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Geophysics as an aid in geological mapping and development of mineral resources

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The contribution of airborne magnetic surveys to geological mapping

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Abstract. This paper describes the procedures used for the interpretation of an aeromagnetic survey used to aid geological mapping, and discusses both advantages and shortcomings. It is one of the most useful tools available to help with geological mapping, providing information at a reasonable proportion of the cost of ground mapping. To be most effective it must be used in close co-operation with the geologists who have the over-all responsibility for the production of the geological map.

A detailed aeromagnetic map is a permanent record of a set of related facts, and it increases in value as more becomes known about the geology. The aeromagnetic survey covers an area quickly and provides geologists with an over-all picture of structure, even though the boundaries may be obscured by overburden, forest, swamp or water; it reveals major structures and magnetic divisions which may not be recognised in the field; it can contribute to mineral or oil exploration programs.

More important, it produces a whole series of ideas which can be tested by the geologist and which may help him to understand more fully the geological data he had collected.

Résumé. Cette étude décrit les procédés utilisés pour l'interprétation des levés aéromagnétiques utilisés comme auxiliaires de la cartographie géologique; les avantages et les insuffisances de cette méthode sont également discutés. La carte aéromagnétique est un des moyens les plus utiles mis à la disposition de la cartographie géologique; on peut, par cette méthode, obtenir des renseignements à un coût représentant une proportion raisonnable de celui de la cartographie au sol. Pour plus d'efficacité, cette méthode doit être utilisée en étroite collaboration avec les géologues qui ont la pleine responsabilité d'établir la carte géologique.

Une carte aéromagnétique détaillée constitue un régistre permanent d'un ensemble d'observations et elle acquiert une importance de plus en plus grande à mesure que la géologie des lieux est mieux connue. Le levé aéromagnétique est rapide à exécuter et il donne aux géologues une image d'ensemble de la structure même s'ils sont recouverts de morts-terrains, de forêts, de marécages ou d'étendues d'eau. Il peut révéler des traits majeurs de la structure et les divisions magnétiques qui échappent au géologue en campagne peuvent être reconnues. Il peuvent constituer un élément important d'un programme d'exploration minière ou pétrolière.

Plus importantes sont les suggestions et les indices nombreux qui ne demandent qu'à être vérifiés par le géologue et qui peuvent l'aider à mieux comprendre les données géologiques qu'il a rassemblées.

In 1967 detailed geological maps cover only a small percentage of the earth's land surface. In no country is there complete geological coverage at a scale of 1:50,000 and there are many places where reliable maps at a scale of 1:250,000 do not exist; geological maps of the continental shelf and inland seas are even scarcer. Yet geological maps are required for the properly planned development of national and global resources. They provide the basic information which is needed for an assessment of water and mineral resources, for the agricultural and engineering potential of the planet on which we live, and the basis of all scientific exploration for oil and minerals. They are urgently required in the industrialised countries of North America, Europe, Asia, and Australia and even more urgently required in the developing nations of South America, Africa and Asia.

Good geological maps of a whole country cannot be prepared overnight; time is required to search the ground and to co-ordinate the observations of many field geologists. Proper geological comprehension of an area only comes with years of experience and familiarity; geologists with this experience are in short supply in many areas where they are required, and they need all the help they can get, to make the fullest use of their time and abilities.

There is no simple solution. Photogeology and airborne magnetic surveys, supplemented in part by other geophysical methods, are probably the most useful tools at present available to speed these needed geological surveys; the best use of aeromagnetic surveys can be made only if they are planned as part of a mapping program. This includes proper planning of the surveys, the careful choice of areas of the survey, support from geologists at the interpretation stage, and properly directed follow-up to check and extend the interpretation.

To do this both the potential and limitations of the airborne magnetic method must be appreciated: the cost of using other methods should be considered as they may be more appropriate in some cases.

At its simplest the aeromagnetic map, when interpreted, gives information similar to that provided by the geologist, except only that the aeromagnetic survey will produce it much more quickly and be unrestricted by forests, superficial deposits, or water. In this case the map will show magnetic and nonmagnetic beds, folds and faults, which affect certain of the igneous, sedimentary and metamorphic rocks and intrusions.

At its best it provides a fund of fresh information and ideas about well mapped areas, where the abundant geological data let us understand the problems which have to be solved. The magnetic map gives information about geology in depth, it reveals unobserved differences in rocks and shows new major structures.

This is the case in western Europe where aeromagnetic maps of France and U.K. provide fresh facts about the basement on which the younger rocks lie, and suggest the presence of major structures which have influenced their development.

The value of a survey does not end with the first interpretation, but rather increases as more is discovered about the geology. Indeed it has always surprised me how much more information an airborne magnetic survey will yield in areas where the geology is well known, because here, the geological problems are more clearly defined and it is possible by means of the control provided by the geology to appreciate the significance of individual anomalies.

The best results from an aeromagnetic survey are obtained when geologists and geophysicists work as a team, combining the geological and magnetic information so that each illuminates the other. The interpretation of the results of a magnetic survey involves not only seeing what geology is in an area, but also recognising its significance. This requires scientific imagination as well as the ability to analyse the data.

The outstanding advantage of the magnetic survey comes when very large areas are covered. The uniform presentation of a single property of the rocks permits a rapid comparison and assessment of widely separated areas, and reveals major structures which can be missed if only small areas are mapped.

This is, to my mind, the most important of the many advantages of the aeromagnetic survey.

Geological mapping and magnetic survey mapping

Geological maps may be made for a specific purpose as part of a water, mineral, or oil exploration program, or as part of an engineering project; or they may be made by government surveys to provide a scientific basis for a variety of commercial operations both present and future, or they may be part of a purely academic enterprise.

In each case the geological map performs two functions:

1. It presents a summary of the geological observations, made perhaps by several men working over a number of years, in such a way that many observations may be conveniently compared. The rocks are classified and groups are established; deductions are then drawn about the age and structural relations of different rock masses to each other, and the history of geological events.

2. A map also illustrates very precisely the geologist's interpretation of his observations. The lines, drawn on the map, which indicate the boundaries of the rock groups (e.g., granite bosses, sandstone beds, dykes, etc.) or structures such as faults or folds, are the geologist's interpretation of the data. During his interpretation, use is made of geological concepts such as faults or nappes; some of the structures that he postulates cannot really be proved in the particular area, but he uses ideas which have been proved elsewhere and which are consistent with his observation.

The procedures and techniques used to map gently folded fossiliferous sediments and those used for highly folded metamorphic rocks or igneous rocks differ appreciably, though obviously they still have much in common. A similar distinction is made in aeromagnetic surveying, where a difference is drawn between oil type surveys, mineral type surveys, and regional surveys.

An oil type survey is flown at a constant barometric altitude (usually between 1500 and 3000 feet above the mean ground level and on lines 2 to 5 km apart) over weakly magnetic sedimentary rocks, the main purpose being to determine the depth of the strongly magnetic basement. A mineral type survey is flown at a constant ground clearance, usually 500 feet, on lines which are 400 to 800 metres apart (although they may be as close as 150 metres and as far apart as 3000 metres) to define the pattern of the magnetic rocks at or near the surface. The height and spacing are interrelated and are determined by the size of magnetic features expected. In an oil survey the structures may be several miles in extent. In a mineral survey the geology may be so complex that adjacent lines less than 400 metres apart may be difficult to relate to each other. The height and spacing of the flight lines determine the resolution of the method and will be discussed again later. A scintillation counter and spectrometer are often operated at the same time on mineral surveys; thus additional information about radioactive and non-radioactive rocks can add appreciably to the information obtained from the magnetic interpretation.

As the regional survey is usually for reconnaissance, undertaken to find the larger geological units and structures in an area, it may be flown at about 1000 feet above ground level at 2 km spacing. Closer spacing is preferred but it will cost more to cover the same area.

The process of magnetic mapping is similar to geological mapping. It consists of a) The collection of data, from which the magnetic contour map is produced, and b) The interpretation of this map and the original magnetic profiles recorded in the aircraft.

The measurement of the magnetic field and construction of the magnetic map have been described by Reford and Sumner, in a review article in *Geophysics.*

The effectiveness of the aeromagnetic survey depends on the widespread distribution of magnetite and a few other magnetic minerals in igneous, metamorphic and a few sedimentary rocks. The aims of magnetic surveys are to recognise the depth, position, shape and attitude of the magnetic bodies in an area and then to interpret these values in terms of geological models which are consistent both with the observed geology and with accepted geological theory.

As the method responds exclusively to magnetic contrasts, it can miss important structures if they affect homogeneous or only weakly magnetic rocks; on the other hand it can locate differences which cannot be observed by geologists, either because they are not detectable in hand specimen, or because the rocks are not exposed. For these reasons the magnetic interpretation and the geological interpretation may be different; the methods therefore complement each other.

Special advantages of airborne magnetic surveys

Airborne magnetic surveys have the following special advantages: they are quick and can operate in areas where normal ground surveys, either geological or geophysical, are not readily carried out; the magnetic response from the rocks is normally unaffected by cover of boulder clay, thick forest, deep weathering, lakes or seas which hinder or prevent detailed geological or photogeological mapping; magnetic surveys provide continuity of information which is rarely obtained in a geological survey. A magnetic contour map, if the survey is properly planned and carried out, is a permanent record of the effect of the rocks. It may be interpreted many times with improvements on each interpretation, but the original pattern of the anomalies on the magnetic map will not change.

The depth from which information is obtained by the magnetic method greatly exceeds the thickness of the superficial deposits. Provided the basement rocks are magnetic and there are no shallower strongly magnetic bodies, geologically significant information may be obtained from depths of at least 40,000 feet. No other airborne method does this. The magnetic survey presents a uniform picture of a large area as it records consistently the effect of the magnetic properties of the rocks.

An aeromagnetic survey discriminates against small anomalies due to minor concentrations of magnetite in the soil which complicate a ground survey, and only the major features are picked out. This discrimination may be useful over highly magnetic lava flows in which the major geological structure may be obscured by lack of an identifiable horizon, and where the ground magnetic pattern is too complex to be recorded adequately.

Two less appreciated but possibly far more important advantages of an airborne survey are:

1. It can distinguish between two petrologically similar rock groups if they contain different amounts of magnetite or have had different magnetic histories.
2. It can reveal major structures which are not easily recognised on the ground because they are so big.

A geologist cannot tell the difference between 0.5 per cent magnetite or 1.0 per cent magnetite in large volumes of rock, but it will be readily evident in the records of an airborne survey. Small variations in the quantities of magnetite do occur within a series of gneisses or intrusions of granite. Irregularities in the composition of rocks which extend over a few tens of feet may present only a confusing variation in rock to the geologist who usually sees only a small sample of the rocks and therefore may be unable to classify them properly. An airborne survey, by recording the effects of these moderate-sized variations in the composition, may be able to distinguish between two different groups of similar weakly or strongly magnetic rocks.

Major structures extend over large parts of a country, but because they are so large, they may not be fully appreciated by the geologist who sees a small part of them. Many large linear and circular features have been detected on airborne geophysical maps which still remain to be explained. Some of these features can be related to the structural development of an area. The aeromagnetic map thus provides a special link between the geological map and major tectonic features.

Some limitations of airborne surveys

I have been, and will be, concerned to show the uses and advantages of the airborne magnetic method, but to use it properly you should also be aware of what it will not do, and not expect too much from it.

The method will only be effective if the rock bodies of special interest are magnetic or associated in some way with magnetic rocks (or if they are nonmagnetic but within a highly magnetic block). This applies particularly to surveys over sedimentary rocks. As the sensitivity of magnetometers increases, the number of effectively weakly magnetic rocks decreases.

The resolution of the aeromagnetic method is limited by the flight-line spacing, by the distance between the aircraft and the magnetic body, and by the angle between the flight line and the strike of the major axis of the body. If there are magnetic horizons at various levels it may be very difficult to distinguish one from the other especially if they are close to each other. For better resolution of outcropping bodies you must use photogeology or ground surveys.

You cannot usually recognise a structure which is so small that the whole of it lies between two flight lines.

A satisfactory analysis of the magnetic anomalies will only be possible if the distribution of magnetic bodies is fairly simple. If geological control is available much more complex structures can be investigated.

The method is more difficult to use if the noise level, either from other magnetic bodies or from man-made sources, is greater than the anomalies we are looking for.

Surveys can be flown in many inaccessible areas, but in some very mountainous country, deep valleys prevent a constant ground clearance being maintained and do not permit satisfactory uniform coverage at low level. This can be overcome in two ways: by carrying the magnetometer in a helicopter and flying either along traverse lines or around the contours of the mountain, or by flying with a sensitive magnetometer at a greater height. This last solution is usually preferred as it provides anomalies undisturbed by solid angle effect, which you can get in narrow valleys, thus permitting quantitative interpretation.

Although there are some problems for which the airborne magnetic method may be less useful than other methods, it is impossible to foresee what unexpected information a survey may produce which could solve a problem, so that it is difficult to predict that a magnetic survey will not be of assistance. The only way to find out is to try it.

Interpretation

The first, and possibly most important, step in interpretation is to understand the geological problem and to regard the airborne magnetic survey as one of several tools used to solve it. The interpretation must be done in two stages:

1. The magnetic contour maps and records are analysed to give an answer which consists of a number of geometrical shapes. The geologist may use this analysis himself if he wishes to obtain an alternative interpretation.
2. The geometrical shapes must then be translated into geological terms.

The part of the process of interpretation which is routine, much of it just common sense, can be described fairly simply. Interpretation also requires insight and inspiration which only come after much hard work, and this is much more difficult to classify. There are six steps in the routine process:

1. Establish the geological character and tectonic style of the area.
2. Define the aims of the interpretation and find out what geology may be expected.
3. Work out the shape, attitude, and apparent magnetic susceptibility of the magnetic bodies from the contour map and records.
4. Correlate the geometrical pattern of the magnetic bodies with the geological observations and theories, and with the magnetic properties of any rocks from the area.
5. Test the magnetic interpretation by field observations.
6. Review the conclusion of these tests and repeat the cycle.

In areas where the geology is already well known, the problems are more specific and a question and answer technique may be used; specific geological problems or ideas are tested against the information contained in the magnetic maps. Three possible answers may be obtained: a) A structure is consistent with the magnetic data, b) it is inconsistent with the magnetic data, or c) the map gives us no help either way.

By doing this it is often possible to choose between alternative solutions which are suggested by the geology or other geophysical surveys, and to produce an answer where the interpretation of the magnetic data by itself is obscure.

Practical interpretation

The first steps in the practical interpretation are: a) Study the known geology, b) calculate mathematical models, and c) review

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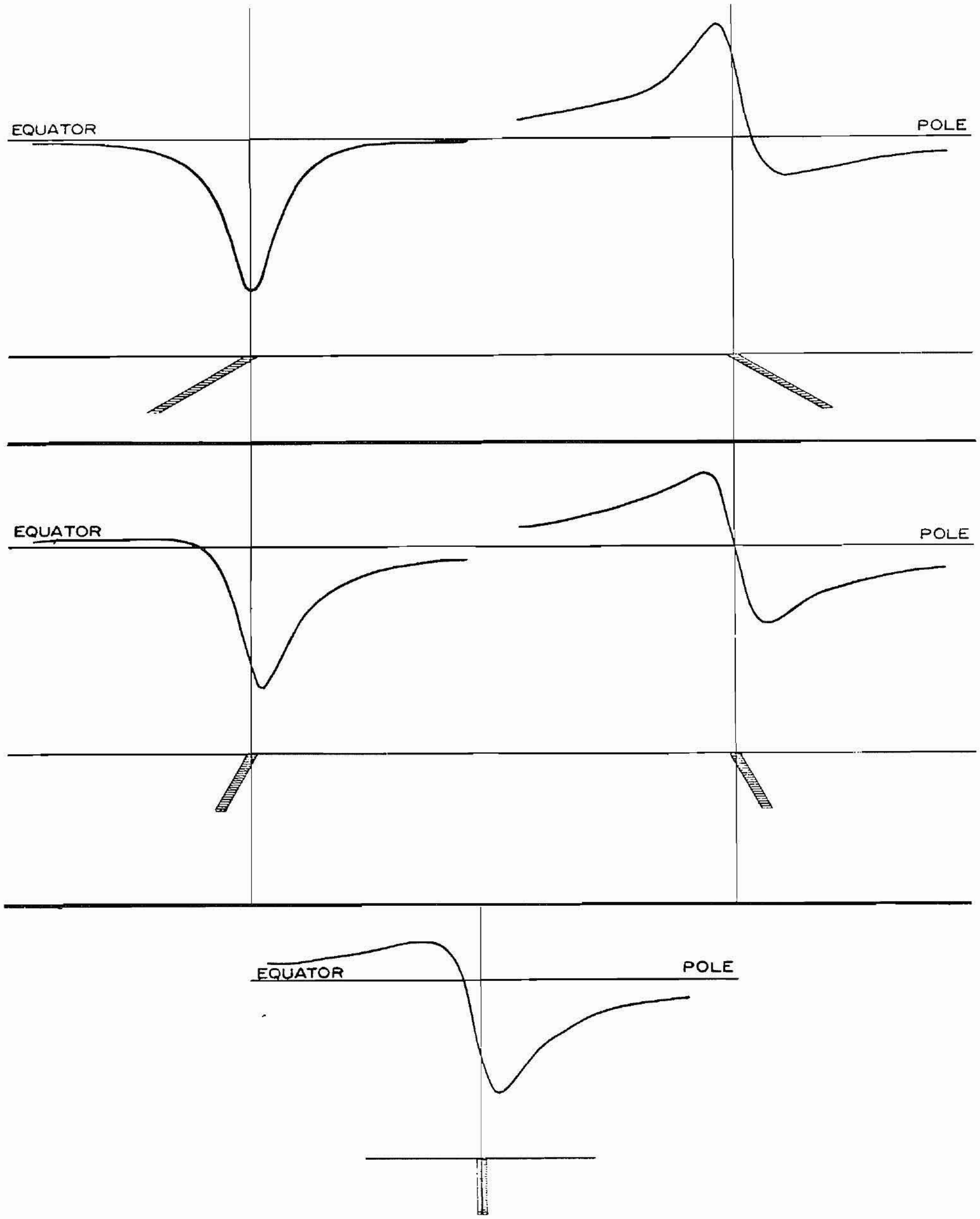

Figure 1. Shape of magnetic anomaly found over a thin east-west striking sheet dipping at different angles, in an area where the inclination of the earth's magnetic field is 30°.

the quality of the aeromagnetic data. When this has been done we can start the interpretation.

At the start of all surveys I ask four very simple and obvious questions. What is known about the area? What is there likely to be in the unknown parts of the area? What do we want to know about the area? Why was the survey flown? From the answers we can classify the interpretation under one of three headings:

1. Mineral type interpretation in which the main purpose is to establish the outcrop pattern of magnetic rocks.
2. An oil type interpretation in which the main purpose is to establish the depth at which the magnetic rocks occur beneath the cover of relatively nonmagnetic rocks, and
3. The regional interpretation in which the main interest is to establish the structural pattern of an area and the magnetic characteristics of the main rock groups.

The aims of the different surveys are not exclusive. In a mineral survey we may want to find the depth of a magnetic horizon or body which does not reach the surface. With an oil survey the interpretation of the pattern of the magnetic basement rocks can provide exceedingly important information from which the structural development of an area may be understood. With a regional survey we are normally concerned to discover all possible information about an area so that it may be used for many different purposes. A regional survey shows in which area detailed surveys may be helpful, and provides background information which may make all the difference in interpreting the magnetic map of a limited area.

The first thing to do is to obtain both original field maps and completed geological maps (with geological boundaries and structures) of the area, preferably at the same scale and using the same base map as that used on the magnetic survey.

The geological map indicates what rocks occur in the area and from experience we know which ones are usually magnetic. Most basic intrusions, some acid intrusions, basic dykes, basic lavas, magnetite quartzites, and some schists and sediments are strongly magnetic. Most, but by no means all sediments, many granites and acid lavas, and some metamorphic rocks such as phyllites are weakly magnetic. However, a rock name is an uncertain guide to its magnetic properties; it is preferable to collect samples from the survey area, and measure the magnetic properties of specimens from each rock group. Both the susceptibility and the remanent magnetic moment should be measured, but this is often impossible at an early stage of a survey. Further information about the magnetic properties of the rocks may be obtained by ground magnetometer traverses, which in effect measure the bulk magnetic properties of the rocks, and by studying the results obtained by any previous airborne survey flown in adjacent areas when the geology is known.

The tectonic style of an area should also be established. The interpreter likes to know the mean strike direction of each part of the area, and the approximate angle of dip of the rocks. It is important to know if there are any big thrust faults or nappes in the area, and helpful to know the direction of any major faults.

If the survey is planned to find minerals we should know the exact position of all mines and prospects in, and adjacent to, the area; we should know the dip and exact strike direction of each deposit, what rocks and structures are associated with it, and what theories there might be on ore-genesis. In this way we know what kind of rocks and structures to look for with the aeromagnetic survey.

Aerial photographs or mosaics can provide useful information and some form of photogeological study should certainly be undertaken in areas in which little geological mapping has been done, if photographs are available.

In most aeromagnetic surveys the interpretation is ambiguous, so that all information available from geological or geophysical surveys must be used if the best interpretation is to be obtained.

The answer to all these questions and the availability of the information will vary according to the area. In places where the rocks are entirely obscured by swamp or jungle, or are covered by desert sands, or water, we start from nothing; usually some geological survey has been made in an area, and the fullest use should be made of this information in planning the survey and interpreting the results.

The best way to display the miscellaneous information about an area is to plot it on a map at the same scale as the magnetic map.

Mathematical models

It is normal at the start of an interpretation to calculate the anomalies expected over certain simple magnetic shapes on the assumption that they are produced by induction by the present magnetic field. Various contour maps and profiles of this kind have been published (Vacquier, *et al.*, 1951; Hutchinson, 1958; Gay, 1963; Reford, 1964; and Bruckshaw and Kunaratnam, 1963). The anomalies for bodies of less standard shapes can now be made using a computer (Grant and Martin, 1966; Bhattacharyya, 1964; and Bott, 1963).

Initially the calculations are made for a dyke-like body. Figure 1 has been prepared for a north-south traverse across bodies which are striking east-west. A similar traverse is usually prepared for bodies which strike NE or NW.

In areas of low magnetic inclination the induced total magnetic field anomaly over a magnetic dyke is predominantly a negative one, which at first seems curious, but is a normal consequence of magnetic induction.

There are two other curious features on any aeromagnetic map flown in areas of low magnetic inclination. The strongest anomalies found over a narrow dyke-like body which is elongated north-south are at the north and south ends only, and not over the north-south striking sides; this makes it very difficult to recognise structures which strike north-south. In practice we often find that a magnetic body which strikes north-south in low magnetic latitudes is marked by a bead-like string of anomalies.

For the same reason the anomalies are strongest along the east-west striking faces of a magnetic body; consequently the anomalies are seen most clearly on flight lines which run north and south, and the pattern of the anomalies on a map is predominantly east-west.

The changes in the shape of the anomalies which occur over a dipping sheet are shown in Figure 1. From this it is clear that the shape of the anomaly changes in both shape and intensity over a bed whose strike and dip vary around the outcrop of a fold, and it is not easy to follow the anomaly unless you know what to expect.

The recorded anomaly is due to the resultant of the induced and permanent magnetisation. Rocks which have a strong remanent magnetic moment may be less affected by changes in strike. In low latitudes, north-south striking dykes which have a remanent moment often stand out prominently on a magnetic contour map.

As the total magnetic field is appreciably weaker in low latitudes (between 25,000 and 35,000 gammas in contrast to a field of about 58,000 gammas at Niagara), the anomalies are weaker in low latitudes for the same susceptibility, shape and size.

One other feature of fields of intermediate and steep dip angle is that vertical and steeply dipping prismatic magnetic bodies are marked by a positive anomaly on the side nearest the equator and by a negative anomaly on the side nearest the pole. After a little experience you get used to the varieties of anomaly patterns.

Anomaly amplitudes to be expected from bodies of various magnetic susceptibilities are calculated for references. The actual susceptibility used will depend on the information already obtained from samples as indicated in the previous section, but we usually use a value of $k = 100$ to 1000×10^{-6}.

Standard of data

When we use information, whether it be a geological map, drill hole logs, or geophysical data, we must find out how reliable the data are. A geological map which is based on a two-week reconnaissance on a 1:50,000 scale map obviously lacks the reliability of one which is based on several years of carefully detailed survey on a 1:10,000 scale map. The same is true for airborne surveys. Before starting work we must check on the flying height and the flight line spacing because these dictate what size of body of a given magnetic susceptibility we can detect from the air and what we may miss.

We must also note the direction in which the flight lines run because this will determine the strike of the bodies which are most readily detected by the survey. Bodies which strike obliquely to the flight lines are much more difficult to recognise than those which strike at right angles and some allowance must

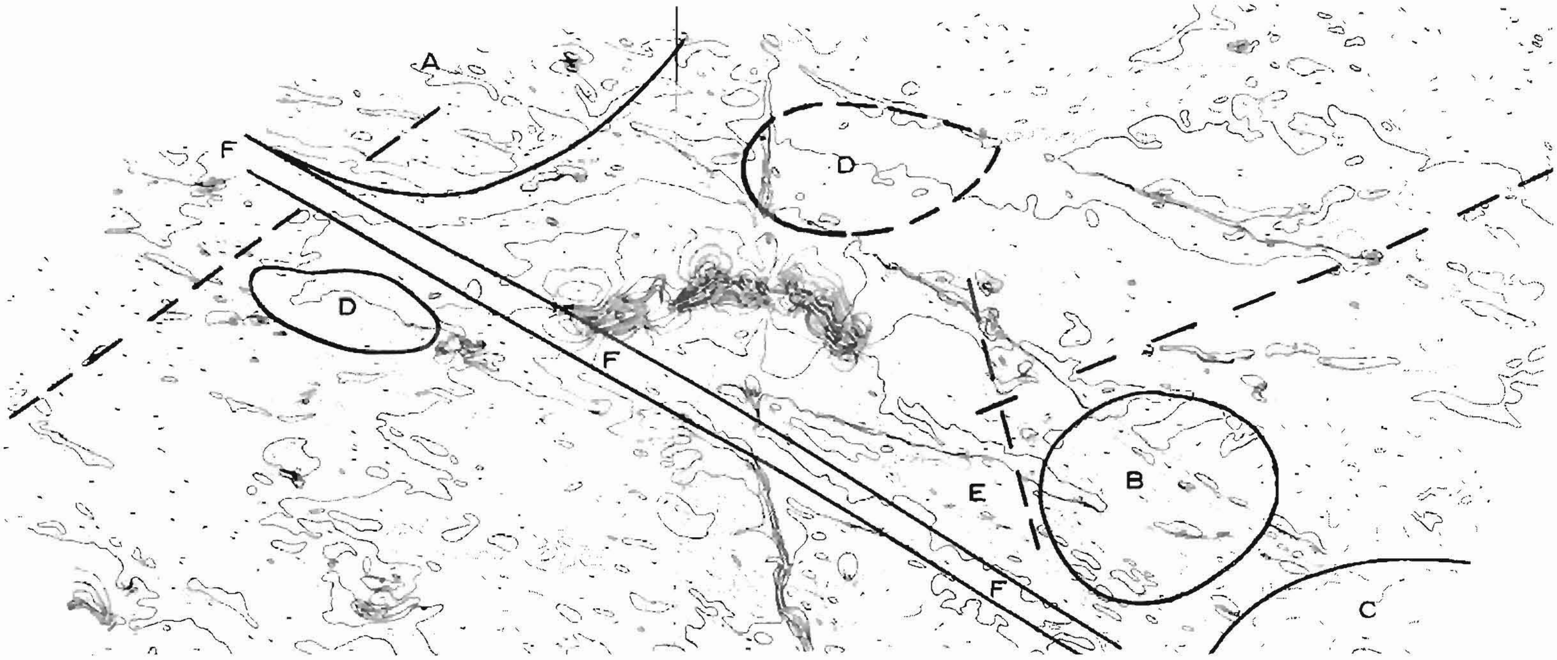

Figure 2. (Scale 1:400,000 approx.) Aeromagnetic survey flown at 500 feet above Archean rocks in Tanzania (line spacing 1/4 mile). The area lies south of the Magnetic Equator. $I = -30°$. *A*. Magnetic granite. *B*. Slightly magnetic granite within synorogenic granite. *C*. Weakly magnetic granite within synorogenic granite. *D*. Weakly magnetic granite within Nyanzian rocks. *E*. East south east striking diabase dyke deflected at aureole of granite B. *F*. Major shear zone cutting banded ironstone and crossing a large dyke. (Flown at the request of the United Nations Development Program in association with the Government of Tanzania. Reproduced by permission of the Geological Survey of Tanzania.)

be made in the interpretation for the bodies and structures which have been missed in this way. In a combined airborne geophysical survey the line spacing and flying height may have been chosen to suit the requirements of the electromagnetic or radiometric survey rather than the magnetic survey. A well planned survey will include a number of lines flown at right angles to the main lines both for magnetic control and for extra information.

The noise level and sensitivity of the magnetometer are important. The instrument noise level limits the resolution of the survey; the geological noise level is due to small magnetic bodies, superficial magnetite concentrations of no interest; industrial magnetic noise may seriously reduce the effectiveness of a survey in certain parts of the world. If the magnetic susceptibilities of the important rocks are known we can calculate the size of the anomaly expected for a given width of the body. This will indicate what noise level is acceptable if we want to detect magnetic bodies of a certain size.

We must also examine the accuracy of flight path recovery, the care with which the reduction has been carried out and the magnetic control has been applied, and the quality of the base map used. If the base map is a mosaic, distortions in hilly country may appear as anomalies on the magnetic map. Contouring of a magnetic map is an art and to an appreciable extent it is an art of interpretation and some contour maps are more logically drawn than others. In areas where the flight line spacing is so wide as to introduce ambiguity in correlating from peak to peak or trough to trough on adjacent lines, significant differences in the contour pattern are possible and these may strongly prejudice the interpretation of the results. The experienced interpreter is familiar with these difficulties, and will inspect and check his maps as he proceeds with the interpretation. Ideally, contouring should be based on magnetic trends as determined by a geophysicist, who can compare anomaly shapes as well as amplitudes. Good drafting is also important; a poorly drawn map will obscure some of the subtler features on a contour map. Sometimes a profile map will show up minor anomalies which are missed by the contouring; this is particularly true where the anomaly is merely a slight break of gradient on a larger feature.

As explained later the areal extent of a survey can at times greatly influence the amount of information that can be obtained from it. If the survey is restricted to a small area the full significance of many of the features on it may not be appreciated. This must be taken into account when the interpretation is planned, and regional magnetic maps of adjacent areas obtained if they are available. All geologists and geophysicists know that the most interesting anomalies are always at the edge of the area.

Interpretation proper

A mineral-type survey is often one in which the magnetic bodies dip steeply and in which variations in the magnetic intensity are large. In the first or preliminary interpretation we are concerned to establish the outcrop pattern of the shallow magnetic bodies by distinguishing areas of different magnetic character. This is done from the average difference in intensity of the magnetic anomalies, the variation in strike direction, or the length of strike of individual anomalies. By dividing up the area in this way we produce a pattern composed of groups of magnetic bodies which we may then start to interpret in terms of the geology. If the flight lines are too far apart the pattern of the anomalies is made less clear because definition and hence character is lost.

The following geological bodies are those which most commonly produce magnetic anomalies: basic dykes and sills, acid and basic bosses, greenstone horizons, lavas and volcanic necks, magnetite quartzites, ironstones, and charnockite rocks. These magnetic rocks together with faults form the elements of a magnetic interpretation.

Dykes. Swarms of basic dykes are frequently the most prominent objects to be seen on an airborne magnetic map. Much work has been done recently, particularly in Canada and Australia, but too little is still known about the pattern of dykes to make the fullest use of this information. Part of the increase in both interest and information about the dykes stems from the increasing information about them now provided by aeromagnetic surveys, which cover extensive areas in America, Europe, Africa and Australia. In the interpretation we are interested in the frequency with which dykes occur, as this may indicate a change in the character of the rocks or in the state of the crust. If we know the width of the dykes we can calculate the susceptibility and may be able to classify dykes of the same composition in these groups. Conversely, if we know the susceptibility of the dyke material, we can calculate the width of individual dykes. In many cases we must look at the individual magnetometer records rather than the contour map to recognise the smaller anomalies produced by thinner dykes. We can frequently recognise the effect of remanent magnetisation from the pattern of the anomaly; this is another way to differentiate between groups of dykes on the strength or direction of their remanent magnetisation.

A dyke sometimes changes its strike direction as it passes from one rock type to another: variations in direction can therefore be used to recognise changes in the rock types which it is crossing. An example of this is shown in Figure 2 where the dyke is deflected as it crosses the aureole of a granite. The amplitude of the anomaly produced by a dyke frequently changes as the dyke traverses different rock types; e.g., when a dyke crosses a band of schist the intensity increases; when it passes through granite the intensity decreases. This may be interpreted as a change in the susceptibility contrast between the dyke and country rock, or as a change in width of the dyke (Figure 4).

In some areas similar intrusions (e.g., granites) can be distinguished because some are cut by dykes but others are not (Figure 2). This may be due to either a different texture or a different age.

A dyke may take on a zigzag pattern in an area where it is running obliquely to a strong joint or fault pattern. The segments follow the joints or faults running at an acute angle to the over-all line of the dyke and stop at those which run approximately at right angles to the dyke. Information of this kind can sometimes help us to understand the distribution of mineralisation in an area if it is related to the fault pattern.

In some areas dyke swarms follow major shear zones. In adjacent areas other shear zones may be suggested, though not proved, by similar concentrations of dykes.

Isolated major dykes or groups of a few large dykes probably indicate special conditions in the earth's crust although at present we may not fully understand their significance.

Although dykes frequently appear to be displaced by faults, interpretation of faults based on dykes alone is always a little unsure, as the amount of displacement may not be due to a fault but may be produced by other conditions which we do not fully appreciate.

Major intrusions. Granite, diorite, gabbro and syenite frequently occur as intrusive bosses which have a diameter usually between 2 and 20 kilometres. Granite or a granite gneiss may outcrop over much more extensive areas. Gabbros, diorites, and some granites and syenites are strongly magnetic and show up as distinctive magnetic anomalies on the maps; weakly magnetic granites and syenites may be equally distinctive if they are much less magnetic than the surrounding rocks, when they would appear as areas of uniform magnetic field surrounded by large anomalies (Figures 2 and 4).

In some areas where the magnetic properties of an intrusive rock do not differ appreciably from that of the surrounding rocks its outline may still be indicated by a halo of slightly more magnetic rock; this halo may be due either to magnetite or phyrrhotite which has been introduced into the country rock by the intrusions (Figure 3) or to the baking of the country rock and subsequent production of thermoremanent magnetisation.

In some extensive areas of apparently uniform granite the magnetic map reveals distinctive circular features which appear to indicate a number of moderate sized bosses within the main granite mass (Figure 2). As the amplitude of the anomalies may be only 10 to 20 gammas they are often not obvious. In some areas of granitic rocks there is scope for surveys made with a high-sensitivity magnetometer capable of reading to about 0.1 gamma.

The results of a radiometric survey flown in conjunction with the magnetic survey can be particularly valuable in studying granite intrusions.

In some areas where there are several granite intrusions some granites are strongly magnetic, whilst others (as indicated from the relative intensity of the maximum and minimum anomalies) have a strong remanent magnetic moment which permits the granites to be further subdivided. In one area in Africa, gold mineralisation is associated with certain magnetic granites and not with other granites in the area.

Gabbro intrusions are normally strongly magnetic. Like the granite bosses they are on occasion associated with rings of strong anomalies, which seem to be due to magnetite or ilmenite mineralisation around the margins. Circular and less regular structures are sometimes observed within masses of gabbros which in some intrusions correspond to ring structures which have been mapped on the ground.

