

A PROGRAMME FOR GEOPHYSICAL EXPLORATION IN GHANA

By

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ABSTRACT

An appraisal of all the Geophysical methods has been made here, in the light of the geology and the type and pattern of mineralization in the area of interest. The physical properties namely, densities, electrical resistivities and magnetic susceptibilities of the important rock types at the camp of the "Ashanti Gold Fields," a well known mineralized zone, have been measured.

An Induction Coil specially built for measuring magnetic susceptibilities of small unpowdered samples is described in detail in Section II of this work.

The results obtained from the various measurements indicate that density contrasts among the rock types are not high enough to make Gravity methods useful. On the other hand, the susceptibility, the electrical resistivity and the metal-factor contrasts are significantly high and suggest that Magnetic and Electrical Methods could be the most useful geophysical tools in the search for sulphides and other economic minerals in Ghana.

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S E C T I O N I

A PROGRAMME FOR GEOPHYSICAL EXPLORATION IN GHANA

INTRODUCTION

Ghana is better known, especially in Scientific literature by its former colonial name of the Gold Coast. In 1957 the British Colony of the Gold Coast (with a population of approx. 6,500,000) obtained its independence from colonial rule, thus becoming the first self-governing West African country within the British Commonwealth of nations. It was in this historic year that the name Gold Coast was changed to Ghana, in memory of the legendary Empire of Ghana, allegedly destroyed during the 12th Century as a result of several wars during the Great Islamic expeditions in Northern Africa.

GEOGRAPHY

Ghana is roughly rectangular in shape, with a north-south to east-west ratio of 6:5. It covers approximately 91,000 square miles, with a fairly smooth 330 miles of coastline of extensive white sandy beaches, washed by strong breakers from the Gulf of Guinea.

As one travels from the coast to the northernmost border, one passes through three distinct geographical belts, namely; (a) The Coastal Belt, (b) the Forest Belt and (c) the Northern Plains.

The general relief of the country is moderate. The southern region covering the Coastal Belt and the greater part of the Forest Belt is relatively low (200-400 ft. high) or rolling, and it is characterized by

dissected scarps of ancient peneplains and many isolated peaks, which are in the general order of 1500-2500 ft. high. The northern region, covering mostly the Northern Plains and only a small portion of the Forest Belt, is plateau-like with an average height of 500 ft. It is, however, gouged in places by the Volta River and its many tributaries. The Coastal Belt has lost a great deal of its forest through land deforestation; and in the east, where the belt is broadest, the scrub-land breaks up into a fairly extensive plain. The Forest Belt is heavily vegetated. It contains large reserves of hard wood timber including different species of mahogany, odum, and cedar. The Forest Belt is, in general, much more fertile than the Coastal Belt or the Northern Plains. It is the richest cocoa growing region in the world.

Ghana has a typically hot and dry - hot and wet climate. The average temperatures for the southern region is 85° F. The north is much warmer, with an average of 90° F., but less humid. The humidity in the southern region is between 76 and 90%. Coastal towns and spots of high relief in the interior are generally cooler and healthier.

The country, particularly in the southern region, is well drained. However, during the long dry season from December to March, all the small streams and most of the intermediate streams dry up, thus creating an acute shortage of water. One of the important jobs of the Geological Survey, therefore, is locating aquifers for well sinking. In this case, the geophysical method commonly employed is the electrical resistivity.

THE MINERAL INDUSTRY

Although the major industry of Ghana is agriculture (it produces half the world's cocoa), the mining industry constitutes an important source of revenue in the country. The chief mineral exports include manganese, diamonds, gold and bauxite. It is the leading producer of high grade manganese in the West and second only to Russia in the world (Bateman, Econ. Min. Deposits, 2nd Ed.). The bauxite reserves in the world at the end of 1958 were estimated at 3.2 billion tons, and Ghana is one of the six countries which hold these reserves; the others are Guinea, Australia, Jamaica, Surinam and Hungary (U. S. Bureau of Mines, Alumina and Bauxite, Preprint, Bulletin 585, 1960). Until now, only the British Aluminum Company has been mining bauxite in Ghana; but the reserves are estimated at several hundred million tons. Ghana is also a great world producer of industrial diamonds, second only to the Belgian Congo. The record of the world production of diamond in 1958 was as follows: Belgian Congo, 70%; Ghana 12%; South Africa 7%; Sierra Leone 4%; and six other countries were responsible for the rest (U.S. Bureau of Mines, Diamond - Industrial, Preprint, Bulletin 585, 1960). Gold mining is equally important. There are many small streams with placer gold yet to be worked. At present only three dredges operate in the large streams and rivers. Reef and "banket" gold are mined in several places. The "Ashanti Gold Fields" at Obuasi is said to be the richest gold mine in the British Commonwealth.

Aside from these four major minerals, there is also a high-grade hematite ore deposit estimated at 100 million tons in the Yendi - Zabuzugu area, in the N. W.; there are showings of chromite in serpentine and pyroxene rocks in the south eastern region. Kyanite

gravels are found in a number of streams in the central region and platinum is found in some basic rocks in the south west.

OUTLOOK FOR THE FUTURE

For its size therefore, it can be said that Ghana has high mineral potentialities. The mineral industry in Ghana is nowhere near the peak of productive capacity at present and mineral revenue constitutes only 15% of the annual income of the country. The largest bulk of the annual revenue comes from the sale of cocoa. Fearful of what might happen if cocoa prices suddenly dropped, the Government is very anxious to see a new impetus put into the mineral industry. The first pressure is therefore on the Geological Survey, which is required to outline the ore reserves in manganese, gold, diamonds and bauxite, and to start a major mineral exploration programme with the aim of finding new economic minerals.

As far as exploration work is concerned, there are no great difficulties envisaged in a survey programme to outline in detail the reserves in manganese, bauxite or diamonds; these are by and large near-surface residual deposits formed by prolonged weathering under tropical conditions. The problem at hand is to attempt to extend the known zones of gold and associated sulphide mineralization into unknown regions of similar geologic conditions. Several obstacles have prevented this approach from being successful and one of these hinderances is the surface weathering, which not only covers extensive areas, but is so deep in places (from few feet to 300 feet) that leaching of sulphides in at least the first 10 ft. from the surface is almost complete. Geochemical surveys in many target areas hardly show anything beyond the background values of copper and lead.

But before the problem is stated more clearly, the geology of the country will here be discussed briefly.

GEOLOGY

The following is the stratigraphical succession of Ghana prepared from the latest Geological Map, issued under the Directorship of Mr. D. A. Bates.

Fig. 1. (detached sheet) is the Geological Map of Southern Ghana.

- UPPER TERTIARY:** Red lateritic beds of continental origin.
- UPPER CRETACEOUS - EOCENE:** Sands, clays and limestones.
- UPPER JURASSIC - AMISIAN:** Unconsolidated Conglomerates and shales.
- DEVO - CARBONIFEROUS - (a) SEKONDIAN:** Sandstones; black shales; chocolate siltstones and arkoses.
- UPPER PALEOZOIC (b) ACCRARIAN:** Fine brown shales containing marine Devonian fauna.
- VOLTAIAN:** Shales, chocolate brown sandstones, mudstones, quartzites and conglomerates.
- LOWER PALEOZOIC BUEM FORMATIONS:** Basaltic, andesitic and trachytic lavas. Shales, sandstones, greywackes and tillite?
- TOGO SERIES:** Quartzites and mica schists, phyllites, and silicified limestones.
- TARKWAIAN:** Phyllites, sandstones, quartzites with "basket" conglomerate, and basal conglomerate.
- UPPER BIRRIMIAN:** Metamorphosed lavas, epidiorite tuffs, agglomerates and tuffaceous phyllites.
- LOWER BIRRIMIAN:** Greywackes, tuffaceous phyllites, and graphitic schists.
- PRECAMBRIAN DAHOMEYAN:** Quartz - schists, marble, granulites, migmatites, and syenites.

INTRUSIVES

BASIC: POST TARKWAIAN: norites, pyroxenites, peridotites, serpentine, dolerites and gabbros.

ACID: POST BIRIMIAN GRANITES:

(a) **WINNEBA GRANITES:** medium grained biotite granites.

(b) **DIXCOVE GRANITES:** Hornblende granites, granodiorites, pegmatites, aplites and diorites.

(c) **CAPE COAST GRANITES:** Biotite and muscovite granite-gneisses, aplites and migmatites.

DETAILED DESCRIPTION

1. As shown on the stratigraphic column above, the DAHOMEYAN constitutes the most ancient group of rocks in Ghana. It occurs in the southeast corner of the country and extends to as far as Nigeria, maintaining a constant northeast strike and low angles of dip. The common rock types in the group include schists, granulites and migmatites. As stated by D. A. Bates in his paper entitled "The Geological Evolution of the Gold Coast," 1955 (3), the Dahomeyan formed a continental shield in Precambrian time, and in later geologic periods it was slowly uplifted and eroded to reveal the deep seated rocks now seen on the surface. According to Bates the area northwest of the Dahomeyan block constituted a major region of repeated subsidence and geosynclinal depositions, dating from Birrimian time to the Voltaian.

2. The BIRIMIAN geosyncline is now known to have been the deepest and the most extensive. It stretched from the edge of the Dahomeyan land mass northwestward. It covered the whole of Ghana and extended as far as Sierra Leone and Mauritania. The sediments formed have a typical geosynclinal association; i.e., predominantly argillaceous sediments at the

base, followed by great thicknesses of waterlain tuffs, pillow lavas and rhyolitic lavas, intruded by numerous diabase dykes. Later, metamorphism altered the argillaceous sediments and greywackes to phyllites and meta-greywackes, the tuffs to tuffaceous phyllites, the lavas to greenstones, and the dykes to epidiorites. The Birrimian series now covers wide areas of the southern regions, particularly within the area bounded by heavy broken lines in the accompanying map, fig. 1, where its thickness ranges from tens of feet as roof pendants over the Birrimian granites, to several thousands of feet. The Upper and Lower Birrimians are found in several places together, though in many places only the Lower Birrimian occurs. The Upper Birrimian is marked by great thicknesses of metavolcanics such as tuffs, altered lavas, with abundant pillow structures and greenstones; while the Lower consists of more greywackes, phyllites and graphitic schists, and less tuffs and greenstones. All these altered sediments still maintain their sedimentary nature. A typical section consists of some 60 - 100 ft. of greywacke, followed upwards by some 40 - 60 ft. of phyllites, above which is a tuff or tuffaceous phyllite band 30 - 200 ft. thick and followed by 100 - 200 ft. of altered lavas or greenstone. This sedimentary series repeats several times, though the order of succession may change.

The Birrimians maintain a persistent N.N.E. strike with steep to very steep dips (48-85°). They are isoclinally folded in general, but in several places the folds get even more intense and complicated with the competent beds forming recumbent folds while the phyllites and other incompetent beds form anticlinoriums, and other minor folds.

For economic purposes, the Birrimian constitutes the most important geologic group. All the gold and sulphide mineralizations known, occur in

the Birrimian. The black phyllites contain sedimentary manganese oxides which under tropical weathering are reconstituted into manganese ores that cap several hills. Similarly, the tuffaceous phyllites weather to form large deposits of bauxite and lateritic iron oxides. The diamond deposits in the east occur in weathered Birrimian greenstones and tuffs. Because of its economic importance, much of the geology in this work is directly connected with the Birrimian system in the southern part of the country, though only the most relevant topics can be discussed.

As the other formations in the succession are not too important in this discussion, only brief comments are here necessary to complete the geologic picture.

3. The next system after the Birrimian is the TARKWAIAN. The Tarkwaian geosyncline occupied the eastern half of the area which was covered by the Birrimian geosyncline, and here also the presence of subsidence along the edge of the Dahomeyan was maintained.

The Tarkwaian rocks rest unconformably on the Upper Birrimian series and consist of phyllites, sandstones, quartzites and a basal conglomerate. The basal conglomerate is the source of the alluvial diamond gravels in the west. It is much more magnetic than any other formation of the Tarkwaian system and can therefore be identified by magnetometer survey. There is also a persistent 5 - 10 ft. conglomeratic band called the 'banket,' in the quartzite formation which is mined for gold. The Tarkwaian is also folded and faulted, but less intensely as compared to the Birrimian.

4. The TOGO Series developed in a much narrower geosyncline formed after the Tarkwaian period. The Togos lie on post-Birrimian granites.

They are relatively undisturbed at the northwest margin, but on the southeast they are folded and thrust against the Dahomeyan.

5. The BUEM formations include an Upper group of basalts and other volcanic rocks and a Lower sedimentary group which formed in a narrow but long geosyncline on the western margin of the Togo series. Like the Togo, the Buem is also folded and thrust from the east. Its strike is approximately parallel to the Dahomeyan.

6. The VOLTAIAN shales, siltstones and sandstones are said to have been deposited in a shallow, gently subsiding basin and are now, for the most part, a flat lying series of sediments. The Voltaian Basin is thought to be a mild repetition of the subsidences that formed the earlier systems. However, it is believed that the actual geosynclinal conditions, which started in Precambrian time with the deposition of the Birrimian sediments, died out after the Buem geosyncline, and that the Voltaian rocks were actually deposited in a shallow continental basin on the shield which consisted of all the previous formations.

Bates (3) pointed out, in his paper already referred to, that the remarkable feature in the geological evolution of Ghana since Paleozoic time is the persistence of the landform, and the development of another geosynclinal condition along the present continental edge of the coast. Thus all the sediments formed after the Voltaian are found only on the coastal belt. For instance in 1957 a borehole put into the outcropping Cretaceous beds on the coast in the southwest penetrated through an unexpected 10,000 ft. of sediments. The work was undertaken by the Gulf Oil Company and the drill cores showed faunal assemblages in the formations which date from Permian to Cretaceous age.

7. The ACCRARIAN series outcrop prominently on the coast of Accra. They consist of brown shales and sandstones about 600 ft. thick containing marine fauna of Middle Devonian age. The series rest unconformably on the Precambrian rocks.

8. Further west, from Cape Coast to Ajua through Elmina, Kommenda, Sekondi and Takoradi, more sediments of Devo-Carboniferous age occur. These sediments, known as the SEKONDIAN series, consist of greenish black shales (at the base), grey and green glauconitic sandstones, chocolate coloured sandstones and arkoses ranging up to about 5000 ft. thick. The shales at the base show intra-formational, slump and varve structures, and are thought to have formed under glacial conditions.

The Accrarian and the Sekondian (Devo-Carboniferous) series are not folded; but they are block faulted into a series of horsts and grabens, which strike roughly parallel to the coastline.

9. The AMISIAN which is said to contain ostracods of Upper Jurassic to Lower Cretaceous age, occurs on the coast from Saltpond to Winneba. The beds consist of an unconsolidated conglomerate at the base and shales at the top. Boreholes through the formations at Saltpond revealed thicknesses of 300 - 400 ft. of sediments. Like the Sekondian and the Accrarian of the Devo-Carboniferous age, the Amisian is not folded, but faulted into horsts and grabens.

10. UPPER CRETACEOUS AND EOCENE: Beds forming a continuous series of sands, clays and limestones occur on the extreme southeast and southwest corners of the country (see section 7). They dip very gently at about 3° to the sea. Unlike the Devo-Carboniferous systems, they are not faulted.

GRANITE INTRUSIVES:

The geologic map of S. Ghana shows wide areas of granites. In fact, with the exception of the few comparatively small bodies of dolerites and gabbros, the granites constitute the only major intrusives in the country. The granites are of three distinct types and they bear the names of the type localities. They are: (a) the Cape Coast granites, (b) the Dixcove granites and (c) the Winneba granites.

The Cape Coast granites consist of biotite gneisses, muscovite biotite granite - gneisses and migmatites, and are cut by aplites and pegmatites.

The Dixcove granite complex consists of hornblende and biotite granodiorites, pink porphyritic felspar granites, and dioritic differentiates.

The Winneba granites are essentially medium grained biotite - muscovite granites. They are usually distinguished from the Cape Coast granites by their lack of foliation, their medium grained texture, their more sodic composition, and their minor constituents such as cassiterite, molybdenite, wolframite, etc.

It is generally thought that the Dixcove granites are younger than the Cape Coast granites, mainly because the former are associated with the Upper Birrimian Volcanics, while the latter are associated with the Lower Birrimian phyllites and greywackes. However, the Dixcove granites have nowhere been found intruding the Cape Coast granites. Similarly, the Winneba granites have not been found intruding the Dixcove granites, though there is evidence that the Winneba granites intrude the Cape Coast

granites in places. The future solution to this problem may be age determination by the potassium - argon method, or by the strontium - rubidium ratio method.

Although the type localities of the three granites are on the coast, each type is widely distributed all over the country. For instance samples of Dixcove granites collected by the writer in the type locality were matched with those collected by Dr. R. J. Murray in the Zuarungu area (some 300 miles away from the coast) and found to be similar in texture, colour and composition.

The granites in Ghana are generally called "Birrimian granites" because they are strictly post Birrimian in age. Field evidence shows that only one granite magma was responsible for the formation of the three granites and that this magma intruded the Birrimian system at various levels and was thoroughly contaminated in the later phase, giving rise to granodiorites and diorites which are so typical of the Dixcove type. Indeed the granites seem to form a continuous batholith beneath the whole Birrimian system.

GOLD AND SULPHIDE MINERALIZATION IN THE BIRRIMIANS

The association of Dixcove granites with the Birrimians is of great economic importance. In several regions the boundary zones show many gold-bearing quartz veins or lodes intruding the Birrimian tuffs, greenstone, phyllites and graphitic schists. At Agona Nkwanta near Dixcove, the author examined a gold-bearing pegmatite vein intruding the Upper Birrimian meta-volcanics. This vein had been worked partly from an adit and partly by trenching, and could be traced from the Birrimian complex

into the Dixcove granite, which is here a pink porphyritic felspar granite. No gold is associated with the quartz veins which occur in post Birrimian systems such as the Togo series or the Buem.

It is therefore accepted by most authorities that the Birrimian granites and in particular the Dixcove type have been largely responsible for the gold mineralization. It is believed that the Birrimian sediments originally contained small amounts of disseminated gold and sulphides. The granite magma by intruding and stopping its way upwards assimilated large quantities of the Birrimian, then reconcentrated the gold and the sulphides and liberated these back into the overlying Birrimian rocks at the pegmatitic or hydrothermal stage. If this theory has any substance, one should expect gold mineralization near or in the granite-Birrimian contact zones; and this is in fact what happens in the field. The gold-bearing quartz veins or lodes are found more often near the contact zones. It is further observed that the mineralization is more intense when the boundary is between Dixcove granites and Upper Birrimian Series. This is shown clearly by the position of the gold mining towns and districts (see fig. 1). At certain localities in the western region, delineated by heavy broken lines on the map, there are numerous small circular pits or shafts 50 - 100 ft. deep. These pits are ancient gold workings located on the disintegrated auriferous quartz veins in the weathered Birrimian Series. All the present day gold mines are located, without exception, on old workings.

In the deep modern mines where the rocks are fresh, the mineralization is not only confined to lodes or quartz veins, nor does it consist only of gold. In several of the mines, the gold is associated with such sulphides

as pyrite, chalcopyrite, sphalerite and arsenopyrite. The last mineral may be of considerable interest in future exploration work for at the Obuasi mines the arsenopyrite, carrying up to about 18 penny-weights of gold (\$30.0) per ton of rock, is mined. The gold occurs as an ex-solution in the arsenopyrite. The arsenopyrite is not in the quartz veins but occurs disseminated in tuffs and graphitic schists. These tuffs and schists are mined only at Obuasi, though it is very likely that such disseminated tuffs occur in other places where the Birrimian has been mineralized. In the Ariston Gold Mines at Prestea and at Bibiani Mines further north, graphitic schists associated with the gold veins contain stringers of pyrite and chalcopyrite. At a small mine 3 miles east of the diamond town of Dompim, the author examined several drill cores of greenstone and tuffs, which were stained in places with malachite and chrysocolla, while unweathered cores contained pyrite and chalcopyrite.

WEATHERING PROBLEM

There are only a few places aside from stream beds that show fresh, unweathered rocks in this southwestern region under consideration. In most places and especially in the contact zones, both Birrimian and granites are deeply weathered. The depth of weathering, as pointed out earlier, ranges from a few feet to over 200 ft. Where the weathering is more than 50 ft. deep, the first 10 - 30 ft. from the surface shows no structure or semblance of any particular bedrock; but just lateratized soil even when the weathered material is in situ. At some Prospects, adits put at hillsides to approach auriferous veins often penetrate through highly weathered Birrimian rocks which contain in places numerous voids from

disseminated sulphides. Gravels in streams which cut weathered Birrimians often contain abundant cubic crystals of limonite pseudomorphic after pyrite; and gold dredges on the larger streams dredge large quantities of fresh pyrite from phyllites and graphitic schist which form partially weathered bedrocks.

GEOCHEMICAL WORK

Owing to the weathering problems, detailed geologic mapping of the country has proceeded very slowly. However, most of the existing mine camps have been mapped in detail by the Geological Survey. Attempts to extend the zones of mineralization from known areas such as the mine camps to adjacent areas by geochemical methods have proved unsuccessful. This is because in most places the first 6 - 10 ft. of top soil has been almost completely leached.

POSSIBILITIES IN GEOPHYSICAL METHODS

It appears that some geophysical methods will of necessity be employed, if the mineral exploration work is to continue. The question then is what kind of geophysical methods, in the light of the geology and mineralization patterns described above are likely to produce good results.

(a) Available Methods. Geophysical methods employed in mineral exploration include the following:

1. MAGNETIC

Resistivity

Electro-magnetic

2. ELECTRICAL

Self-potential

Induced Polarization

3. GRAVITY
4. RADIOACTIVITY
5. SEISMIC

A. CHOICE OF A SUITABLE METHOD

The choice of a geophysical method for mineral exploration depends often on several factors. These factors may be (a) financial, (b) technical or (c) geologic.

(a) The question of finance is of prime importance in every enterprise, and mineral exploration is no exception. For any exploration project requiring a geophysical method, a thorough study of cost must be made. The particular geophysical method chosen must be compared with other non-geophysical methods. If a less expensive method is found that can produce the same satisfactory result as the geophysical method, then for economic reasons, the latter method may not be used.

(b) The technical aspects involve adequate and competent personnel for collecting data in the field, for processing and interpreting the data, and for maintaining the equipment in satisfactory condition.

