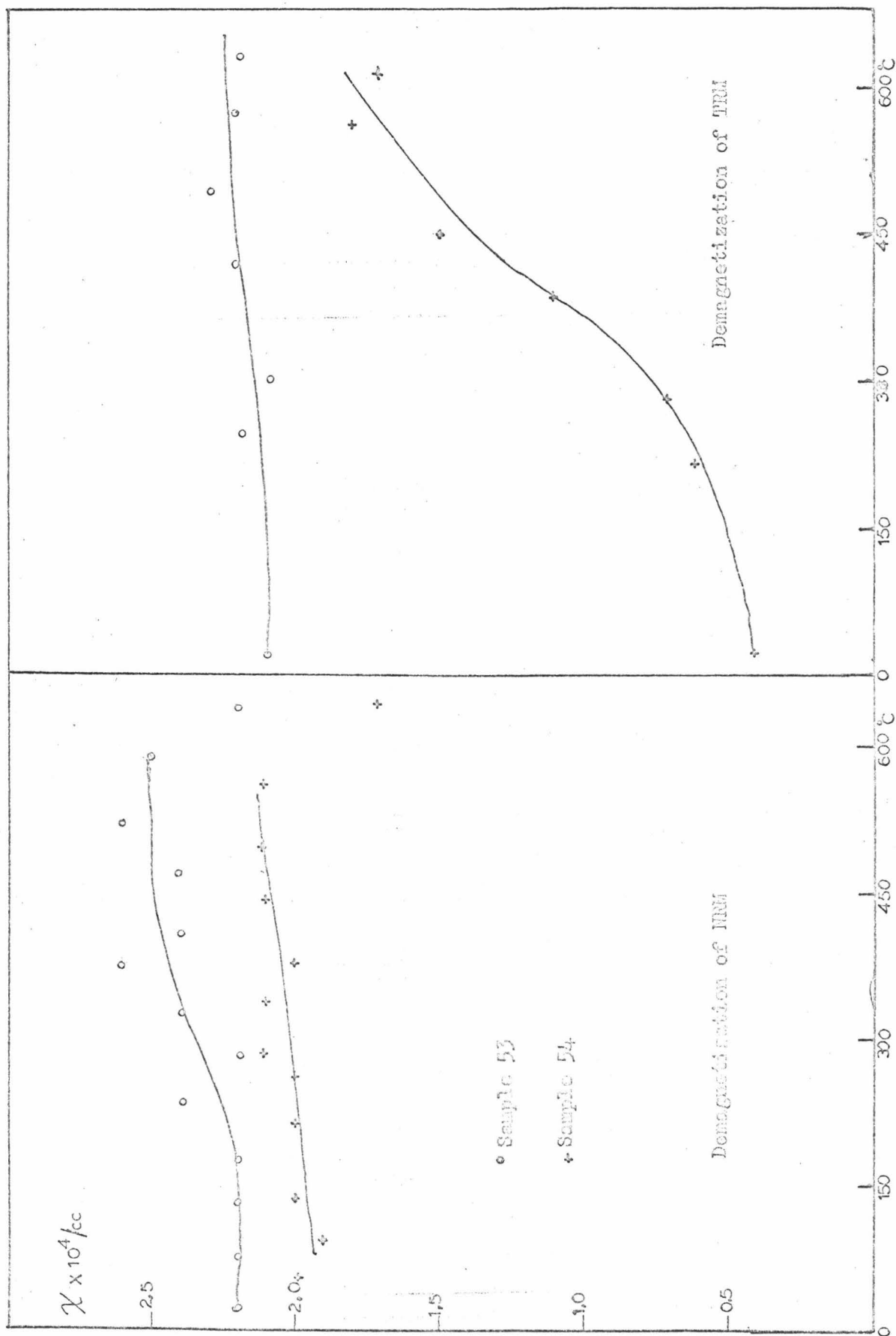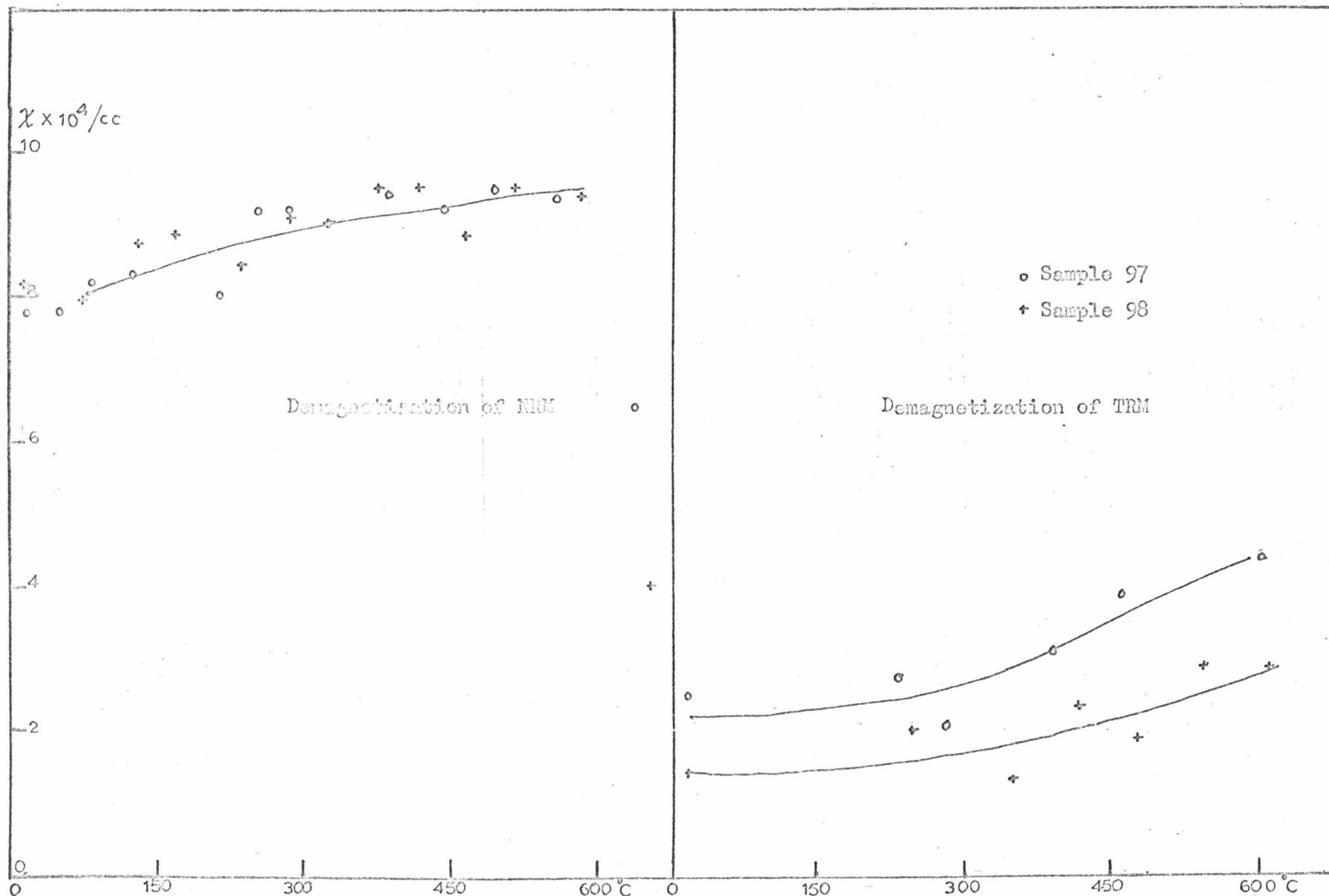
+ Sample 54

Fig 10.20   Changes in χ after heating

SIGNIFICANCE OF EXPERIMENTAL RESULTS

11.1 DIRECTION OF N.R.M.

In this chapter the properties of samples are supposed to
be the same as those of the specimens examined.   The
direction of the N.R.M. appears to be different for the
two exposures, even after thermal washing, but to settle
this point the two sets of results were assumed to be
independent Fisher distributions, and the usual methods
(Fisher, 1953, Watson, 1956) used to test for equal
dispersion and equal mean.   The statistical parameters
are listed in table 11.1.

TABLE 11.1

	Mean Direction		Precision	Angle of 95% Confidence	Number of Samples
	D	I	k	α	N
Before Washing					
Exposure 1	359°	40°	40	22	17
Exposure 2	355°	29°	100	14	22
After Washing					
Exposure 1	000°	40°	44	21	17
Exposure 2	359°	31°	116	13	22

The significance of the difference between the k's may be found (Watson, 1956) by comparing k_{max}/k_{min} with the expected maximum values of the ratio

$$\frac{s_{max}^2}{s_{min}^2},$$

where the s's are mean square deviations in sets with normal distributions. This ratio is tabulated by Pearson & Hartley (1958), Page 179. For use in this table the k's are based on $2(N - 1)$ degrees of freedom, where N is the number of samples on which each k estimate is based. In the present case the value of k_{max}/k_{min} will, with 95% probability, be less than some number between 2.1 and 1.7. The actual value is 2.6, so that the difference is significant.

Watson has given a test for whether two statistical samples give estimates of the same mean direction, when the samples have approximately the same dispersion. The quantity

$$(N - 2) \left(\frac{R_1 + R_2 - R}{N - R_1 - R_2}\right)$$

is distributed approximately as the F-ratio with degrees of freedom $\nu_1 = 2$, and $\nu_2 = 2(N - 2)$ (Pearson & Hartley, 1958, page 159), where R_1 is the sum of the N_1 unit vectors with the directions of the first set of samples, R_2 that corresponding to the second set, and R is that corresponding to both sets combined, the total number of measurements being N. In this case

$$N = 39 \qquad\qquad R = 38.01$$
$$N_1 = 17 \qquad\qquad R_1 = 16.64$$
$$N_2 = 22 \qquad\qquad R_2 = 21.82,$$

which gives $F_{2,74} = 31$. The upper 5% value for $F_{2,74}$ is 3.1, which implies that the sets have significantly different

mean directions. This probably indicates that the two
exposures are separated by a fault (refer Section 10.1.1),
which has resulted in a relative change of dip of 10°, in
a magnetic north direction. The difference in dispersions
may indicate minor slumping on exposure 1. No reliable
palaeomagnetic direction could be calculated from such
divergent results, but it will obviously be near the present
geomagnetic direction, in agreement with previous results on
Quaternary rocks.

11.2   VARIATION WITH ALTITUDE OF MAGNETIC PROPERTIES OF THE IGNIMBRITE

11.2.1   Changes in Magnetization Intensity After Heating to 300°C.

Table 11.2 shows various properties of samples arranged as
well as possible in stratigraphic sequence. The ratio of
the intensity of N.R.M. to the intensity after washing in
zero field at 300°C $(\frac{M_{NRM}}{M_{300}})$ shows particularly well the
variation in the nature of the magnetic properties, which
appear to depend on stratigraphic position.

It is tempting but not fully justifiable to suppose that
those samples within each group which were fully demagnetized
are representative of the group as a whole, and that the
information about the group assists the description of the
individual samples. Taking this last point, all the samples
between 400 and 360 feet (sheet 1) show a similar large
decrease in magnetization below 300°C., so removal of a P.T.R.M.
(explanation (a) of paragraph 10.4.4) seems unlikely, since
it is hard to imagine a mechanism for uniform heating of all
the samples. Removel of an I.R.M. (explanation (b)) is
unlikely because an I.R.M. requiring 300°C. to remove it

would probably be caused by a high field. Such high
fields could only be produced by lightning strikes, and
then could not be uniform in direction. No changes in
direction of N.R.M. were observed so lightning is not
likely to be responsible. The low temperature
magnetization of sample 41 is evidently unstable to heating.