I have seen large circular structures with a diameter of 30 or 40 kilometres in basement areas on aeromagnetic maps, but I have no information about the geological features associated with these structures, as detailed geological maps do not exist.

The magnetic map, as well as indicating the presence of these major intrusions, may also reveal the structural context in which they occur.

Conformable magnetic horizons. The common conformable horizons found in metamorphic rocks are greenstones, magnetite quartzites, some schist bands, and banded ironstones.

Greenstones form broad magnetic zones, which can be followed for miles across the country. They are useful for mapping because they can be followed around the crests and troughs of the folds and we can be sure that displacements of the boundaries are due to faults. In some cases it is possible to

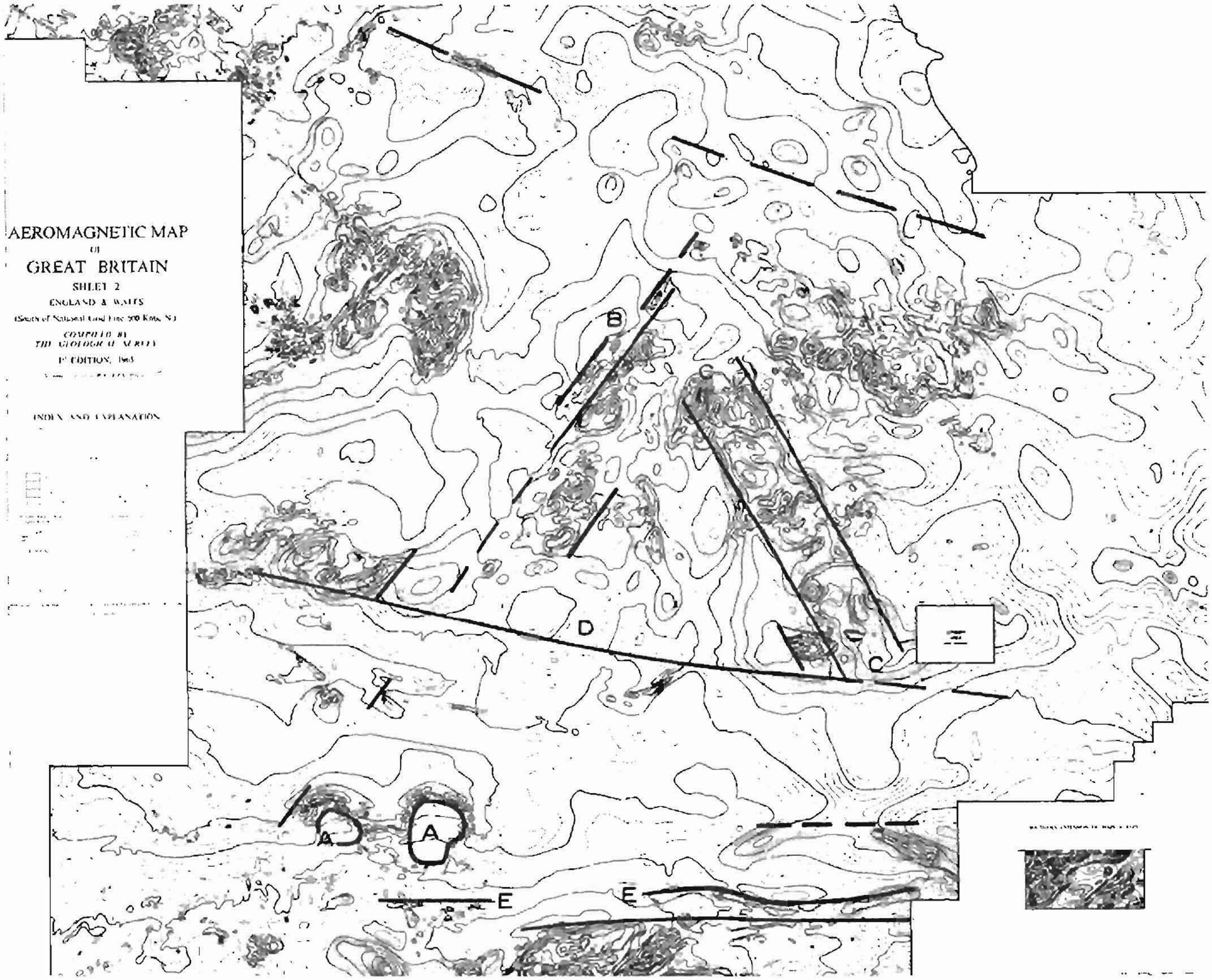

Figure 3. (Scale 1:3,400,000 approx.) Aeromagnetic survey flown at 1,000 feet above southern Britain; line spacing 2 km. *I* = 67°. *A*. Magnetic halo around Hercynian granites (Cornwall). *B*. Major fault (Church Stretton Fault). *C*. Major magnetic feature lying below Palaeozoic and Mesozoic rocks. *D*. Hercynian front. *E*. Basement boundaries in rocks lying below the English Channel (Crown Copyright, Geological Survey Map. Magnetic map. Reproduced by permission of the Controller, H.M. Stationery Office).

estimate the direction and angle at which these horizons are dipping. Greenstone horizons will show distortion around granite intrusions, and in places a change in character. This is probably due to the reheating effect of the granites and subsequent production of a thermoremanent magnetic moment. Magnetic schist horizons are like greenstone horizons; they are broad and easily followed. In both greenstones and magnetic schists a change in character is frequently seen along the strike of the body, which may indicate a change in the rock type, a change in depth extent, or a variation in thickness.

Some quartzites contain appreciable quantities of magnetite. These quartzites can represent key horizons for the determination of structure, but although the anomalies are strong, they often disappear in the region of the trough or crest, on account of the change in the dip and strike and the accompanying change in character of the magnetic anomaly, described in the section on "Mathematical models". Consequently it is often difficult to locate the axis and to follow the magnetic horizon around the complete outcrop. This is particularly true in areas of low magnetic dip where a distinctive anomaly obtained from a body striking northwest will break into a series of small bead-like anomalies when the magnetic horizon strikes north-south. The anomalies due to magnetite quartzites frequently look much like those due to dykes but the former are usually more continuous and parallel. In some areas, divisions within the stratigraphic column may be established by the presence or absence of numerous bands of magnetite quartzite, which mark a change in sedimentation.

In some areas fault lines are marked by quartzite ridges. These hills often appear as zones of rubble up to half a mile wide, but they are probably due to quartz veins which are very much thinner. These quartzites may be strongly magnetic and must be distinguished from the sedimentary quartzites to understand the structure.

Banded ironstones generally produce very large magnetic anomalies (Chamberlain and Quilty, 1965, Figure 1), but some banded ironstones are highly siliceous and are therefore not strongly magnetic. The change in magnetic content along the strike between strongly magnetic and weakly magnetic ironstones may be sudden. Magnetic ironstones are easily followed, but it can be difficult to work out the structure from the outcrops; in some areas there are either rapid changes in the composition of the sediments, or they have been involved in large faults. The difference in physical properties between the ironstones and surrounding rocks makes their edges a likely place in which failure of the rock would take place. Banded iron formations have been used extensively in the west Australian Precambrian Shield as key horizons in the determination of geological structure.

Charnockites. It has been my experience that charnockite rocks are almost invariably magnetic, and this makes the mapping of them both easy and difficult. They are easy to recognise en bloc but it is difficult to work out an internal structure for them. At the present moment I do not know the reason for the high magnetic polarisation of the charnockites; it may be caused by the ultrametamorphism to which they have been subjected.

In Uganda (Hepworth, 1967) the aeromagnetic map indicated a certain structural direction over which later metamorphism implanted another trend which was at first the only one found in the geological mapping. Further work of this kind remains to be done with the magnetic interpretation of hidden metamorphic structures.

Structures

A variety of structures can be recognised from the aeromagnetic maps. Where wide conformable horizons such as greenstones occur, strikes and dips can be recognised or calculated. Folds of several miles in extent can be recognised (see Quilty and Chamberlain, 1965, Figure 1), and may be of great help to the geologist who is mapping the area, especially if it is poorly exposed. These folds are most easily seen in the broad greenstones and schist horizons, but are recognised only with difficulty in the thinly bedded magnetic quartzites. Cross-fold axes may be recognised by a nonparallelism of the rock bands which define the major folds.

Faults may be recognised on magnetic maps where they displace a magnetic marker horizon that can be identified on either side of the fault. Frequently the fault may be recognised by the abrupt disappearance of a horizon at the fault contact. In other places it may be recognised by a complete change of magnetic strike across the fault line or by a decrease in magnetic intensity along the line of the fault itself. Occasionally a fault can be detected by the presence of magnetic infilling material.

Individual faults may be recognised as outlined above. Many aeromagnetic maps show wide belts of parallel faults which have widths of between 10 and 30 miles and have a strike extent of several hundred miles. These zones of disturbance play an important part both in Precambrian geology and in the geology of the overlying sedimentary unaltered rocks.

Some faults may be recognised by a complete disappearance of minor magnetic anomalies in the fault zone although the faults do not themselves produce an anomaly (Figure 2); other fault zones are marked by a reduction in magnetic susceptibility which may cause the disappearance of a magnetic horizon over a distance of half a mile or more. This occurs when the fault is large and may be due to the complete mixing of the country rocks to produce a uniform mixture of the magnetic and less magnetic minerals. In other major shear zones the magnetic constituents appear to be pulled out into long streaks from the magnetic body on the side of the fault, and show the direction in which the movement has taken place.

Under appropriate conditions information may be obtained about the dip of thrust faults.

Testing the interpretation

The various rock bodies and structures, identified from the magnetic map, provide the elements from which an interpretation is created. This information is drawn on a map which is at the same scale as the contour map.

This first stage of an interpretation map must now be carefully compared with the observed outcrops of all rocks and structures shown on the geological map. We start by finding out which rock groups recognised by the geologist correspond to the groups of magnetic or nonmagnetic rocks. It is important to note discrepancies or contradictions that may exist between the geological observations and the magnetic interpretation of boundaries and rock types, because these indicate either one or the other method, or perhaps both, are wrong. It sometimes happens that the point on which the geological and geophysical interpretations disagree contains the vital information which leads to the correct interpretation of the results.

When this first check of the magnetic interpretation has been made the results should be discussed with all field geologists who are mapping or have recently mapped in the area, and who are still actively interpreting the geological data. Geologists and geophysicists who are interpreting their respective data frequently have embryo ideas about structures or geological features which are difficult to justify and difficult to express in a report, or on maps; but these ideas may provide a valuable clue to help the other man, or may suggest confirmation where the two independent methods indicate similar structures in the same area. In practice it is much easier to get over the ideas of a magnetic interpretation and put them in the form in which they are of most use to the geologist by discussion in front of the geological and magnetic maps. Few reports can get across all the nuances of a geological or magnetic interpretation. Personal contact and the different approaches by geologists and geophysicists working as a team are essential.

After the interpretation has been reviewed in the light of the various ideas and facts which emerge from the comparison of maps and discussions with the geologist, the completed interpretation must be checked on the ground. This check may take the form of preliminary reconnaissance mapping. The composition of various rock groups, indicated by the different magnetic zones, should be identified to find out whether there is any confusion of two different rock groups having similar magnetic properties, or of a magnetic rock group changing its character. The different rocks responsible for the airborne anomalies should be located by carrying out ground magnetic surveys which will indicate where they outcrop or come closest to the surface. (It is not sufficient to identify the rock beneath the airborne anomaly,

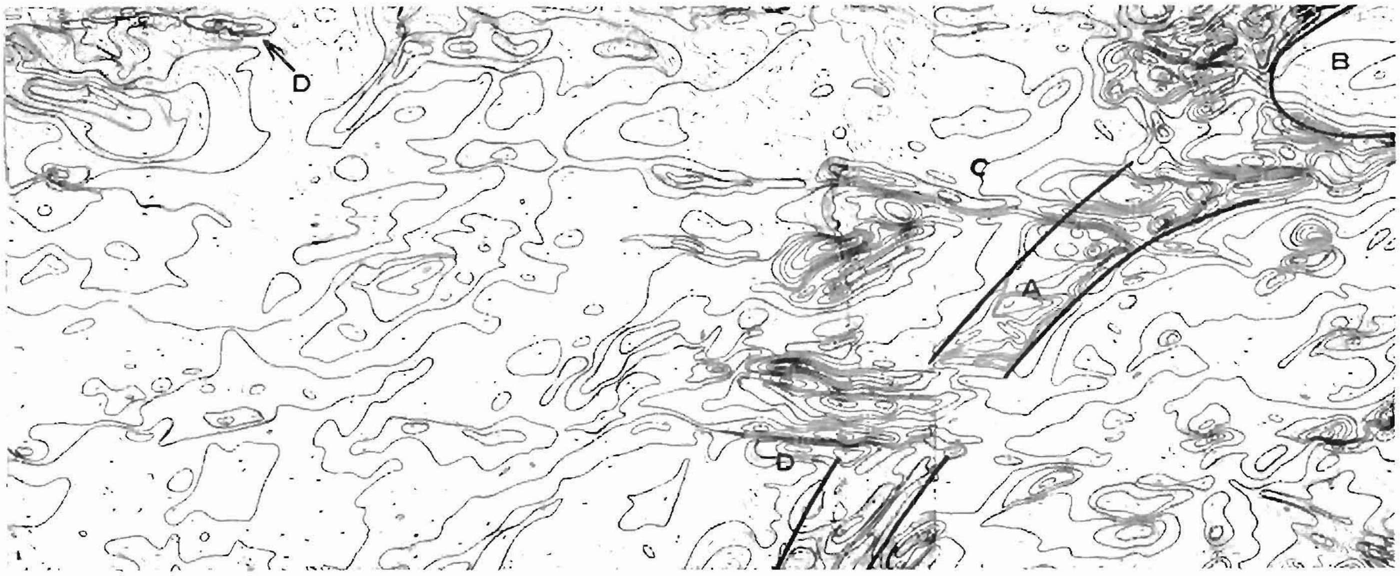

Figure 4. (Scale 1:200,000 approx.) Aeromagnetic survey flown at 500 feet above Precambrian rocks in Uganda; line spacing 1/4 mile. This area lies south of the Magnetic Equator. $I = -20°$. *A*. Band of magnetic schists. *B*. Weakly magnetic granite. *C*. Dykes showing changes in anomaly amplitude where they cross lithological boundaries. *D*. Dykes showing apparent abnormal remanent magnetisation. (Flown at the request of the United Nations Development Program in association with the Government of Uganda. Reproduced by permission of the Geological Survey of Uganda.)

or even to collect the rocks from this area and measure the susceptibility afterwards; the magnetic rock might be a soft schist which does not form outcrops.) One traverse with a magnetometer is the easiest way, for example, to confirm that a quartzite horizon does contain magnetite, and is the rock responsible for an anomaly; it is a good way to locate magnetic dykes which are deeply weathered: dykes can often be recognised from the change in soil colour and texture above them. Wherever possible, rock samples should be collected from individual horizons and both their magnetic susceptibility and remanent magnetisation measured. If a representative number of samples are collected it is possible to calculate the anomaly expected, and so to confirm that an individual group of rocks is indeed responsible for the observed anomaly. Such careful checking as has been done by Books is the only way to ensure that we have fully accounted geologically for the anomaly observed. Extensive collecting of representative samples is not easy, and a thorough and scientific check is not always possible at first. At an early stage we can only confirm that the rock group near the anomaly is strongly magnetic and the susceptibility of the sample is of the right order to account for the anomaly.

Further interpretation

All the work described so far constitutes a preliminary interpretation of the results. The magnetic anomalies have usually been attributed to groups of rocks and the larger structures only have been considered. As more information becomes available about the geology, and the problems are more clearly defined, it becomes necessary to examine and account for the individual anomalies. For example if a horizon of greenstone is more magnetic in certain areas than in others we try to explain this and to determine its significance. There are usually so many anomalies to be explained that we must select our areas for detailed interpretation in response to geologically directed questions. This selection takes place because we have a limited time to do interpretations, and we cannot extract or appreciate the significance of all the information that the map and records contain. This reinterpretation of the results follows the same sequence outlined earlier; discussions with field geologists, and testing of the interpretation by sample collecting and subsequent anomaly calculation make up the bulk of the work. At this stage more refined methods of interpretation are usually applied.

Variations on the mineral style survey

Every magnetic survey is different. Mineral surveys so far considered have been in areas where the rocks have been strongly folded, metamorphosed and intruded by igneous rocks. Magnetic horizons may be inclined at a low angle and be due either to magnetic sediments which are not strongly folded, or to sills which are strongly magnetic. The outcrop of gently dipping rocks may be complex; the variation in magnetic susceptibility or remanent magnetic moment throughout the sheet may change considerably and be difficult to recognise. The resulting pattern of magnetic anomalies can be very confusing and a useful interpretation is sometimes difficult to make. Partial mapping of the near-horizontal body, either on the ground, or from photogeology may help greatly in the interpretation of the magnetic data.

A thick sequence of lava flows often presents rather different problems. Generally basic lavas are strongly magnetic, and the magnetic map is complex on account of the rapid variation in magnetic properties of the rock. Flight lines should be closely spaced to construct a reasonably correct magnetic map. In some areas geological mapping of lava flows is restricted because of the lack of distinctive horizons, and even in well exposed ground it is difficult to recognise the major structures which occur within the area. Ground magnetic surveys in these areas may be of little help

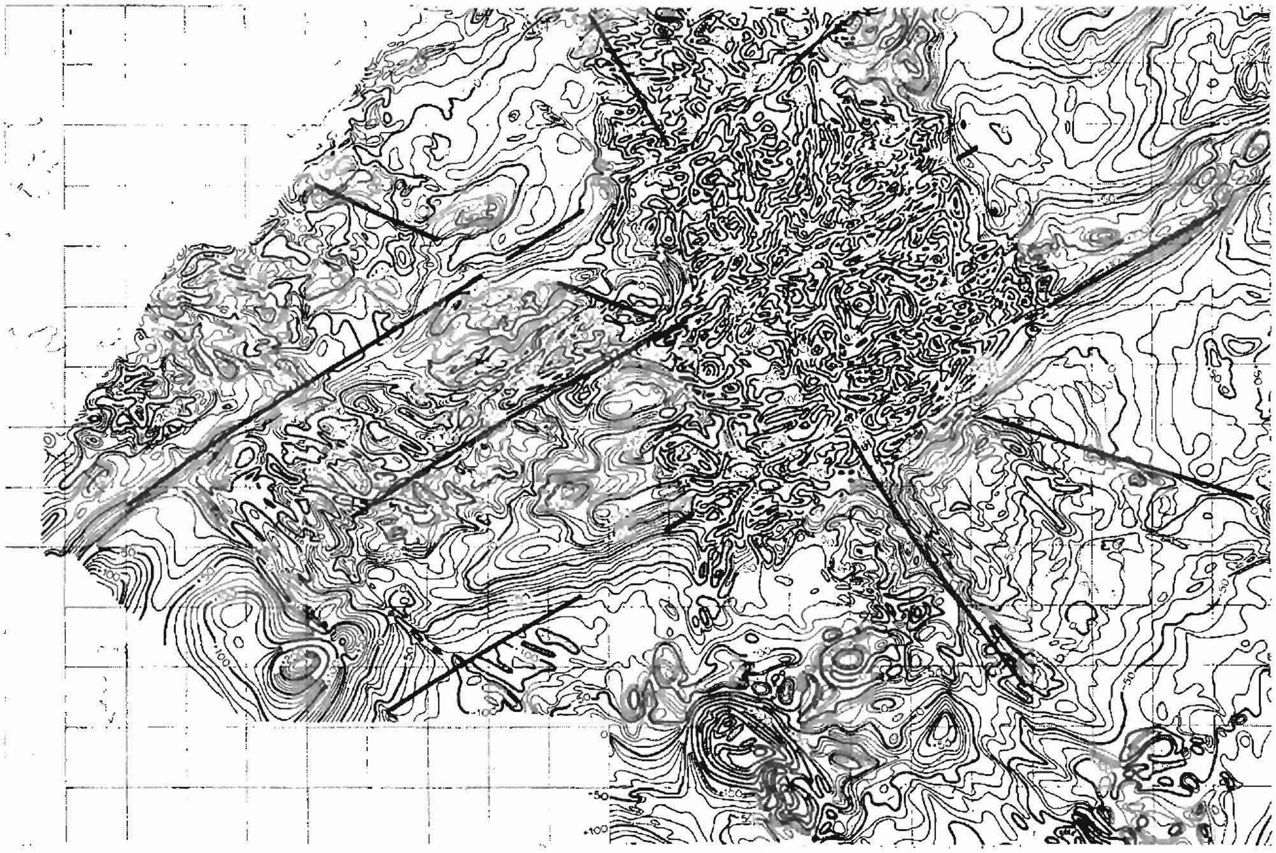

Figure 5. (Scale 1:1,250,000 approx.) Aeromagnetic survey flown at 1,000 feet above Tertiary basalt lava flows illustrates major structural lines which show through the magnetic cover. *I* = 69°. (Crown Copyright, Geological Survey Map. Reproduced by permission of the Controller, H.M. Stationery Office.)

because the rapid variation in the magnetic properties of the lava yield a patternless mass of anomalies; the airborne survey, by flying at a height of 500 or 1000 feet, produces a filtering effect, selecting only major units within the lavas and rejecting minor features. Although even at 500 feet the magnetic pattern may be very complex, we have observed strong linear features in various surveys over magnetic lavas (Figure 5). Some of these probably represent fault zones or areas with multiple dyke intrusions. In other areas we notice wide zones of positive and negative magnetic anomalies some of which may be due to reversely magnetised bodies resulting from a reversal of the earth's magnetic field during the rocks' original or subsequent cooling. A change in the intensity of the magnetic anomalies in volcanic areas indicates major changes in the magnetic character of the lavas which are not always recognised by the geologists.

Weakly magnetic areas

So far I have been looking at areas in which magnetic anomalies of several tens and probably several hundreds of gammas are observed. There are extensive areas of igneous and metamorphic rocks in which anomalies of no more than 5 gammas are found; strata-bound orebodies of great economic importance are often found in weakly magnetic sedimentary rocks. The records must be studied to distinguish the weakly magnetic from the slightly more magnetic areas. Bands of magnetic rocks producing anomalies of only 1 or 2 gammas have been followed for several miles within schists and phyllites. Granite intrusions may be distinguished from the surrounding rocks by a change in character of the magnetic record, which will generally show a completely smooth line over the magnetically uniform granite, and anomalies of 1 gamma over the less uniform metamorphic rocks. This is about the limit of noise level for the standard fluxgate magnetometer. In these areas the high-sensitivity cesium vapour or rubidium vapour magnetometer would produce more useful information.

In many cases an apparently uniform series of phyllites or gneisses will vary slightly in their magnetic character; in one area the magnetic field will be completely flat whereas another area will have anomalies of 1 or 2 gammas. This difference represents a change of a fraction of a per cent in the magnetite content of the rock; this can be detected by the airborne magnetometer because it measures a bulk sample, but not by a geologist mapping on the ground. As far as I know, very little use has been made so far of this property of the aeromagnetic survey; here I think there is scope for increased co-operation between geologist and geophysicist.

Magnetic horizons have been found in Mesozoic and Tertiary sediments; these horizons have been used in oil exploration to map open folds from the outcrop pattern. Magnetic horizons possibly exist in areas of lead-zinc deposits, and would help to show both structure and changes in sedimentation as indicated by the change of magnetite content between the individual beds.

Certain other aspects of the application of magnetic methods for mineral surveys are covered in the following section.

Oil type surveys

Airborne magnetic surveys have been used for over 20 years by oil companies for reconnaissance surveys of large areas; in some cases the magnetic data are reinterpreted as more information comes in from the detailed seismic surveys and from drilling. With an oil survey the main problem is to determine the depth of the magnetic basement so that the shape of the basin of sedimentation can be found and the areas of maximum thickness of potentially oil-bearing sediments can be outlined. For this purpose the shapes of the magnetic anomalies are analysed as described by Peters (1949); Vacquier, *et al.* (1951); Gay (1963); Moo (1965); Bruckshaw and Kunaratnam (1963); and Bean (1966) to determine the depth of the magnetic body producing the anomaly. The positions of faults and basement uplifts have been interpreted by some using the minor anomalies.

If magnetic volcanic rocks occur within the section they can be identified and separated from the anomalies due to basement. The information about the presence of volcanic rocks can be of considerable assistance in understanding facies variations within the sediments and minor folding overlying the volcanic rocks.

However, the application of depth determination calculations is not limited to oil surveys. The method can be used in areas where the mineral-bearing rocks are magnetic and are covered by an unknown thickness of sands or other nonmagnetic sediments to show in what areas the potentially mineral-bearing rocks may occur at depth, and where it is economically worthwhile carrying out detailed investigation on the ground. The same application may be made in other areas to indicate the depth of weathering.

In an aeromagnetic survey for oil prospecting, major structures which extend for great distances may be detected from the pattern of anomalies in the basement rocks beneath the sediments. These major structures are probably belts of shearing within the metamorphic basement rocks, which in some areas appear to influence folding and faulting within the overlying sediments. The understanding of basement structures from the aeromagnetic survey may lead to an appreciation of the development of structures in the overlying sediments.

As a result of an aeromagnetic survey, some major shear zones in Cyprus have been recognised within the pillow lavas which form the magnetic basement in this area. The overlying Cretaceous and Tertiary sediments are very gently folded; minor folds in the sediments are truncated where they meet the extension of the shear lines found in the volcanics. Rivers which are flowing over the younger sediments are deflected along the projection of these shear lines, although there is no structure seen in the sediments to account for this. I think, and this is still open to confirmation on the ground, that jointing is possibly more frequent in the sediments overlying these shear zones, and that this has made it easier for the river to establish itself along the line of the shears.

In England, Upper Carboniferous sedimentary basins coincide with major magnetic trend lines which presumably follow structures within the Precambrian basement. I suspect that examples of this relation of sedimentation to earlier structures are much more common than I can illustrate, and only in such places as England, where detailed geological and geophysical maps are available, can the coincidence of these structures be recognised.

The interpretation of an aeromagnetic survey commonly shows small anomalies with an amplitude of 1 or 2 gammas which indicate magnetic bodies occurring at the surface in areas where the magnetic basement may lie at a much greater depth. We have been able to correlate some of these shallow magnetic anomalies with conglomerates composed largely of igneous boulders; in another place the shallow magnetic beds correlate with ironstones and ferruginous sands. In some areas it has been possible to follow these horizons for 20 to 30 miles below the sea, and from them to mark stratigraphic horizons which may be of value to the geologist. This type of information is obviously more important in areas where geological mapping is not possible because of swamps, forests or the sea. If the outcrop can be followed for several miles it may be possible to recognise folds and faults, and if the anomalies disappear, there is presumably a change in the facies of the sediments, or else the body itself has been cut out by an unconformity.

As these anomalies are very small there is considerable advantage to be gained by using a high-sensitivity magnetometer and making use of the large dynamic range provided by digital recording of the magnetic data.

Regional surveys

A regional survey is usually conducted by a government agency with the purpose of providing magnetic cover over a large portion of the country and is often flown prior to regional geological mapping. Regional surveys are flown at a moderately wide spacing of about 2 km usually at about 1000 feet, although in both Canada and Australia large areas have been flown at 500 feet and closer spacing.

Regional surveys are intended to pick up the major features of both outcrop distribution and structural pattern in a country. They serve two very useful purposes. First, they show in which parts of the country detailed magnetic surveys can most effectively be applied, and indicate what sensitivity will be required from the magnetometer. Secondly they show the regional geological pattern, the magnetic character of different rock groups, the variation of character established over a wide and representative area, while certain major structural features may be picked out which would not be evident if the survey covered only a limited area. This is exceptionally valuable background for the interpretation of the detailed surveys.

The outlining of the major structural lines in a country is one of the most fascinating of the features which we can see on the aeromagnetic map. In providing this the aeromagnetic map bridges the gap between the geological map and the tectonic map. These major features may be clear-cut where the basement is shallow, but much less obvious in areas where the basement rocks are covered by thousands of feet of sediments. They seldom present spectacular features on the ground because their effect may be spread out across a zone which is several kilometres wide.

An example of one such major feature can be seen on the magnetic map of the United Kingdom and France. A large prominent magnetic anomaly stretches south from Birmingham to Reading in England (Figure 3) and a similar large magnetic anomaly extends from Le Havre to south of Orléans in France. These two anomalies have approximately the same width, and are in line with one another. The total length of these structures is 500 kilometres. To the north this anomalous zone passes into a major belt of faults referred to as the Preston fault zone, and beyond this we can see the Tertiary dyke swarm in Scotland which lies on the same line and has the same strike. A major basement feature, until the aeromagnetic survey was flown, has been unrecognised by geologists in such a very well mapped country as England. This structure does not show itself obviously in the Mesozoic and Tertiary rocks except perhaps in the pattern of Tertiary folds of southern England.

Regional surveys can be of great assistance in understanding the distribution of mineral deposits in a country as far as they are related to major structural lines.

In Uganda in east Africa an airborne magnetic survey with a regional character has indicated a number of major shear zones which strike NW. The major volcanoes in this area are situated on these shear zones, suggesting some structural relation between the shear zones and the volcanoes.

Planning an airborne survey

A good interpretation will only come from satisfactory data that have been obtained by proper planning, which should ensure that the best use is made of the funds and effort available for the survey.

Every magnetic survey is different and requires a different plan. It should be seen in context as part of a larger geological mapping or exploration program. It is a tool for obtaining the best possible geological information in the shortest time or at a reasonable cost for the special information which it produces.

Regional surveys. Regional surveys are normally undertaken by government agencies. They are probably the simplest type of surveys to plan. A regional survey will cover a large area or the whole country, and will be intended for a number of purposes. The first problem is to decide over how many years the survey should be spread. This is partly a matter of economics, as only a certain part of the budget can sensibly be spent on airborne magnetic surveys. What this portion is, is a matter for each individual survey; the cost for a regional aeromagnetic survey using two-kilometre spacing is approximately $8 per square mile outside North America.

The first technical problem is to decide what areas are to be flown, always bearing in mind that the larger the area, the cheaper the cost per line mile and the fewer the practical problems in relating one area to the next. For each survey it is necessary to decide a flight direction, flying height and line spacing. Most interpreters would like flight lines 800 metres (or less) apart and flying height of 500 feet; a less expensive alternative is to fly the survey at 1000 feet and 2 kilometre spacing. To some extent the flying height is determined by the topography; in hilly country it will be necessary to allow a greater flying height for the safety of the aircraft and crew. The flight direction should be approximately at right angles to the main structures, and as far as possible it should be kept constant over any one survey area. In the equatorial regions, where the inclination of the earth's field is less than 30°, the flight-line direction should be within about 20° of magnetic north, although this obviously could conflict with the previous requirement and a compromise must be reached.

Allowance should be made for the economic significance of the results in the choice of the areas, precedence being given to areas where minerals, if found, can be most easily worked. The maximum amount of information should be obtained regarding any mines in the area.

It is important to decide at the start what base map will be used, and at what scale the map will be produced, as it may be necessary at some stage to relate the map of one country to that of the surrounding countries. The magnetic maps should be on the same scale as the standard geological maps; in addition a reduction of the magnetic map to some convenient scale such as 1:250,000 permits very large areas to be studied at one time.

In most magnetic surveys a correction is made for the earth's regional gradient. Co-operation with the surrounding countries will ensure that the results of one country's survey is compatible with that of the neighbouring countries by using a common datum.

It is in the interest of all users of geological and geophysical maps to have the results of airborne magnetic surveys published with the minimum delay.

Some aspects of the interpretation of the airborne magnetic maps are best carried out by a government organisation. They have broad experience, a wide knowledge of the geology of the country, and the facilities to back up the interpretation with sufficient ground work and rock sampling to provide very valuable background assistance to the interpretation of the magnetic maps.

Mineral surveys. The planner of a mineral survey must clearly understand what he hopes to obtain from a magnetic survey. Is the ore magnetic? Is it associated with magnetic rocks? Is it associated with any known structures which affect magnetic rocks? If the mineralisation is not known to be associated with any magnetic material we rely entirely upon picking up the structure from the magnetic map in which case we must be sure that the sensitivity of the magnetometer is appropriate to the type of rocks in the area.

A wise preliminary to the planning of an aeromagnetic survey is to collect rock samples, measure their magnetic susceptibility and remanent magnetic moment, and calculate the expected effect at the detector height of any known geological bodies. Useful data can also be obtained from ground magnetic surveys. When we have this information about both mineralisation and the rocks of the area, we can decide whether a normal magnetic survey or a high-sensitivity magnetic survey is more appropriate to the problem.

The base map for the work must be chosen; a map is preferable to a mosaic, as the results are spatially more accurate, but sometimes a mosaic is easier for the follow-up work. The base map should be on the same scale as the geological field maps, probably around 1:25,000 scale, the choice being dependent also on the flight-line spacing. If a large area is covered by the survey, a compilation of the magnetic maps at about 1:100,000 or 1:25,000 scale can be a great help.

Lines should be flown over all the known orebodies, and wherever convenient the survey should be extended to include any adjacent mining areas, as structures shown only by the magnetic map may be found to coincide with mineral deposits and so give a lead to the interpretation of the aeromagnetic map. The shape of the survey should preferably be a simple rectangle, because it is always more difficult to interpret geophysical results close to the boundary or to the corner of a survey.

I have explained the advantages of covering a large area; the selected area should be as large as possible compatible with the cost of the survey. There is no point in flying a larger area than can be usefully examined on the ground with the budget available. The size of the area surveyed is closely linked to the choice of line spacing which determines the cost of flying a given area. If the line spacing is too wide, the features on the resulting contour map are blurred; anomalies cannot be followed from line to line, the individual character of geological areas is confused, the evidence for faults is lost, and the whole survey fails. On the other hand if the flight lines are closer together than needed the cost of the survey is unnecessarily high, and more information would have been obtained by covering a greater area at the same cost. The optimum flight spacing which is related to the flying height, is a problem which comes up in the planning of every mineral survey (see Agocs, 1955). The normal flying height for a mineral survey is 500 feet or less. At half-mile spacing the cost of the survey will be about $18 per square mile for a standard 1-gamma sensitivity survey. In planning, this cost must be set against the cost of carrying out the survey on the ground or using some other method.

The flight lines are at right angles to the main structures or the strike of the known mineral deposits in the area. If a mineral type survey is flown over the sea, a land-based positioning system may be needed to make sure that the relative positions of points on adjacent lines are accurate.

In a mineral survey, where so much depends on recognising the pattern of the anomalies, it is very important to have logically drawn contour maps. Much more can be seen from a final drafted contour map than is evident on the preliminary work sheets, and the extra cost of fairdrawing is normally well justified.

The best airborne survey is of no value until it is properly interpreted and this involves the co-operation of geologists and geophysicists. It also requires time for ideas to mature. It is a universal experience I think, that the most illuminating and valuable ideas occur within the final week of interpretation. In the initial planning, therefore, it is important to allow plenty of time for interpretation.

Oil surveys. The most convenient or economic flight-line direction is usually chosen for an oil survey, except in equatorial regions where a north-south direction is preferred, or where there is a very marked structural direction in the basement. The cost of the survey is determined mainly by the line spacing which may vary from 2 km for a detailed survey up to 10 or 12 km for reconnaissance surveys. The accuracy with which depth determinations can be made depends on the density of the lines, because the apparent depth varies with the angle between the flight lines and the strike of the anomaly; you get the accuracy that you pay for.

If the airborne magnetic map is used to obtain information about the structures within the basement, it must be both extensive and of a reasonable line density. In areas where lavas are expected it is advisable to fly low to get more information about the lavas, or high to minimise their effect; if the survey is intended to pick out magnetic horizons within the sediments it is advisable to fly lines sufficiently close together to define the structures which may be indicated by the shallow anomalies. Information about sedimentary horizons may be particularly important in surveys carried out over sea areas, tropical forest or deserts.

If the survey is flown over water or over unmapped and unphotographed territory a system of radio navigation must be chosen. For many purposes a doppler navigator, which is carried entirely within the aircraft, is adequate, but if the survey extends for great distances over the sea and the relative positional accuracy of the lines must be high, a land based radio-location system such as Raydist, Shoran, or Toran must be used.