(c) The geologic factors are not less important than the other two. In fact if the geology of the region under consideration is entirely unsuited to any geophysical method, the financial and personnel factors must be considered from an entirely different viewpoint. In the present work, geophysics, applied essentially as a technique in mineral exploration, or as an aid to geologic investigations, will be dealt with.

B. GENERAL LIMITATIONS

Before discussing the usefulness of each method, the chief limitations of geophysical methods can be summarized as follows.

1. Geophysical, unlike geochemical methods are indirect. For instance, the information or data collected from a magnetometer survey can be plotted to give an Intensity-Distance curve, but without any other information, geologic or otherwise, the interpretation of the curve may not be anything like the actual object that produced the data.
2. All geophysical methods depend on some physical contrast of the geologic formation under investigation. These contrasts are often referred to as "anomalies." For instance, without a density contrast between the country rocks and the ore body sought, there can be no successful gravity survey. Similarly, without a magnetic susceptibility contrast between ore and surrounding country rocks, a magnetic method cannot be useful.
3. With the exception of Seismic methods, all geophysical methods are, according to A. A. Brant, limited in their usefulness, by the depth to which a body is buried (4). This limitation due to depth varies with the particular geophysical method used. For instance, in the case of Radio-activity methods, response cannot be obtained, in general, below 1 - 10 ft.
4. Finally, response by all geophysical methods to a contrasting ore body depends on shape and volume of the latter. For example, for magnetic methods, anomalies due to buried objects will decrease as:

- $\frac{1}{r}$ for long and thin dyke-like bodies,
- $\frac{1}{r^2}$ for bodies with single poles such as steeply dipping cylindrical pipes, with the other pole far away from the surface,
- $\frac{1}{r^3}$ for lens-shaped bodies,

where r is the distance from the body to the point of observation (11). The serious limitations brought about (particularly in mineral exploration) by the volume and shape problem, in relation to geophysical methods, are expressed in very realistic terms by A. A. Brant (4). He maintains that the response from a tabular body 1000 ft. wide buried at a depth of 1000 ft., is similar to the response from a 10 ft. wide body of similar shape under 10 ft. cover. Furthermore, a lens-shaped body cannot be detected further than 10 times its width or thickness.

C. THE SEISMIC METHODS

The Seismic methods namely, Refraction and Reflection methods, which have been widely used with much success in oil exploration, have had rather limited application in mineral exploration; the principal obstacle being the size and shape problem, mentioned above. In both Refraction and Reflection methods, which use the principles of wave propagation, the minimum size body detectable, as quoted by Brant (4) has the following relations

$$\bar{V} = \sqrt{\frac{ur}{f}} \quad (1)$$

where \bar{V} is the average volume of the object, r the distance of the object from the point of observation, v the velocity of propagation and f the frequency of propagation.

Aside from their smallness in relation to the surrounding country rocks, ore bodies often have such steep dipping and rather complicated structures that the propagating wave is apt to miss them for the surrounding country rocks which are often more extensive in size, and simpler in structure.

However, the Refraction method has had a particularly successful application in the determination of the depth of overburden or thickness of weathered material over the actual bed rock. The procedure here involves the interpretation of a two-layer travel-time curve, which is a simple and straight forward operation. As part of the solution to the weathering problem mentioned earlier, the Refraction seismic method is recommended for preliminary determination of the thickness of the weathered cover. Portable Refraction equipment which can be transported and operated successfully by two, is now obtainable. There is a fairly wide claim that such 'portables' can detect minimum thicknesses of 4 - 10 ft. of overburden.

D. THE RADIOACTIVITY METHODS

These methods have been widely used of late, in the search for radioactive mineral deposits. The methods depend on the detection of gamma and other particle radiations of radioactive minerals in rocks.

Because of their limitations, the Radioactive methods are of no immediate use in the search for the type of minerals under the present investigations.

E. GRAVITY AND MAGNETIC METHODS

Gravity and Magnetic methods are very widely used in exploration geophysics. The Gravity methods depend on the density contrasts among rock types in any particular area under investigation. The Magnetic methods on the other hand depend on the differences in the magnetic properties of rocks.

Gravity and Magnetic methods have several properties in common. They both depend on some force of attraction. In the case of Gravity, the gradient of the gravitational potential is measured. In Magnetic methods the gradient of the Horizontal component can be obtained from the Vertical magnetic potential. Both Gravity and Magnetic methods suffer from a fundamental limitation, namely, the nonuniqueness of gravitational or magnetic solutions. D. C. Skeels (23) has discussed the question of non-uniqueness thoroughly in his paper, by practical as well as mathematical demonstrations. Skeels maintains that even when sufficient data of a gravity or magnetic survey have been carefully assembled, and all relevant corrections made, the interpretation of the curves from such a data is still ambiguous; this being due, as he puts it, to the fact that the gravitational (or magnetic) field is in itself insufficient "to define the mass distribution which produces it." In other words a gravity or magnetic curve is liable to several interpretations, unless some other independent information, usually geological, is known.

It is for this reason that the geology of the area under investigation, namely, Southern Ghana was described in some detail in the early part of this work. Also, careful measurements of densities and magnetic susceptibilities of a group of rocks, representative of the common rock types in the area, have been made with the view to eliminate, almost completely, the ambiguities in the interpretation of magnetic and gravity surveys.

1. DENSITY MEASUREMENTS

The densities of the various rock types (described in page 47), were obtained by first weighing a number of pieces of each rock type in air with

a chemical balance, and then re-weighing each of them while completely submerged in water. For each sample, the density is the weight in air divided by the difference of the two weighings. Detailed results of the rock densities are tabulated with the magnetic and electrical measurements in table 6, page 58.

2. MAGNETIC MEASUREMENTS

For the determination of the magnetic properties of the rock types, an apparatus was built to satisfy certain requirements. The building of this equipment constitutes a major section of this work, as later discussions will show. But before discussing the magnetic properties of the rock types and the methods of measurements, a short enquiry into the possible use of electrical methods for the types of minerals sought will be made.

F. THE ELECTRICAL METHODS

The Electrical methods are more widely used in mineral exploration than Gravity, Seismic or Radioactivity methods. Electrical methods are many, and available equipments numerous. However, most of these methods fall in two groups, namely:

- (a) those that use natural ionic or electrical fields in the earth's crust, such as Self Potential and Telluric Current methods, and
- (b) those that require electrical energy, artificially transmitted into the ground, such as Resistivity, Electromagnetic and Induced Polarization methods.

LIMITATIONS OF ELECTRICAL METHODS IN EXPLORATION GEOPHYSICS

1. RESOLUTION AND DEPTH PROBLEMS

Though widely used in Geophysical Exploration, Electrical methods are significantly limited by their low resolving power and lack of penetration (9).

Several methods lack the ability to isolate the contrasting electrical effects of the mineralized body from those of the country rocks immediately surrounding it. This is partly due to the polarizing effect of the saturated overburden or weathered upper layer which may be significantly conductive.

Regarding the depth problem, M. B. Dobrin (9) maintains that Electrical methods rarely give any information of subsurface structures deeper than 1000 ft. For some methods this depth is definitely not reached. For instance, in the Self Potential method, the depth of penetration is said to be only 100 ft. For the Electromagnetic methods, Peters and Bardeen (21) have shown that there is a maximum depth of penetration h closely related to the resistivity ρ of the rock mass and the frequency f used; that is,

$$h \propto \rho^{\frac{1}{2}} \quad (2)$$

$$\propto \frac{1}{f^{\frac{1}{2}}} \quad (3)$$

It has been observed that for rocks with average electrical properties, the maximum effective depth of penetration is less than 1500 ft.

2. ADAPTABILITY

Some Electrical methods have very limited range of application. The Self Potential method for instance will only work successfully for massive sulphides undergoing oxidation above the water table; and it is said to be irresponsive to massive sulphides not undergoing oxidation(4); nor can the method be used for disseminated sulphide bodies. The Induced Polarization method, on the other hand, is said to be the most successful method in the search for disseminated sulphides.

3. ELECTRICAL PROPERTIES OF ROCKS

Each of the most widely used electrical methods, such as those mentioned above, respond effectively to one of the three principal electric properties of rocks, namely, electrochemical, conductivity, and capacitance. For instance:

(a) the Self Potential method depends on the electrochemical action associated principally with massive sulphide bodies in the zone of oxidation, which is generally above the water table;

(b) the Resistivity method depends on the inverse of 'unblock' conductive properties of rocks.

(c) the Electromagnetic method depends on the capacitance, or the ability of the rock to store electrical charges.

4. ON INDUCED POLARIZATION

Of all the Electrical methods, the Induced Polarization method, is said to be the most successful in the detection of 'porphyry coppers' and other disseminated ores, including primary oxides such as magnetite in gneisses and schists. This method therefore deserves a fuller note here, since it has already been mentioned that an important ore zone which is being successfully mined in the 'Ashanti Gold Fields' is an altered tuff, highly disseminated with gold-bearing arsenopyrite, pyrrhotite and other sulphides (see page 13).

The Induced Polarization method was originally referred to as the 'Electric-Transient' method, simply because unlike the other steady-state methods, it is the decay of a voltage or current with respect to time, after the sudden termination of the artificial voltage induced in the ground, that is observed. The Transient method was not a success, in its early use (9). This is partly because it was used indiscriminately as

'another Electrical method', and partly because its working principles were not as fully understood as they are today. Its singular success not long ago in the search for 'porphyry coppers', resulted in its revival.

The important advancement made in recent time was the recognition of the fact that the transient phenomenon in rock materials is mostly due to the polarizing effect on particles of metallic minerals, as the ionic current flows through the rock. On a sudden termination of the inducing current, the 'overvoltage' built up by this polarization, sets up a secondary flow of current that decays with time (9). Such a current is related to the amount of disseminated metallic minerals in the rock.

THE NEW CONCEPT AND TECHNIQUES

In recent years further advances in concept and techniques in Induced Polarization methods have taken place; a typical example being the contributions made by Dr. T. R. Madden and his group in the Department of Geology and Geophysics at the Massachusetts Institute of Technology (15, 16, 17). From their work, the subtle difference between the polarizing action of the inducing current or voltage in the metallic mineral particles and the more straight forward and comparatively large conductive effects of the inducing current on massive sulphides and other conductive bodies have been recognized, and studied in detail. In the Induced Polarization method, the polarized mineral particles are said to retain large charges like condensers while the inducing current is on, but discharge at definite rate when the current is cut off. The voltage developed, as a result of polarization, is what is referred to as the 'overvoltage.' Other effects attendant to polarization, namely, electromagnetic coupling and membrane polarization, were also studied by the group.

Several techniques are employed in measuring polarization effects in rocks. The methods developed by Madden, Marshall and others at M.I.T. included measuring the frequency of the overvoltage. The frequency measurement is interpreted as impedance. In practice the frequency spectrum of the induced polarization effects are so widely spaced, that the impedance is almost resistive, and this then enables one to use resistivity data to interpret the polarization effects of a disseminated ore zone (15).

The electrical conduction in a disseminated rock as demonstrated by T. R. Madden, et al, may be described as a circuit, which consists of an 'unblocked' ionic conductive path and 'blocked' conductive path with the two connected in parallel. The blocked conductive path consists of (a) resistance due to the metallic mineral, (b) a blocked ionic path and (c) a large impedance, due to the chemical action of the solution around the metallic mineral, which acts like a capacitor. The resultant impedance of the rock will include the blocked and the unblocked conductive paths of the 'rock circuit'. The blocked impedance which is frequency dependent is then isolated from the resultant impedance by measurement of the frequency. For this purpose, the impedance of some alternating frequency (A.C.) is compared with a much lower frequency referred to as the 'D.C. impedance'. Since this blocking frequency is due mostly to the metallic minerals in the rock, this quantity is referred to as the 'metal factor' which is expressed as follows (17):

$$m.f = \frac{2\pi \{R(D.C.) - R(A.C.)\} \times 10^5}{R(D.C.) R(A.C.)}$$

where $R(D.C.) = D.C.$ impedance.

and $R(A.C.) = A.C.$ "

The 'metal factor' is much used in determining polarization effects due to conducting particles of metallic minerals in rocks. The following are some figures quoted from the work already referred to.

<u>Rock type</u>	<u>Common Metal Factor at 10 c.p.s.</u>
Unmineralized granite	1
" basic rock	1-10
Finely disseminated sulphides	10-100
Disseminated sulphides	100-1000
Fracture filling sulphides	1000-10,000
Massive sulphides	> 10,000

INDUCED POLARIZATION MEASUREMENTS OF SMALL SAMPLES

The resistivities and metal-factors of a number of rock samples from the 'Ashanti Gold Fields' in Ghana were measured with an induced polarization measuring apparatus built for previous work at M.I.T. The rock types measured included greenstones, greywacke, tuff, altered tuff disseminated with sulphides, and graphitic schists which are usually associated with auriferous quartz veins. The apparatus which is designed to measure the time of decay of the overvoltage, consists of three units (see Plate 1.)

(a) an electrical unit consisting of a timing motor with relays for current output, a reversing system, and a triggering voltage device.

(b) a sample holder which has four electrodes, two for receiving current from the relays and two for sending the transient voltage. The electrodes consist of silver gauze coated with AgCl, which are inserted in wet pads of felt to produce an electrolytic contact with the rock sample.

(c) The oscilloscope which traces decay voltages triggered into it, and measures the impedance, etc. for resistivity measurements.

Procedure:

Samples are soaked thoroughly in tap water for several days before measurements. During measurement, the receiving electrodes are open-circuited when current is passed into the sample. When the polarized voltage is being observed the sending electrodes are open circuited. In each operation the electrodes must make good electrolytic contact with the specimen.

Results:

Results of the induced polarization measurements of the rock samples mentioned above are tabulated in table 1. Induced Polarization methods have been found to have more resolving power than the straight forward resistivity method (15). However, it has been found that in field measurements, only a fraction of the polarization effects can be measured, since in most cases, the measuring apparatus is some distance removed from the bedrock from which measurements are being made.

Another problem is the fact that the induced polarization effects in a rock are not only due to the polarizing effects of the metallic mineral particles. As mentioned earlier, polarization effects are also known to be due to electromagnetic coupling and membrane effects. The former can be eliminated by using low frequency (approx. 10 c.p.s.).

Membrane polarization, however, operates in the same frequency range as the metallic mineral or 'electrode' polarization; but the former is often so small in magnitude as compared to the latter, that it (i.e. the membrane effect) can be neglected without serious error.

PLATE 1. Apparatus for measuring Induced Polarization of rock samples. Essential parts consist of a Sample Holder (left), a Timing Motor and a Triggering Voltage Device (center), and an Oscilloscope for tracing the Decay-Voltages (right).

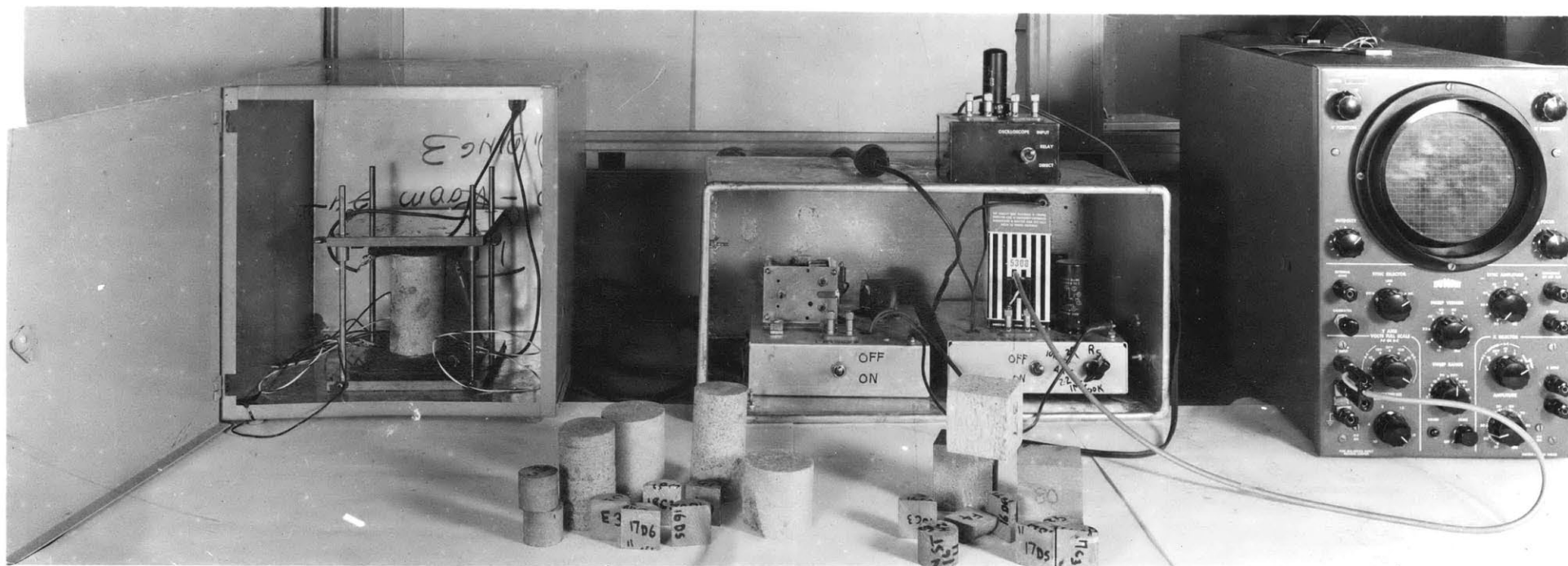


Table 1. Results of Rock Sample Measurements by Induced Polarization

Sample No.	Rock Description	Resistivity in $\frac{\text{ohm} - \text{ft.}}{2\pi}$	Frequency Effect	Common Metal Factor
16	Greenstone	4,090	1.03	0.732
17	Greenstone	2,370	1.30	13.6
18	Tuff	568	1.055	9.7
19	Greywacke	3,000	1.15	5.0
20	Altered tuff with disseminated Sulphides	140	1.48	344.0
21	Graphitic Schist	157	1.9	572.0

SECTION II

SUSCEPTIBILITY MEASUREMENTS OF SMALL UNPOWDERED ROCK SAMPLES

BY MEANS OF AN INDUCTION BALANCE

DEFINITIONS OF RELEVANT TERMS

A material placed in a uniform magnetic field of force H will tend to increase or decrease the field that passes through it. The new field within the material can be expressed as the flux density or lines of force per unit volume, B . The ratio of the flux density within the material B and the surrounding field H , is the permeability of the material, denoted by μ .

That is
$$\mu = \frac{B}{H} \quad (1)$$

If the material is considered as a magnet with moment M , then the magnetic intensity, designated by J is defined as the magnetic moment per unit volume, and B is related to J as follows:

$$B = 4\pi J + H \quad (2)$$

The ratio of the intensity of magnetization induced in the material to the magnetizing field H in which the material is placed is known as susceptibility k .

$$k = \frac{J}{H} \quad (3)$$

Therefore
$$J = kH \quad (4)$$

From equations (1), (2) and (4) we obtain the following relations:

$$\mu = 4\pi k + 1 \quad (5)$$

or
$$k = \frac{1}{4\pi} (\mu - 1) \quad (6)$$

From equation (3), it is clear that susceptibility has no units, for both J and H are measured in oersteds (or gauss).

Materials with high susceptibilities are referred to as ferro-magnetic. They include iron, ferro-alloys, and minerals such as magnetite, pyrrhotite, and ilmenite. Materials with low susceptibilities are said to be paramagnetic and those with negative susceptibilities are referred to as diamagnetic.

The susceptibility (i.e. J/H) of para- and diamagnetic materials should, for all theoretical purposes be constant over any given range of magnetic fields. The susceptibility of a ferro-magnetic material will on the other hand change with change in magnetic field as well as change in temperature. Above a certain temperature a ferro-magnetic material will lose most of its intensity of magnetization and become paramagnetic; the temperature at which such a change occurs is referred to as the Curie Point. A ferro-magnetic material also exhibits the well known hysteresis phenomenon in which the ratio J/H increases non-linearly over a certain range of H , till it reaches a saturation point after which J remains unchanged when H is increased. When H is reduced to zero, the magnetic moment of the material remains finite. In such a state the magnetic moment of the material per unit volume is referred to as the Remanent magnetization, designated by J_r . Fig. 2 shows the relationships between J and H for ferro-, para- and diamagnetic materials.

