METHODS and
CASE HISTORIES in
Mining
Geophysics

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Metallurgical
Congress
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Methods and Case Histories in MINING GEOPHYSICS

Arranged by a Committee of Geophysicists of the Canadian Institute of Mining and Metallurgy

Published by Authority of the General Committee of the Sixth Commonwealth Mining and Metallurgical Congress.
Foreword

The material in this volume is intended to provide the delegates who attended the Sixth Commonwealth Mining and Metallurgical Congress with a study of some of the exploratory work of the geophysicist related to development in several Canadian mining districts visited during the Congress tour.

Canada is not alone in applying the science of geophysics to mineral discovery and to include some perspective of world-wide activity, sketchy though it may be, examples of geophysical surveys have been drawn from other countries of the Commonwealth.

For those readers who are not geophysicists but may be geologists, mining engineers, or others concerned with developing and conserving mineral resources, it is hoped this volume will provide an insight into methods of geophysical exploration.

The authors who have so willingly contributed their intimate knowledge of techniques in a new field, aid mankind to achieve in the years ahead immenurable benefits in the flow of metals and minerals into our complex civilization.

On behalf of the General Committee of the Sixth Commonwealth Mining and Metallurgical Congress and the Canadian Institute of Mining and Metallurgy, I am pleased to express my sincere thanks for the dedicated teamwork which has produced this volume.

Chairman, Publications Committee
Sixth Commonwealth Mining and Metallurgical Congress.
Introduction

This is a volume devoted to recording a series of case histories dealing with geophysical methods in mining exploration and other subsurface investigations.

Such methods have proven particularly effective in the exploration of Canada's Precambrian Shield, where glacially transported debris conceal bedrock formations beneath an unrelated mantle of overburden.

In order to give perspective to world-wide activity in this field, examples of geophysical surveys have been drawn from other countries of the Commonwealth.

The case histories in this volume are prefaced with a series of papers on the theory and techniques of geophysics most widely employed in mining and civil engineering. An idea is given of field procedures and the pitfalls to which the geophysicist is subject. They are planned to help the reader unacquainted with geophysical theory to better grasp the discussions presented in the case histories. The book is aimed principally at readers who are not geophysicists, but are the mining engineers, geologists and civil engineers concerned with the development of mineral resources.

Sincere thanks are tendered the many who have given so much of their time to this publication. It is due to their efforts that the book has been made possible.

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GENERAL

GEOPHYSICS, as a science, is more than three centuries old, but as an exploration tool it is much younger, although not as recent a development as most people believe.

To those interested primarily in exploration for mineral resources, the word geophysics signifies certain specialized prospecting techniques which actually are the outgrowth of the older and broader science of geophysics. This science embraces the study of the earth, the word itself meaning the physics of the earth. This study involves investigations of the materials of our planet, their natures, movements and transformations, and their changes in energy states; it involves speculation on the origin and date of this satellite, as well as studies of its age, present appearance and constitution and of its fields of force and its reactions to forces, external and internal, acting upon it. Some of the knowledge thus gained, especially from the latter studies, when applied to the search for mineral deposits, becomes the art of geophysical exploration.

This statement may surprise those who look upon geophysicists as practitioners of an exact science; the methods used by geophysicists are the techniques of exact science, but the interpretation, or translation, of the observations thus made into terms of geology and mineralogy is an art in which the knowledge, the experience, the ability, and especially the integrity of the geophysicist are fully as important as the physical quantities he measures.

Started in Antiquity

The story of the physics of the earth—geophysics—begins in the obscurity of antiquity. Could we ever learn his name, we could crown as the first geophysicist the man who invented the compass. This is a geophysical instrument, because it responds to a physical force of the earth, its magnetism. There are legends that the Chinese knew the use of the compass two milleniums before Christ, but the first authentic description of the instrument was written in the 12th century by Alexander Neckham. Little progress was made in magnetics for many centuries, particularly because the ancients believed that the property of attracting the magnetic needle resided in the heavens. Not until Sir William Gilbert published his masterly study on magnetism in 1600 did it become known that the earth itself is the magnet which controls the orientation of the compass needle. It is Gilbert, who has been called the Father of Electricity and the Galileo of Magnetism, who deserves the title of the First Geophysicist.

A little over 200 years after Gilbert’s time a Cornishman, Robert W. Fox discovered the phenomenon of the spontaneous polarization of sulphide bodies. In 1835 he utilized this phenomenon to discover a body of copper sulphides in the Penzance mine at Cornwall. It was also he who first suggested that electrical resistance observations could be employed to study concealed, sub-surface geological formations. About the same time an Irish engineer, Robert Mallet, suggested that artificial earthquakes, caused by charges of explosives, be utilized to determine the types of concealed rock formations, and was conducting experiments to that end. Early in the last quarter of the nineteenth century Baron Roland von Eotvos of Hungary developed an instrument, the torsion balance, bearing his name, to study minute variations in the earth’s gravitational pull. He thus hoped to learn more of the constitution of the crust of the earth, and of the geological formations concealed beneath the surface.