It seems that the rock in sheet one contains a mineral
which is either chemically unstable above 250°, or has a
Curie point at $250^{\circ}C$ and decomposes at some temperature
between this and $600^{\circ}C$. Further experiments could
eliminate one alternative, but the point is not worth
pressing at the moment. The samples in sheet two (330 -
360 feet) also show a decrease in intensity below $300^{\circ}C$
and with the detailed information on samples 97 and 98,
it appears that they contain a lesser amount of the same
mineral present above, together with mostly high Curie
point magnetite.

The samples from 330' to 250' (sheet 3) appear to contain
practically pure magnetite.

The nature of the magnetic minerals in sheet 4 is not
obvious. The rock might contain magnetite with a
continuous blocking temperature distribution.

These regions have been called "sheets" merely for convenience.
Hatherton (1954b), in describing the Whakamaru ignimbrite finds
horizontal boundaries at which there is a sharp increase in $\frac{M}{\chi}$,
which he correlates with supposed cooling between separate
depositions of several layers of rock. Some of these
boundaries had been recognised by geologists, and taken as
boundaries between "sheets", the origin of which was left

undefined.　　Current opinion is uncertain as to whether these sheets are always due to separate depositions or whether they are due to surges during continuous deposition of the ignimbrite.　　Here the term "sheets" refers only to a region of the ignimbrite, with no implications about mode of formation.

11.2.2　Changes in $\frac{M}{\chi}$) N.R.M.

It may be seen that this ratio takes different and roughly constant values in each sheet.　　The values obtained are similar to those for most igneous rocks and are about the same as those obtained by Hatherton for the Whakamaru ignimbrite, where $Q = \frac{M}{\chi H}$ was about 2 to 4 away from boundaries of sheets, and rose at the boundaries to a maximum value, up to 18.　　H would be about $\frac{1}{2}$ oe. in this expression for Q.　　The highest values of $\frac{M}{\chi}$) N.R.M. occur near the postulated boundaries of sheet 3, but in view of the low sampling density at these points, no comparison with Hatherton's work can be made.

11.3　SIGNIFICANCE OF THE VALUES OF $\frac{M_{TRM}}{M_{NRM}}$

This ratio is about 7 in sheet one, about 3 to 4 in sheets two and three, and about 4 to 6 in sheet four.　　Possible reasons for these generally high values are

a)　The N.R.M. is not a T.R.M.

b)　The original N.R.M. has decayed with time.

c)　When these rocks were formed the earth's field was several times lower than it is at present.

d)　Owing to minerological changes, minerals are present in the rock now which were not there originally, and which may now acquire a T.R.M.

Discussion of these alternatives follows.

a) This may be decided from the shapes of the graphs
   of demagnetization of N.R.M. and T.R.M.   An I.R.M.
   generally decreases at much lower temperatures than
   a T.R.M., even when the I.R.M. is acquired in a much
   higher field.   It is seen here that except for samples
   41, 53 and 54, most of the N.R.M. is destroyed over the
   same high temperature range as the T.R.M.   There is
   still the possibility of a chemical remanent magnetization
   (Haigh, 1958, Kobayashi, 1959) for in some circumstances
   this is almost indistinguishable from T.R.M.   However,
   in view of the known igneous origin of the rocks, and
   the low likelihood of all the samples from each sheet
   being subject to the same chemical alteration process,
   to the same extent, it will be assumed that all the
   rocks have a T.R.M. as their main magnetic component.

b) At first sight this appears to be consistent with the
   observation that samples from sheets one and four, which
   have a low temperature (and therefore magnetically
   unstable) component also have the highest ratio of
   T.R.M./N.R.M.   However, it has been shown that the low
   temperature component of magnetization is not present in
   the T.R.M., so these samples ought to have a lower ratio
   than the other, thermally stable, rocks.   The experiment
   of paragraph 9.9 was designed to estimate the decay of
   the magnetization with time after production of a T.R.M.
   in the laboratory.   Suppose the magnetization decays
   logarithmically with time at all times from, say,
   several seconds after formation to several million years,
   i.e. $J = J_0(1 - \alpha \log t)$.

The change in J from t_1 = 3 hours to t_2 = 60 hours is

is given by $\dfrac{J_{t1} - J_{t2}}{J_{t1}} < 1\%$

$$\frac{1 - \alpha \log t_1}{1 - \alpha \log t_2} = \frac{J_{t1}}{J_{t_2}}$$

so $\qquad \dfrac{\log t_2/t_1}{1 - \alpha \log t_2} < 0.01$

giving $\qquad \alpha < 0.0076,$

so the maximum rate of decay of magnetization gives

$$J_{min} = J_o(1 - 0.008 \log t)$$

where t is in hours after formation of T.R.M.   After 10^6 years = 10^{10} hours

$$J_{min} = 0.92 J_o$$

so $\qquad \dfrac{J_{TRM}}{J_{min}} = 1.09.$

In other words the magnetization could not have decayed to the observed values if the logarithmic decay law is valid and no changes in minerals occurred when the T.R.M. was given.

c) Some palaeomagnetic evidence has been obtained of past values of the strength of the earth's magnetic field, but work on this aspect is restricted by the great amount of effort required to prove that the intensity of the N.R.M. has been completely stable. E. & O. Thellier (1959) have performed good work on hematite-bearing baked clays, and have shown that the local geomagnetic intensity in Europe has been decreasing for the last 2000 years or so, but their work does not go further back in time, and there is no justification for any extrapolation.   Wilson (1961), has used baked hematite —bearing rocks to estimate a field strength in Tertiary times, and found a value comparable with the present field.   Some work has been done on magnetite-bearing rocks, by Momose (1963), and van Zijl

Graham & Hales, (1962), but little discussion of stability was given. They showed that between reversals the earth's field strength fell to about a quarter of its normal value in the Upper Tertiary.

Although it seems that changes in field strength may occur, it is necessary either to show that no decay or mineralogical changes could have occurred in a particular rock, or to show that several rocks of different types and the same age show the same apparent change in field strength.

d) It has been pointed out that at least some of the minerals present in parts of the ignimbrite are unstable at high temperatures. The observed changes in susceptibility also point towards partial instability.

The changes in susceptibility with temperature are shown in Figs. 10.16 to 10.20, and the general trend can be seen to be a gradual increase in susceptibility on the first heating, followed by an abrupt decrease above $600^{\circ}C$., the amount of the decrease depending partly on the length of time the samples were held at that temperature. (The samples were heated three times to more than $600^{\circ}C$ - once to remove the N.R.M., once to produce the T.R.M., and again to remove the T.R.M.). The changes in susceptibility could be taken to represent simple corresponding changes in the amount of ferromagnetic material. This is hard to reconcile with the values of $\dfrac{M_{TRM}}{M_{NRM}}$, which is about twice as large for sample 41 as 98, which have equal changes in susceptibility, and is the same for samples 97 and 50, which have very different changes in susceptibility.

These variations must derive from a fairly complicated set of changes in minerals.

11.4 POSSIBLE CHANGES IN THE MAGNETIC MINERALS

The author has not had time to pursue this point to any
sort of conclusion, but has acquired some information
which may be relevant.

The magnetic fraction was separated by crushing and
extracting with a permanent magnet, the minerals in sample
41. An X-Ray powder pattern examination identified only
a mineral similar to magnetite or maghemite, but no
accurate measurements of unit cell size were possible.
An attempt was made to show the presence of maghemite, by
heating the powder specimen at successively higher
temperatures up to 700°C. (in air), and taking X-Ray records
between each heating. To check against the possibility of
oxidation of any magnetite which might be present a specimen
of Magnet Cove lodestone, which was identified as magnetite
in the Geology Department collection, was prepared and
subjected to the same heating processes. The lodestone
started changing to hematite at about 400°C., the transition
being nearly complete at the end of the experiment. On the
other hand, the magnetic fraction from sample 41 changed
only slightly after about 20 minutes at 700°C. It was
concluded that most of the fraction separated from sample
41 is magnetite, while the lodestone is maghemite.

Weaving (1962), has pointed out that the mineral chlorophaeite,
which is an alteration product of olivine, is weakly
ferromagnetic, with Curie temperatures 300° - 400°C., but
alters on heating to 600°C. to an impure form of hematite
which may be 5 times more strongly magnetic. This type of
behaviour may be expected to lead to some of the results
observed here. This mineral is usually found in basalts,

but because of its indefinite composition and somewhat variable properties, is not always accepted as a mineral by geologists. It has not been mentioned in any of the literature on ignimbrites read by the author (few petrological studies of N.Z. ignimbrites have been published), but one point arises in an article by Steiner, (1960). He reports finding a yellow-green glass of refractive index 1.52 in some "very fresh" samples of some ignimbrites, but the existance of this glass, which is of some importance in Steiner's theory of emplacement of the ignimbrites, is doubted by other workers on the rocks, (R. Martin, pers. comm.). The relevant properties of chlorophaeite are its colour, green; refractive index, 1.50 - 1.60; and a tendency to go black rather quickly on exposure to air (Campbell & Lunn, 1925), (Deer, Howie & Zussman, 1962). Its tendency to oxidize could well mean that different techniques used in making slides for the petrological examination could lead to differences in opinion as to its presence.

The origin of the observed changes in susceptibility will require further, possibly extensive, investigation. Until this is done it will be impossible to decide whether the apparently low intensity of the N.R.M. compared to the T.R.M. is due to inherent properties of the rock, or changes in intensity of the earth's magnetic field.

T A B L E   11.2

	Altitude	Sample	$\dfrac{M_{NRM}}{M_{300}}$	$\dfrac{M}{NRM}$	$\dfrac{M_{TRM}}{M_{NRM}}$
Sheet 1	400 – 360	43, 44	1.7, 1.4	1.3, 1.9	7.5, 4.6
		41, 42	1.7, 1.5	1.4, 1.5	6.3, 6.9
		103,104	1.7, 1.9	1.5, 1.5	7.5, 6.1
Sheet 2	360 – 330	39, 40	1.2, 1.2	4.2, 3.1	4.4, 4.4
		101,102	1.2, 1.2	3.0, 2.2	3.1, 3.7
		99,100	1.2, 1.2	3.3, 3.6	3.2, 3.3
		97, 98	1.2, 1.2	3.1, 3.1	4.3, 2.9
Sheet 3	330 – 250	35, 36	1.1, 1,1	5.3, 4.9	3.0, 3.8
		45, 46	1.0, 1.0	13.2,11.5	3.9, 3.8
		95, 96	1.0, 1.0	3.4, 3.0	2.8, 4.2
		93, 94	1.1, 1.2	4.4, 4.0	3.5, 3.8
		91, 92	1.1, 1.1	6.4, 6.1	3.1, 3.0
		37, 38	1.1, 1.1	5.9, 4.6	3.4, 3.3
		89, 90	1.1, 1.1	5.0, 6.0	3.0, 3.1
		87, 88	1.1, 1.1	5.5, 5.3	3.2, 3.6
		47, 48	1.0, 1.1	12.0,12.5	4.0, 3.3
		49, 50	1.0, 1.0	7.5, 6.8	6.8, 4.5
Sheet 4	250 – 220	51, 52	1.4, 1.2	2.5, 3.9	5.5, 5.0
		55, 56	1.2, 1.4	3.3, 2.5	2.5, 6.6
		53, 54	2.1, 1.3	0.7, 1.2	5.1, 4.4

MAGNETOMETER CORRECTION FACTORS FOR CYLINDRICAL SAMPLES

The field of a cylinder magnetized perpendicular to its axis
differs from that of a dipole by a factor

$$F_x = \frac{1}{2u \ v^2} \left[\frac{1 + u}{\left((1 + u)^2 + v^2 \right)^{\frac{1}{2}}} - \frac{1 - u}{\left((1 - u)^2 + v^2 \right)^{\frac{1}{2}}} \right]$$

for points close to the axis.