A. MAGNETIC PROPERTIES OF MINERALS

1. MAGNETITE $FeO \cdot Fe_2O_3$. k from 1.6 to 0.15, is responsible for the magnetic properties of most rocks. It is distributed in the groundmass of most igneous rocks as an accessory mineral or as ex-solution intergrowth in certain minerals. Magnetite also occurs in small quantities in some

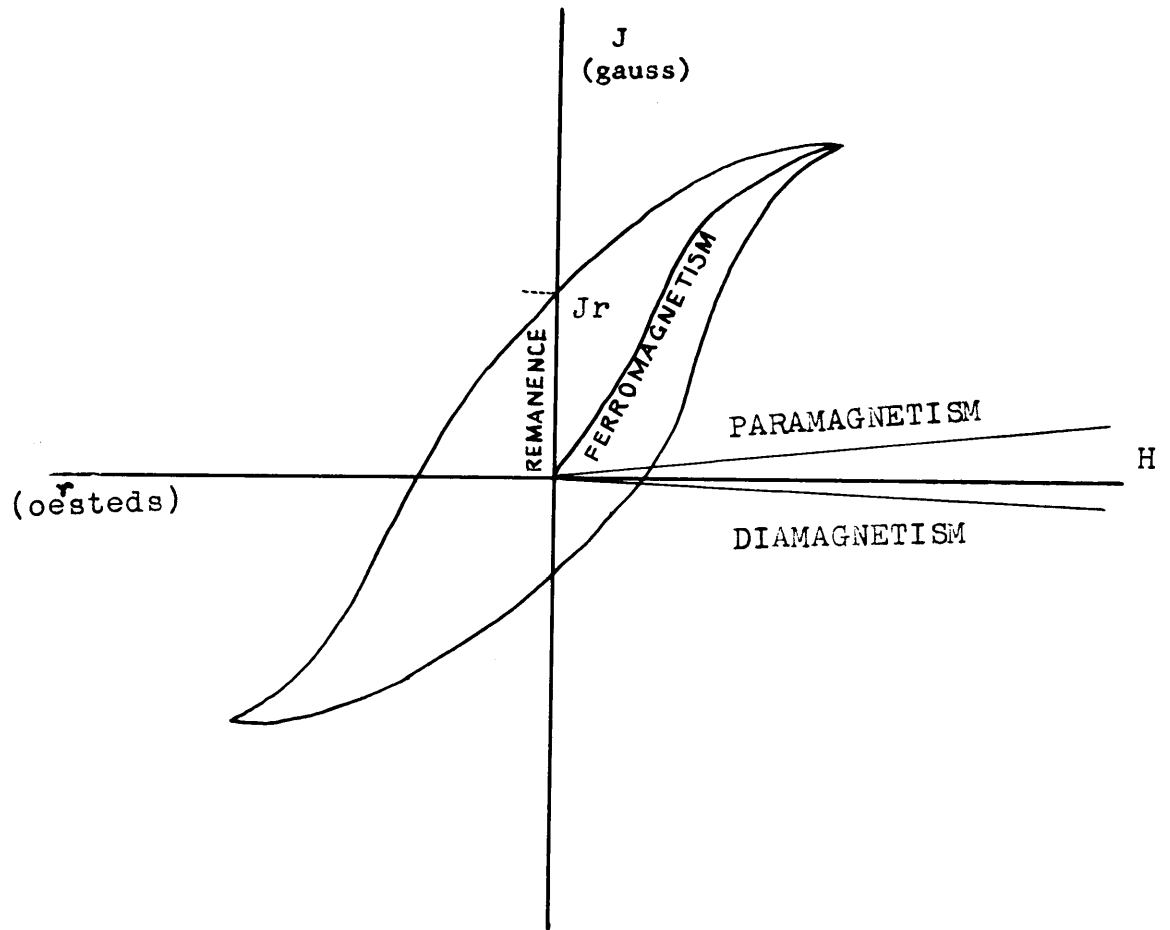


Fig.2. Relationship between J and H in ferro-para- and diamagnetic materials (after P.W. Selwood)

sandstones, shales and other sedimentary rocks. Metamorphic rocks generally contain significant quantities of the mineral.

2. The next mineral of importance is ILMENITE $TiO_2 \cdot FeO$. k is from 0.25 to 0.135. Like magnetite, ilmenite is also a fairly common accessory mineral in igneous rocks. In magmatic crystallization, Ti^{+++} is apt to replace Fe^{+++} . This gives rise to the isomorphous series in which magnetite and ilmenite are the two end members, with the titano-magnetites (e.g. the ferrous titanate Spinel $TiFe_2O_4$, and the tetragonal ferric titanate $Ti_3Fe_4O_{12}$) constituting the complex intermediate group. Susceptibilities in this isomorphous series decrease from magnetite to ilmenite.

It may be noted in passing that although hematite α - Fe_2O_3 has a high Fe^{+++} concentration, it nonetheless has low k , i.e. from 0.00016 to 0.00004. In certain instances, however, hematite has been reported with fairly high k . This is thought to be due to traces of magnetite within the hematite. Maghemite γ - Fe_2O_3 , a variety of hematite with spinel structure is ferro-magnetic in character, with high k (19). The mineral is said, however, to transform permanently to α - Fe_2O_3 at high temperatures.

3. Another important mineral of high k is PYRRHOTITE, with the general formula FeS_{1+x} . It ranges in composition from $Fe_{11}S_{12}$ to Fe_6S_7 , with max. k around 0.125. The susceptibility curve by Jura and Blitz (see fig. 3), shows that the magnetic properties of pyrrhotite are maximum when $X = 0.1$ and minimum when $X = 0.9$. Beyond $X = 0.9$ the mineral is practically non-magnetic. Pyrite FeS_2 which has very weak magnetic properties is in this last group. Pyrrhotite though not as common an accessory mineral as magnetite, in igneous rocks, is nonetheless an important constituent of

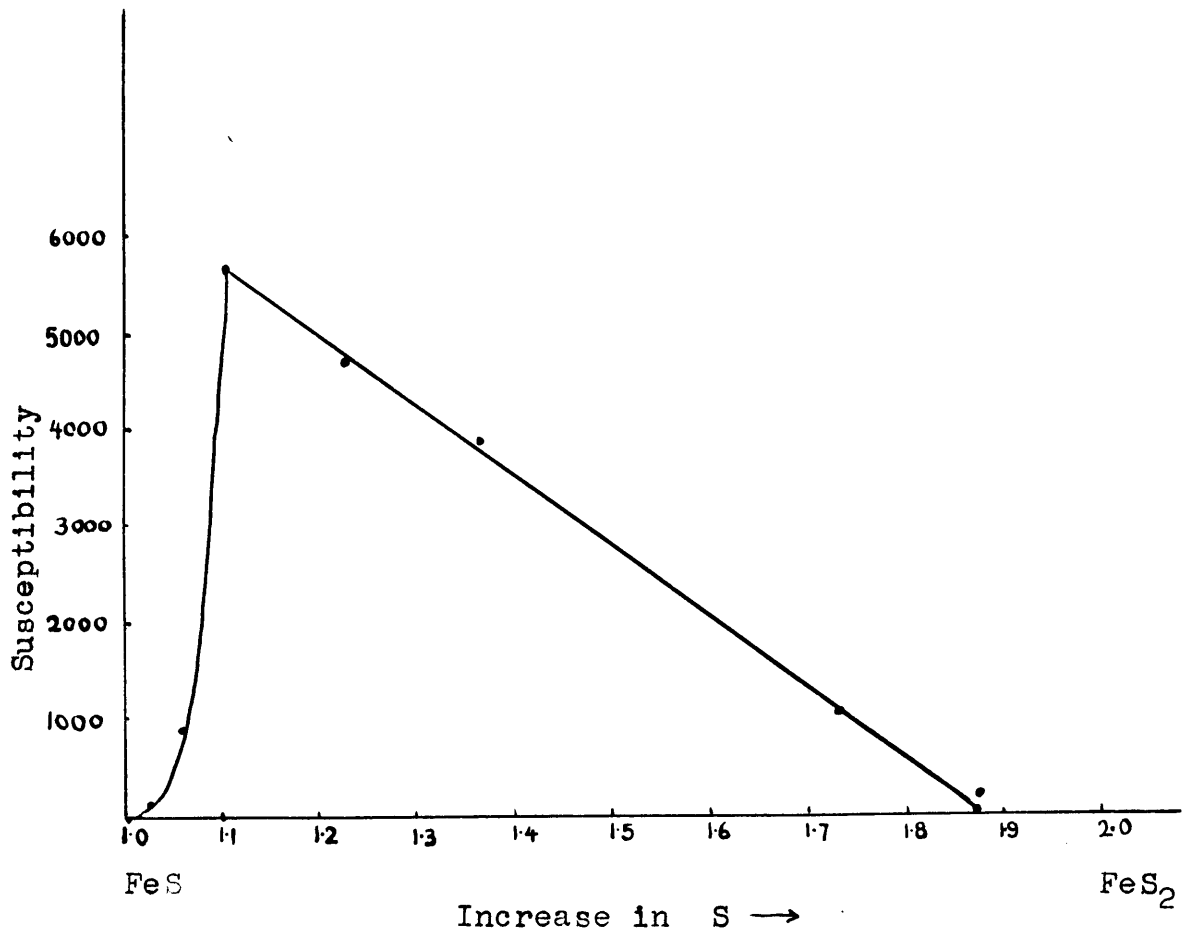
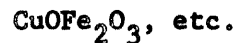
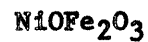


Fig. 3. Susceptibility of Pyrrhotite FeS_{1+x} with change in S. Measurements made in $H_{\text{max}} \rightarrow 3670$ Oe, at 20° C. (after Juza and Biltz)

many sulphide ores. It is often the mineral that gives the high k values to most complex sulphide bodies.

B. COMPLEX MINERALS

Complex minerals with noticeably high susceptibilities include Franklinite and the so called ferrites e.g.



The ferrites are iron compounds which can be prepared artificially. However, they are not common ore-forming minerals.

C. MAGNETIC PROPERTIES OF ROCKS

The ferromagnetic nature of a rock depends on the amount of magnetite and or ilmenite in it. Grain size of these two minerals is also an important factor in the k values of ferromagnetic rocks. This is clearly shown in figure 4. The non-linearity of the curve in figure 4 is also worthy of notice. Also, as already mentioned above, the increase in the amount of TiO_2 in magnetite decreases the magnetic properties of the latter. Consequently, a wide range of k values do occur even among any one rock type. For instance, two granite specimens from two localities may be similar in composition but may have entirely different k values due to their magnetite and ilmenite content.

Appendix 1 shows the variations in susceptibilities among some common rock types.

Most rocks are weakly ferro-magnetic, and a few are either para- or diamagnetic. In general, basic rocks are more magnetic than acid or

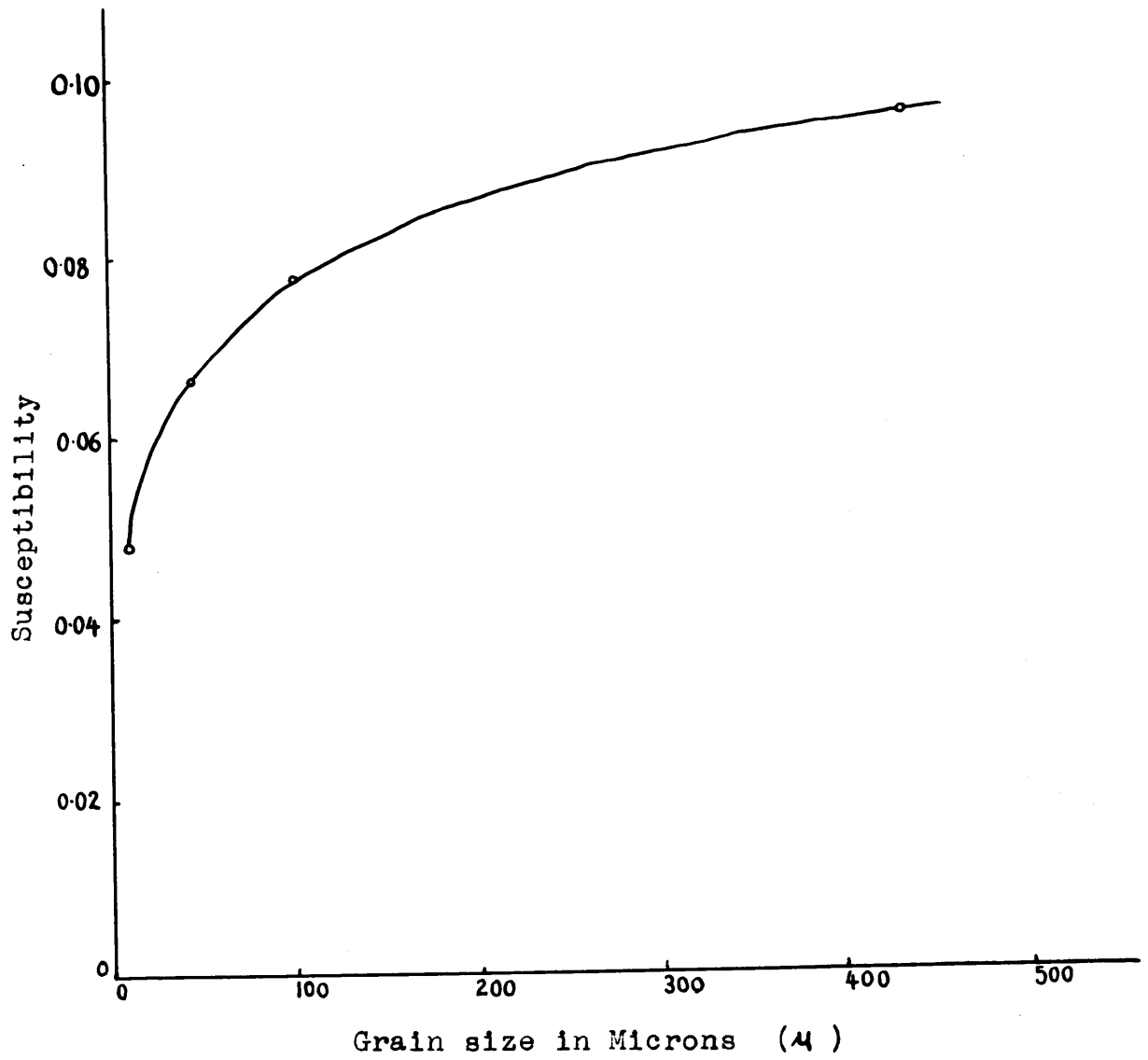


Fig.4. Susceptibility of rockforming ferro-magnetic minerals in relation to grain size (after T. Nagata).

intermediate rocks, though some granites and syenites have significantly high susceptibilities. Sedimentary rocks are generally low in k ; metamorphic rocks, on the other hand, may be high or low in k depending upon the original rock type, the texture and the grade of metamorphism. A few rock types have such low susceptibilities that they are for practical purposes said to be non-magnetic.

D. INDUCED MAGNETIZATION IN ROCKS

Excepting this last group mentioned above, all rocks exhibit induced magnetization - just as a piece of iron will do if placed in a magnetic field, only the intensity of the latter is several million times the intensity of most rocks.

E. REMANENT MAGNETIZATION IN ROCKS

Apart from induced magnetization some rocks also exhibit remanent or residual magnetization, which unlike the former is permanent and fixed in direction. Remanent magnetization is usually acquired by a rockmass at the time of its emplacement. It is, however, so weak in most rocks as compared with the induced magnetization that its effects are generally ignored in geophysical exploration.

F. FIELD STRENGTH

In nature the magnetizing field for all rocks is the earth's magnetic field, which ranges from 0.3 oested near the equator to about 0.6 oested in the vicinity of the magnetic poles.

PREVIOUS WORK ON MEASUREMENT OF ROCK SUSCEPTIBILITY

There are a large number of methods available for susceptibility measurements, and almost all of these are based on two principles, namely,

- (a) the steady field principle
- (b) the alternating field principle.

The steady field method makes use of a magnetic field which is time independent in its effect in causing induced magnetization in the sample. In the steady field method, care must be taken to avoid measurement of remanent magnetization. In general, apparatus used in this method requires rigid support. Examples of various adaptations of the steady field method include:

- (a) the Astatic Magnetometer method by E. A. Johnston and W. F. Steiner (13).
- (b) the Unifilar Magnetometer method by J. Konisberger (14).
- (c) the Balance Magnetometer method by P. Curie and C. Cheneveau (8); and also the modified form of the balance magnetometer by Lord Kelvin (12).

In the alternating field method, a time dependent field usually, sinusoidal, is applied to the specimen to produce a time dependent induced magnetization. Here the remanent magnetization effects are completely avoided. A few of the methods which adopt the alternating field principle include:

- (a) Induction Coil method by W. M. Barret (1).
- (b) the Induction Bridge Method by J. Mc. G. Bruckshaw and E. I. Robertson (5).
- (c) the Hughes Induction Balance method which was separately adapted by R. J. Diffin (10) and Harold M. Mooney (18).

REQUIREMENTS FOR THE PRESENT WORK

The requirements set forth for susceptibility measurements in this particular work are:

- (a) that the apparatus should be made sensitive enough to measure susceptibilities of the order of 10^{-5} in magnitude.
- (b) that the alternating field in which the rock samples are measured should be in the order of the Earth's field (i.e. about 0.5 Oe.); this being necessary since almost all the rocks to be measured are weakly ferro-magnetic in character.
- (c) that the apparatus should be fairly insensitive to vibrations since condition for rigid support of the apparatus could not be obtained in the laboratory.

Other factors taken into consideration included the fact that

- (a) the susceptibility measurements were to be made in the laboratory where interferences due to stray fields are unavoidable;
- (b) small samples were to be measured;
- (c) samples were expected to be as close to their natural state as possible, that is, they should be unpowdered, since powdering tends to change the grain size of the magnetic part of a rock sufficiently to change its susceptibility (see page 35).

It was also considered that by using unpowdered samples, any directional change in magnetic susceptibility or anisotropy, if present could be observed.

THE APPARATUS

The apparatus (plate 2) was designed by Dr. David Greenwalt and it is essentially an adaptation of Duffin (10) and Mooney's Induction Balance methods (18).

GENERAL PRINCIPLE

A system of induction coils may be arranged in a way such that when an alternating current of known amplitude and frequency is applied to a part of the coil system the net voltage produced, as a result of a material placed near one of the coils, is directly proportional to the susceptibility of the material. The constant of proportionality will of course depend on the sample position and coil geometry.

COIL ARRANGEMENT

(a) Theory "The Method of Images": If a circular coil of wire carrying a current i , is placed parallel to and at a distance d from a large flat slab of material of susceptibility k , the field outside the slab is the same as that produced in empty space by the coil carrying current i , and another (imaginary) coil of the same size parallel to the first coil and at a distance d behind the slab surface, carrying a current $i \left(\frac{2\pi k}{1+2\pi k} \right)$. If k is very small, the imaginary coil can be considered as carrying a current of $i \left(2\pi k \right)$.

This method of images offers a convenient way of interpreting the behavior of the coil arrangement used in this work.

(b) General Arrangement (see fig. 5)

(1) Two identical secondary coils are placed coaxially on either side of a primary coil. The two secondary coils are equi-distant from the primary coil and are wound in series opposition such that the total voltage E_s is zero, in space, for any current i generated in the primary coil.

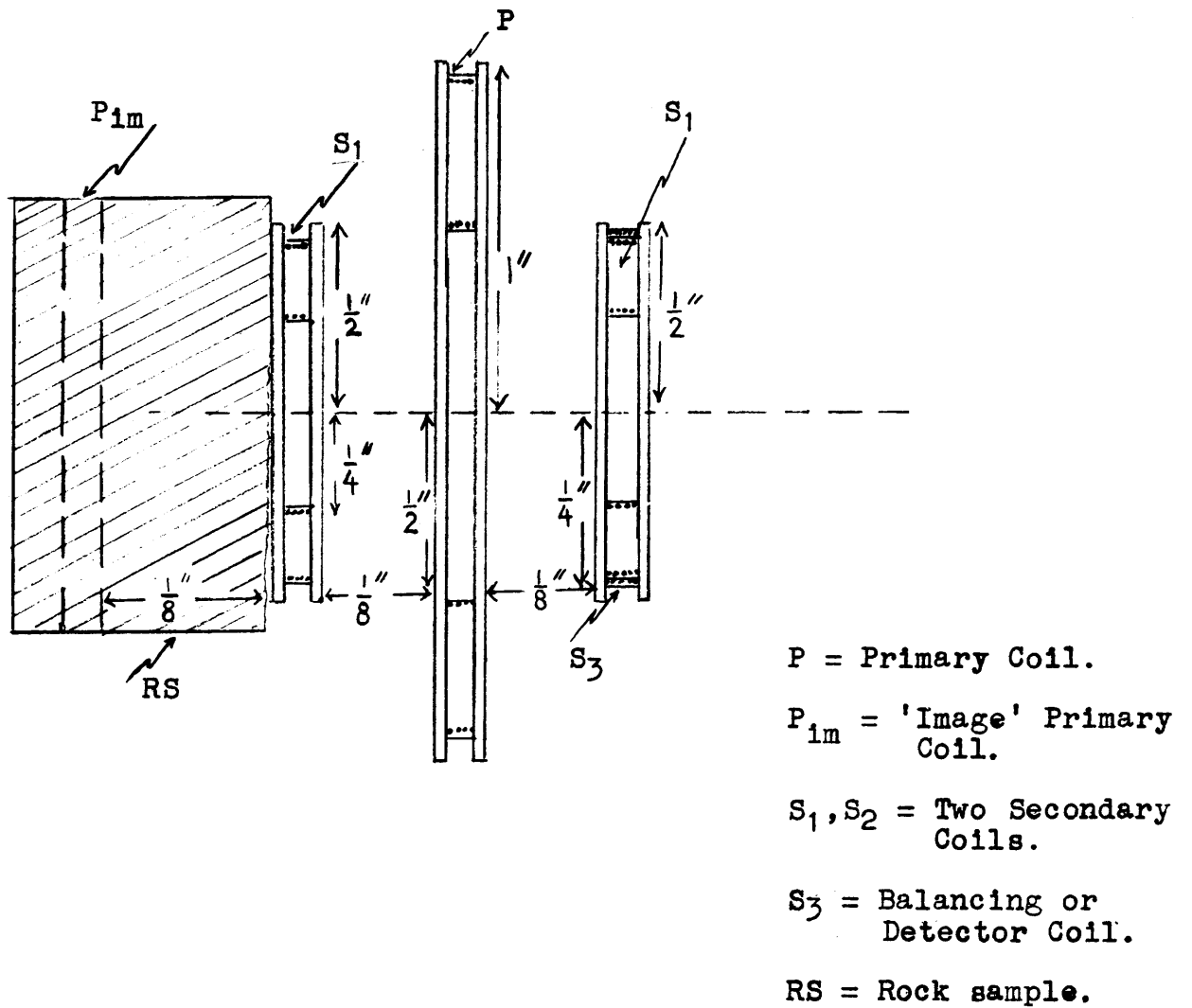


Fig. 5. Coil arrangement and rock sample in position.

(2) When a sample, large compared to the cross-section of the coils, with a flat surface perpendicular to the axis of the coils, is brought close to the coils, and of course much closer to one secondary coil than the other, the total voltage is no longer zero; and its magnitude is the same as if the sample were replaced with an image primary coil, according to the principles of the "method of images" stated above.

(3) The resultant voltage of the secondary coils then depends on the mutual inductance between the image primary and the two secondary coils in the following relation:

$$E_s = 2\pi k \omega i (M_1 - M_2) \quad (7)$$

where i is the magnitude of the sinusoidal current in the primary; M_1 and M_2 are the mutual inductances (with the 'image' primary) of the near (S_1) and far (S_2) secondary coils respectively. ω is the angular frequency of the primary current.

(4) If a small coil (of fewer turns) is placed near the primary coil and if k is small, the voltage produced in this small coil E_3 will be proportional to $i\omega$, i.e.

$$E_3 = \omega i M_3 \quad (8)$$

where M_3 is the mutual inductance of the small coil with the real primary. The ratio of the voltages may then be stated as follows:

$$\frac{E_s}{E_3} = \frac{2\pi k \omega i (M_1 - M_2)}{\omega i M_3} \quad (9)$$

In other words, the ratio $\frac{E_s}{E_3}$ is proportional to the susceptibility k ,

of the sample, the constant of proportionality being determined by means of a substance of known susceptibility. The voltage ratio is measured by means of a potentiometer and null-detector arrangement.