Thus, slowly over a period of nearly three centuries, accelerating in the nineteenth century and suddenly bursting into widespread activity in the twentieth century, where it now culminates in the International Geophysical Year, engineers and physicists have continued the discovery of new phenomena of the earth. They have developed new tools for measuring these phenomena and for perfecting the art of interpreting their measurements.

The geophysical methods of exploration, although utilizing measuring techniques of high precision, nevertheless remain essentially qualitative, not quantitative.
MINING GEOPHYSICS

They serve to detect discontinuities or changes in character of concealed geological formations, or outline mineral bodies of certain characteristics capable of producing an 'anomaly'. A geophysical anomaly may be defined as a group of observed physical values of either higher or lower intensity than those in the surrounding area. There is no technique which is quantitative in the sense that it will indicate the precise nature and amount of a given metal or mineral which may be present in a subsoil formation. Even the geochemical techniques cannot approach this ideal, although they take one step in that direction by indicating that certain metals may be present. To what extent they may be present, and whether of commercial value, must still be determined by drilling. These are some of the reasons for saying that, while geophysics is a science, geophysical exploration is still an art.

REFERENCES


THE GEOPHYSICAL SETTING OF MINERAL DISTRICTS

by J. Tuzo Wilson*

Abstract

Some geophysical methods are being used to search large areas for ore, and this raises the question of which are the most favourable areas to choose. It is obvious that areas around existing mining camps and areas which appear favourable but which are covered by thin overburden or water are suitable places to look, but can more precise guides be found? Are there not already some rules? Could more order be found if the geophysical methods were applied to do research upon the nature of the crust as well as to prospect directly?

Some order is already known and examples are discussed of the relation of some copper camps to particular mountain structures and of the relation of gold camps to the oldest Precambrian rocks of Kee-watin type.

In most prospecting four ingredients are now employed, geological data and geophysical data, geological insight and geophysical calculations. It is suggested that future progress in studying the earth will also employ all four. What the mining industry needs is neither geologists nor geophysicists but exploration engineers and earth scientists, both trained to use the best of both geology and geophysics in applied studies and in research studies of the earth.

A VOLUME of geophysical case histories contains accounts of mineral discoveries drawn together so that the experience of the past may be available as a guide for future exploration. These histories describe how searches were conducted in selected areas, but the broader question of why those particular areas were chosen for search also deserves consideration.

*Professor of Geophysics, University of Toronto.

This introduction will discuss some aspects of the role geophysics does play and can play in locating and defining favourable areas in which to prospect, in contrast to the rest of the volume which deals with methods of looking for orebodies within areas already selected as promising. It is proposed to deal particularly with the part that the physics of the earth as a whole can be expected to play in guiding future prospecting.
This article is not intended as an exact guide to prospecting. The writer does not know precisely where to find any mine, and if he did it would be unconventional, to say the least, to publish that information. The object rather is to suggest that a much more basic approach to the study of the earth has recently become possible. As long as our knowledge of it was limited to geological examination of a quarter of its surface, as long as nothing was known about the ocean floors or about its interior, as long as our concepts of Precambrian time were compressed and distorted, there was no chance of developing any sound theories about the earth. Indirect physical methods are rapidly increasing the scope of our knowledge about the earth and enabling us to see it in proper perspective.

The intention of this article is to stimulate the development of these ideas rather than to give answers. Experience suggests that some of the views stated will probably be found to be mistaken. Many need developing. There are unexplained exceptions. The author is ignorant of most of the geological literature of the world and in defence against justifiable criticisms would add simply that he is not alone, for recent information on age of Precambrian rocks on isotopic ratios, on structure of the crust, and from other branches of geophysics shows that many traditional and widely held views are flagrant distortions.

Now for the first time we can combine physical knowledge of the greater part of the earth with geological observations about its surface, so that we have some hope of finding out what the whole earth is like and how it has behave. Such knowledge needs pursing. It is bound to assist prospecting.

At this time it is appropriate to thank E. W. Westrick and Sherwin F. Kelly for their constructive comments, and to acknowledge the assistance given by Elizabeth Morrison and Michael Dence in preparing this paper. The latter was responsible for compiling the maps.