If a high-sensitivity magnetometer is required, as in areas where the magnetic basement is very deep or weakly magnetic, extremely accurate positioning is needed, and in sea areas a ground-based navigation system is essential for the full utilisation of the high-sensitivity instrument. Oil surveys are frequently presented at a scale of 1:100,000 or 1:250,000, or whatever compilation scale is used for the ground geological and geophysical work.

If magnetic sediments are indicated by the survey, samples should be taken from drill holes to provide more information.

Conclusion

The information about rock types and both major and minor structures which can be obtained from an airborne magnetic survey can be used at all stages of geological mapping, from reconnaissance to detail, for academic research and in the specialised geological mapping required for mineral, oil and other exploration activities.

Its use as an aid to geological mapping is a matter of common sense, considerable experience, disciplined imagination and a little mathematics and physics. An appreciation of the magnetic properties of rocks, and of the physical basis of interpretation is desirable.

The best results are obtained if the interpretation is undertaken by geologists and geophysicists working closely together. After the first interpretation has been completed, the geophysicist should reinterpret the results of the survey frequently to make use of all the new facts discovered and new ideas developed by the geologists. The routine to be followed has been described.

Any country which invests in an extensive aeromagnetic survey, and this I think most countries will do within the next few years, should have at least one geophysicist permanently concerned with the use and reinterpretation of the maps and records. His contribution represents a small fraction of the cost of the survey; his increasing familiarity with the results makes sure that the fullest use is made of them.

If a magnetic map and interpretation is available before geological mapping starts, the geologist goes into the field with a broad view of the geological structure, and the distribution of some of the main rock groups. As a result the field work may be done more quickly and the final map should certainly be more complete because it includes the extra information provided by the magnetic survey.

The major structure revealed by an aeromagnetic survey of a large area may give a better understanding of the geological development of an area and indicate unexpected coincidences between mineral deposits and structures.

The cost of a magnetic survey is much less than that of a detailed geological survey, but this full potential is only realised if the data are properly interpreted.

Acknowledgments

I am indebted to the Commissioner for Geological Survey, Tanzania, and the Project Manager of the United Nations Special Fund, Mineral and Groundwater Project, for the map shown in Figure 2; to the Controller H.M. Stationery Office for the use of aeromagnetic maps shown in Figures 3 and 5, which were flown for the Institute of Geological Sciences; to the Director of the Geological Survey of Uganda for the aeromagnetic map shown in Figure 4 and for reference to results obtained from the aeromagnetic survey flown for the United Nations Special Fund Project; to the Director of the Geological Survey of Cyprus for permission to refer to results obtained from an aeromagnetic survey flown for the Geological Survey of Cyprus.

I am also indebted to numerous colleagues and clients for many long animated and enjoyable discussions on the interpretation of aeromagnetic maps.

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AFMAG for electromagnetic mapping

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Abstract. The main advantage of the audio frequency magnetic method, AFMAG, over conventional two-coil electromagnetic systems, is its inherently greater range. Naturally occurring fields in the audio frequency range are utilized by the method and the nature of these fields is briefly reviewed.

The ground apparatus provides extended range with lightweight equipment. It is particularly well suited for reconnaissance surveying since the data indicates the direction and often the strike of the conductor disturbing the field. As an airborne system, AFMAG is virtually independent of the aircraft used and surveys can be carried out by light aircraft. Many major fault and shear zones give rise to strong AFMAG anomalies that are easily recognized from airborne results.

Limitations of the AFMAG method are chiefly the restricted period of useful measurements which is most pronounced in high latitudes and the reduced response from conductors lying parallel to strongly oriented regional fields. The latter cannot be overcome but can be minimized by the proper choice of the direction of measurement.

Résumé. Le principal avantage de la méthode magnétique à basse fréquence (fréquence audible) (AFMAG), sur les appareils électro-magnétiques ordinaires à deux bobines repose sur le fait que la gamme est beaucoup plus étendue. Les champs qui se produisent naturellement dans la gamme des basses fréquences sont ceux qu'utilise cette méthode et l'auteur explique brièvement la nature de ces champs.

L'appareil au sol fournit une gamme prolongée tout en utilisant un outillage de poids léger. Il convient particulièrement bien aux relevés de reconnaissance vu que les données indiquent l'orientation et souvent la direction du conducteur qui perturbe le champ magnétique. Comme système aéroporté, l'AFMAG est pratiquement indifférent à la catégorie d'avion utilisé et les relevés peuvent être effectués par des avions légers. Plusieurs grandes zones faillées et cisaillées donnent naissance à de fortes anomalies AFMAG faciles à reconnaître par les résultats des relevés aériens.

Les limites d'efficacité de la méthode AFMAG sont, principalement: la période de mesures utiles qui est très restreinte aux hautes latitudes et la faible réponse des conducteurs qui gisent parallèlement à des champs magnétiques régionaux fortement orientés. On ne peut surmonter cette dernière difficulté mais il est possible de la réduire au minimum par le choix approprié de la direction des mesures.

Most electromagnetic systems depend on the measurement of the coupling between a transmitter and receiver coil. The depth of penetration of such equipment is controlled by the separation of the coils and the accuracy of measuring the coupling. Larger coil separations inherently increase the depth of exploration, but since the primary transmitted field falls off as the cube of the distance, the over-all response of a conductor to any two-coil system necessarily follows a minimum of a fourth power law.

AFMAG can be regarded as a dip angle technique in which the source is located at infinity. Consequently, the method has much greater horizontal range and exploration depth than conventional inductive methods. Ward (1959) has demonstrated that for a long linear conductor the amplitude of the AFMAG response is approximately inversely proportional to height, as predicted by theory. Since only a receiver is required, the equipment weight is minimal for both the ground and airborne applications.

The AFMAG method utilizes naturally occurring electromagnetic radiation in the audio frequency range. The primary source of this radiation is atmospheric electrical discharges (i.e., lightning strokes) that occur throughout the world. Most of this energy arises in the major thunderstorm areas located near the equator and AFMAG fields are generally strongest near the equator and decrease toward the poles. The propagation of the energy is controlled by the Earthionosphere waveguide and consequently the strongest magnitude fields correspond roughly to the number of hours of daylight; the strongest fields occur in July in north latitudes and during January in south latitudes.

There is also a diurnal variation (Ward, 1959) and with present equipment surveying is usually restricted to the hours after noon for the six-month period from May to September in the Northern Hemisphere. In southern latitudes the field season

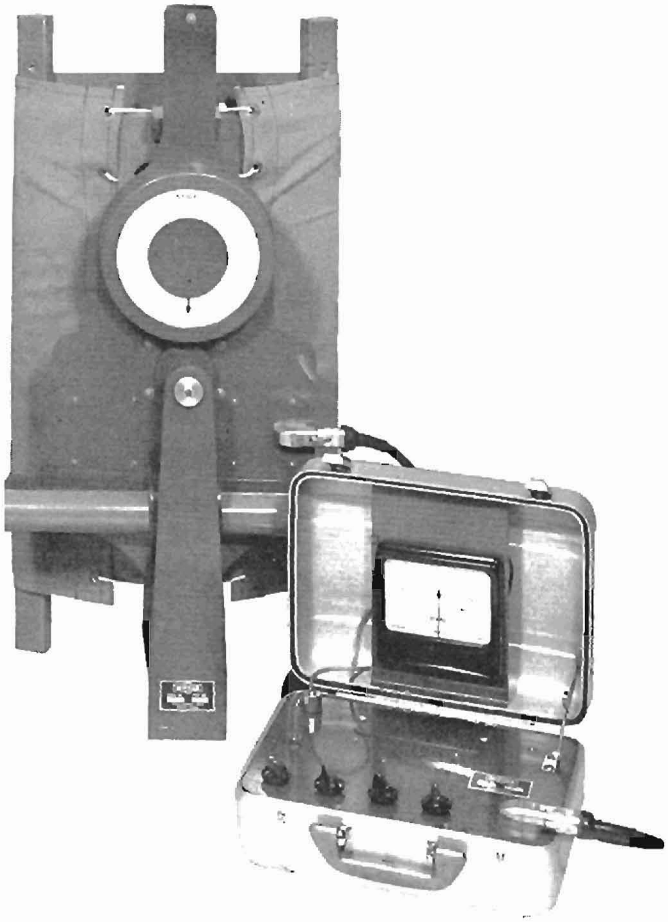

Figure 1. Ground AFMAG unit. Operating frequencies 130 and 475 cps.

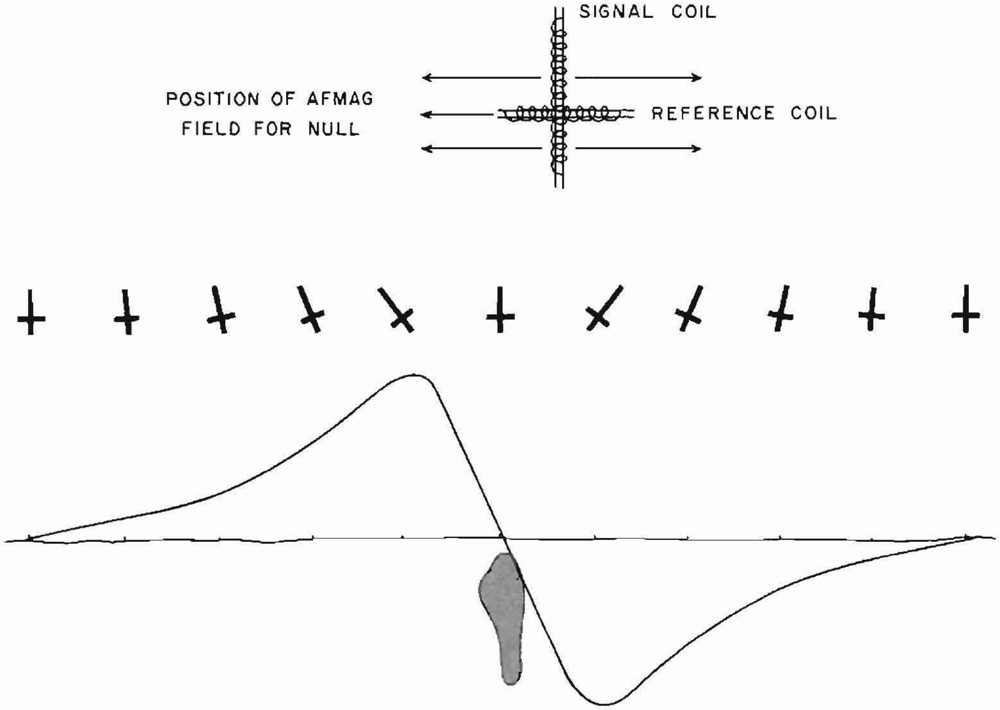

Figure 2. Position of AFMAG coil at null near conductor.

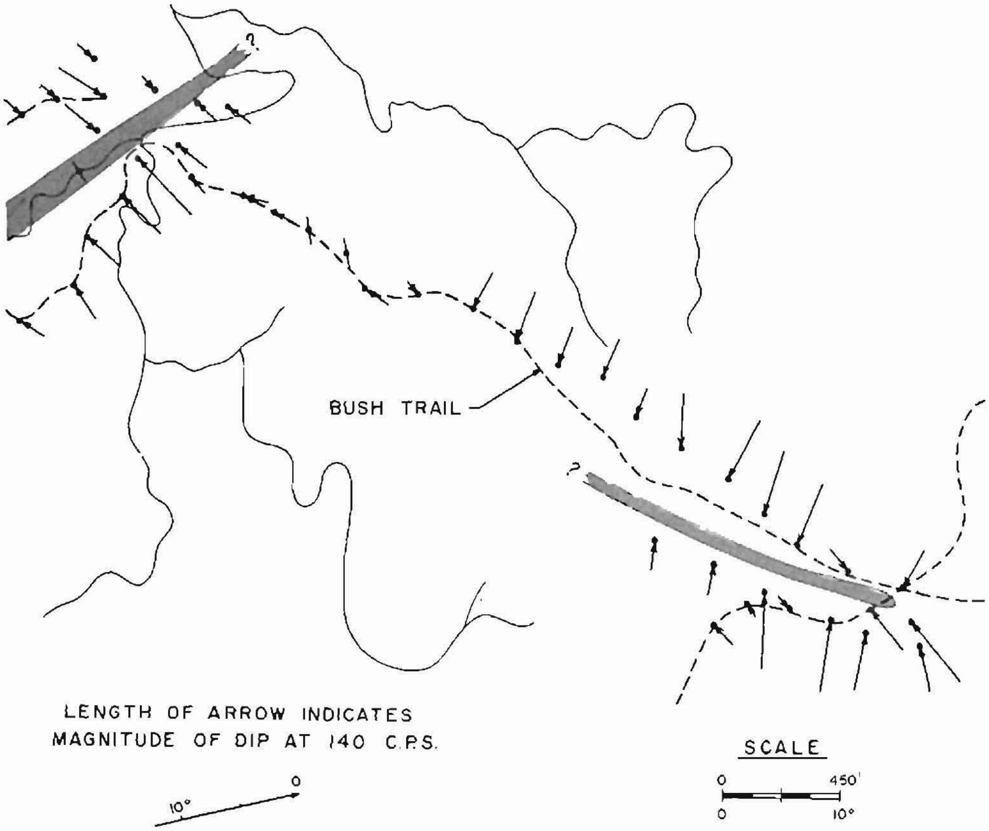

Figure 3. AFMAG survey – Carribean island.

extends from November to March, while year-round surveying is carried out in near-equatorial regions.

The nature of the AFMAG fields has been described in detail in a number of previous papers (Ward, *et al.*, 1958; Ward, 1959; Aaron, 1956). In simple terms, the AFMAG fields may be described as a series of rapidly occurring pulses of short duration that contain all frequencies in the audio spectrum. In the absence of any conductors the propagation direction of the individual pulses is random and the magnetic field is horizontally polarized. As a single conductor is approached, the propagation direction of the pulses becomes less random and more and more of the magnetic field is oriented perpendicular to the conductor. At the

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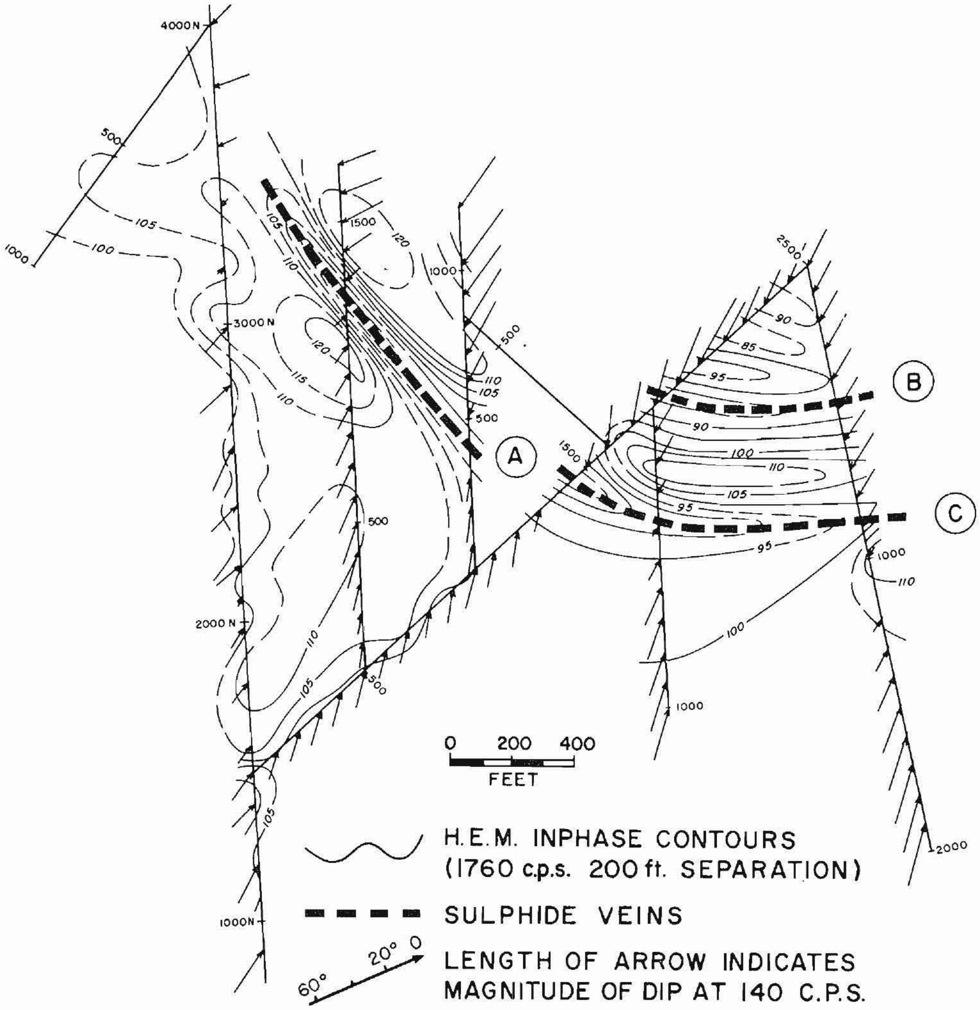

Figure 4. AFMAG and horizontal E.M. survey, Tanzania, Africa (after Makowiecki, *et al.*, 1967).

same time, the plane of polarization of the magnetic field is tilted out of the horizontal. In exploration, this tilt of the plane of polarization of the audio frequency magnetic field is used to locate subsurface conductors.

Ground surveys

A transistorized ground unit operating at frequencies of 130 and 475 cycles per second is shown in Figure 1. The coil assembly weighs 19 pounds and the console 9 pounds. The entire unit is easily carried by one man and observations can be made by a single field operator. Several units may be operated on a survey, since there is no interference between instruments.

The output of the larger signal coil is compared to that of the reference coil by means of a phase-sensitive detector. To determine the azimuth or maximum field direction strength the coil system is placed in a horizontal position and rotated about a vertical axis. After the azimuth direction has been established, the coil system is placed vertically in the azimuth direction and rotated to determine the tilt of the field.

The position of the coils for a null reading is shown in the upper portion of Figure 2. Note that the signal coil is at minimum coupling to the field while the reference coil is at maximum coupling. The central part of Figure 2 shows the successive positions of the coil system at null for a traverse over a subsurface conductor. The bottom of the signal coil is pointing in the direction of the conductor and the field is again horizontal directly over the conductor. When the azimuth is parallel to the traverse line, the results can be plotted in profile form as illustrated on the bottom of the figure.

However, both the tilt and azimuth may vary from station to station. There are then three pieces of information to be recorded; the field azimuth, the magnitude of the tilt of the field or plane of polarization and the direction of the tilt. This may be represented by a vector or arrow. The orientation of the arrow indicating the azimuth, its length the magnitude of the tilt, and its head the tilt direction.

In practice, there are two arrows at each station since measurements are made at two frequencies, e.g., 140 cps and 475 cps. The variations in the field at two frequencies give an estimate of the conductivity of the subsurface conductors and, on the data plots, the low-frequency measurements are shown as solid arrows and the high as broken arrows. For simplicity, only the low-frequency results are shown on the cases presented here.

The vector method of plotting is illustrated in Figure 3. Our convention has been chosen so that the arrow points in the direction of the conductor; which corresponds with the direction of the bottom of the signal coil at null. It can be seen that the azimuth orientations are roughly perpendicular to the con-

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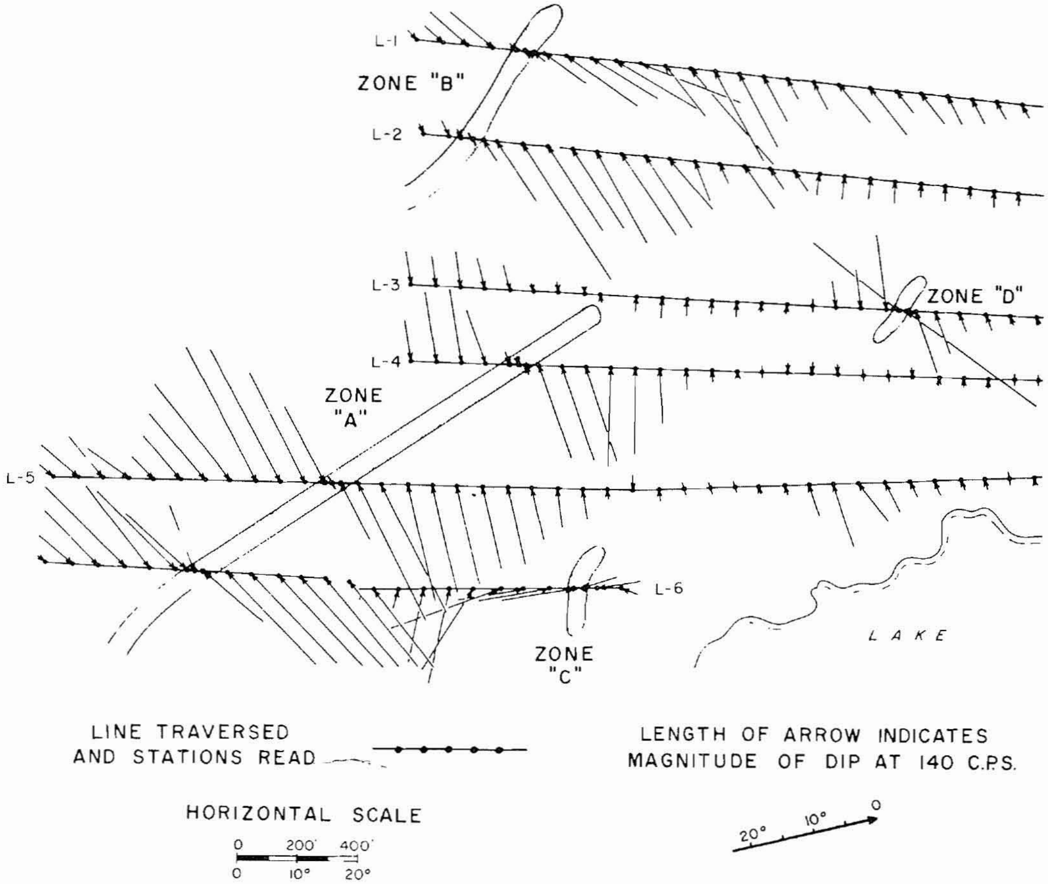


Figure 5. Portion of AFMAG survey in western Canada.

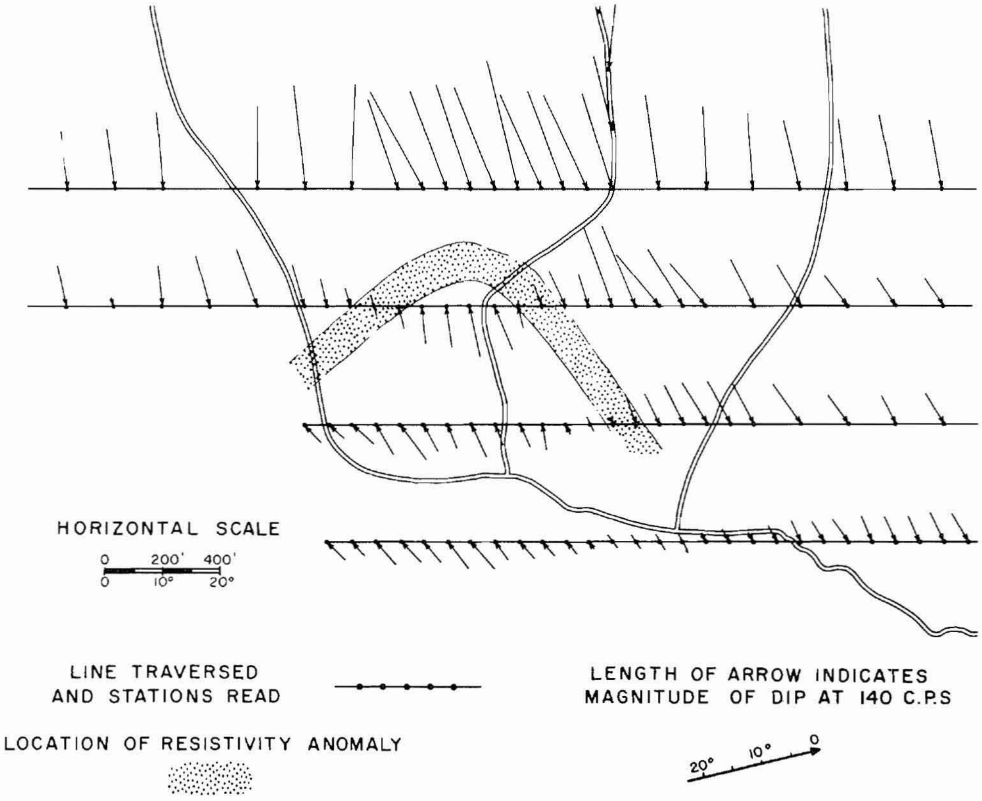


Figure 6. Portion of AFMAG survey in the Appalachian belt.

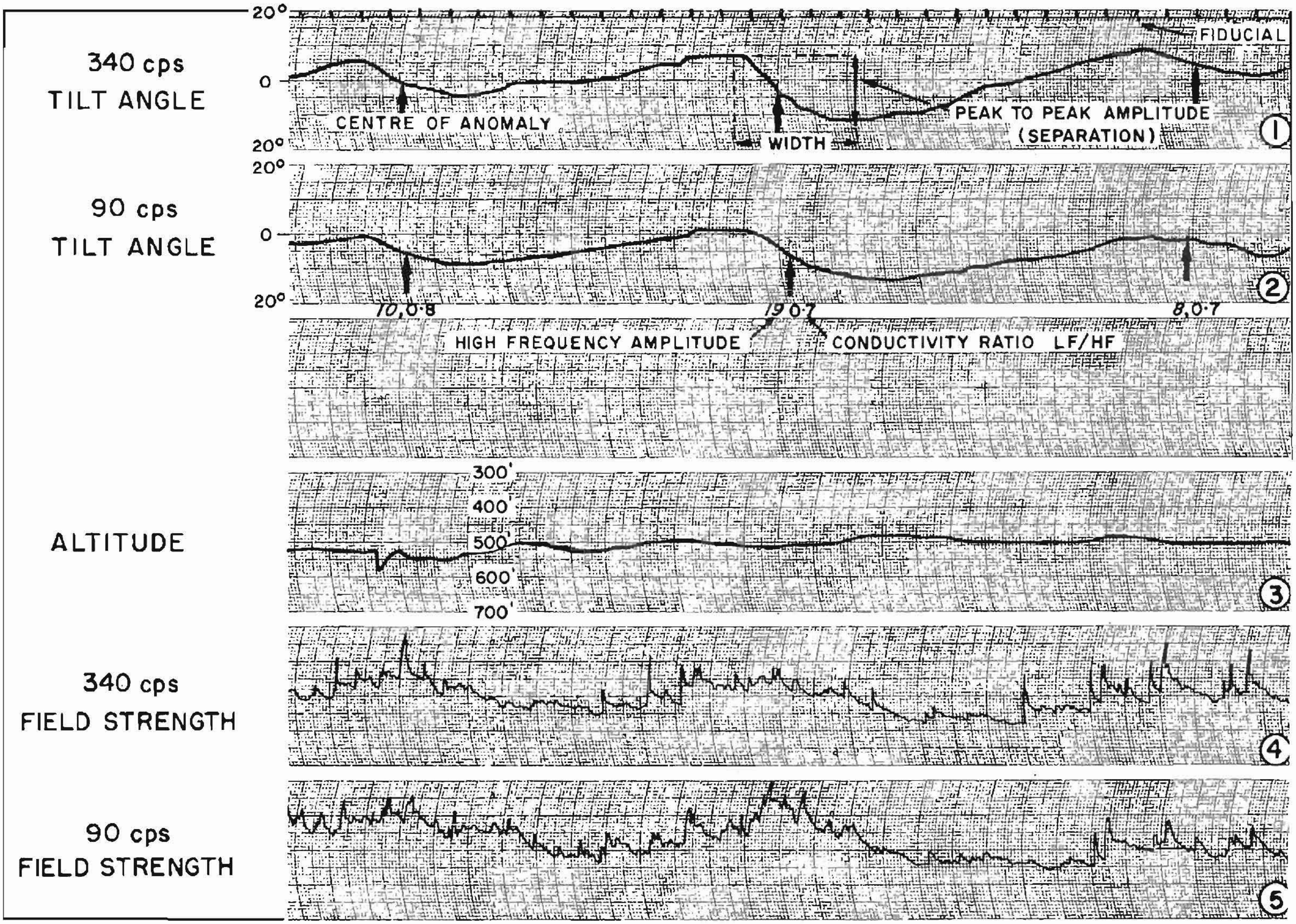


Figure 7. Photocopy of airborne AFMAG flight trace.

ductors. These results are from a Caribbean Island where the topography was steep and the only easy access was on bush trails. The orientation and alignment of a conventional two-coil electromagnetic system would have been quite difficult under these conditions. However, the AFMAG observations made along existing trails pointed out two conductive zones that were later detailed. The horizontal reach of the method is demonstrated by the sizable tilt angles recorded at distances up to 800 feet from the conductors.

Figure 4 shows a combined AFMAG and electromagnetic survey in Tanzania (Makowiecki, *et al*, 1967). The 140 cps AFMAG results are shown as vectors together with a contoured presentation of the In-Phase values obtained with a horizontal electromagnetic system operating at 1760 cps and using a 200-foot coil separation. Conductors A and C are clearly delineated by both the AFMAG and electromagnetic results, although there are slight differences in the trends, as suggested by the two methods, near the east and west limits of the survey. Conductor A, which is due to massive sulphides, has an AFMAG anomaly with a total amplitude of 40 degrees and an In-Phase response of about 30 per cent. The two subparallel conductors, B and C, are associated with strong magnetic anomalies and drilling has intersected massive magnetite with disseminated sulphides on conductor C.

A portion of an AFMAG survey in western Canada is shown on Figure 5. There is little regional effect in this area and each of the shallow, highly conductive zones has a strong local influence. Zones A and B obviously control the field on the left side of the grid and orient it perpendicular to their strike. Zones C and D are much shorter but also produce significant changes in the azimuth and tilt of the field. The results on the right side of lines 4 and 5 suggest the existence of another zone lying between these two lines.

The above examples show that the AFMAG fields are oriented almost perpendicular to the strike of a conductive zone and are strongly influenced in its immediate vicinity. All of these are for simple cases where there are no regional effects and the field can be described as being elliptically polarized.

The results on Figure 6 are taken from a survey in the Appalachian area where the field has a regional dip of about 10

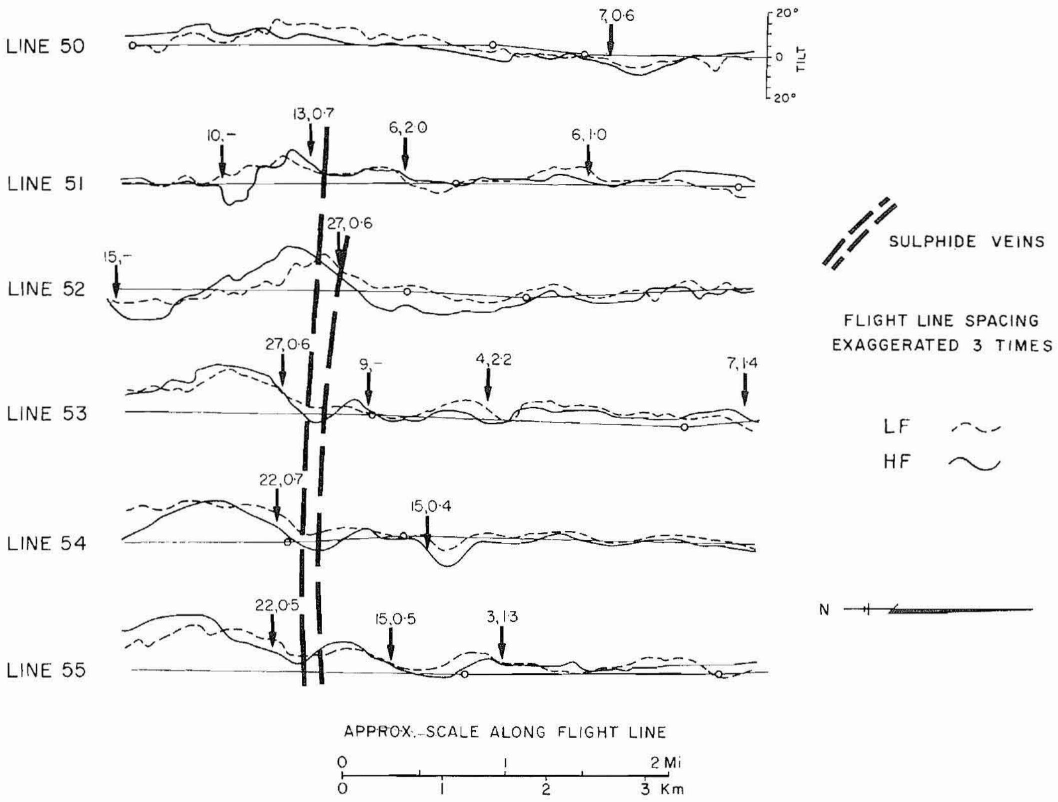


Figure 8. Airborne AFMAG response over massive sulphides, Tanzania, Africa (after Makowiecki, *et al.*, 1964).

degrees. The conductor is curved and the vectors over the central part indicate its position very clearly. However, on the right side of the diagram the end of the conductor is parallel to the regional field and there is very little change in the azimuth direction. There is a reversal in the dip angles but this could be mistaken for simply a change back to the regional dip. The existence of this portion of the conductor was later confirmed by a resistivity survey.

This example illustrates the problem of a conductor paralleling a regional AFMAG field. Recently it has been found that in areas where there is more than one conductor the field is ellipsoidal rather than elliptical and a measurable angle can be found at 90 degrees to the azimuth direction. Thus two measurements are made at each field station, the first in the azimuth direction and the second perpendicular to it. For simple cases, no reading will be found in the perpendicular direction, where there is only one conductor influencing the field.

Several interesting and definitive anomalies have been outlined parallel to strong regional fields using this procedure. Illustrations of conductors lying parallel to a regional field will be shown in the following airborne examples. Unfortunately, no examples of ground surveys are available for publication.

This problem is similar to that encountered in electromagnetics when the conductor is parallel to the primary field.

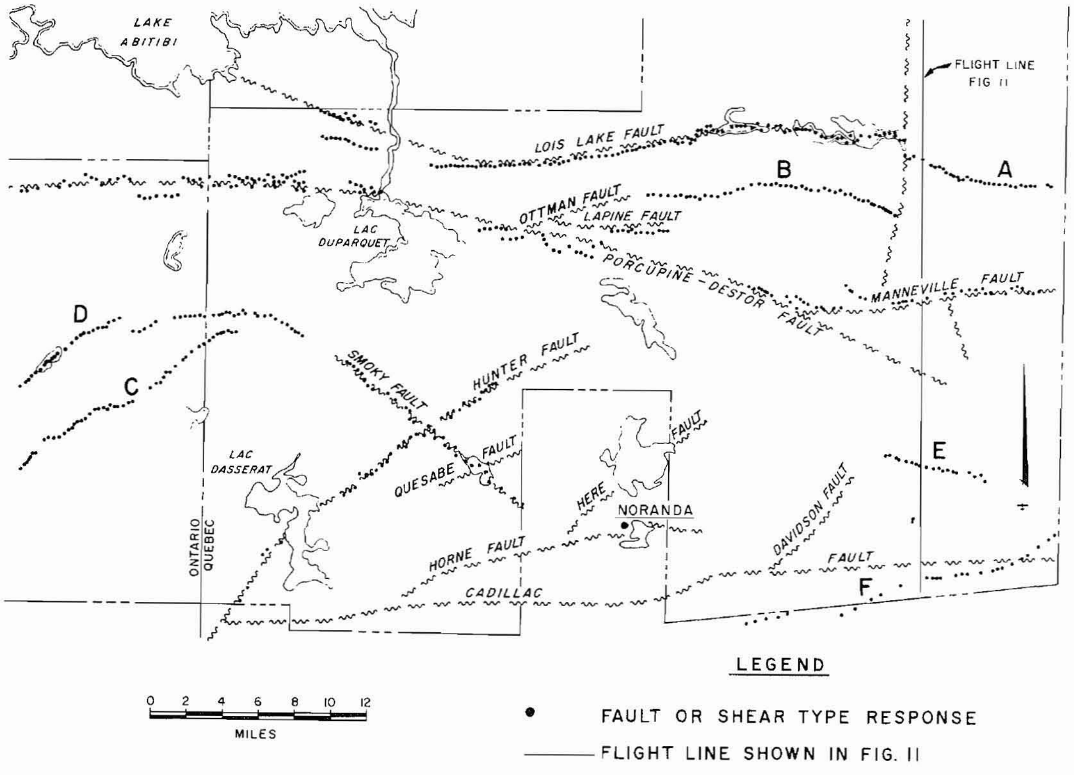
Airborne surveys

In the present airborne apparatus, the measurement is restricted to the determination of the tilt angle in the direction of flight. This is done by comparing the signal amplitude of two mutually perpendicular coils with their axes at 45° to the horizontal. When the field is horizontal, the voltages in the two coils are equal; this is recorded as a zero tilt angle. Any departure from the horizontal results in a positive or negative dip angle which is recorded above or below a center line.