DETAILED ARRANGEMENT

A "lucite" coil form was used, and the coils wound upon it as described previously. The coil dimensions are given below in Table 2.

Table 2. Shows Coil Dimensions Chosen.

Coil	No. of turns	Outside Diameter	Inside Diameter	Thickness
P	2,000	2"	1"	1/8"
S ₁ = S ₂	2,500	1"	1/2"	1/8"
S ₃	50	1"	1"	1/8"

The diameter of the primary coil with respect to the secondary coils and the spacing between them relative to the diameters were chosen from the point of minimum inflexion on the curve, plotted with M, the mutual induction between primary and secondary coils as ordinate and X, the distance between the two coils as the abscissa.

The calculation of M is given by Grover's formula as follows (See Table 3, and Figure 6.):

$$M = \frac{mn\sqrt{rR}}{50} \left(\frac{p-q}{p+q} \right)^{\frac{3}{2}} + \text{Microhenries} \quad (10)$$

where M = mutual inductance for the primary and secondary coils,

m,n = No. of turns for the primary and secondary coils respectively,

R, r = radii of the primary and secondary coils respectively,

$$p^2 = [X^2 + (R+r)^2]$$

$$q^2 = [X^2 + (R-r)^2]$$

X = spacing between primary and secondary coils.

The curves in figure 6 were obtained by applying a series of numerical values to Grover's formula in equation (10). Curve 2 provides the most suitable dimensions for the coil arrangement. Dimensions chosen at the point of minimum inflexion of Curve 2 produces

- (a) constant signal for small changes in sample position; and
- (b) maximum signal.

To determine the minimum size of a sample that could be considered 'large', experiments were made with solutions of ferric chloride and also with apparently homogenous rock samples. By reducing the size and thickness of the material at a fixed position to the coils, a minimum limit of size was reached after which the signal began to reduce.

The dimensions obtained, were $3/8''$ for such a thickness and $1''$ for the diameter. Thus a small sample $1\frac{1}{4}''$ in diameter and $\frac{1}{2}''$ thick could be treated as a slab of infinite dimensions with respect to the apparatus.

Table 3. Shows Calculated Results of the Mutual Inductance between Primary and Secondary Coils, using Grover's Formula (see equa. 10) with different values for coil radii R , r and separation X .

X	M		
	R = r = 1	R = 2, r = 1	R = 3, r = 1
0	1.0	0.35	0.19
0.2	0.74	0.34	0.19
0.4	0.55	0.32	0.18
0.6	0.42	0.30	0.18
0.8	0.31	0.28	0.17
1.0	0.20	0.22	0.16
1.5	0.093	0.17	0.14
2.0	0.070	0.12	0.12
2.5	0.06	0.07	0.09
3.0	0.03	0.06	0.07
4.0	0.13	0.03	0.04
5.0	0.008	0.02	0.02

ACCESSORIES

Other parts of the apparatus included the following:

- (1) A Hewlet Packard Audio Oscillator which supplies power to the primary coil.
- (2) A Potentiometer arrangement consisting of a helipot with 10 turns in series and 10 position step-switch resistances which allow resistances to be read to 4 significant figures. Details of the potentiometer arrangement and calibration process with cupric oxide are discussed in Appendices 3c and 3b.

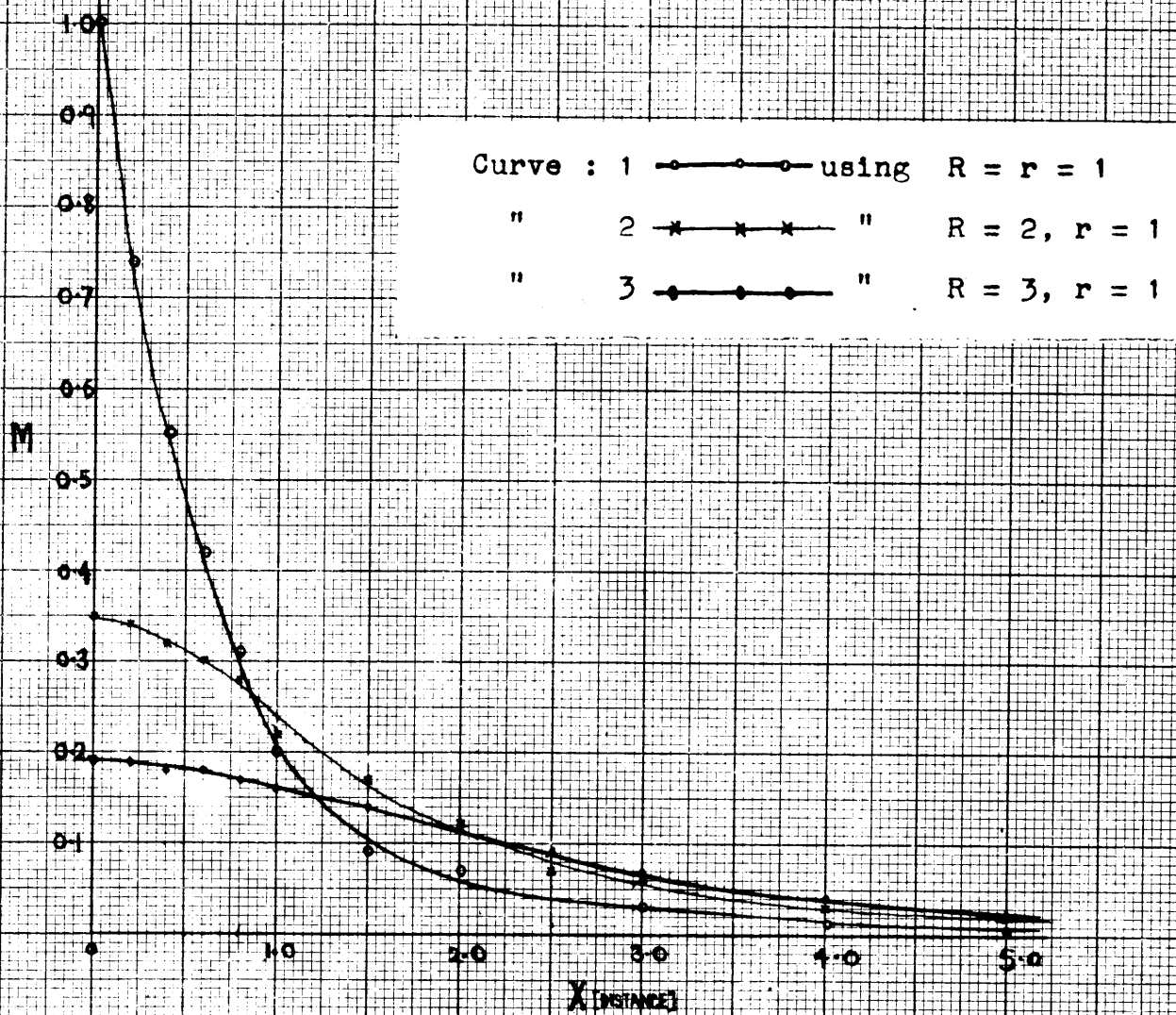


Fig. 6., Plots of Values obtained from Calculations, using Grover's Formula (See Table 3., page 45).

- (3) A General Radio Co. Amplifier and Null Detector Type No. 1231B.
- (4) An Oscilloscope for observing sharp balancing point and extraneous frequencies due to stray fields.

ROCK TYPES

As stated before, it was required in this work that small unpowdered specimens be used in order to:

- (a) obtain a fair sampling of the few large lumps of rock types and drill cores received for the experimental work, and
- (b) check the possibility of any directional differences in the intensity of magnetization (i.e. anisotropy) in each sample.

The samples dealt with include the following:

- (1) Three drillcores each about a foot long and $1\frac{1}{2}$ inch in diameter. Two of these were described as GREENSTONES and were labeled as specimen Nos. 16 and 17. The third was described as tuff and labeled here as sample No. 18.
- (2) A large lump of black compact rock described as GREYWACKE, was labeled as specimen No. 19.
- (3) Two large lumps of ALTERED TUFF, disseminated conspicuously with needles of arsenopyrite and veinlets of pyrite and other sulphides. This altered tuff was labeled sample No. 20.
- (4) The fourth rock type was an intensely sheared black graphitic schist with quartz stringers which are auriferous. The schist was labeled sample No. 21. These rock types were collected from the 'Ashanti Gold Fields' at Obuasi (see page 14) where the author visited five years ago; and they are representative of the country-rocks in the mining camp.

SAMPLE PREPARATION

(a) The drill cores were first cut perpendicular to the axes, in inch-and-a quarter lengths. Each of these $1\frac{1}{2}$ " pieces was then split diametrically along the axis of the core - and for each piece the split was made in a plane normal to the split plane of the preceding sample piece.

(b) For the lump samples, rectangular blocks about 2" on a side and a minimum of $\frac{1}{2}$ " in thickness were cut.

All the cutting was done with a diamond saw. Owing to the fixed orientation of bedding to the axes of the drill core, samples Nos. 16, 17, and 18 could not be cut parallel to and at right angles to the bedding plains. On the other hand samples 19 and 20 were cut parallel and perpendicular to the bedding or stratigraphic plains, thus making it possible to measure susceptibilities in three mutually perpendicular directions.

Also for Nos. 19 and 20 a sample face, if large enough, was quartered into α , β , δ and λ sections. This tended to improve the bulk average value of the measurement for each rock sample.

SAMPLE NOTATION

The notations found in the tabulated results of susceptibilities (see appendices 2a and 2b) mean the following:

(a) For the drill cores.

(1) Numbers 16, 17, etc., represent the rock types.

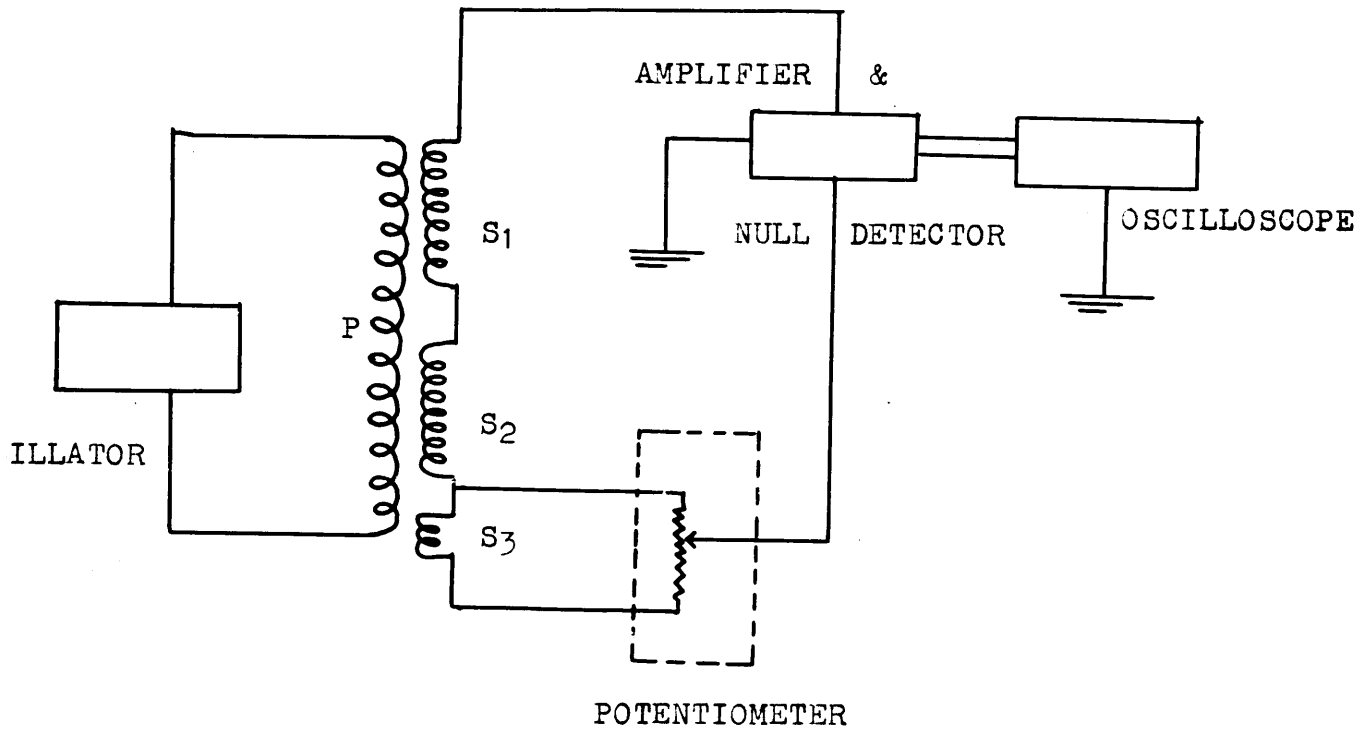
(2) Capital letters A, B, C, D, etc., represent the inch-and-a-quarter pieces of a rock type.

- (3) Subscripts 1 and 2 represent top and bottom respectively of each $1\frac{1}{2}$ " piece.
 - (4) Subscripts 3 and 4 represent longitudinally split surfaces of (2).
 - (5) Subscripts 5 and 6 represent longitudinally split, surface, normal to 3 and 4.
- (b) For the block samples.
- (1) Numbers 19 and 20 represent rock types as described above.
 - (2) A,B,C,D, etc., represent the blocks cut from the original lumps.
 - (3) Subscripts 1 and 2 represent surfaces parallel to the bedding.
 - (4) Subscripts 3, 4, 5, and 6 are surfaces at right angles to the bedding.
 - (5) Each flat surface when large enough was divided into 4 sections and arbitrarily designated by the letters α , β , δ , and λ .

The graphitic schist (sample No. 21) crumpled to fragments when wet, hence only a few pieces were saved for electrical resistivity measurements.

PROCEDURE FOR TAKING MEASUREMENTS

The primary coil P is energized by the oscillator at about 600 c.p.s. (see figs. 5 and 7). Since the two identical coils S_1 and S_2 are connected in series opposition, the net voltage developed in them due to the primary coil should be zero. In practice, however, this is not achieved owing to unavoidable imperfections in the two coils; thus a small voltage difference between the two secondary coils remains. The potentiometer is adjusted until this voltage is just balanced by the voltage generated in coil S_3 .



. 7. GENERAL CIRCUIT DIAGRAM OF SUSCEPTIBILITY MEASURING APPARATUS.

The balance point is determined by means of the amplifier and oscilloscope. Under this null condition the flat surface of the rock specimen is brought as close as possible (in fact touching) and perpendicular to the axis of the coil S_1 . A new alternating field proportional to that produced by the primary is generated. Since S_1 is much closer to the specimen than S_2 , a difference in voltage arises as shown in Equation (7). The ratio of this voltage and the voltage generated in coil S_3 is proportional to the susceptibility of the specimen as shown in Equation (9). The potentiometer is again balanced by the method described above, and the difference in potentiometer positions is proportional to the susceptibility of the rock sample.

RESULTS

Results of the susceptibility measurements are tabulated in Table 4 and the detailed measurements are in Appendix 2a. The results in Table 4 show the average values of:

- (a) 52 readings obtained from 26 pieces of Sample No. 16.
- (b) 39 " " " 18 " " No. 17.
- (c) 32 " " " 16 " " No. 18.
- (d) 59 " " " 30 " " No. 19
- (e) 131 " " " 85 " " No. 20

The range of variation in susceptibility for each rock type was obtained by the application of the Theory of Error Analysis (7) which is explained in Appendix 4. The analytical treatment of the results reveals some facts of interest, which may be summed up as follows:

Table 4. Results of Susceptibility Measurements.

Sample No.	Rock Description	No. of Readings	Average $K \times 10^6$	Interval of Confidence 90%
16	Greenstone (Altered volcanic rock)	52	31.5	± 0.41
17	Greenstone (Altered basalt)	39	213.4	± 7.58
18	Altered tuff	32	122.8	± 4.6
19	Greywacke	59	34.3	± 1.1
20	Altered tuff with disseminated Sulphides	131	451.0	± 56.0

Table 5. Results of Susceptibility Measurements in different Plane - Surfaces.

Sample No.	No. of readings taken	Average K $\times 10^6$	Interval of Confidence (90%)
16 _{1,2}	32	31.7	± 0.54
16 _{3,4}	16	31.6	± 0.75
16 _{5,6}	4	30.3	± 1.4
17 _{1,2}	23	220	± 9.42
17 _{3,4}	12	225	± 11.65
17 _{5,6}	4	162	± 9.9
18 _{1,2}	16	128.5	± 8.2
18 _{3,4}	12	120.0	± 4.6
18 _{5,6}	4	108	± 4.8
19 _{1,2}	40	34	± 2.64
19 _{34,56}	19	35	± 2.38
20 _{1,2}	60	364.0	± 54.6
20 _{34,56}	63	545.0	± 84.5

(a) Although each rock type is represented by one or two large pieces, the variation in susceptibility for different parts of the same sample is in most cases small, except for sample No. 20 (see Table 4). This suggests consistency of susceptibility values for most of the rock types; though it does not alter the fact that the samples measured were few.

(b) Anisotropy - The next point of interest is the variation in susceptibilities in the direction normal to the plane of each sample surface. (Notations of subscripts used in this section are explained in page 48).

(1) For Sample No. 16, the average k for faces $16_{5,6}$ and $16_{3,4}$ are 30.3 ± 1.4 and 31.6 ± 0.75 respectively. The maximum susceptibility at $16_{5,6}$ is 31.7 (see Table 5), and the minimum at $16_{3,4}$ is 30.85. Therefore the range of variation of susceptibilities at $16_{5,6}$ overlaps that at $16_{3,4}$. Similarly the range of variation at $16_{1,2}$ overlaps that of $16_{5,6}$. It can also be shown that the range of variation of susceptibilities at $16_{1,2}$ and that at $16_{3,4}$ overlap. Hence no anisotropy is indicated.

(2) For Sample No. 17, the maximum susceptibility at $17_{1,2}$ lies within the range of the average susceptibility at $17_{3,4}$. However, the maximum susceptibility value at $17_{3,4}$ which is 171.9, is below the minimum at $17_{1,2}$, which is 210.58 and the minimum at $17_{3,4}$, which is 213.35. This indicates that anisotropy exists, for 90% probability, in Sample No. 17. No attempt was made, however, to determine the magnitude of this anisotropy.

(3) Similarly, Sample No. 18 shows anisotropy. Sample No. 19, however, does not.

(4) The clearest case of anisotropy is presented by Sample No. 20. Here, the maximum susceptibility at $20_{1,2}$ is less than the minimum susceptibility at $20_{3,4,5,6}$ by 36 units. This means, that the magnetic properties of the disseminated tuff are weaker in the direction normal to the plane of stratification.

Anisotropy could be an important factor to reckon with in a quantitative magnetic interpretation. For instance, a mineralized rock which shows strong anisotropy could, in a folded region, lose much of its contrasting magnetic properties if the plane of weak susceptibility is oriented in the direction of the inducing field.

Hence, it is often necessary, at least to find out if anisotropy exists, when susceptibility measurements are being made; and for this purpose, the rock samples must be in their natural condition, that is, they must not be powdered.

SPECIAL FEATURES OF THE APPARATUS

- (a) By making the secondary coils identical in dimensions and connecting them in series opposition, the effect of stray fields in the laboratory was almost entirely eliminated.
- (b) The maximum alternating field in which susceptibility measurements were made was 5 oersteds; and the apparatus was sensitive enough to detect magnetic susceptibilities as low as $1.0 - 2.0 \times 10^{-6}$ c.g.s. units.
- (c) Rock samples were generally small, the minimum dimensions of a sample being $1\frac{1}{2}$ " in diameter and $\frac{1}{2}$ " in thickness. Sample preparation occupied a minimum time - the only essential requirement being one fairly smooth flat surface.

DEFECTS OF THE APPARATUS

- (a) In taking readings, some amount of drift was often noticed at the first balance position, that is, before sample was introduced. To remedy this effect, the null point was read twice, that is, before and after each rock sample was introduced; and the two readings were averaged. Measurements were repeated three times in the case of some specimens, and twice in the case of others, to check consistency and reproducibility of results.
- (b) Sample positioning against the coil-face was somewhat critical and time-consuming.
- (c) The coil form was sensitive to pressure, being presumably deformable and hence producing a signal when its geometry was altered. Samples were therefore positioned such that they barely touched the coil face.

SUGGESTIONS FOR IMPROVEMENT

- (a) The present apparatus can be said to have achieved its purpose, namely, the rapid measurement of small unpowdered samples in a weak alternating field in the laboratory. The speed of measurement, however, could be increased by improving the support of the coil. Instead of a rigid rod from the base, at S₂, a ball and socket arrangement could be used to allow greater direction of movement of the coil form.
- (b) The instrument could be used in the field for susceptibility measurements
 - (1) if the oscillator and the null detector are made small and portable, and

(2) if the dimensions of the coil arrangement are increased proportionately, since it is apparent that the degree of roughness of the flat surface of a sample to which the coil will show no variation in signal depends on the size of the coils themselves. It can be shown that up to a certain limit, the greater the coil dimensions, the more indifferent it is to the rough surfaces of rock samples.

CONCLUDING ANALYSIS

The results of all the measurements carried out in this investigation are retabulated in Table 6 for comparison purposes. With the geology, the pattern of mineralization and the physical properties of the important rock types in the area of investigation known, the stage is set for more concrete proposals for the best methods suited to the area.

- (a) Mention has already been made of the use of portable Refraction Seismic equipment for the determination of the depth of the over-burden or weathered tops of bedrocks.
- (b) The Density contrast among the rock types is small (see Table 6, page 58); hence Gravity methods will be of limited use here. Recalling the detailed geologic description given in the early part of Section I, one can calculate the maximum anomaly from the density contrast between the greywacke with the least density and the mineralized tuffs (Sample 20) and the greenstone (Sample No. 17) with higher densities, by using the formula for a vertical sheet body as given in Dobrin (9), page 177;

$$\text{i.e. } g_z = 4.68 \sigma t \left[\log \frac{\left(1 + \frac{Z_2^2}{\lambda^2}\right)}{\left(1 + \frac{Z_1^2}{\lambda^2}\right)} \right] \quad (11)$$

Table 6. Results of Magnetic Susceptibilities, Densities, Electrical Resistivities, and Metal Factors of the Rock types measured.