Circumstances of Discovery of Ore

Consider first some of the ways in which ore has been found. There is a popular idea that many mines have been found by chance, and that the lucky fellow who picked a diamond off the ground or kicked the moss off rich ore had only to dig to make his fortune. While it is true that some diamond pipes, some placer gold, and some mining camps like Cobalt were discovered unexpectedly and returned great wealth to their finders without much effort on their part, such chance finds have certainly not been common. Most mines have been found and developed by hard work and intelligent efforts directed for long periods to that end. It is pertinent to ask what considerations have guided prospectors.

One obvious guide has been the desire to extend a known mining camp or discovery. For example, once it had become apparent that many orebodies were to be found where faults intersect the outer rim of the Sudbury norite intrusive, or along the Kirkland Lake-Cadillac fault zone, or in a certain area of New Brunswick, or in Huronian conglomerates north of Blind River, Ontario, it was clearly worthwhile to search in those areas for additional bodies by the methods most suitable for finding the local type of ore. In most cases this involved a combination of geological mapping, geophysical methods, trenching and drilling, although the early work made no use of geophysics and some later discoveries have been made in areas where geological field work was of little help.

Although it is undoubtedly sensible to look for more ore where ore already is known, it is important to ask how camps have been found in the first place. One basis upon which this has been done successfully is by the recognition of similar rock types in widely separated localities. Thus Hargraves realized that the gravels of his native Australia were the counterpart of the placers which he was working in California, and he returned home in 1851 to prove it. Franc Joubin considered correctly that the ancient conglomerates of Ontario resembled those in South Africa which carry gold and uranium. The search for nickel and chromousium has been dominated by the observation that these metals occur only in basic and ultrabasic rocks and in resident deposits formed from them.

In recent years some deposits probably have been found through random geophysical sweeps or through drilling in some spot that took a prospector's fancy, but most ore has been found after consciously choosing an area with the thought that it would prove more favourable than its surroundings. Some discoveries have been made by farmers and settlers who looked for ore for no other reason than that they lived where they did and perhaps owned the ground which they prospected. Many orebodies have been made valuable through changes in economics, in transportation or in metallurgy, which have transformed what had been useless rock into good ore.

Although those examples brought rich rewards, such good fortune has not always been the case. For
every area which contains rich orebodies there are many others with apparently similar rocks and structures which have none at all, or have deposits so lean and small that they are only a source of loss and disappointment to their finders. What is very badly needed is some guide to indicate which are the truly favourable areas, and which are not.

The introduction of geophysical methods of prospecting makes this question more important for several reasons. In the first place, certain geophysical methods enable sweeps of great areas to be rapidly made so that it is now important to be able to choose broad regions for prospecting. In the second place, there are great areas of the earth which are hidden and which now can be prospected by indirect geophysical methods. In many places shallow water, drift, or young uncomformable strata make surface geological mapping useless as a guide to what lies beneath.

**Widespread Cover**

There are enormous areas in the world so covered by shallow water, drift or young rocks that the surface is hidden. Hence search must be by a combination of geophysical methods, by drilling, and by the accumulation of sub-surface geological data. Geophysical methods have proved of great value in such locations. Near Bathurst, New Brunswick, many conducting bodies have been located through drift by electromagnetic devices. Off-shore oil has been found under water by seismic methods, and the geology of England and France is being linked across the English Channel in that way. Iron-rich rock has been found near Neepawa, Manitoba, and near Marmora, Milton and Simcoe, Ontario, through hundreds of feet of shales and limestones, by its effect upon the earth’s magnetic field. One of these deposits is now in production.

Until now most mines have been found in areas of good outcrop. In part this is due to the alteration which accompanies ore and hardens the surrounding rock against erosion, so that many mining camps are on hills, but other orebodies are covered and search for them will be made increasingly by geophysical methods. Better guides to the presence of ore would have to searching these hidden areas blindly, and would be of great economic value.

One can see that the problem in prospecting is the twofold one of knowing how to limit the search, and then of conducting it in the most efficient manner. Since geology, geophysics, geochemistry, trenching, drilling and exploratory mining can all be used to do these things, it follows that prospectors should be trained not as geologists only, or as geophysicists only, but rather as exploration engineers with some knowledge of all the pertinent methods of exploration.

Many think of geophysical exploration only as a direct method of finding ore. This is scarcely true. As Sherwin Kelly (1939 and 1952) pointed out, the exploration geophysicist is "concerned primarily with the discovery of mineral formations favourable to the occurrence of commercial ore". Seismic methods can delineate structure and electromagnetic methods may find sulphide bodies, but usually it is only the drill that can determine whether the structures contain oil or whether the sulphides are rich enough to be worth mining. Since geophysical methods already are used to limit search, can their use in that direction be extended? Can we in fact agree with Kelly when he says "we will find that the exploration geophysicist working in mining fields contributes much to the knowledge of earth structure, even as his brother in the oil fields already is doing; and conversely that the geophysical revelations of continental structure in time will have a profound influence on the future search for districts likely to contain mineral deposits".