When the magnetization is parallel to the axis, and the point is
distant x from the axis, the factor is

$$F_z = \frac{1}{6u} \left[\frac{1}{\left((1 - u)^2 + v^2 \right)^{3/2}} + \frac{1}{\left((1 + u)^2 + v^2 \right)^{3/2}} \right]$$

where

$$u = \frac{h}{2z}, \text{ and } v = \frac{a}{z}.$$

These two factors are functions of $\frac{h}{a}$ and $\frac{z}{a}$ and so can easily be
tabulated for any cylinder and specimen distance.

To get the 1% accuracy required of the tabulated points, graphs were
drawn from the values tabulated by Blackett (1952). It was decided
from these to use values of h/a ranging from 0.6 to 2.1 in 0.1
increments, and also the values for $h/a = 0.1$ and 0.4.

The values of z/a started at 2.00, increased by 0.05 increments till
$z/a = 3.00$, by 0.10 increments till $z/a = 5.00$, by 0.20 up to 7.00,
and then by 0.5 steps up to $z/a = 10$. These values resulted in
differences between successive points on the table of about 1% in
most cases, and 2% in a few.

The calculation was performed on an I.B.M. 1620 computor at
Canterbury University, using a FORTRAN programme written by the
author. The printed output of the computor was arranged so that

by a small amount of cutting and pasting, the tables could be prepared for direct copying by Xerox and Multilith processes. The programme is shown in Fig. I.1.

When allowance is made for the upper magnet, the simple dipole formulae must be multiplied by

$$G_X = F_{X_1} \left(1 - \frac{F_{X_2}}{F_{X_1}} \left(\frac{z_1}{z_2}\right)^3\right)$$

$$\text{and} \quad G_Z = F_{Z_1} \left(1 - \frac{F_{Z_2}}{F_{Z_1}} \left(\frac{z_1}{z_2}\right)^4\right)$$

where z_1 and z_2 are distances to the lower and upper magnets. Since $z_2 = z_1 + 2.51$, the functions cannot be written as functions of z/a and h/a, so the tabulation was performed for $a = 1.75$ cm. The effects of changes in a are greatest for the factors F_{X_1} or F_{Z_1}, and the ratios F_{Z_1}/F_{Z_2} and F_{X_1}/F_{X_2} are little affected, so that multiplication of G_X by $\frac{F_X(a, h, z_1)}{F_X(1.75, h, z_1)}$ will correct for changes in a, and similarly for G_Z. The functions G_X and G_Z were tabulated for h increasing from 0.20 to 4.00 by 0.20 increments, and for z increasing from 3.00 to 20.07 by 2% increments, and many copies made by multilith. The programme is shown in Fig. I.2.

The results are shown as Tables I.1 and I.2.

FIG. I.1

```
C     Z FIELD OF CYLINDER
      DIMENSION Y(11)
      Z=2.00
    4 I=0.0
      V=1.0/Z
      W=1.4
    3 U=V*W/2.0
      URED=1.0-U
      UINC=1.0+U
      ROOT1=SQRT(URED**2+V**2)
      ROOT2=SQRT(UINC**2+V**2)
      I=I+1
    5 Y(I)=1.0/(6.U)*(1.0/ROOT1**3-1.0/ROOT2**3)
      GO TO (11,12,13,14,15,16,17,18,19,20,6),I
   11 W=1.6
      GO TO 3
   12 W=1.7
      (up to W=2.1)
   21 FORMAT(F7.2,F7.3,10F6.3)
    6 PRINT21Z,Y(1),Y(2),Y(3),Y(4),Y(5),Y(6),Y(7),Y(8),Y(9),Y(10),Y(11)
      IF(Z-3.0)25,22,22
   22 IF(Z-5.0)37,23,23
   23 IF(Z-7.0)38,24,24
   24 IF(Z-10.0)39,40,40
   25 Z=Z+0.05
      GO TO 4
   37 Z=Z+0.10
      GO TO 4
   38 Z=Z+0.20
                                    GO TO 4
                                 39 Z=0.50
                                    GO TO 4
                                 40 STOP
                                    END
```

FIG. I.2

```
      DO22M=1,2
C     VUW MAGNETOMETER CORRECTION FACTOR - HORIZONTAL COMPONENT
      DIMENSION X(2),G(10)
    5 FORMAT(F7.2,F7.3,10F6.3)
      DO21L=1,2
      Z=3.00
      DO2K=1,200
      IF(M-2)31,32,32
   31 H=0.20
      GO TO 33
   32 H=2.20
   33 DO31=1,10
      DO4J=1,2
      V=1.75/Z
      U=H/(2.*Z)
      IF(L-2)11,12,12
   11 W=1.+U
      X(J)=1./(2.*U*V*V)*((W)/SQR(W*W+V*V)-(1.-U)/SQR((1.-U)**2+V*V))
      GO TO 4
   12 X(J)=1./(6.*U)*(1./((1.-U)**2+V*V)**1.5-1./((1.+U)**2+V*V)**1.5)
    4 Z=Z+2.50
      Z=Z-5.00
      IF(L-2)13,14,14
   13 G(1)=X(1)*(1.-X(2)/X(1)*(Z/(Z+2.50))**3)
      GO TO 3
   14 G(1)=X(1)*(1.-X(2)/X(1)*(Z/(Z+2.50))**4)
    3 H=H+0.2
      PRINT5,Z,G(1),G(2),G(3),G(4),G(5),G(6),G(7),G(8),G(9),G(10)
      IF(Z-20.0)2,6,6
    2 Z=1.02*Z
```

```
      6 PRINT1
      1 FORMAT(//////////)
C       VUW MAGNETOMETER CORRECTION FACTOR - VERTICAL COMPONENT
     21 CONTINUE
     22 CONTINUE
        STOP
        END
```

TABLE I.1 $F_x(a, h, z)$

h/a	0.1	0.4	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
z/a																		
2.00	.716	.724	.735	.742	.750	.760	.771	.783	.797	.812	.829	.847	.867	.889	.913	.938	.966	.996
2.05	.726	.734	.745	.752	.760	.770	.781	.793	.806	.821	.838	.856	.876	.897	.921	.946	.973	1.003
2.10	.736	.744	.755	.762	.770	.779	.790	.802	.815	.830	.846	.864	.884	.905	.928	.953	.980	1.009
2.15	.745	.753	.764	.771	.779	.788	.799	.810	.824	.838	.854	.87_	.891	.912	.935	.959	.986	1.015
2.20	.754	.762	.773	.779	.787	.796	.807	.818	.831	.846	.861	.879	.898	.918	.941	.965	.991	1.020
2.25	.763	.771	.781	.788	.795	.804	.815	.826	.839	.853	.868	.885	.904	.924	.946	.970	.996	1.024
2.30	.771	.779	.789	.795	.803	.812	.822	.833	.845	.859	.875	.891	.909	.929	.951	.974	1.000	1.027
2.35	.779	.786	.796	.803	.810	.819	.829	.840	.852	.866	.880	.897	.915	.934	.955	.978	1.003	1.030
2.40	.787	.794	.803	.810	.817	.826	.835	.846	.858	.871	.886	.902	.920	.939	.959	.982	1.006	1.032
2.45	.794	.801	.810	.816	.824	.832	.841	.852	.864	.877	.891	.907	.924	.943	.963	.985	1.009	1.034
2.50	.800	.807	.817	.823	.830	.838	.847	.858	.869	.882	.896	.911	.928	.946	.966	.988	1.011	1.036
2.55	.807	.814	.823	.829	.836	.844	.853	.863	.874	.887	.900	.916	.932	.950	.969	.990	1.013	1.038
2.60	.813	.820	.829	.834	.841	.849	.858	.868	.879	.891	.905	.919	.936	.953	.972	.992	1.015	1.039
2.65	.819	.825	.834	.840	.847	.854	.863	.873	.884	.896	.909	.923	.939	.956	.974	.994	1.016	1.040
2.70	.825	.831	.840	.845	.852	.859	.868	.877	.888	.900	.912	.927	.942	.959	.977	.996	1.017	1.040
2.75	.830	.836	.845	.850	.857	.864	.872	.882	.892	.903	.916	.930	.945	.961	.979	.998	1.018	1.041
2.80	.835	.841	.849	.855	.861	.868	.877	.886	.896	.907	.919	.933	.947	.963	.981	.999	1.019	1.041
2.85	.840	.846	.854	.859	.866	.873	.881	.890	.900	.910	.922	.936	.950	.965	.982	1.000	1.020	1.041
2.90	.845	.851	.859	.864	.870	.877	.885	.893	.903	.914	.925	.938	.952	.967	.984	1.002	1.021	1.041
2.95	.849	.855	.863	.868	.874	.881	.888	.897	.906	.917	.928	.941	.954	.969	.985	1.003	1.021	1.041
3.00	.854	.859	.867	.872	.878	.884	.892	.900	.909	.920	.931	.943	.956	.971	.987	1.003	1.022	1.041
3.10	.862	.867	.875	.879	.885	.891	.898	.906	.915	.925	.936	.947	.960	.974	.989	1.005	1.022	1.041
3.20	.869	.875	.882	.886	.891	.898	.904	.912	.921	.930	.940	.951	.963	.977	.991	1.006	1.023	1.040
3.30	.876	.881	.888	.892	.897	.903	.910	.917	.925	.934	.944	.955	.966	.979	.992	1.007	1.023	1.039
3.40	.883	.888	.894	.898	.903	.909	.915	.922	.930	.938	.948	.958	.969	.981	.994	1.008	1.023	1.039
3.50	.889	.893	.899	.904	.908	.914	.920	.926	.934	.942	.951	.961	.971	.983	.995	1.008	1.022	1.038
3.60	.894	.899	.905	.908	.913	.918	.924	.930	.937	.945	.954	.963	.973	.984	.996	1.008	1.022	1.036
3.70	.899	.904	.909	.913	.917	.922	.928	.934	.941	.948	.956	.965	.975	.985	.997	1.009	1.022	1.035
3.80	.904	.908	.914	.917	.921	.926	.931	.937	.944	.951	.959	.967	.977	.987	.997	1.009	1.021	1.034
3.90	.909	.913	.918	.921	.925	.930	.935	.940	.947	.954	.961	.969	.978	.988	.998	1.009	1.021	1.033
4.00	.913	.917	.922	.925	.929	.933	.938	.943	.949	.956	.963	.971	.980	.989	.998	1.009	1.020	1.032
4.10	.917	.920	.925	.928	.932	.936	.941	.946	.952	.958	.965	.973	.981	.989	.999	1.009	1.020	1.031
4.20	.920	.924	.928	.932	.935	.939	.944	.949	.954	.960	.967	.974	.982	.990	.999	1.009	1.019	1.030
4.30	.924	.927	.932	.935	.938	.942	.946	.951	.956	.962	.969	.975	.983	.991	1.000	1.009	1.019	1.029
4.40	.927	.930	.934	.937	.941	.944	.948	.953	.958	.964	.970	.977	.984	.992	1.000	1.009	1.018	1.028
4.50	.930	.933	.937	.940	.943	.947	.951	.955	.960	.966	.971	.978	.985	.992	1.000	1.009	1.018	1.027
4.60	.933	.936	.940	.942	.945	.949	.953	.957	.962	.967	.973	.979	.985	.993	1.000	1.008	1.017	1.026
4.70	.935	.938	.942	.945	.948	.951	.955	.959	.963	.968	.974	.980	.986	.993	1.000	1.008	1.017	1.026
4.80	.938	.941	.944	.947	.950	.953	.957	.961	.965	.970	.975	.981	.987	.993	1.001	1.008	1.016	1.025
4.90	.940	.943	.947	.949	.952	.955	.958	.962	.966	.971	.976	.982	.988	.994	1.001	1.008	1.016	1.024
5.00	.943	.945	.949	.951	.954	.957	.960	.964	.968	.972	.977	.982	.988	.994	1.001	1.008	1.015	1.023
5.20	.947	.949	.952	.954	.957	.960	.963	.966	.970	.974	.979	.984	.989	.995	1.001	1.007	1.014	1.022
5.40	.950	.953	.956	.958	.960	.963	.965	.969	.972	.976	.980	.985	.990	.995	1.001	1.007	1.014	1.020
5.60	.954	.956	.959	.961	.963	.965	.968	.971	.974	.978	.982	.986	.991	.996	1.001	1.007	1.013	1.019
5.80	.957	.959	.961	.963	.965	.967	.970	.973	.976	.979	.983	.987	.992	.996	1.001	1.006	1.012	1.018
6.00	.959	.961	.964	.965	.967	.969	.972	.975	.978	.981	.984	.988	.992	.996	1.001	1.006	1.012	1.018
6.20	.962	.964	.966	.968	.969	.971	.974	.976	.979	.982	.985	.989	.993	.997	1.001	1.006	1.011	1.016
6.40	.964	.965	.968	.969	.971	.973	.975	.978	.980	.983	.986	.990	.993	.997	1.001	1.005	1.010	1.015
6.60	.966	.968	.970	.971	.973	.975	.977	.979	.981	.984	.987	.990	.994	.997	1.001	1.005	1.010	1.014
6.80	.968	.970	.972	.973	.974	.976	.978	.980	.982	.985	.988	.991	.994	.997	1.001	1.005	1.009	1.013
7.00	.970	.971	.973	.974	.976	.977	.979	.981	.983	.986	.988	.991	.994	.998	1.001	1.005	1.009	1.013
7.50	.974	.975	.976	.978	.979	.980	.982	.984	.986	.988	.990	.992	.995	.998	1.001	1.004	1.008	1.011
8.00	.976	.978	.979	.980	.981	.983	.984	.985	.987	.989	.991	.993	.996	.998	1.001	1.004	1.007	1.010
8.50	.979	.980	.981	.982	.983	.984	.986	.987	.989	.990	.992	.994	.996	.998	1.001	1.003	1.006	1.009
9.00	.982	.982	.983	.984	.985	.986	.987	.988	.990	.991	.993	.995	.997	.999	1.001	1.003	1.006	1.008
9.50	.983	.984	.985	.986	.987	.987	.988	.990	.991	.992	.994	.995	.997	.999	1.001	1.003	1.005	1.007