Sample No.	Rock Description	No. of Readings for k	Average $k \times 10^6$ c.g.s	Density Av. of 4 Samples	ELECTRICAL	
					Resistivity	Metal factor
16	Greenstone (altered volcanic rock)	52	31.5 ± 0.41	2.81	4090	0.732
17	Greenstone - (altered basalt)	39	213.4 ± 7.58	3.02	2370	13.6
18	Altered tuff	32	122.8 ± 4.6	2.94	568	9.7
19	Greywacke	59	34.3 ± 1.1	2.77	3000	5.0
20	Altered tuff (ore)	131	451 ± 56	3.13	140	344.0
21	Black graphitic Schist	-	--	--	157	572.0

where

g_z = vertical component of gravity in milligals

σ = the density contrast

t = thickness of bed in Kilofeet (1000 ft.)

Z_1 and Z_2 = upper and lower parts, respectively, of the vertically dipping bed or sheet

x = horizontal distance from the instrument station to the point vertically above the center of the sheet.

For maximum g_z , obtained directly above the center of the disturbing body, x is zero and equation (11) simplifies to:

$$g_z = 4.68 \sigma t (k) \quad (12)$$

where $k = \log \left(\frac{Z_2}{Z_1} \right)^2$

Assuming that the following figures

$$Z_2 = 10,000 \text{ ft.}$$

$$Z_1 = 50 \text{ ft. or } 100 \text{ ft.}$$

$$t = 100 \text{ ft. or } 200 \text{ ft.}$$

are well within the limits of the geologic conditions of the area, then the factor k in equation (12) will be 4.6 and 4.0 for $Z_1 = 50$ ft. and 100 ft. respectively. The density contrast σ between the greywacke (the less dense rock) and the mineralized tuff and the greenstone are respectively 0.36 and 0.25.

Using the maximum conditions as set forth above, one obtains, g_z (for the mineralized tuff) = $4.68 \times 0.2 \times 4.6 \times 0.36$
= 1.55 milligals

and g_z (for the greenstone) = $4.68 \times 0.25 \times 0.2 \times 4.6$
= 1.07 milligals.

Further, if the mineralized tuff is adjacent to, or within the greenstone, a density contrast of 0.11 will produce an anomaly of 0.473 milligals for maximum conditions.

The gravity results calculated for maximum geologic conditions show that:

(1) only few geologic conditions can produce maximum anomalies of the order of 2 milligals.

(2) when the mineralized tuff is adjacent to the greenstone, the former may be missed, since a maximum anomaly of less than 0.5 milligals is regarded as being quite small.

(c) On the other hand, the magnetic susceptibility, the metal factor and resistivity contrasts among the rock types are significantly high to suggest that Magnetic and Electrical methods would be more useful in the area of investigation.

(1) The general formula for calculating the anomaly of a dyke or an inclined bed using a vertical magnetometer is quoted in Dobrin (9), page 276, (from the article by K. L. Cook in "Geophysics" Vol. 15, page 667, 1950) as follows:

$$\Delta Z_0 = 2k \sin \delta \left[(H_0 \sin \alpha \sin \delta + Z_0 \cos \delta) \ln \frac{r_2 r_3}{r_1 r_4} - (H_0 \sin \alpha \cos \delta - Z_0 \sin \delta) (\phi_1 - \phi_2 - \phi_3 + \phi_4) \right] \quad (13)$$

where ΔZ_0 = vertical anomaly in gammas
 k = contrast in susceptibility
 δ = angle of dip of the bed
 α = the strike of the bed from the Magnetic North

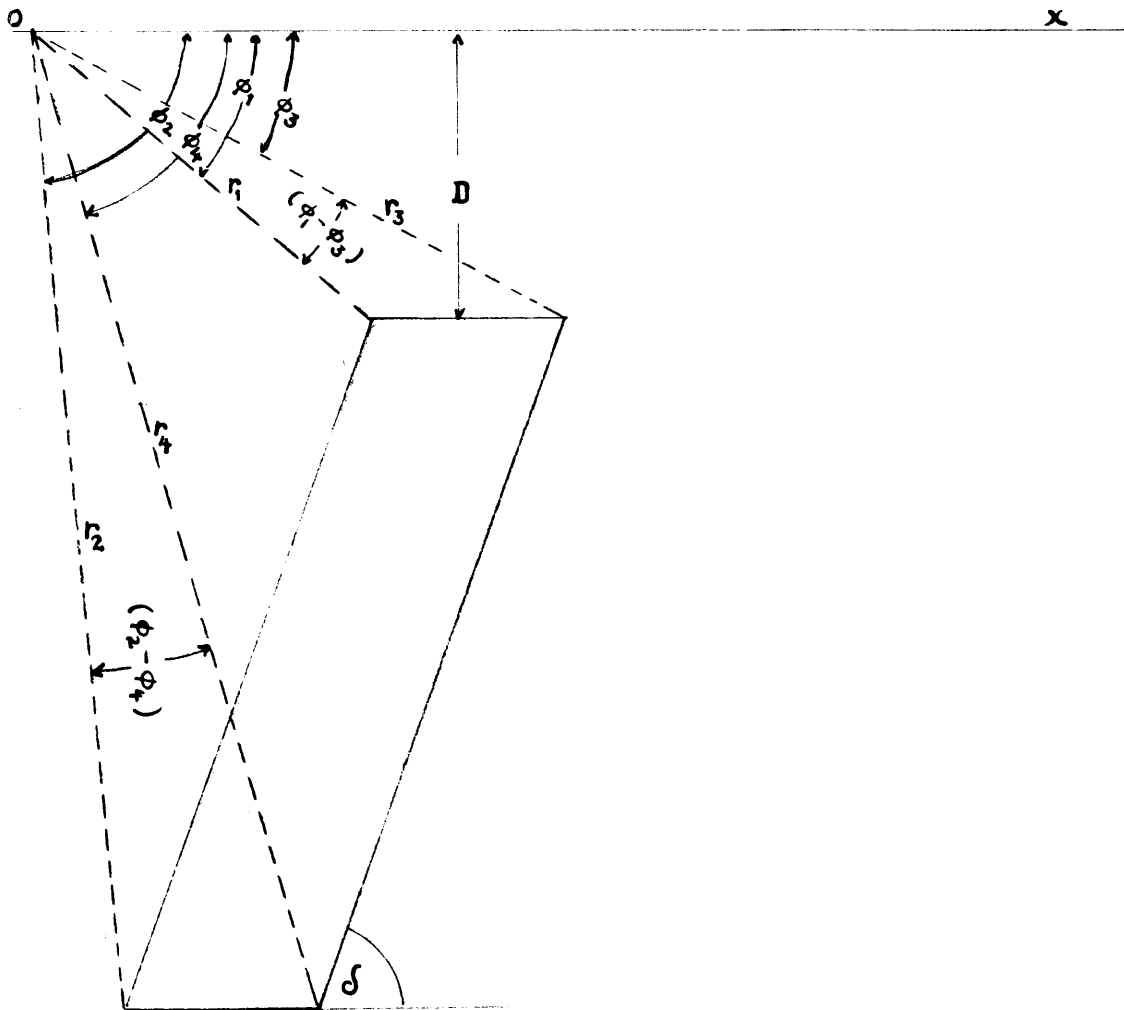


Fig. 8. A Diagrammatic Representation of a Buried Dyke or Steeply Dipping Bed with Strike Normal to the Plane of the Paper and at α° to the Magnetic North (After M.B. Dobrin).

H_0 = the Earth's Horizontal Component

Z_0 = the Earth's Vertical Component

$r_1, r_2, r_3,$ and r_4 = distances from the point of observation to the top and bottom edges of the bed as shown in fig. 8.

$\phi_1, \phi_2, \phi_3,$ and ϕ_4 = the angles the distances $r_1, r_2, r_3,$ and r_4 make with the horizontal plane.

It can easily be seen from figure 8 that as the depth of the lower part of the bed increases, r_2 and r_4 become equal and cancel out in equation (13). Similarly $(\phi_2 - \phi_4)$ become zero at infinite depth. Hence for an inclined bed of infinite depth equation (13) becomes:

$$\Delta Z_0 = 2k \sin \delta \left[(H_0 \sin \alpha \sin \delta + Z_0 \cos \delta) \ln \frac{r_3}{r_1} - (H_0 \sin \alpha \cos \delta - Z_0 \sin \delta) (\phi_1 - \phi_3) \right] \quad (14)$$

In most parts of Ghana H_0 and Z_0 in the above equation are respectively 0.31 and 0.051 Oersted (6). The strike α of the Birrimian Series is about N. 25° E. (magnetic) and is fairly persistent in many areas.

Use has been made of equation (14) in calculating 10 possible cases for the mineralized tuff in the light of the geologic conditions in the area of investigation. Table 7a shows the number of cases dealt with. Assuming that the susceptibility values of the other rock types are too low to affect the magnetic effects of the mineralized tuff, the average susceptibility value of 451×10^{-6} c.g.s. has been used as the susceptibility contrast (k) in the calculation, to obtain the results (in gammas) in table 7a.

Table 7a. Geologic Cases Dealt with and Calculated Anomalies.

Case	Thickness of bed (t)	Depth of cover (D)	Dip of bed (δ)	Anomaly (γ)	
a	1	40	150	45°	1.67
	2	"	300	"	0.84
b	1	"	150	60°	1.6
	2	"	300	"	0.84
c	1	"	150	85°	2.1
	2	"	300	"	1.06
d	1	200	50	"	21.6
	2	100	50	"	13.7
e	1	200	100	"	13.8
	2	100	100	"	7.7

It is obvious that for conditions under a, b and c in table 7a, no sensitive magnetometer can detect the small anomalies. However, the results in (d) and (e) can be detected.

It may be pointed out here, that the figures used in cases (d) and (e) are not unrealistic; on the contrary the chances of meeting such conditions are just as prevalent as those in cases a, b and c since the tuff is a stratified rock with thicknesses ranging from 30 - 200 ft. Another point worthy of note is that although the average susceptibility value for the mineralized tuff is given as 451×10^{-6} , many samples gave readings well above 1000×10^{-6} c.g.s. Hence there is every likelihood

that the average susceptibility of 451×10^{-6} obtained from the relatively few samples measured by the author, will turn out to be lower than the average for a larger bulk of samples.

Table 7b shows the calculated values for the vertical anomalies using $k = 1$ in equation (14) and the ten cases delineated above. Also figures 9 (a-e) are plots of the characteristic profiles obtained by using the data given in table 7a. Such magnetic profiles are, as one can see, very valuable for the interpretation of magnetic surveys. In fact, if knowledge of the geology and the susceptibilities of most of the rock types in the area are available, the use of such 'calculated profiles' makes the ambiguity associated with magnetic curves almost non-existent.

(2) The electrical properties of the mineralized tuff and the graphitic schists are so distinctly high as compared to the other rock types (see table 6), that Electrical methods must invariably be used in conjunction with or as a "follow-up", to the magnetic methods. In particular, the Induced Polarization method should be preferably tried.

Table 7b. Detailed Vertical Magnetic Anomaly Calculations for the Ten Cases outlined in Table 7a.

Distance x (ft.)										
	Case a		Case b		Case c		Case d		Case e	
	1	2	1	2	1	2	1	2	1	2
1000	749	647	922	760	1079	910	5476	2720	5500	2726
800	964	856	1183	925	1387	1225	6700	3300	7100	3700
600	1242	1158	1530	1323	1810	1605	9210	4600	9180	4580
400	1828	1548	2141	1674	2560	2080	13980	6979	13784	6793
300	2305	1783	2634	1847	3206	2341	19195	9153	18015	8875
200	3090	1848	3350	1774	4165	2339	39070	13784	24940	12378
100	3705	1712	3550	1415	4670	2015	48070	24960	30050	16640
50	3400	1500	2190	900	3650	1600	47200	30030	28750	17100
0	2064	1075	980	510	1950	1020	16800	11940	19930	7050
-50	400	650	-900	-50	-100	410	20000	-13230	-1000	4100
-100	-715	228	-2130	-495	-1850	-185	-27930	-17920	-13190	-8760
-200	-1530	-356	-2610	-1066	-2695	-931	-24530	-11896	-17900	-9222
-300	1550	-697	-2226	-1333	-2394	-1319	-17365	-8307	-14685	-7325
-400	-1308	-772	-1899	-1306	-2080	-1348	-12980	-6501	-11896	-5887
-600	-1015	-724	-1410	-1117	-1570	-1195	-8750	-4350	-8380	-4140
-800	-822	-829	-1117	-865	-1253	-930	6900	-3200	6400	3100
-1000	-653	-468	-879	-674	-991	-740	-5364	-2636	-5200	-2574

Fig. 9.a, Characteristic Magnetic Profiles Representing Conditions set forth in Cases a. (1) and (2), in Table 7a, (page 63).

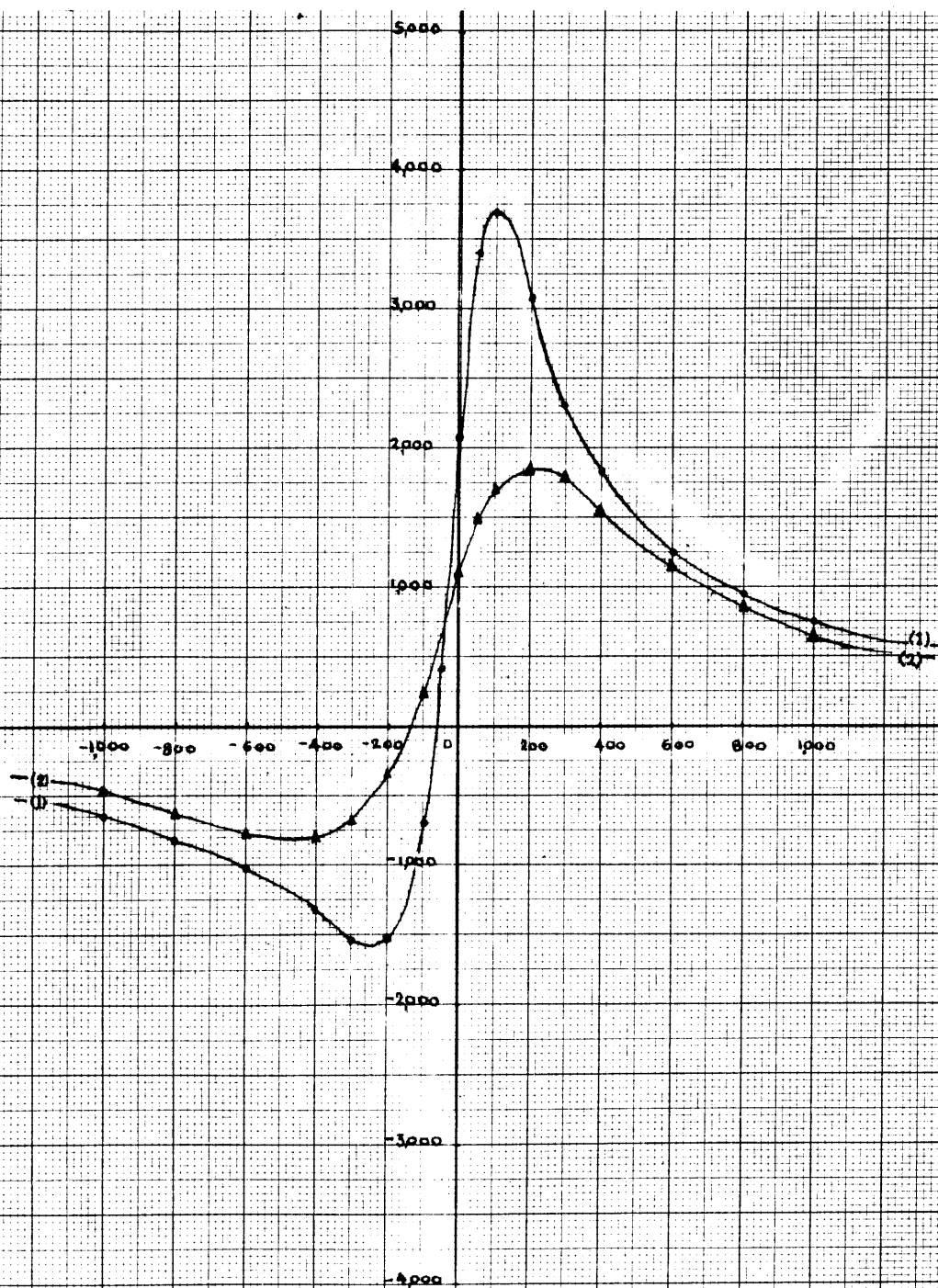


Fig. 9.b, Characteristic Magnetic Profiles Representing Conditions set forth in Cases b. (1) and (2), in Table 7a, (page 63).

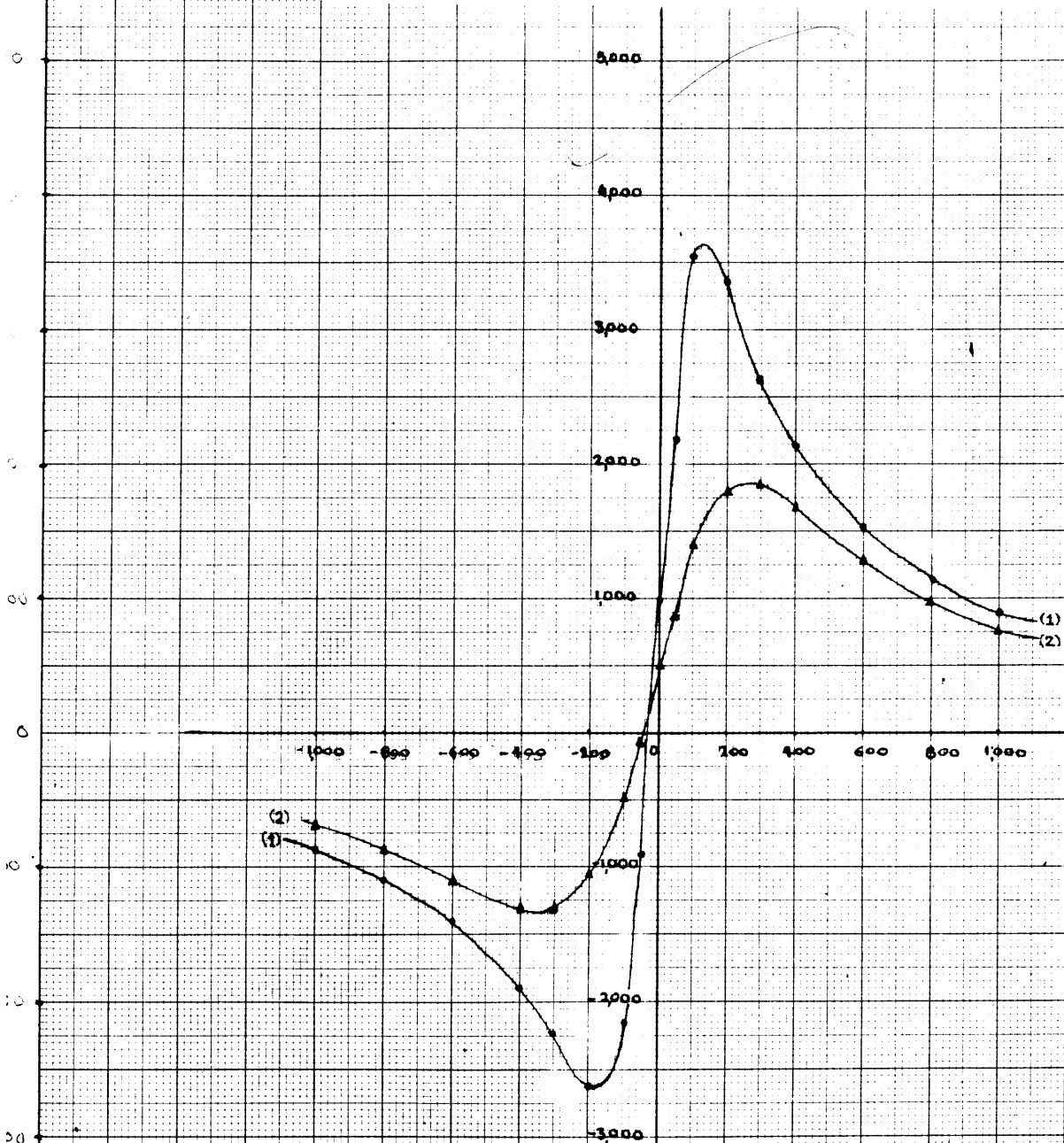


Fig. 9.c, Characteristic Magnetic Profiles Representing Conditions set forth in Cases c. (1) and (2), in Table 7a, (page 63).