**Geophysics as an Aid in Developing Theories of Prospecting**

As illustrations of the ways in which geophysical methods may help to develop better theories to guide prospecting, it will suffice to point to examples. Firstly, we can expect physicists eventually to develop a theory of manner of behaviour of the earth like the theories which already exist for the behaviour of stars and atoms. Secondly, the study of isotopes shows signs of making major contributions to the problem of the origin of ores. Thirdly, the geophysical methods already useful in prospecting are being applied now to study general problems in earth structure. Thus seismic methods are used to measure the thickness of the crust, and age determinations to help in subdividing continents. Finally, it is important to think of prospecting as a form of search for the unusual. Many geophysical methods depend upon finding "anomalies". An anomaly can be recognized only by contrast with the normal. It is important to extend our broad studies of the normal earth so that we may see more easily the abnormal which has economic significance.

Consider first the possibility of developing a general theory of earth behaviour. No such theory exists, but the development of one can be looked upon as probable and useful. Such discoveries do happen.
For example, only a few years ago it was not known how stars obtained their energy, or how atoms and nuclei were constituted and behaved. The men who investigated such things were regarded as impractical. Recently much has been learned about these remote subjects and nuclear theory has been found to be very useful. As a group, physicists are much more sanguine than geologists. Although the stigma of being impractical often has been attached to them, they are scarcely concerned with it, for they are exhilarated by the tremendous successes to which their methods have led in electricity, in astronomy, in nuclear energy, and in so many other fields that have transformed civilization. Most physicists would be much more optimistic about solving the problem of how the earth operates than are geologists, but to tackle the problem at all they need an understanding of what geologists have learned. This is one reason for believing that geologists should be taught more physics, so that they themselves can manage such problems with the physicist's tools.

A second use of physical methods is in finding the origin of oil and of ore-bearing solutions. Much light now is being thrown on the problem of the origin of petroleum by studies of the ratios and the ages indicated by isotopes of hydrogen, carbon, oxygen and sulphur. The investigation of the origin of ores by the study of isotopic ratios of sulphur and lead has been started with promising results. (Thode, et al., 1953, and Kulp, et al., 1956.) At least some of these authors believe that most ores came from the mantle rather than from the crust, and that it is possible to distinguish between them. Obviously this would have an important bearing upon the structures in which to prospect.

A third reason concerns the extent to which the methods which have been used so successfully in geophysical prospecting should be applied more widely to fundamental research in geology. One example will suffice to illustrate what can be done. It is well known that ores often are associated with mountains or with the eroded stubs of former mountains. "There's gold in them there hills" is a simple statement of this. It would seem reasonable, therefore, that those interested in prospecting should encourage fundamental research upon mountains, and to that end the surface geology of many mountain regions has been mapped. Much less is known about their third dimension. It is held widely that mountains have roots, but the evidence for this is extremely scanty. A delay in the passage of seismic waves across the Sierra Nevada has long been held by Gutenberg and Richter and by Byerly to be due to the existence of a low velocity root under these mountains. Recently Press has interpreted the dispersion observed in surface waves to give additional information about the shape and depth of this root.

On the other hand, seismic methods resembling those employed in prospecting have been used by Tatel to measure the thickness of the crust beneath the high Colorado Plateau and he found no root present there. These methods which have been used widely to measure the thickness of the crust in Shield areas and on ocean floors could easily be applied to study mountain roots, but this has been done rarely.

Large negative gravity anomalies which have been found over some mountains have been supposed to be due to roots, although it is possible that some of these anomalies may be caused at least in part by density deficiencies within the crust rather than by roots below it. Some mountains, for example the Green Mountains of Vermont and the Sutton Hills in south Quebec, are marked by positive gravity anomalies, and by that argument are likely to have an antiroot rather than a root. That particular problem is under investigation now by the Geological Survey of Canada, the Dominion Observatory and by graduate students at Harvard University.

The negative gravity anomalies under island arcs were explained ingeniously by Vening Meinesz as due to tectogenes, that is, huge roots or downfolds. Unfortunately Coulomb pointed out that accumulations of light mud on the sea floor might reasonably be large enough to cause the negative anomalies; and Ewing and Worzel have shown by seismic evidence that the mud is present and that under the West Indies no root exists where one had been postulated.

The best that can be said at this time is that the evidence suggests that some mountains do have roots, some have antiroots, and some have neither. For most mountains there is no information and there is little evidence about how large any of these features are, although it is clear that a root would be a most important feature of a mountain. How can one expect to relate orebodies to mountains when so little is known of their sub-surface shape? Nevertheless, the matter is quite capable of geophysical investigation. Seismic prospecting was developed from scientific study of earthquakes. There is a need to apply the methods of geophysical prospecting more to general studies of the earth.

