ASSEMBLY OF A SUSCEPTIBILITY MEASURING EQUIPMENT & STUDIES OF MAGNETIC SUSCEPTIBILITY OF ROCKS & ORES

A DISSERTATION
SUBMITTED IN PARTIAL FULFILMENT
OF THE REQUIREMENT FOR THE DEGREE OF
M. Sc. Tech.
IN APPLIED GEOLOGY

By
PRAKASH CHANDRA PARAKH

DEPARTMENT OF GEOLOGY & GEOPHYSICS
UNIVERSITY OF ROORKEE
ROORKEE (INDIA)
1965-66

V.K. GAUR,
M.Sc., Ph.D.(Lond), D.I.C.,
F.R.A.S.,

READER IN GEOPHYSICS

UNIVERSITY OF ROORKEE
ROORKEE

Dated 23rd March, 1966.

C E R T I F I C A T E

CERTIFIED that the dissertation entitled ' Assembly of a susceptibility measuring equipment and studies of magnetic susceptibility of rocks and ores" being submitted by Shri Prakash Chandra Parakh in partial fulfilment for the award of the Degree of M.Sc. Tech. in Applied Geology of the University of Roorkee, is a record of the student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

VKGaur

Reader in Geophysics,
Department of Geology & Geophysics,
University of Roorkee.

ACKNOWLEDGMENTS

The author thanks Dr. R.S. Mithal, Head of the Department of Geology & Geophysics for making the necessary laboratory facilities available to him for the present work.

He thanks Dr. V.K. Gaur under whose guidance the work was completed. He also thanks Dr. K.K. Singh and Shri O.P. Verma for their help.

He is obliged to Mr. G.S. Malhotra of Central Building Research Institute for his help in having the samples cut, Shri R.S. Chaturvedi and Shri Sher Bahadur for helping him take the photographs and Mr. Prakash for typing the manuscript.

ABSTRACT

A complete equipment for measuring the susceptibility of rocks and ores has been assembled and calibrated. Susceptibilities of 16 samples, each in the form of one inch cube, has been determined. Of these, three samples are of magnetite ore, seven samples contain varying amounts of pyrrhotite, chalcopyrite, pyrite and magnetite, and six samples are of rocks from intermediate to basic composition. Ferromagnetic mineral content of these samples has also been determined. A correlation has been made between the susceptibilities and the magnetite content of the rocks. The susceptibilities of chalcopyrite-pyrrhotite samples were found to increase with pyrrhotite content as excepted, but no correlation could be made owing to the presence of some magnetite in these samples.

CONTENTS

CHAPTER I

INTRODUCTION

The knowledge of magnetism can be said to have commenced with the discovery of the north seeking character of lodestone (Fe_3O_4). However, very little attention was given to those naturally magnetised bodies, which were spread over many parts of the earth's surface, and it seems that physics of magnetism of matter developed almost independently of this parent discovery.

The first significant study towards the magnetization of rock bodies was made by William Gilbert[1-i] in 1600 A.D. who imagined the earth as a giant magnet. The magnetic compass was first used round about 1640 for prospecting of iron ores in Sweden. Amongst the later examples of magnetic prospecting may be cited those conducted in the Michigan iron district by T.B. Brooks in 1873 and by H. Smock in 1875.

Melloni[2-i] (1853) of Italy first measured the remanent magnetisation of rocks, and suggested that the permanent magnetisation of volcanic rocks i.e. the thermoremanent magnetisation (T.R.M.) is imparted to them by the inductive action of the earth's magnetic field at the time of their cooling. Nakamura in 1912 proved through careful experiments, that a strong remanent magnetisation could be aquired by volcanic rocks, cooling in the geomagnetic field, and that the direction of this magnetisation coincided with the direction of the prevailing geomagnetic field.

The discovery of the famous iron-quartzite ore deposit of Kurak[2-ii] in the U.S.S.R. as a result of magnetic prospecting aroused a great interest in the study of the magnetic properties of rocks. Thus the concept of the magnetic susceptibility or permeability of rocks was first established.

A systematic study of the magnetism of rocks from the view point of basic physics developed steadily from about 1925 onwards, especially by the efforts of Konigsberger and Chevallier.[2-iii] In the 1930's Mc Nish and J Johnson measured the weak remanent magnetisation of sediments, and produced the first systematic studies of the depositional remanent magnetisation (D.R.M.) of sediments, as well as of paleomagnetic data on a continuous series of samples.

In the last two decades rock magnetism has been a subject of extensive investigation not only in connection with the paleomagnetic studies and magnetic prospecting, but also as a tool for other geological and geophysical problems. Many interesting developments have already been made in this field and the scope of its application can hardly be said to have exhausted yet.

ROCK - MAGNETISM IN GEOLOGICAL PROBLEMS:[3-i] With Mc Nish's study of the D.R.M. in sediments, it was established that most of the rocks on earth possess some amount of magnetism, which can be attributed to their ferromagnetic mineral content. It was also established that the directions of remanent magnetisation of rocks represent the directions of the earth's magnetic field at the time of their formation. These observations opened the possibility of rock magnetism being applied to some global problems such as the continental drift, the wandering of poles, the expanding of the earth, deformation of the continents and orogenic belts, as well as to the small scale problems of immediate interest to geologists. The latter constitutes problems such as, stratigraphic corelation, determination of thickness of an overburden, delination of the attitude of layered rocks, magmatic differentiation, distinction between sills and lava flows, geological thermometry and petrofabric analysis.

ROCK-MAGNETISM IN MAGNETIC PROSPECTING:- The discovery of the Kursk magnetite deposit made it clear that provided there is a significant contrast between the magnetic susceptibility of a buried ore-body and that of the surrounding rocks, it is possible to locate the ore body with the help of a magnetometer.

The magnetization of a rock in situ can be expressed as the sum of the susceptibility magnetization kH_o induced by the geomagnetic field H_o, and the natural remanent magnetization. J_n, aquired by the rock during its formation.

$$\text{or } J = kH_o + J_n \qquad \text{————————}(1.1)$$

If J_n in a particular area can be assumed to be constant, the variation in J will be only due to a variation in k.

Determination of the magnetic susceptibility of rocks is therefore of fundamental importance in magnetic prospecting. Numerous methods have been devised to determine susceptibility of rocks, both in the field and in the laboratory.

The present work includes results of susceptibility determinations of rocks and ore samples in a magnetic field of the same order as that of the earth by means of an instrument designed and fabricated in the laboratory. The instrument is similar to that used by Bruckshaw with some modifications.

The experiments intended for this dissertatiom were of two kinds. The first includes the determinations of (a) susceptibility of some rock samples which were available in the department, and (b) their magnetite content and the corelation of these two results.

The second part of the investigations were intended to determine the complex susceptibility of rocks containing both conducting and magnetic materials. For this purpose, rocks from Madan Kudan section of the Khetri

Copper Belt (Rajasthan) were collected. These rocks contain varying amount of Chalcopyrite and Pyrrhotite. The determination of the complex susceptibility of rocks containing both magnetic and conducting materials was planned in the hope that this might help resolve the ambiguity in electromagnetic anomalies produced by these bodies.

The percentage of magnetic or conducting material was determined by visual inspection of polished samples under the microscope and by counting with the help of a SWIFT COUNTER.

CHAPTER II

MAGNETIC PROPERTIES OF MATERIALS

It has been long observed that certain materials when placed in a magnetic field become magnetised. Such materials are said to be magnetic. This condition is also described by saying that a magnetic flux is established in the body or, magnetic lines force their way into it. The flux per unit area normal to the surface, is called flux density or magnetic induction.

$$\text{Thus} \quad B = \frac{\Phi_n}{A} \quad \text{--------------} (2.1)$$

Where B is the induction, Φ_n the total normal flux and A, the area of cross - section. The c.g.s. unit for magnetic induction is gauss.

MAGNETIC PERMEABILITY :- The ease with which a magnetic flux can be established in a body, can provide a physical measure for the magnetism aquired. One such quantity is the ratio of the total flux through a unit cross section of the body to the magnetizing field. This is called the magnetic permeability. If H is the magnetizing field, the permeability can be written as

$$\mu = \frac{\Phi_n/A}{H} = \frac{B}{H} \quad \text{--------------} (2.2)$$

INTENSITY OF MAGNETIZATION : - The intensity of magnetisation (J) of a material is a measure of its magnetic strength. It can be expressed as the magnetic moment per unit volume, or the equivalent quantity polestrength per unit area.

$$J = \frac{M}{V} = \frac{mL}{A.L} = \frac{m}{A} \quad \text{--------------} (2.3)$$

where M is the magnetic moment, V the volume, A the area of cross section and L, the length of the material. The unit of J will be called an oersted.

SUSCEPTIBILITY : - Intensity of magnetization aquired by a substance when placed in a magnetic field depends upon the strength of the magnetic field and on the nature and physical condition of the substance. When the latter are not varying the intensity is found to be proportional to the magnetising field H.

$$J = kH \text{ ---------------- } (2.4)$$

The constant of pooportionality k is termed Magnetic susceptibility.

VOLUME AND MASS SUSCEPTIBILITY : - The magnetic susceptibility of a substance can be referred either to unit volume or to unit mass. According to definitions given above $J = M/V$ and the volume susceptibility $k = J/H$.

To express susceptibility in relation to mass of a perticular substance, another term i.e. specific magnetization will have to be introduced which is defined as the magnetic moment per gram. Thus, the specific magnetization $Q = M/W$, and mass susceptibility k' will be given by,

$$k' = \frac{Q}{H} \text{ ------------------ } (2.5)$$

$$\text{Thus } Q = \frac{M}{W} = \frac{M}{V\rho} = \frac{M.L}{AL\rho} = \frac{m}{A\rho} = J/\rho \text{ ------- } (2.6)$$

$$\text{Hence } k' = \frac{J/\rho}{H} = k/\rho$$

$$\text{or} \quad k'\rho = k \text{ ------------ } (2.7)$$

Thus volume and mass susceptibility are related in a paradoxial manner, i.e. to obtain volume susceptibility, the mass susceptibility is multiplied by the specific gravity k' is usually represented by χ

RELATION BETWEEN PERMEABILITY AND SUSCEPTIBILITY : - When a magnetic material of volume V is placed in a magnetic field H, it will aquire some magnetization by induction. The quantity M/V as defined previously is called the intensity of magnetization J. The total flux in the material will be the sum of the flux produced by the field H, and that arising from the magnetization induced in the body. As a unit magnetisation gives rise to a flux equal to 4 ,M/V units of magnetization will contribute a flux equal to $\frac{4\pi M}{V}$. Hence

$$\frac{\phi_n}{A} = H + 4\pi M/V \text{ ----------- } (2.8)$$

Where $\frac{\phi_n}{A}$ is the total normal flux per unit area i.e. B.

$$\text{Hence } B = H + 4\pi\frac{M}{V} = H + 4\pi J.$$

$$= H + 4\pi kH = H(1+4\pi k)$$

$$\text{or } \frac{B}{H} = 1 + 4\pi k$$

$$\text{or } \mu = 1 + 4\pi k \text{, and } k = \frac{\mu - 1}{4\pi} \text{ ----------- } (2.9)$$

Whilst permeability describes the amount of flux through a unit cross section of a substance, relative to the flux through the same cross section of free space, susceptibility describes how strong a magnetisation a given magnetizing field will produce in a substance.

It is apparent that these two quantities, relate to somewhat different aspects of magnetic characters of materials. These quantities have specific applications in magnetic exploration. The magnetic strength and hence the detectability of a magnetic body such as a dyke depends upon the susceptibility of the rock, forming the dyke or more precisely upon the contrast in susceptibility of this rock from that of the surrounding rocks.

DEMAGNETIZING FACTOR : - When a magnetic field is applied to a body, free magnetic poles appear at both ends of the material producing a field in a sense, which opposes the applied field. Thus the effective magnetic field Heff differs appreciably from the applied external field H_{ex}. The demagnetising field H_d arising from the free poles is generally not uniform and depends upon the distribution of magnetization and the shape of the ferro - magnetic elements. However as long as J is uniform, H_d is proportional to J and the direction of the former is opposite to that of the latter. Thus,

$$H_{eff} = H_{ex} - H_d \quad \text{------------} \quad (2.10)$$

$$\text{and} \quad H_d = NJ \quad \text{------------} \quad (2.11)$$

Here N will be appropriately called the demagnetising factor and will depend upon the shape of the body.

<u>ORIGIN OF MAGNETISM</u>:- The origin of the magnetic moments of materials can be traced to the moment of the atoms of which they are composed. Revolving electrons inside the atoms, being equivalent to a circular current behave like a magnetic shell or a tiny magnetic doublet possessing a magnetic moment.

The flow of a current i in an electric circuit of face area A, produces a magnetic field equal to that produced by a magnetic shell of moment Ai. Electrons each of charge e (e.m.u.) revolving with an angular velocity w (= v/r), about the positive nucleus of its atom would constitute an electric current of strength i = nerw, where n is number of electrons per centimeter length of the circuit.

Now since r is the radious of the circular circuit number of electrons per centimeter will be given by $n = \frac{1}{2\pi r}$.

$$\text{Hence } i = \frac{ewr}{2\pi r} = \frac{ew}{2\pi} \quad \text{e.m.u.}$$

Thus the magnetic moment of a rotating electron considered as a magnetic shell is

$$M = Ai = \pi r^2 \frac{eW}{2\pi} = \frac{r^2 ew}{2}$$

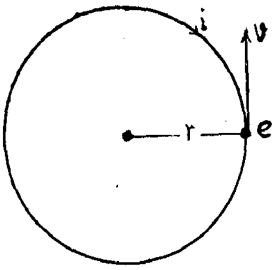


FIG.1

As seen in figure 1, an electron moving in an anticlockwise direction constitutes a current flowing in a clockwise direction. Hence the magnetic moment M is directed perpendicularly to the plane of the paper and into it.

Further, if m_0 is the static mass of an electron its motion gives an angular momentum equal to $m_0 r^2 w$, which is perpendicular to the plane of the paper, and directed upwards. Thus magnetic moment per unit momentum

$$b = -\frac{M}{m_0 r^2 w} = -\frac{r^2 ew}{2m_0 r^2 w} = -\frac{e}{2m_0} \quad \text{————————}(2.12)$$

The negative sign implies that the magnetic moment is directed opposite to the angular momentum. In order for the electron to remain in the orbit, the nucleus must excert a force of attraction on the electron, which will furnish the necessary centripetal force $mw^2 r$.

According to Bohr's theory, angular momentum of an electron can have only definite values, which are multiples of $h/2$, where h is the Plankk's constant. Hence magnetic moment corresponding to angular momentum $M = \frac{ph}{2}$ is

$$m = p \frac{eh}{4 m_0} \quad \text{————————————}(2.13)$$

where p is identified as the asimuthal quantum number, and has values 1,2,3 ..... etc. only.

Hence the smallest amount of magnetic moment of an orbital motion of an electron is given by

$$\mu_B = \frac{eh}{4\pi m_0} = \frac{1.6 \times 10^{-20} \times 6.62 \times 10^{-27}}{4 \times 3.14 \times 9.10 \times 10^{-28}} = 0.9274 \times 10^{-20} \text{ emu}$$

This quantity is called a 'Bohr Magneton' and is the smallest unit of magnetic moment available from a fundamental particle.

The ratio of the angular momentum N of the orbital motion of an electron to the magnetic moment m is given by

$$\sigma_0 = \frac{N}{m} = \frac{2m_0}{e}$$

On the otherhand the ratio of the angular momentum of spin to the magnetic moment is $\sigma_s = \frac{m_0}{e}$

That is, the ratio in respect of the spin is half of that in respect of its orbital motion.

Generally speaking, the magnetic moment of an atom is caused either by the spin or by the orbital motion of electrons, or by both of them. Hence the ratio of the magnetic moment to angular momentum of electrons within an atom can be expressed by

$$\sigma = \frac{2m_0}{e} \cdot \frac{1}{g} \quad \text{where } 1 \leq g \leq 2 \text{ ———————— (2.14)}$$

The quantity 'g' is the Lande's factor which gives the rate of contribution of the spin and the orbital motion to the magnetic moment of atoms.

CLASSIFICATION OF MATERIALS

Stern and Gerlach verified it experimentally that all atoms possess a magnetic moment. Therefore, all materials fundamentally composed of atoms should be expected to be magnetic. However, it has been found that different materials behave very differently, when placed in a magnetic field. On the basis of this behaviour materials will be classified magnetically as follows:-

DIAMAGNETIC:$^{4-1}$ - If a magnetic field of flux density B is applied, perpendicular to the plane of the paper and upwards in figure 1, it will exert a magnetic force F_m equal to $ev \times B = ewrB$, which according to Fleming's left hand rule will be directed radially inward along the radius vector r. Thus the orbital radius of the electron is reduced and its angular velocity is increased to w_1, for a given B. The total force which the attraction of the nucleus must now furnish is $m_0 w_1^2 r - e w_1 r B$.

Hence $m_0 w^2 r = m w_1^2 r - e w_1 r B$.

or $w_1 - w = \Delta w = \dfrac{eBw_1}{m_0(w_1+w)}$

However, even for the strongest magnetic fields which are achieved in the laboratory w_1 will differ but little from w, and can therefore, be taken to be equal to d it approximately

Therefore, $\Delta w = \dfrac{e}{2m_0} B$ ——————(2.15)

Δw is positive in this case. If in figure 1, the electrons were moving in the clockwise direction (i.e. current in an anticlockwise direction) The angular velocity of the electron would have decreased by $\dfrac{e}{2m_0} B$

On account of this change in angular velocity, the angular momentum is made to precess (Larmer precession), with a velocity of precession equivalent to w. In fact all electron orbits in the atom will precess forming a large merry go round, resulting in an additional orbital angular momentum Δp of the whole atom, given by $\Delta p = I\Delta w$, where I is the effective moment of inertia of all the electrons in the atom. Hence

$$\Delta p = I \frac{e}{2m_0} B \text{ ——————(from 2-15)}$$

From equation (2-12), we know that this change in angular momentum Δp will result in a change in the orbital magnetic moment mor, where

$$\begin{aligned} \Delta m_{or} &= -(e/2m_0)\Delta p \\ &= -I(e/2m_0)^2 B \text{ ————(2-16)} \end{aligned}$$

This Δm_{or} can be interpreted as an induced magnetic moment, whose direction is opposite to that of the applied magnetic field as shown by the negative sign.