A typical airborne AFMAG flight trace is shown on Figure 7. Traces 1 and 2 record the tilt angle at 90 and 340 cps while traces 4 and 5 display the relative field strengths at these frequencies. A crossover or conductor axis is indicated by a descending slope as the record is read from left to right as shown by the arrows. A reversal, or ascending slope is usually a return to the zero line followed by the influence of another conductor and normally has no interpretational significance. The peak to peak amplitude of the high-frequency response is measured in degrees of tilt angle. The conductivity ratio is obtained by comparing the amplitudes at the two frequencies. Theoretically this ratio should not exceed unity but in some instances ratios as high as 2 or 3 have been observed. These abnormally high ratios can be attributed to the greater depth of penetration obtained with the lower frequency in the presence of conductive surface layers.

There is an increase in the field strength over each of the three conductors. This effect is most pronounced over the strongest conductor in the center of the trace.

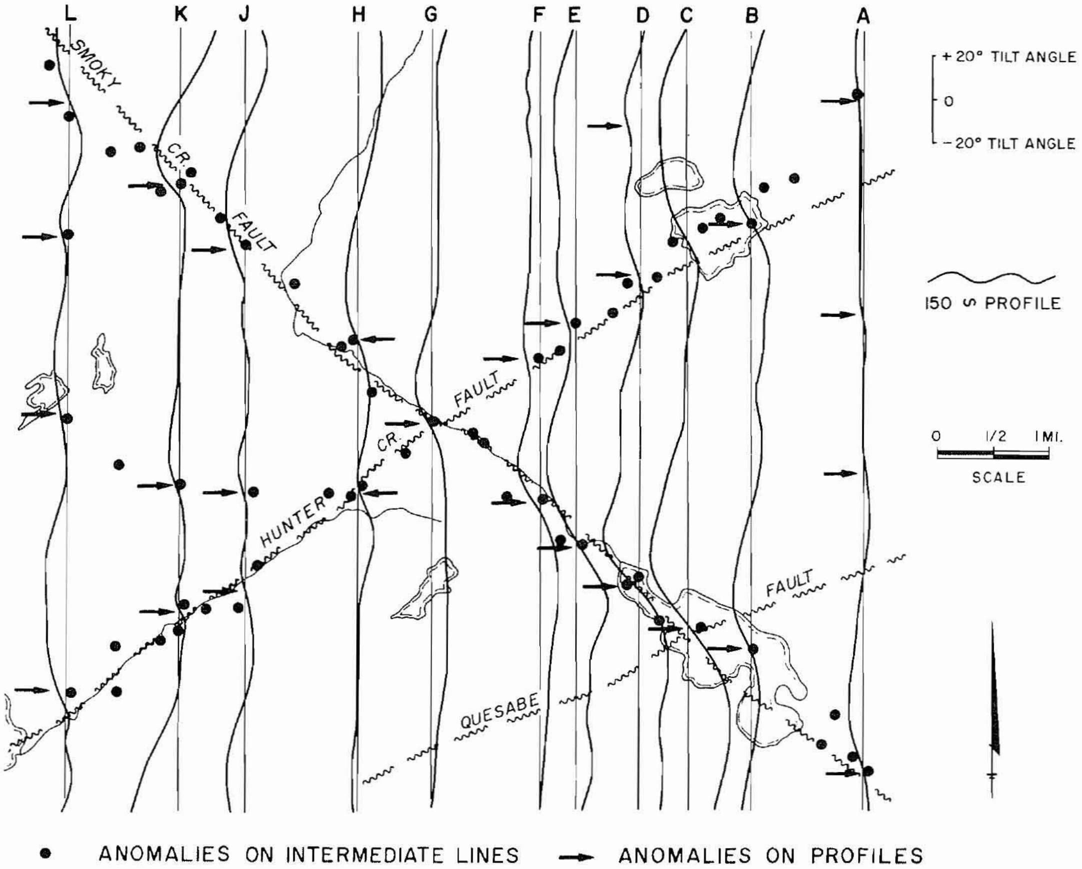
The airborne results shown in Figure 8 are from a Precambrian area immediately south of Lake Victoria in Tanzania. Observations with a ground unit showed the north-south flight lines to be within 15 degrees of the azimuth of the regional fields. These data are taken from a paper by Makowiecki, King and Cratchley (1964) that compares the AFMAG method with two airborne electromagnetic systems. A flight altitude of 500 feet was used for the surveying.



(AFTER SHAW, 1962)

Figure 9. Key map showing fault and shear type AFMAG responses. 150 and 510 cps.

Figure 10. Airborne profiles over Hunter Creek and Smoky Creek faults. Duprat twp., Quebec (after Shaw, 1962).



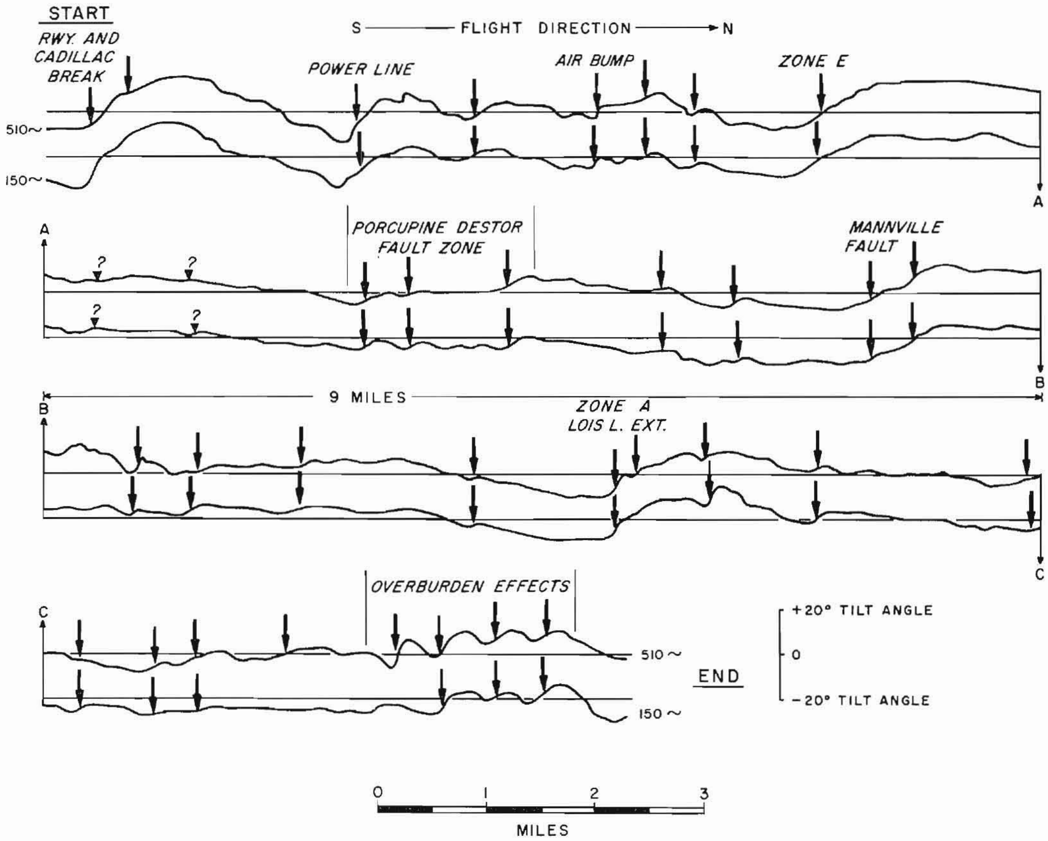


Figure 11. Relative abundance of minor and major anomalies (after Shaw, 1962).

Arrows indicate the location of the AFMAG anomalies that correlate closely with two parallel sulphide veins. The veins have a strike length of about 1 1/2 miles and are approximately 400 feet apart. The AFMAG responses are quite strong and consistent and the conductivity ratio is above 0.5 over the length of the zone.

The mineralization near line 51 occurs at a depth of 100 feet and there is an easily recognizable AFMAG anomaly on this line. Strong anomalies were recorded by the other airborne systems over the shallow part of the zone but no significant anomalies were recorded near Line 51 where the mineralization is deeper. These results illustrate the effectiveness of the AFMAG method in outlining along sulphide zones, as well as its depth capabilities.

Perhaps the most important application of the airborne AFMAG method is in outlining fault and shear zones. These features are frequently poorly conductive structures and are difficult to recognize with conventional electromagnetic methods. However, because of their length and depth extent, their size-conductivity product is appreciable in the AFMAG frequency range and they give rise to sizable anomalies. Fault or shear anomalies are typified by very long and gradual buildups extending a mile or more on either side of the crossover. The peak to peak amplitudes are frequently as large as 40 degrees and the conductivity ratio is often greater than unity. These characteristics distinguish them from the sharper, concave responses of limited extent that are typical of smaller, highly conductive structures, such as sulphide bodies.

Figure 9 has been taken from Shaw's 1962 paper. It covers a large area of northern Quebec and Ontario that is typical of the Canadian Precambrian Shield. Flight lines were oriented north-south and spaced at 1/4-mile intervals. The disposition of "fault and shear type AFMAG responses", as selected by the author, are shown together with the mapped faults in the area. There is excellent correlation with many of the east-west trending structures in the area. This is particularly noteworthy since the azimuth direction is essentially east-west and parallels many of these features (Shaw, 1961). These data emphasize the importance of surveying perpendicular to the geologic trend regardless of the prevailing direction of the AFMAG fields.

In the eastern part of the area, the Lois Lake Fault is recorded on every flight line and Zone A probably represents its extension. The Manneville Fault is clearly defined and Zone B lies on strike with the Ottman Fault. Zones E and F show good line-to-line correlation and are typical fault anomalies.

In the northwest, the Porcupine-Destor Fault agrees closely with the AFMAG responses and Zones C and D trend NE.-SW. which is a common direction for major discontinuities in the area.

The large and well mapped Cadillac, Horne, Here and Davidson Faults fall within strong powerline interference surrounding the town of Noranda and much of this area could not be flown. However, the intersecting Smoky and Hunter Faults which lie to the northwest of Noranda are clearly outlined.

Figure 10 (Shaw, 1962) is a detail of the Smoky Creek and Hunter Creek showing the profiles on 9 of the 29 flight lines flown in the area. The plotting convention on Figures 10 and 11 is the reverse of that used for the previous examples but the conductor axes are clearly indicated by the arrows. The profiles on the Smoky Creek Fault display gradual buildups to quite large

Figure 13. AFMAG equipment on De Haviland Beaver (DHC-2, Mark II).

Figure 12. AFMAG equipment installed in a Cessna 172.

amplitudes before a well defined crossover. The Hunter Creek responses are consistently smaller in amplitude but display similar characteristics.

A typical dual frequency trace, 31 miles long, taken from the eastern part of the northwestern Quebec area is shown on Figure 11 (Shaw, 1962). The Lois Lake, Manneville and Zone E Fault responses are easily distinguishable in character from the sharper, more concave, responses due to smaller conductors which may be either sulphides or overburden effects. The response from the Porcupine-Destor Fault Zone is more complex but is reported to be characteristic of this structure. On the top left of the figure there is a strong anomaly coincident with the Cadillac Fault, but the presence of a railroad and a powerline greatly reduces its certainty as a fault response.

Conclusions

The above examples demonstrate the effectiveness of the AFMAG method as an electromagnetic mapping tool.

The ground system is ideal for rapid reconnaissance coverage of an area for either small highly conductive bodies such as sulphides or large poorly conductive structures. Its exceptional horizontal range and exploration depth permit a much greater station spacing and line interval, and the results indicate the direction and strike of the disturbing body. The main disadvantage is its limited operational period.

Multiple conductors generate interpretational problems in the AFMAG method similar to those encountered with electromagnetic methods. However, with electromagnetics better resolution can be obtained by changing the transmitter location.

On a series of closely spaced subparallel conductive bands the AFMAG method will give an unbiased sample and will emphasize the conductor with the greatest size-conductivity product. The effects of a smaller conductor which may be economically important will not be as great. Similarly, a strong conductor will orient the field perpendicular to it and tend to mask a smaller conductor lying parallel to the field direction. This can be assessed by taking observations at right angles to the azimuth direction, but some reduction of the anomalous effects can be expected. For these reasons, it is sound practice to confirm any AFMAG anomaly by a secondary method prior to drilling. Induced polarization and electromagnetics are customarily used for this purpose but differences in exploration depth must be carefully considered in assessing the results (Hallof and Sutherland, 1962).

The potential of the airborne equipment as a geologic mapping tool is now beginning to be recognized. In many areas of the world large fault and shear zones have been proven to be controlling structures for mineral deposits. Many of these can be mapped accurately even under several hundred feet of overburden or overlying formations. Large sulphide bodies are easily recognizable with existing equipment and its depth of exploration has been used to advantage in many mountainous areas where topography has precluded the use of conventional electromagnetic systems.

One of the most significant advantages of the airborne AFMAG method is its minimal weight and the ease with which installations can be made in virtually any type of helicopter or aircraft. Figure 12 shows the equipment installed in a Cessna 172 using a cradle assembly which replaces the luggage compartment door. Figure 13 is a detail of the bird and cradle assembly mounted through the camera hatch of a float version of the De Haviland Beaver (DHC-2, Mark II). Both of these installations were performed without any structural modifications to the aircraft and once installed, the equipment can be mounted or dismantled in a few hours.

Limitations of the present airborne and helicopter AFMAG equipment result from the restriction of the measurement to the flight direction and the relatively long time constants employed. Development is presently being carried out on a three-component system which will allow for a vector-type analysis of the airborne results and recent electronic advances will result in better response times for the recognition of smaller events.

A recent airborne development is a combined electromagnetic-AFMAG system. This unit records both methods simultaneously and combines the great range of AFMAG with the definition of shallow conductors provided by electromagnetics.

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Erratum

A new gravity anomaly map of Canada: an aid to mineral exploration

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Abstract. During the past decade, the Dominion Observatory carried out systematic gravity surveys (at intervals of about 12 km) over approximately 2/3 of the land mass of Canada including portions of the adjoining continental shelves of the Atlantic, Pacific, and Arctic Ocean basins. Reconnaissance gravity surveys (intervals of about 25 km) were completed also for large portions of the Northwest Territories, Hudson Bay and the rugged mountainous areas of western Canada. Data for 93,000 stations, including 3000 stations observed by universities, 4000 by the petroleum exploration industry and 1000 by the mineral exploration industry, have been used to compile the new Bouguer Gravity Anomaly Map of Canada at a scale of 1:2,500,000.

Although regional gravity surveys, as opposed to detailed work, are not aimed at the direct detection of orebodies, they provide fundamental information regarding the nature, composition and structure of the earth's outer shell, which may have a profound influence on the future search for mineral deposits. In this paper, the larger variations of the gravitational field are examined in relation to major structural elements. Particular attention is given to the interpretation of the anomalies for the Precambrian Shield as follows: (i) the positive anomaly belt marking the boundary between the Churchill and Superior structural blocks in northern Manitoba and in Quebec; (ii) the Kapuskasing positive anomaly belt of northern Ontario; (iii) the intensely negative anomalies along the boundary of the Grenville-Superior structural provinces of Quebec; (iv) the positive and negative anomaly belts of the Bear and Slave structural provinces in the Northwest Territories.

Résumé. Au cours des dix dernières années, l'Observatoire du Canada a effectué des relevés gravimétriques systématiques (à intervalles d'environ 12 km) d'à peu près les deux tiers des terres canadiennes, y compris des parties des plateaux continentaux adjacents aux bassins des océans Atlantique, Pacifique et Arctique. Les relevés gravimétriques de reconnaissance (à équidistances d'environ 25 km) ont été terminés également dans de grandes parties des Territoires du Nord-Ouest, de la baie d'Hudson et des régions montagneuses de l'Ouest du pays. Les données recueillies à 93,000 stations (dont 3000 dirigées par des universités, 4000 par l'industrie pétrolière et 1000 par l'industrie minière) ont été utilisées pour établir la nouvelle carte des anomalies de Bouguer au 2,500,000^{e}.

Bien que les relevés gravimétriques régionaux, contrairement aux relevés détaillés, ne soient pas entrepris en vue de détecter des gisements de minerai, ils fournissent des données fondamentales sur la nature, la composition et la structure de la croute extérieure qui peuvent exercer une profonde influence à l'avenir sur la recherche de minéraux. Dans cette étude, les variations les plus importantes du champ gravitationnel sont étudiées en fonction des principaux éléments structuraux. L'auteur accorde une attention particulière à l'interprétation des anomalies dans le Bouclier précambrien que se présentent comme suit: (i) une zone d'anomalies positives qui marque la limite entre les blocs structuraux des provinces Churchill et Supérieure dans le nord du Manitoba et au Québec; (ii) la zone d'anomalies positives de Kapuskasing dans le nord de l'Ontario; (iii) des anomalies négatives intenses le long de la limite entre les provinces structurales de Grenville et Supérieure au Québec; (iv) des zones d'anomalies positives et négatives dans les provinces structurales de l'Ours et des Esclaves dans les Territoires du Nord-Ouest.

In Canada's Centennial year it is appropriate, as an introduction to this paper on the new Gravity Map of Canada, to review briefly the history of gravity measurements in this country. As far as can be learned the earliest gravity work was carried out in conjunction with Sir William Parry's voyages early in the nineteenth century to discover a navigable east-west route through the Arctic Seas.

In 1902, the Dominion Observatory initiated pendulum measurements as a contribution to international studies to determine the shape of the earth and to test the theory of isostasy as it applied to the North American continent. During the next forty years some two hundred pendulum measurements were made throughout Canada. In later years the results of these measurements provided a valuable framework for the control of early gravimeter measurements.

Initially government interest in geophysics lay in its applications to the larger problems of the earth, but it became obvious very soon that geophysics had possibilities in the search for minerals. Accordingly in 1928 and succeeding years, the late A.H. Miller, former chief of the Gravity Division of the Dominion Observatory, recognized as one of the pioneers of Canadian geophysics, carried out, in cooperation with the Geological Survey of Canada, many original investigations dealing with the fundamental and practical aspects of gravitational and magnetic methods of prospecting.

The results of a pioneer gravity investigation carried out in 1934 over the Malagash salt deposit in Nova Scotia are shown in Figure 1 (Miller, 1940). Gravity measurements were made with an Eötvös torsion balance, a remarkably sensitive instrument which measures the gradient of gravity in a horizontal direction. The gravity map faithfully outlines the area in which there is a deficiency of mass due to the salt. As the rock exposures were limited to the shore of Northumberland Strait, the precise boundary of the low-density salt deposit was not known before the gravity survey was done.

Tests carried out some twenty years ago by the Observatory over the MacDonald Mines property in Dufresnoy township in western Quebec, demonstrated quite clearly that gravity measurements were capable of delineating near-surface orebodies (Figure 2). The orebody is completely covered with overburden and consists chiefly of pyrite with some sphalerite and has an estimated ore reserve of 12 million tons. It was discovered by diamond drilling along the contact between the volcanic rock (pyroclastics) and a large granodiorite intrusion. The orebody produces an anomaly of nearly 3 mgal and is clearly outlined by the gravity contours.

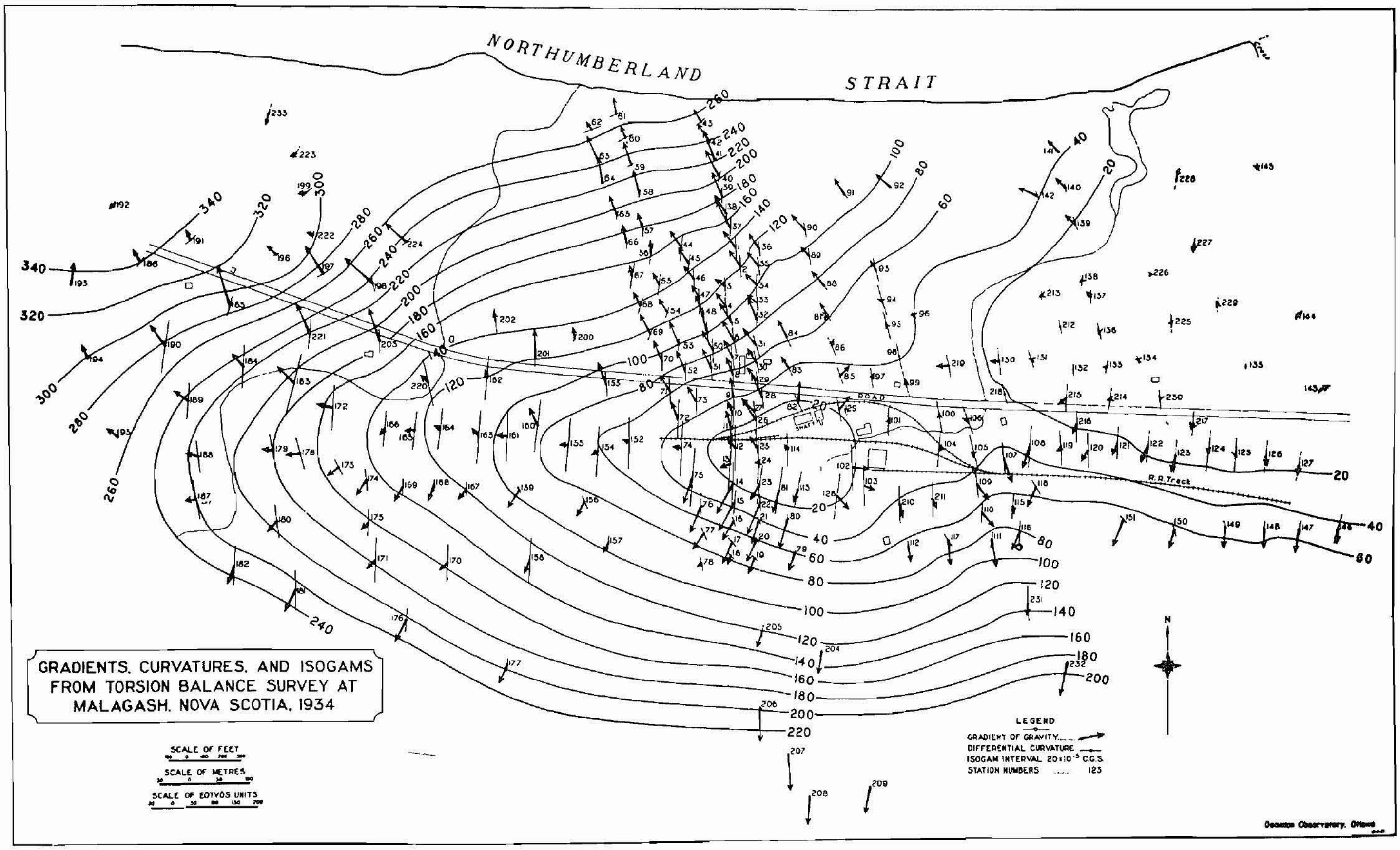

Figure 1. Torsion balance survey of the Malagash salt mine area, Nova Scotia.

These examples are but two of the early investigations in Canada to test geophysical methods of prospecting. Since their time, a great store of professional and scientific competence has been gained by exploration geophysicists working in Canada and other parts of the world. Although gravity surveys are still used extensively by the oil exploration industry in delineating structures favourable to the accumulation of oil, the method is seldom used for reconnaissance work to locate orebodies. So far there has been little success in measuring gravity from an aircraft, and detailed gravity surveys currently find their greatest application in testing potential or producing areas that have been detected by other methods. Once a mineralized zone has been located, gravity surveys sometimes prove invaluable in delineating its extent and determining its total mass.

The new Gravity Map of Canada

Regional gravity surveys in this country for geodetic and geophysical studies had their beginning near the end of World War II, as the result of a radical change in both the speed and accuracy of measurement, through the use of gravimeters for the first time. Figure 3 shows the accumulation of gravity data resulting from these surveys to the end of 1966. Between 1944 and 1955, what are now classified as reconnaissance surveys, with measurements at intervals of 15 km or greater, were carried out through southern Canada with automobile transportation, and over wide areas of northern Canada with light aircraft suitable for landing on lakes and rivers. During this period some 10,000 regional measurements were obtained, which provided the data for the first edition of the Gravity Map of Canada issued by the Dominion Observatory in 1956. As the value of gravity information to the exploration industry and to earth science generally became more apparent, the rate of gravity mapping was more than doubled, to approximately 2000 stations per year. At the same time, systematic surveys were initiated to provide a uniform gravity coverage of Canada at a station interval of 15 km or less.

To meet the steadily increasing demand for gravity data, the rate of mapping was again stepped up. Since 1961, more than 10,000 stations have been observed annually (Figure 3). This was accomplished partly by doubling the number of survey parties operating in the Canadian Shield and partly by increasing the efficiency of the surveys, by using helicopter transportation. Also, since 1961 systematic surveys have included measurements over the continental shelves and inland lakes using underwater gravimeters. The present rate of mapping also reflects the measurements now being made annually over the arctic islands, and on the sea ice between the islands and on the adjoining Arctic Ocean basin in conjunction with the federal government's Polar Continental Shelf Project.

The progress that has been made with gravity mapping to date, and the station density, are shown in Figure 4. Systematic surveys with measurements at intervals of 10 to 15 km have been completed for more than 60% of Canada. Reconnaissance surveys with stations at intervals of 15 km or more, cover about 25% and

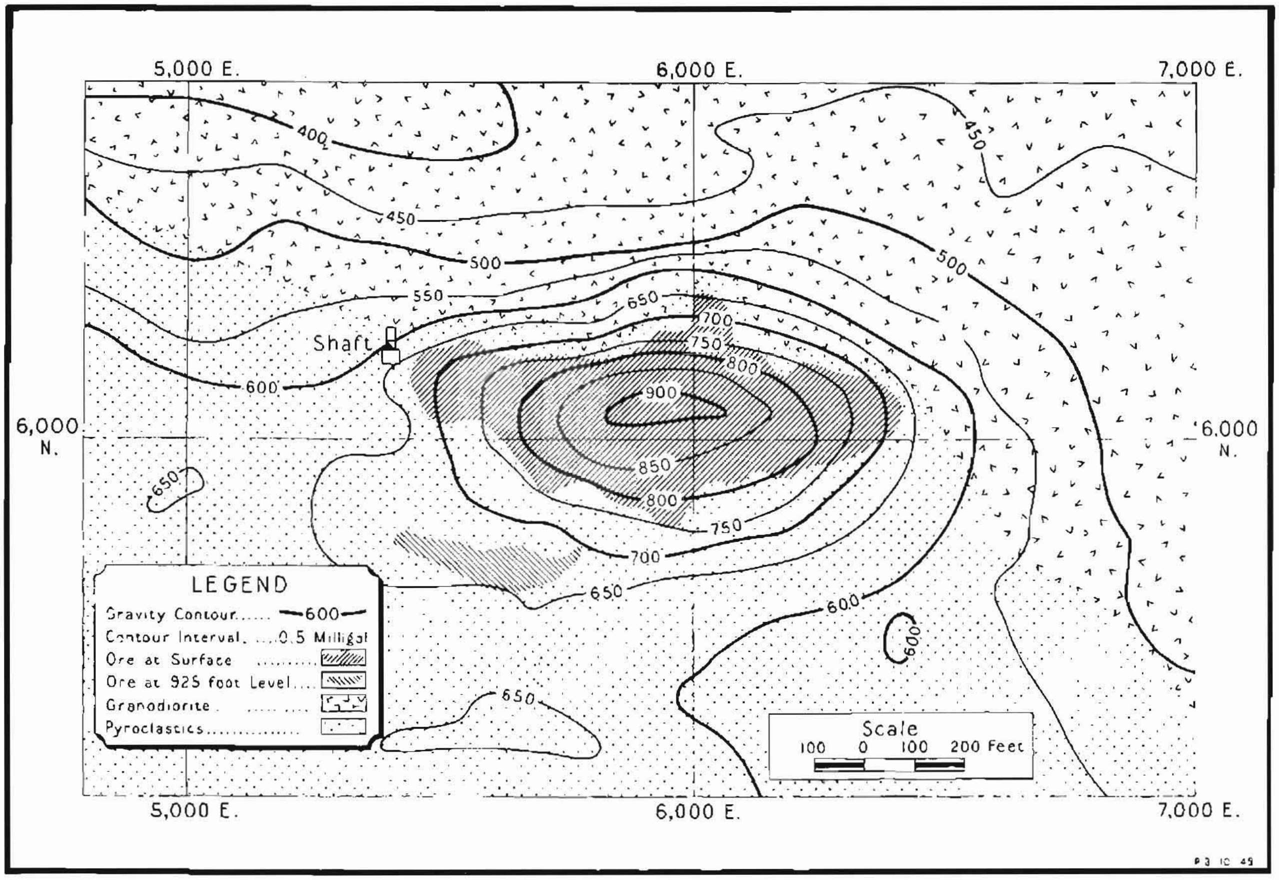

Figure 2. Positive gravity anomaly over an orebody, MacDonald Mines, Dufresnoy township, western Quebec.

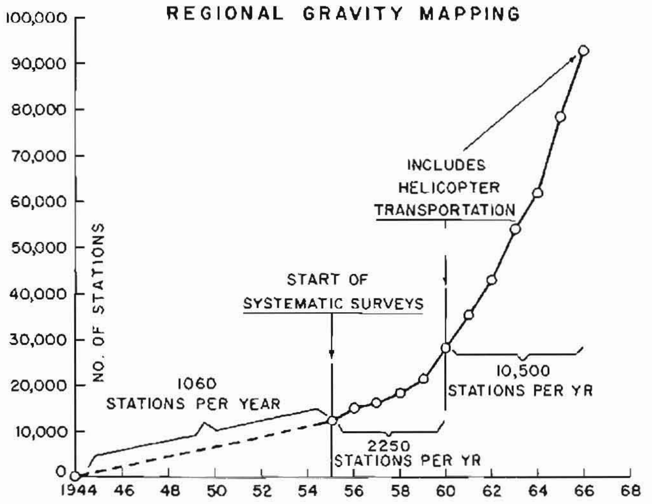

Figure 3. The annual increase of gravity stations established in Canada for the period 1944 to 1966.

in the remaining area no observations have been made. At the present rate, systematic mapping of all of Canada should be completed in about six years.

More than 93,000 regional stations were observed by the end of 1966 and all the results have been used in compiling the new Gravity Map of Canada. The new map has a scale of 1:2,500,000 or approximately 40 miles to an inch, similar in scale to the Bouguer anomaly map recently produced for the United States. It consists of four sheets, and the whole map covers an area of about 7 by 8 feet. Contours of the Bouguer anomalies are shown at intervals of 10 mgal and the map is coloured to permit easy identification of the gravity highs and lows. Figure 5 is a photographic reproduction of the new Bouguer anomaly map of Canada.*

Regional gravity measurements yield information, in common with other geophysical disciplines and with structural geology, on the broad architecture of the earth. Anomaly maps are now becoming available in most countries and it is important that geologists as well as exploration geophysicists understand the gravity map and its limitations. Bouguer gravity anomalies are formed by reducing the observations to sea level and by making corrections for the mean shape of the earth and its rotation. All information concerning the geology and structure of an area that can be learned from gravity is contained in the Bouguer anomalies. A Bouguer anomaly map reflects the lateral variations of density of the outer portions of the earth and, therefore, contributes to our understanding of the structural makeup of the continents and ocean basins.

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* The New Gravity Map of Canada is available from the Dominion Observatory, Department of Energy, Mines and Resources, Ottawa, Canada.

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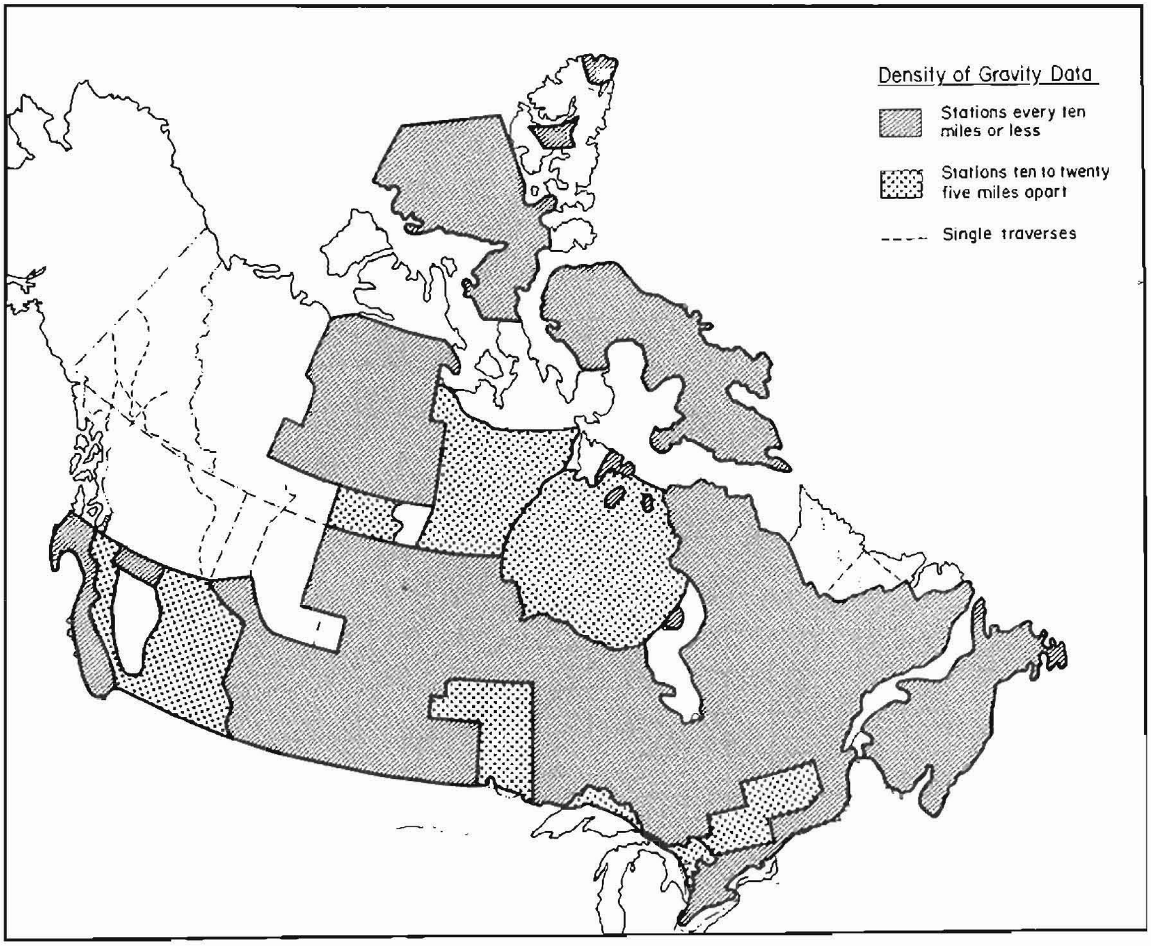

Figure 4. Distribution and density of gravity observations used in compiling the gravity map of Canada.