No one would pretend that these kinds of physical investigation of the whole earth have yet been carried
very far. Not enough is yet known to permit us to advance acceptable theories about earth behaviour, ore genesis, and mountain roots, but some general observations about the regular occurrence of ores can be mentioned, in particular the relation of gold ores to the oldest Precambrian terrains, and the relation of copper ores to certain mountain structures. Such case histories should become more numerous and more precise as our knowledge of the earth improves.

**Association of Gold Quartz Veins with the Oldest Rocks**

A clear example of the relation of a particular type of metal deposit to rocks of a certain age, type and structure is afforded by the quartz veins from which so much of the world's gold is derived. Gold-bearing veins occur especially in those areas of the oldest known rocks which have been called continental nuclei (Figure 1). These areas are marked by the following characteristics: (Wilson, Russell and Farquhar, 1956A):

- **Age:** Pegmatites and veins alike yield age determinations of from two to three billion years.

- **Structure:** Narrow, sinuous synclines of volcanics of Keewatin type, sometimes interbedded and generally overlain by sediments of Timiskaming type, both cut by ovoid granitic batholiths.

- **Rock types:** The Keewatin type lavas are basalts, andesites and some more acid types, often showing pillow structure. The Timiskaming sedimentary rocks are poorly sorted greywackes, conglomerates and tufts. Sandstones, limestones and arkoses are scarce or lacking. There are more volcanic than sedimentary rocks.

The following continental nuclei have been recognized and linked to one another.

- **North America**
  - Keewatin,
  - Yellowknife.

- **South America**
  - Guiana and Venezuelan Highlands.

- **Africa**
  - Swaziland-Transvaal,
  - Southern Rhodesia,
  - Kenya-Uganda,
  - North Belgian Congo,
  - Sierra Leone-Gold Coast.

- **Asia**
  - Mysore (India),
  - Ukraine (USSR).

- **Australia**
  - Kalgoorlie.

When it is realized that the gold of the Rand is considered by the great majority of South African geologists to have accumulated as placers by the disintegration of the gold ores of the Swaziland-Transvaal nucleus, it can easily be understood that most of the world's gold comes directly or indirectly from veins formed more than two million years ago. No explanation has been offered for this, but it is a valid guide
LEGEND

- Mid-Ocean Ridges
- Ocean depths less than 1500 fathoms
- Ancillary fracture
- Land

Figure 3. Oceanic system of shallow fractures and mid-ocean ridges.
in prospecting. Of course there are important exceptions, for example in California and in southeast Australia.

**Relation of Some Copper Deposits to Mountain Structures**

Another example of the regular occurrence of one type of ore is the occurrence of many copper ores in special positions in mountains having an Appalachian type of structure. To develop this idea it is necessary first to say something about mountain structure in Indies.

- **The Two Fracture Systems**

  Active mountains are those that sporadically give rise to seismic and volcanic disturbances. Today there are two important systems of active mountains. The first or better known is the continental system which was first identified by Edouard Suess and which forms two belts about the earth (Figure 2). One belt extends from the Atlas and the Alpine Mountains across southern Eurasia and into the Pacific Ocean beyond Indonesia as far as New Zealand. The other belt circles the Pacific Ocean clockwise from Celebes, at which island the two belts join in a T-shaped intersection. The distinguishing features of these belts are andesitic volcanism, large negative gravity anomalies, deep-focus earthquakes, deep ocean trenches, and elements that are frequently shaped in arcs of circles.

  The second and lesser known oceanic mountain system has been identified in part for many years, but it was only this year that Ewing and Heezen (1956) recognized it as a single system 40,000 miles or more long (Figure 3). This system is the sum total of interconnected mid-ocean ridges. It is marked by basaltic volcanism, no great gravity anomalies, only shallow-focus earthquakes, no ocean trenches, and no circular arcs. Little of it is above sea level and such islands as the Azores or the Hawaiian Islands which do rise above sea level are devoid almost entirely of orebodies, so that this system need not be considered further here.

- **The Continental Mountains**

  In order to analyze the active continental system (and its now inactive predecessors) it is necessary to know that it is made up of two kinds of mountains, one chiefly igneous and volcanic, the other principally sedimentary. Both tend to form arcs. The igneous mountains have been called primary because they are the source of new volcanic material and are related to patterns of earthquakes. Along continental margins they lie closer to the oceans than do the sedimentary arcs. Examples of the primary volcanic arcs, in different stages of evolution, are the Aleutian Islands, the Coast Range of British Columbia, the west part of the Andes, the Apennines, the Himalayas and the West Indies.