In materials whose atoms have a net zero magnetic moment in the absence of an external magnetic field, the spin and orbital magnetic moments of the electrons add vectorially to zero. When a magnetic field is applied the induced magnetic moment of each atom is given by (2-16), and it is in the direction opposite to that of the applied field. Hence, the resultant flux density in the vicinity of the atom is smaller than that due to the applied field alone, and thus smaller, than it would have been if the material had been absent, and the space empty. Evidently such materials will exhibit a negative susceptibility and are called ' diamagnetic'.

The diamagnetic susceptibility is given by

$$k = -N \frac{e^2}{6m_0} \quad r^2_{oi} \text{ ——————(2.17)}$$

where N and r_{oi} denote respectively the number of atoms in a unit volume and the radius of the orbit of an electron from the centre of the nucleus.

The above relation shows that diamagnetic susceptibility is independent of the temperature. The theoretical considerations also show that although, temperature brings about agitation of atoms as a whole, it does not affect motion within the atoms.

PARAMAGNETIC[4-ii, 2-v] ; - The above discussion shows that diamagnetism is fundamental to all materials. However, in certain materials, diamagnetic effect is masked by other stronger phenomena of paramagnetism and ferromagnetism.

If the magnetic moment of electron spins and orbital motion in atom of some materials do not add to zero, the atoms will have a small net magnetic moment, and will consequently experience a torque if a magnetic field is applied. The tendency of this torque is to align them in the direction of the field, which will be the state of minimum potential energy. The total magnetic field will thus have a greater magnetic flux density. This effect is called paramagnetism, which, although the diamagnetic effect is still present, predominates, being stronger.

Paramagnetic materials have therefore, a small positive susceptibility given by

$$k = \frac{\mu_0^2 N}{3kT} = \frac{C}{T} \quad \text{———————} (2.18)$$

The intensity of magnetization for such materials is given by

$$J = \frac{N \mu_0^2 H}{3kT} \quad \text{———————} (2.19)$$

where μ_0 is the magnetic moment per atom, N the number of atoms in a unit volume k , the Boltzmann's constant and T, the absolute temperature. This is Curie's law and the constant $C = \frac{N\mu_0^2}{3k}$ is called the Curie constant.

The above law shows that paramagnetic susceptibility is inversely proportional to the absolute temperature, which promoting thermal agitation tends to produce a random orientation of atoms, thus decreasing the paramagnetic susceptibility.

4-ii, 2-v

FERROMAGNETIC :- In ferromagnetic materials, interaction between neighbouring atoms is so strong that the magnetic moment of all atoms tend to align themselves against the disturbing force of thermal agitation. According to experiments, the Lande's factor 'g' of ferromagnetic atoms is almost 2 in most cases, indicating that their magnetic moment originates chiefly from the spin of electrons. It is to be noted that magnetic moments of the orbital motion or of the spin, belonging to the closed shells should be nullified as a whole. The magnetic moment of atoms is therefore contributed by the electrons belonging to the unclosed shells. Energy of interaction among neighbouring atoms consists chiefly of (a) magnetic energy between electrons and (b) the exchange energy between them, which concerns the direction of spin of the related electrons, as was derived quantum mechanically by Heisenberg.Of these, the exchange energy usually predominates.

If the total energy of the state where in the spin of the electrons in unclosed shells of the neighbouring atoms is parallel (controlled chiefly by the exchange energy) attains the minimum value, the magnetic moment of these atoms become parrallel, producing the ferromagnetic character.

The above mentioned effect of exchange energy can be replaced by a molecular field, introduced by Weiss, in his classical theory of ferromagnetism.

i.e. $H'_{eff} = H_{ex} + WJ$ —————(2.20)

where H_{ex} here is given by H_{eff} of equation (2-10), J is the intensity of magnetization, and W a constant, WJ showing the assumed molecular field. If we put $H = (H_{ex} + WJ)$ in equation (2.19) it becomes

$$J = \frac{N \mu_0^2 (H_{ex} + WJ)}{3\ T} \text{ ———————— } (2.21)$$

$$\text{or} \quad J = \frac{N \mu_0^2 H_{ex}}{3k\left(T - \frac{N \mu_0^2 W}{3k}\right)}$$

Hence ferromagnetic susceptibility

$$k = \frac{J}{H_{ex}} = \frac{N \mu_0^2}{3k\left(T - \frac{N \mu_0^2 W}{3k}\right)},\ \frac{C}{(T - \psi)} \text{ ————— } (2.22)$$

This is Curie - Weiss Law. The temperature ψ is known as the Curie temperature. Equation (2.22) shows that ferromagnetic materials become paramagnetic at temperatures higher than the Curie temperature .

It $H_{ex} = 0$ in equation (2.20), $H'_{eff} = WJ$, showing that there exists magnetization inspite of there being no external magnetic field. This magnetization is called spontaneous magnetization.

<u>Magnetocrystalline Anisotropy</u>$^{2-V}$: - A significant point about ferromagnetic materials is that they are crystals, having a regular lattice madeup of atoms. Consequently various magnetic characterstics of crystals depends on their direction, though the special case of an isotropic character of material is assumed in Weiss Theory. For simplicity we consider a crystal of iron which is a body centred cubic crystal (Fig. 2 a). Figure shows directions 100, 110 and 111 in an iron crystal. Figure (2b) and (2b) are plots between H and J for iron and magnetite respectively. For iron we see that 100 is the direction of easiest magnetization, while 111 is the direction of the most difficult magnetisation. The reverse is the case with magnetite for which 111 is the direction of easiest magnetization, and 100 that of most difficult magnetization. This anisotropic character of magnetization in ferromagnetic crystals is called magnetocrystalline anisotropy, and the difference of magnetization energy between the axis of

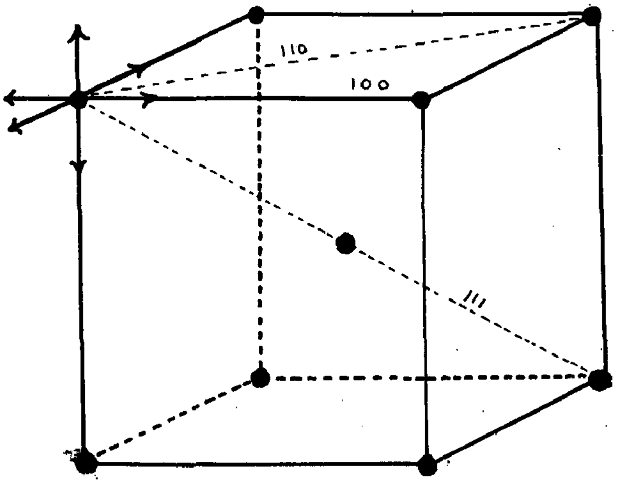


FIG. 2a BODY CENTRED CUBIC IRON CRYSTAL

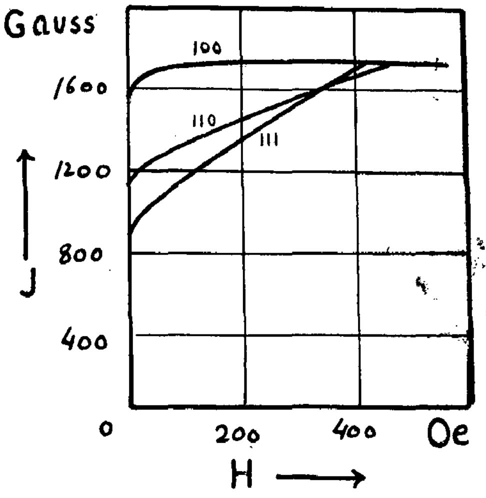


FIG.2b MAGNETIZATION CURVES OF IRON (AFTER HONDA AND KAYA)

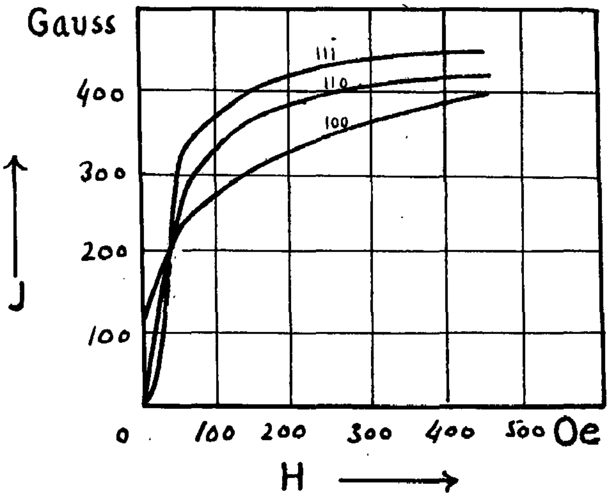


FIG.2c MAGNETIZATION CURVES OF MAGNETITE (AFTER WIESS)

the most difficult magnetization and that of the easiest one is defined as magnetocrystalline anisotropic energy.

<u>Domain Structure of Ferromagnetics</u>:- [2-vi,3-iii] Inspite of the existance of spontaneous magnetization, ferromagentics, cooled from a temperature higher than their Curie temperature in a field free space, have no magnetization. To explain this it is assumed that the spontaneous magnetization applied to domains within ferromagnetic crystals. Each domain is magnetized to saturation eventhough no external field is applied. Hence, within each domain, uncompensated electron spins have their magnetic moments, aligned parallel to each other due to strong interatomic forces (exchange energy). If, however exchange energy were the only one effective a domain would extend over a whole crystal, but there is another effect, which tends to discourage formation of large domains. It is magnetostatic energy, which has a significant magnitude, owing to the appearence of free magnetic poles. This effect tends to minimize the potential energy, within the system and splits the domains into parts with different directions of amagnetization. The actual domain size represents a compromise between the disturbing and aligning forces. Size of individual domains range from 10^{-2} to 10^{-6} c.m.^{3} The transition layer between two oppositely magnetized domains is called ' Bloch wall'.

According to the domain theory the direction of easiest magnetization in a crystal is the direction of actual magnetization of each domain, provided that there is no external magnetic field and the material is not strained. In an iron crystal there are six directions of easy magnetization, (counting both senses along a cubic edge), as seen in figure 2 a. In an unmagnetized crystal, domains are magnetized along these directions, more or less at random, and the crystal as a whole produces no magnetic flux. This is shown in figure 3a, for a single iron crystal, where the domains have been idealised to cubes. The resultant magnetic moment in each domain is represented by an arrow parallel to 100 direction. The crystal as a whole has no magnetic flux density.

On applying a weak magnetic field H, as shown in the diagram, those domains which are most nearly parallel to the applied field H, grow in volume at the expense of their neighbours (Fig. 3 b) resulting in a net magnetic moment in the direction of the applied field. If the field is removed, the boundaries will go back to their original configuration. This is called reversible boundary displacement, and it is represented by part A of the curve in figure 3 e.

If the field becomes stronger, the boundaries continue to change, but now in an irreversible way and the flux density in the crystal increases, repidly for small changes in H, till all magnetic domains rotate and become parallel to 100, as shown in figure 3 c. This is represented by part B of the curve in figure 3 e. As it is difficult to rotate, the direction of magnetisation within the domain, itself, a relatively large change in H is required to produce a certain change in B. As the field is further increased magnetic moments of domains gradually rotate until all the magnetic moments are parallel to the applied field, as shown in figure 3 d, causing saturation. This situation is represented by part CD of the curve in figure 3e.

Ferromagnetic materials are made up of a large number of crystals, which are rendomly oriented. Each little single crystal contains many domains, and these domains and crystals are randomly oriented to give a net flux density equivalent to zero as seen in figure 3f.

Hysteresis[4-iii] : - As has been discussed already, if we continuously increase the magnetising field H, the intensity of magnetisation reaches, a saturation value Js, when all domains are aligned with their magnetic moments parallel

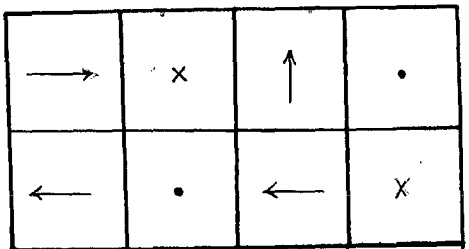


FIG.3a

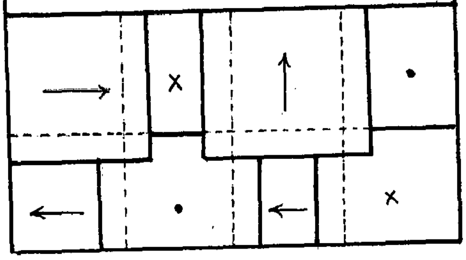


FIG.3b

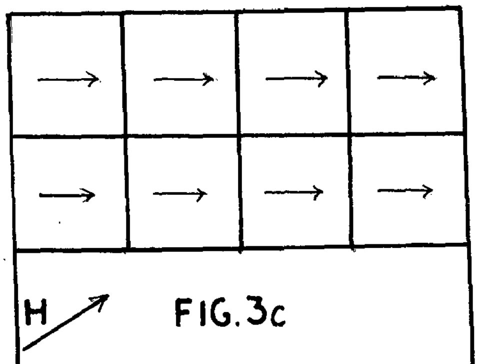


FIG.3c

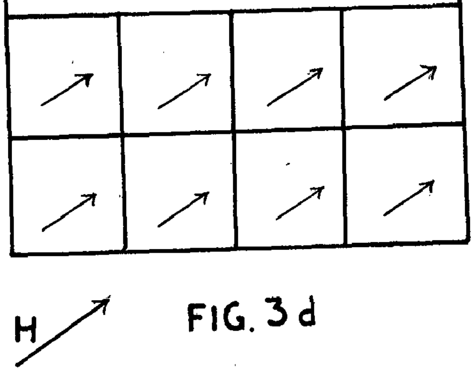


FIG. 3d

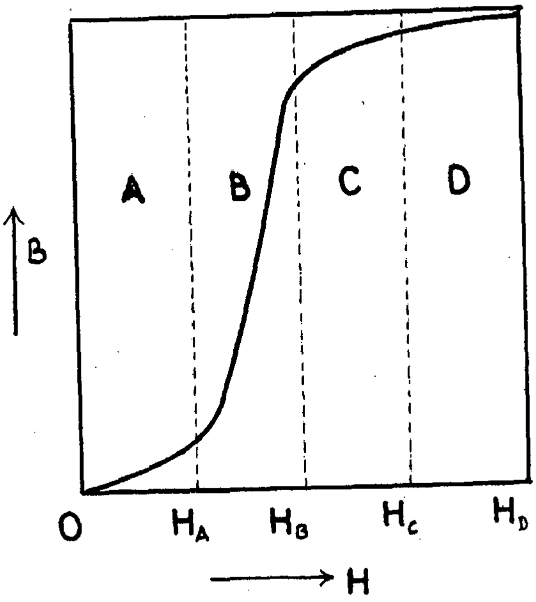


FIG.3e MAGNETIZATION CURVE OF FERROMAGNETICS

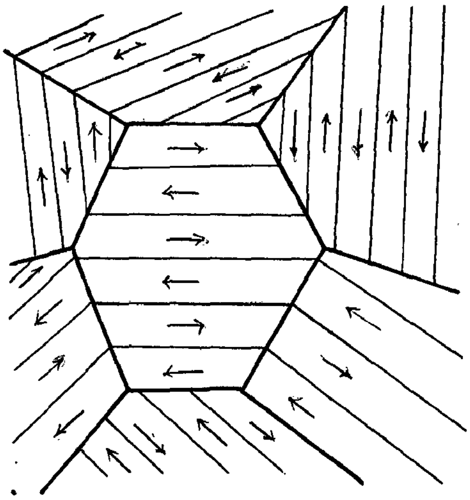


FIG.3f SCHEMATIC DOMAIN ARRANGEMENT IN A POLYCRYSTALLINE SPECIMEN

to the applied field. After this there is no increase in J for any increase in H. On decreasing H, however, it is found that magnetization does not retrace, the path followed, by it when H was increasing. Instead it follows a curve (CD) shown in figure 4. Thus when H has been completely removed the intensity of magnetization, has still a positive value, equal to J_r, This is called residual magnetism, rententivity or remanence.

If the direction of H is now reversed, the curve DEF is obtained, and residual magnetization J reaches to zero, for a certain value of $H = - H_c$ called the coercive force. A further decrease in the magnetic field, results in a negative saturation value at F. Again repeating the cycle of H in its original form, curve FGHC is traced. This phenomenon of the intensity of magnetization lagging behind the magnetizing force is called magnetic hysteresis, and the closed curve CDEFGHC is called the hysteresis loop. Hysteresis is characterstic of all ferromagnetic materials, and it is due to the time lag involved in the rotation of domains in these materials, in the direction of the applied field.

<u>Magnetostriction:</u>[2-vii] - Another factor concerning ferromagnetics is the phenomenon of Magnetostriction, Magnetization of ferromagnetics is usually accompanied by their mechanical deformation. Figure 4 shows the rate of elongation and contraction, along the three principal axes of a single crystal of iron, as dependent upon its magnetization along the respective axes.