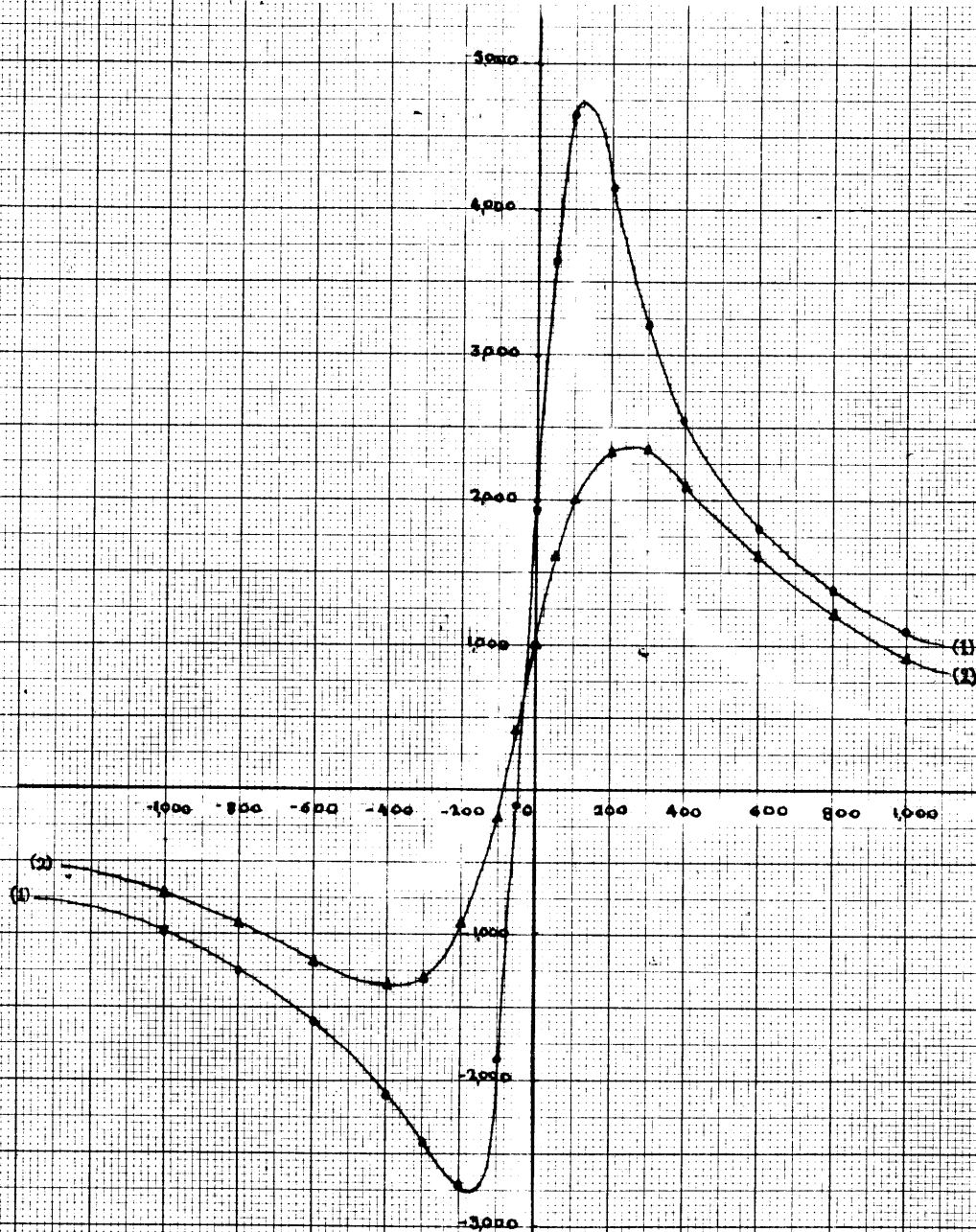


Fig. 9.d, Characteristic Magnetic Profiles Representing Conditions set forth in Cases d, (1) and (2), in Table 7a, (page 63).

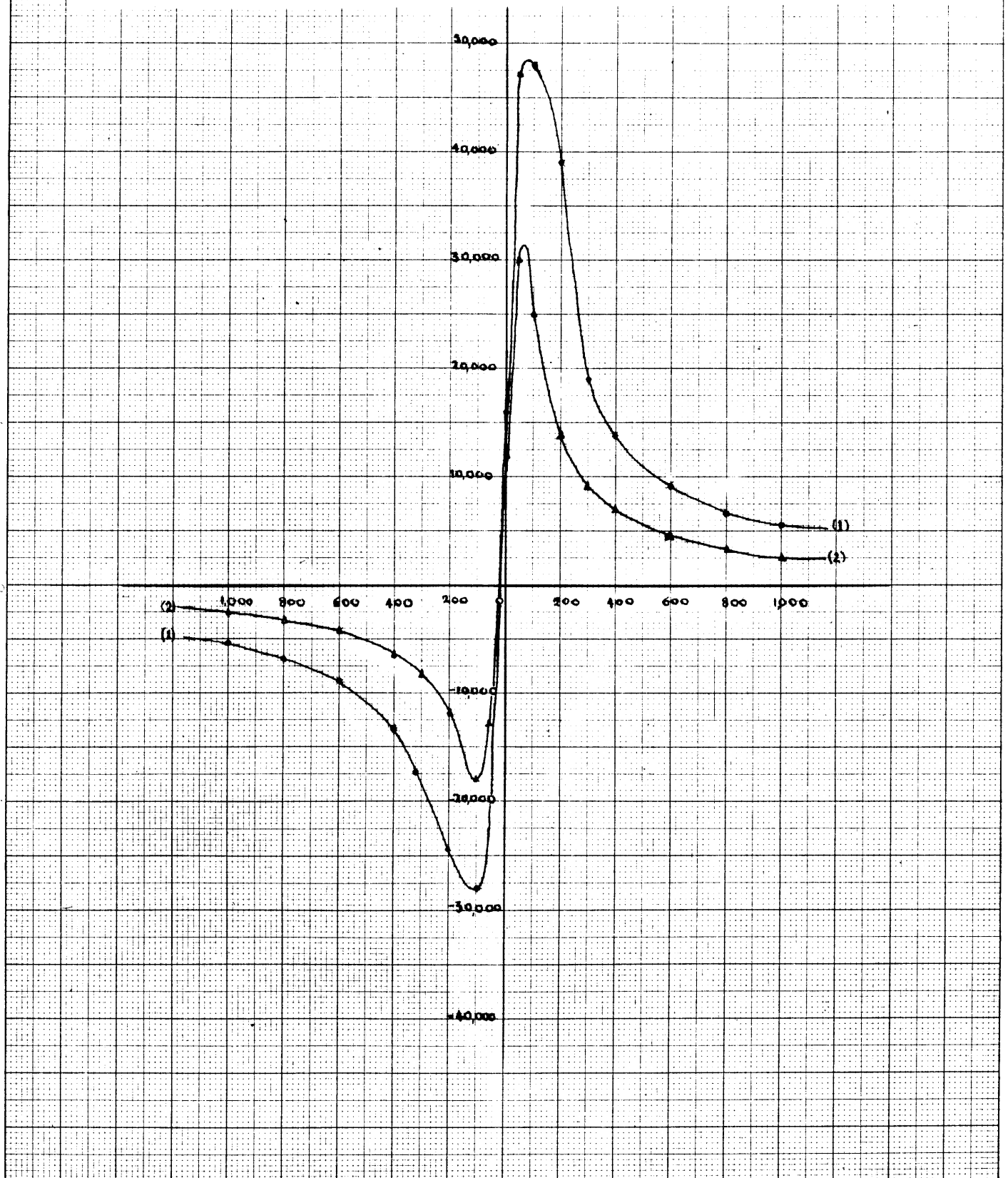


Fig. 9.e, Characteristic Magnetic Profiles Representing Conditions set forth in Cases e, (1) and (2), in Table 7a, (page 63).

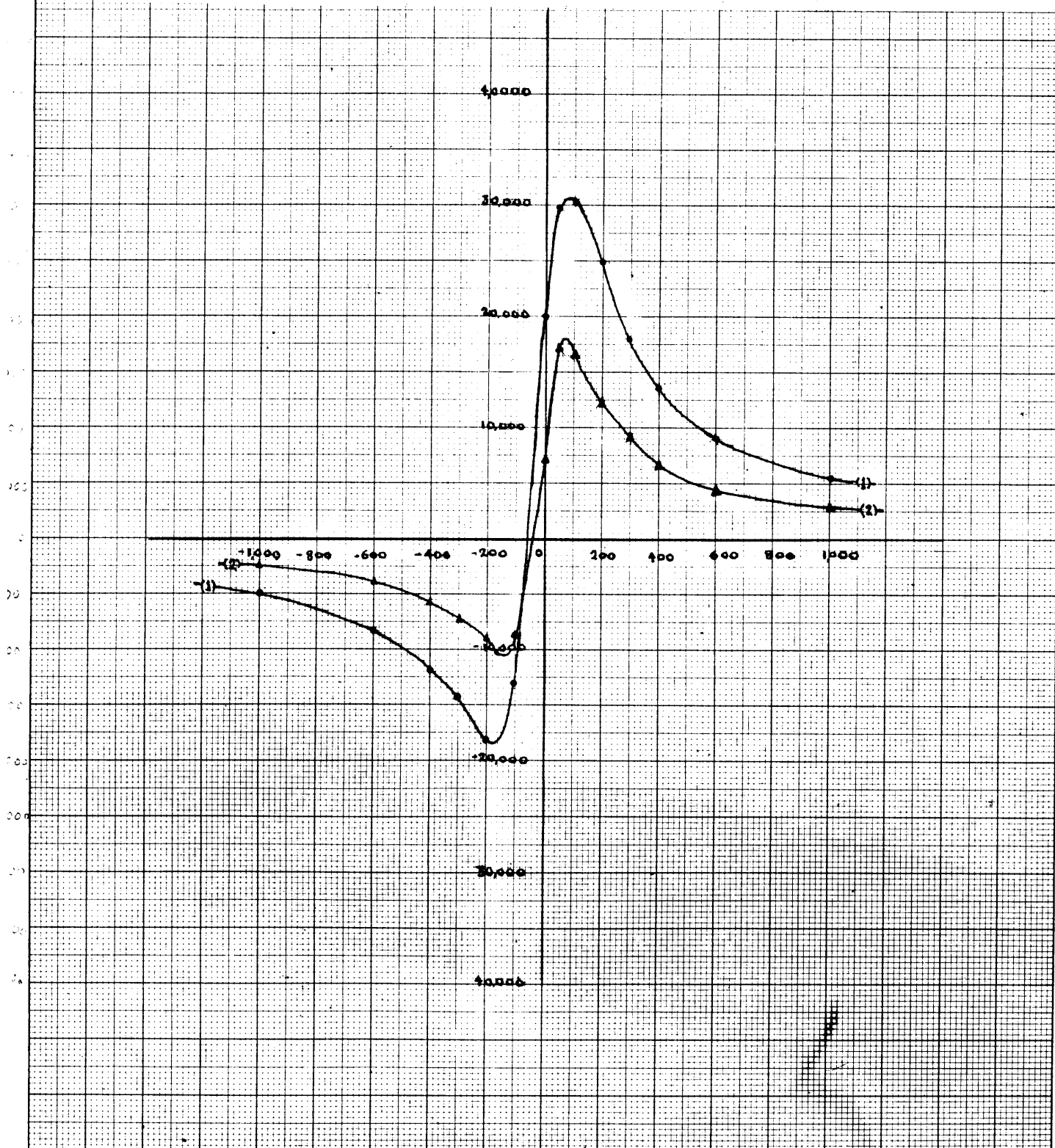
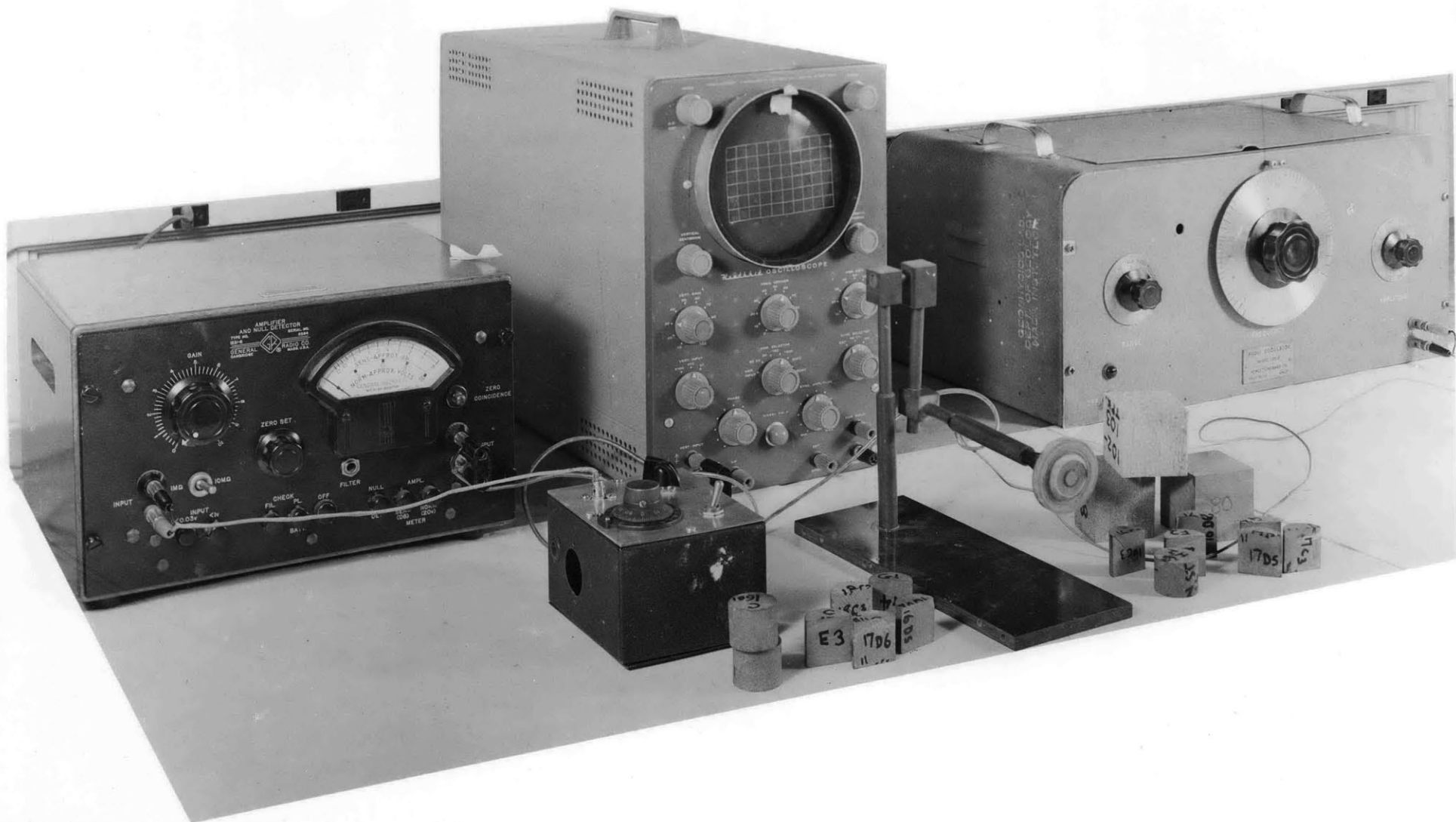


PLATE 2. An Induction Coil for measuring Magnetic Susceptibilities of small unpowdered rock samples. The apparatus consists, essentially of the 'Coil' (front - right), a Potentiometer (front - left), an Amplifier or Detector (back - left), an Oscilloscope (back - center) and an Oscillator (back - right).



APPENDIX 1: Susceptibilities of some common rocks.

Name of Rock	Susceptibility x 10 ⁶ c.g.s.	Type of Magnetism	Locality	Investigator
Sedimentary:				
Dolomite	14	paramagnetic	Balaton Lake	Steiner
Limestone	3.8	"	Leicester- shire	Wilson
Clays	20-39	ferromagnetic	several	several
Shales	44-54	"	"	"
Metamorphic:				
Magnetite- Amphibolite	9000	"	Krivoj Rog	Bahurin
Amphibolite Gneisses	10-260(low)	"	Ballinzona	Koenisberger
Phyllite	130 (240)	"	Seitzerland	Koenisberger
Acid Igneous:				
Granites	8-1900	"	several	several
Intermediate:				
Augite Syenite	2720-3538 (10 - 100)	"	Harz	Puzicha
Basic Igneous:				
Basalts	680-1680	"	several	several
Nepheline Basalt	6070-7170	"	Tetschen	Pockels
Diabases (Dolerites)	88-4200	"	several	several
Gabbros	230-2370	"	"	"
Ultrabasic:				
Norites	52-107	"	"	"

Name of Rock	Susceptibility x 10 ⁶ c.g.s.	Type of Magnetism	Locality	Investigator
Harzbergite (Peridotite)	7600-15,600	ferromagnetic	Harz	Puzicha
Serpentine (Rock)	25-14,000	"	several	several

Note: The figures in brackets under "susceptibility" designate the field in which the measurements were made.

APPENDIX 2a: Detailed Potentiometer Readings of Rock Samples

SAMPLE No. 16 Average = 31.5 (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6$ (x)	$(\bar{x} - x)$	$(\bar{x} - x)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
16	A1	341.0	28.0	3.5	12.25
	A2	347.5	34.0	2.5	6.25
	B1	345.5	31.5	0	0
	B2	348.0	33.0	1.5	2.25
	C1	346.0	31.0	0.5	.25
	C2	347.0	32.5	1.0	1.0
	C3	346.0	33.0	1.5	2.5
	C4	345.0	32.0	0.5	0.25
	D1	347.0	32.0	0.5	0.25
	D2	348.0	32.0	0.5	0.25
	D5	345.0	31.5	0	0
	D6	444.5	31.0	0.5	0.25
	E1	347.0	32.0	0.5	0.25
	E2	346.0	31.5	1.5	2.25
	E3	346.0	31.5	0	0
	E4	345.0	31.5	0	0
	F1	350.5	35.0	3.5	12.25
	F2	344.0	32.0	0.5	0.25
	F3	343.5	32.0	0.5	0.25
	F4	349.0	36.0	4.5	20.25
	G1	353.5	31.5	0	0
	G2	355.0	34.0	2.5	6.25
	G3	349.0	33.0	1.5	2.25
	G4	448.5	33.0	1.5	2.25
	H1	355.0	32.0	.5	.25
	H2	353.0	32.5	1.0	1.0
	A1	357.0	29.0	2.5	6.25
	A2	360.0	34.0	2.5	6.25
	B1	359.5	33.5	2.0	4.0
	B2	359.5	33.5	2.0	4.0
	C1	359.5	33.0	1.5	2.25
	C2	358.5	31.5	0	0
	C3	357.0	31.0	0.5	0.25
	C4	358.5	32.5	1.0	1.0
	D1	354.5	28.5	3.0	3.0
	D2	357.0	33.5	2.0	4.0
	D5	354.5	29.5	2.0	4.0
	D6	355.0	29.0	2.5	6.25
	E1	354.0	28.5	2.0	9.0
	E2	355.0	33	1.5	2.25
	E3	355.5	30.5	1.0	1.0
	E4	355.5	30.0	1.5	2.25
	F1	357.0	31.5	0	0
	F2	354.0	29.0	2.5	6.25

APPENDIX 2a: (Cont.)

SAMPLE No. 16 (Cont.) Average = 31.5 = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6 (\chi)$	$(\bar{x} - x)$	$(\bar{x} - x)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
16 F3	355.5	325.0	30.5	1.0	1.0
F4	355.0	325.5	29.5	2.0	4.0
G1	356.0	325.0	31.0	0.5	0.25
G2	355.0	325.0	30.0	1.5	2.5
G3	355.0	325.0	30.0	1.5	2.25
G4	356.0	326.0	30.0	1.5	2.25
H1	357.0	326.0	31.0	0.5	0.25
H2	355.0	324.5	30.5	1.0	1.0

APPENDIX 2a: (Cont.)

SAMPLE No. 17 Average = 213.4 = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6 (x)$	$(\bar{x} - x)$	$(\bar{x} - x)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
17 A1	555.0	326.5	228.5	15.1	228.0
A2	597.0	326.0	271.0	57.6	3317.8
B1	546.0	325.5	220.5	7.1	50.4
B2	570.0	325.5	244.5	31.1	967.2
C1	556.0	325.0	231.0	17.6	309.8
C2	523.0	324.5	198.5	14.9	222.0
C3	515.0	322.5	192.5	20.9	436.8
C4	532.0	321.0	216.0	2.6	6.8
D1	521.0	323.0	198.0	15.4	237.2
D2	496.0	323.0	173.0	30.4	924.2
D5	480.0	322.0	158.0	55.4	3069.2
D6	490.0	321.0	169.0	44.4	1971.4
E1	555.0	322.0	233.0	19.4	376.4
E2	543.0	322.0	221.0	7.6	57.8
E3	570.0	321.0	249.0	35.6	1267.4
E4	561.0	320.5	240.5	27.1	734.4
F1	543.0	323.0	220.0	6.6	43.6
F3	551.0	324.0	227.0	13.6	185.0
F4	555.0	322.0	233.0	19.6	384.2
A1	554.0	327.0	227.0	13.6	185.0
A2	606.0	327.0	279.0	65.6	4303.4
B1	549.0	328.0	221.0	7.6	57.8
B2	571.0	328.0	243.0	29.6	876.2
C1	556.0	329.0	227.0	13.6	185.0
C2	526.0	328.0	198.0	15.4	237.2
C3	513.0	328.0	185.0	28.4	806.6
C4	544.0	329.0	215.0	1.6	2.61
D1	519.5	327.0	192.5	20.9	436.8
D2	495.0	325.0	170.0	43.4	1883.6
D5	478.0	326.0	152.0	61.4	377.0
D6	496.0	327.0	169.0	44.4	1971.4
E1	555.0	326.0	229.0	15.6	243.4
E2	550.0	325.0	225.0	11.6	134.6
E3	577.0	326.0	251.0	37.6	1141.4
E4	570.0	326.0	244.0	30.6	936.4
F1	546.0	325.5	220.5	7.1	50.4
F2	530.0	324.5	205.5	7.9	62.4
F3	551.0	326.0	225.0	11.6	134.6
F4	552.0	325.0	227.0	13.6	185.0

APPENDIX 2a: (Cont.)

SAMPLE No. 18 Average = 122.8 = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility k x 10 ⁶ (χ)	$(\bar{x} - \chi)$	$(\bar{x} - \chi)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
18 A1	429.0	323.0	107.0	15.8	249.64
A2	449.0	322.0	127.5	4.7	22.09
A3	435.0	319.5	115.5	7.3	53.29
A4	437.0	318.0	119.0	3.8	14.44
B1	483.0	321.0	161.0	38.2	1459.24
B2	442.0	321.0	121.0	1.8	3.24
B3	450.0	319.0	131.0	8.2	67.24
B4	450.0	318.0	132.0	9.2	84.64
C1	476.0	321.0	155.0	32.2	1036.8
C2	448.0	321.0	127.0	4.2	17.64
C3	437.0	322.0	115.0	7.8	60.84
C4	435.0	321.5	113.5	9.3	86.49
D1	443.0	322.5	120.5	2.3	5.29
D2	434.0	321.5	112.5	10.3	106.09
D5	434.0	320.5	113.5	9.3	86.49
D6	425.0	319.0	106.0	16.8	282.24
A1	437.0	325.0	112.0	10.8	116.6
A2	452.0	326.0	126.0	3.2	10.2
A3	439.0	325.0	114.0	8.8	77.4
A4	440.0	326.0	114.0	8.8	77.4
B1	491.0	325.0	116.0	43.2	1866.2
B2	448.0	325.0	123.0	0.2	0.04
B3	456.0	326.0	130.0	7.2	51.8
B4	458.0	326.0	132.0	9.2	84.6
C1	470.0	326.0	144.0	21.2	449.4
C2	452.0	326.0	126.0	3.2	10.2
C3	440.0	326.0	144.0	8.8	77.4
C4	436.0	326.0	110.0	12.8	163.8
D1	444.0	326.0	118.0	4.8	23.0
D2	436.0	326.0	110.0	12.8	163.8
D5	434.0	326.0	108.0	14.8	219.0
D6	430.0	326.0	104.0	18.8	353.4

APPENDIX 2a: (Cont.)