  The sedimentary mountains are much less active. They have few volcanoes and igneous intrusives, although blocks of the basement may be uplifted in them. On the whole they are not highly metamorphosed and their structure can be worked out by stratigraphic methods. Examples of secondary mountain arcs are the Rocky Mountains, the east part of the Andes, the Alaska Range, the Alps and the Pyrenees.

  These two kinds of mountains are combined together in at least two patterns to form mountain systems. One pattern is that of wide mountain systems like the Cordillera of Canada and the United States; the other is that of the narrow mountain systems like the Andes or the inactive Appalachians (Figure 4). In the Cordillera from the Yukon to Mexico there are four primary arcs: (1), the St. Elias Mountains; (2) the British Columbia and Alaska Coast Ranges and off-shore islands; (3), the Cascades, Sierra Nevada and adjacent coast ranges; and (4), the mountains of Lower California. There are also four secondary mountain ranges: (1), the Mackenzie Mountains; (2), the Canadian Rockies; (3), the American Rockies; and (4), the Sierra Madre Occidental. The four secondary arcs are offset to lie opposite the junctions of the primary arcs; both sets of arcs present their concave sides to one another; between the two sets is a wide and complex plateau area or Zwischenengeberge which is well mineralized.

  Two attempts to analyze the relation of ore deposits to structure within this system have been made by Billingsley and Locke (1939 and 1956). The other present-day examples of mountain systems which follow the Cordilleran pattern enclose the Zwischenengeberge of Spain, Hungary, Yugoslavia, Turkey, Persia and Afghanistan. The mountains south of these countries are primary, like the Atlas. Those to the north are secondary, like the Pyrenees. In the other kind of mountain system of the Andean type the primary and secondary arcs adjoin so closely the Zwischenengeberge is almost lacking and the whole mountain system is narrow. Many copper deposits lie in a characteristic place in this type of mountain pattern. Most of the present-day mountain belts are of this type, and so were many mountain systems of the past.
Figure 4. Known mountain systems and basement provinces of North America.
**Legend**

- [ ] Proterozoic type strata
- [ ] Paleozoic strata
- [Cu•] Major copper deposits

*Figure 6.* Copper deposits along the Grenville-Keewatin boundary (●) and along the Keewatin province (●).
Copper Camps in the Appalachians

One of these was the Appalachian Mountains in which seven salients, as they were called by Keith (1923) and King (1951), form secondary sedimentary arcs of the Valley and Ridge type. These have been called from their locations the Belle Isle, Gaspé, Champlain, Pennsylvania, Tennessee, Ouachita and Marathon arcs (Figure 5). The primary arcs are now less distinct and they are partly buried by coastal plains and by waters over the continental shelf, but they are considered to range through the batholiths of central Newfoundland, Nova Scotia, New Brunswick, New England and the Piedmont. The roots of old volcanoes along part of one of the primary arcs are beautifully clear on the new geological map of New Hampshire (Billings, 1955).

The Appalachians thus analysed show great regularity (Wilson, 1954, Wilson, Russell and Farquhar 1956b). On the continental side of six of the seven salients are six parallel grabens, with some of which lead and zinc ores are associated. Along the boundary between the primary and the secondary arcs are many showings of copper but all the important mining areas are opposite the centres of secondary arcs: near Tilt Cove, Newfoundland; Murdockville, Gaspé; Sherbrooke, Eastern Townships; and Ducktown, Tennessee. Copper deposits should be, therefore, along this boundary and also opposite the Pennsylania, Ouachita and Marathon arcs, but in all these cases, if they exist, they may well be hidden by Triassic or Cretaceous cover.

The southeast part of the secondary arc is the Blue Ridge together with its north extension as the Green Mountains, Sutton Hills, Shickshock Mountains and the Long Range of Newfoundland. This ridge everywhere is a structural uplift, marked where studied by positive gravity anomalies. These have been interpreted in Canada to be the result of uplift of the mantle which may even break through to form the ultrabasic intrusives on the faulted boundary along which copper deposits lie. De Sitter (1956) has lent substance to this view by suggesting that the salients are superficial folds sliding off the Blue Ridge along incompetent beds in the Cambrian. This is a justification for calling the salients secondary.

Here then is a regular structural and gravity pattern in which several copper camps are found at a particular location in the pattern, that is, between primary and secondary sets of arcs opposite the secondary arcs. True, the locations are not precise, but if the interpretation is correct the field of search would be greatly narrowed. Are there other similar cases elsewhere?

Copper in Some Shield Areas

It has been suggested by Adams and Barlow (1910) and many later geologists that the Grenville province once was a mountain system and bears the same relation to the older Keewatin rocks that the Appalachians have to the Grenville. Faults have been found at intervals along the contact, and the fact that in some places which are heavily drift-covered no faults have yet been seen seems immaterial in view of the agreement that everywhere there is a zone of metamorphism, a change in rock types, and a change in age of pegmatites.