Magnetostriction is interpreted as strain in the crystal form owing to magnetic interaction, among atoms forming the crystal lattice. On application of an external magnetic field, the elastic deformation of the crystal lattice, is accompanied by a change in magnetocrystalline anisotropy

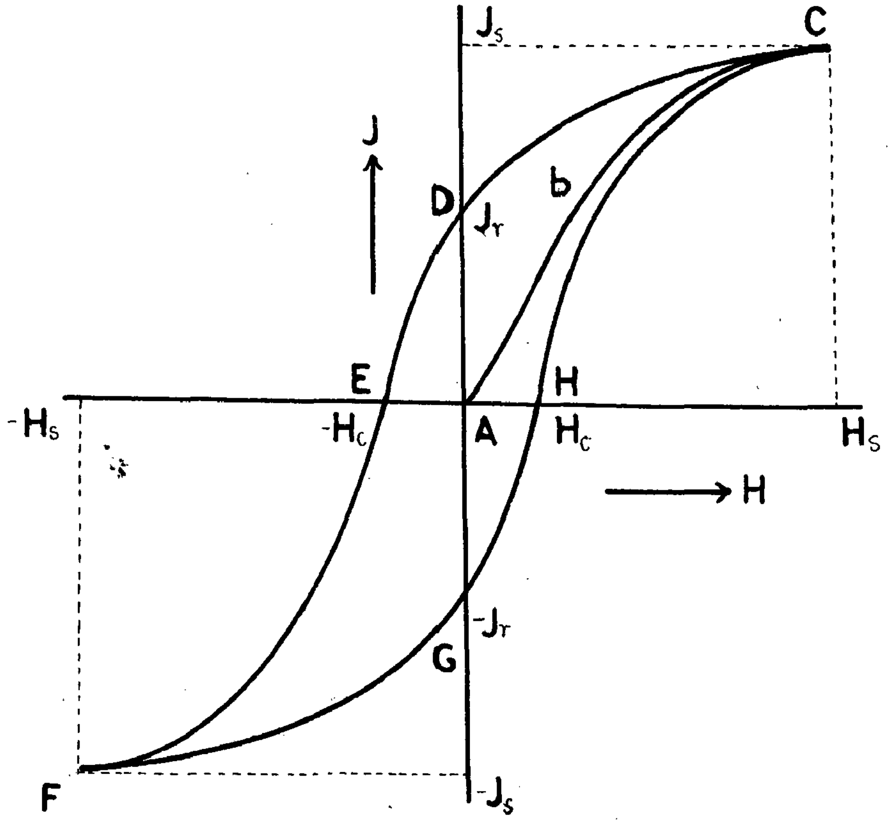


FIG. 4 HYSTERESIS CURVE OF FERROMAGNETICS

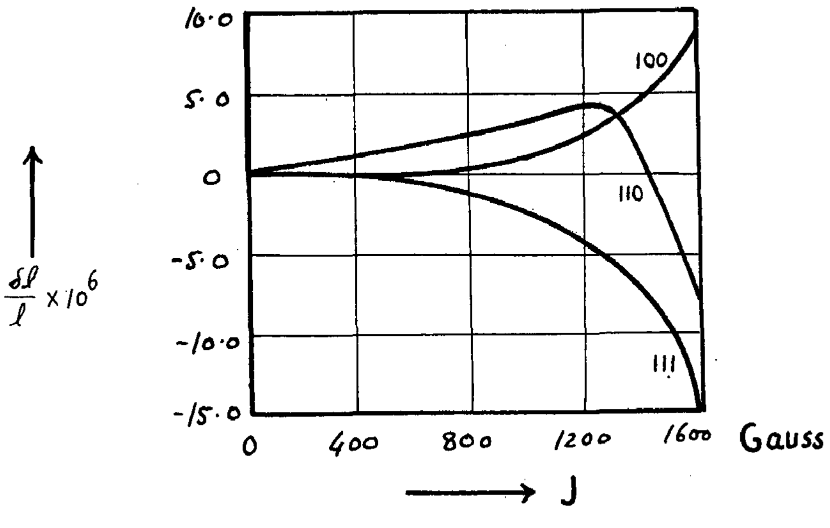


FIG. 5a MAGNETOSTRICTION OF IRON

(AFTER KAYA AND TAKAKI)

energy as well as the magnetoelastic energy. Hence magnetostriction takes place, so that there is a minimum change in the sum of these different kinds of energies. Thus magnetisation of ferromagnetics is strongly effected by elastic strain or stress, and if there is some internal stress in crystals, for example due to presence of some impurity, its magnetization curve will change.

Effect of Grain size[5-i]:- It has been said above that the ferromagnetic crystals contain large number of domains, If however grains become smaller than 10 (mincrons) diameter, the number of domains become very small and domain boundaries find themselves more deeply trapped. Thus, the magnetization induced by an external field in fine grained ferromagnetic material is rather less than what would be induced in a coarse grained material, of equivalent concentration. Moreover, when the field is removed, a strong residual magnetization remains.

When grainsize is so small as to form monodomain grains, domain wall movement ceases, to be a significant factor in determing magnetic properties and magnetisation occurs only by rotation of the unoriented grains. Since strong energy barriers exist between the different directions in which magnetization, is stable, strong fields are required to produce a change. Also once changed, the magnetization, does not return to its original state. However these grains are extremely susceptible to thermal agitation, and magnetic properties of such grains are controlled by interplay between the thermal agitation and the grainsize.

Neel has proved this theory experimentally and has shown that susceptibility of monodomain grains increases while remanence decreases with decreasing grain size untill a critical value is reached, when the thermal agitation, maintains the magnetization in completely free state. In this condition, a material behaves as a paramagnetic substance, and it is called superparamagnetic. Such grains are submicroscopic in size and are only barely

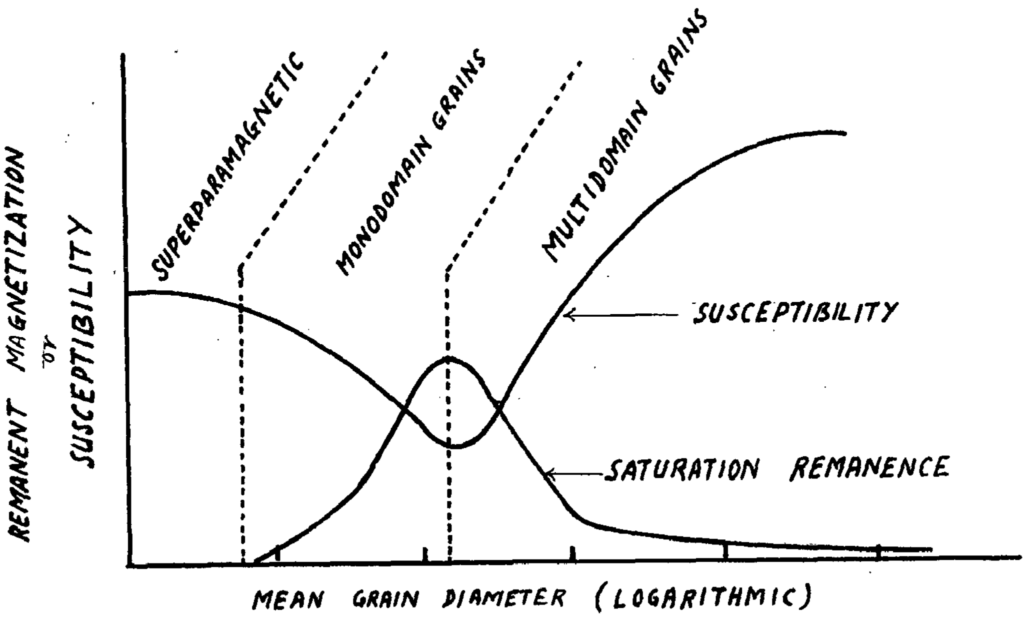


FIG. 5b VARIATION OF SUSCEPTIBILITY AND SATURATION REMANENCE WITH GRAIN SIZE (SCHEMATIC ONLY)

(AFTER NEEL)

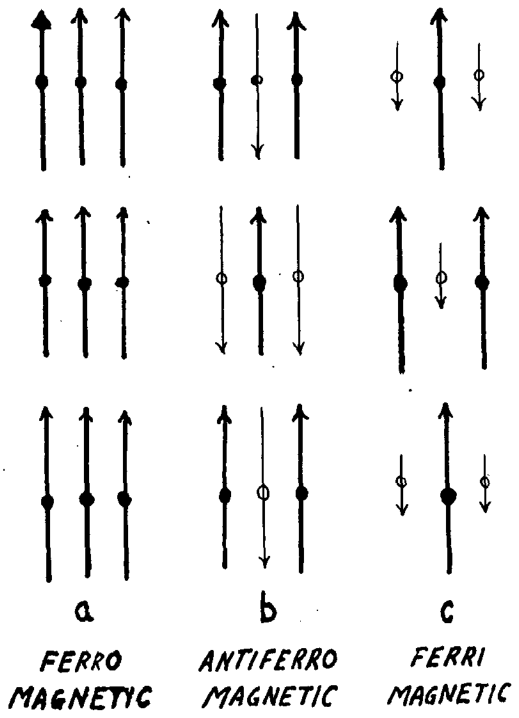


FIG. 6 SCHEMATIC ILLUSTRATION OF DISTRIBUTION OF MAGNETIZATION VECTORS IN CRYSTALS

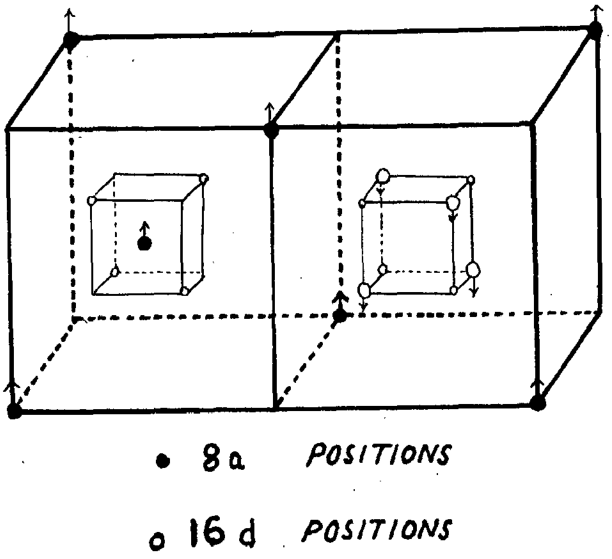


FIG. 7 INVERSE SPINEL STRUCTURE (MAGNETITE). THE ARROWS INDICATE THE SPIN MAGNETIC MOMENTS

visible under the electron microscope. Figure 5, shows these results.

ANTIFERROMAGNETIC:$^{2-VIII}$ It has been found that certain materials, behave as paramagnetic substances at ordinary temperature, but their susceptibility takes a maximim value at a certain temperature T_n, at which an abnormal value of specific heat is also found. The perticular temperature is called - point or Neel temperature. The magnetic state at temperatures, below T_n, can be attributed to the condition that spin of neighbouring atoms are antiparallel to one another owing to a negative exchange energy. This state is called antiferromagnetism accordingly, and substances exhibiting such characterstics are called antiferromagnetic.

Figure 6b shows an arrangement of magnetic moments of antiferromagnetic crystals according to experimental results of diffraction of neutrons by these materials, showing an antiparallel coupling of the spins.

FERRIMAGNETIC^{2-ix} It has been found that certain materials having spinel structure possess a behaviour similar to that of the ferromagnetics.

Generally, 8 molecules of XY_2O_4 form comprise one unit cell resulting in X_8 $(Y_{16})O_{32}$ for normal spinel and Y_8 $(X_8Y_8)O_{32}$, for reverse spinel, where 8 metallic ions outside the bracket occupy 8a sites, and 16 ions inside, 16 d sites, Figure 7 shows one fourth part of a unit cell, where 8a sites are surrounded by four Oxygen ions tetrahedrally, while the 16d sites are surrounded by 6 Oxygen ions octahedrally.

For magnetite (Fe_3O_4), 8a sites are occupied by $8Fe^{2+}$, while 16d sites by $8Fe^{+2} + 8Fe^{+3}$. Neutron diffraction analysis reveals that the magnetic moment of Fe at 8a sites and that at 16d sites are in the opposite directions. That is, magnetite has an antiferromagnetic character. However the magnitude of magnetic moments at two different crystallographic sites differ from each other resulting in the appearance of a spontaneous magnetic moment as a whole as shown in figure 6c. Such magnetism is called ferrimagnetism.

Paramagnetic susceptibility of ferrimagnetics above the curie temperature does not follow the curie-Weiss law of ordinary ferromagnetics, but varies according to a hyperbolic law in the form of

$$\frac{1}{k} = \frac{T}{C} + \frac{1}{k_o} - \frac{\sigma}{T - \Theta} \qquad \text{------} (2.23)$$

where C is a theoritical Curie constant of ions present and k_o, T and Θ depend on the magnitude of magnetic interaction between the metallic ions.

Almost all ferromagnetic minerals contained in the rocks are, strickly speaking ferrimagnetics as defined above. But because their behaviour at ordinary temperature is similar to that of ferromagnetics, the ' term 'ferromagnetism' is commonly employed for ferrimagnetic minerals.

CHAPTER III

2-x,3-ii,5-ii

MAGNETIC PROPERTIES OF ROCKS

Since rocks are essentially aggregates of various mineral grains, it is necessary to study the magnetic properties of minerals in order to understand those of rocks. Rockforming minerals can be classified into three main groups based on their magnetic properties i.e. diamagnetic, paramagnetic and ferrimagnetic.

Silicate minerals, which constitute the greater part of ordinary rocks are either paramagnetic or diamagnetic, depending upon the presence or absence of Fe^{+2},Fe^{+3}, Mn^{+2} etc. in their crystal structure. Quartz and felspar are typical diamagnetic minerals in rocks where as olivines, pyroxenes, and biotites are the commonest paramagnetic minerals. Natural occurence of ferrimagnetic or antiferromagnetic silicate minerals have not so far been reported. Therefore, the various ferromagnetic characterestics of rocks can be traced principally to the ferrimagnetic oxides or the sulphide minerals, which are scattered although in very small proportions, in the practically non magnetic silicate minerals.

In all practical problems in which rock magnetic studies are of help, we are interested only in the ferromagnetic character of rocks. Therefore, the study of ferromagnetic minerals is of great importance. The minerals responsible for the ferromagnetic properties of rocks belong predominantly to the ternary system $FeO-TiO_2-Fe_2O_3$ (Fig. 8). Among sulphides, pyrrohotite is the only important magnetic mineral.

The composition of magnetic minerals in igneous rocks is governed by the composition of the parent magma and the physical conditions operative during cooling. Crystallization of magnetic minerals, usually occurs above the Curie point, commonly between 1100°C and 800°C. The grainsize depends upon

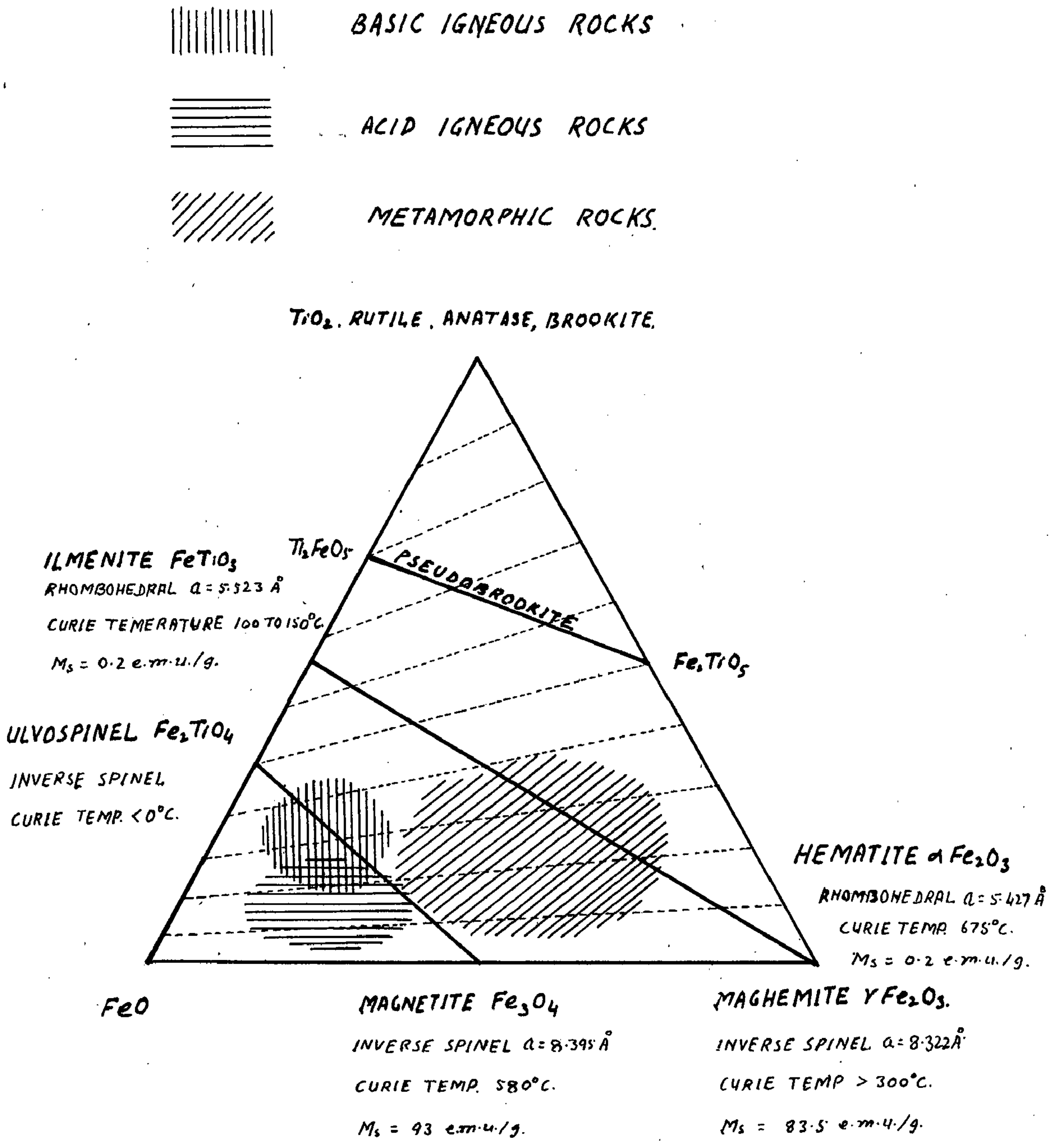


FIG.8 A REVIEW OF MINEROLOGICAL AND MAGNETIC DATA CONCERNING THE SYSTEM $FeO - TiO_2 - Fe_2O_3$.

BROKEN LINES ARE OXIDATION LINES

the rate of cooling during crystallization and ranges from 0.05 to 1 m.m., in volcanic rocks. However, in plutonic rocks crystals of even 1.00 m.m. or larger size are not incommon.

Magnetic minerals are rarely homogeneous, and may involv several phases, either owing to exsolution or due to replacement or alteration. This inhomogenity has to be taken into consideration, while investigating magnetic properties.

The main magnetic minerals and their interrelation in chemical composition is shown in the figure No. 8. Important magnetic properties of these minerals are given below:-

<u>Magnetite</u> (Fe_3O_4):- It is the most important ferrimagnetic mineral in rocks. It has inverse spinel structure, with cell dimensions a = 8.39 Å. Although optically isotropic it is magnetically anisotropic, the (111) direction being that of the easiest magnetization, and the (100) direction being that of the most difficult. Its curie point is 5.78°C, and its saturation magnetization at room temperature is 92 to 93 e.m.u./gram.