Unlike magnetic field intensities, which vary inversely as the cube of the distance from a dipolar source, gravitational fields vary inversely as the square of the distance and often reflect much deeper disturbances. Bouguer anomalies may be due not only to near-surface bodies and to geological structures which may penetrate the entire crust, but may be due to density variations in the mantle. Regional gravity data often provide valuable guidelines to one seeking structures favourable for the occurrence of mineral deposits.

Fundamental difficulties in quantitative interpretation of gravity, as with other geophysical data, are ambiguity and lack of resolution. Ambiguity reflects dependence of the gravity field on several factors, including form, size, depth and density contrast. When all of these factors are known, which is seldom, it is possible to predict uniquely the effect of gravity at the surface. If these factors cannot be evaluated individually, the many possible permutations allow a corresponding number of solutions.

However, much concerning the geology of an area can be learned simply by studying the gravity variations. Correlations between gravity and geology are often clear without sophisticated interpretation. Areas of high density produce relatively positive anomalies, while areas underlain by low-density rocks produce negative anomalies. Gravity is often particularly helpful to geologists and exploration geophysicists operating in shield areas, where one usually finds a good correlation between gravity and the surface geology.

Some gravity anomalies of the Canadian Shield

Some examples of correlations found in the Canadian Shield between gravity and geology are described in this section. The Shield has been subdivided into several major structural provinces by Stockwell (1964) (Figure 6). The anomalies to be discussed occur in the Grenville, Churchill and Superior provinces as shown in Figure 6.

Anstruther batholith. A generalized geological map and a corresponding Bouguer anomaly map of an area of about 1000 square miles in the Burleigh-Anstruther area of the southern part of the Grenville province is shown in Figure 7. The Anstruther batholith of granite gneiss is the dominant feature of the region. Granite occurrences are widespread in the area and are separated by denser septa of sediments of variable composition, mainly limestone, dolomite, silicated limestone, pelitic schists, quartzite and amphibolite. Some diorite and gabbro occur, particularly to the east and northwest of the batholith. There is a one-to-one correspondence between the Bouguer anomalies and the geology. The more negative anomalies in the −40 to −50 mgal range are

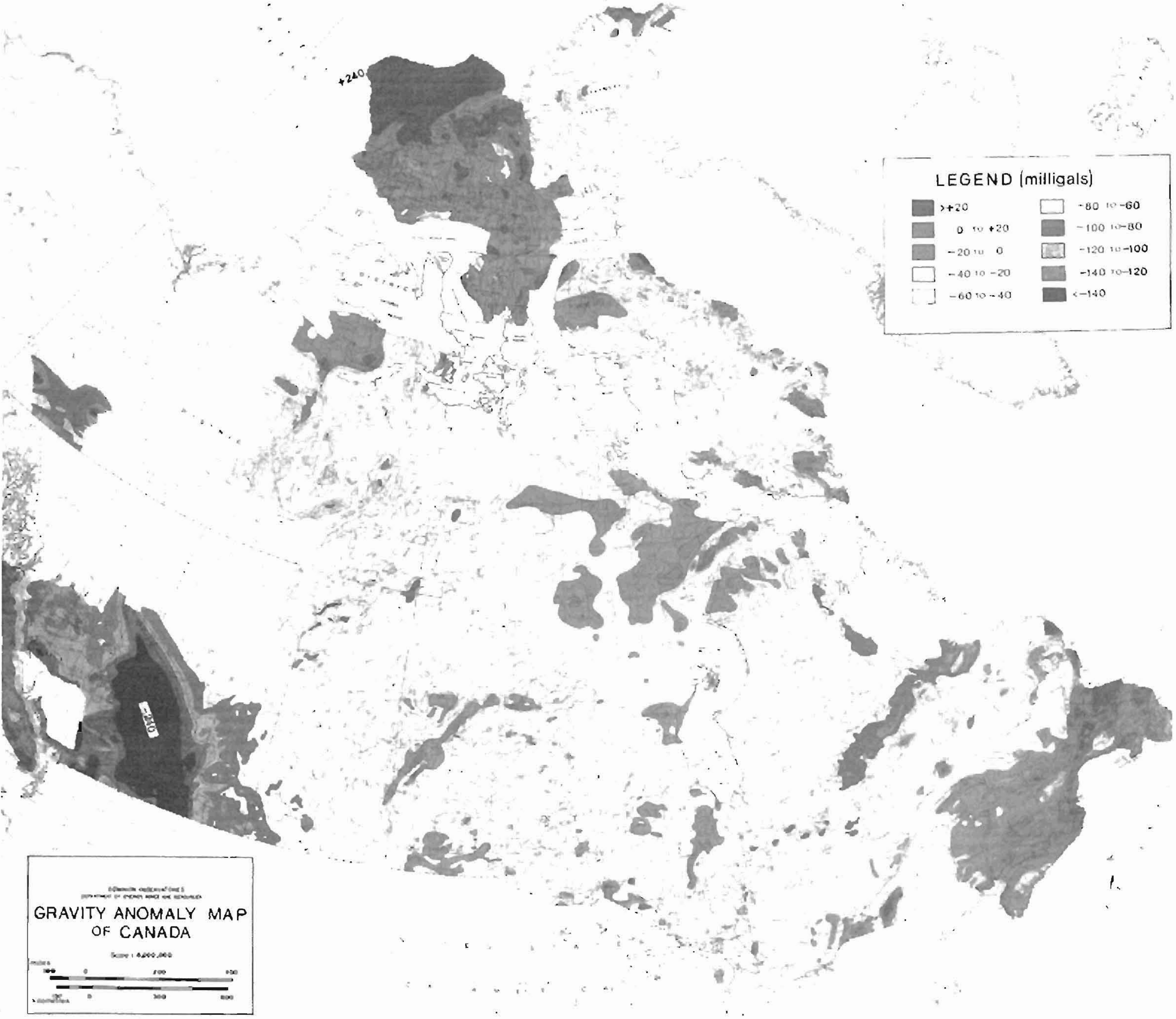

Figure 5. Photographic reproduction of the new coloured Bouguer gravity anomaly map of Canada.

underlain by granitic rocks and the more positive anomalies in the −30 to −40 mgal range correspond to areas of denser sediments. A detailed study of the gravity field in this region is in progress and preliminary results indicate that the sediments have a maximum thickness of 1.5 km and are everywhere underlain by the granitic rocks (Jacoby, in preparation).

Athabasca formation. The Athabasca formation is a large block of relatively flat-lying Proterozoic sandstone which occurs in the vicinity of Lake Athabasca in the Churchill structural province (Figure 8). The sandstone has a density of about 2.4 g/cm^3 and has been estimated to be no more than 1000 metres thick. In this example it will be shown how the gravity anomalies over the sandstone are related in fact to the metamorphic basement. The gravity field in this region is discussed in more detail by Walcott (1968).

The most striking feature of the map is the central belt of unusually intense anomalies bounded on the northwest and southeast by areas of low gravity relief (Figure 8). The widths of the gravity highs and lows are in the range 40 to 70 km, and

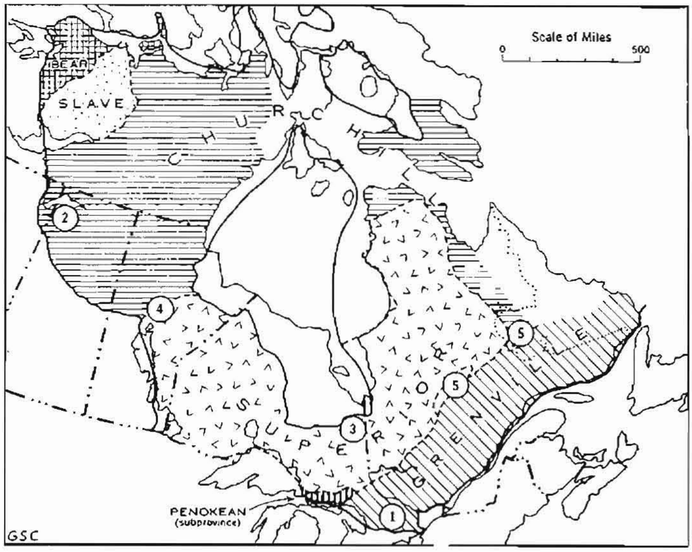

Figure 6. The structural provinces of the Canadian Shield (after Stockwell, 1964). The numbers refer to the locations of the anomalies discussed: (1) Anstruther batholith, (2) Athabasca formation, (3) Kapuskasing high, (4) Nelson River high, (5) Grenville low.

indicate large-scale variations in mean crustal density of the basement rocks. That is, the gravity maps show a variation in crustal lithology of very great wavelength, a variation which is not indicated on existing small-scale geological maps. In detail, however, where adequate large-scale geological mapping does exist, a correlation between surface geology and gravity is indicated. For instance north of Stony Rapids, the gravity high is closely related to unusually high density norites and metavolcanics; the gravity low appears to be related to alkaline granite. The latter can only be tentatively suggested as no large-scale maps completely cross the low anywhere. Anomalies of similar wavelength occur on the magnetic maps of the area. The great advantage of gravity is that we are able to extrapolate from areas of known geology, to areas of unknown basement geology. This is clearly indicated by the composite gravity and geological map. The anomalies trend from north of Stony Rapids and continue uninterrupted across the Athabasca sandstone.

Variations in the thickness of the sandstone will tend to be masked by the much stronger anomalies due to the basement geology. For instance, a variation in the thickness of the sandstone due to relief of the basement rocks of about 700 metres would produce a gravity anomaly of no more than 8 mgal. This would be difficult to detect, as the actual range of the anomalies is some 60 mgal.

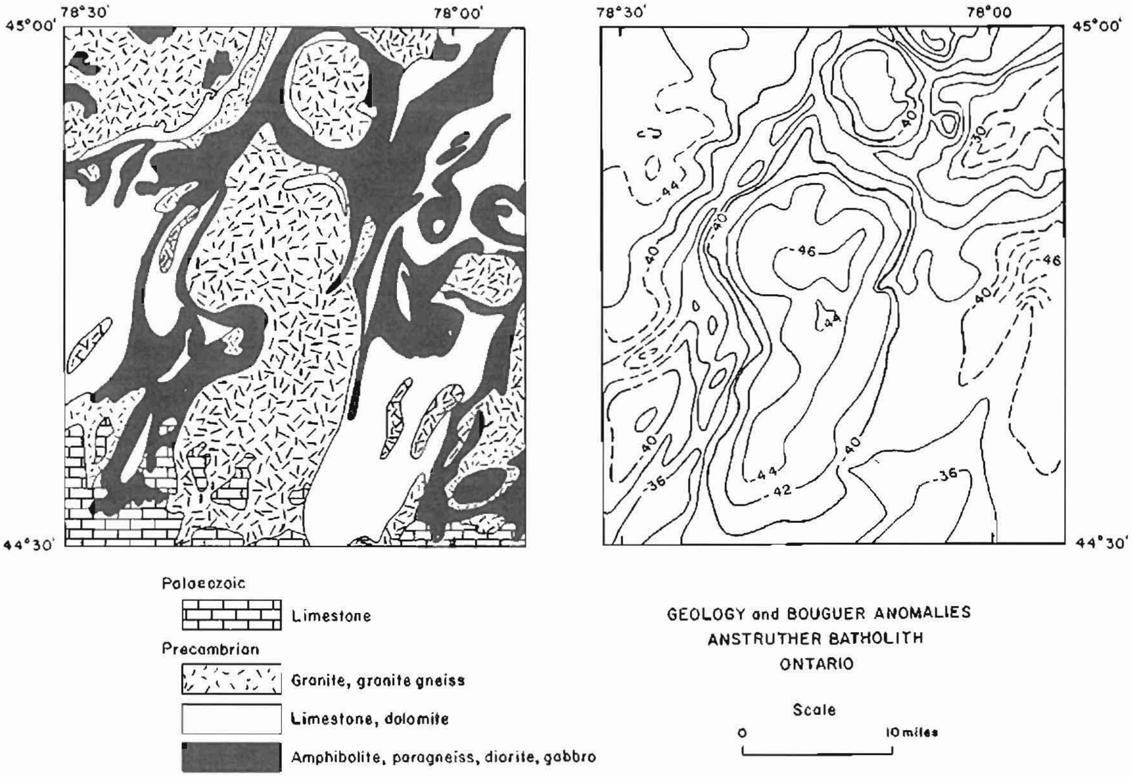

Figure 7. Simplified geological map and Bouguer anomaly map of the Anstruther batholith, Grenville province, Ontario.

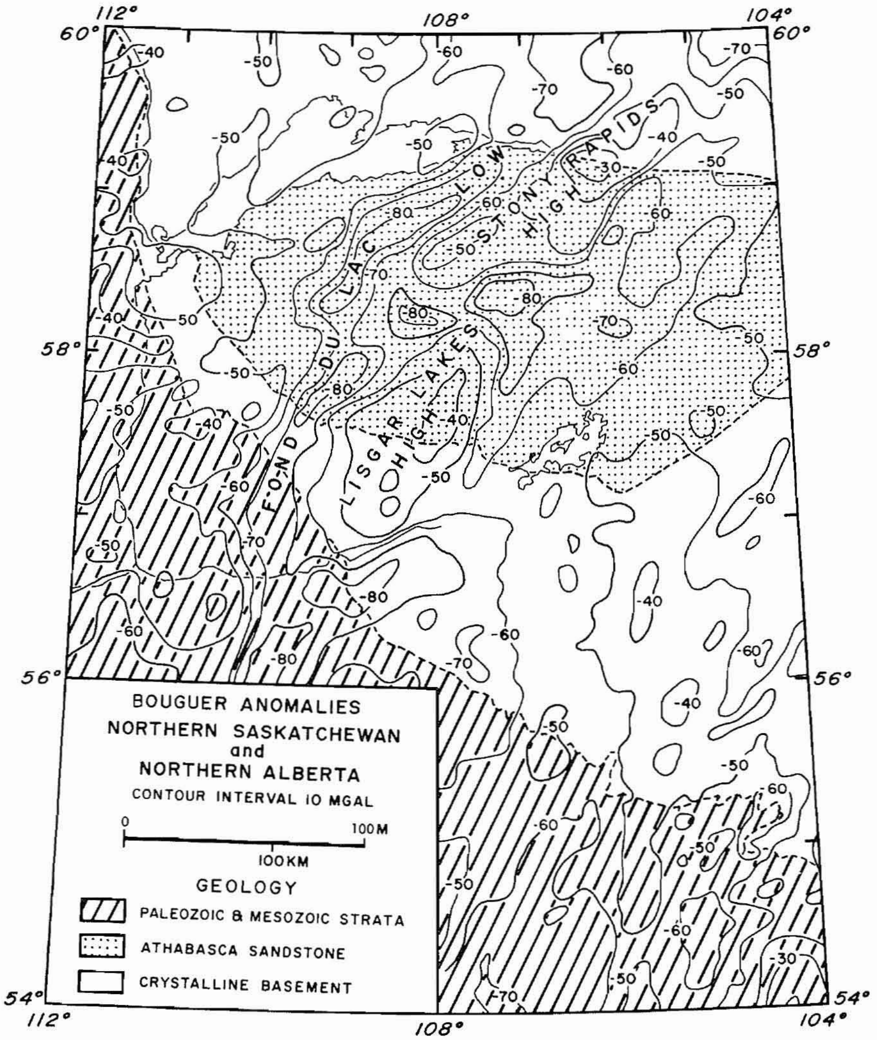

Figure 8. Simplified geological map and Bouguer anomalies, northern Saskatchewan and northern Alberta, Churchill province.

Gravity data alone, therefore, contribute very little to our knowledge of the structural relationship between the sedimentary strata and the crystalline basement. However, perhaps better than any other method, they do detect large-scale variations in crustal lithology, even when covered by considerable thicknesses of sedimentary rock.

Kapuskasing high. A remarkable positive anomaly belt known as the Kapuskasing gravity high lies in the Superior province of the shield and extends south from James Bay at least 600 km. Figure 9 shows the gravity anomalies and the regional geology, based largely on the work of Bennett, *et al.* (1966). From south to north the anomaly belt broadens from about 30 to more than 100 km. The more positive anomalies rise, on the average, some 35 mgal above background values. Unlike anomaly belts over other parts of the Superior province this belt cuts directly across the predominantly east-west structural trends, suggesting a deep-seated origin.

Geological evidence supports the view that the anomaly belt reflects a deeply eroded rift zone, a major structure involving the entire thickness of the crust.

1. It marks the western limit of the Porcupine-Quebec belt of basic volcanic rocks and the eastern limit of the Ontario belt of metasedimentary rocks.
2. A number of alkaline ring complexes, presumably intrusions from the mantle, lie along the axis of the high.
3. Large blocks of high-grade metamorphic rock, mainly granulites of higher than average density, about 2.8 g/cm^3, have been brought to the surface by faulting. It has been pointed out by geologists (Kalliokoski, personal communication, 1966) working in the area, that the crust has fractured rather than flowed, with little or no evidence of folding.
4. Within the main anomaly belt local gravity highs correlate with the alkaline ring complexes, with gabbroic intrusions, and with occurrences of granulite, but these obviously do not provide the major control for the regional high.
5. Figure 10 shows an east-west geological section across an area where the surface rocks are predominantly massive granite. As these rocks are of lower density than most crustal rocks, it is clear that the surface geology does not provide major control over the anomalies. A deep-seated source is required. Calculations on models show that the gravity disturbance can be accounted for by a local rise of the Conrad discontinuity of about 8 km. This

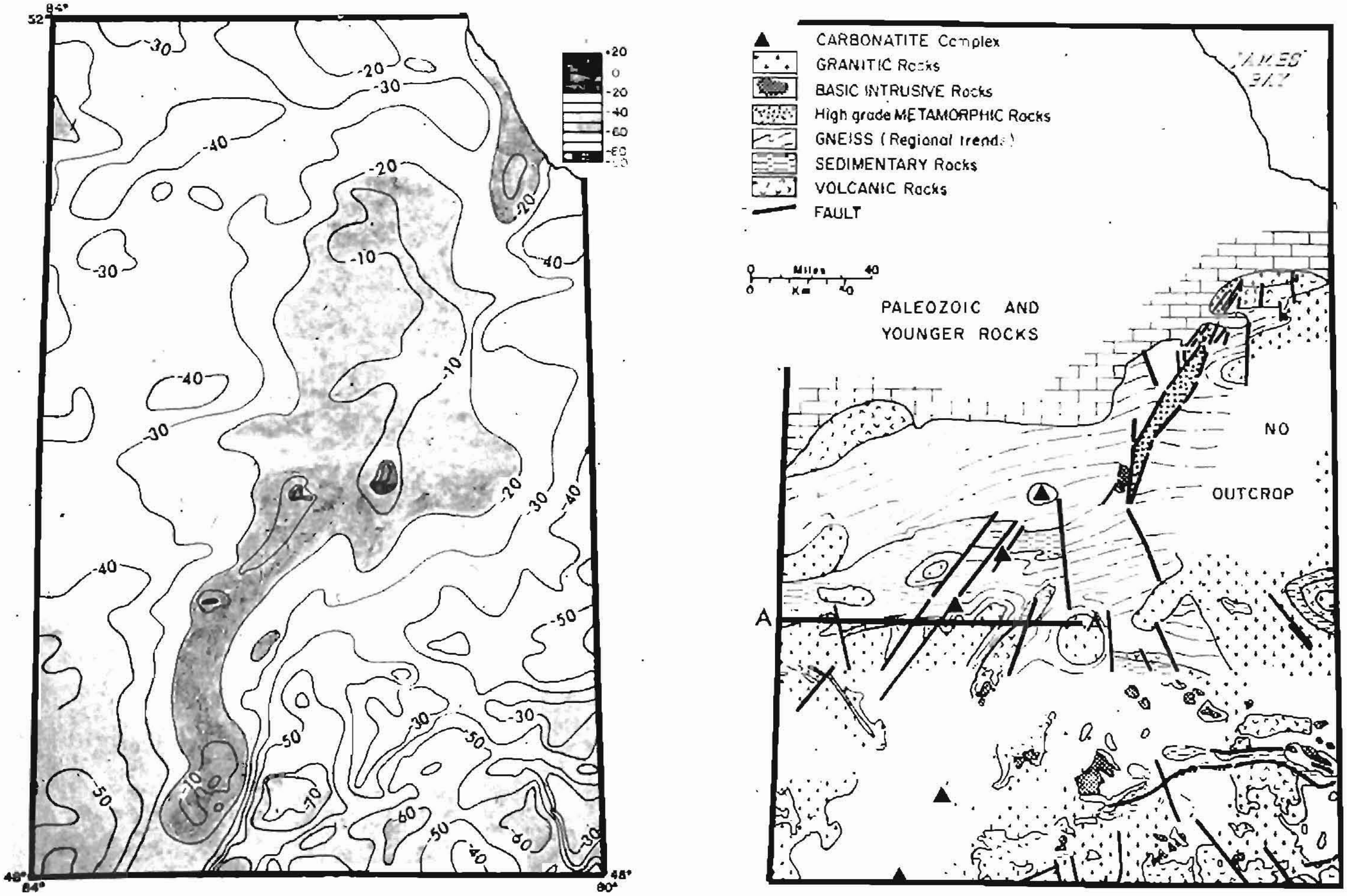

Figure 9. Geology and Bouguer anomaly maps, contour interval 10 mgal, Kapuskasing high, Superior province, Ontario (geology from Bennett, *et al.,* 1966).

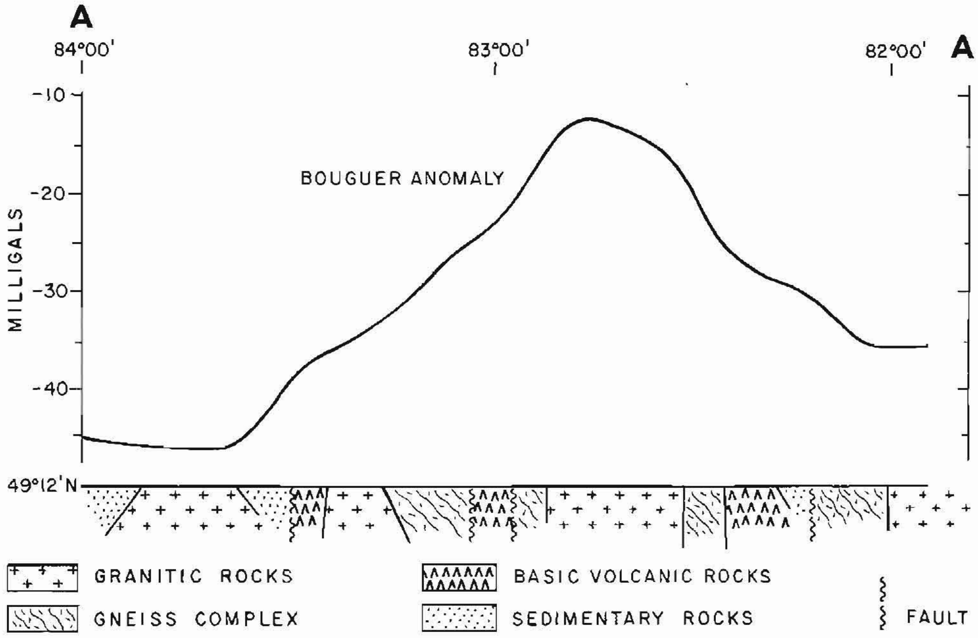

Figure 10. Geological section and Bouguer anomaly profile A-A across the Kapuskasing fault zone at latitude 49° 12'N (for location see Figure 9).

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suggests that the Kapuskasing feature is a major structure involving perhaps the entire thickness of the crust. The regional gravity high is discussed more fully by Innes (1960) and Innes, *et al.* (1967), and associated aeromagnetic anomalies and detailed geophysical studies within the belt are discussed by MacLaren, *et al.* (1968).

Nelson River high. The boundary between the Churchill and Superior provinces in northern Manitoba is flanked to the southeast by the Nelson River gravity high and to the northwest by a series of three gravity lows (Figure 11). There is an excellent correlation between geology and gravity in this region. The high is underlain by relatively dense granulites of the Superior province, whereas the lows in the Churchill province are underlain by a zone of less dense metamorphic rocks with an average composition equivalent to that of granodiorite. Intrusive granites are associated with all three gravity minima. These interesting anomalies are further discussed by Innes (1960) and Gibb (1968).

However, because of the similarities of tectonics, lithology and geophysical anomalies apparent in the Nelson River and Kapuskasing areas it is of some interest to compare these areas in more detail.

1. Archaean granulite facies rocks, characteristically associated with gabbroic or anorthositic intrusive masses, occur in both areas.
2. These granulite belts are fault-bounded in whole or in part in both areas, and they cut across the major regional trends.
3. Both belts are elongated in a northeasterly direction.
4. In both areas local gravity anomalies are superimposed on regional gravity highs of wide extent. Both regional highs can be related to uplifts of the lower crustal layer which may imply uplift of whole crustal blocks in these areas. Alternatively the high regional anomalies may indicate crustal blocks which are both thicker and denser than the average for the Shield.
5. In both areas, intrusive rocks – nickeliferous peridotites and alkaline intrusive rocks (Kapuskasing belt only) – originating probably from the mantle, are present at the surface.

A common origin or mechanism for these two structural zones is possible, although Innes (1960) has suggested an orogenic origin for the Nelson River belt, while Innes, *et al.* (1967) have suggested that the Kapuskasing belt is an orogenic domain.

Bailey (1964) suggests that rift zones and alkaline magmatism in ancient shield areas are both expressions of the same major process of crustal warping controlled by regional compression. This may explain why alkaline intrusive centres are not always localized along the rifts. Moreover, the presence of alkaline intrusions does not necessarily imply that rifting has occurred but rather that crustal upwarping has occurred. Old orogenic belts where the crust has already been thickened or uplifted form preferred loci for renewed uplift. This tendency for swells and rifts to parallel earlier orogenic trends has been observed in Africa (Bailey, 1964).

In this perspective it is perhaps possible now to reconcile the different interpretations suggested for the Nelson River and Kapuskasing belts. Both belts may occur along ancient Archaean orogenic zones, which have been submitted to renewed crustal

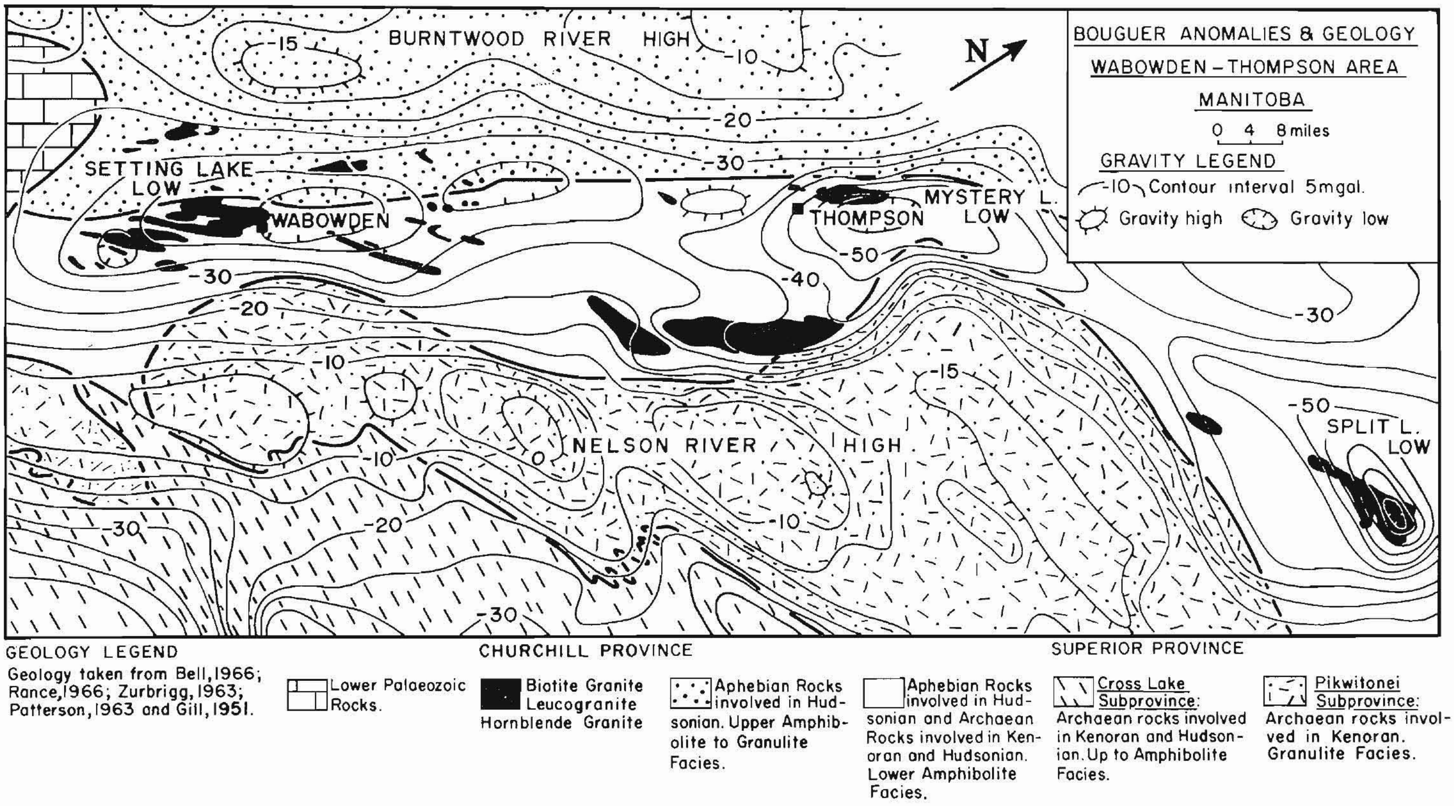

Figure 11. Bouguer anomalies and geology, Churchill-Superior province boundary, northern Manitoba.

uplift, related in the former case to a period of renewed orogeny (Hudsonian) and in the latter case resulting in Proterozoic block faulting and alkaline intrusion with or without the formation of a rift valley, traces of which may have long been lost by erosion.

Grenville front. The most remarkable negative anomaly belt in the Canadian Shield lies along what is known as the Grenville front, or the boundary separating the Superior and Grenville structural provinces. It has been traced more than 1300 km almost to the Labrador coast (Figure 5). Figure 12 shows the anomaly pattern of an 800-km portion of the anomaly belt in the vicinity of the Labrador trough; contours of the Bouguer anomalies are superimposed on a simplified geological map of the same area. The negative anomalies reach a minimum of about −130 mgal. It is interesting to note that west of the Labrador trough, the axis of the belt follows the contact between the Superior and Grenville rocks. East of the trough, the more intensely negative anomalies lie within the Grenville province.

The full significance of this anomaly belt is not yet understood and several interpretations have been suggested. An early interpretation suggested that the negative anomaly might be due to a buried granitic intrusion (Innes, 1960). The steep gradients suggest a near-surface body. Tanner (personal communication) in a recent study points out that the steep gradients stem largely from intrusions of anorthosite and gabbro, and if the effects of these are removed, the negative anomaly could be explained by crustal thickening. Grant (1966) attributes the anomaly to a thick sequence of sediments that are less dense than the surrounding rocks. One difficulty with this interpretation is the great thickness of sediments required to explain the anomaly. A minimum thickness of 8 km would be required.

Further investigations into the source of this interesting anomaly are needed. Perhaps seismic work to be carried out in 1968 by the Dominion Observatory will be rewarding.

Reconnaissance gravity as an aid to mineral exploration

In the areas described above no orebodies have been discovered as a direct result of mapping the gravity anomaly fields. However, in the case of the four major anomalies discussed, the gravity anomalies provide information about both the near-surface and deep crustal structure and therefore the possible location of deposits of economic interest.

The ores have usually been located by geological mapping and airborne magnetic surveys, followed usually by detailed mapping and different types of ground geophysical surveys when necessary. Such a sequence resulted in the discovery of the commercial nickel at Thompson in Manitoba. The nickel mineralization occurs as disseminations and stringers in serpentinized peridotite, and as massive bodies and stringers in schist, metasediments and gneiss (Zurbrigg, 1963). The ores lie scattered along the axis of the belt of gravity lows which lies to the northwest of the Nelson River high from south of Wabowden to north of Thompson (Figure 11). As noted by Wilson and Brisbin (1961), the ores always lie within a mile or two of the centre of the low. With this pattern established, the gravity map provided an additional control to guide the search for ore in this area. The natural trend to follow has been the northerly and southerly extensions of the belt of low-gravity values, although to the south the pattern becomes less distinct.

Various explanations of the origin of the ore in this region have been proposed and it is not intended to review them all. However, it is of considerable interest that Patterson (1963) suggested (as one of several possibilities) an origin due to the reaction between nickel-bearing serpentinite and a granitic magma (or pegmatitic or hydrothermal solutions related to it), involving release of sulphides which, being less soluble in acid than in basic fluids, would collect to form a sulphide liquid. The gravity lows of the nickel belt have been attributed to the presence of subjacent granitic bodies (Gibb, 1968). This interpretation may

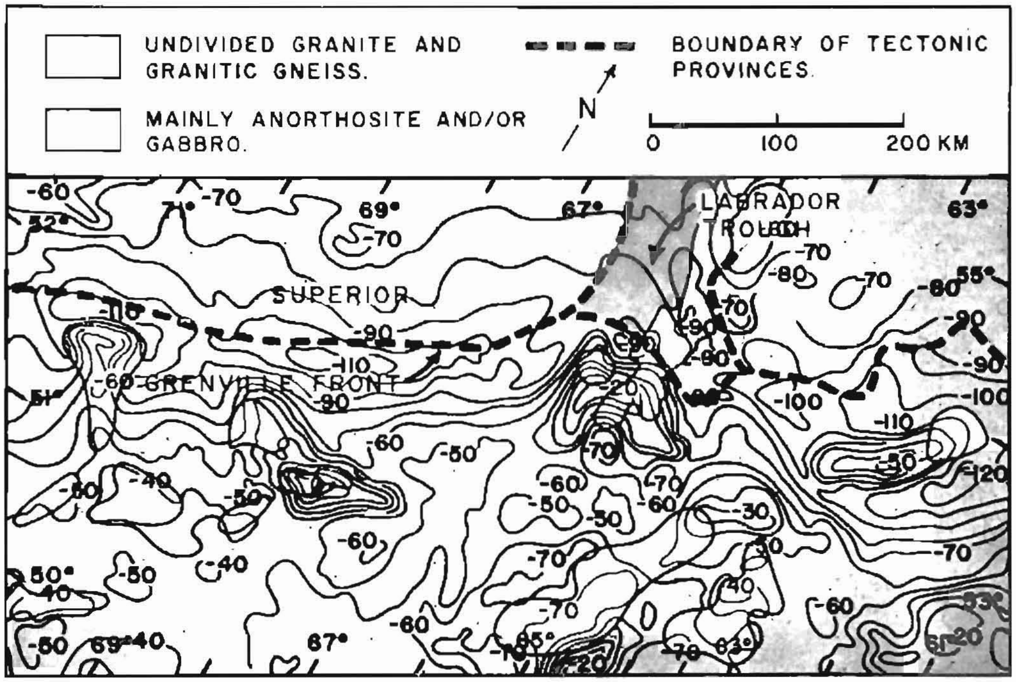

Figure 12. Geological sketch map with Bouguer anomalies, Grenville front, Quebec and Labrador.

explain the localization of the ores along the axis of the gravity low which is also the locus of the roofs of the granites.