The Grenville province is a series of primary arcs, and the secondary arcs form a basin of sedimentary rocks of Proterozoic type (Figure 6). Copper deposits are present in these basins at Keweenawan peninsula, Sudbury, Chibougamau and Seal Lake, in positions similar to the copper deposits of the Appalachians. Some of these ores have been shown to be about 1,200 million years old and therefore of about the same age as the Grenville pegmatites. The copper at Golden Mani-tou mine in northeast Quebec, which might be expected to be associated with these, is much older, like that at Manitouwadge, Ontario, and probably like that at Noranda, Quebec. These ores are about 2,500 million years old and of the same age as Keewatin pegmatites. Thus there are two ages of copper mineralization differing by over one billion years, with the older related to the gold camps.

Another Precambrian example of copper ores similarly situated is in India, where the Eastern Ghats along the coast of the Bay of Bengal have been well dated by pegmatites to be about 1,600 million years old (Figure 7). Like the Grenville, this province consists of primary arcs, and on its inner side are two very clear secondary arcs forming the Cuddapah basin in Madras and another basin in Orissa, both basins containing rocks similar to the Huronian. At least the southernmost of these basins has a very obvious graben extending northwest from it, and there have been suggestions of a fault contact between the older Dharwar series (similar to the Keewatin) upon which these basins rest and the Eastern Ghats (similar to the Grenville). It is interesting to note that of three copper-bearing areas in India, two, according to Krishnan (1949), lie on the east sides of these two basins near the fault zone, in positions like those of the Appalachian deposits (Holmes, 1955). Western Australia shows similar features (Figure 8).
Copper in Some Young Mountains

Three other junctions of Appalachian type form high and well-known mountains. The Alaska Range is a secondary arc at the junction of the St. Elias and Aleutian primary arcs. The important copper deposits at Kennicott, at Copper Centre and in Prince of Wales Sound are near this junction. The Alps form a secondary arc (complex, but largely sedimentary and not highly metamorphosed, so that the structure has been elucidated in great detail) at the junction of the Apennine and the Dinaric primary arcs. The Rhine graben is a classic example of a graben in the usual position on the continental side of a secondary arc, but important copper deposits are not known there. The Puna block of Bolivia is at the junction of the primary arcs of volcanoes of the north and south Andes. There is a well-known graben in the interior and there are important copper deposits at Arica at the junction, but many other greater deposits do not fit the simple pattern suggested here for the Andes.

Of course these brief notes do not account for the position of more than a few of the world’s copper deposits and those only in a very general way, but they do seem at least to provide a lead upon which to make predictions. For example, it has been suggested that in Palaeozoic time a range of mountains was formed along the Atlantic coast of Brazil, resembling the Appalachians in age, structure and position (Figure 9). As in the Appalachians, the secondary arcs form salients which can be seen easily on the geological map of South America (Stose, 1950). On the basis of this similarity and knowing nothing about local conditions, it seems reasonable to suggest that copper deposits might be present along the line of contact of primary
and secondary arcs, and especially opposite the secondary salients in the general vicinity of 31°S, 54°W; 24°S, 50°W; 20°S, 46°W; and 11°S, 43°W and perhaps 5°S, 42°W. While these predictions are not precise enough to encourage anyone to rush off to find ore in Brazil, the point is that enough is known already to enable rough predictions to be made. Are present methods of selecting areas in which to prospect based upon any surer methods? Should more effort not be devoted to the study of how to make more accurate predictions?

New Concepts in African Structure

Africa presents an interesting opportunity which might be tackled if only a few more data were available. Many interesting papers provide purely geological data without much reference to new age data and geophysical studies. Two of the most recent by Brock (in press) and Dixey (in press) give reference to others.

In 1948 Holmes made a first attempt based upon the study of age determinations, to subdivide the basement of Africa into its constituent old mountain belts. This was extended by Holmes and Cahen in 1955 and again in 1956. The latest work is based on about 400 African age determinations (Figure 10). They suggest that the Mozambique belt which extends from Abyssinia to Mozambique is made up of primary arcs of late Precambrian to Cambrian age. These seem to connect with the secondary early Palaeozoic arcs of Natal and Cape Province. These in turn very probably connect with the latest Precambrian and early Palaeozoic belt which appears to extend from southwest Africa north along the coast to Nigeria. The intrusives there have been likened to those of the Appalachians (Greenwood, 1951).

The northward extension into the Sahara is unknown, but this young belt separates the old, gold-bearing continental nucleus of Gold Coast and Sierra Leone from the nucleus in north Belgian Congo.