<u>Ulvospinel</u> (Fe_2TiO_4) :- This is also of inverse spinel structure. It is not found as natural crystals, but occurs intergrown with magnetite. It exhibits paramagnetism at normal temperatures.

<u>Ulvospinel Magnetite series or Titano-Magnetite</u>:- These form a complete solid solution above 600°C, but exsolve at low temperature, ferrimagnetism decreasing with increasing Ulvospinel part.

<u>Maghemite</u>: (Fe_2O_3):- It has inverse spinel structure like magnetite, but inverts to hematite between 200 to 700°C. Its saturation magnetization is 83.5 e.m.u./gram.

<u>Hematite</u> (Fe_2O_3) : - It has a rhombohedral structure. Individual crystals are paramagnetic in the direction of triad axis, but exhibit a very weak

ferromagnetism perpendicular to this axis. For all practical purpose this can be taken as paramagnetic.

ILMANITE ($FeTiO_3$):- It is also of rhombohedral form and is antiferromagnetic, with a Neel* temperature of about 100 to 150°C. Usually it shows a small unbalance in theoritically perfect cancellation which gives it a saturation magnetization of about 0.2 e.m.u./gram.

Pyrrhotite:- This is the only sulphide mineral showing ferromagnetic properties The structure is defective in iron and should be written as $Fe_1 - y\ S$, but is usually written as FeS_{1+x} where $0 < x \leq 0.14$. It becomes paramagnetic at 300°C Below this temperature it is antiferromagnetic for $0 < x < 0.09$, and ferrimagnetic in the remaining range, with saturation magnetization of 300 to 325 e.m.u./gram.

ROCKS AS FERROMAGNETIC SUBSTANCE:- Rocks usually contain some amount of ferromagnetic grains in the form of fine particles, dispersed throughout the matrix of paramagnetic or diamagnetic silicates. Because of the presence of these particles, the bulk of rocks show characteristics of ferromagnetism, such as magnetic hysteresis and curie temperature, although the intensity of magnetization, may sometimes be not much more than that of paramagnetics.

APPARENT MAGNETIC SUSCEPTIBILITY :- Since the ferromagnetic minerals in rocks are dispersed as fine particles, a self demagnetising field comes into play in every particle, when an external field is applied. The magnitude of this field depends upon the shape of particles. Hence the susceptibility of rocks determined in the laboratory are not true susceptibilities, but the apparent magnetic susceptibilities k_A.

If we assume that each ferromagnetic grain is surrounded by a hollow cavity in the continuous phase of the rock, the effective magnetic field in the hollow cavity, Heff, can be given by

---

*It is the temperature at which an antiferromagnetic substance has maximum susceptibility.

$$H_{eff.Cav.} = H_{ex} - (L-M)J, \text{ where } J = k_A H_{ex} \text{ ———— (3.1)}$$

Here L and M are demagnetising factors of the rock specimen and of the cavity respectively.

If $H_{eff.}$ is the effective magnetic field, J_i the intensity of magnetisation, k the true susceptibility, N the demagnetising factor of a single ferromagnetic grain, and p the volume of the ferromagnetic material in the rock then

$$H_{eff} = H_{eff\ Cav.} - NJ_i \text{ ———————— (3.2)}$$

$$\text{where } J_i = k\ H_{eff.} \text{ and } J = pJ_i \text{ ———— (3.3)}$$

By combining (1),(2) and (3) we get the following general expression for the apparent magnetic susceptibility

$$k_A = \frac{pk}{1+\left\{N+(L-M)p\right\}k} \text{ ———————— (3.4)}$$

If $p << 1$, i.e. mutual magnetic interaction among the ferromagnetic grains can be ignored, equation (3.4) reduces to

$$k_A = \frac{pk}{1+Nk} \text{ ———————— (3.5)}$$

where specific susceptibility is used the expressions (3.4) and (3.5) can be written as follows:-

$$\chi_A = \frac{k_A}{\rho_A} = \frac{q\chi}{1+\left\{N+(L-M)q\ \rho_A/\rho\right\}\chi} \text{ ——— (3.6)}$$

$$\text{and} \qquad \chi_A = \frac{q}{1+N\rho\chi} \text{ ———————— (3.7)}$$

where ρ_A, ρ and q are respectively the specific gravity of the rock that of the ferromagnetic mineral and the weight content of the latter.

MAGNETIC SUSCEPTIBILITY OF ROCKS AND THEIR MAGNETITIE CONTENT : - Several attempts have been made to formulate statistical 'laws' relating the bulk susceptibility of rocks to petrological parameters.

Money and Bleifuss, after studing rocks from Minnesota, derived a relation, between, bulk susceptibility and magnetite content, found by crushing magnetic separation and chemical analysis for iron, which is

$$k = 2.89 \times 10^{-3} V \text{ ———————— } (3.8)$$

where V is the volume percentage of magnetite.

Balsley and Buddington have related the susceptibility of a suite of Adirondack rocks to the fractional volume of all minerals visually identified as magnetite (which include F_e-Ti Oxides of spinel structure). Their relation gives

$$k = 2.6 \times 10^{-3} V \text{ ———————— } (3.9)$$

A similar relationship has been determined by Barth from the analysis of magnetite bearing iron ores. His findings give

$$k = 1.16 \times 10^{-3} V \text{ ———————— } (3.10)$$

where V is volume percentage of magnetite determined by magnetic separation.

The discrepancy in the constants of the above three equations may be attributed to the fact that the ferromagnetic minerals in rocks are usually not pure magnetite, but have a fairly varied composition. Besides, the magnetic susceptibility in weak fields is strongly influenced by the size and shape of the particles as well as by their internal stresses.

CLASSIFICATION OF ROCKS BASED ON MAGNETIC SUSCEPTIBILITY : - Although magnetic susceptibility of rocks in weak fields depend on the kind and the abundance of ferromagnetic mineral grains and their size in a complicated manner, the following general conclusions can be drawn:-

(1) Basic rocks have greater magnetic susceptibility than acidic rocks.

(2) Susceptibility of volcanic igneous rocks ranges from 10^{-4} to 10^{-2} emu

(3) Susceptibility of plutonic igneous rocks ranges from 10^{-4} to 5×10^{-3} e.m.u./c.c.

(4) Susceptibility of metamorphic rocks is from 10^{-5} to 3×10^{-4} e.m.u/c.c.

(5) Susceptibility of sedimentary rocks is below 10^{-5} e.m.u./sec.

The following table[6-1], which gives susceptibility of common rock types will further corroborate the above observations.

ROCK TYPE	SUSCEPTIBILITY IN e.m.u./c.c.	REMARKS
1. Igneous Rocks*		
Granites	0.00003 to 0.0027	14 samples
Diorite	0.000046	1 sample
Dolerite (Diabase)	0.000078 to 0.0042	8 samples
Basalt	0.00068 to 0.0063	8 samples
Peridotite	0.0125	1 sample
2. Metamorphic Rocks		
Gneisses	0.00001 to 0.0020	2 samples
Schists	0.00026 to 0.00024	2 samples
Slate	0.000039 to 0.0030	3 samples
Amphibolite	0.000058	1 sample
Serpentinite	0.00025 to 0.014	2 samples
3. Sedimentary Rocks		
Limestones	0.000004	1 sample
Sandstone	0.000005 to 0.000017	2 samples
Shale	0.00004 to 0.00005	3 samples

---

* Basicity increasing downwards.

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY OF ROCKS[2-x] : - It has been found that the susceptibility of a rock sample in all directions is not the same. This anisotropy may be due to (1) shape of the magnetic body or (2) regular orientation of magnetically anisotropic crystals. Anisotropic magnetic susceptibility is a tensor of second rank k_{ij}. Therefore, with analogy to the strain ellipsoid it can be represented by a susceptibility ellipsoid. The inverse square ($1/\sqrt{r}$) of the length of the radius vector of the susceptibility ellipsoid is equal to the magnitude of susceptibility in the direction of the radius vector.

Ising has reported that the magnitude of susceptibility is maximum in the bedding plane of the sediments, and minimum in a direction perpendicular to it. In the case of metamorphic rocks, the maximum susceptibility will be in the plane of foliation. The degree of anisotropy is expressed by the ratio.

$$P_{max/min} = \frac{\text{Maximum } k_A}{\text{Minimum } k_A} = \frac{k_{A\,max}}{k_{A\,min.}} \text{ ———— } (3.11)$$

This ratio usually lies between 1 and 1.5 and rarely exceed 2.

Igneous rocks, with the exception of layered intrusions may safely be considered as magnetically isotropic.

MAGNETIC HYSERESIS OF ROCKS[2-x] : - Rocks show the hysteresis phenomena similar to that shown by the ferromagnetic minerals. In rocks saturation of magnetisation is attained at or above 3000 to 4000 oesteds. The magnetic hardness of rocks vary widely depending upon the grain size, the internal stresses and the intrinsic properties of ferromagnetic grains contained in them. Usually the coercive force of igneous rocks is a few hundred orested. whereas that of hematite bearing sediments amounts to over 1000 oested.

The demagnetising factor N of grains play an important role in the hysteresis characteristic of rocks. The hysteresis curve for ferromagnetic mineral grains in rocks is flatter than the hesteresis curve for the ferromagnetic mineral itself.

CHAPTER IV

MEASUREMENT OF SUSCEPTIBILITY

A number of methods have been developed for the quantitative determination of the magnetic susceptibility of rocks. Most of these are mainly laboratory techniques, but some of them can be used in the field also. Since the strongest magnetic minerals posses about one e.m.u. of susceptibility it is custmary to employ one millionth part of this unit in practical work, and extremely sensitive instruments are required to measure this small quantity.

A. REVIEW OF EARLIER METHODS

I. MAGNETOMETER METHODS

(a) **Koenigsberger's Method**[6-ii]:- The instrument used is a simple unifilar magnetometer, consisting of a magnetic needle 10" long and 0.2" in diameter, attached at its centre to a fine torsion fibre of about the same length. The deflection of needle is measured with a mirror and telescope system. The sample to be tested may be either cut to a suitable size and shape or may be pulverized and put in a test-tube. This sample is brought within a few centimeters of one of the poles of the magnetic needle and the resulting deflection is measured.

A standard sample[1-ii]* of known susceptibility is then put in place of the test sample, and the deflection of the needle is observed. Since deflection is directly proportional to susceptibility for a given separation from the needle

---

* In most of the susceptibility determinations, ferric chloride is used as a standard sample. Its susceptibility is given by $k(\text{mass}) = (p/100)H + (1-p/100)H_0$ where $H = 90 \times 10^{-6}$ is mass susceptibility of pure ferric chloride, H_0 = mass susceptibility of water = -0.79×10^{-6} and p = percent ferric chloride in solution.

and a given controlling field. A comparison of the two readings will give the susceptibility of the test sample.

The controlling field in the above experiment is the earth's horizontal component, which orients the needle. If a bar magnet of strength slightly smaller than that of the earth's field is placed below the needle in such a way as to oppose the earth's field, the controlling field is reduced thus increasing the sensitivity considerably.

(b) Field Magnetometer Method[5-iii]:- Comparison with a standard sample as a means of measuring susceptibility has been also employed using a high sensivity Askania Vertical Magnetometer. The procedure is the same as in the Koenigsberger method. The sample to be tested is placed on top of the magnetometer above the north pole of its magnetic system. Readings are taken with different faces of the sample in contact with the top of the instrument, and also with a standard sample. Susceptibility in various directions is calculated by finding the appropriate ratios.

(c) Astatic Magnetometer Method[2-xi]: - This instrument consists of two magnets of nearly equal strengths forming an antiparallel arrangement. The increased time period of this system produces a relatively high sensitivity The comparison method outlined above can also be used with this instrument.

Disadvantages of the Magnetometer Methods:- It has been observed that a specimen should have the dimensions of atleast 6 c.c. in order to produce a deflection equal to the theoritically predictable deflection produced by one of infinite thickness. Quite large samples are therefore required, whilst using the magnetometers.

(ii) The magnetometers are very sensitive to outside magnetic disturbances, and may therefore be affected by fortuitous magnetic fields.

II. SOLENOID METHODS : -

(a) Loring's Two Solenoid Method[1-vi]:- In this method two solenoids identical in shape and size are mounted symmetrically on either side of the lower magnet of an astatic magnetic system as shown in figure 9. One of these solenoids carry a secondary winding through which a measured current can be passed. The solenoids are connected in series, with near poles in opposition. They are set so that with a certain current flowing through their primary windings, no deflection is produced on the magnetic system. With the current still flowing, a test sample is than put in the solenoid which is surrounded by the secondary winding. This causes a deflection, which is neutralised, by flowing a current in the secondary winding. The current required to neutralise the deflection provides a measure of the induction in the test sample, from which its susceptibility is obtained.

(b) Ballistic Method[2-xii]:- This method is based on the principle that the total electric charge induced in a search coil as a result of the change in magnetic flux through it produced by reversing the applied field can be measured by means of a ballistic galvanometer. In figure 10, L_1, L_2 and L_3, L_4 constitute two mutual inductances M_1 and M_2. L_4 is adjusted till the induced e.m.f. in the secondary circuit becomes nearly zero, so that $M_1 \simeq M_2$. The specimen is than inserted to form the core of the mutual inductance M_2. Any imbalance of induced emf is corrected by the transformer T. The field in which susceptibility is to be determined can be produced by a magnetizing coil M.

For measurements, the current i through L_1 and L_3 is reversed by means of a mercury switch and the resultant deflection of the galvanometer is read. The electric charge q induced in the secondary circuit is given by

$$q = 2Ri\,(M_1\mu - M_2\mu_0)$$

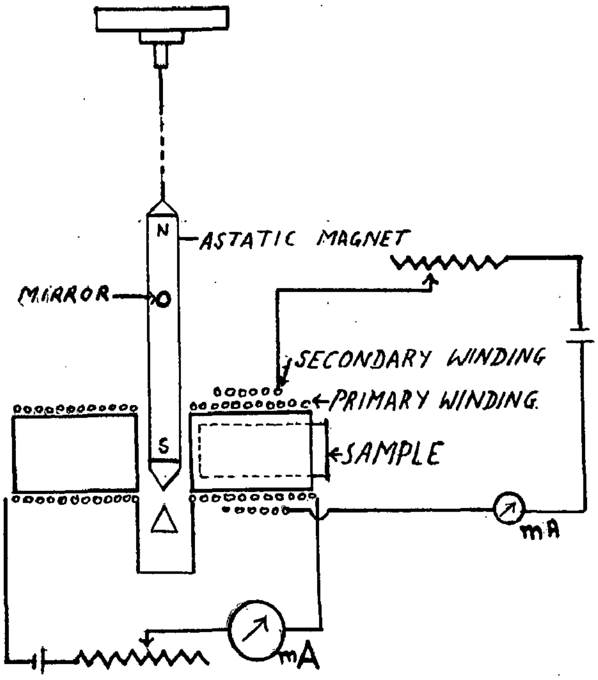


FIG. 9 TWO SOLENOID METHOD FOR SUSCEPTIBILITY DETERMINATION

(AFTER LORING)

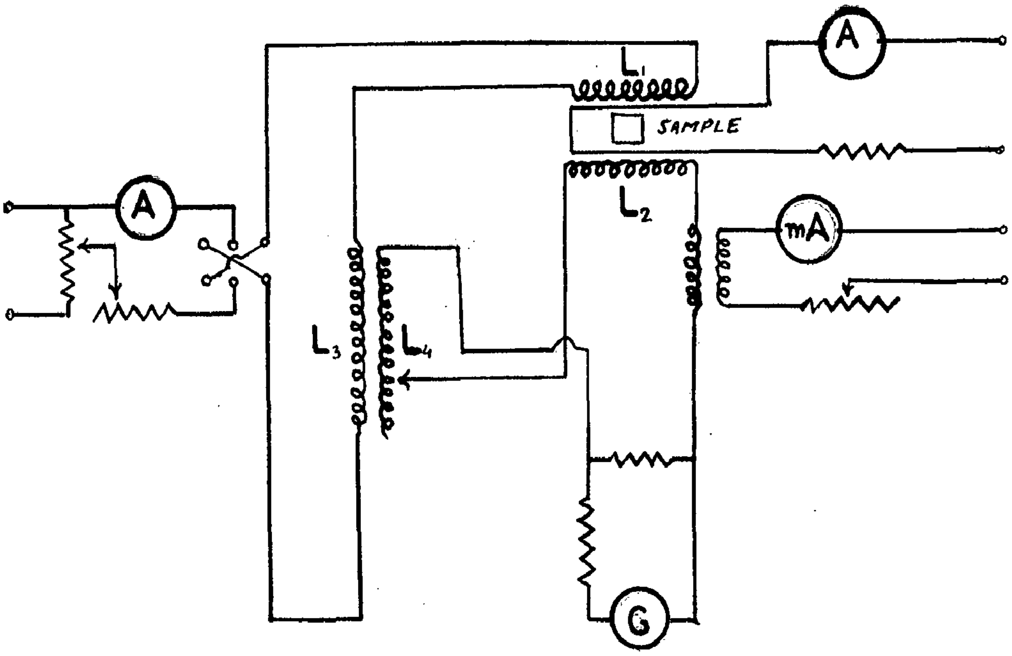


FIG. 10 ELECTRIC CIRCUIT FOR BALLISTIC METHOD OF MEASURING SUSCEPTIBILITY

where $\mu = 1+4\pi Cks/A$ and $\mu_0 = 1$ (for space)

Here R is a constant depending on the resistance of the secondary circuit, s the effective cross section of the inserted specimen, A the effective cross section of the coil L_2 and C a constant depending upon the dimension of the specimen with respect to that of L_2. Thus we get a relation between k and the deflection of the galvanometer θ as

$$k = \frac{\theta}{RH} - \varepsilon$$

where ε is a small constant which appears when M_1 is not exactly equal to M_2. The sensitivity R' is calibrated with a standard sample.

Advantages of the above method over Magnetometer Methods:- (i) The necessary size of the specimen is considerably reduced.

(ii) By placing the coil system perpendicular to magnetic meridian, changes in the earth's field can be eliminated.

(iii) Magnetizing field is at our control and hence complete hysteresis loop can be studied.

Disadvantages:- It has been found that in weak fields, induction does not attain its maximum value when the magnetising current is altered due to magnetic creeping. This time lag is sometimes very large.