Of recent years carbonatite-alkaline ring complexes have become recognized as important sources of numerous minerals including niobium, rare earths, uranium and base metals. In Ontario 32 such complexes have been discovered mainly by aeromagnetic surveys (Satterly, 1968) and outlined by follow-up ground surveys, using magnetometers and scintillometers, and by geological mapping. A prominent linear distribution of eight of these circular complexes stretches from Chapleau to Moosonee along the axis of the Kapuskasing gravity high (Figure 9). A genetic relationship between the high and the carbonatites has been proposed by Innes, *et al.* (1967) and by Gittens, MacIntyre, and York (1967), who have also shown that this region has been the locus of carbonatite magmatism from 1750 m.y. to about 1000 m.y. ago, a period of about 750 m.y. Thus, in combination with more direct methods, the gravity pattern again provides important information on the broad structure of the region, and apart from this regional correlation, detailed gravity surveys have also shown that the carbonatite complexes are defined by local gravity anomalies.

In the Lake Athabasca region (Figure 8) the Stony Rapids high is underlain by a large partially exposed body of norite which accounts for much of the anomaly by its higher-than-average density (Walcott, 1968). The area has been actively explored for minerals; copper, nickel and cobalt ores have been found in a siliceous phase of the norite at Axis Lake (Beck, 1959).

The regional gravity pattern delineates both the exposed portion of the norite and its probable southwesterly extension beneath the Athabasca sandstone. Furthermore, the gravity map has revealed the existence of a second anomaly of similar magnitude, the Lisgar Lakes high, to the southwest (Figure 8). A similar intrusion of norite probably is the causative body, providing a prime indication of where further mineralization may occur.

Iron formations are widely distributed throughout the geosynclinal sequence of the Labrador trough. Within the trough these rocks are not highly metamorphosed and the ores are mainly hematite-goethite deposits as in the Knob Lake area (Gross, 1961). Southwest of the Sawbill Lake area, coarse-grained metamorphosed iron formations yielding high-grade ore occur at Wabush Lake, Mt. Reed and Matonipi, in what may be considered as an extension of the Labrador iron formations (Neilson, 1963). Farther to the southwest, at Lake Albanel, the iron formation is again relatively unmetamorphosed. Neilson suggests that the comparative lack of metamorphic action in the Lake Albanel area may be explained if the area has not been directly affected by Grenville deformation and metamorphism. However, the deposits of metamorphosed high-grade ore consistently occur within the Grenville gravity low; this gravity feature apparently delineates the region of relatively high metamorphic grade (upper epidote amphibolite facies). The higher thermal gradients which must have occurred in this region may be genetically related to the source of the gravity low, whether it is a vast batholith of granite, or localized changes in the thickness and average density of the crust.

The gabbroic-anorthosite intrusions which stud the Grenville province are frequently rich in ilmenite and titaniferous magnetite, which occur as magmatic segregations. In each case these intrusions are related to accompanying gravity highs (Figure 12). The anomalies show that the gabbroic-anorthosites are often of much larger areal extent than outcrops reveal. As mentioned above, interpretation suggests that these intrusions may penetrate the entire crust. In this example the reconnaissance gravity method may be used for the direct location of the large intrusive masses, and detailed work used to delineate the bodies may also prove a valuable aid for locating the ores themselves, because of the high density of the ore minerals (Rose, 1961; I.G. Tanner, personal communication).

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Regional geophysical mapping

L.W. Morley

Geological Survey of Canada

Abstract. The role of geophysics in mineral prospecting has traditionally been the pinpointing of suitable drilling targets. Its success in this respect has been good, as many case history studies have shown.

However, a new role for exploration geophysics has been developing in the last ten years – that of providing information on the regional geological setting of ore deposits, i.e., delineating geological provinces and subprovinces and verifying inferred geological structures.

This new role will become increasingly important as the high signal-to-noise ratio anomalies caused by shallow ore deposits are exploited leaving only the deeper and more elusive ones. These deeper deposits will have to be found by costly exploratory drilling and drill-hole geophysics. The importance of being able to identify favourable regions by geophysical as well as geological and geochemical means therefore cannot be over-emphasized. Gravity and magnetics show promise of this new usefulness in North America, and in the U.S.S.R. Seismology will also be used in this way.

The aeromagnetic map of Canada is an example of the advantages of regional geophysical interpretation. This map indicates tectonic styles and boundaries between major geological provinces, and delineates the volcanic and metasedimentary belts where most mineral deposits are found. What other significant correlations will be found is difficult to say because the map is so new. The advantage of such a geophysical map lies in its objectivity, its standard quality from area to area, and in the unexpected continuity of several features which, in some cases, extend for 500 or 600 miles.

In addition to these conventional methods for gathering regionally significant data, new airborne and satellite methods must be exploited on a world-wide basis to help meet the needs of a world on the threshold of greatly increased industrialization.

Résumé. Le rôle de la géophysique dans la prospection minérale a porté dans le passé sur la localisation précise des forages. Ses succès dans ce domaine ont été excellents, comme l'ont démontré de nombreux exemples récents.

Toutefois, au cours des dix dernières années, on a conçu un nouveau rôle pour la géophysique: celui de fournir des renseignements sur le cadre géologique régional des gîtes de minerai, c'est-à-dire la délimitation des provinces géologiques et des sous-provinces et la vérification des structures géologiques déduites.

Ce nouveau rôle deviendra de plus en plus important à mesure que les anomalies présentant un haut rapport entre le signal et le bruit causés par des gîtes de minerai de faible profondeur seront exploitées, ne laissant que les anomalies causées par les gîtes plus profonds et plus difficiles à trouver. Ces gîtes plus profonds ne pourront être découverts que par les forages d'exploration et des essais géophysiques coûteux. On ne peut donc trop souligner l'importance qu'il y aurait de pouvoir identifier les régions prometteuses autant par des méthodes géophysiques que géologiques. Les méthodes gravimétriques et magnétiques ont démontré leur importance en Amérique du Nord, et en U.R.S.S. La séismologie sera aussi utilisée de cette façon.

La carte aéromagnétique du Canada est un exemple des avantages que présente l'interprétation géophysique régionale. Cette carte indique les caractères tectoniques, les frontières entre les provinces géologiques importantes, et délimite les zones volcaniques et parasédimentaires où se trouvent la plupart des gîtes minéraux. Il est difficile de prédire quelles autres corrélations importantes pourront être établies à cause de la grande nouveauté de la carte.

La beauté d'une carte géophysique de ce genre réside dans son objectivité, dans l'uniformité de sa qualité d'une région à l'autre, et dans la découverte de la continuité inattendue de nombreux accidents géologiques, qui, dans quelques cas, atteignent de 500 à 600 milles de longueur.

En plus de ces méthodes ordinaires utilisées pour recueillir des données régionales importantes, il faudra faire appel à de nouvelles méthodes utilisant avions et satellites à une échelle mondiale pour répondre aux besoins d'un monde au seuil d'une industrialisation considérablement accrue.

Many countries have two approaches to geological and mineral exploration. There is the direct approach in which speed and short-term economy are the essence and there is the approach characterized by systematic mapping and long-term economy, in which sound data of both immediate and lasting value can be handed down to succeeding generations as a national heritage.

This second approach is the subject of this paper; in particular, reconnaissance geophysical mapping of various sorts. At what stage in the sequence of topographical and geological mapping should it be fitted in, to be both economical and of maximum benefit?

I shall argue that, contrary to older policies, certain types of reconnaissance geophysical mapping should be done before ground geological mapping. Subsequent geological mapping can then be carried out more efficiently and will result in better, more complete maps.

Geophysical methods were previously regarded as costly, detailed surveys, to be used only after the target area for drilling had been greatly narrowed down. This concept was changed with the advent of relatively low-cost airborne reconnaissance surveys, such as reconnaissance aeromagnetic surveys. It is now known that airborne AFMAG and airborne gamma-ray spectrometer surveys with wide line-spacing can be applied in the same way. However to be economical such surveys must be done over large areas at one time. When calculated on a cost-per-square-mile basis, rather than on a project basis, the cost of airborne geophysical surveys is not large compared to geological mapping. In Canada, geological mapping at a scale of 1 inch to 1 mile is approximately 10 times more costly than aeromagnetic mapping at 1/2-mile spacing.

It is a part of a geophysicist's professional life that the package he has to sell is regarded with suspicion. To some, he is a purveyor of mysterious black boxes whom you would approach in the same way that you would go to a manipulator of bones or a faith healer after all accepted methods have failed. To others, he is the keeper of an arsenal containing an assortment of geophysical weaponry. He will tell you the right weapon to use for every situation. It is understandable then that the use of the various

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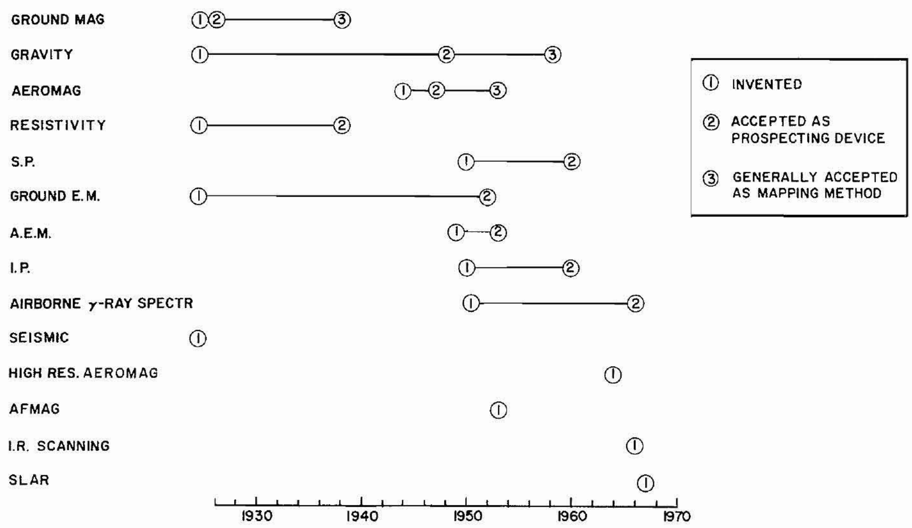


Figure 1. Evolution of geophysical methods for mineral exploration in Canada.

methods run like fashions. Certain methods become accepted, often because of specific spectacular successes. They start as 'gimmicks', proceed to ore detectors and sometimes reach the stage of reputable geophysical mapping methods suitable for use by governments.

The acceptance of geophysical methods is all-important. Figure 1 attempts to portray the evolution of geophysical methods for mineral exploration in Canada.

Comparison of regional geophysical mapping methods

The following survey methods will be discussed in the context of their suitability as pre-geological mapping methods: (1) The production of photomaps as the primary base for geophysical and geological mapping. (2) Side-look radar maps for interpretation of structure reflected in topography. (3) Conventional aeromagnetic surveys. (4) High-resolution aeromagnetic surveys. (5) Gravity surveys. (6) Airborne gamma-ray spectrometer surveys. (7) Airborne EM, AFMAG or VLF surveys. (8) Reconnaissance seismic refraction surveys. The Canadian Federal/Provincial Aeromagnetic Survey Program (Geological Survey of Canada 1951-1969) will be used as a test model against which to compare these other methods. To judge their suitability for pregeological mapping, the following criteria are applied:

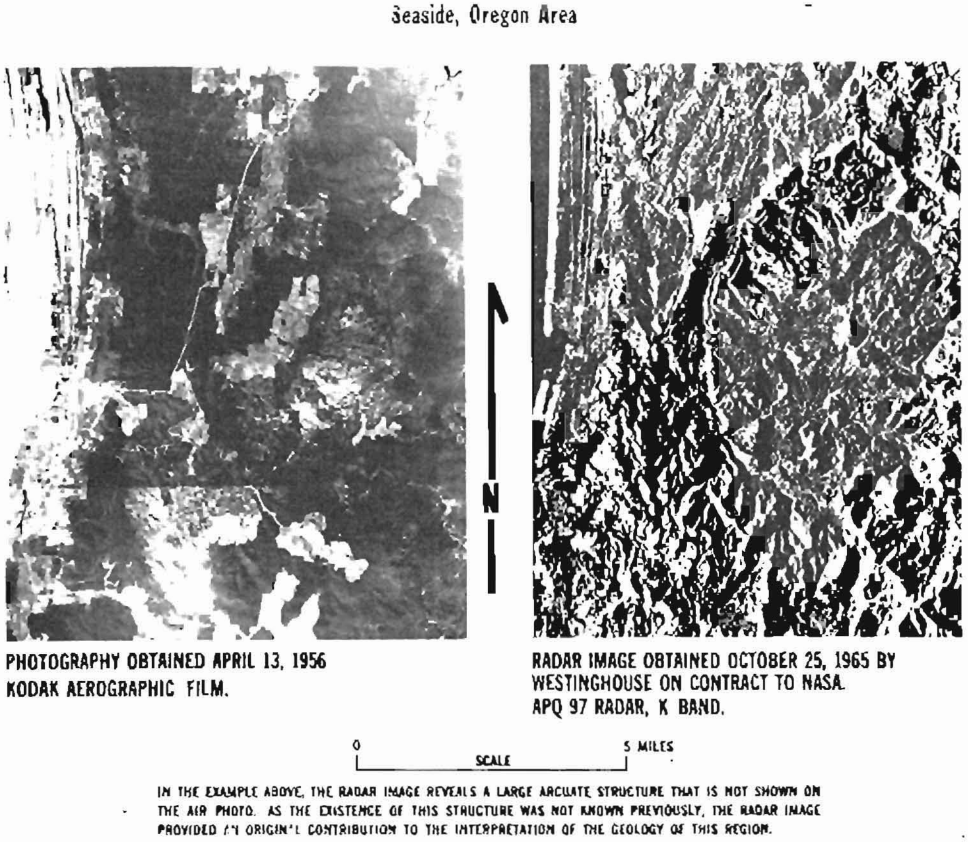
1. Is the method less costly than primary geological mapping and therefore does not violate the common-sense rule that less costly surveys should precede the more costly ones?
2. Is the method objective and quantitative, not depending upon the eye of the observer and therefore less subject to errors?
3. Does the method not depend upon a large number of professionally trained people, of whom there is a current world-wide shortage?
4. Can it penetrate surficial cover, thus affording a more continuous picture than can be achieved by examination of outcrops?
5. Does it produce a type of quasi-geological map which can be used directly by prospecting organizations, while awaiting the subsequent geological maps?
6. If the surveys are properly made and systematic map series are published, will the data have lasting value?
7. Can the data be readily interpreted into geological terms?

Photomaps. It should be axiomatic that adequate base maps be available in advance of all geological or geophysical mapping. It is mentioned here only because in many parts of the world (and it was true in Canada) geological and geophysical investigations were undertaken before adequate base maps were available. Every geologist and geophysicist has experienced the frustration of inadequate base maps. There may have been excuses for this in the past, but no longer. If adequate line maps do not already exist for an area, photomaps, which are simply controlled photomosaics, are now relatively cheap and quick to produce. Geologists and geophysicists, as well as those concerned with other resources, much prefer photomaps to the more conventional line maps because they are not only better for navigating in the field, but they aid enormously in transferring photo-interpreted data to the map. We shall not have to worry about this problem much longer, because if such maps do not already exist, satellite photos of the whole world should be available within the next few years. Such photos, when rectified and brought to the proper scale, become photomaps in themselves.

Side-look radar maps. Some may regard it as premature to consider this method because, for the earth scientist, side-look radar maps are still very new and unproven. It is only within the last few months that this technique has been militarily declassified (Crandall, 1968). It produces a photo-like image which could be described as an 'instant relief map'. There is not space here to describe the method in detail. Suffice it to say that it produces an image of the terrain which is almost equivalent to an aerial photo taken on a clear day when the sun is at a very low angle. The slightest relief features are accentuated by the shadows they cast. An immediate picture of the minor as well as of the major relief is obtained, thus facilitating the interpretation of faults and folds. Frequently the surface expression of these features is so subtle that they would not be recognized on stereo pairs of conventional airphotos.

Since the equipment is very costly, side-look radar maps would be economical only on a mass production basis. To map the entire area of Canada at 1:250,000, for instance, if done under one contract, might cost less than $4 million.

The advantage to the photogeologist of having this type of



PHOTOGRAPHY OBTAINED APRIL 13, 1956 KODAK AEROGRAPHIC FILM.

RADAR IMAGE OBTAINED OCTOBER 25, 1965 BY WESTINGHOUSE ON CONTRACT TO NASA APQ 97 RADAR, K BAND.

IN THE EXAMPLE ABOVE, THE RADAR IMAGE REVEALS A LARGE ARCUATE STRUCTURE THAT IS NOT SHOWN ON THE AIR PHOTO. AS THE EXISTENCE OF THIS STRUCTURE WAS NOT KNOWN PREVIOUSLY, THE RADAR IMAGE PROVIDED AN ORIGINAL CONTRIBUTION TO THE INTERPRETATION OF THE GEOLOGY OF THIS REGION.

Figure 2. Comparison of photomosaic and side-look radar image (courtesy National Aeronautical and Space Administration).

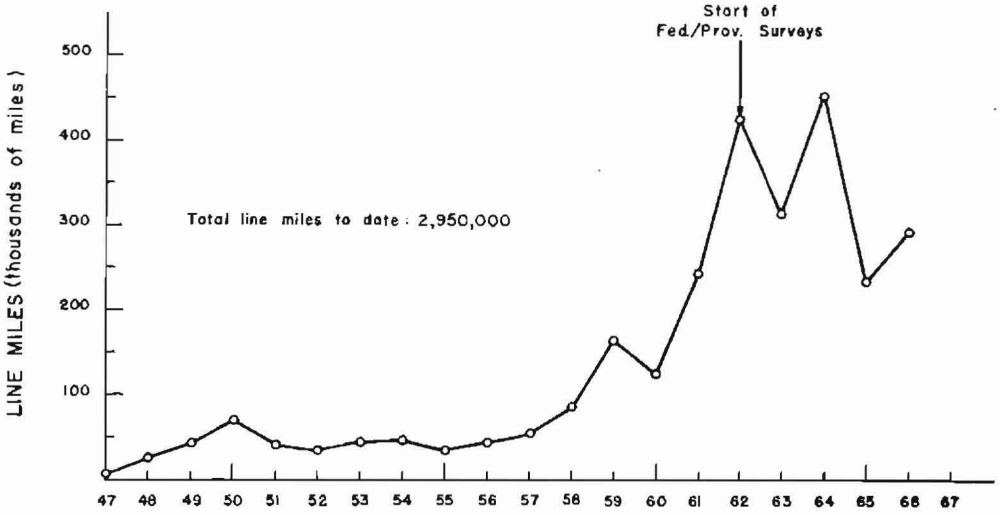


Figure 3. Line miles of government aeromagnetic surveys flown in Canada, by year.

imagery available, as well as photographs, should be evident from Figure 2.

There is a wealth of structural detail available in imagery of this type which would take many photointerpreters years to glean from stereoscopic examination of large-scale photographs over a continent-wide area. The method satisfies all the criteria mentioned except for penetrability. Some geologists have suggested that the method penetrates foliage but physicists strongly deny this on theoretical grounds.

Conventional aeromagnetic mapping. The Canadian Federal/Provincial Aeromagnetic Survey Program (Geological Survey of Canada, 1951-1969), in which more than 3 million line-miles have been flown on a systematic basis at 1/2-mile intervals and 1000 feet above the terrain, has resulted in the publication of about 5000 aeromagnetic maps at a scale of 1 mile to the inch. The combined expenditure to date by the provinces and the federal government is about $13,000,000 and the program is two-thirds complete (Figure 3).

Figure 4. Moose River magnetic belt.

In retrospect, the program cannot be described as a case of great foresight and bold planning. In fact it was more a matter of building up confidence over a long period and overcoming natural human conservatism. Ground surveys in the 1920s showed that the magnetometer was not only good for direct prospecting, but was also useful as a mapping aid in delineating structure and buried contacts. Once the technological step of making the magnetometer airborne was accomplished, the potential of the new instrument was easily recognized. Even so, it was nearly 15 years before a large effort was put into the program (Figure 3).

Now that the present aeromagnetic program in Canada is nearing completion, some remarks might be worthwhile in retrospect about its value. Several factors contributed to the success of the aeromagnetic program. In the first place, there existed in Canada, when the program started, an extremely viable exploration industry which was, and still is, thirsting for the data. In many parts of Canada these maps served as quasigeological maps where proper geological maps did not exist or where the mapping had not been done at a large enough scale. Since more than two-thirds of the Shield is covered by water and overburden, the aeromagnetic maps provided some structural control in these areas. Those maps were, and still are, used to supplement airborne electromagnetic data for detection of sulphide deposits. Many massive sulphide deposits have been found to have both a

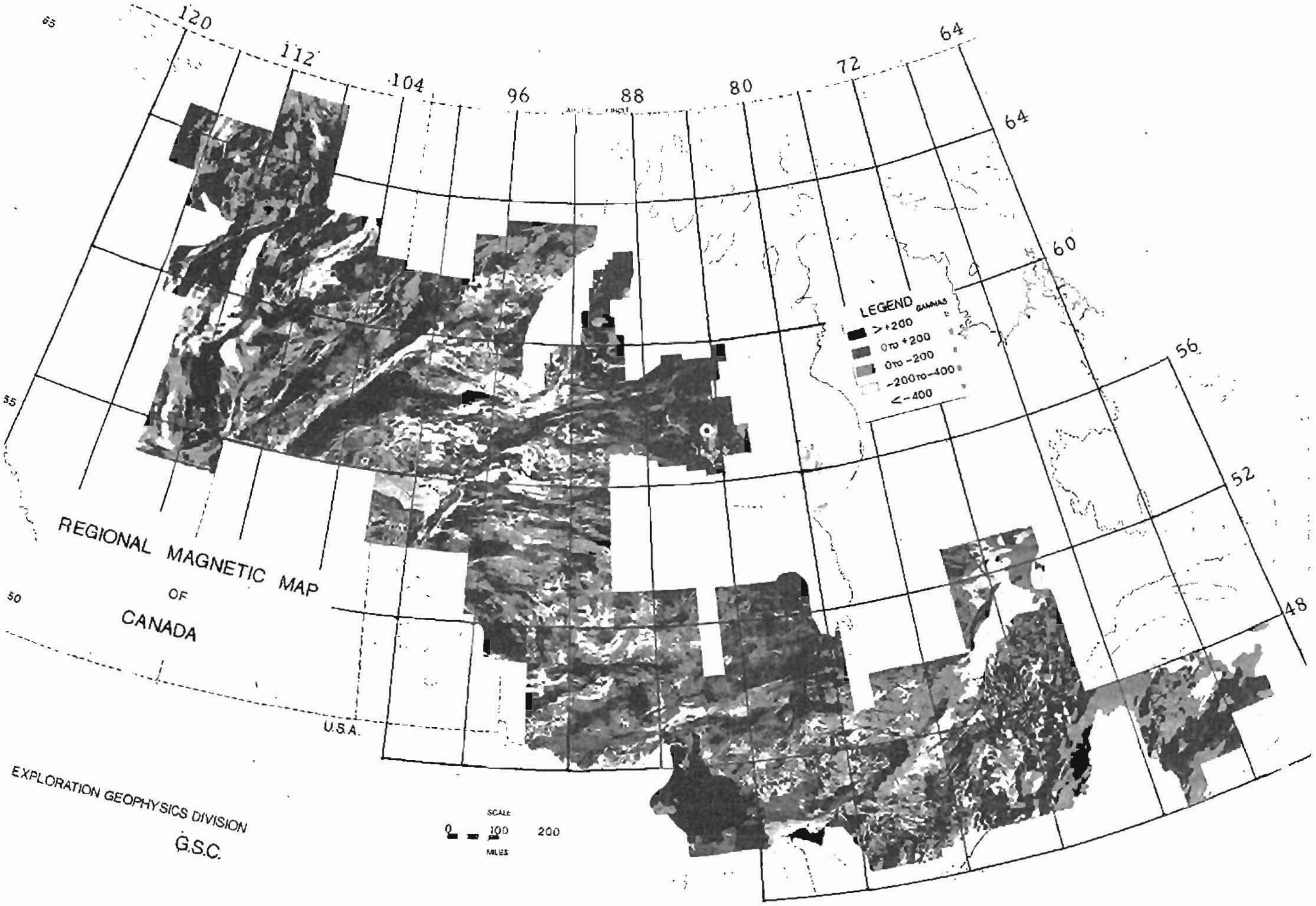


Figure 5. Regional Aeromagnetic Map of Canada.

magnetic and electromagnetic anomaly associated with them. Thus the magnetics serve as a second criterion. This is more fully discussed in the base-metal section of this volume.

Starting in 1947 when only one aircraft was used in the program, the priority in the choice of areas was hotly debated because of preconceived notions about where mineral deposits might be found. It gradually became apparent that the best system would be to blanket the Canadian Shield with systematic surveys regardless of geology. As a result, quite a few important and unexpected anomalous belts were mapped. For example the Moose River structure in the James Bay area, which is still undergoing intensive ground investigation for possible base metals, diamond pipes and columbium was discovered entirely by the magnetic maps (see Figure 4) (Skinner, *et al.*, 1967).

The program got off to a rather good start when in 1950 the Marmora magnetite deposit was detected under 200 feet of limestone in the heart of southern Ontario (Bower, 1959). This discovery alone was enough to pay for the whole subsequent aeromagnetic program several times over. Following shortly on this stroke of luck, was the major assist in the delineation of the geology in the New Brunswick base-metal camp. This resulted indirectly in the discovery of 12 base-metal deposits of which five are now in production.

No record was kept as to how much the maps contribute to discoveries. They are regarded as a fact of life in the Canadian exploration scene, are extensively used and if they do prove helpful in the discovery of mines, the fact is probably considered to be routine and therefore not worth reporting.

One of the unforeseen fringe benefits of this aeromagnetic program is the composite map (Figure 5) (Morley, *et al.*, 1968a). This example was constructed by photographically reducing all the 1-mile maps to the 4-mile scale. The maps were then 'tied in' to one another by reference to the Dominion Observatory Total Field Map for epoch 1965.0 (Figure 6). The regional magnetic variation, as determined from the Dominion Observatory map, (Dominion Observatory, 1965) was then removed and the resultant map was coloured with a 200-gamma contour separation. The result was unexpected. It had not been known previously that magnetic features 3 or 4 hundred miles long existed because areas large enough to encompass such extensive magnetic structures had not been surveyed in one block.

Perhaps the greatest surprise in the map was the extraordinarily good correlation between the regional 'low' magnetic belts and the volcanic and metasedimentary belts of the Shield, while the regional 'high' correlated well with the granite-gneiss terrains

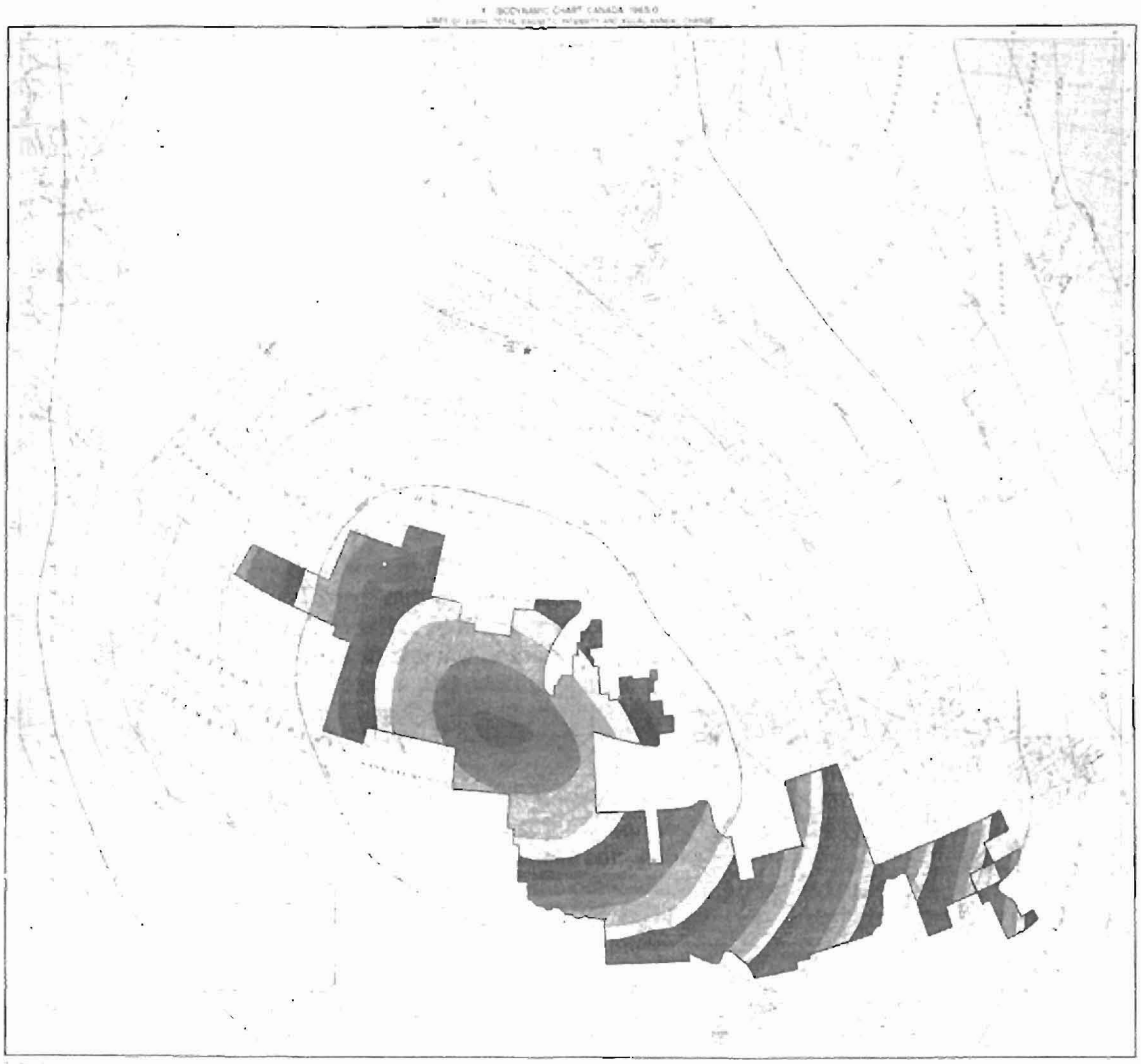


Figure 6. Absolute total field map of Canada — Dominion Observatory.

(Morley, *et al.*, 1968b). This was unexpected because, when viewed on the 4-mile scale, the volcanic and metasedimentary belts are much more active magnetically than the gneissic terrains. This new information will permit aeromagnetic interpretations to be made with much greater confidence in large areas where little geology is known. For example the nature of the basement rocks beneath the Palaeozoic cover of the Great Plains could now be interpreted with much more confidence.

Why the striking correlation between regional magnetic 'lows' and areas of volcanic and metasedimentary rocks in the Shield should exist is of great interest and importance to the understanding of crustal structure. Possibly the magnetic troughs and ridges are caused by undulations in the Conrad or basaltic layer. This suspicion is not confirmed on the gravity map of Canada which is shown in the paper by M.S. Innes in this volume. If it were true, positive gravity anomalies should coincide with the magnetic 'highs' and gravity negatives with the magnetic 'lows'. This is not the case. More likely, in the metasedimentary belts most of the iron is in the ferric state – less magnetic than the ferrous iron which would be more abundant in the granitized belts where reduction had taken place by heating.

Bhattacharyya and Morley (1965) had speculated that these magnetic troughs and ridges were due to normal and reverse magnetic remanence effects caused by the slow cooling rate of orogenic belts from their centres outwards. During this cooling which would undoubtedly have lasted for a few million years, the earth's field would have been reversing, causing magnetic banding.

One of the lessons learned from this map is that these broad magnetic belts could have been adequately delineated by survey lines flown as far apart as 15 kilometres. This information is too late as far as the Canadian Shield is concerned, since almost all of it has already been flown at 1-km spacing, but it could be applied to other large unsurveyed areas of the world.

Comparing the magnetic and geological maps of the Canadian Shield we realize how well the geologists have done in their 100 years of mapping and study! They succeeded in subdividing the Shield into its five tectonic provinces and picked the main 'breaks' dividing these provinces. These subdivisions and bound-

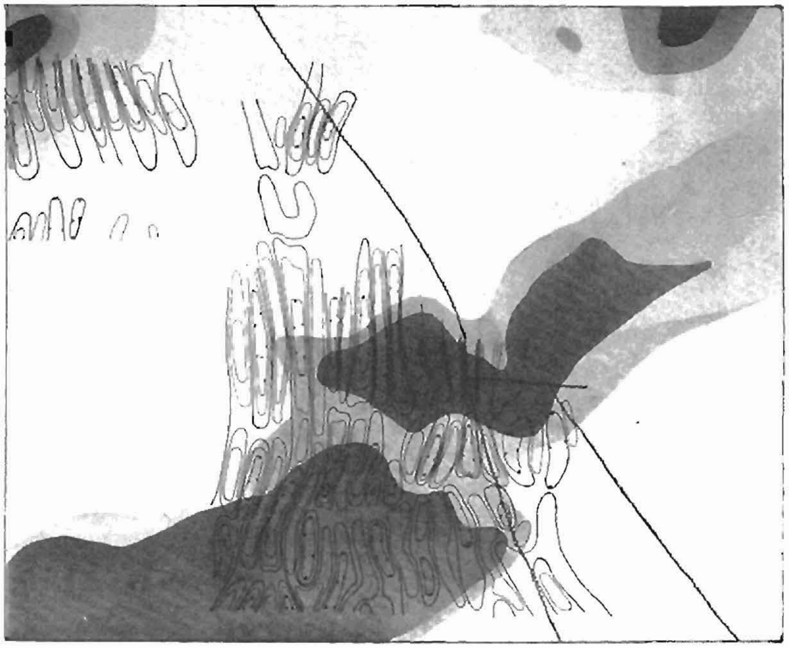


Figure 7. Comparison of conventional and high-sensitivity aeromagnetic data.

aries stand out clearly on the magnetic map (MacLaren and Charbonneau, 1968). One or two large features also might be investigated as possible further subdivisions, such as the Kapuskasing - Moose River 'high' which has both a major gravity and a magnetic feature associated with it.

As an academic exercise, the question might be asked: "If we had our present knowledge of interpretation of magnetics and a complete aeromagnetic map, but had no specific geological knowledge of Canada, what could be interpreted from the magnetics alone? " The following geological features could have been safely interpreted from the magnetics alone had they been available in advance of the geology:

1. The extent and general depth and configuration of all the sedimentary basins.
2. A complete inventory of all the magnetic iron formations.
3. A subdivision of the basement into probable geological provinces.
4. A reasonable approximation of the greenstone or volcanic metasedimentary belts and the gneissic belts.
5. Complete delineation of all the large basic dikes (Fahrig, *et al.*, 1965).
6. A delineation of the plateau basalt areas together with their 'windows'.
7. A delineation of many of the fault and fold structures.
8. The recognition of circular intrusive bodies of granites, anorthosites, gabbros and carbonatites.

A reconnaissance aeromagnetic survey of this type is one of the least expensive means of delineating the geological framework of a country. The author firmly believes that such a program should be placed high on the natural resources survey program of any developing country.

High-resolution magnetometer surveys. This is still an unproven and unaccepted method of either mineral prospecting or mapping in Canada but it shows enormous potential. Any program involving this method would have to be more selective than for the conventional airborne magnetometer, because it is more detailed and costly. It involves mapping the detailed structure of the earth's magnetic field caused by the near-surface features. Figure 7 illustrates both the old type of 1-gamma fluxgate data shown in the grey-tone and the high-resolution detailed structure illustrated by the superimposed contours. The longer wavelength anomalies caused by the deeper sources are filtered out from the original data that are recorded digitally. In the Canadian Shield much structure which is not seen on the existing aeromagnetic maps would be delineated. In the areas of sedimentary rocks, many faults and tight folds within the sediments, which escape detection with present 1-gamma sensitivity magnetometers, would be detected. Much better geological maps could be prepared, particularly of areas with few outcrops.