TABLE I.1 (Cont.) $F_z (a, h, z)$

z/a \ h/a	0.1	0.4	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1
2.00	.573	.582	.595	.603	.613	.624	.637	.651	.667	.684	.703	.724	.747	.772	.799	.827	.858	.891
2.05	.587	.596	.609	.617	.627	.638	.651	.665	.681	.699	.718	.740	.763	.788	.815	.845	.876	.910
2.10	.600	.610	.622	.631	.641	.652	.665	.679	.695	.713	.733	.754	.777	.803	.831	.860	.892	.927
2.15	.613	.622	.635	.644	.654	.665	.678	.692	.708	.726	.746	.767	.791	.817	.844	.875	.907	.942
2.20	.625	.635	.648	.656	.666	.677	.690	.705	.721	.739	.758	.780	.803	.829	.857	.888	.920	.955
2.25	.637	.647	.660	.668	.678	.689	.702	.716	.732	.750	.770	.791	.815	.841	.869	.899	.932	.968
2.30	.649	.658	.671	.679	.689	.700	.713	.727	.743	.761	.781	.802	.826	.852	.880	.910	.943	.978
2.35	.660	.669	.682	.690	.700	.711	.724	.738	.754	.771	.791	.812	.836	.861	.889	.920	.952	.988
2.40	.670	.680	.692	.700	.710	.721	.734	.748	.764	.781	.801	.822	.845	.871	.898	.928	.961	.996
2.45	.680	.690	.702	.710	.720	.731	.743	.757	.773	.790	.810	.831	.854	.879	.906	.936	.969	1.004
2.50	.690	.699	.712	.720	.729	.740	.752	.766	.782	.799	.818	.839	.862	.887	.914	.944	.976	1.011
2.55	.699	.708	.721	.729	.738	.749	.761	.775	.790	.807	.826	.847	.869	.894	.921	.950	.982	1.016
2.60	.708	.717	.729	.737	.747	.757	.769	.783	.798	.815	.833	.854	.876	.900	.927	.956	.987	1.021
2.65	.717	.726	.738	.746	.755	.765	.777	.791	.805	.822	.840	.860	.883	.907	.933	.961	.992	1.026
2.70	.725	.734	.746	.753	.762	.773	.785	.798	.813	.829	.847	.867	.889	.912	.938	.966	.997	1.030
2.75	.733	.742	.753	.761	.770	.780	.792	.805	.819	.835	.853	.873	.894	.917	.943	.971	1.001	1.033
2.80	.741	.749	.761	.768	.777	.787	.799	.811	.826	.842	.859	.878	.899	.922	.947	.974	1.004	1.036
2.85	.748	.756	.768	.775	.784	.794	.805	.818	.832	.847	.865	.884	.904	.927	.951	.978	1.007	1.039
2.90	.755	.763	.774	.782	.790	.800	.811	.824	.838	.853	.870	.888	.909	.931	.955	.981	1.010	1.041
2.95	.762	.770	.781	.788	.797	.806	.817	.829	.843	.858	.875	.893	.913	.935	.959	.984	1.012	1.042
3.00	.768	.776	.787	.794	.803	.812	.823	.835	.848	.863	.879	.897	.917	.938	.962	.987	1.014	1.044
3.10	.781	.789	.799	.806	.814	.823	.833	.845	.858	.872	.888	.905	.924	.945	.967	.992	1.018	1.046
3.20	.792	.800	.810	.816	.824	.833	.843	.854	.867	.881	.896	.913	.931	.951	.972	.995	1.021	1.048
3.30	.803	.810	.820	.826	.834	.842	.852	.863	.875	.888	.903	.919	.936	.955	.976	.999	1.023	1.049
3.40	.813	.820	.829	.835	.843	.851	.860	.871	.882	.895	.909	.925	.941	.960	.980	1.001	1.024	1.049
3.50	.822	.829	.838	.844	.851	.859	.868	.878	.889	.901	.915	.930	.946	.964	.983	1.003	1.025	1.049
3.60	.830	.837	.846	.851	.859	.866	.875	.884	.895	.907	.920	.934	.950	.967	.985	1.005	1.026	1.049
3.70	.838	.845	.853	.859	.865	.873	.881	.890	.901	.912	.925	.939	.954	.970	.987	1.006	1.027	1.049
3.80	.846	.852	.860	.865	.872	.879	.887	.896	.906	.917	.929	.942	.957	.972	.989	1.007	1.027	1.048
3.90	.853	.859	.867	.872	.878	.885	.893	.901	.911	.922	.933	.946	.960	.975	.991	1.008	1.027	1.047
4.00	.859	.865	.873	.878	.883	.890	.898	.906	.915	.926	.937	.949	.962	.977	.992	1.009	1.027	1.046
4.10	.865	.871	.878	.883	.889	.895	.902	.911	.920	.929	.940	.952	.965	.979	.993	1.009	1.027	1.045
4.20	.871	.876	.884	.888	.894	.900	.907	.915	.923	.933	.943	.955	.967	.980	.994	1.010	1.026	1.044
4.30	.876	.882	.889	.893	.898	.904	.911	.919	.927	.936	.946	.957	.969	.982	.995	1.010	1.026	1.043
4.40	.882	.886	.893	.898	.903	.908	.915	.922	.930	.939	.949	.959	.971	.983	.996	1.010	1.026	1.042
4.50	.886	.891	.898	.902	.907	.912	.919	.926	.933	.942	.951	.961	.972	.984	.997	1.011	1.025	1.041
4.60	.891	.895	.902	.906	.910	.916	.922	.929	.936	.945	.953	.963	.974	.985	.998	1.011	1.025	1.040
4.70	.895	.900	.906	.909	.914	.919	.925	.932	.939	.947	.956	.965	.975	.986	.998	1.011	1.024	1.039
4.80	.899	.903	.909	.913	.917	.923	.928	.935	.942	.949	.958	.967	.977	.987	.999	1.011	1.024	1.038
4.90	.903	.907	.913	.916	.921	.926	.931	.937	.944	.951	.959	.968	.978	.988	.999	1.011	1.023	1.037
5.00	.906	.910	.916	.919	.924	.928	.934	.940	.946	.953	.961	.970	.979	.989	.999	1.011	1.023	1.036
5.20	.913	.917	.922	.925	.929	.934	.939	.944	.950	.957	.964	.972	.981	.990	1.000	1.010	1.022	1.034
5.40	.919	.922	.927	.930	.934	.938	.943	.948	.954	.960	.967	.974	.982	.991	1.000	1.010	1.021	1.032
5.60	.924	.928	.932	.935	.939	.942	.947	.952	.957	.963	.969	.976	.984	.992	1.001	1.010	1.020	1.030
5.80	.929	.932	.937	.939	.943	.946	.950	.955	.960	.966	.972	.978	.985	.993	1.001	1.010	1.019	1.029
6.00	.933	.937	.941	.943	.946	.950	.954	.958	.963	.968	.974	.980	.986	.993	1.001	1.009	1.018	1.027
6.20	.938	.940	.944	.947	.950	.953	.956	.961	.965	.970	.975	.981	.987	.994	1.001	1.009	1.017	1.026
6.40	.941	.944	.947	.950	.953	.956	.959	.963	.967	.972	.977	.982	.988	.995	1.001	1.008	1.016	1.024
6.60	.944	.947	.950	.953	.955	.958	.962	.965	.969	.974	.978	.984	.989	.995	1.001	1.008	1.015	1.023
6.80	.948	.950	.953	.955	.958	.961	.964	.967	.971	.975	.980	.985	.990	.995	1.001	1.008	1.015	1.022
7.00	.950	.953	.956	.958	.960	.963	.966	.969	.973	.977	.981	.985	.990	.996	1.001	1.007	1.014	1.021
7.50	.957	.959	.961	.963	.965	.967	.970	.973	.976	.980	.983	.987	.992	.996	1.001	1.007	1.012	1.018
8.00	.962	.963	.966	.967	.969	.971	.974	.976	.979	.982	.985	.989	.993	.997	1.001	1.006	1.011	1.016
8.50	.966	.967	.970	.971	.973	.974	.977	.979	.981	.984	.987	.990	.994	.997	1.001	1.005	1.010	1.015
9.00	.969	.971	.973	.974	.975	.977	.979	.981	.983	.986	.988	.991	.994	.998	1.001	1.005	1.009	1.013
9.50	.972	.974	.975	.977	.978	.979	.981	.983	.985	.987	.990	.992	.995	.998	1.001	1.004	1.008	1.012
10.00	.975	.976	.978	.979	.980	.981	.983	.985	.986	.988	.991	.993	.995	.998	1.001	1.004	1.007	1.011