SAMPLE No. 19 Average = 34.3 = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6$ (x)	$(\bar{x} - x)$	$(\bar{x} - x)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
19 A1 α	354.0	323.5	30.5	3.8	14.4
β	356.0	322.0	34.0	0.3	0.09
B1	353.5	323.0	30.5	3.8	14.4
C1 α	356.0	325.5	30.5	3.8	14.4
β	356.0	324.5	31.5	2.8	7.4
γ	357.5	323.5	34.0	0.3	0.09
C2 α	354.0	324.0	30.0	4.3	18.5
β	355.0	323.0	32.0	2.3	5.3
γ	355.0	322.0	33.0	1.3	1.69
λ	355.0	321.0	34.0	0.3	0.09
C3 α	354.0	321.0	33.0	1.3	1.69
β	355.0	325.0	30.0	4.3	18.5
C4 α	354.0	322.0	32.0	2.3	5.3
β	356.0	322.0	34.0	0.3	0.09
C6	364.0	323.0	41.0	6.7	44.9
D1 α	360.0	325.5	34.5	0.2	0.04
β	364.0	328.5	36.5	2.2	4.8
γ	356.5	328.0	28.5	5.8	33.6
λ	360.0	327.5	32.5	1.8	3.2
D2 α	362.0	362.5	36.5	2.2	4.8
β	365.0	325.0	40.0	5.7	32.5
γ	358.0	324.0	34.0	0.3	0.09
λ	362.0	323.5	38.5	4.2	17.6
D3 α	364.0	323.0	41.0	6.7	44.9
β	561.0	323.0	38.0	3.7	13.7
D4	358.5	325.5	33.0	1.3	1.69
D5	372.0	324.5	47.5	13.2	174.2
E2	370.0	330.5	49.5	15.2	231.0
E3	365.0	330.5	24.5	9.8	96.0
E6	366.0	329.5	36.5	2.1	4.4
A1 α	351.0	326.0	25.0	9.3	86.8
β	359.0	325.0	34.0	0.3	0.09
B1	352.0	324.0	38.0	6.3	39.7
C1 α	357.0	326.0	31.0	3.3	10.9
β	363.0	326.0	37.0	2.7	7.3
γ	364.0	328.0	36.0	1.7	2.9
C2 α	359.0	328.0	31.0	3.3	10.9
β	360.0	327.0	33.0	1.3	1.7
γ	358.0	326.0	32.0	2.3	5.3
λ	359.0	327.0	32.0	2.3	5.3
C3 α	357.0	326.0	31.0	3.3	10.9
β	349.0	324.0	25.0	9.3	86.8

APPENDIX 2a: (Cont.)

SAMPLE No. 19 (Cont.) Average = 34.3

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6 (\chi)$	$(\bar{x} - \chi)$	$(\bar{x} - \chi)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
19 C4	α 359.0	325.0	34.0	0.3	0.09
	β 359.0	323.0	36.0	2.3	5.3
C5	355.0	323.0	32.0	2.3	5.3
C6	360.0	322.0	38.0	3.7	13.7
D1	α 356.0	320.5	35.5	1.2	1.4
	β 363.5	324.0	39.5	5.2	27.0
D2	γ 357.0	326.0	31.0	3.3	10.9
	δ 360.0	326.0	34.0	0.3	0.09
	ϵ 363.0	326.0	37.0	3.7	13.7
	ζ 365.0	325.0	40.0	4.7	22.1
	η 360.0	324.0	36.0	1.7	2.9
	θ 361.0	324.0	37.0	4.2	17.6
E2	367.0	322.5	44.5	6.7	44.9
E3	361.0	326.0	35.0	1.7	2.9
E6	370.0	326.0	44.0	9.7	94.1
A1	354.0	326.0	28.0	7.3	53.3
	356.0	327.0	29.0	5.3	28.1

APPENDIX 2a: (Cont.)

SAMPLE No. 20 Average = 451. = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6 (\chi)$	$(\bar{x} - \chi)$	$(\bar{x} - \chi)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
20 D1	447.0	330.5	116.5	334.5	111,890.0
D5	456.0	330.0	126.0	325.0	105,625.0
E5	446.0	330.0	116.0	335.0	112,225.0
F1 α	422.0	329.0	93.0	358.0	128,164.0
F1 β	440.0	328.5	111.5	339.5	115,260.0
γ	451.0	327.0	124.0	327.0	106,920.0
λ	483.0	328.0	155.0	296.0	87,616.0
F2 α	422.0	326.0	96.0	355.0	126,025.0
β	438.0	324.5	113.5	337.5	113,906.0
γ	468.0	324.5	143.5	307.5	94,556.0
λ	479.0	323.5	155.5	295.5	87,320.0
G1 α	442.0	319.0	123.0	328.0	107,584.0
β	458.0	319.0	139.0	312.0	97,344.0
G2 α	474.0	319.0	145.0	306.0	93,636.0
β	497.0	318.5	180.0	271.0	73,441.0
γ	428.0	318.0	110.0	341.0	116,281.0
λ	420.0	316.5	103.5	347.5	120,756.0
33 α	578.0	318.5	259.5	191.5	36,672.0
β	611.0	316.0	295.0	156.0	24,336.0
44	430.0	319.5	110.5	340.0	115,600.0
55	523.0	318.0	205.0	246.0	60,516.0
H3	525.0	323.0	202.0	249.0	62,001.0
H4	607.0	321.0	286.0	165.0	27,225.0
I3	621.0	322.5	298.5	152.5	23,256.0
I4	513.0	321.0	192.0	259.0	67,089.0
J1	2268.0	325.0	943.0	492.0	242,064.0
J3	2271.0	325.0	946.0	495.0	245,025.0
K1	888.0	321.5	564.5	113.5	12,882.0
K3	2317.0	319.5	997.5	546.5	298,662.0
K4	2163.0	321.0	842.0	391.0	152,881.0
L1	2120.0	321.5	798.5	347.5	120,756.0
L4	2293.0	323.0	970.0	519.0	269,361.0
M1	2593.0	323.0	1273.0	822.0	675,684.0
M2	2479.0	323.0	1156.0	705.0	497,025.0
M3	2515.0	322.0	1193.0	742.0	550,564.0
M5	2316.0	321.0	995.0	544.0	295,936.0
N1	484.0	321.5	163.0	288.0	82,944.0
N3	2142.0	323.0	819.0	368.0	135,424.0
N4	2113.0	322.5	780.0	329.0	108,241.0
N5	2332.0	322.5	1010.5	559.0	312,481.0
A1	444.0	328.0	116.0	335.0	112,225.0
A2	417.0	326.0	91.0	360.0	129,600.0
B1	552.0	326.0	226.0	225.0	50,625.0

APPENDIX 2a: (Cont.)

SAMPLE No. 20 (Cont.) Average = 451. = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6 (\chi)$	$(\bar{x} - \chi)$	$(\bar{x} - \chi)^2$
	Maximum Deflection	Mean of Initial & Final Balance			
20 B2	800.0	326.0	474.0	23.0	529.0
C1	750.0	326.0	424.0	27.0	729.0
C2	602.0	326.0	276.0	175.0	30,625.0
D1	450.0	326.0	124.0	327.0	106,929.0
D5	443.5	325.0	118.5	332.5	110,556.0
E5	440.0	324.5	115.5	335.5	112,560.0
E6	444.0	326.0	118.0	333.0	110,889.0
F1 α	423.0	326.0	97.0	354.0	125,316.0
β	440.0	326.0	114.0	337.0	113,569.0
γ	440.0	326.5	113.5	337.5	113,906.0
F2 λ	479.0	323.0	156.0	292.0	87,025.0
α	415.0	323.0	92.0	359.0	121,889.0
β	437.0	318.5	118.5	332.5	110,556.0
γ	462.0	323.0	139.0	312.0	97,344.0
G1 α	441.5	327.0	114.5	336.5	133,232.0
β	463.5	320.0	143.5	307.5	94,556.0
FG3 α	611.0	324.0	287.0	164.0	26,896.0
β	545.0	323.0	222.0	229.0	52,441.0
FG4	450.0	323.0	127.0	324.0	104,976.0
FG5 α	513.5	322.0	191.5	259.5	63,340.0
β	475.0	319.5	155.5	295.5	87,320.0
H3	536.0	321.0	215.0	236.0	55,696.0
4	523.0	326.0	197.0	254.0	64,516.0
J1	2211.0	1326.0	885.0	434.0	188,356.0
3	2199.0	1327.0	872.0	421.0	177,241.0
K1	2045.0	1326.5	818.0	367.0	134,689.0
3	2328.0	1328.0	1000.0	549.0	301,401.0
4	2191.0	1327.0	864.0	413.0	170,569.0
L1	2213.0	1327.0	886.0	435.0	189,225.0
4	2325.0	1327.0	998.0	547.0	299,209.0
M1	2982.0	1327.0	1655.0	1204.0	1,449,619.0
2	2889.0	1327.0	1562.0	1111.0	1,234,321.0
3	2487.0	1328.0	1159.0	708.0	501,264.0
N1	497.0	327.0	171.0	280.0	78,400.0
N3	2224.0	1328.0	896.0	445.0	198,025.0
N4	2102.0	1329.0	773.0	322.0	103,684.0
N5	2309.0	1328.0	981.0	530.0	280,900.0
O1	2284.0	1328.0	956.0	505.0	255,025.0
2	1634.0	1328.0	306.0	145.0	21,025.0
3	2239.0	328.0	911.0	460.0	211,600.0
4	2152.0	329.0	823.0	372.0	138,384.0
5	2115.0	230.0	885.0	434.0	188,356.0

APPENDIX 2a: (Cont.)

SAMPLE No. 20 (Cont.) Average = 451. = (\bar{x})

Sample No.	Potentiometer Reading		Susceptibility $k \times 10^6 (\bar{x})$	$(\bar{x} - \bar{x})$	$(\bar{x} - \bar{x})^2$
	Maximum Deflection	Mean of Initial & Final Balance			
20 E5	452.0	328.0	124.0	327.0	106,929.0
E6	440.0	330.0	110.0	341.0	116,281.0
D1	445.0	327.0	118.0	333.0	110,889.0
D5	456.0	327.7	129.0	322.0	103,684.0
F1	424.0	329.0	95.0	356.0	126,736.0
	442.5	327.0	115.5	335.5	112,560.0
	445.5	327.0	118.5	332.5	110,556.0
	476.5	326.0	150.5	300.5	90,300.0
F2	419.5	326.0	93.5	357.5	127,806.0
	445.0	327.0	118.0	341.0	116,281.0
	463.0	326.5	136.5	314.5	98,910.0
	467.0	326.0	141.0	310.0	96,100.0
G1	449.0	327.0	122.0	329.0	108,241.0
	472.0	330.0	142.0	309.0	95,481.0
G2	450.0	331.0	119.0	332.0	110,224.0
	472.0	329.5	142.5	308.5	95,172.0
	440.0	329.5	110.5	340.5	115,940.0
	434.5	328.0	106.5	344.5	118,680.0
FG3	603.0	325.0	278.0	173.0	29,929.0
" M	540.0	322.5	217.5	333.5	111,222.0
4	445.0	325.5	119.5	331.5	109,892.0
5	515.0	322.0	193.0	258.0	66,564.0
"	476.0	321.0	155.0	296.0	87,616.0
H3	510.5	329.0	181.5	269.5	72,630.0
H4	577.5	330.0	247.0	203.5	41,412.0
I3	580.0	322.0	258.0	193.0	37,249.0
I4	513.0	330.0	183.0	268.0	71,824.0
J1	2229.0	1330.0	899.0	448.0	200,704.0
J3	2288.5	1331.0	957.5	506.5	256,542.0
K1	2096.0	1329.5	766.5	315.5	99,540.0
K3	2300.0	1329.0	971.0	520.0	270,400.0
K4	2247.0	1328.0	919.0	468.0	219,024.0
L1	2146.0	1329.5	816.5	265.5	133,590.0
L4	2347.0	1327.0	1020.0	569.0	323,761.0
M1	2665.0	1327.0	1020.0	569.0	323,761.0
M2	2482.0	326.5	1155.0	704.0	495,616.0
M3	2427.0	1328.0	1099.0	648.0	419,904.0
N1	482.0	326.0	156.0	295.0	87,025.0
N3	870.0	328.0	542.0	91.0	8,281.0
N4	928.0	329.0	599.0	148.0	21,904.0
N5	2281.0	1327.5	953.5	502.5	252,506.0
O1	2263.0	1328.0	935.0	484.0	234,256.0
O2	621.0	329.0	292.0	159.0	25,281.0
O3	2245.0	1330.0	915.0	464.0	215,296.0
O4	2155.0	1329.0	826.0	375.0	140,625.0
O5	2104.0	1327.5	776.5	325.5	105,950.0

APPENDIX 2b. Results of susceptibility measurements of samples in different orientations. (See system of notation on page 48).

SAMPLE No. 16

16 _{1,2} Average k 31.7			16 _{3,4} Average k 31.6			16 _{5,6} Average k 30.3		
x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$
28	3.7	13.69	33	-1.4	1.96	31.5	-1.2	1.44
34	-2.3	5.29	32	-0.4	0.16	31.0	-0.7	0.49
31.5	0.2	0.04	31.5	0.1	0.01	29.5	0.8	0.64
33	-1.3	1.69	35.5	0.1	0.01	29	1.3	1.69
31	0.7	0.49	32	-0.4	0.16			
32.5	-0.8	0.64	36	-4.4	19.36			
32	-0.3	0.09	33	-1.4	1.96			
32	-0.3	0.09	33	-1.4	1.96			
32	-0.3	0.09	31	0.6	0.36			
30	1.7	2.89	32.5	-0.9	0.81			
35	-3.3	10.89	30.5	1.1	1.21			
32	-3.3	0.09	30	1.6	2.56			
31.5	0.2	0.04	30.5	1.1	1.21			
34	-2.3	5.29	29.5	2.1	4.41			
32	-0.3	0.09	30	1.6	2.56			
32.5	-0.8	0.64	30	1.6	2.56			
29	2.7	7.29						
34	-2.3	5.29						
33.5	-1.8	3.24						
33.5	-1.8	3.24						
33	-1.3	1.69						
31.5	0.2	0.04						
28.5	3.2	10.24						
33.5	-1.8	3.24						
28.5	3.2	10.24						
33	-1.3	1.69						
31.5	0.2	0.04						
29	2.7	7.29						
31	0.7	0.49						
30	1.7	2.89						
31	0.7	0.49						
30.5	0.2	0.04						

APPENDIX 2b. (Cont.)

SAMPLE No. 17

17 _{1,2} Average k 220			17 _{3,4} Average k 225			17 _{5,6} Average k 162		
x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$
227	- 7	49	185	40	1600	152	10	100
279	-57	3481	215	10	100	169	-7	49
221	- 1	1	251	-26	676	158	4	16
243	-23	529	244	-19	361	169	-7	49
227	- 7	49	225	0	0			
198	22	484	227	- 2	4			
192.5	27.5	736.3	192	33	1089			
170	50	2500	216	9	81			
220	0	0	249	-25	625			
220	0	0	240	-15	225			
220.5	- 0.5	0.3	227	2	4			
205.5	14.5	210.3	233	8	64			
228.5	- 8.5	72.3						
271	-51	2601						
220.5	- 0.5	0.3						
244.5	-24.5	600.3						
231	-11	121						
198.5	21.5	462.3						
198	22	484						
173	47	2209						
233	-13	169						
221	- 1	1						
220	0	0						

APPENDIX 2b. (Cont.)

SAMPLE No. 18

18 _{1,2} Average k 128.5			18 _{3,4} Average k 120			18 _{5,6} Average 108		
x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$
107	21.5	462.3	115.5	4.5	20.25	113.5	5.5	30.25
127.5	1	1	119	1	1	106	2	4
161	32.5	1056.3	131	11	121	108	0	0
121	7.5	56.3	132	12	144	104	4	16
155	26.5	702.3	115	5	25			
127	1.5	2.3	113.5	6.5	42.25			
120.5	8	64	114	6	36			
112.5	16	256	114	6	36			
112	16.5	272	130	10	100			
126	2.5	6.3	132	12	144			
166	37.5	1406.3	144	6	36			
123	5.5	30.3	110	10	100			
144	15.5	240.3						
126	2.5	6.3						
118	10.5	110.3						
110	18.5	342.3						

APPENDIX 2b. (Cont.)

SAMPLE No. 19

19 _{1,2} Average k 34			19 _{3,4,5,6} Average k 35		
x	$(\bar{x}-x)$	$(\bar{x}-x)^2$	x	$(\bar{x}-x)$	$(\bar{x}-x)^2$
30.5	3.5	12.25	33	2	4
34.0	0	0	30	5	25
30.5	3.5	12.25	32	3	9
30.5	3.5	12.25	34	1	1
31.5	2.5	6.25	41	6	36
34	0	0	41	6	36
30.16	4	16	38	3	9
32	2	4	33	2	4
33	1	1	47.5	12.5	156
34	0	0	36.5	1.5	2
34.5	0.5	.25	24.5	10.5	110
36.5	2.5	6.25	31	4	16
28.5	5.5	30.25	25	10	100
32.5	1.5	2.5	34	1	1
36.5	2.5	6.25	36	1	1
40	6	36	32	3	9
34	0	0	38	3	9
38.5	4.5	20.25	35	0	0
49.5	5.5	30.25	44	9	81
25	9	81			
34	0	0			
28	6	36			
31	3	9			
37	3	9			
36	2	4			
31	3	9			
33	1	1			
32	2	4			
32	2	4			
35.5	1.5	2.25			
39.5	5.5	30.25			
31.0	3	9			
34	0	0			
37	3	9			
40	6	36			
36	2	4			
37	3	9			
44.5	10.5	110.25			
28	6	36			
29	5	25			

APPENDIX 2b. (Cont.)

SAMPLE No. 20

20 _{3,4,5,6} Average k 545 = (\bar{x})					
x	$(\bar{x} - x)$	$(\bar{x} - x)^2$	x	$(\bar{x} - x)$	$(x - \bar{x})^2$
126.0	419.0	175,561.0	129.0	416.0	173,056.0
116.0	429.0	184,041.0	278.0	267.0	71,289.0
259.5	285.0	81,510.0	217.5	327.5	107,256.0
295.0	250.0	62,500.0	119.5	425.5	181,050.0
110.5	434.5	188,790.0	193.0	352.0	123,904.0
205.0	340.0	115,600.0	155.0	390.0	152,100.0
202.0	343.0	117,649.0	181.5	363.5	132,132.0
286.0	259.0	67,081.0	247.5	297.5	88,506.0
298.5	246.5	60,762.0	258.0	287.0	82,369.0
192.0	353.0	124,609.0	183.0	362.0	131,044.0
946.0	401.0	160,801.0	957.5	412.5	170,156.0
997.5	452.5	245,481.0	971.0	426.0	181,476.0
842.0	297.0	88,209.0	919.0	374.0	139,876.0
970.0	425.0	180,625.0	1020.0	475.0	225,625.0
1193.0	648.0	419,904.0	1099.0	554.0	306,916.0
995.0	450.0	202,500.0	542.0	3.0	9.0
819.0	274.0	75,076.0	599.0	14.0	196.0
780.0	235.0	55,225.0	953.5	408.5	166,872.0
1010.0	465.0	216,225.0	915.0	370.0	136,900.0
118.5	426.5	181,902.0	826.0	281.0	78,961.0
115.5	429.5	184,470.0	776.5	231.5	53,592.0
118.0	427.0	182,329.0			
287.0	258.0	66,564.0			
222.0	323.0	104,329.0			
127.0	418.0	174,724.0			
191.5	353.5	124,962.0			
155.5	389.5	151,710.0			
215.0	330.0	108,900.0			
197.0	348.0	121,104.0			
872.0	327.0	106,929.0			
1000.0	455.0	207,025.0			
864.0	319.0	101,761.0			
998.0	453.0	203,401.0			
1159.0	614.0	376,996.0			
896.0	351.0	123,201.0			
773.0	228.0	51,984.0			
981.0	437.0	190,969.0			
911.0	366.0	133,956.0			
823.0	278.0	772,840.0			
885.0	340.0	115,600.0			
124.0	421.0	177,241.0			
110.0	435.0	189,225.0			

APPENDIX 2b. (Cont.)

SAMPLE No. 20

20 _{1,2} Average k = 364 = (\bar{x})					
x	$(\bar{x} - x)$	$(\bar{x} - x)^2$	x	$(\bar{x} - x)$	$(\bar{x} - x)^2$
116.5	247.5	61,256.0	115.0	791.0	625,681.0
93.0	271.0	73,441.0	156.0	208.0	43,264.0
111.5	252.5	63,756.0	935.0	571.0	326,041.0
124.0	240.0	57,600.0	292.0	72.0	5,184.0
155.0	209.0	43,681.0	226.0	138.0	19,044.0
96.0	268.0	71,824.0	474.0	110.0	12,100.0
113.5	250.5	62,750.0	424.0	60.0	3,600.0
143.5	220.5	48,620.0	276.0	88.0	7,744.0
155.5	208.5	43,472.0	124.0	240.0	57,600.0
123.0	241.0	58,081.0	97.0	267.0	71,289.0
139.0	225.0	50,625.0	114.0	250.0	62,500.0
145.0	219.0	47,961.0	113.5	250.5	62,750.0
180.0	184.0	33,856.0	156.0	208.0	43,264.0
110.0	254.0	64,516.0	92.0	272.0	73,984.0
103.5	260.5	67,860.0	118.5	245.5	60,270.0
943.0	579.0	335,241.0	139.0	225.0	50,625.0
564.5	200.5	40,200.0	114.5	249.5	62,250.0
798.5	434.5	188,790.0	143.5	220.5	48,620.0
1273.0	909.0	826,281.0	885.5	521.0	271,441.0
1156.0	792.0	627,264.0	818.0	454.0	206,116.0
163.0	201.0	40,401.0	886.0	522.0	272,484.0
116.0	248.0	61,504.0	1655.0	1291.0	1,666,681.0
91.0	273.0	74,529.0	1562.0	1198.0	1,435,204.0
118.0	246.0	60,516.0	171.0	193.0	37,249.0
95.0	269.0	72,361.0	956.0	592.0	350,464.0
115.5	248.5	61,752.0	306.0	58.0	3,364.0
118.5	245.5	60,270.0			
150.5	213.5	45,582.0			
93.5	270.5	73,170.0			
118.0	246.0	60,516.0			
136.5	227.5	51,756.0			
141.0	223.0	49,729.0			
122.0	242.0	58,564.0			
142.0	222.0	49,284.0			
119.0	245.0	60,025.0			
142.5	221.5	49,062.0			
110.5	253.5	64,262.0			
106.5	257.5	66,306.0			
899.0	535.0	286,225.0			
766.5	402.5	162,006.0			
816.5	452.5	204,756.0			
1020.0	656.0	430,336.0			

APPENDIX 3a. Potentiometer Calibration.