This method meets most of the criteria required to qualify as a pre-geological mapping method except for its high cost. This would place it in a position of lower priority, after 1:250,000 reconnaissance geological mapping but before 1:50,000 detailed geological mapping.

Gravity mapping. The Dominion Observatory Bouguer Gravity Map of Canada, based on stations spaced about 8 miles apart, is shown as Figure 5 in the article by Dr. M.J.S. Innes in this volume. Dr. Innes, the principal author of this map, discusses it in detail there. I only wish to raise the question here of whether such a survey should precede geological mapping. It qualifies in cost, since the estimated total cost to date of this survey is about 3 million dollars, not including salaries and overhead.

It seems also to qualify in all other respects except, perhaps, in usefulness to prospecting organizations awaiting subsequent geological maps. The data obtained on these surveys are not closely enough spaced for this purpose.

The gravity method has much greater penetration than the magnetic method and at this scale is probably more affected by the depth and configuration of the top of the Moho discontinuity than by the nature and configuration of the nearer-surface rocks.

For example, the regional gravity 'highs' near the continental margins are no doubt a reflection of the shallow Moho in these areas, while under the Rocky Mountains and in the Grenville portion of the Shield these 'lows' are no doubt caused by crustal thickening. Several authors Wilson and Brisbin, (1961) have postulated that the gravity 'high' striking northeasterly along the Nelson River in Manitoba is caused by a ridge in the Moho. Although previous knowledge of these facts would not have been too helpful to either geologist or prospector. However subsequent knowledge may prove vital in the long term.

The regional aeromagnetic map should provide a link between the mapped surface geology and the gravity map of Canada, since it has more penetration than surface mapping but less than gravity mapping. We conclude therefore that reconnaissance gravity need not be done before primary geological reconnaissance. However, since it is a long and painful process, it should be organized early, on a long-term basis. Its value will be realized after the primary geological reconnaissance has been completed and the three-dimensional structure is being pieced together.

The airborne gamma-ray spectrometer as a mapping device. Where does gamma-ray spectrometry fit in to geophysical mapping? Because it has virtually no power of penetrating overburden, it can not add to the detailed geological knowledge of the bedrock, except in areas which are nearly totally exposed. On the other hand, if rocks can be assayed for their potassium, uranium and thorium content from the air, it should be excellent for reconnaissance mapping (say at 1:250,000 with lines spaced 4 miles apart). It should also be possible to quantitatively delineate broad areas of higher-than-normal uranium content such as the Bancroft area of Ontario and the Beaverlodge area of Saskatchewan. It is fortunate that there are three elements which are naturally radioactive, enabling us to map them from the air. The airborne gamma-ray spectrometer can perhaps be considered the first airborne geochemical mapping device (Darnley and Fleet, 1968).

Let us now examine how well airborne gamma-ray spectrometry meets the above criteria as a method of mapping before geological mapping. If all three elements (potassium, uranium and thorium) are to be mapped on a detailed scale with lines placed, for example, 1/4 mile apart, a large crystal volume of NaI is required in a fixed-wing aircraft. A smaller crystal volume can be used at the slower helicopter speeds. In either case, the cost per line-mile, including all the necessary compilation and corrections which would have to be made, would perhaps be three times that of standard aeromagnetic surveying. Furthermore, barring the prospecting use which we are not considering in this paper, the information gained would be rather specialized and not at present susceptible to interpretation in terms of a geological map. The method is not capable of penetrating surficial cover so that no information on the nature of the bedrock is obtained over drift-covered areas.

On the other hand, if the method is used for broad reconnaissance with lines spaced from 3 to 5 miles apart, and if average potassium, uranium and thorium values can be reliably obtained on a 3-to-5-mile grid over large areas, the picture changes. The cost per square mile is considerably less and a knowledge of the distribution of these three elements over wide areas would have considerable geological importance. Uraniferous provinces could be delineated. Belts of dominantly acid rocks could be differentiated from those of the basic rocks. Such differences would have more geological meaning when mapped, for example, at the 4-mile scale than at the 1-mile scale.

Airborne electromagnetic and AFMAG. What place has airborne electromagnetic surveying as a regional geophysical mapping device? This question has been raised intermittently in Canada since the method was first developed in 1949. Some have argued that it is only useful for the detection of individual anomalies which may be worth investigating for base metals and that the resultant data have little correlation with mapped geology. There is no doubt about its ability as a locator of conductors. According to Lang (1967) of the 19 producing metal mines discovered in Canada since 1955, 15 were found by airborne electromagnetic surveys.

Most knowledge of various airborne electromagnetic systems in Canada and their results are private information. However the geophysical contracting companies have made available much of the information about the instruments and some about their results. Apparently the airborne electromagnetic method suffers from much the same problem as do many other geophysical methods, namely the difficulty of differentiating significant from non-significant anomalies. By analogy with aeromagnetic results, one might then ask, 'Cannot this profusion of unwanted anomalies be used as an aid to geological mapping? ' Many who have had experience with electromagnetic interpretation maintain that it can be used for mapping, but there are few papers on the subject and few data are available for study.

If regional airborne electromagnetic surveys were to be done in Canada, even on a much more limited basis than the aeromagnetic surveys, a number of technical problems should first be solved. In the first place, present methods of mapping the data are much too subjective for creating maps of long-standing value. Anomalies are selected from the raw data and their locations are transferred to the map. These anomalies are then frequently graded *A, B* or *C* according to their suitability for further investigation based on unspecified criteria. Except in a few cases, it is difficult to obtain trend directions of electromagnetic anomalies. Either the anomalies are too short in wave length in relation to the line-spacing or they are not persistent enough in strike length to establish a trend. Without a trend, they are of little use in geological mapping.

It is obvious that the deeper-penetrating methods are much more apt to show continuity of anomalies from line to line, thereby establishing trend. Methods now under development may be able to measure enough parameters to establish trend from a single traverse over an anomaly.

Surveys by AFMAG have shown major anomalies with continuity between lines up to 5 miles apart, probably caused by deep structures such as major breaks or shear zones. This would qualify the method in every respect as one suitable for use prior to geological mapping except for the question of whether the anomalies can be interpreted in terms of geology. It is the writer's opinion that a great deal of work must still be done to be able to interpret these major AFMAG anomalies.

The AFMAG apparatus can be handled in a light aircraft and, provided the surveys are carried out during the prime AFMAG months, costs should be at least an order of magnitude less than reconnaissance geological mapping. The relatively deep-penetrating capabilities of the method should allow it to provide continuity of information regardless of overburden cover. If, in

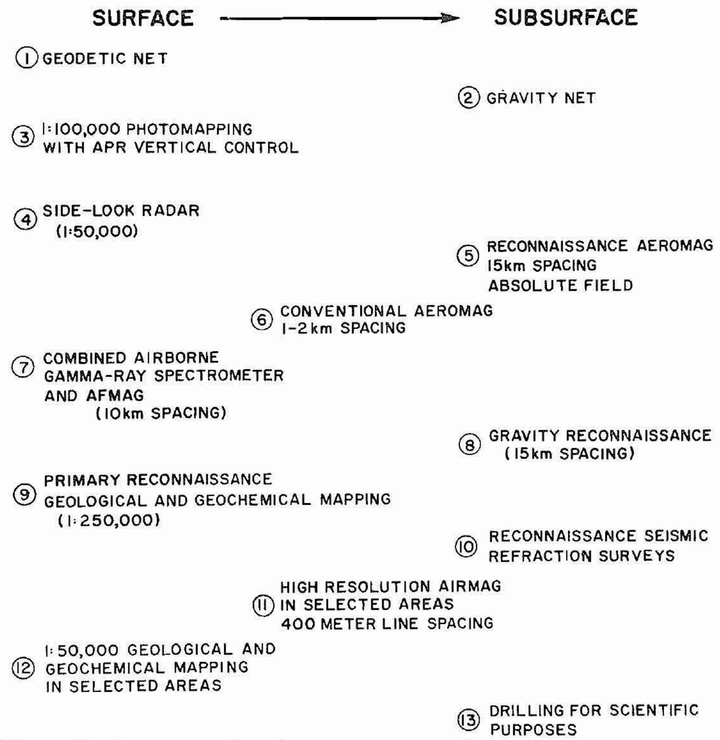


Figure 8. A suggested optimum sequence of surveys.

fact, it is able to map major breaks and faults, it will provide invaluable structural information which the magnetometer cannot provide. If many or most of the metalliferous deposits are genetically related to faulting, which is a view widely held by geologists, the importance of this method as a reconnaissance geophysical mapping tool cannot be overemphasized.

Seismic surveys. Only two types of seismic surveys have been carried out extensively in igneous and metamorphic areas – refraction surveys for depth of overburden, and deep refraction surveys for Conrad and Moho depth determinations. It is difficult to argue that either of these would contribute much useful knowledge to the geologist to help him in his surface mapping, although the value of crustal thickness maps for regional tectonic studies may be very important.

If methods were developed for mapping horizontal velocities under thin layers of overburden such information would be of enormous assistance as an aid to geological mapping. Because of high costs, such a method would not qualify as a pregeological one. For subsurface mapping in near-horizontal layered rocks, however, the method is unparalleled (Hobson, 1969).

Conclusions

In the Canadian Shield, the primary reconnaissance geological mapping at 1:250,000 is nearing completion. If little or none of it were done and we were starting from the beginning, but with present knowledge and equipment, in what order would the various types of surveys best be done?

In the first place, adequate planimetric base maps at 1:100,000 or better are a necessity. These were provided in Canada in the form of line maps in time for most subsequent survey work. In retrospect, it would have been cheaper, quicker and better if planimetric photomaps had been provided for this purpose.

We have known for at least 14 years that it would have been desirable to have had 1:50,000 aeromagnetic mapping with half-mile spacing completed in advance of the geological mapping. It has been possible to arrange this in a few areas and the results have shown the desirability of the principle.

Pre-field-interpretation of aerial photographs during the reconnaissance geological mapping of Canada proved to be an essential, but very time-consuming process. We submit that side-look radar could be regarded as semi-automated photogeologic interpretation which would enable a geologist to interpret more structure in a very much shorter time because a stereoscope is not required and the significant features are brought out in much smaller scale imagery than standard air photos. At a maximum price of about $2 per square mile, it could be economic.

The job of describing and explaining the composition, structure and history of the crust is one which requires many different methods of geological, geophysical and geochemical mapping. So complex is the geological edifice, that the work must be regarded as a continuing thing; knowledge of it will never be complete but must be considered, like much other knowledge in this world, as cumulative. The economic justification and incentive for this work is to provide the background information to reduce the enormously unfavourable prospecting odds. The amount of money spent on these projects must be determined in the light of other economic priorities. To avoid wasted effort, it is important for the appropriate governmental agencies to plan the work so that it can be economically and systematically done and the results be cheaply and readily available to government, university and industry users, preferably as several systematic series of maps.

The order in which the various types of surveys is carried out is crucial to the overall efficiency of the procedure since the accuracy and completeness of one type of survey often depends on the preceding ones. There are some common-sense guidelines which should be followed, based mainly on the principle that the least expensive surveys be done first: thus reconnaissance surveys before more detailed, surface before subsurface, and objective before interpretive investigations, combining those which are logistically and instrumentally compatible. Figure 8 is a suggested scheme for the optimum sequence of systematic surveys.

These surveys are not designed to find mineral deposits directly. Prospecting should be done, not instead of, but parallel to these programs. In Canada direct prospecting is done by private companies. In countries where a mineral exploration industry does not exist, prospecting would have to be done either by the government, or by foreign exploration companies, or by a combination of both.

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The role of geophysics in the development of mineral resources

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Abstract. Many examples may be given where geophysics has been the decisive factor in the development of mineral resources. Nevertheless, throughout the world today, mineral production is still predominantly from traditional mining areas and only a modest proportion can be directly attributed to geophysics. At the present time there is an urgent need for keener tools. Existing methods are being used on a fairly substantial scale, their usage is steadily increasing and some notable discoveries are being made.

In the future the demand for metals will increase. Vast stretches of potentially mineralised country still lie hidden beneath comparatively thin cover, many lenticular orebodies are believed to occur at accessible depths and additional mineral resources no doubt lie on and beneath the continental shelves. It is concluded that in the years ahead mining geophysics will play a vital role in the development of mineral resources. However, the extent to which it can do so will depend upon the emergence of more powerful methods.

Résumé. Plusieurs exemples peuvent être cités où la géophysique a été le facteur décisif dans la mise en valeur des ressources minérales. Néanmoins, dans le monde entier, de nos jours, la production minérale provient encore des régions minières habituelles et une faible proportion seulement en est attribuable à la géophysique. Il y a un besoin urgent d'outils mieux adaptés. Les méthodes actuelles sont employées à une assez grande échelle dans le monde de nos jours; leur usage augmente constamment et quelques découvertes remarquables sont faites.

A l'avenir, la demande de métaux va augmenter. Des vastes étendues probablement minéralisées demeurent encore cachées sous des morts-terrains relativement minces, plusieurs massifs lenticulaires de minérais peuvent se trouver à des profondeurs accessibles et des ressources minérales supplémentaires reposent sans doute sur ou sous les plateaux continentaux. Il faut en conclure que dans les années à venir la géophysique minière jouera un rôle essentiel dans la mise en valeur des ressources minérales. Cependant, l'importance de ce rôle dépendra de l'apparition de méthodes plus efficaces.

In this paper it is proposed to take a brief philosophical look at the role of geophysics, past, present and future in the development of the world's mineral resources. Such a quasi-chronological approach has some advantages but for purposes of discussion it is convenient to place the transition from the past to the present some four or five years ago. Moreover words such as 'role', 'development' and 'resources' normally require definition but it is hoped to clarify them in the following. Discussion will be confined almost entirely to mining geophysics and to metalliferous resources with only a few comments on underground water resources.

The role in the past

In reviewing the role of geophysics in the past it is natural to reflect on what sort of problems were set, the method, how these problems were approached, how the method was used, whether largely by itself or in combination with other methods such as geology, geochemistry, drilling, underground exploration and the work of prospectors. It would also be of interest to consider to what extent geophysics has been used since its introduction, especially in comparison with other exploration methods. Finally it would be desirable to assess, if possible, what contribution to the ore reserves of today can be attributed primarily to geophysics.

Clearly enough the pursuit of these points runs into considerable difficulties. Case histories show that more often than not geology and geophysics have been interwoven and have been quickly followed, or even accompanied, by drilling so that it is difficult to determine which method played the decisive role. There are cases where geophysics has been the dominant factor in an exploration campaign, many cases where it has made an important but not dominant contribution, other cases where it has indicated a generally favourable region for other methods to detail, and some cases where it has failed, at least in the initial stages of a campaign, while other methods such as geochemistry have given useful results.

In the period between the two world wars, which might perhaps be termed the first effective phase in the practical use of geophysical methods, the approach to problems was generally direct and unsophisticated. Usually the object was to search for extensions of known orebodies or explore a favourable environment on an established mineral field using as a background whatever geological information was available. The approach was characterised by intensive surveys over small areas (Edge and Laby, 1931) and use was made of a considerable variety of methods, not only magnetic and electrical but also gravity and seismic, the latter particularly in the search for deep leads, i.e., buried placer deposits. Some early notable successes were achieved, especially where well defined orebodies lay beneath shallow overburden, but the easier targets became exhausted and in the latter stages of the period there was a tendency to apply the methods in areas where an unsophisticated approach had little chance of success. It is true that during this period there were examples of the indirect approach using geophysical methods to trace marker beds, thus unravelling geological structure in an endeavour to define the ore environment, for example in the Witwatersrand area of South Africa (Weiss, 1934) and at Broken Hill in Australia (Rayner, 1950).

The second phase in the use of practical geophysics is taken to extend from the Second World War until some four or five years ago. This period was characterised by the introduction of airborne methods–originally to give greater speed of coverage and accessibility, by a greater appreciation of the regional approach in exploration and by technical improvements in methods. In Australia the airborne geophysical methods were first used in the direct search for iron ore and uranium deposits. Although there was some success in this field, it became evident that a particularly valuable contribution in the hard rock areas was the outlining of regional structural patterns. It might be noted that in some areas the full significance and exploration value of such patterns were not realised till long afterwards when a close study was made of the areas for some specific purpose.

This period produced the induced polarisation method as perhaps its other principal contribution to the geophysical approach, but also notable improvements in instrumentation and the development of bore-hole techniques. Nevertheless at the close of the period, after nearly half a century of geophysical exploration, it was difficult to be complacent about the state of the art or to feel that earlier promises had been fulfilled. However, it is believed that some four or five years ago a third phase opened in the practical use of geophysics and that this is putting the method on a sounder, more substantial and successful basis than it had previously known.

The extent to which geophysics has been used in exploration is indicated by figures published annually by the Committee on Geophysical Activity of the Society of Exploration Geophysicists (Smith, 1966). The Committee is careful to state the limitations of its coverage but its figures show clearly the trends in total usage, in the relative usage of the various methods, and in research activities. For mining geophysics the figures demonstrate a general increase in utilization over the years and a notable increase over the last few years. However, as a matter of perspective it is difficult to avoid the belief that utilization over past years has been less than the opportunities and rewards warranted.

It is virtually impossible to give anything like an accurate figure for the proportion of today's total ore reserves, as distinguished from new additions to ore reserves within the last few years, which can be primarily attributed to the use of geophysical methods. The figure can only be a very modest one as is true for any other scientific exploration method. A high proportion of today's total ore reserves still lie in the long known traditional mining centers. Nevertheless over past years geophysics has played an important role in many exploration programs and has been primarily responsible for the discovery of many important orebodies.

Turning aside from mining geophysics, what can be said of the role of geophysics over past years in the development of groundwater resources? If the utilization of mining geophysics appears to have been somewhat sporadic and limited in comparison with petroleum geophysics, in the ratio of perhaps 1:30, then the utilization of groundwater geophysics appears to have been on a small scale in comparison with mining geophysics, in the ratio of say 1:10. This was due perhaps, not only to certain inherent difficulties in groundwater geophysics, but also to a widely held opinion that the search for groundwater resources offered less opportunity and, with some notable exceptions, demanded less urgency. Even in Australia, which is the driest of the continents, only a comparatively small effort has been devoted specifically to groundwater geophysics due to the belief that saline water was more likely to be found than fresh water, or that the occurrence of water in hard rocks was too irregular, or that the more desirable supplies of water at shallow depths were more cheaply investigated by shallow drilling. Nevertheless, many successes have been achieved, valuable researches have been carried out and, most important, geophysical work in the major basins has greatly increased knowledge of deep water supplies.

The role at the present time

In reviewing the role of mining geophysics at the present time it is necessary to examine the degree of utilization, the way in which the methods are being deployed in exploration campaigns and the degree of success achieved, measured if possible by the proportion of newly discovered ore which can be attributed primarily to the geophysical methods.

At present the utilization of geophysical methods is at a record level and is still increasing. Although this substantially exceeds 10,000 man-months in performance and 20 million U.S. dollars in expenditure annually, it might still be regarded as being small when viewed in relation to the value of mineral production.

It is not appropriate here to discuss details of methods but to refer only to such matters as have a bearing on their ability to play an effective role. It is of interest to note that expenditure on research has been increasing, instrumentation is being continually improved, new techniques are emerging, and data processing methods are becoming more sophisticated. These amount to steady progress but scarcely provide breakthroughs to such long sought and elusive targets as deep penetration, direct detection and high resolution. At different times various methods have dominated usage or become fashionable but it is clear that there is still no particular method that can be regarded as a primary tool.

Some aspects of the changing role of geophysics in exploration campaigns can best be seen by reference to actual cases. For example, it is true that in some problems the application of one geophysical method only is all that is required. At Savage River, Tasmania, airborne and ground magnetic surveys were used in a direct and detailed way and in combination with drilling to play an important part in the development of major iron orebodies (Thyer, 1963). In this area of extremely rugged terrain and dense rain forests scattered occurrences of magnetite had been known for some time. However they had attracted limited attention, work on the ground was difficult, and comparatively little importance was attached to the area.

An aeromagnetic survey, using a DC-3 aircraft flying at 500 to 1000 feet above ground level, outlined two major magnetic anomalies as shown in Figure 1. The northern anomaly which was in the vicinity of the scattered outcrops, attained an amplitude of some 15,000 gammas and extended over a strike length greater than 4 miles. The second anomaly, some 5 miles further south, was smaller and less intense and occurred in an area where iron ore had not previously been known.

The results of the aeromagnetic survey indicated where detailed ground magnetic traverses could be made to best advantage. It might be noted that whereas the aeromagnetic surveys had been made within a few hours the ground surveys required some 18 months to complete. The ground surveys mapped some extremely intense anomalies, exceeding 100,000 gammas in vertical intensity, and indicated that the magnetite occurs in a complex series of lenses in a zone several hundred feet in width. A subsequent drilling and testing campaign has indicated several hundred million tons of iron ore which are at present being developed for exploitation.

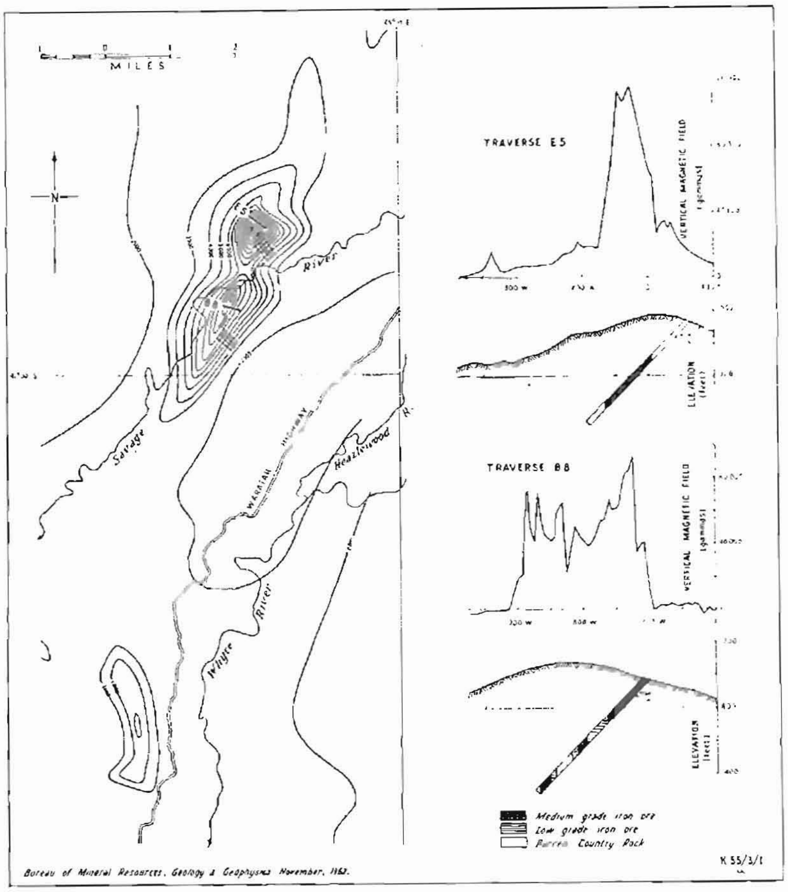

Figure 1. Aeromagnetic contours and ground magnetic profiles, Savage River, Tasmania.

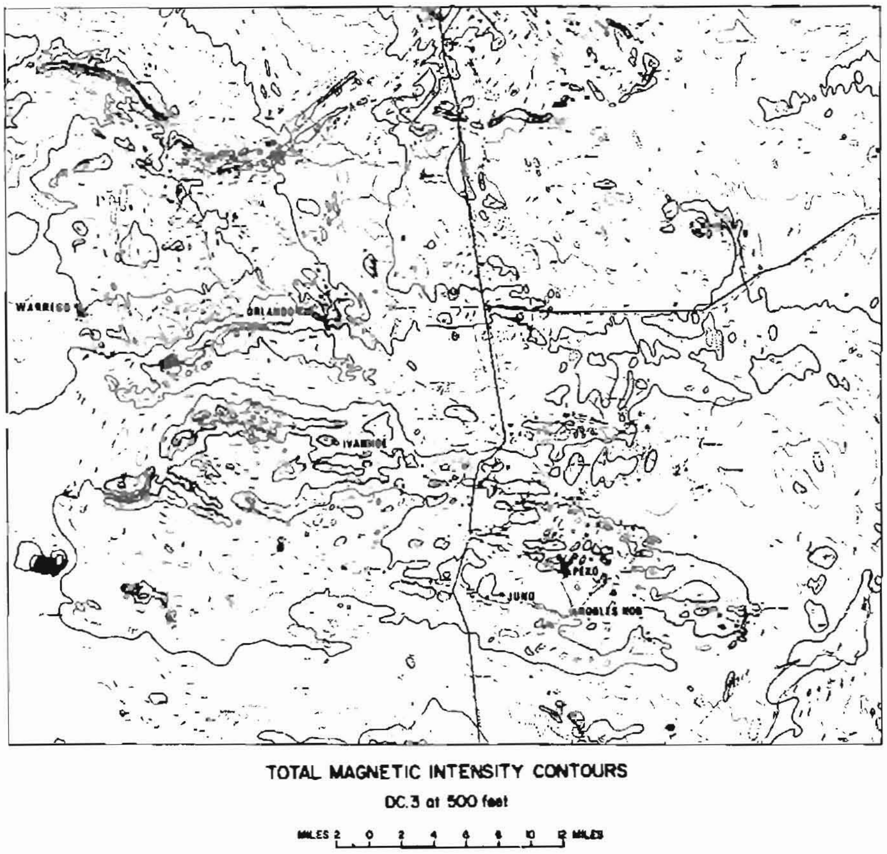

Figure 2. Aeromagnetic anomalies at Tennant Creek, Northern Territory.

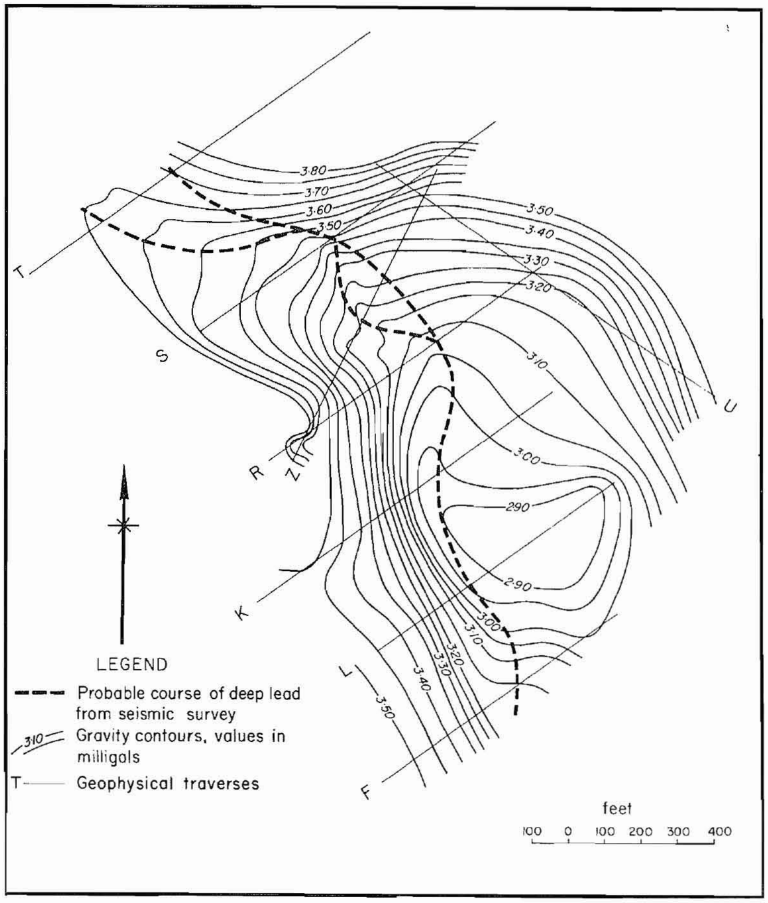

Figure 3. Gravity contours of unweathered bedrock, Upper Yithan deep lead, Ardlethan, N.S.W.

The stages in the approach to a prospecting problem can be illustrated in another Australian setting at Tennant Creek, Northern Territory (Rayner and Nye, 1936; Daly, 1957; Thyer, 1963). On this field copper and gold are intimately associated with lenticular bodies of massive hematite derived from primary magnetite. The geophysical approach is direct as far as the search for iron orebodies is concerned but indirect as copper and gold, the objects of the search, are concerned, these being found only by their association with the iron orebodies. The principal exploration tools have been ground and airborne magnetic surveys in association with geological work and drilling campaigns. From the historical point of view, following the discovery by prospectors of some outcropping, gold-bearing iron orebodies, the geophysical program opened with intensive ground magnetic surveys in the vicinity of known orebodies and continued with ground surveys on a semiregional scale. These outlined many clearcut magnetic anomalies and subsequent drilling proved iron orebodies, some carrying gold values, and showed the presence of copper at depth for the first time on the field.

In the next phase of prospecting at Tennant Creek an aeromagnetic survey was made over a wide area, traverses being flown at one fifth of a mile apart and at an elevation of 500 feet (Figure 2). This yielded a pattern of magnetic anomalies which threw much light on structural trends and the presence of ironstone bodies. In the next phase much more detailed magnetic surveys were made using a Cessna aircraft flying at 250-foot elevation with the bird at 200-foot elevation. This in turn led full circle in prospecting this field back to very detailed ground magnetic surveys over small areas. As the result of this program it is clear that the magnetic method has played a leading role in the discovery and development of several copper-gold orebodies which are now being exploited.

A very different approach to a prospecting problem has been made in the vicinity of Mt. Lyell, Tasmania, where a vast array of different geophysical methods have been used in direct detection campaigns. The copper orebodies of this area, both disseminated and high grade, have long attracted geophysical work and their geophysical history opened as long ago as 1934 with the application of equipotential line surveys. More recently a portion of the field, known as the Corridor area, was the subject of surveys (Boniwell and McKenzie, 1961) using electromagnetic (Turam), selfpotential, geochemical and both ground and airborne magnetic methods. Of these the Turam method yielded anomalies which, on being tested by drilling, led to the discovery of the Corridor orebody consisting of about 10 percent sulphides. Subsequently gravity, AFMAG, induced polarisation and vertical loop electromagnetic methods were used over the same area, positive results being obtained with the last two methods named.

In contemplating the role of geophysics in an indirect approach but still on a detailed scale and using completely different methods for confirmation, reference is made to the search for deep leads near the Ardlethan tin field in central New South Wales. A deep lead is the term used, at least in Australia, for an ancient stream bed containing alluvial gold or tin in its

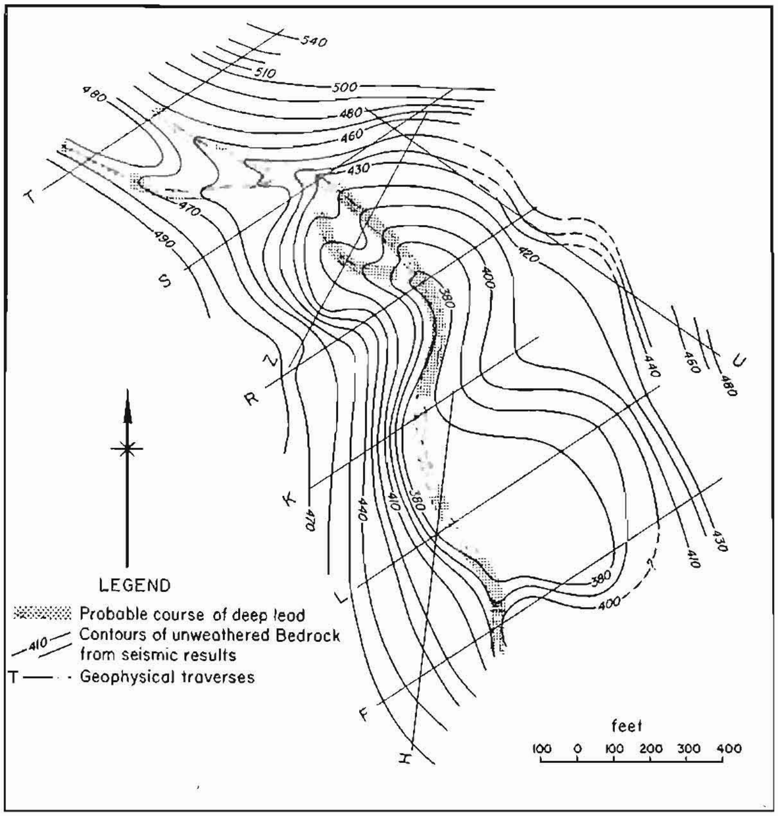

Figure 4. Seismic contours of unweathered bedrock, Upper Yithan deep lead, Ardlethan, N.S.W.

gutter but now lying well hidden at a considerable depth beneath alluvial or basalt cover. The object of a geophysical campaign is to determine the course, depth, and section, especially the gutter; magnetic, electrical, gravity and seismic methods have all been used for this purpose.

In the vicinity of a deep lead near Ardlethan the country is flat, the channel is covered by lateritic and sandy clays and the tin bearing wash, where present, is lying on a weathered bedrock. In this area gravity and seismic methods were both used successfully over the same ground to complement each other (Urquhart, 1956; Daly, 1965). The gravity method (Figure 3) was much the faster and less expensive and thus suitable for reconnaissance work; although lacking in resolution it had the particular advantage of being less affected by variations in the weathered layer of bedrock.

The seismic method (Figure 4) although more expensive was of value in confirming the gravity results and bringing more resolving power to bear in some areas. In general the gravity and seismic methods agreed well and two test shafts, without preliminary drilling, intersected the deep lead in predicted positions. The third test shaft was sunk in an area where results were less definite and it was necessary to make a cross cut of about 100 feet to reach the deep lead.

In planning an exploration program there is an increasing role for geophysics in a broad regional and indirect approach. For example, extensive aeromagnetic surveys have been made over the Australian shield which, in the Southern Cross area of Western Australia (Chamberlain and Quilty, 1965), consists generally of Archaean granites and gneisses, metavolcanics (greenstones) and meta-sediments (whitestones). The original sediments and volcanics have been strongly folded along NNW–SSE axes and another set of folds was developed along easterly trending axes. Within the greenstones and whitestones there are banded iron formations, probably chemically altered and metamorphosed sediments, which are strongly magnetic as a rule and can be used as marker beds in mapping geological structures. Mineral deposits may be associated with the banded iron formations themselves or with the structures which they outline.

An aeromagnetic map of part of the Southern Cross area (Figure 5) shows intense anomalies which permit the trend, width and dip of the banded ironstone formations to be determined under cover. Easterly trending negative anomalies are ascribed to basic intrusive rocks, which are magnetised in the reverse direction and are useful in mapping the cross folded axes. Areas of granite or gneiss give rise to isolated low intensity anomalies and the whitestones are virtually nonmagnetic.

Geophysics has played an important role in the recent discovery and development of substantial nickel deposits near Kambalda and other places in the vicinity of Kalgoorlie, Western Australia. The exploration campaign illustrates a notable integration of the work of prospectors, geology, regional and detailed geophysics, geochemistry and drilling. Because of its proximity to important gold mines this area has attracted the attention of prospectors over a period of many years. However, their attention was focused on gold and although the presence of nickel was in fact noted during this period, it was only very recently that such prospects were judged worthy of close examination by modern methods.