TABLE I.2 V.U.W. MAGNETOMETER CORRECTION FACTOR - HORIZONTAL COMPONENTS (G_x)

Z	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
3.00	.504	.506	.509	.514	.520	.528	.536	.547	.559	.572	.588	.605	.624	.645	.667	.692	.719	.748	.779	.811
3.06	.510	.512	.515	.519	.525	.533	.542	.552	.564	.578	.593	.610	.629	.650	.673	.698	.725	.754	.785	.819
3.12	.515	.517	.520	.525	.531	.538	.547	.557	.569	.583	.598	.615	.634	.655	.678	.703	.730	.759	.791	.825
3.18	.520	.522	.525	.529	.535	.543	.552	.562	.574	.587	.602	.620	.638	.659	.682	.707	.735	.764	.796	.830
3.24	.524	.526	.530	.534	.540	.547	.556	.566	.578	.592	.607	.624	.642	.663	.686	.711	.739	.768	.800	.835
3.31	.529	.531	.534	.539	.544	.552	.560	.570	.582	.596	.611	.627	.646	.667	.690	.715	.742	.772	.804	.839
3.37	.533	.535	.538	.543	.548	.556	.564	.574	.586	.599	.614	.631	.649	.670	.693	.718	.745	.774	.807	.841
3.44	.537	.539	.542	.547	.552	.559	.568	.578	.589	.603	.617	.634	.652	.673	.695	.720	.747	.777	.809	.843
3.51	.541	.543	.546	.550	.556	.563	.571	.581	.593	.606	.620	.637	.655	.675	.697	.722	.749	.778	.810	.845
3.58	.544	.546	.549	.554	.559	.566	.574	.584	.595	.608	.623	.639	.657	.677	.699	.723	.750	.779	.811	.845
3.65	.548	.549	.552	.557	.562	.569	.577	.587	.598	.611	.625	.641	.659	.678	.700	.724	.750	.779	.811	.845
3.73	.551	.552	.555	.560	.565	.572	.580	.589	.600	.613	.627	.642	.660	.679	.701	.725	.751	.779	.810	.844
3.80	.553	.555	.558	.562	.568	.574	.582	.592	.602	.614	.628	.644	.661	.680	.701	.725	.750	.778	.809	.842
3.88	.556	.558	.560	.565	.570	.576	.584	.593	.604	.616	.630	.645	.662	.681	.701	.724	.749	.777	.807	.840
3.95	.558	.560	.563	.567	.572	.578	.586	.595	.605	.617	.631	.645	.662	.681	.701	.723	.748	.775	.805	.837
4.03	.560	.562	.565	.569	.574	.580	.587	.596	.607	.618	.631	.646	.662	.680	.700	.722	.746	.773	.802	.834
4.11	.562	.564	.566	.570	.575	.581	.589	.597	.607	.619	.632	.646	.662	.680	.699	.721	.744	.770	.799	.830
4.20	.563	.565	.568	.572	.576	.582	.590	.598	.608	.619	.632	.646	.661	.679	.698	.719	.742	.767	.795	.825
4.28	.565	.566	.569	.573	.577	.583	.590	.599	.608	.619	.631	.645	.660	.677	.696	.717	.739	.764	.791	.821
4.37	.566	.567	.570	.574	.578	.584	.591	.599	.608	.619	.631	.644	.659	.676	.694	.714	.736	.760	.787	.816
4.45	.567	.568	.571	.574	.579	.584	.591	.599	.608	.619	.630	.643	.658	.674	.692	.711	.733	.756	.782	.810
4.54	.567	.569	.571	.575	.579	.585	.591	.599	.608	.618	.629	.642	.656	.672	.689	.708	.729	.752	.777	.804
4.63	.568	.569	.571	.575	.579	.585	.591	.599	.607	.617	.628	.641	.654	.670	.687	.705	.725	.748	.772	.798
4.73	.568	.569	.572	.575	.579	.584	.591	.598	.606	.616	.627	.639	.652	.667	.684	.702	.721	.743	.766	.792
4.82	.568	.569	.571	.575	.579	.584	.590	.597	.605	.615	.625	.637	.650	.664	.680	.698	.717	.738	.761	.786
4.92	.567	.569	.571	.574	.578	.583	.589	.596	.604	.613	.623	.635	.647	.661	.677	.694	.712	.733	.755	.779
5.02	.567	.568	.570	.574	.577	.582	.588	.595	.603	.611	.621	.632	.645	.658	.673	.690	.708	.727	.749	.772
5.12	.566	.568	.570	.573	.576	.581	.587	.593	.601	.609	.619	.630	.642	.655	.669	.685	.703	.722	.742	.765
5.22	.565	.567	.569	.572	.575	.580	.585	.592	.599	.607	.617	.627	.639	.651	.665	.681	.698	.716	.736	.758
5.32	.564	.566	.568	.570	.574	.578	.584	.590	.597	.605	.614	.624	.635	.648	.661	.676	.692	.710	.729	.750
5.43	.563	.564	.566	.569	.572	.577	.582	.588	.595	.602	.611	.621	.632	.644	.657	.671	.687	.704	.723	.743
5.54	.562	.563	.565	.567	.571	.575	.580	.586	.592	.600	.608	.618	.628	.640	.652	.666	.681	.698	.716	.735
5.65	.560	.561	.563	.565	.569	.573	.578	.583	.590	.597	.605	.614	.624	.635	.648	.661	.676	.692	.709	.727
5.76	.558	.559	.561	.563	.567	.571	.575	.581	.587	.594	.602	.611	.620	.631	.643	.656	.670	.685	.702	.720
5.88	.556	.557	.559	.561	.564	.568	.573	.578	.584	.591	.598	.607	.616	.627	.638	.650	.664	.679	.695	.712
5.99	.554	.555	.557	.559	.562	.566	.570	.575	.581	.587	.595	.603	.612	.622	.633	.645	.658	.672	.688	.704
6.11	.552	.553	.554	.557	.559	.563	.567	.572	.578	.584	.591	.599	.608	.617	.628	.640	.652	.666	.680	.696
6.24	.549	.550	.552	.554	.557	.560	.564	.569	.574	.580	.587	.595	.603	.613	.623	.634	.646	.659	.673	.688
6.36	.547	.548	.549	.551	.554	.557	.561	.566	.571	.577	.583	.591	.599	.608	.618	.628	.640	.652	.666	.681
6.49	.544	.545	.546	.548	.551	.554	.558	.562	.567	.573	.579	.586	.594	.603	.612	.622	.634	.646	.659	.673
6.62	.541	.542	.543	.545	.548	.551	.554	.559	.563	.569	.575	.582	.589	.598	.607	.617	.627	.639	.651	.665
6.75	.538	.539	.540	.542	.544	.547	.551	.555	.560	.565	.571	.577	.585	.593	.601	.611	.621	.632	.644	.657
6.89	.535	.536	.537	.539	.541	.544	.547	.551	.556	.561	.566	.573	.580	.587	.596	.605	.615	.625	.637	.649
7.02	.532	.532	.534	.535	.538	.540	.544	.547	.552	.557	.562	.568	.575	.582	.590	.599	.608	.618	.629	.641
7.17	.528	.529	.530	.532	.534	.537	.540	.543	.547	.552	.557	.563	.570	.577	.584	.593	.602	.612	.622	.633
7.31	.525	.525	.527	.528	.530	.533	.536	.539	.543	.548	.553	.558	.565	.571	.579	.587	.595	.605	.615	.626
7.45	.521	.522	.523	.524	.526	.529	.532	.535	.539	.543	.548	.553	.559	.566	.573	.581	.589	.598	.607	.618
7.60	.517	.518	.519	.521	.522	.525	.528	.531	.534	.539	.543	.548	.554	.560	.567	.574	.582	.591	.600	.610
7.76	.514	.514	.515	.517	.518	.521	.523	.526	.530	.534	.538	.543	.549	.555	.561	.568	.576	.584	.593	.602
7.91	.510	.510	.511	.513	.514	.516	.519	.522	.525	.529	.534	.538	.544	.549	.555	.562	.569	.577	.586	.595