III. ALTERNATING CURRENT METHODS

(a) Barret's Inductive Method[6-iii]:- This is one of the earliest A.C.Method. The inductance bridge is shown in figure 11. Two arms contain pure resistances R_1 and R_2. The third arm contains a variable inductance L_2 together with a test coil for holding the sample. The fourth arm contains a tapped inductance L_3 and a variable inductance L_4. In operation, the bridges is first balanced for D.C. by adjusting r_5 and rebalanced for A.C., without the specimen, by adjustment of L_4 while L_2 is set to zero. The specimen is then inserted, and

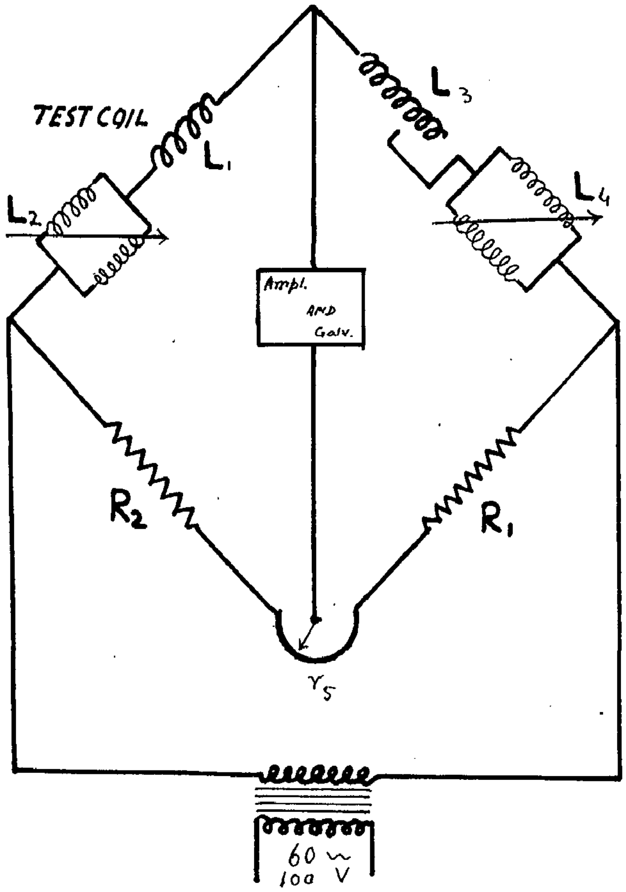
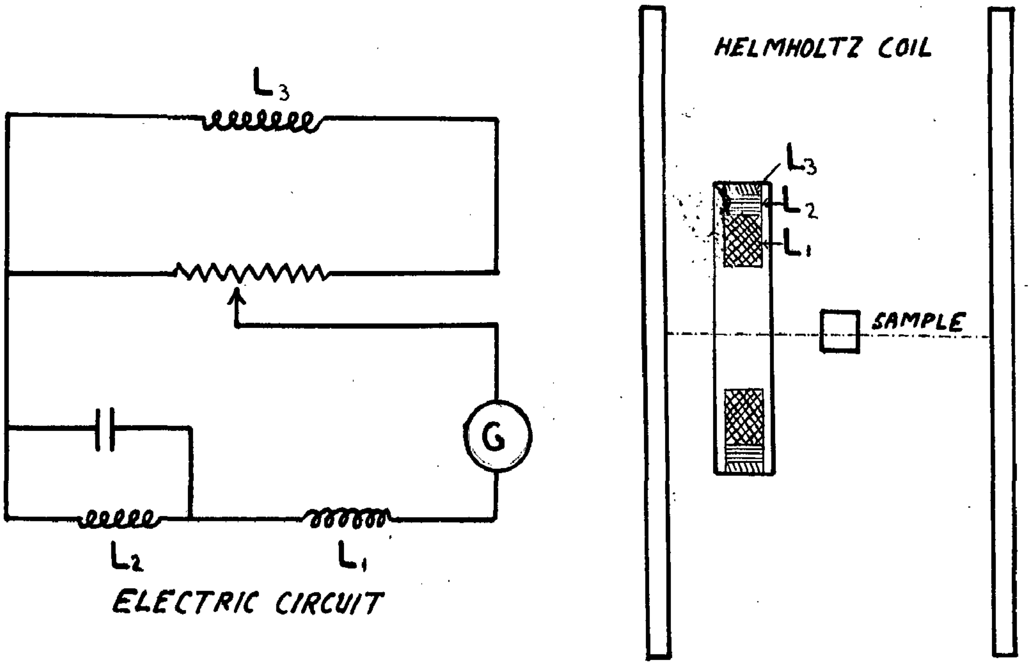


FIG. 11 INDUCTANCE BRIDGE FOR SUSCEPTIBILITY DETERMINATION (AFTER BARRET.)



ELECTRIC CIRCUIT

FIG. 12 SCHEMATIC VIEW OF THE APPARATUS FOR MEASUREMENT OF THE MAGNETIC SUSCEPTIBILITY OF ROCKS.

(AFTER BRUCKSHAW AND ROBERTSON)

resulting galvanometer deflection is balanced out by adjustment of L_2. This change in inductance gives the susceptibility of the sample.

(b) Paterson's Method[1-v]:- By this method susceptibilities of rocks in situ can be measured. Inductance of a coil carrying a current is first measured in free space, with the help of an inductance bridge. The coil is then placed on the face of the rock under investigation. The change in inductance thus produced is a measure of the susceptibility of rock. A calibration curve is used which gives the change in microhenries in terms of susceptibility.

(c) Bruckshaw and Robertson's Method[2-xiii,7]:- In this method, magnetizing field is produced by an alternating current of 50 to 60 c/s by means of a Helmholtz coil. Within this field a coil former is rigidly mounted carrying three windings L_1, L_2 and L_3 (See figure 12). Coils L_1 and L_2 form an astatic coil system and are designed to pickup equal amounts of e.m.f.'s and are connected in series opposition.

In a uniform magnetic field H, parallel to the axis, the e.m.f. across the twin coil system will be zero. It is generally necessary to put a small condenser parallel to L_2, in order to cancel perfectly the complex e.m.f.'s produced by the L_1 and L_2 coils. A rock sample of cubic shape placed on the axis of the double coil becomes an alternating magnet. The e.m.f.'s set up in L_3, a coil of few turns connected to a potentiometer, supplies a reference e.m.f., against which the e.m.f. due to the alternating rock magnet is balanced. The detector G consists of a tuned high gain amplifier, and a tuned vibration galvanometer. The e.m.f. produced by the sample is proportional to its susceptibility and can be calculated by the potentiometer readings.

(d) Likhite and Radhakrishnamurty's Method[8]: - The above authors have slightly modified Brucksahw's method to measure susceptibility of rocks at different frequencies. (from 60 to 2000c/s). They have used a third winding of 500 turns connected through a potentiometric arrangement, in series with the double coil to obtain greater accuracy in compensation. They used a Tektron -ix 317 oscilloscope to measure e.m.f. produced by the specimen in double coil. The samples studied were of cylindrical shape, with a radius of 1.1 c.m. and length equal to 2.2 c.m. placed at the centre of the double coil.

B. THE PRESENT METHOD

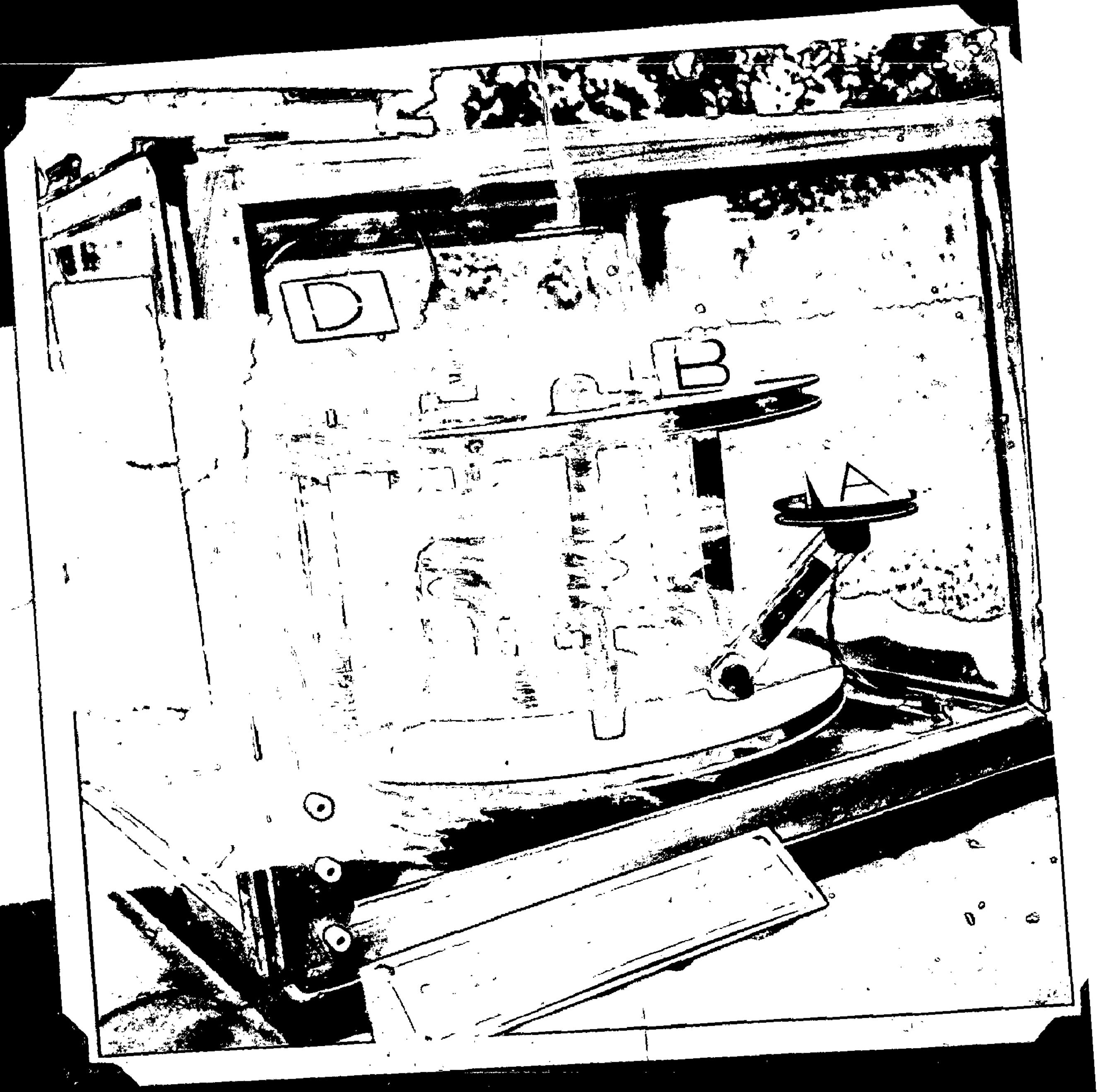
The apparatus used for the present measurements, is also a modification of Bruckshaw's method. Instead of 50 c/s however, the measurements were made at 529 c/s.

The equipment consists of an energizing pair of Helmholts coils* a search coil*, a compensating coil* to backoff the primary field in the search coil, and the measuring bridge and dectector. The various coil formers were machined by M/S PIE Ltd. of Roorkee, according to our specifications, and the entire system was assembled in the department. The measuring bridge was also designed in the department, but owing to lack of workshop facilities, its fabrication was handed over to M/S Electronic Appliences of Roorkee. The latter also wired up the amplifier for the detector, which is wholly transisterized and consists of a tuned amplifier at the working frequency.

THE ENERGIZING SYSTEM :- The energizing system consisted of a Helmholts coil assembly (see photograph No.1) having 100 turns of 20 s.w.g. enamelled copper wire. The radius of each coil was 22.86 c.m. The coil system was made entirely of ebonite. The energizing field was produced by feeding the Helmholts coils from a PHILIPS power amplifier, which was in turn excited by a PHILIPS beat frequency oscillator (See photograph No.2). A sinusoidal current of 128 m.A. was necessary to produce a peak field of 0.5 oersted at the centre of the coil system.

---

*Details of various coils are given in appendix 1.


D
B
A

SEARCH COIL : - A search coil having 2000 turns of 40 s.w.g. enamelled copper wire was rigidly attached to the base, so as to be coaxial and concentric with the Helmholtz coil system. (see phtograph No. 1) This coil was provided with eight tappings to permit calibration of fractions of the total field or e.m.f. The coil former carried a circular slot at the centre, in which a circular disc carrying a test sample of cubic sh-ape (1" x 1" x 1") could be fitted. The cubic rock sample thus automatically lay at the centre of the system, with one of its axes coaxial to it.

COMPENSATING COIL : - Since the secondary field produced by the test sample placed in the magnetic field at the Helmholtz coils was too small as compared to the primary field, it was necessary to cancel the primary field in the search coil. This proved to be quite a difficult task, but was achieved after a lot of trial and error. A compensating coil of 2250 turns of 40 s.w.g. enamelled copper wire with an adjustable centre was placed above the upper Helmholtz coil (see photograph No. 1), and was joined in series opposition with the search coil. With the help of a stud and slot arrangement, the former could be adjusted so as to annul most of the e.m.f. picked up by the search coil.

The e.m.f. induced in the search coil and the compensating coil will be mainly inphase, but contain a small Quadrature component,, due to the self capacitances of the coils and leads. To compensate for this an inductometer was used, whose primary formed a part of the energizing circuit as shown in figure 13. However, not much success was achieved owing to the limited mutual inductance available from the existing inductometer in the laboratory. Hence the remaining uncompensated e.m.f. was read on the potentiometer and treated as zero error.

REFERENCE COIL :- A small coil of 775 turns of 34 s.w.g. enamelled copper wire,

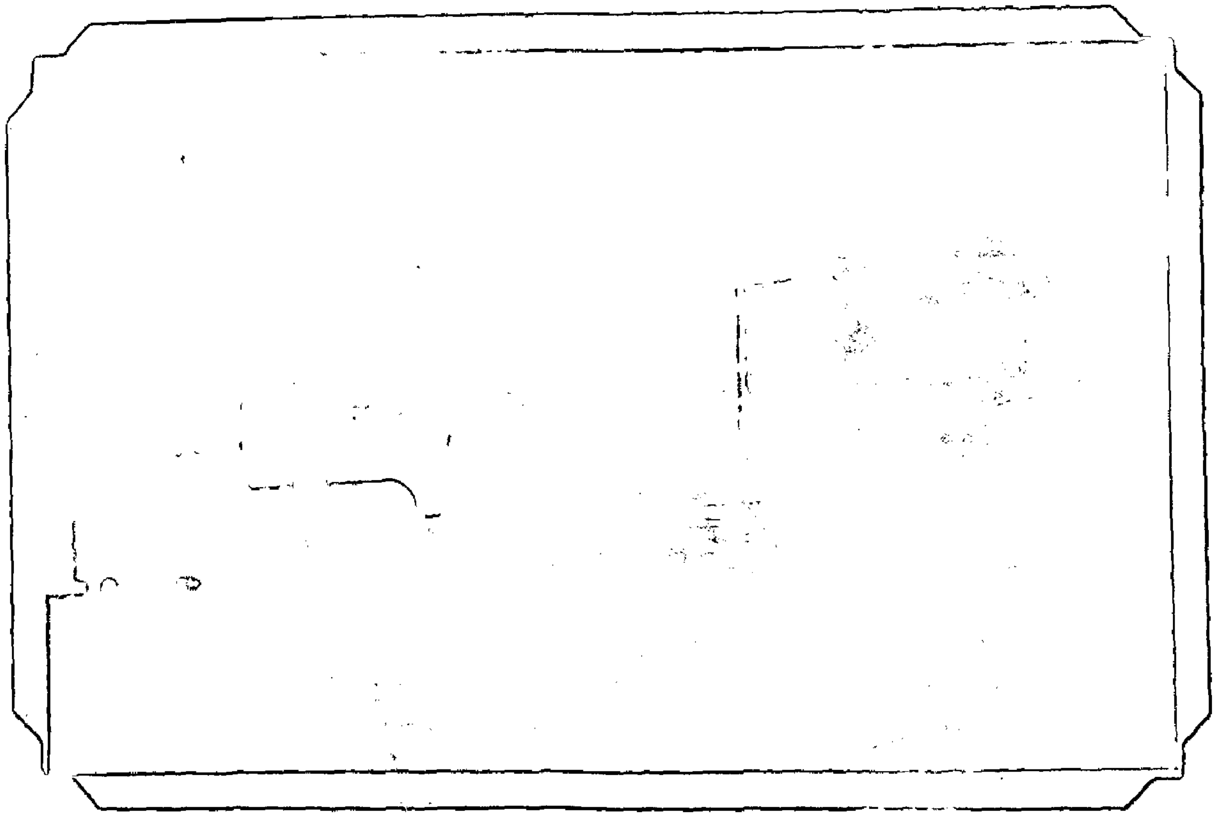
PHOTOGRAPH NO. 2 EXPERIMENTAL SET UP FOR THE MEASUREMENT OF SUSCEPTIBILITY

A. Oscillator

B. Power Amplifier

C. Oscilloscope

D. Mili-Ammeter



connected to the potentiometer supplied a reference e.m.f. (see figure 13). This coil could be rotated about a vertical and a horizontal axis (photograph No.1), and by setting it in a certain position, a given e.m.f. could be obtained.

THE MEASURING BRIDGE[9] - For measurements a bridge of Bruckshaw's design was used. This consisted of a potentiometer of resistance R, flanked by two equal inductances $L/2$ each, and another potentiometer also of resistance R flanked by two equal capacitances 2C, connected across the reference coil as shown in figure 13.

When a resistance and an inductance are connected in series and an e.m.f. applied across them the phase of the current in the circuit lags on the applied e.m.f. by an angle equal to $\tan^{-1}\frac{wL}{R}$. If $wL = R$, this angle will be equal to 45°.

Similarly if, a resitance and a capacitance be connected in series and an e.m.f. applied to them, the phase of the current in the circuit will lead the applied e.m.f. by an angle equal to $\tan^{-1}\frac{1}{wCR}$. If $wCR = 1$, this angle will also be 45°.

Thus if the total reactance of each arm is equal to the total resistance in that arm, the phase of the voltage drops over the whole length of the potentiometers would differ from the phase of the voltage difference appearing across the whole arm by 45° in the capacitance arm and by - 45° in the inductive arm.