The area presents difficulties to exploration geology but geological work revealed the key to the structure and the nature

Contents

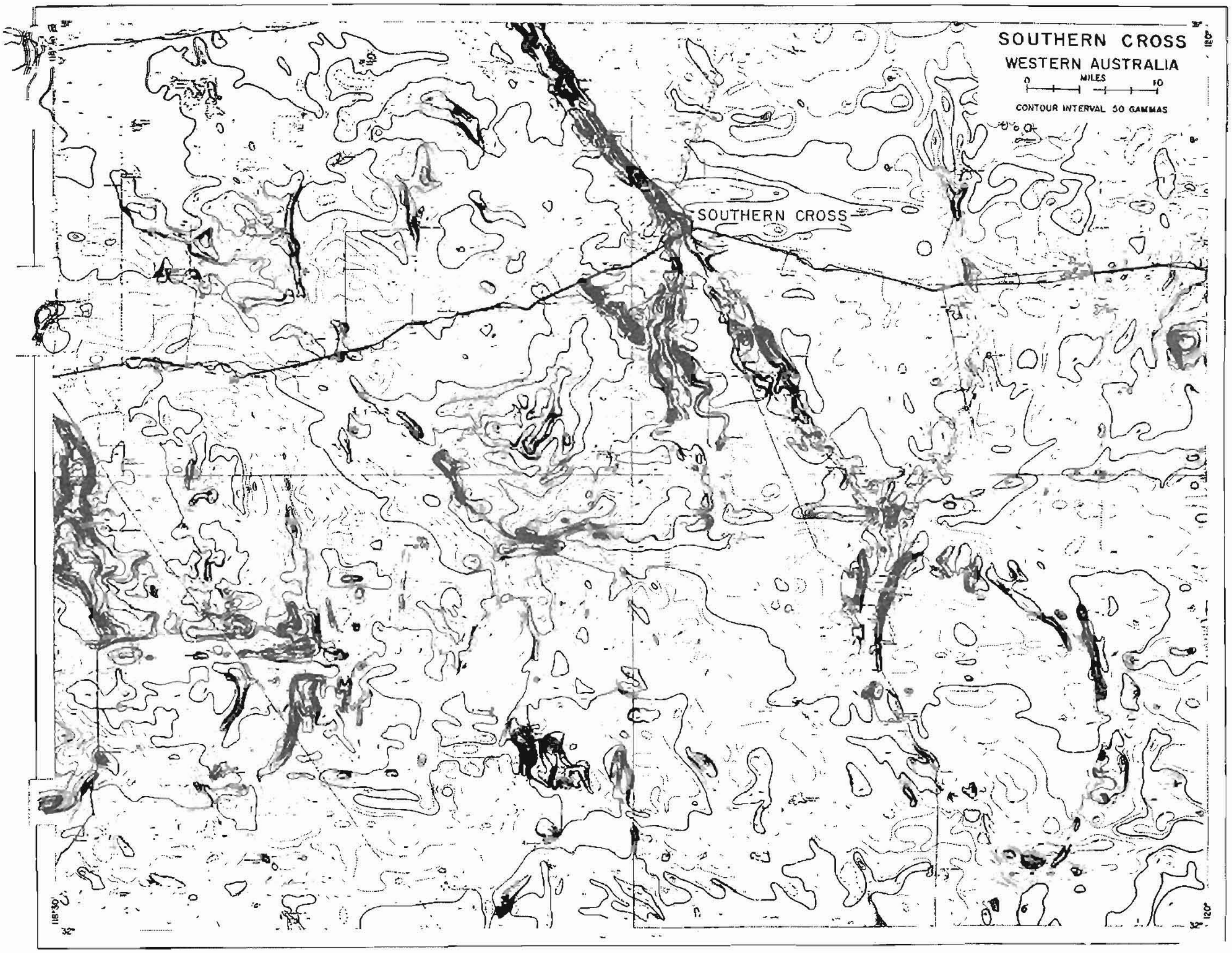

Figure 5. Aeromagnetic map of Southern Cross area. Western Australia.

of the nickel occurrences. Lavas are overlain by peridotites, the ore occurrences consisting of nickel sulphides with some platinum lying at the base of the peridotites. It was apparent that there was opportunity for finding orebodies beneath cover and this consideration paved the way for a vigorous interplay between magnetic prospecting, the use of induced polarisation, geochemistry and drilling. The results of aeromagnetic surveys, carried out prior to the main discoveries, have been used intensively in studying the environment on a regional scale. At the present time several orebodies are being developed, production of nickel ore has commenced, and further discoveries and regional studies give some promise of the existence of a major nickel province.

These Australian examples may indicate some aspects of the role of geophysics in the field but it is necessary to go further than this and consider whether on a world-wide basis the increasing use of mining geophysics is being accompanied by adequate successes in adding to mineral resources. Some notable discoveries are at present being made due to geophysics but, based on a sampling process rather than an inventory, it would appear that mining geophysics is playing a leading role in the discovery of something of the order of 10 percent of the new ore reserves being brought to light at the present time. There is of course a second category of new ore reserves in which geophysics is playing an important but not a leading role.

To keep this matter in perspective it is recognised that there is a third category in which the new ore reserves owe little or nothing to geophysics but have resulted from geology, geochemistry or drilling operations. This happens to be a large category in the Australasian area since it includes very large reserves of iron ore, bauxite, manganese, copper and lead-zinc, which were lying at the surface or had ample surface expression. In such cases there was in fact little or no requirement for the use of geophysical methods. There is also a fourth category in which the new ore reserves have primarily resulted from following orebodies underground by drilling and mining methods.

The role in the future

In looking to the future there is little doubt that there will be great opportunities and increasing demand for mining geophysics. However, if it is a fact that geophysics is the dominant method in finding something like 10 percent of the new ore reserves being added at the present time and is a subsidiary method in finding a further percentage, then this may appear to be a rather modest contribution. Among special reasons for this situation it needs to be remembered that the present high activity in all forms of exploration has found substantial orebodies with good surface expression and has led to the development of additional reserves in existing mines by underground mining methods. However, the very intensity of present exploration will largely decrease future possibilities in these two areas for finding further new ore.

In particular it is difficult to believe that in the years ahead there will be many outcropping or easily accessible orebodies to be found by simple methods. Exploration campaigns will be forced to rely increasingly on the geophysical approach in view of the nature of the environments where future ore reserves might expect to be found. For example, in many parts of the world vast stretches of potentially mineralised rocks still lie hidden beneath comparatively thin superficial cover. Of course it may well happen that the nature of this superficial cover and its thickness present a challenge to geophysical techniques, as in Australia where in many mineralised areas the depth of weathering may be around 400 feet.

In addition there must be many more orebodies with no surface expression but lying enclosed in the rocks, like plums in a pudding, in the zone from the surface to a depth of say 1000 feet. It is true that the number of these is probably much less than the number already outcropping at the surface (Fisher and Walpole, 1965) but they present one of the major fields of challenge to geophysics either for direct or indirect approach through structural studies. In the neighbourhood of important mines the possible occurrence of orebodies lying at depths much exceeding 1000 feet will justify expensive geophysical campaigns using elaborate techniques.

Beyond these possibilities it can be reasonably expected that increasing geophysical work will be required on the continental shelves. The opportunities for finding orebodies outcropping on the sea floor might be remote but, as bearing on the occurrence of detrital mineral deposits, a substantial amount of geophysical work could be directed to obtain basic information concerning this new environment.

Trends in metal prices will no doubt have a bearing on the degree of utilization of mining geophysics and, as in the past, cause fluctuations in it from time to time. However, in the long run only an increasing demand for metals can be foreseen. Moreover, because of some of the factors discussed above, exploration costs by all methods can only be expected to be substantially greater in the years ahead and this should tend to mitigate the fact that geophysics is often regarded as a relatively expensive method.

Thus opportunities for mining geophysics are likely to increase greatly with time and the same is true for groundwater geophysics. There are many arid and semi-arid regions of the world where geophysics can give more assistance in developing the groundwater potential. In Australia there are some very broad regions in which the limit of development will depend primarily on water resources.

In the face of these opportunities and economic factors what will be the nature of the geophysical approach in future exploration campaigns? At present there is little evidence that in the foreseeable future some primary method will emerge or, for that matter, any technique that is as dominant in mining geophysics as is the seismic technique in petroleum geophysics. Thus future campaigns will continue to use a variety of techniques to select the most appropriate, to check each other, and to throw light on the different characteristics of a target area. No doubt other present trends will continue such as, on the one hand, the use of intensive work on small but highly prospective areas and, on the other hand, the search for speedier coverage of wide areas by airborne surveys of increasing scope.

In the early days of geophysics it was hoped that eventually a technique would emerge which would be capable of the direct detection of orebodies under most conditions with little concern for the geological environment. Many years of research and field experience have not made this prospect much brighter. Since this path appears to be barred, geophysics will be forced more and more into the quite divergent path of the closest integration with all other prospecting methods. In the past there has frequently been a tendency for these methods to stand aloof from each other but it is believed that in the future geophysics, geology, geochemistry, shallow and deep drilling will need to yield a measure of their autonomy and that exploration campaigns will rely increasingly on a very close interplay between them.

In the approach to such a difficult field as mineral exploration it is hard to overemphasise such qualities as imagination in planning and conducting a campaign and persistence in getting the most out of the interpretation. On looking back over the case histories of a large number of projects there appear to be many where the field work was too routine in nature, where too little effort was put into the interpretation or where the subsequent test drilling lacked resolution. In fact there are cases where reinterpretation of old data has shown that an orebody should have been brought to light long before.

As the opportunities for direct detection by mining geophysics become more restricted, it is expected that in time there will be an increased emphasis on the indirect approach. Trial surveys would be used to place mineralisation in its setting of geophysical anomalies and then surveys on a regional scale would be made to help unravel structure and stratigraphy in the search for favourable environments. The hope would be to find new mineral fields as well as new orebodies on old fields. The part being played at present in this sort of approach by airborne methods is impressive, so much so that there is a case for all potential mineralised areas to be covered by such methods. In fact some countries have carried out, or are carrying out such a program. Of course it is necessary for the results of the airborne work to be followed up on the ground and closely integrated with ground surveys by geophysical, geological and geochemical methods.

Whether the geophysical approach can take full advantage of the opportunities will depend also on further improvements in the technique, increased research effort and an adequate supply of well trained men. There are signs that in the near future new and exciting techniques will be used (Brant, 1966) although it is doubtful whether they will amount to radical advances. Any technical breakthrough in the field of depth penetration would be a radical advance sorely needed in many areas. In looking for improved performance it would appear that mining geophysics puts a substantial proportion, say 10 percent, of its total expenditure into research. However, the actual annual amount spent on research, although in excess of 2.5 million U.S. dollars, can only be regarded as small in comparison with the prizes to be won. As regards the training of men for mining geophysics it does seem that in many countries the educational establishments are not at present well geared to turn out men either in sufficient numbers or with the most appropriate background.

Mining geophysics will undoubtedly play a very important role in finding the ore reserves of the future. However, whether it can fully exploit all the opportunities available to it will depend on increased efforts to develop ever keener tools and provide well trained men to use them.

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The role of geophysics in the development of the world's groundwater resources

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Abstract. The application of the techniques of exploration geophysics to groundwater investigations has developed concurrently with their application to the search for petroleum and mineral resources. All of the standard airborne, surface, and borehole geophysical methods have found some use in groundwater investigations. Electrical and seismic surveys are the most common surface methods, and electrical and gamma-ray logs the most common borehole methods. However, adequate geophysical support for a diversified groundwater program requires that all of the standard geophysical techniques be available when needed. Many groundwater programs have suffered from attempts to solve all problems by one or two techniques. The trend in groundwater investigations is toward looking at problems on a regional basis rather than to the development of a single well or well field. A properly designed and executed program of geophysics can make a major contribution to programs of this type.

Exploration geophysics has not played as important a part in groundwater investigations as it has in petroleum and mineral exploration. This situation has resulted from economic considerations that have restricted the financial support available to develop and apply geophysical methods to groundwater problems. The development in recent years of more extensive and better-supported water resource programs has resulted in a greater effort in groundwater geophysics. As the value of fresh water increases, and as societies become more aware of the long-range problems relative to obtaining adequate supplies of fresh water, the need and support for groundwater geophysics will expand. It seems highly probable that a major increase in use and effectiveness of geophysical techniques in groundwater exploration will occur in the next decade. Standard geophysical methods will probably continue to be the most commonly used, but new techniques, including remote sensing from aircraft and spacecraft, will become increasingly important.

Résumé. L'application des techniques de la géophysique d'exploration à la recherche des eaux souterraines a été mise au point concurremment avec leur application à la recherche du pétrole et des ressources minérales. Toutes les méthodes géophysiques ordinaires aéroportées, au sol et par sondages ont trouvé leur usage dans la recherche des eaux souterraines. Les relevés électriques et séismiques sont les méthodes les plus communément utilisées au sol tandis que le carottage électrique et par rayons gamma sert surtout aux méthodes par sondages. Cependant, une bonne utilisation des méthodes géophysiques appliquées à un programme complet de recherche des eaux souterraines exige que l'ensemble des techniques géologiques classiques soit disponible en cas de besoin. Plusieurs programmes d'exploration ont subi des contretemps du fait que l'on tentait de vaincre les difficultés à l'aide d'une ou deux techniques seulement. La tendance est à envisager les problèmes à une échelle régionale plutôt que de s'arrêter à la mise en valeur d'un seul puits ou d'une seule nappe. Un programme de méthodes géophysiques conçu et exécuté de façon appropriée peut apporter une contribution importante à des entreprises de ce genre.

La géophysique d'exploration n'a pas joué un rôle aussi important dans la recherche des eaux souterraines que dans la recherche du pétrole et des minéraux. Cette situation a résulter de considérations d'ordre économique qui ont restreint l'appui financier nécessaire à la mise au point et à l'application des méthodes géophysiques à la question des eaux souterraines. La mise en oeuvre des dernières années de programmes plus vastes et mieux organisés a amené comme résultat un déploiement d'effort plus considérable au domaine de la géophysique des eaux souterraines. Les méthodes géophysiques et l'appui qu'on leur accordera prendront de l'expansion en fonction de l'accroissement de l'importance des eaux douces et de l'éveil des populations aux problèmes à longue échéance que représente un approvisionnement suffisant en eau douce. Il semble hautement probable qu'une augmentation considérable dans l'usage et l'efficacité des techniques géophysiques se produira au cours des prochains dix ans. Les méthodes géophysiques classiques continueront probablement d'être le plus communément employées, mais de nouvelles techniques, y compris les télémesures effectuées à partir d'avions ou de satellites artificiels, deviendront de plus en plus importantes.

The development of water resources has always been a primary concern of societies in arid and semiarid regions. In areas of more abundant rainfall the problem of obtaining an adequate supply of fresh water has generally become more acute as population density has increased and industrialization has resulted in the pollution of major sources of water. Today almost every nation of the world is concerned with obtaining an adequate supply of water for current needs and assuring that water will be available to support continued growth. Water problems are being examined at almost every scale ranging up through national programs and the worldwide scope of the International Hydrological Decade.

What is the fundamental nature of the world's water problem? Are we running out of fresh water? Raymond Nace, in examining this question, makes it clear that present water supplies are adequate except in chronically arid or semiarid regions. For example, the United States is currently consuming only about 5 percent of its total water supply. The fundamental problems then are basically technical, economic and political considerations relating to the management of generally adequate resources of fresh water.

The water of the world is unevenly distributed. Of the 9 million cubic miles of water on or beneath the surface of the continents and islands, about 77 percent is locked up in polar icecaps and glaciers. Streams and lakes of the world contain only about 1 percent of the total and nearly half of this is brackish. Rocks of the earth's crust contain about 22 percent of the total and at least half of the water in this vast underground reservoir is fresh enough to drink. It is with the development and management of this reservoir of groundwater that the exploration geophysicist is primarily concerned.

The tasks that face the exploration geophysicist working on groundwater problems can be grouped into three general categories: (1) identifying the location of groundwater; (2) determining

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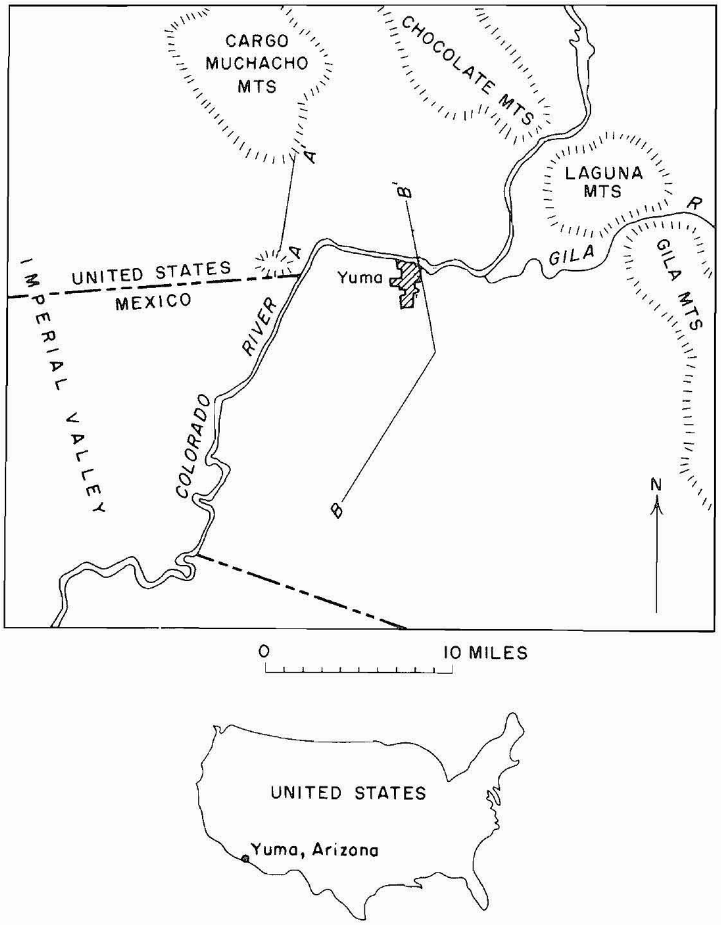

Figure 1. Index map of the Yuma, Arizona area.

the quality of groundwater in situ; and (3) determining the potential yield. Estimating yield using surface geophysical data is a difficult task. Often zones of relatively high yield can be identified indirectly by using geophysical techniques to locate zones of high porosity; however, except with borehole methods, quantitative estimate of yield cannot usually be based on geophysical data alone. Because the electrical conductivity of near-surface earth material primarily depends on the interstitial water, geophysical methods that measure conductivity can often be used to obtain reliable indications of water quality. However, most geophysical surveys in groundwater investigations are directed toward the location, either directly or indirectly, of producible groundwater, and in this effort, all standard geophysical methods have found some application.

Exploration geophysics began to develop as an important geologic tool in the years following World War I. Some of the earlier applications of the emerging discipline were related to groundwater investigation; however, the development of groundwater applications of geophysical techniques did not keep pace with their development in the search for petroleum and mineral resources. This was partly because of the greater financial rewards that were to be obtained from the discovery of petroleum and mineral deposits and the greater support that was thus available to geophysicists developing and applying geophysics to petroleum and mineral exploration. Also important in explaining the relatively slow development of geophysics as a tool in groundwater exploration was the fact that the kind of information which exploration geophysics could supply was often not as important to the solution of groundwater problems as it was to the search for petroleum and mineral resources. Most groundwater investigations could and did achieve their objectives with little or no geophysical support. Most of the major advancements in geophysical instrumentation and interpretation techniques were pioneered by petroleum and mining groups; the electrical methods are an exception where groundwater geophysicists have been in the forefront. With the other methods, the groundwater geophysicist usually is in the position of applying methods that were developed primarily for other applications.

Often groundwater programs are too small to support an effective program of geophysical exploration. A comprehensive program of geophysical exploration is not usually feasible in developing a water supply for a small user, although a simple geophysical survey can be effective, particularly if the geophysicist is experienced in the local problem. However, if obtaining an adequate supply of water is a major consideration in establishing or continuing a major industrial or agricultural development, or if the needs of a large group of people can be combined, as in the development of a water supply for an urban area, support for a major geophysical program can often be obtained. In the appraisal or development of the total water resources of a large area, geophysical exploration is often highly productive.

To be effective on a wide variety of groundwater problems a geophysics organization must be capable of applying several geophysical techniques. It is true that one geophysical method may prove effective in obtaining information on one type of problem over a wide area, for example the refraction seismic method has proven useful for mapping gravel-filled channels in well indurated rock over large areas of the United States. However, there are innumerable examples of attempts to use one geophysical method to solve problems where another standard method would have been much more effective. These misapplications have retarded the acceptance of groundwater geophysics in many areas and by many hydrologists.

An example of the multimethod approach to groundwater geophysics is provided by the work the U.S. Geological Survey has done, partly in cooperation with the U.S. Bureau of Reclamation, in the Yuma area of southwestern Arizona. The area of investigations (Figure 1) is an arid region along the east side of the Imperial Valley where the Colorado River flows from the United States into Mexico. Surface relief is generally gentle except in the mountains which bound the area on the north and east. Cenozoic sediments as much as several thousand feet thick cover most of the surface. Much older, predominantly igneous and metamorphic rocks are exposed in the mountains and as small isolated hills between the ranges. Cenozoic volcanic rocks occur locally in the ranges, and in at least one location they underlie Cenozoic sediments in the valley. The Cenozoic sediments consist of an upper unit of predominantly unconsolidated sands and gravels, with some clay; a middle predominantly clay zone; and a lower partly indurated unit of conglomerate, sands, gravel and clay. The upper and lower units contain large volumes of groundwater.

Because of the large density contrast between the Cenozoic sediments and the older rocks, gravity observations can be used to infer the gross distribution and thickness of the Cenozoic sediments. The first phase of the geophysical program in the Yuma area was a reconnaissance gravity survey with stations on about a 1-mile grid in the area of greatest interest (Figure 2). The gravity survey clearly reveals the major areas of thick Cenozoic fill and these data can be used to estimate the thickness of the fill. Gravity highs occur at all the exposures of basement rock, and a previously unknown basement high was revealed by the gravity data at point *H*. Subsequent drilling revealed basement rock at shallow depths.

A few aeromagnetic profiles were flown in the central part of the area. One of these profiles with a corresponding gravity profile is shown in Figure 3. Along most of the profile a close correspondence exists between the gravity and the magnetic anomalies; both reflect relief on a dense magnetic basement. At the north end of the profile, however, a prominent magnetic high is not reflected by a comparable gravity anomaly. A hole drilled in the area of this magnetic high encountered basalt at a shallow depth. The magnetic data are useful in mapping the surface of magnetic basement rock and in locating volcanic material within the sedimentary fill.

Refraction seismic surveys in the Yuma area have proven effective in determining the thickness of unconsolidated sediments overlying bedrock and in locating the water table in unconsolidated sediments. A seismic and gravity profile northwest of Yuma illustrates both applications (Figure 4). However, comparable information on the basement configuration could have been obtained with less expense from the few gravity observations.

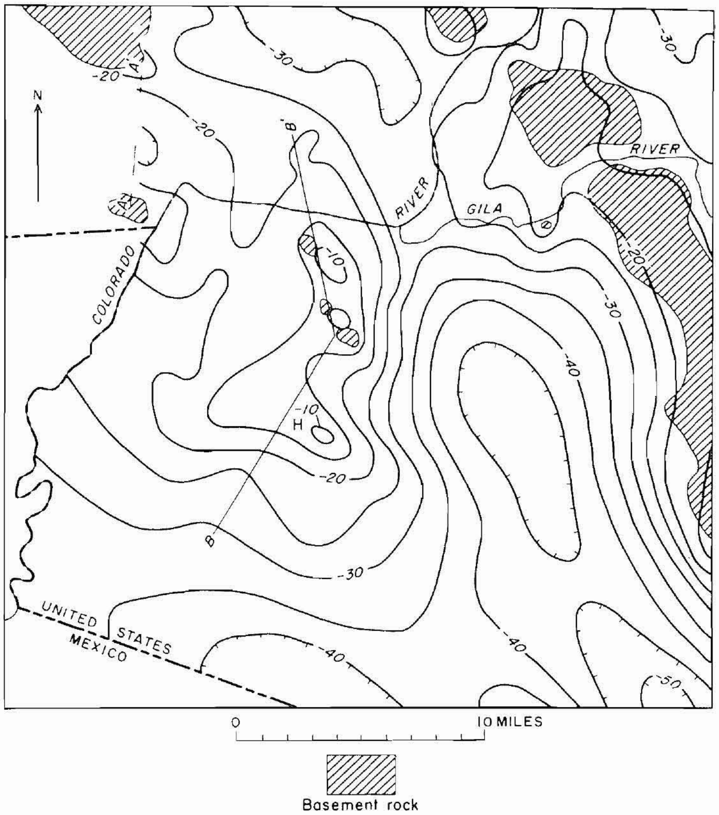

Figure 2. Bouguer gravity anomaly map of the Yuma, Arizona area. Contour interval is 5 milligals.

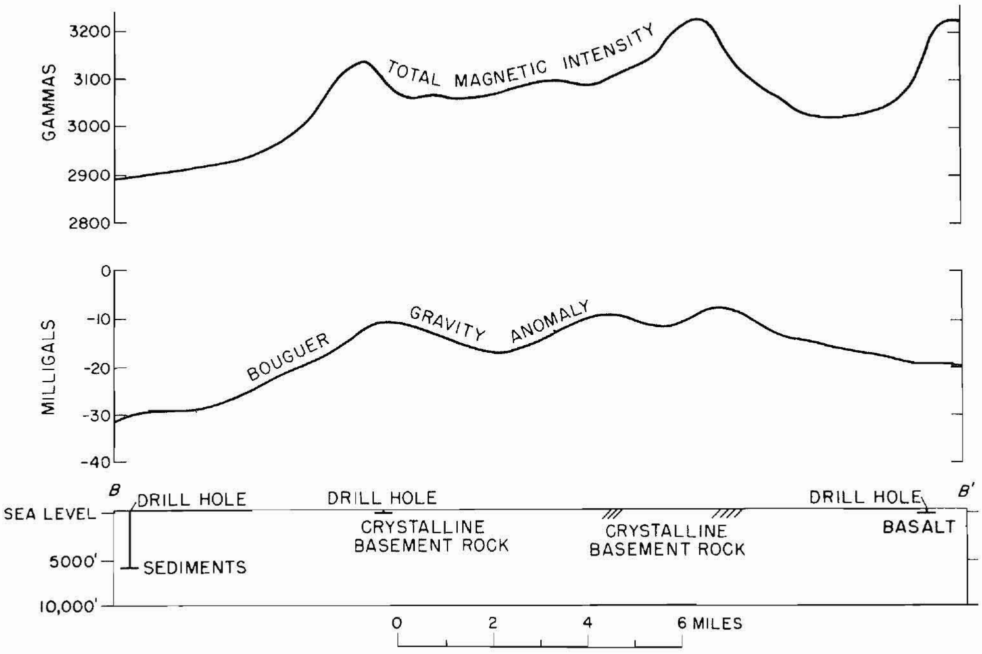

Figure 3. Magnetic and gravity profiles across basement high at Yuma, Arizona.

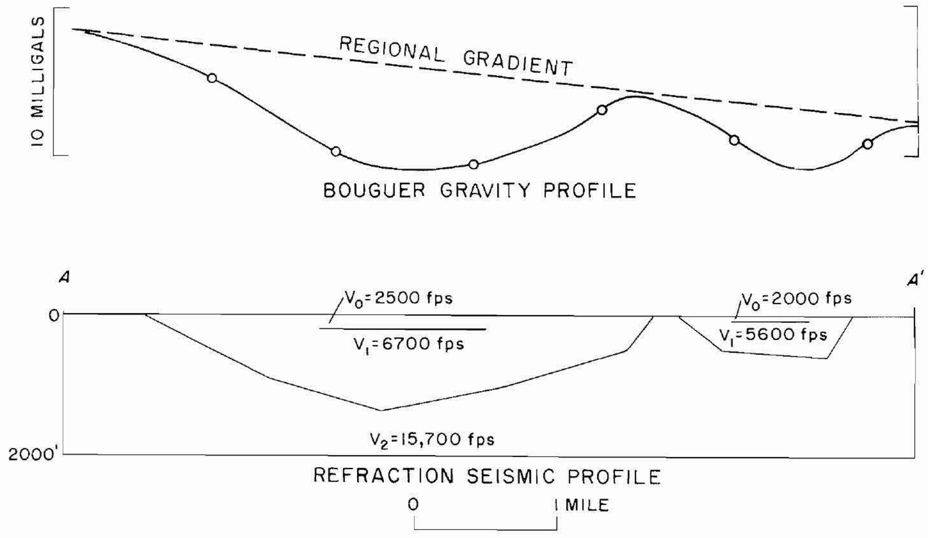

Figure 4. Refraction seismic and gravity profile north of Pilot Knob near Yuma, Arizona. Seismic survey by R.E. Mattick.

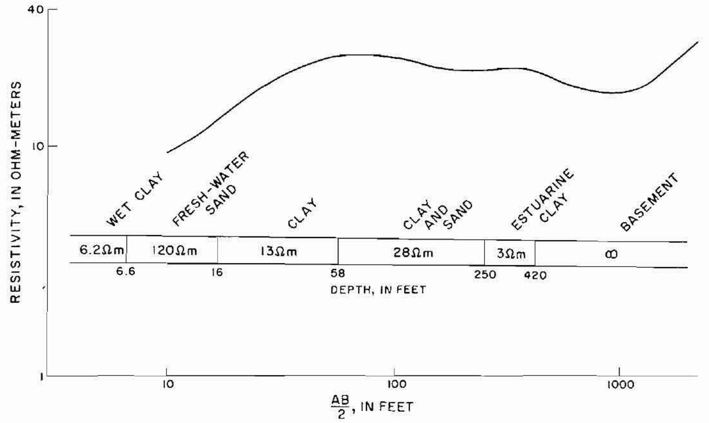

Figure 5. Resistivity sounding northeast of Yuma, Arizona. Resistivity survey by A.A.R. Zohdy using Schlumberger array.

The main clay layer dividing the two main aquifer systems has a lower velocity than the enclosing sediments and could not be mapped with refraction methods. However, reflections were recorded from numerous levels within the sediments, and the reflection data can be used to trace horizons that could not be traced by refraction methods.

Resistivity soundings have proven effective in the Yuma area for mapping the depth to the high-resistance basement rock and in mapping several horizons within the sediments. The sounding in Figure 5 is an example where five sedimentary layers and the basement were detected. Resistivity profiling techniques also proved useful.

Using a multimethod geophysical program in the Yuma area, it has been possible to obtain subsurface data related to the major hydrological problems. In the Yuma area no program that was limited in the number of geophysical techniques that could be applied could match the effectiveness of the multimethod program.

The successful application of exploration geophysics usually involves three steps. The first concerns the analysis of the geophysical aspects of the problem. The analysis must determine first if the problem can be solved by geophysical methods and if the use of geophysics is practical and economically feasible. Often subsurface information can be obtained more efficiently by drilling or augering than by a geophysical survey. The analysis should also include the selection of the geophysical method or methods to be used and the design of the surveys. This analysis is most effectively made by a geophysicist who has an understanding of the capabilities of all the standard geophysical methods and an appreciation for the geology and hydrology involved. The second step is field utilization of the appropriate method or methods. The rapid advances in geophysical instrumentation since World War II have resulted in a high degree of specialization that makes it impractical for all but the largest organizations to possess and operate a complete array of all the equipment that can be used in groundwater geophysics. It is often necessary to obtain the help of specialized organizations for one or more of the field surveys. The third step is the interpretation. Although electronic computing devices have revolutionized the handling of geophysical data, they have not decreased the need for skilled geophysicists to translate the geophysical data into a geologic interpretation. On the contrary, by making it practical to perform a wide variety of operations on a set of geophysical data, computers have increased the talent required of the interpreter. Throughout the geophysical program coordination of all activities is important. An effectively integrated program is usually much more productive than a series of uncoordinated operations.

What are the essential ingredients for the geophysical phase of a groundwater investigation? First is adequate geophysical talent. The successful application of geophysical techniques to groundwater investigations requires as much or more skill than other geophysical applications. However, there are not enough well trained groundwater geophysicists to meet current requirements and staffing of expanding groundwater programs with geophysicists will continue to be a major problem. Adequate equipment is a second essential ingredient. Major advancements are being made in the development of geophysical equipment. The more effective equipment often, but not always, is more expensive to acquire. However, in most large-scale operations the best equipment is often the most economical to operate on a long-term basis. Operating with obsolete or poor-quality equipment is usually a false economy. Access to electronic computers is important to the success of many modern geophysical surveys.

What does the future hold for groundwater geophysics? Few would dispute the contention that geophysics can play a major role in the development of the world's water resources. Nevertheless, reaching agreement on the definition of this role would be difficult. I believe that most knowledgeable individuals would agree that the use of geophysics in many and probably most groundwater programs should be greatly expanded.

In many areas of the world, as water becomes scarcer and more valuable, deep sources of water are being sought. The importance of exploration geophysics usually increases as deeper water wells are drilled because of a greater need for subsurface information and a greater cost of test drilling to obtain it.

Another trend in groundwater investigations stimulating the need for geophysics is the appraisal of the total groundwater resources of large regions. The increased need for long-term planning in water development is being recognized in many areas of the world with the realization that the traditional sources of water are not adequate to support projected needs. Usually three sources of additional water are considered: (1) the development of new local sources, (2) the importation of water, and (3) the purification of available water. An accurate appraisal of the total groundwater potential of a region is often an essential input into this long-term planning, and exploration geophysics can usually contribute considerably in the evaluation of the groundwater potential.

Ground geophysical methods will continue to be more commonly used than airborne methods in groundwater geophysics. The electrical methods, both galvanic and inductive, will continue to find wide application on groundwater problems as major advances are made in the processing and interpretation of data. Important developments can be expected in inductive instruments. Ground gravity measurements are not likely to be greatly refined beyond what is presently available, but the increased use of automatic computers will improve the usefulness of gravity data. The increased precision of magnetometers using optical pumping principles is opening some new applications in groundwater work. Advanced seismic reflection techniques will find increasing application in groundwater exploration and seismic refraction will continue to be important.

Borehole geophysical methods have been used far less in groundwater investigations than in the petroleum industry. Many of the logging techniques developed by the petroleum industry have, with some modification, found application to groundwater investigations. However, the available logging techniques are not extensively used in water wells in many parts of the world. For example, it is estimated that only 1 percent of the water wells drilled in the United States are logged by any geophysical means. Borehole methods should be more widely used in groundwater studies and a major expansion in their use can be anticipated.

In groundwater investigations where access is difficult and large areas must be studied, airborne geophysical surveys are more advantageous than ground surveys. Despite inherent limits to the type of data obtainable from airborne operations, airborne geophysics will probably become increasingly important in groundwater exploration. Even though the cost per hour of airborne surveys is relatively high, the cost per unit area is usually much lower than surface surveys. The use of airborne magnetometer surveys is now routine and the use of high-sensitivity magnetometers may expand the application. Airborne electromagnetic surveys have been used to map near-surface conductivity anomalies related to buried channels and variations in water quality, and the use of airborne EM surveys in groundwater investigations will undoubtedly expand. Airborne gamma-ray surveys have also proven useful in a number of near-surface groundwater studies, and this use, too, can be expected to expand.

Remote sensor techniques will undoubtly become increasingly important in development of the world's water resources. Aerial photographs have been used widely in hydrology and their usefulness will grow with the increasing use of colored and multispectral photography. Infrared surveys from aircraft have been successfully applied to various hydrologic problems such as studying evapotranspiration, rainfall distribution and infiltration patterns, groundwater discharge, and measuring water-surface temperatures. Numerous additional applications are being tested. Other remote sensor techniques such as radar and passive-microwave will find hydrologic applications. Although some local data can be obtained by remote sensors more effectively than by ground observations, a primary advantage of remote sensor techniques is that broad areas can be surveyed rapidly. Orbiting spacecraft have already contributed data to hydrologic investigations, and future orbiting sensors designed specifically to obtain geologic and hydrologic data will undoubtedly be much more effective. The U.S. Geological Survey has announced plans to orbit a satellite for this purpose.

In summary, I conclude that geophysics has not yet achieved its full potential in the development of the world's groundwater resources, but that current developments toward large-scale water resource investigations will provide the impetus that will advance geophysics to a more prominent role. Development and refinement of new techniques and research directed toward groundwater applications will accelerate the expansion of geophysics in groundwater investigations. The limiting factor in how rapidly groundwater geophysics can expand will be the availability of qualified geophysicists.

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