Z	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
8.07	.506	.506	.507	.508	.510	.512	.515	.518	.521	.524	.529	.533	.538	.544	.550	.556	.563	.570	.579	.587
8.23	.502	.502	.503	.504	.506	.508	.510	.513	.516	.520	.524	.528	.533	.538	.544	.550	.556	.564	.571	.580
8.40	.497	.498	.499	.500	.502	.503	.506	.508	.511	.515	.519	.523	.527	.532	.538	.544	.550	.557	.564	.572
8.56	.493	.494	.494	.496	.497	.499	.501	.504	.507	.510	.513	.517	.522	.527	.532	.537	.544	.550	.557	.565
8.74	.489	.489	.490	.491	.493	.494	.496	.499	.502	.505	.508	.512	.516	.521	.526	.531	.537	.543	.550	.557
8.91	.484	.485	.486	.487	.488	.490	.492	.494	.497	.500	.503	.507	.511	.515	.520	.525	.531	.537	.543	.550
9.09	.480	.480	.481	.482	.484	.485	.487	.489	.492	.495	.498	.501	.505	.509	.514	.519	.524	.530	.536	.542
9.27	.475	.476	.477	.478	.479	.480	.482	.484	.487	.490	.493	.496	.500	.504	.508	.513	.518	.523	.529	.535
9.46	.471	.471	.472	.473	.474	.476	.477	.479	.482	.484	.487	.491	.494	.498	.502	.507	.511	.517	.522	.528
9.65	.467	.467	.467	.468	.470	.471	.473	.475	.477	.479	.482	.485	.488	.492	.496	.500	.505	.510	.515	.521
9.84	.462	.462	.463	.464	.465	.466	.468	.470	.472	.474	.477	.480	.483	.486	.490	.494	.499	.503	.508	.514
10.03	.457	.458	.458	.459	.460	.461	.463	.465	.467	.469	.471	.474	.477	.481	.484	.488	.492	.497	.502	.507
10.24	.452	.453	.453	.454	.455	.456	.458	.460	.461	.464	.466	.469	.472	.475	.478	.482	.486	.490	.495	.500
10.44	.448	.448	.449	.449	.450	.451	.453	.454	.456	.458	.461	.463	.466	.469	.472	.476	.480	.484	.488	.493
10.65	.443	.443	.444	.444	.445	.446	.448	.449	.451	.453	.455	.458	.460	.463	.467	.470	.474	.477	.482	.486
10.86	.438	.438	.439	.440	.440	.442	.443	.444	.446	.448	.450	.452	.455	.458	.461	.464	.467	.471	.475	.479
11.08	.433	.434	.434	.435	.436	.437	.438	.439	.441	.443	.445	.447	.449	.452	.455	.458	.461	.465	.468	.473
11.30	.429	.429	.429	.430	.431	.432	.433	.434	.436	.437	.439	.441	.444	.446	.449	.452	.455	.458	.462	.466
11.53	.424	.424	.424	.425	.426	.427	.428	.429	.430	.432	.434	.436	.438	.441	.443	.446	.449	.452	.456	.459
11.76	.419	.419	.419	.420	.421	.422	.423	.424	.425	.427	.429	.431	.433	.435	.437	.440	.443	.446	.449	.453
11.99	.414	.414	.415	.415	.416	.417	.418	.419	.420	.422	.423	.425	.427	.429	.432	.434	.437	.440	.443	.446
12.23	.409	.409	.409	.410	.411	.412	.413	.414	.415	.416	.418	.420	.422	.424	.426	.428	.431	.434	.437	.440
12.48	.404	.404	.405	.405	.406	.407	.408	.409	.410	.411	.413	.414	.416	.418	.420	.423	.425	.428	.430	.433
12.73	.400	.399	.400	.400	.401	.402	.402	.403	.405	.406	.407	.409	.411	.413	.415	.417	.419	.422	.424	.427
12.98	.394	.395	.395	.395	.396	.397	.397	.398	.399	.401	.402	.404	.405	.407	.409	.411	.413	.416	.418	.421
13.24	.390	.390	.390	.390	.391	.392	.392	.393	.394	.396	.397	.398	.400	.402	.403	.405	.408	.410	.412	.415
13.51	.384	.385	.385	.385	.386	.387	.387	.388	.389	.390	.392	.393	.394	.396	.398	.400	.402	.404	.406	.409
13.78	.380	.380	.380	.381	.381	.382	.382	.383	.384	.385	.386	.388	.389	.391	.392	.394	.396	.398	.400	.403
14.05	.375	.375	.375	.376	.376	.377	.377	.378	.379	.380	.381	.382	.384	.385	.387	.389	.390	.392	.394	.397
14.33	.370	.370	.370	.371	.371	.372	.372	.373	.374	.375	.376	.377	.379	.380	.381	.383	.385	.387	.389	.391
14.62	.365	.366	.365	.366	.366	.367	.367	.368	.369	.370	.371	.372	.373	.375	.376	.378	.379	.381	.383	.385
14.91	.360	.361	.361	.361	.362	.362	.363	.363	.364	.365	.366	.367	.368	.369	.371	.372	.374	.375	.377	.379
15.21	.356	.356	.356	.356	.357	.357	.358	.358	.359	.360	.361	.362	.363	.364	.365	.367	.368	.370	.372	.373
15.52	.351	.351	.351	.351	.352	.352	.353	.353	.354	.355	.356	.357	.358	.359	.360	.362	.363	.364	.366	.368
15.83	.346	.346	.346	.347	.347	.347	.348	.349	.349	.350	.351	.352	.353	.354	.355	.356	.358	.359	.361	.362
16.14	.342	.341	.341	.342	.342	.343	.343	.344	.344	.345	.346	.347	.348	.349	.350	.351	.352	.354	.355	.357
16.47	.337	.337	.337	.337	.338	.338	.338	.339	.339	.340	.341	.342	.343	.344	.345	.346	.347	.348	.350	.351
16.80	.333	.332	.332	.333	.333	.333	.334	.334	.335	.335	.336	.337	.338	.339	.340	.341	.342	.343	.344	.346
17.13	.327	.328	.328	.328	.328	.328	.329	.329	.330	.330	.331	.332	.333	.334	.335	.336	.337	.338	.339	.340
17.47	.323	.323	.323	.323	.324	.324	.324	.325	.325	.326	.326	.327	.328	.329	.330	.331	.332	.333	.334	.335
17.82	.317	.318	.318	.318	.319	.319	.320	.320	.320	.321	.322	.322	.323	.324	.325	.326	.327	.328	.329	.330
18.18	.314	.314	.314	.314	.314	.314	.315	.315	.316	.316	.317	.318	.318	.319	.320	.321	.322	.323	.324	.325
18.54	.309	.310	.309	.309	.310	.310	.310	.311	.311	.312	.312	.313	.313	.314	.315	.316	.317	.318	.319	.320
18.92	.304	.304	.305	.305	.305	.305	.306	.306	.307	.307	.307	.308	.309	.309	.310	.311	.312	.313	.314	.315
19.29	.301	.300	.300	.300	.301	.301	.301	.302	.302	.302	.303	.304	.304	.305	.305	.306	.307	.308	.309	.310
19.68	.296	.296	.296	.296	.296	.296	.297	.297	.297	.298	.298	.299	.299	.300	.301	.301	.302	.303	.304	.305
20.07	.291	.291	.291	.291	.292	.292	.292	.293	.293	.293	.294	.294	.295	.295	.296	.297	.297	.298	.299	.300

TABLE **I**.2 (Cont)   V.U.W. MAGNETOMETER CORRECTION FACTOR - VERTICAL COMPONENTS (G_z)

Z	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
3.00	.411	.414	.417	.422	.428	.436	.445	.455	.467	.481	.496	.513	.531	.550	.570	.592	.614	.637	.659	.681
3.06	.421	.423	.426	.431	.437	.445	.455	.465	.478	.492	.507	.524	.543	.563	.585	.607	.631	.655	.680	.704
3.12	.430	.432	.435	.440	.447	.455	.464	.475	.488	.502	.518	.536	.555	.576	.598	.622	.647	.673	.699	.726
3.18	.439	.441	.444	.449	.456	.464	.474	.485	.498	.512	.528	.547	.566	.588	.611	.636	.662	.690	.718	.746
3.24	.447	.449	.453	.458	.465	.473	.483	.494	.507	.522	.539	.557	.577	.599	.623	.649	.677	.705	.735	.766
3.31	.456	.458	.462	.467	.473	.482	.492	.503	.516	.531	.548	.567	.588	.610	.635	.662	.690	.720	.752	.784
3.37	.464	.466	.470	.475	.482	.490	.500	.512	.525	.540	.558	.577	.598	.621	.646	.673	.703	.734	.767	.801
3.44	.472	.474	.478	.483	.490	.498	.508	.520	.534	.549	.566	.586	.607	.631	.656	.684	.714	.747	.781	.817
3.51	.480	.482	.486	.491	.498	.506	.517	.528	.542	.557	.575	.594	.616	.640	.666	.695	.725	.758	.794	.831
3.58	.488	.490	.494	.499	.506	.514	.524	.536	.550	.565	.583	.603	.625	.649	.675	.704	.735	.769	.806	.844
3.65	.495	.497	.501	.506	.513	.522	.532	.544	.557	.573	.591	.610	.632	.657	.683	.713	.744	.779	.816	.856
3.73	.502	.504	.508	.513	.520	.529	.539	.551	.565	.580	.598	.618	.640	.664	.691	.721	.753	.788	.825	.866
3.80	.509	.511	.515	.520	.527	.536	.546	.558	.571	.587	.605	.624	.647	.671	.698	.728	.760	.795	.834	.875
3.88	.516	.518	.522	.527	.534	.542	.552	.564	.578	.593	.611	.631	.653	.677	.704	.734	.767	.802	.841	.883
3.95	.522	.524	.528	.533	.540	.548	.558	.570	.584	.599	.617	.637	.659	.683	.710	.740	.772	.808	.847	.889
4.03	.528	.530	.534	.539	.546	.554	.564	.576	.590	.605	.623	.642	.664	.688	.715	.745	.777	.813	.852	.894
4.11	.534	.536	.540	.545	.552	.560	.570	.581	.595	.610	.628	.647	.669	.693	.720	.749	.782	.817	.856	.898
4.20	.540	.542	.545	.550	.557	.565	.575	.587	.600	.615	.632	.652	.673	.697	.724	.753	.785	.821	.859	.901
4.28	.545	.547	.551	.556	.562	.570	.580	.591	.605	.620	.637	.656	.677	.701	.727	.756	.788	.823	.861	.903
4.37	.550	.552	.555	.560	.567	.575	.585	.596	.609	.624	.641	.659	.681	.704	.730	.759	.790	.825	.863	.904
4.45	.554	.557	.560	.565	.571	.579	.589	.600	.613	.627	.644	.663	.684	.707	.732	.761	.792	.826	.864	.905
4.54	.559	.561	.564	.569	.576	.583	.593	.604	.616	.631	.647	.666	.686	.709	.734	.762	.793	.826	.863	.904
4.63	.563	.565	.569	.573	.580	.587	.596	.607	.620	.634	.650	.668	.688	.711	.735	.763	.793	.826	.863	.903
4.73	.567	.569	.572	.577	.583	.591	.600	.610	.623	.637	.652	.670	.690	.712	.736	.763	.793	.825	.861	.900
4.82	.571	.572	.576	.580	.586	.594	.603	.613	.625	.639	.654	.672	.691	.713	.737	.763	.792	.824	.859	.898
4.92	.574	.576	.579	.583	.589	.597	.605	.616	.627	.641	.656	.673	.692	.713	.737	.763	.791	.822	.857	.894
5.02	.577	.579	.582	.586	.592	.599	.608	.618	.629	.643	.657	.674	.693	.713	.736	.762	.789	.820	.853	.890
5.12	.580	.581	.584	.589	.595	.602	.610	.620	.631	.644	.659	.675	.693	.713	.736	.760	.787	.817	.850	.886
5.22	.582	.584	.587	.591	.597	.604	.612	.621	.632	.645	.659	.675	.693	.713	.734	.758	.785	.814	.846	.881
5.32	.584	.586	.589	.593	.599	.605	.613	.623	.633	.646	.660	.675	.693	.712	.733	.756	.782	.810	.841	.875
5.43	.586	.588	.591	.595	.600	.607	.614	.624	.634	.646	.660	.675	.692	.711	.731	.754	.779	.806	.837	.869
5.54	.588	.589	.592	.596	.601	.608	.615	.624	.635	.646	.660	.674	.691	.709	.729	.751	.776	.802	.831	.863
5.65	.589	.591	.593	.597	.602	.609	.616	.625	.635	.646	.659	.673	.689	.707	.727	.748	.772	.798	.826	.857
5.76	.590	.591	.594	.598	.603	.609	.616	.625	.635	.646	.658	.672	.688	.705	.724	.745	.768	.793	.820	.850
5.88	.591	.593	.595	.599	.604	.610	.617	.625	.634	.645	.657	.671	.686	.703	.721	.741	.763	.788	.814	.843
5.99	.592	.593	.596	.599	.604	.610	.617	.625	.634	.644	.656	.669	.684	.700	.718	.737	.759	.782	.808	.836
6.11	.592	.593	.596	.599	.604	.610	.616	.624	.633	.643	.655	.667	.682	.697	.714	.733	.754	.777	.802	.829
6.24	.592	.593	.596	.599	.604	.609	.616	.623	.632	.642	.653	.665	.679	.694	.711	.729	.749	.771	.795	.821
6.36	.592	.593	.596	.599	.603	.608	.615	.622	.631	.640	.651	.663	.676	.691	.707	.725	.744	.765	.788	.813
6.49	.592	.593	.595	.598	.603	.608	.614	.621	.629	.638	.649	.660	.673	.687	.703	.720	.739	.759	.781	.805
6.62	.591	.592	.594	.598	.602	.607	.612	.619	.627	.636	.646	.658	.670	.684	.699	.715	.733	.753	.774	.798
6.75	.590	.591	.594	.597	.600	.605	.611	.618	.625	.634	.644	.655	.667	.680	.694	.710	.728	.747	.767	.789
6.89	.589	.590	.592	.595	.599	.604	.609	.616	.623	.631	.641	.651	.663	.676	.690	.705	.722	.740	.760	.781
7.02	.588	.589	.591	.594	.597	.602	.607	.614	.621	.629	.638	.648	.659	.672	.685	.700	.716	.734	.753	.773
7.17	.586	.588	.589	.592	.596	.600	.605	.611	.618	.626	.635	.645	.655	.667	.680	.695	.710	.727	.745	.765
7.31	.585	.586	.588	.590	.594	.598	.603	.609	.615	.623	.631	.641	.651	.663	.675	.689	.704	.720	.738	.757
7.45	.583	.584	.586	.588	.592	.596	.600	.606	.613	.620	.628	.637	.647	.658	.670	.683	.698	.713	.730	.748
7.60	.581	.582	.584	.586	.589	.593	.598	.603	.609	.617	.624	.633	.643	.653	.665	.678	.691	.706	.723	.740
7.76	.579	.580	.581	.584	.587	.591	.595	.600	.606	.613	.621	.629	.638	.649	.660	.672	.685	.699	.715	.732
7.91	.576	.577	.579	.581	.584	.588	.592	.597	.603	.609	.617	.625	.634	.644	.654	.666	.679	.692	.707	.723