More over if the total impedance in each arm is made equal, the current in the two arms would be equal and differ in phase by 90°. That is $\sqrt{w^2L^2+R^2} = \sqrt{1/w^2C^2+R^2}$ or $wL = 1/wC$ or $w^2LC = 1$.

All these conditions mentioned above can be written as $wCR = w^2LC = 1$, where $w = 2\pi f$ is the working angular frequency.

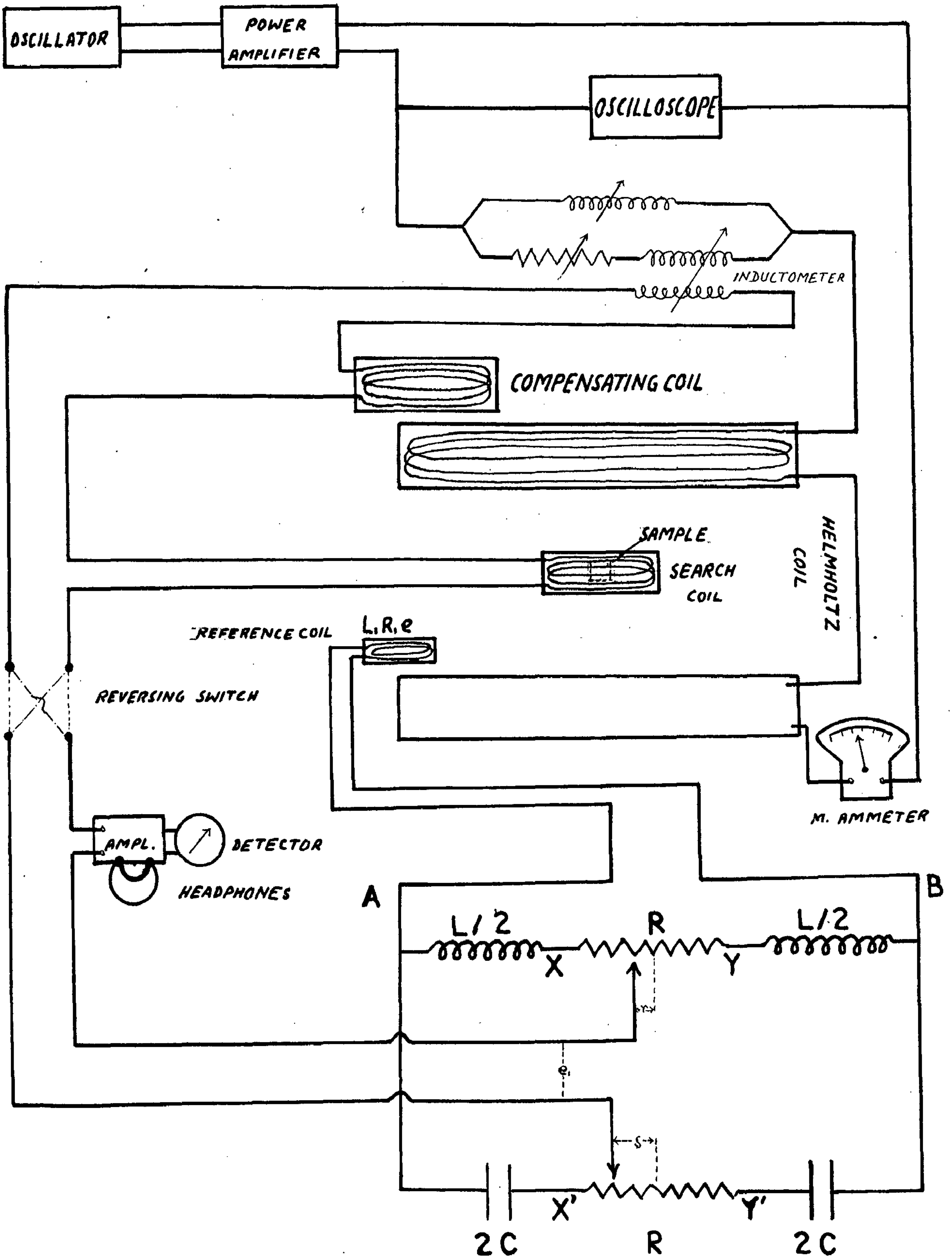


FIG. 13 ELECTRIC CIRCUIT AND SCHEMATIC VIEW OF THE APPARATUS USED FOR DETERMINATION OF SUSCEPTIBILITY.

The two arms in parallel, however together behave as a single resistance equal to R. This can be varified for two extreme values of frequency, i.e. zero and infinity.

If the frequency of the applied field is zero, the reactance of the capacitance branch tends to infinity, and all current flows only through the inductive branch, which behaves as a single resistance R. If on the otherhand, the frequency tends to infinity, the reactance of the inductive branch becomes infinitely large and all current flows through the capacitive branch only, which behaves as a single resistance equal to R. Thus it can be concluded by induction that the network as looked from its common terminals behaves as a pure resistance of value R.

Now, if the reference coil has a resistance R_1 and an inductance L_1, the phase of the voltage drop appearing across the function of the two arms, (across AB in figure 13) with reference to the e.m.f., induced in the reference coil would be given by $-\tan^{-1}\left(\frac{\omega L_1}{CR} + R_1\right)$. By suitably winding the reference coil this phase can be made equivalent to -45°. The voltage drop appearing across the potentiometers in the capacitive and the inductive branch could then be respectively in phase and in quadrature with the e.m.f. induced in the reference coil. The voltage vectors between various points in the bridge circuit are shown in figure 14.

An application of Maxwell's analysis shows that for balance of an unknown e.m.f. e_1 against the reference e.m.f. e, the following condition should be satisfied

$$\begin{vmatrix} j\omega L_1 + R_1 + \frac{1}{j\omega C} + R & - R - 1/j\omega C & e \\ -\frac{1}{2j\omega C} - \frac{R}{2} - bR & \frac{1}{2j\omega C} + \frac{j\omega L}{2} + R - aR - bR & -e_1 \\ -\frac{1}{2j\omega C} - \frac{R}{2} + bR & \frac{1}{2j\omega C} + \frac{j\omega L}{2} + R - aR - bR & -e_1 \end{vmatrix} = 0$$

$$\text{or} \quad \frac{e_1}{e} = -\frac{(a+ib)}{2(R+R_1)} \qquad \text{———————}(4.1)$$

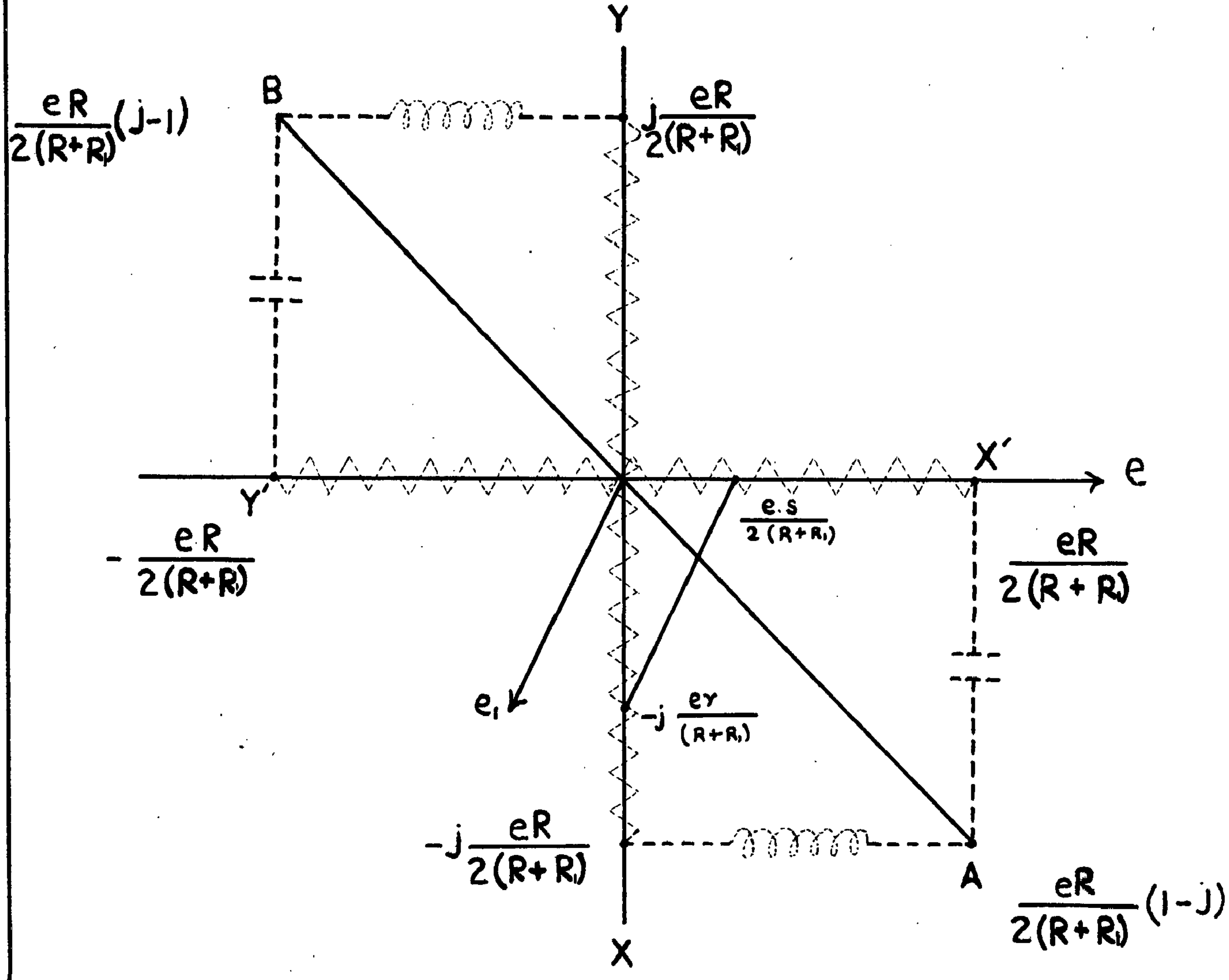


FIG.14 PHASE DIAGRAM OF THE E.M.F.'S BETWEEN VARIOUS POINTS IN THE BRIDGE AT BALANCE

The search coil is inserted between the two potentiometers as shown in figure 13. At balance, the e.m.f. across the search coil should be equal to the difference of voltages between the tappings of the two potentiometers. Thus for the tappings r and s towards the terminal A, the unknown e.m.f. e_1 is given by $-\frac{e(s+ir)}{2(R+R_1)}$, which is directly read from the potentiometer dials.

Values for the various compoents of the bridge at 529 c/s can be seen in figure 15, which shows the circuit of thebridge. The bridge was made for measurements at 529 c/s and 829 c/s but for the present experiment it was used only at 529 c/s.

TEST OF THE BRIDGE.- The bridge was tested on a dual beam Tektronix oscilloscope at 529 c/s. The ends YY' of both the potentiometers were earthed, and their tappings were connected to the two beams of the oscilloscope. The magnitudes and the phases of the voltages were compared at the similar readings of the two potentiometers, and were found to be equal within the reading accuracy of the oscilloscope. Then the ends XX' were earthed and similar results were obtained. This proved symmetry of the circuit, the equivalance of the total impedance in each arm, and the linear accuracy of the potentiometers.

To check the relative phases of the voltage on two potentiometers, the tappings of one of them XY, was centered and earthed, and one of its ends connected to one beam of oscilloscope, while the tapping on other potentiometer X'Y', was connected to the other beam of the oscilloscope, the earth for both beams being common. As the tapping on the potentiometer X'Y' was moved from one end to the other, the magnitude of the voltage varied from a maximum value equal to that shown by the first beam, to zero and then again to a maximum and the phase varied from 90° on one side of zero to - 90° on the other side. The same results were obtained when the roles of the potentiometers were interchanged.

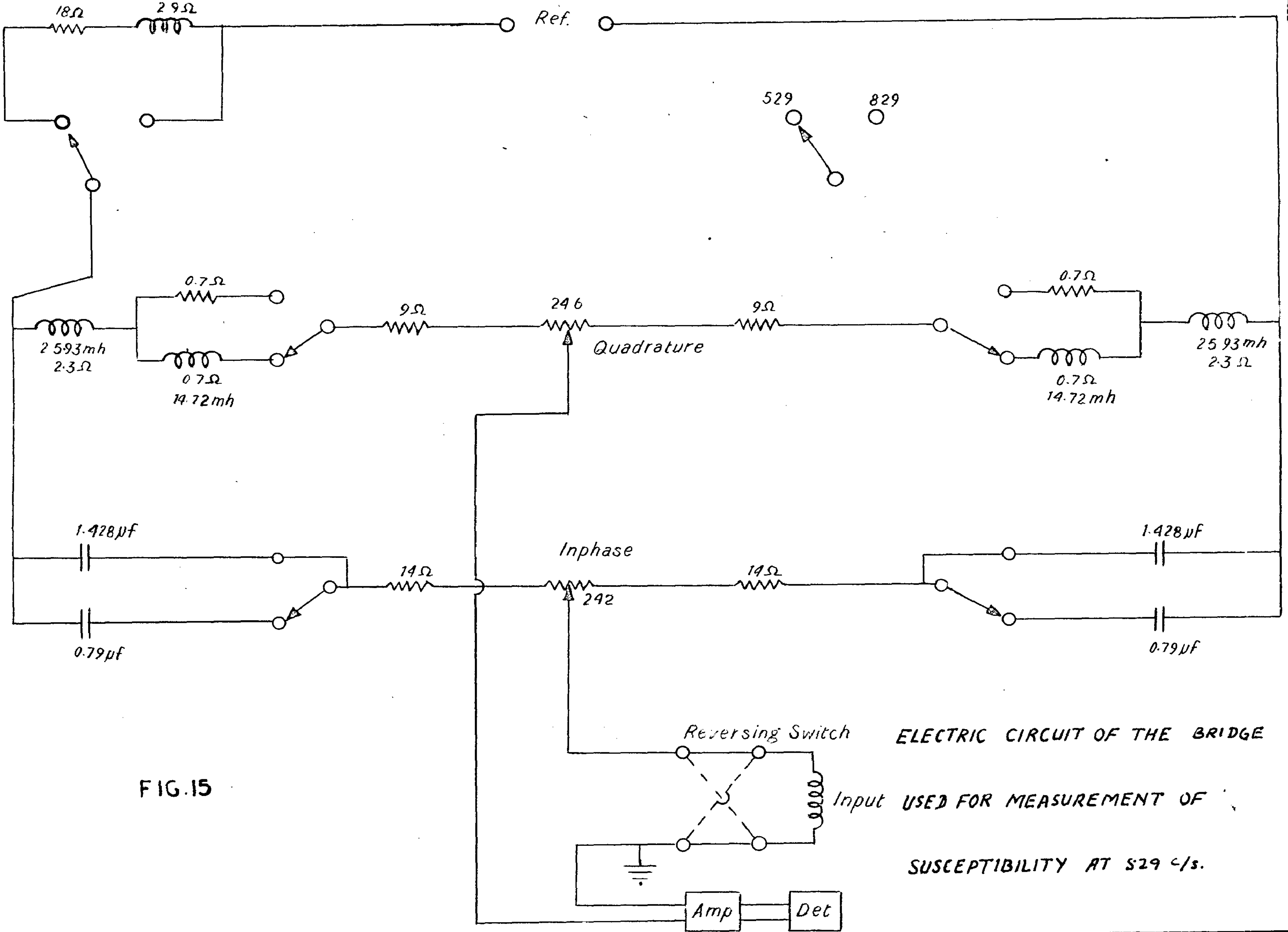


FIG.15

ELECTRIC CIRCUIT OF THE BRIDGE USED FOR MEASUREMENT OF SUSCEPTIBILITY AT 529 c/s.

These results confirmed the accuracy of the bridge within that of the Tectronix oscilloscope.

DETECTOR. - The detector consists of a transisterised high gain amplifier, which was tuned at the working frequency and a pair of headphones. The circuit of the detector amplifier is given in figure 16.

DETERMINATION OF SUSCEPTIBILITY.- When no specimen is placed at the centre of the search coil, the e.m.f. induced in the search coil will be proportional to the field H, produced by the current flowing in the Helmholtz coils, Thus,

$$e = jwHR \text{ ——————— } (4.2)$$

where R is a constant of the search coil.

Now, if a test sample is placed at the centre of the search coil, the flux linking the search coil will change and the induced e.m.f. will be

$$e_1 = jwHR\left(1 + \frac{4\pi kV}{C}\right) \text{ ———— } (4.3)$$

where C is another constant depending upon the distance of the search coil winding from the centre of the specimen, and the shape and size of the specimen, and V is the volume of the speciemn.

Hence the e.m.f. induced by the specimen alone is

$$e_s = e_1 - e = \frac{RjwH\,4\pi kV}{C}$$

$$\text{and } \frac{e_s}{e} = \frac{RjwH.4\pi kV}{jwHRC} = \frac{4\pi kV}{C} \text{ ———— } (4.4)$$

The e.m.f. picked up by the search coil in the absence of the specimen is compensated by an arrangement described above. The specimen is then placed at the centre of the search coil, and the resulting e.m.f. is balanced against a reference e_r. The ratio $\frac{e_s}{e_r}$ is obtained directly from the bridge as already described.