Figure 10 is a diagrammatic circuit of the four induction coils and the balancing system of the potentiometer. The method for obtaining balance, when a rock sample is brought near coil S_1 has already been described (see page 42), and the following is a mathematical derivation of the relationship between the susceptibility of the rock sample and the resistance obtained from the potentiometer under balance condition.

When sample is introduced to coil S_1

$$E_{s1} - E_{s2} = C_1 k E_1 \quad (1)$$

and for coil S_3 ,

$$V_B = \frac{r}{R} V \quad (2)$$

For balance condition, it is required that

$$E_{s1} - E_{s2} - V_B = 0 \quad (3)$$

i.e.

$$V_B = C_1 k E_1 \quad (4)$$

or

$$C_1 k E_1 = \frac{r}{R} V \quad (5)$$

Let

$$V = C_2 E_1$$

from equa. (4)

$$C_1 k E_1 = \frac{r}{R} C_2 E_1 \quad (6)$$

i.e.

$$k = \frac{C_2}{C_1 R} r \quad (7)$$

Again let

$$C = \frac{C_2}{C_1 R}$$

from equa. (7)

$$k = C r \quad (8)$$

i.e.

$$k \propto r$$

C , C_1 , C_2 are all constants, and k is the susceptibility.

r is read from the potentiometer dial and must be calibrated with the resistance in the potentiometer itself.

C is also calibrated, with some material of known susceptibility

APPENDIX 3b. Calibration of the Potentiometer Constant (C) with Cupric Oxide; $k = 10.8 \times 10^{-6}$ c.g.s.

The cupric oxide crystals were tightly packed to a thickness of $1\frac{1}{2}$ " in a small beaker $2\frac{1}{2}$ " in diameter. The coil was brought close to the leveled surface of the crystals and measurement of susceptibility made as described before, for rock samples. Ten readings were taken altogether as shown in Table 8.

Table 8. Ten Potentiometer Readings of Cupric Oxide.

Balance	Deflection	No. of Divisions
8.5	20.5	12.0
11.0	22.0	11.0
12.0	22.0	10.0
12.5	23.5	11.0
13.5	24.5	11.0
13.5	23.5	10.0
14.5	24.0	9.5
14.0	24.5	10.5
14.0	25.0	11.0
15.0	26.0	11.0

The average number of dial divisions on the helipot is 10.7 for susceptibility of 10.8×10^{-6} c.g.s. This means that each helipot dial division is equivalent, in susceptibility, to $\frac{10.8}{10.7} = 1.009$
 $= 1.01 \times 10^{-6}$ c.g.s.

The next task is to evaluate the resistance each division on the dial actually stands for. This task is accomplished in Appendix 3c.

APPENDIX 3c. Potentiometer Arrangement and Calibration of Resistance r .

The range of susceptibilities to be measured in this work was from 10^{-6} to 10^{-2} in magnitude. A potentiometer was therefore required from which resistance ratios could be read ranging from $\frac{1}{10,000}$ to 1. For this purpose a 10 turn precision helipot was used, coupled with a 10-position double decker step-switch arrangement as shown in figure 11. The potentiometer resistance ratio could be determined by the angular position of the helipot shaft; and with a suitable dial, it could be read to the nearest $\frac{1}{100}$ of a turn. The potentiometer resistance ratios could thus be read from $\frac{1}{1,000}$ to 1. Ideally, the step-switch should increase this range by a factor of 10, that is, the step switch resistances $R_{A1}, R_{A2}, \dots, R_{A9}; R_{B1}, R_{B2}, \dots, R_{B9}$ and R_p should all be equal and equal to R ; so that the resistance ratio for the step-switch at any position n (where $1 \leq n \leq 10$) will be given by:

$$\frac{E}{R_{AB}} = \frac{r_p + nR}{10R} \quad (9)$$

Since in practice the resistances are not quite equal, the actual resistance ratio for the above position will be:

$$\frac{r}{R_{AB}} = \frac{r_p + \sum_n R_{Bn}}{R_p + \sum_n R_{Bn} + \sum_{q-n} R_{Aq}} \quad (10)$$

The voltage ratio which this resistance ratio determines, can then be obtained from the step-switch position and the shaft position of the helipot, if their resistances are known.

RESISTANCE VALUES

The variable helipot resistance r_p ranges from 0 to R_p . So that if all resistances R_{A1}, R_{B1} and R_p are equal and equal to R , the ratio of

resistance, when the switch is at a position n and $r_p = R_p = R$, will be equal to the ratio of resistance, when the step-switch is at position $n + 1$ and $r_p = 0$;

$$\text{that is, } \frac{R + nR}{10R} = \frac{0 + (n+1)R}{10R} \quad (11)$$

However, if the R_{A_i} values of resistances are all equal but different from R_p , then with $r_p = R_p$ and the switch at position n , the ratio will be given by:

$$\frac{r}{R_{AB}} = \frac{R_p + \sum_n R_B}{R_p + \sum_n R_B + \sum_{q-n} R_A} \quad (12)$$

while with $r_p = 0$ and switch at position $n + 1$, equa. (12) will be expressed as:

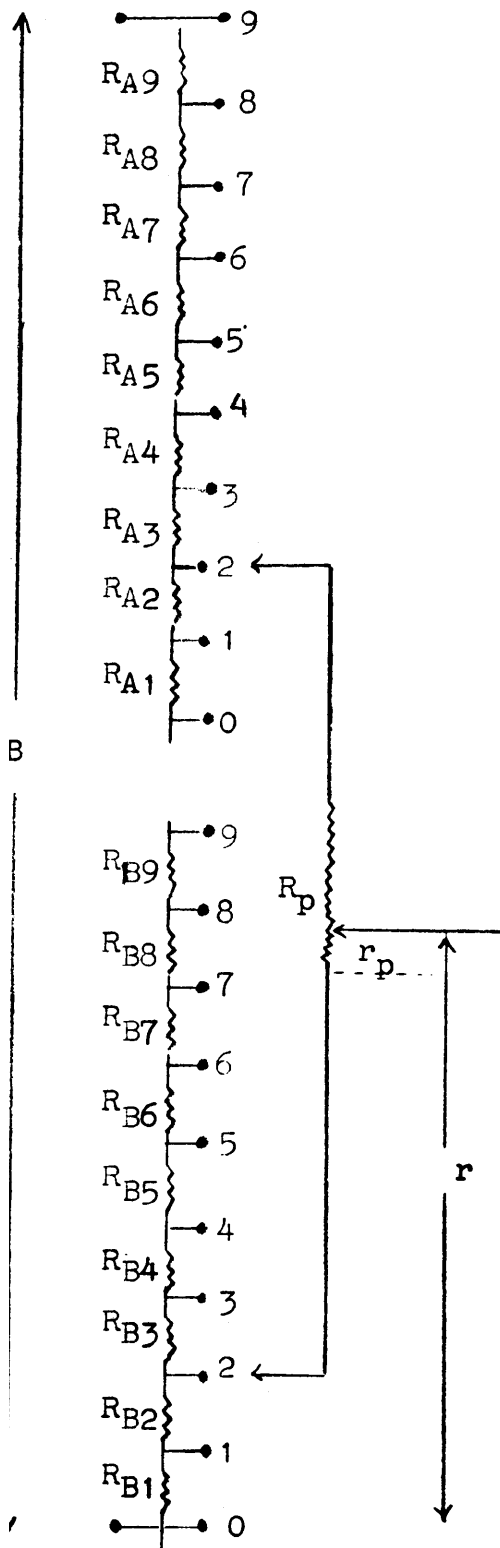
$$\frac{r}{R_{AB}} = \frac{\sum_{n+1} R_B}{R_p + \sum_{n+1} R_B + \sum_{q-(n+1)} R_A} \quad (13)$$

Now, R_{A_i} and R_{B_i} may be greater or less than R_p . If R_{A_i} and R_{B_i} are each less than R_p , all resistance ratios from 0 to 1 may be obtained; but some in two different ways. This condition is of course preferable; hence the resistances R_{A_i} and R_{B_i} were made about $0.9 \times R_p$.

Table 9 shows the actual values of the potentiometer resistances as measured on the wheatstone bridge.

Table 9. Potentiometer Resistances

Position of Dial		Resistance (ohms)	
Step-switch	Helipot	True	Observed
0	200	1,980	2,000
0	400	4,000	4,000
0	500	4,980	5,000
0	600	5,980	6,000
0	800	7,980	8,000
0	1,000	10,000	10,000
1	000	9,250	10,000
2	000	18,500	20,000
3	000	27,300	30,000
4	000	36,800	40,000
5	000	46,400	50,000
6	000	55,600	60,000
7	000	64,900	70,000
8	000	74,300	80,000
9	000	83,100	90,000
10	000	94,200	100,000
11	000	103,000	110,000



R_p = Total resistance in helipot.

r_p = Part of helipot resistance in circuit.

$R_{A1} \dots R_{A9}, R_{B1} \dots R_{B9}$ = Step-Switch arrangement.

r = total resistances at balance
 $= r_p + (R_{An} + R_{Bn})$, where $n = 1, 2 \dots 9$.

R_{AB} = Total resistance of potentiometer.

Fig.11. Arrangement of Helipot and Step-Switch Resistances in Potentiometer.

It is clear from Table 9, that the ratio of dial divisions on the helipot to resistance is linear and each helipot division is about 10 ohms. But this is not the case with the step-switch resistances. With the exception of step-switch 1, each step-switch resistance used as part of r must be corrected separately to satisfy equa. (12). The system tends to be cumbersome, especially, if high resistance values are required for balancing purposes. Fortunately, in this work, only the first three step-switch resistances were used in the entire work and these were corrected for. Corrections made in the step-switch resistances were as follows:

(a) For step-switch 2:

$$\text{The reading } \frac{I}{R} - \frac{r_{\text{bal.}}}{R} = \frac{20,000 - 10,000}{R} = \frac{10,000}{R}$$

$$\text{The true reading is } \frac{1850 - 9250}{R} = \frac{9250}{R}$$

$$\text{Difference in resistance} = 750 \text{ ohms.}$$

Hence each reading when dial is on step-switch 2 must be reduced by 75 divisions.

(b) Similarly each reading on step-switch 3 must be reduced by 195 divisions.

(c) Also, each reading on step-switch 4 must be reduced by 270 divisions.

From the calculations in Appendix 1a., we know that a helipot division is equal to a susceptibility of 1.01×10^{-6} c.g.s. Hence, the divisions on the helipot dial can be read directly as susceptibilities.

APPENDIX 4. General Treatment of Susceptibility Results.

(1) The range of variation in susceptibility for the samples of each rock type was determined by means of Error Analysis techniques (7). From the theory of Statistical Error Analysis the Mean Value of the bulk readings, \bar{x} and the standard Deviation S are calculated by means of the usual formulae:

$$\bar{x} \equiv \sum_{i=1}^N x_i \quad (a)$$

$$S \equiv \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N-1}} \quad (b)$$

where x , represents the value of a reading or observation, and N the total number of observations.

(2) If δ represents the mean of the frequency of distribution for each group of observations, then the Confidence Interval \mathcal{F} , that is the range of values of x in which δ lies, may be expressed as follows:

$$\bar{x} - \frac{\mathcal{F}S}{\sqrt{N}} < \delta < \bar{x} + \frac{\mathcal{F}S}{\sqrt{N}} \quad (c)$$

(3) The value of \mathcal{F} depends on N and the degree in % of Confidence required for the particular work. In this work a degree of Confidence of 90% was chosen and the table below was used for each N.

Table 10. Values of f as Determined from Equation (c).

Size of Bulk Sample N.	f -interval 90%	Size of Bulk Sample N.	f -interval 90%	Size of Bulk Sample N.	f -interval 90%
2	6.31	11	1.81	20	1.73
3	2.92	12	1.80	21	1.73
4	3.35	13	1.78	22	1.72
5	2.13	14	1.77	23	1.72
6	2.02	15	1.76	24	1.71
7	1.94	16	1.75	25	1.71
8	1.90	17	1.75	30	1.70
9	1.86	18	1.74	40	1.68
10	1.83	19	1.73	∞	1.65

For N above 40, the Confidence Interval f was taken as 1.65.

(4) The final susceptibility value is therefore given in the form,

$$X = \bar{X} \pm \frac{fS}{\sqrt{N}} \quad (\text{at 90\% Confidence})$$

(5) Tables 10 and 11 show the full calculations of susceptibilities and range of variation as given in tables 4 and 5 on pages 52 and 53.

Appendices 2a and 2b are detailed tabulations of Potentiometer readings.

Table 11. Detailed Calculations of the Range of Susceptibilities of Rock Types at 90% Probability.

	\bar{x}	$\sum(\bar{x}-x)^2$	N	S^2	S	\sqrt{N}	f	$\frac{fS}{\sqrt{N}}$
16	31.5	154.0	52.0	3.02	1.74	7.2	1.7	$\pm .411$
17	213.4	28,000.4	39.0	736.85	27.64	6.2	1.7	± 7.58
18	122.8	7,380.0	32.0	238.1	15.43	5.7	1.7	± 4.60
19	34.3	1,421.8	59.0	24.5	5.0	7.7	1.68	± 1.1
20	451.0	20,569,556	131.0	1.58×10^5	3.9×10^2	11.5	1.65	± 56.0

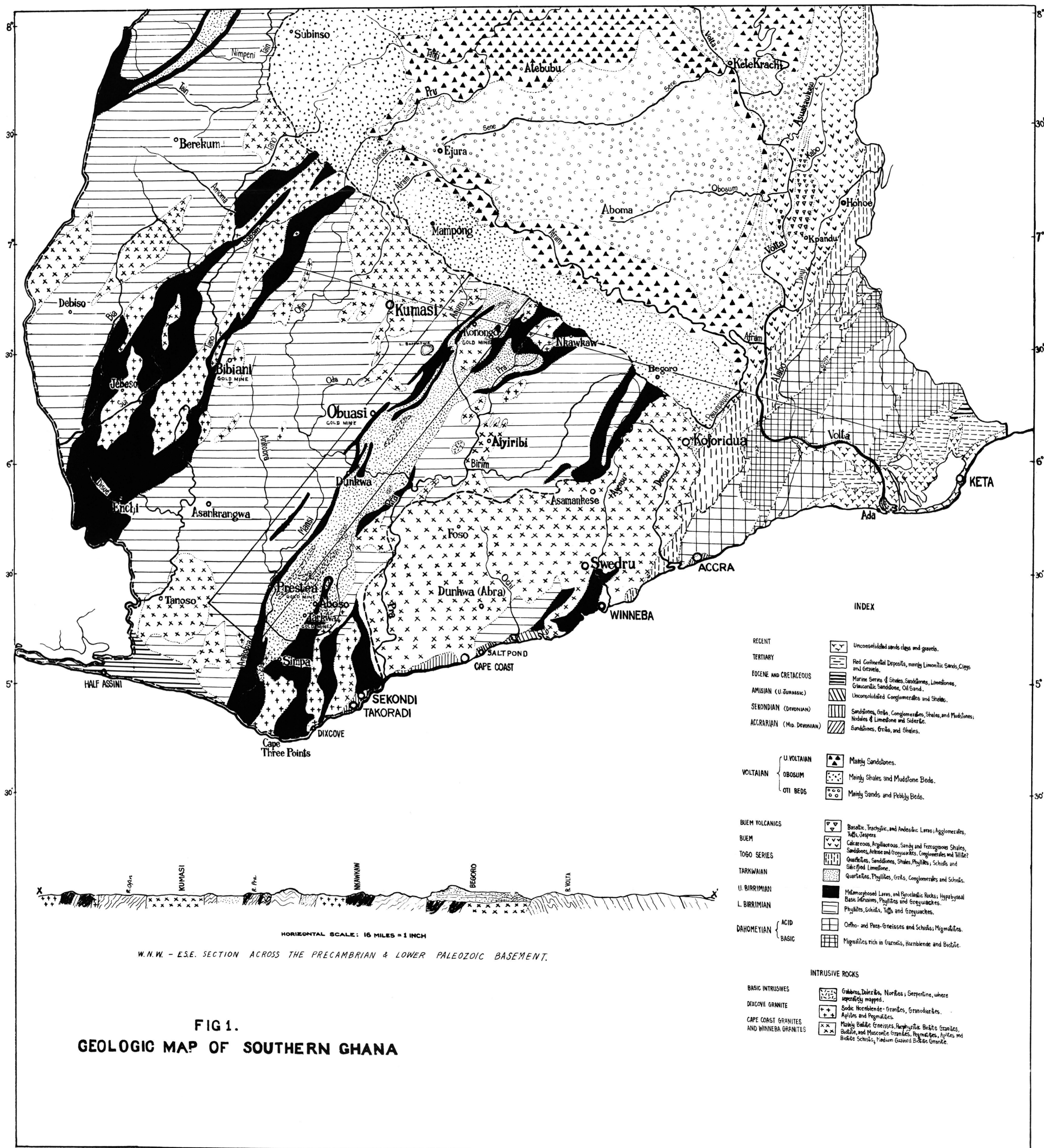
Table 12. Detailed Calculations of the Susceptibilities in Different Plane Surfaces.

	\bar{x}	$\sum (\bar{x} - x)^2$	N	S^2	S	\sqrt{N}	\bar{f}	$\frac{\bar{f}S}{\sqrt{N}}$
16 ₁₂	31.7	99.5	32.0	1.8	5.66	5.66	1.7	± 0.54
16 ₃₄	31.6	41.26	16.0	2.75	1.66	4.0	1.8	± 0.75
16 ₅₆	30.3	4.26	4.0	1.42	1.19	2.0	2.35	± 1.4
17 ₁₂	220.0	15.52×10^3	23.0	0.075×10^4	26.6	4.8	1.7	± 9.42
17 ₃₄	225.0	5.13×10^3	12.0	0.047×10^4	21.68	3.46	1.86	± 11.65
17 ₅₆	162.0	214.0	4.0	71.3	8.44	2.0	2.35	± 9.9
18 ₁₂	128.5	5.015×10^3	16.0	0.334×10^3	18.27	4.0	1.8	± 8.2
18 ₃₄	120.0	805.5	12.0	73.23	8.56	3.46	1.86	± 4.6
18 ₅₆	108.0	50.3	4.0	16.8	4.1	2.0	2.36	± 4.8
19 ₁₂	34.0	623.5	40.0	16.0	4.0	6.32	1.68	± 2.64
19 _{34,56}	35.0	600.0	19.0	33.3	5.77	4.36	1.8	± 2.38
20 ₁₂	364.0	10,888,800	68.0	1.63×10^5	4.03×10^2	8.22	1.65	± 54.6
20 _{34,56}	545.0	9,680,756	63.0	1.61×10^5	4.01×10^2	7.85	1.65	± 84.5

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HORIZONTAL SCALE: 16 MILES = 1 INCH

W.N.W. - E.S.E. SECTION ACROSS THE PRECAMBRIAN & LOWER PALEOZOIC BASEMENT.

FIG. 1.
GEOLOGIC MAP OF SOUTHERN GHANA

INDEX	
RECENT	Unconsolidated sands, clays and gravels.
TERTIARY	Red Continental Deposits, mainly Limonitic Sands, Clays and Gravels.
Eocene and CRETACEOUS	Marine Series of Shales, Sandstones, Limestones, Glauconitic Sandstone, Oil Sand.
AMISIAN (U. JURASSIC)	Unconsolidated Conglomerates and Shales.
SEKONDIAN (DEVONIAN)	Sandstones, Grills, Conglomerates, Shales, and Mudstones; Nodules of Limestone and Siderite.
ACCRAIAN (Mid. DEVONIAN)	Sandstones, Grills, and Shales.
VOLTAIAN	U. VOLTAIAN: Mainly Sandstones.
	OBOSUM: Mainly Shales and Mudstone Beds.
	OTI BEDS: Mainly Sands and Pebbly Beds.
BUEM VOLCANICS	Basaltic, Trachytic, and Andesitic Lavae; Agglomerates, Tuffs, Jasper.
BUEM	Calcareous, Argillaceous, Sandy and Ferruginous Shales, Sandstones, Argillaceous and Greywackes, Conglomerates and Tillite?
TOGO SERIES	Quartzites, Sandstones, Shales, Phyllites, Schists and Siltified Limestone.
TARKWAIAN	Quartzites, Phyllites, Grills, Conglomerates and Schists.
U. BIRIMIAN	Metamorphosed Lavae and Pyroclastic Rocks; Hypabyssal Basic Intrusives, Phyllites and Greywackes.
L. BIRIMIAN	Phyllites, Schists, Tuffs and Greywackes.
DAHOMIAN	ACID: Ortho- and Para-Gneisses and Schists; Migmatites.
	BASIC: Migmatites rich in Garnets, Hornblende and Biotite.
INTRUSIVE ROCKS	
BASIC INTRUSIVES	Gabbros, Dolerites, Norites; Serpentine, where separately mapped.
DIXCOVE GRANITE	Sodic Hornblende-Granites, Granodiorites, Aplites and Pegmatites.
CAPE COAST GRANITES AND WINNEBA GRANITES	Mainly Biotite Gneisses, Amphibolite Biotite Granites, Biotite and Muscovite Granites, Pegmatites, Aplites and Biotite Schists; Medium Grained Biotite Granite.