Z	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60	3.80	4.00
8.07	.574	.575	.576	.578	.581	.585	.589	.594	.599	.606	.613	.620	.629	.638	.649	.660	.672	.685	.700	.715
8.23	.571	.572	.573	.575	.578	.582	.586	.590	.596	.602	.608	.616	.624	.633	.643	.654	.666	.678	.692	.707
8.40	.568	.569	.570	.572	.575	.578	.582	.587	.592	.598	.604	.611	.619	.628	.638	.648	.659	.671	.684	.698
8.56	.565	.566	.567	.569	.572	.575	.579	.583	.588	.594	.600	.607	.614	.623	.632	.642	.652	.664	.676	.690
8.74	.562	.563	.564	.566	.568	.571	.575	.579	.584	.589	.595	.602	.609	.617	.626	.635	.646	.657	.669	.682
8.91	.559	.559	.561	.562	.565	.568	.571	.575	.580	.585	.591	.597	.604	.612	.620	.629	.639	.650	.661	.673
9.09	.555	.556	.557	.559	.561	.564	.567	.571	.575	.580	.586	.592	.599	.606	.614	.623	.632	.642	.653	.665
9.27	.551	.552	.553	.555	.557	.560	.563	.567	.571	.576	.581	.587	.593	.601	.608	.617	.626	.635	.646	.657
9.46	.548	.548	.550	.551	.553	.556	.559	.563	.567	.571	.576	.582	.588	.595	.602	.610	.619	.628	.638	.649
9.65	.544	.545	.546	.547	.549	.552	.555	.558	.562	.566	.571	.577	.583	.589	.596	.604	.612	.621	.630	.641
9.84	.540	.541	.542	.543	.545	.548	.550	.554	.557	.562	.566	.571	.577	.583	.590	.597	.605	.614	.623	.633
10.03	.536	.537	.538	.539	.541	.543	.546	.549	.553	.557	.561	.566	.572	.577	.584	.591	.598	.607	.615	.625
10.24	.532	.533	.533	.535	.537	.539	.541	.544	.548	.552	.556	.561	.566	.572	.578	.584	.592	.599	.608	.617
10.44	.528	.528	.529	.531	.532	.534	.537	.540	.543	.547	.551	.555	.560	.566	.572	.578	.585	.592	.600	.609
10.65	.523	.524	.525	.526	.528	.530	.532	.535	.538	.542	.545	.550	.555	.560	.565	.572	.578	.585	.593	.601
10.86	.519	.520	.520	.522	.523	.525	.527	.530	.533	.536	.540	.544	.549	.554	.559	.565	.571	.578	.585	.593
11.08	.515	.515	.516	.517	.519	.520	.523	.525	.528	.531	.535	.539	.543	.548	.553	.559	.565	.571	.578	.585
11.30	.510	.510	.511	.512	.514	.516	.518	.520	.523	.526	.529	.533	.537	.542	.547	.552	.558	.564	.571	.578
11.53	.505	.506	.507	.508	.509	.511	.513	.515	.518	.521	.524	.528	.532	.536	.541	.546	.551	.557	.563	.570
11.76	.501	.501	.502	.503	.504	.506	.508	.510	.512	.515	.518	.522	.526	.530	.534	.539	.544	.550	.556	.562
11.99	.496	.496	.497	.498	.499	.501	.503	.505	.507	.510	.513	.516	.520	.524	.528	.533	.538	.543	.549	.555
12.23	.491	.492	.492	.493	.494	.496	.498	.500	.502	.504	.507	.511	.514	.518	.522	.526	.531	.536	.541	.547
12.48	.486	.487	.487	.488	.489	.491	.492	.494	.497	.499	.502	.505	.508	.512	.516	.520	.524	.529	.534	.540
12.73	.481	.482	.482	.483	.484	.486	.487	.489	.491	.494	.496	.499	.502	.506	.509	.513	.518	.522	.527	.533
12.98	.477	.477	.477	.478	.479	.481	.482	.484	.486	.488	.491	.493	.496	.500	.503	.507	.511	.516	.520	.525
13.24	.472	.472	.472	.473	.474	.475	.477	.479	.481	.483	.485	.488	.491	.494	.497	.501	.505	.509	.513	.518
13.51	.467	.467	.467	.468	.469	.470	.472	.473	.475	.477	.479	.482	.485	.488	.491	.494	.498	.502	.506	.511
13.78	.462	.462	.462	.463	.464	.465	.466	.468	.470	.472	.474	.476	.479	.482	.485	.488	.492	.495	.499	.504
14.05	.457	.457	.457	.458	.459	.460	.461	.463	.464	.466	.468	.470	.473	.476	.479	.482	.485	.489	.493	.497
14.33	.451	.452	.452	.453	.454	.455	.456	.457	.459	.461	.463	.465	.467	.470	.472	.475	.479	.482	.486	.490
14.62	.446	.447	.447	.448	.448	.449	.451	.452	.453	.455	.457	.459	.461	.464	.466	.469	.472	.476	.479	.483
14.91	.441	.441	.442	.442	.443	.444	.445	.447	.448	.450	.451	.453	.455	.458	.460	.463	.466	.469	.472	.476
15.21	.436	.436	.437	.437	.438	.439	.440	.441	.443	.444	.446	.448	.450	.452	.454	.457	.460	.463	.466	.469
15.52	.431	.431	.432	.432	.433	.434	.435	.436	.437	.439	.440	.442	.444	.446	.448	.451	.453	.456	.459	.462
15.83	.426	.426	.426	.427	.428	.428	.429	.430	.432	.433	.435	.436	.438	.440	.442	.445	.447	.450	.453	.456
16.14	.421	.421	.421	.422	.422	.423	.424	.425	.426	.428	.429	.431	.432	.434	.436	.439	.441	.444	.446	.449
16.47	.416	.416	.416	.417	.417	.418	.419	.420	.421	.422	.424	.425	.427	.429	.431	.433	.435	.437	.440	.443
16.80	.410	.411	.411	.411	.412	.413	.413	.414	.415	.417	.418	.419	.421	.423	.425	.427	.429	.431	.434	.436
17.13	.405	.405	.406	.406	.407	.407	.408	.409	.410	.411	.412	.414	.415	.417	.419	.421	.423	.425	.427	.430
17.47	.400	.400	.401	.401	.402	.402	.403	.404	.405	.406	.407	.408	.410	.411	.413	.415	.417	.419	.421	.423
17.82	.395	.395	.395	.396	.396	.397	.398	.398	.399	.400	.402	.403	.404	.406	.407	.409	.411	.413	.415	.417
18.18	.390	.390	.390	.391	.391	.392	.392	.393	.394	.395	.396	.397	.399	.400	.402	.403	.405	.407	.409	.411
18.54	.385	.385	.385	.386	.386	.387	.387	.388	.389	.390	.391	.392	.393	.395	.396	.398	.399	.401	.403	.405
18.92	.380	.380	.380	.380	.381	.381	.382	.383	.384	.384	.385	.386	.388	.389	.390	.392	.393	.395	.397	.399
19.29	.375	.375	.375	.375	.376	.376	.377	.378	.378	.379	.380	.381	.382	.383	.385	.386	.388	.389	.391	.393
19.68	.370	.370	.370	.370	.371	.371	.372	.372	.373	.374	.375	.376	.377	.378	.379	.381	.382	.384	.385	.387
20.07	.365	.365	.365	.365	.366	.366	.367	.367	.368	.369	.370	.370	.371	.373	.374	.375	.376	.378	.379	.381

CALCULATION OF SAMPLE MAGNETIZATION

The laboratory system of coordinates has its y axis along the direction of the light path from the mirror to the scale at zero deflection, z axis vertically upwards, and the x axis for a right handed system.

The specimen coordinates are X,Y,Z.   For cylindrical specimens the X axis is parallel to the orientation line on one end, in the direction of the arrow, while the Z axis is parallel to the axis, and outwards from that face containing the x axis (the "top" face).

The magnetometer is affected only by fields parallel to the x axis, so that measurements are taken with the X and Y axes in the $\pm$ x direction, and with an x offset, in order to measure all components.   A full set of measurements involves starting with the specimen upright and the arrow to the East, measuring the deflection, rotating 90° and measuring, rotating another 90° and so on up to 270°, having for all these measurements the Z axis offset to the East of the z axis.   The specimen is then inverted and the set repeated.   After rotating the sample holder, to give the same offset, but to the West, the complete set of measurements is repeated.   By taking sums and differences as shown on the measurement sheets, numbers X, Y, Z_m and Z_χ are obtained, which are respectively:

8 times the deflection due to the X component (four measurements of twice the deflection)

8 times the deflection due to the Y component

16 times the deflection due to the Z component.

16 times the deflection due to the induced magnetization in the Z direction.

The measurement of susceptibility needs some comment.   If a field is applied in the Z direction, the magnetization in this direction will be the component of remanent magnetization plus the induced magnetization.   On inverting the specimen, the direction of the remanent magnetization changes sign, while that induced remains the same.   However, there is a possibility of miscentring errors giving rise to a non-zero sum on adding the upright and inverted readings, when there is no induced component.   Such effects were found to be small, but sufficient to give about $\pm$ 10% error in susceptibility measurements.   The presence of the field does not appear to affect angle or intensity measurements when the field is about 1 oe.

The field of a cylinder at the distances used is approximately that of a dipole, but a comparison with the values corresponding to a uniformly magnetized cylinder, calculated by Papapetrou (Blackett, 1952), suggested that a more exact expression is needed. Papapetrou's correction factor F_x and F_z for the x and z components of magnetization has been tabulated by the author (see Appendix I)

Let X_1, Z_1, X_2, Z_2 be the horizontal fields at the lower and upper magnets due to the horizontal and vertical components of magnetization of the specimen.

$$X_1 \;=\; \frac{m_x V}{z_1^3}\, F_{x_1} \qquad\qquad Z_1 \;=\; \frac{3 m_z V_x}{z_1^4}\, F_{z_1}$$

$$X_2 \;=\; \frac{m_x V}{z_2^3}\, F_{x_2} \qquad\qquad Z_2 \;=\; \frac{3 m_z V_x}{z_2^4}\, F_{z_2}$$

where z_1 and z_2 are the distances to the lower and upper magnet

respectively (see Fig. II.1), m_x and m_z are the volume intensities of magnetization of the specimen, and V is its volume.