If the e.m.f. at the m'th tapping of the search coil is balanced against the same reference, the potentiometer readings will give $\frac{e_{om}}{e_r}$. From expression (4.4) above.

$$\frac{4\pi kV}{C} = \frac{e_s}{e} = \left\{ \frac{e_s}{e_r} / \frac{e_{om}}{e_r} \right\} \frac{e_{om}}{e}.$$

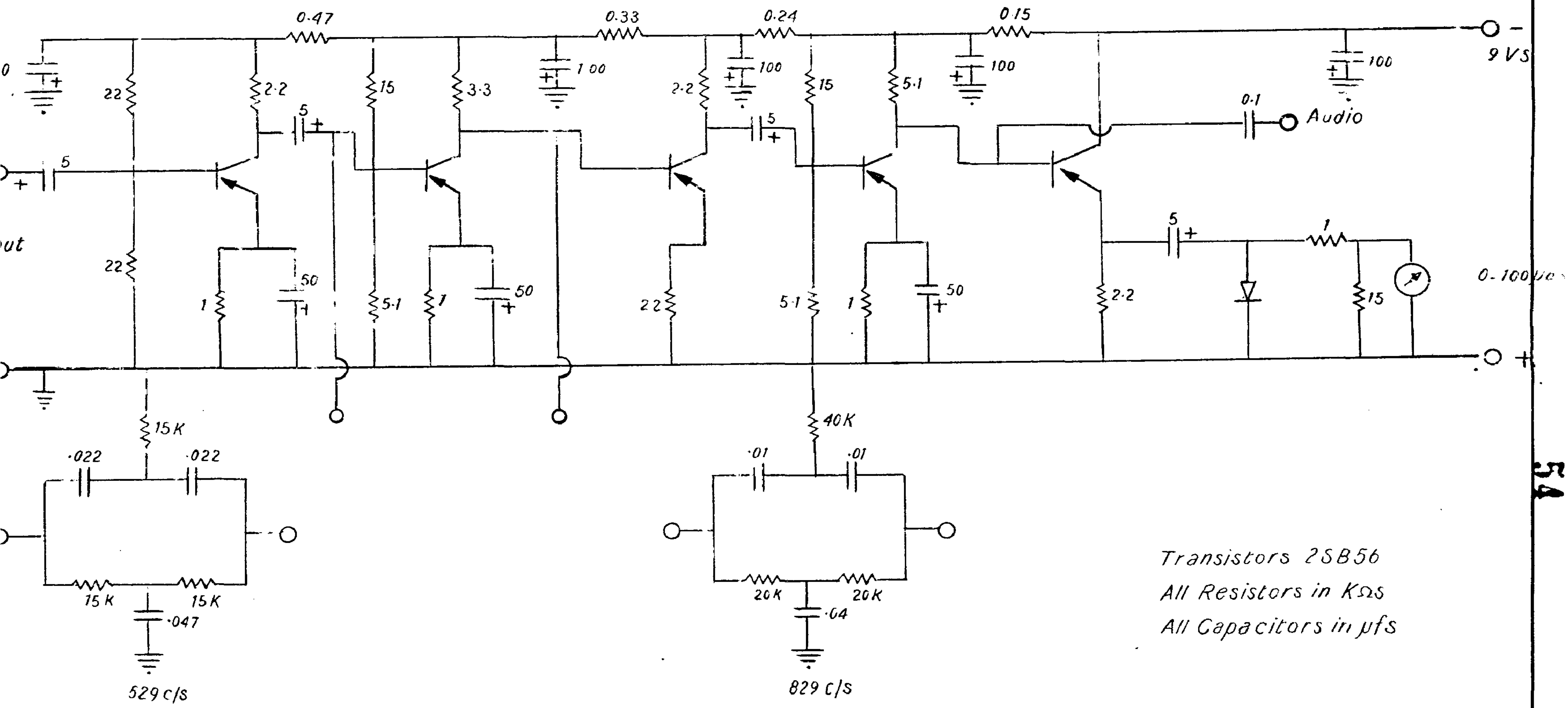
$$\text{or } k = \frac{\left\{ \frac{e_s}{e_r} / \frac{e_{om}}{e_r} \right\} \frac{e_{om}}{e} \quad C}{4\pi V} \qquad \text{———}(4.5)$$

<u>CALIBRATION</u>: In order to calculate the susceptibility it was necessary to know e_{om}/e and C. The ratios e_{om}/e for various values of m depending on the range of k, in respect of different tappings, were determined by a HEWLET PACKARD V.T.V.M (with a reading accuracy of 5 μV), for a given value of the current. By changing the value of current in Helmholtz coils, six sets of readings were taken for e_{om}/e and average values of e_{om}/e were calculated. These ratios are given in appendix 2.

The ratios e_{om}/e_{on} were also determined using the bridge. This offered a check on the values of e_{om}/e_{on} obtained from the voltmeter, for atleast four values of m. The coincidence between these was within the reading accuracy of the instruments.

To determine C, a standard solution (60.8%) of ferric chloride, having a specific gravity 1.70 was used. Its theoritical mass susceptibility was 53.2745×10^{-6} and volume susceptibility was $53.2745 \times 10^{-6} \times 1.70 = 90.56 \times 10^{-6}$ The ratio e_s/e_r for 16 c.c. of this solution was found to be 4, for a position of reference, such that $e_{o1}/e_r = 98$. Using these data in expression (4.5), value of C was found to be 1007.

<u>SOURCES OF ERROR</u>:- The experimental errors can be divided into four groups:-



Transistors 2SB56
All Resistors in KΩs
All Capacitors in μfs

FIG.16 TRANSISTORISED SELECTIVE NULL DETECTOR

(A) Errors due to current fluctuations: (i) Since ratios e_s/e_r were measured for calculating the susceptibility, using a bridge, there will be no effect of any change in current on the susceptibility.

(ii). However, e_{0M}/e were determined using a V.T.Y.M., there was a possibility of error due to fluctuations of the current. But a check of these ratios by potentiometers for four tappings shew that the coincidence in ratios by the two methods was quite close and the error was negligible.

B. Errors due to the wrong setting of the frequency:

(i) Since the reactance of the bridge depends upon the frequency, any error in the latter will alter the potentiometer readings.

If R is reading of the potentiometer, at the wrong frequency w, and R_c at the correct frequency w_c then

$$R = R_c\frac{w}{w_c} = \frac{R_c(w_c+\Delta w)}{w_c} = R_c\left(1+\frac{\Delta w}{w}\right)$$

$$\text{or} \quad \Delta R = R - R_c = \frac{\Delta w}{w} R_c$$

For an error of 2.5 c/s which is the reading accuracy of the oscillator when working at 529

$$R = \frac{2.5 \times 100}{529} = 0.47\%$$

(ii) There may also be a drag in oscillator frequency, which may give rise to the above mentioned error. To gaurd against anydrift error a beat frequency oscillator was used which has an accuracy of ± 1%

(C) Error in potentiometer readings: - The potentiometer dial could be adjusted to within 0.25 of a division. This will introduce an error, depending upon the perticular dial reading. There is obviously no control over, this error, but it is felt that effect is negligible in most cases.

(D) Error due to non uniformity of the field threading the sample: While deriving the relation for susceptibility it was assumed that the specimen is at the centre of the Hemholtz coils, and is hence in a uniform, magnetic field. However, due to the significant dimensions of the specimen, field at its edges is different from the field at its centre.

The field at the centre of the specimen is

$$H_c = \frac{32\pi ni}{50\times5^{1/2}a} = \frac{32\times3.14\times100\times0.128}{50\times5^{1/2}22.86} = 0.5034 \text{ oersted.}$$

The field at one of the edges of the sample is given by

$$H = \frac{2\pi nia^2}{\left\{a^2+\left(\frac{a}{2}+1.27\right)^2\right\}^{3/2}+\left\{a^2+\left(\frac{a}{2}-1.27\right)^2\right\}^{3/2}}$$

$$= \frac{2\times3.14\times100\times0.128\times(22.86)^2}{\left\{(22.86)^2+(10.16)^2\right\}^{3/2}+\left\{(22.86)^2+(12.70)^2\right\}^{3/2}} = 0.4917$$

Hence the percentage error in the field threading the sample is

$$\Delta H = \frac{H_c - H}{H_c}\times100 = \frac{0.5034-0.4917}{0.5034}\times100 \approx 2.32\%$$

ADVANTAGES:- (1) Being an A.C. method it had the advantage over other methods, that the low signal due to rocks could be amplified sufficiently.

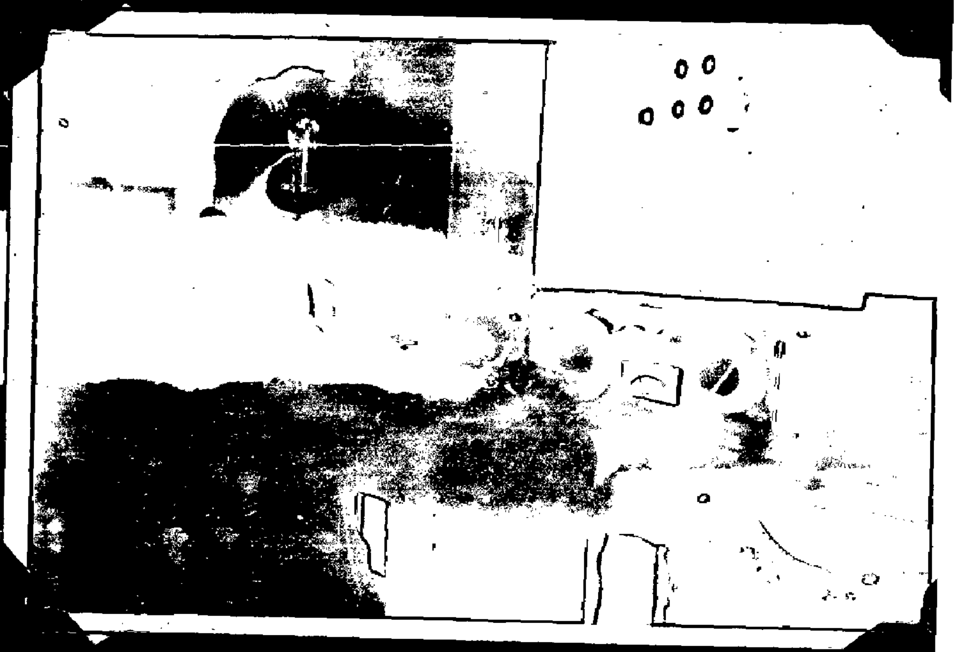
(2) Size of the sample has no effect on measurements and hence small samples could be used.

(3) Since an alternating current is used for energizing, only the susceptibility magnetization kH is measured and any effect due to the remanent magnetization does not appear.

(4) Since the field induced in the search coil is directly proportional to the frequency of the energizing field, sensitivity was considerably increased by using 529 c/s instead of 50 c/s as used by Bruckshaw.

(5) In Bruckshaws double coil system, the outer compensating coil also picks up some of the signal produced by the specimen, and thus a part of the signal was lost. By placing the compensating coil for away from the specimen

this effect was avoided, thus increasing the sensitivity.



CHAPTER V

RESULTS AND DISCUSSION

A. MICROSCOPIC WORK

In order to determine the composition of the rocks whose susceptibility had been measured, they were studied in thin section under a petrological microscope. In addition to this a study of the polished sections of rocks and ores under an ore microscope permitted the determination of the character and distribution of their ferromagnetic content. A model analysis was made of the polished sections of all rocks and ores to determine volume percentage of their ferromagentic content. In rocks model analysis was made only for one face because they have a homogeneous distribution of minerals. In ores, however due to banded and veined character two faces were studied at right angle to each other and the mean percentage of minerals was calculated. A brief sketch of these studies is given below:-

1. Igneous Rocks

Dolerite (Specimen No.M_8) :- This sample was taken from Jainti coal field of Bihar. The main constituent minerals of this rock were augite, diopside, plagioclase and a small amount of magnetite. The rock was coarse grained and had a typical ophitic texture.

In polished section long slender prismatic crystals of magnetite could be seen. The magnetite is fine grained and is not altered. Traces of sulphide minerals were also found.

Olivine Gabbro (Specimen No. M_7) :- This sample also belongs to Jainti coal fields of Bihar. Along with augite, diopside and plagioclase, it also contained some olivine. Small grains of magnetitie could be seen in the polished sections. The magnetite shows incipient alteration to hematite. Fine lines of hematite in cubic pattern can be seen, which are due to alteration along cleavage planes. Some of the magnetite grains are titaniferous, showing a pinkish colour and faint anisotropism under crossed nicols.

Dolerite (Specimen No. M_6):- This specimen also belonging to the same area had, however, more opaque minerals than the previous two samples had. The main constituent minerals were augite, plagioclase, magnetite and a small amount of olivine. Magnetite crystals are fine to medium grained equidimensional and sometimes with perfect boundaries. Some crystals of titaniferous magnetite are also present. Alteration is still in its initial stages and only in some crystals fine alteration lines along the cleavage are seen.

Basalt (Specimen No. M_5) : - This sample was taken from Nagpur traps. The main minerals constituents were oligoclase, augite, potash felspar, magnetite and glassy matter. Vesicles are quite common. Rock is merocrystalline, aphanitic and inequigranular. Magnetite grains are medium grained equidimensional unaltered crystals. Mostly it is titaniferous magnetite.

Basic Sill (Specimen No. M_4) :- This was a sample of basic sill from near Mussorie. It is composed of potash felspar, plagioclase, augite, chlorite, magnetite and apatite. It is a medium grained equigranular rock. Crystals of magnetite are equidimensional but not with perfect development of faces. Mostly magnetite is unaltered except at borders in some grains. Traces of sulphide minerals are also seen.

Dolerite Sill (Specimen No. M_9) :- This sample was taken from lower dolerite sill of Pulivendla area of Andhra Pradesh. It is composed of labradorite, magnetite, antigorite and small amount of quartz. It is medium to coarse grained and has sub ophitic texture. Magnetite crystals are medium to coarse grained sometimes with perfect development of faces. Magnetite crystals are highly oxydized specially at the borders of crystals.

2. Magnetite Ores

Sample No. M_1 :- This magnetite bearing rock was taken from near Singhana (Khetri Copper Belt). It shows very fine grained mixture of magnetite and some silicate minerals filled in the fractures of the rocks. The fractures are sometimes circular in shape. Magnetite content of this sample could not be determined on accounts of its presence as mixturewith silicate.

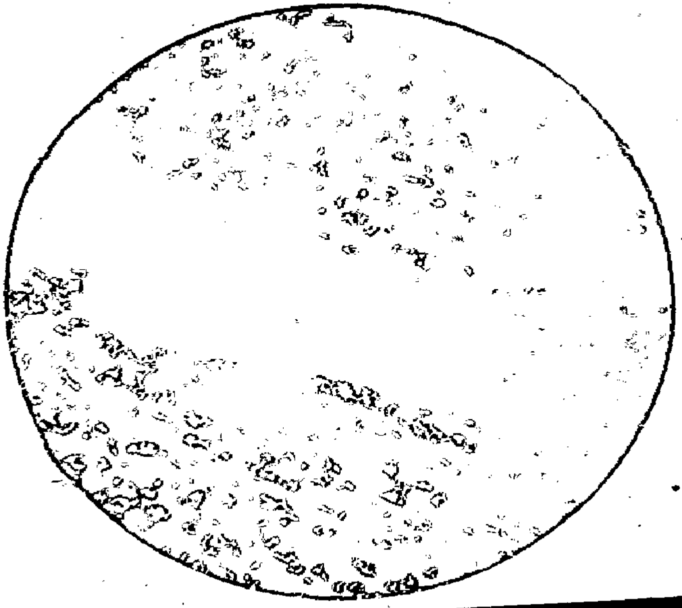
Specimen No. M_2 and M_3 :- These were samples of banded magnetite quartzites from Kanjamalai, Salem . They show alternate layers of magnetite and quartzite (see micro-photograph No. 1). The magnetite is highly oxydised to hematite and complete magnetite grains are rarely seen.

3. Pyrrhotite, Chalcopyrite, Pyrite and Magnetite samples

Specimen No. K_3 :- This sample mostly contained chalcopyrite, which has replaced pyrrhotite. Only small amount of pyrrhotite is left. Photograph (micro) No. 2 shows relation of chalcopyrite and pyrhotite. Model analysis shows 29.20% chalcopyrite 5.75% pyrrhotite and 64.54% gangue.

Specimen No. K_1 :- This sample contained maximum pyrrhotite. It contained 61.96% pyrrhotite, 3.47% magnetite, 0.75% chalcopyrite and 33.82% gangue.

Specimen No. K_6 :- It contained 6.13% pyrrhotite, 4.86% magnetite, 2.85% chalcopyrite 1.40% pyrite and 84.25% gangue. Magnetite is completely unaltered.



Specimen No. K2 :- This sample has big stout crystals of pyrite and magnetite, enclosed by pyrrhotite. Pyrrhotite seems genetically latter than magnetite and pyrite. Pyrrhotite has been replaced by chalcopyrite at places. Magnetite is completely unoxydised. It contains pyrrhotite 20.48%, magnetite 3.55%, pyrite 4.83% chalcopyrite 0.28% and gangue 70.87%.

Specimen No. K4 :- In this sample chalcopyrite has replaced much of the pyrrhotite. It contains 24.70% pyrrhotite, 13.46% chalcopyrite, 4.31% magnetite and 57.58% gangue.

Specimen No. K7 :- This sample contains big grains of pyrite and magnetite. Magnetite is completely unaltered. Pyrrhotite is latter to these minerals and is surrounding them. It contains 34.60% pyrite, 22.77% pyrrhotite 6.90% magnetite, 0.11% chalcopyrite and 35.61% gangue.

Specimen No. K5 :- This specimen was very rich in magnetite as well as pyrrhotite. These two minerals, however, were so intimately mixed that it was not possible to determine exactly their percentage. (See micro-photograph No.3) A rough analysis, however, gave magnetite 35.61% and pyrrhotite 22.77%.

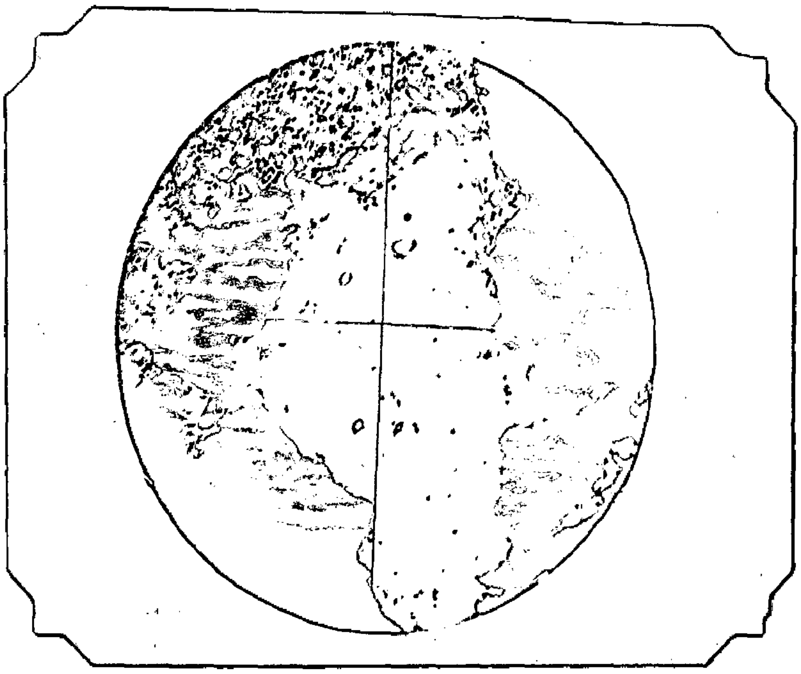
B. RESULTS OF SUSCEPTIBILITY DETERMINATION

Susceptibilities of 6 rocks, (intermediate to basic in character) 3, magnetite ores and 7 samples containing varying amounts of pyrrhotite, pyrite, magnetite and chalcopyrite were measured. The results of these measurements are shown respectively in table No. 1, 2 and 3. The table also shows the percentage of ferromagnetic content of these samples.