Then
$$X_1 - X_2 = \frac{m_x V F_{x_1}}{z_1^3} \left(1 - \frac{F_{x_2}}{F_{x_1}} \left(\frac{z_1}{z_2}\right)^3\right)$$

$$Z_1 - Z_2 = \frac{3 m_z x V F_{z_1}}{z_1^4} \left(1 - \frac{F_{z_2}}{F_{z_1}} \left(\frac{z_1}{z_2}\right)^4\right)$$

For convenience,

$$G_x = F_{x_1} \left(1 - \frac{F_{x_2}}{F_{x_1}} \left(\frac{z_1}{z_2}\right)^3\right)$$

$$G_z = F_{z_1} \left(1 - \frac{F_{z_2}}{F_{z_1}} \left(\frac{z_1}{z_2}\right)^4\right)$$

have been tabulated for the present magnetometer. The values given are accurate only for 2a near 3.5cm., but for other diameters a good approximation to the true value is

$$G_x \frac{F_x(a, z_1, h)}{F_x(1.75, z_1, h)}$$

and

$$G_z \frac{F_z(a, z_1, h)}{F_z(1.75, z_1, h)}$$

so

$$X_1 - X_2 = \frac{m_x V G_x}{z_1^3}$$

$$Z_1 - Z_2 = \frac{3 m_z V x G_z}{z_1^4}$$

Any difference in field, δH, between the two magnets is measured in terms of the deflection, N mm, of the light spot, which it produces.

The sensitivity, σ oe/mm, is defined from $\delta H = \sigma N$.

For the X component of magnetization, $N = \frac{X}{8}$

For the Z component of magnetization, $N = \frac{Z_m}{16}$

σ is determined for each measurement by measuring the deflection, n mm, produced by reversing a current, i mA, in the calibration coil, which produces a field difference of S oe/mA between the

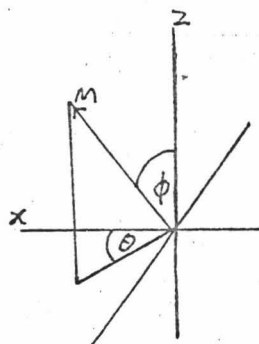magnets. S is calculated from the dimensions of the coil.

$$\sigma = \frac{2Si}{n}$$

so $\qquad M_x = \frac{Xz_1{}^3 Si}{4nVG_x}$ $\qquad\qquad M_y = \frac{Yz_1{}^3 Si}{4nVG_x}$

$$M_z = \frac{Zmz_1{}^4 Si}{24xG_z nV}$$

The directions of magnetization are as shown in the diagram.

$$\tan \theta = \frac{|m_y|}{|m_x|} = \frac{|Y|}{|X|}$$

$$\tan \phi = \frac{(m_y{}^2 + m_x{}^2)^{\frac{1}{2}}}{|m_z|}$$

$$= \frac{6x}{z_1} \frac{G_z}{G_x} \frac{(Y^2 + X^2)^{\frac{1}{2}}}{|Z|}$$

$$= \frac{6xG_z}{z_1 G_x} \frac{|Y|}{|Z| \sin\theta}$$

Let $\qquad\qquad p = \frac{|Y|}{G_x \sin\theta}$

$$q = \frac{|Z|z_1}{6x\ G_z}$$

so $\qquad\qquad \tan\phi = \frac{p}{q}$

The required quantities are the angles

$$\Theta = \mathrm{Tan}^{-1} \frac{m_y}{m_x} \qquad\qquad \Phi = \mathrm{Tan}^{-1} \frac{(m_x{}^2 + m_y{}^2)^{\frac{1}{2}}}{m_z}$$

The relation between Θ, Φ, θ and ϕ is

$X > 0$	$X > 0$	$X < 0$	$X < 0$
$Y > 0$	$Y < 0$	$Y < 0$	$Y > 0$
$\Theta = \theta$	$360 - \theta$	$180 + \theta$	$180 - \theta$

$\Phi = \phi$ if $Z > 0$ $\qquad\qquad\qquad\qquad \Phi = 180 - \phi$ if $Z < 0$

The intensity of magnetization, M, is

$$M = (m_x^2 + m_y^2 + m_z^2)^{\frac{1}{2}}$$

$$= \frac{Siz_1^3}{4nV} (p^2 + q^2)^{\frac{1}{2}}$$

If the value of $\theta < 15^0$, the expression

$$p = \frac{Y}{G_{\bar{x}}\sin\theta}$$

is not sufficiently accurate to use when calculating ϕ and M.
Instead, the expression

$$p = \frac{X}{G_{\bar{x}}\cos\theta}$$

should be used.

Measurement of Susceptibility

The vertical field H_{app}, induces a vertical magnetization
proportional to Z_{χ}

$$\chi = \frac{Si}{4nV} \times \frac{z_1^4 z_{\chi}}{6xG_zH_{app}}$$

The earth's field at Moore's Valley is 0.532oe, so if the vertical
cancellation current is reversed, $H_{app} = 1.064oe$.

Definitions of Distances (Refer Fig.II.1)

z_1 and z_2 are measured from the centre of the specimen.

h is the height of the specimen,

d is the diameter of the specimen,

$a = \frac{1}{2}d$ is the radius of the specimen,

b is the "datum", which is the distance from the bottom magnet to
the bottom of the sample in its lowest position.

c is the elevation of the sample, and is the length of the perspex
rods inserted in the sample holder.   In the lowest position c = 0.

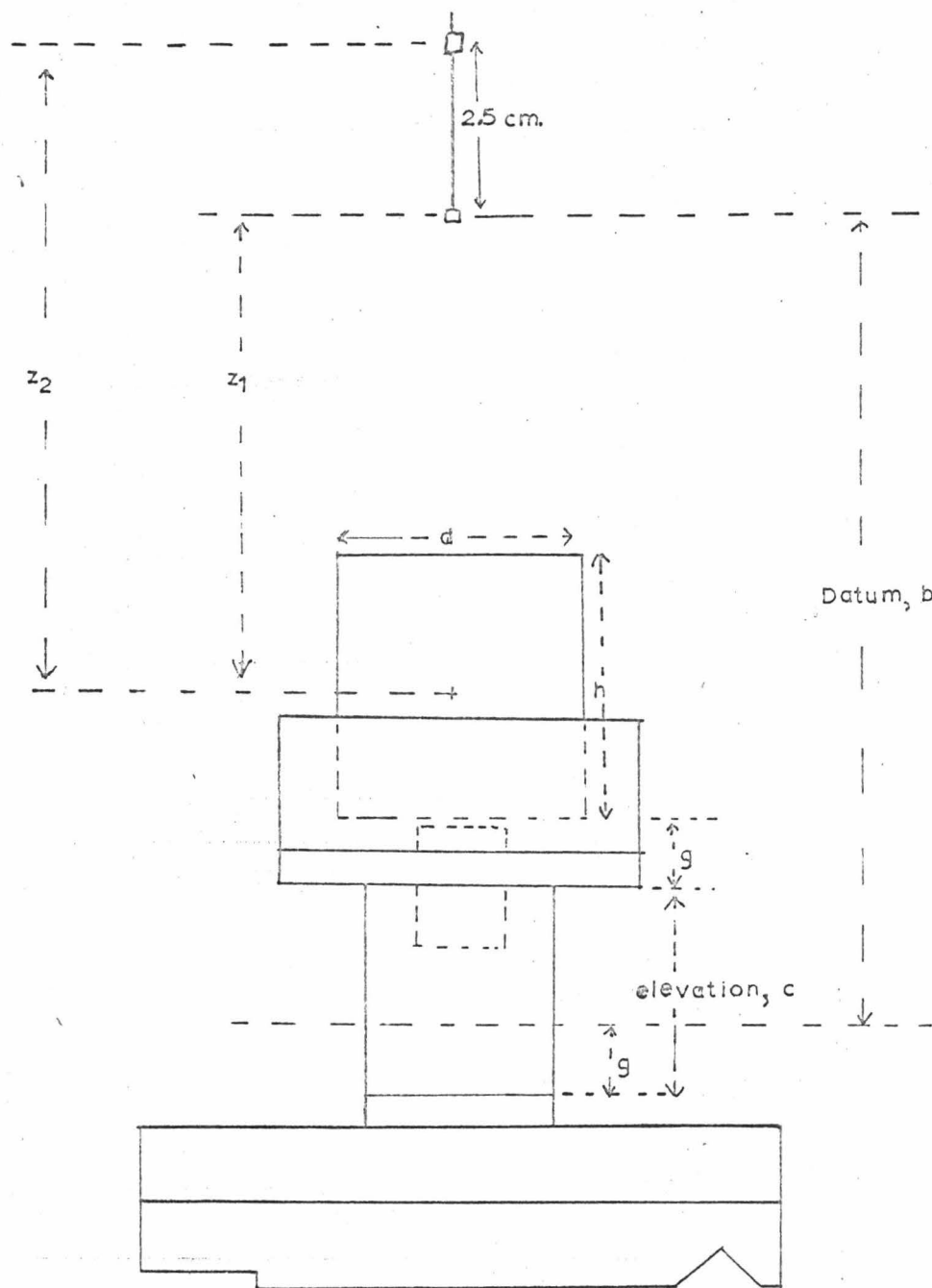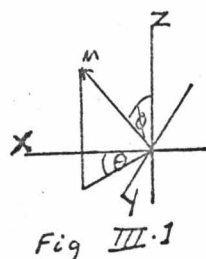$$z_1 = b - c - \tfrac{1}{2}h \qquad\qquad z_2 = z + 2.5.$$

FIG. II.1

USE OF A STEREOGRAM TO TRANSFORM COORDINATES

It is assumed that the direction of magnetization of the specimen
in its own coordinate system
has been measured, with the
angles θ and ϕ defined as
shown in Fig. III.1.

Fig III.1

The geographic coordinate system has axes N, E, and V, representing
north, east and vertical directions.
The relation between the two
coordinate systems is shown in
Fig. III.2.   The X axis was
originally horizontal, i.e., in
the N – E plane.

Fig III.2
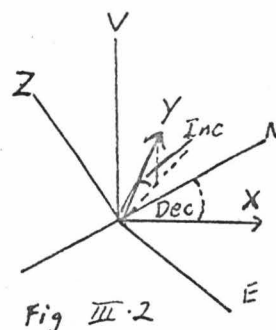
The required transformation is to rotate the specimen coordinate
system about its X axis until its Y axis is in the N – E plane, and
then rotate it about its Z axis, until the X, Y and Z axes are
parallel to the N, E and V directions.   This can conveniently be
done on a stereogram, thus:

1.   Make the centre and zero azimuth on the transparent paper.

2.   Put a mark on the paper at the point on the edge of the
      stereogram, corresponding to the declination of the X axis,
      as recorded in the field book, this angle being measured
      clockwise.   This is now used to define the sample coordinate
      system on the paper.

3. Rotate the paper until the X axis lies on the 0 - 180° line of the stereogram.

4. Mark the position of the magnetization vector in sample coordinates on the paper, measuring θ anti-clockwise and ϕ downwards from vertical. To do this, a mark is put $\theta°$ anti-clockwise from X, then the paper is rotated until this mark lies on the 90° or 270° mark of the stereogram. The required point is then $\phi°$ from the centre.

5. Return the paper so the X direction is on the 0° - 180° line.

6. The rotation of the magnetic vector about the X direction is performed by following the small circle lines the number of degrees equal to the dip of the plane as recorded in the field book, the rotation being performed in a clockwise direction, when looking in the + X direction (i.e., the vector goes from pointing left, to upwards, to pointing right, with the + X direction to the top of the paper). This sense is required because the previously horizontal X - Y plane is now being made to dip in the positive direction.

   The point obtained by this rotation is the magnetization direction, since the rotation about a vertical axis was in effect performed in steps 2 and 3.

7. The coordinates of this point are found by rotating the paper until the point lies on the 0 - 180° axis. The dip can be read directly, off the 0 - 180° line, and the declination is found from the position of the zero mark, reading clockwise.

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