Attempts were also made to measure some samples containing only chalcopyrite and some other samples of acid igneous rocks but they gave no response.

DISCUSSION OF THE RESULTS

Figure 17 shows a plot between magnetic susceptibilities and magnetite



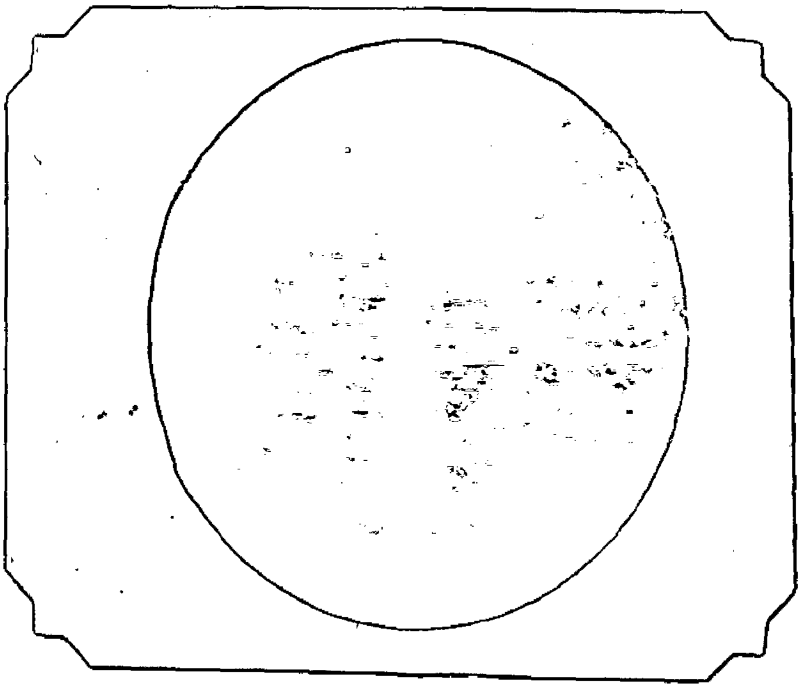
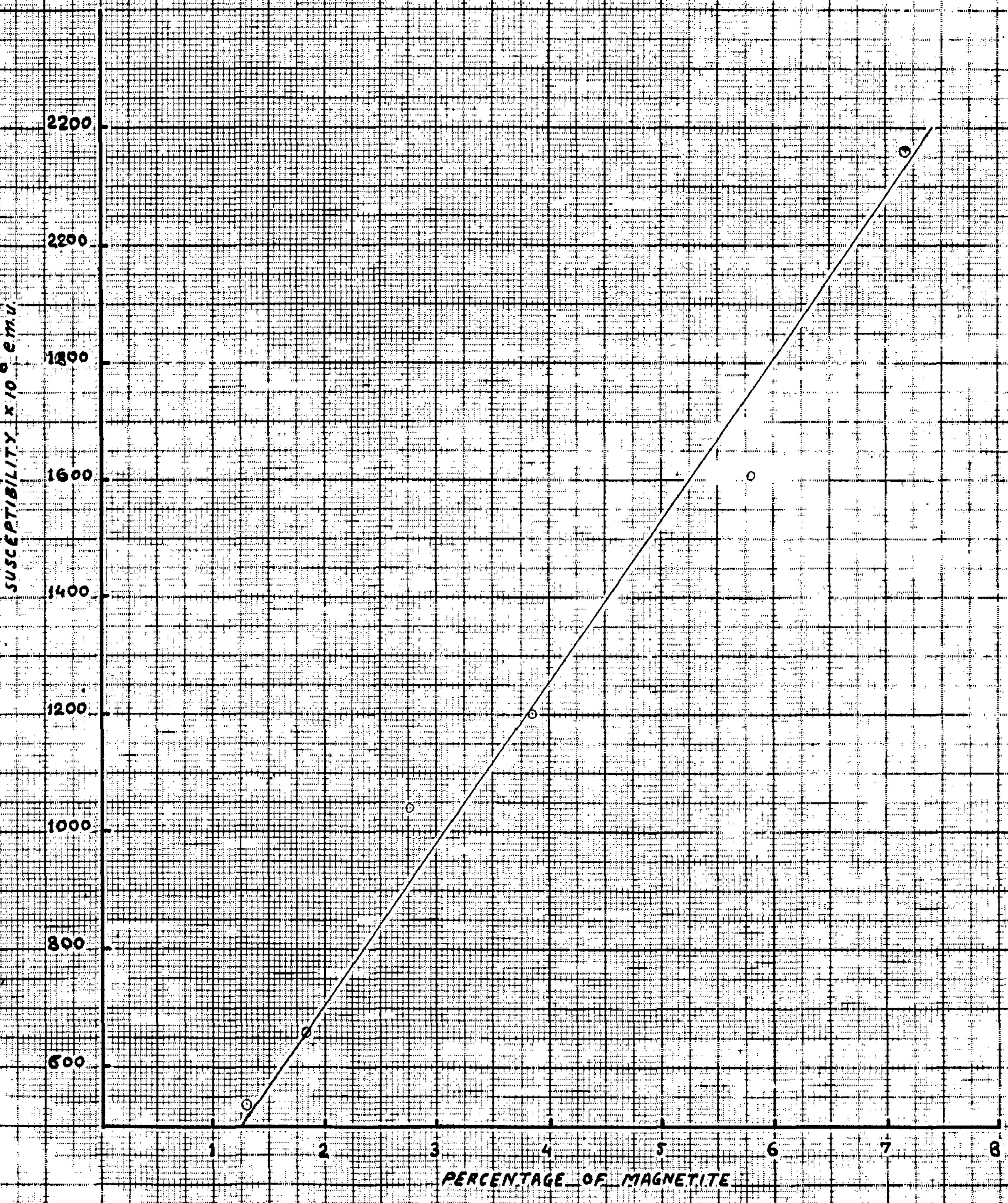


TABLE NO. 1 SUSCEPTIBILITY OF IGNEOUS ROCKS

Sp. No.	Phase	Potentiometer Readings								Vol. in c.c.	Suscpt. x10^{-6}	% Magnetite.
		Face A up	Face A dwn.	Face B up	Face B dwn.	Face C up	Face C dwn.	Mean	e_{o1}			
M_8	Inphase	12.00	13.00	13.00	14.00	14.00	15.00	13.50	70.00	15.40	541.6	1.31
	Qudr.	1.00	2.00	2.00	4.00	3.00	4.00	2.80	11.00			
M_7	Inphase	16.50	16.50	16.50	17.50	17.50	17.50	17.00	72.00	15.30	667.30	1.83
	Qudr.	3.00	3.00	3.00	3.00	4.00	4.00	3.40	12.00			
M_6	Inphase	27.00	27.00	29.00	29.00	27.00	28.00	27.80	70.50	16.00	1042.5	2.76
	Qudr.	4.00	4.00	4.00	4.00	4.00	4.00	4.00	12.00			
M_5	Inphase	33.00	32.00	33.00	32.00	32.00	31.50	32.25	70.00	15.80	1206.5	3.85
	Qudr.	7.50	7.00	6.00	5.50	7.00	7.00	6.60	11.50			
M_4	Inphase	41.00	41.00	43.00	44.00	41.00	41.00	41.80	71.50	15.20	1611.5	5.79
	Qudr.	8.00	9.00	10.00	11.00	9.00	10.00	9.50	12.00			
M_9	Inphase	59.00	58.00	57.00	57.00	53.00	53.00	56.20	67.00	16.20	2167.9	7.17
	Qudr.	14.00	15.00	15.00	15.00	15.00	15.00	14.80	11.50			



SUSCEPTIBILITY x 10 ^{6} e.m.u.
2200
2200
1800
1600
1400
1200
1000
800
600
1
2
3
4
5
6
7
8
PERCENTAGE OF MAGNETITE

FIG. 17

TABLE NO. 2 SUSCEPTIBILITY OF MAGNETITE ORES

Sp. No.	Vol. of sample in c.c.	e_{om}		Magnetization perpendicular to face A			Magnetization perpendicular to face B, **			Magnetisation perpendicular to face C			Mean Suscpt. x10^{-3}	Degree of anisotropy.	% Magnetite.
		Inph.	Qudr.	Inph.	Qudr.	Suscpt. x10^{-3}	Inph.	Qudr.	Suscpt. x10^{-3}	Inph.	Qudr.	Suscpt. x10^{-3}			
M_1	15.90	* 66.00	10.00	66.00	10.00	17.06	52.75	7.50	13.79	63.50	9.50	16.38	15.73	1.238	Could not be determined
M_2	15.30	+ 75.00	8.00	64.50	11.00	59.62	40.50	7.00	36.95	63.50	10.00	55.20	50.256	1.586	30.95
M_3	15.40	+ 75.00	8.00	82.50	14.00	74.64	79.00	13.50	71.64	46.00	8.50	41.62	62.25	1.793	34.09

* m = 3

+ m = 4

** Face B parallel to banding

TABLE - 3 . SUSCEPTIBILITY OF PYRRHOTITE, CHALCOPYRITE, PYRITE AND MAGNETITE SAMPLES

Sp. No.	Vol. of sample in c.c.	Com		Magnetization perpendicular to face A			Magnetization perpendicular to face B			Magnetization perpendicular to face C			Mean suscpt. x10⁻³	Degree of anisotropy.	% of Magnetite.	% of pyrrhotite.	Remarks.
		Inph.	Qudr.	Inph.	Qudr.	Suscpt. x10⁻³	Inph.	Qudr.	Suscpt. x10⁻³	Inph.	Qudr.	Suscpt. x10⁻³					
K_3	15.00	65.75 *	11.25	17.00	4.50	0.716	15.00	3.50	0.632	15.50	3.50	0.653	0.667	1.138	0	5.75	
K_1	14.70	67.00 +	7.00	57.75	12.00	15.70	51.00	10.00	13.85	52.00	11.00	14.12	14.55	1.134	3.47	61.96	
K_6	15.00	67.00 +	7.00	59.00	13.00	15.50	51.00	11.50	13.47	54.00	12.00	14.20	14.39	1.150	4.86	6.13	
K_2	14.70	67.00 +	7.00	57.00	9.00	15.85	57.00	9.00	15.85	57.00	9.00	15.85	15.85	1.00	3.55	20.55	
K_4	14.60	67.00 +	7.00	79.25	13.00	21.96	65.50	11.50	18.15	71.00	12.00	19.68	19.93	1.210	4.31	24.70	
K_7	14.80	74.50 **	8.00	42.50	6.00	40.19	34.00	5.50	32.15	36.50	6.00	33.15	35.62	1.250	6.90	22.77	
K_5	15.50	91.00 ++	10.00	88.00	13.50	160.1	83.75	13.50	152.36	86.00	13.50	156.45	156.3	1.050	35.81	17.07	Roughly.

* m = 1　　** m = 4
+ m = 3　　++ m = 5

Inph. = Inphase component　　Suscpt. = Susceptibility
Qudr. = Qudrature component

content of the six rock samples. The curve shows that susceptibility changes linearly with magnetite content. The irregularity of points on the graph can be explained by the fact that those rocks in which magnetite has been oxydized will have a relatively low value of the susceptibility. The table 1 also shows that quadrature component increases steadily with increasing magnetite content. This may be due to the fact that the electromagnetic field around the specimen will produce electric current in the specimen and magnetite being a mineral of high resistivity shows high quadrature component. Quadrature component being comparatively small, has been neglected in calculation of the susceptibility.

Because magnetite content of specimen No. M_1 could not be determined it was not possible to study linearity of variation in ore samples. However table 2 shows that the susceptibility of these samples has also increased with increasing magnetite content. The table also shows that when magnetization is perpendicular to the plane of the bendings, a sample shows minimum susceptibility while it shows maximum susceptibility when the magnetization is in the plane of banding. This result is in conformity with the fact that susceptibility in sedimentary rocks is maximum in the plane of bedding. In the present samples also the bands of magnetite represent the original bedding planes. High degree of anisotropy probably indicates that all magnetite grains are oriented with their easiest magnetisation direction in the plane of the banding.

The susceptibility determination of pyrrhotite, magnetite, chalcopyrite samples could not, however, be corelated, because the effect of magnetite could not be removed, on account of the fact that results of magnetite samples could not be used for this purpose. The magnetite ore samples were highly oxydized, while magnetite in the samples from Khetri was completely unaltered and gave very high susceptibility.

However, table 3 indicates that if the effect of magnetite can be removed, the susceptibility increases with increasing pyrrhotite content.

Table 3 also confirms the view that quadrature component increases, with increase in the amount of material of high resistivity. Sample No.K_1 which has high pyrrhotite (high resistivity 70*) content, K_6 which has high magnetite (high resistivity 1 to 100*) content and K_5 (which has high magnetite content) show large quadrature components, while, sample No.K_2 which contains chalcopyrite (low resistivity 2.1×10^{-1})* and K_7 which contains pyrite (low resistivity 1×10^{-1})* show a comparatively low quadrature component.

SOME REMARKS CONCERNING THE WORKING OF THE APPARATUS : - Although the compensating coil was kept far away from the specimen, the leads of the two helmholtz coils were taken out symmetrically to a reasonable distance from the coils, the measuring bridge was kept far away from the susceptibilitymeter, and measurements were made at high frequency, the sensitivity of the instrument was unexpectedly low. This was perhaps due to the fact that the search coil had a large inner radius and most of the flux from the specimen failed to link the coil and was lost in the space between the coil and the specimen.

Moreover good compensation could not be obtained on account of the non availability of an inductometer of high mutual inductance or a small capacitance. Also the shield of the connecting wires also picked up a small e.m.f. causing interference.

It is, therefore, suggested that the search coil should be so constructed as to closely hug the specimen.

The effect produced in compensation by the shields can be removed

* Resistivity in ohm.cm.-taken from Heiland, C.A. - p. 659

by using layers of co-Netic shielding ribbon (Jorgenson 1958)

By using a small capacitance in parallel with the compensating coil and the above modification the sensitivity of the instrument can be improved a great deal thereby permitting measurements of the low values of susceptibility also.

APPENDIX 1

DETAILS OF THE VARIOUS COILS OF SUSCEPTIBILITYMETER

I. UPPER HELMHOLTZ COIL

Inductance	—	10.55 mH
Resistance	—	5.95 ohms
No. of turns	—	100 turns of 20 s.w.g. wire.
Mean radius of coil	—	22.86 c.m.

II. LOWER HELMHOLTZ COIL

Inductance	—	11.30 mH
Resistance	—	5.950 ohms.
No. of turns	—	100 turns of 20 s.w.g. wire
Mean radius of coil	—	22.86 c.m.

III. SEARCH COIL

Inductance	—	0.78 H
Resistance	—	1.13 Kilo ohms.
Total No. of turns	—	2000 turns of 40 s.w.g. wire.

No. of turns for various tappings

Tapping No.		No.of turns
1	—	1
2	—	2
3	—	4
4	—	20
5	—	40
6	—	200
7	—	400
8	—	2000

IV. COMPENSATING COIL

Inductance — 1.78 H.

Resistance — 1.855 Kilo ohms.

No. of turns — 2250 turns of 40 s.w.g. wire.

V. REFERENCE COIL

Inductance — 65.30 mH

Resistance — 70.50 ohms.

No. of turns — 775 turns of 34 s.w.g. wire.

In order to be able to use the reference coil (which actually fulfills the required condition i.e. $wL_1 = (R+R_1)$, at 829 c/s) at 529 c/s an inductance of 20.7 mH and resistance 2.6 ohms and an ohmic resistance of 18 ohms was inserted in series with the reference coil.

APPENDIX 2

RATIOS $\frac{e_{om}}{e}$ FOR TAPPINGS OF THE SEARCH COIL

$\frac{e_{o1}}{e}$ — 0.00052

$\frac{e_{o2}}{e}$ — 0.00150

$\frac{e_{o3}}{e}$ — 0.00341

$\frac{e_{o4}}{e}$ — 0.01305

$\frac{e_{o5}}{e}$ — 0.03200

$\frac{e_{o6}}{e}$ — 0.13000

$\frac{e_{o7}}{e}$ — 0.3230

Here e_{om} represents the e.m.f. picked up by the portion of the search coil upto the m'th tapping and , e represents the maximum e.m.f. picked up by the coil.

REFERENCES

1. Jakosky, J.J. Exploration Geophysics
Trija Pub.Co., California - 1961
i- p.5, ii-p.174, iii-p.175, iv-p.178, v-p.182.

2. Nagata, T. Rock Magnetism
Maruzen Co. Ltd. Tokyo - 1961
i-p.327, ii-p.328, iii-p.229, iv-p.3, v-p.6 ,
vi-p.12, vii-p.11, viii-p.30, ix-p.32, x-p.75,to 146,
xi-p.49, xii-p.45, xiii-p.64.

3. Irving, E. Paleomagnetism and its Applications
to Geological and Geophysical Problems.
John Wiley & Sons, INC., Newyork - 1964
i-p.244, ii-p.16.

4. Winch, R.P. Electricity and Magnetism
Prentice Hall INC. - 1960
i-p.573, ii-p.576, iii-p.613 to 620.

5. Grant, F.S. and West, G.F. Interpretation Theory in Applied Geophysics
McGraw-Hill Book Co. Toronto - 1965
i-p.360, ii-p.361-370.

6. Heiland, C.A. Geophysical Exploration
Hafner Pub. Co. Newyork - 1963.
i-p.318, ii-p.301, iii-p.304.

7. Rao, B.S.R. and Bhimasankaram, V.L.S. Proceedings of the National Institute
of Sciences of India.
Vo. 26A, No.1, 1960 - p.16-29.

8. Likhite, J.D. and Radhakrishnamurty, C. Bulletin of the N.G.R.I. Vo. 3, No.1, 1965 - p.1-8.

9. Gour, V.K. Ph.D. Thesis. University of London. London - 1959 p-44 to 60.