Thus it seems likely that at the beginning of Palaeozoic time the whole southern part of Africa, like North America and South America at a somewhat later date, was ringed by coastal mountains in a U-shaped pattern. The age of the mountains covers the same range as at least some of the rich Katanga mineralization. Of course this is a very radical departure from traditional views about African geology which were developed before any age determinations were available, but today radioactivity is too well established for age determinations to be ignored any longer. A little more research in this direction might lead to extensive reorientation in thought about the geology of Africa.

Four Ingredients in Successful Prospecting

Many case histories have shown that there are four ingredients to the best results in exploration: sound geological data, good geophysical data by appropriate methods, mathematical analysis, and geological experience and insight.

The view is advanced here that the same four ingredients are necessary in studying the earth as a whole. Geological data have been available in increasing amounts for some time, and so has geological insight and judgment, but they apply to a very limited part of the earth—only a quarter of its surface, and with accuracy only to the last 11 per cent of its history (0.5 out of 4.5 billion years).

Furthermore, that part of the earth with which the geologist has to deal, is its most complicated part, its surface upon which there have been irregular extrusions of lava and complex local transport of material by water. The application of mathematical analysis to geological data has rarely proved practical. Attempts to find out about the greater part of the earth, its ocean floors and its interior, have had to await the development and widespread application of geophysical methods of exploring the earth. These data have been abundantly available only during the past ten years, and will accumulate much faster during the present International Geophysical Year.

These geophysical data are much more amenable to mathematical and physical analysis than geological data have been. Earth scientists are on the threshold of being able, for the first time, to know what the whole earth is like and to analyze its behaviour.

Naturally geologists have always wanted to be able to do this. As one standard text put it: "The science of geology strives for the full answer to questions about the earth and its history. What are the materials that compose the earth, not merely in its outer parts but also in the deep interior? What is the meaning of mountains and other landscape features? How and when did the earth itself originate?"

Unfortunately, the traditional methods of field mapping alone are not powerful enough to tell more than part of the story. To find out about the interior of the earth, to date the oldest rocks, to explore the ocean
Figure 10. Some structural features of Central and South Africa. The basic intrusive shown in the Orange Free State of South Africa is hidden by Karroo sediment.
floors, require the help of physical methods. It may well be that geophysics is but a part of geology, although it might be argued also that geology is more truly a specialized part of geophysics, but debate about this is irrelevant to the obvious fact that in future those geologists who wish to study the whole of their subject must learn to use and understand geophysical studies of the earth. They are already having to do this in prospecting.

It would be equally wrong to go too far in the opposite direction. The physicist who generalizes about the earth’s crust without an understanding of geology is as much liable to error as the geologist who generalizes about the earth’s interior without a knowledge of physics. Before many physical data about the earth were available, physicists had little guidance on what assumptions to make and were in the habit of departing upon theoretical journeys whose conclusions were as dubious as their starting premises. Now for the first time there is promise of a real opportunity to knit together the four essentials—geological data, geophysical data, geological judgment, and physical theory—and to find out what the earth is really like and how it operates.

May the publishing of this volume of case histories in geophysics be a contribution which will advance man’s knowledge of the earth and improve his exploration tools for discovering deposits therein.

REFERENCES

Adams, F. D., and Barlow, A. E.: Geology of the Haliburton and Bancroft Areas; Geol. Surv., Canada, Mem. 6, 1910.


A—Magnetic

THE COMPASS AND THE MAGNET
by W. George Wahl*

The compass or magnetized needle was the first geophysical instrument devised by man. There are legends that the Chinese knew the use of the compass 2,000 years before Christ, but the first authentic description of the instrument was written in the 12th century, and in the 17th century the basic concepts of magnetism, that is, what it is and how it acts, were described.

A magnet may be described as a piece of iron or iron alloy with the power to attract other bits of the same material. This power is called magnetism and is the physical property applied in geophysical prospecting instruments such as the compass, the dip needle and the magnetometer. Even the magnet itself is a useful tool in prospecting for some types of ore.

A Natural Magnet

A lodestone (the mineral magnetite) is a naturally occurring magnet. If a piece of lodestone is dipped into powdered magnetite or iron filings, it will be observed that fine particles will be concentrated in two separate spots, usually directly opposite each other. If the sharp end of a needle is stroked repeatedly in the same direction across one of these spots, it will be noticed that the needle becomes a magnet. If this needle is suspended by a fine thread it will set itself in a north-south direction and point downwards to the north. Regardless of how the needle is moved it will always return to the same position, thus showing there is a directional force. The end pointing towards the north is referred to as the North pole, and that pointing to the south, the South pole. The earth acts as a huge magnet, and the magnetized needle aligns itself in the earth's magnetic field. This field may be resolved into two components, a horizontal and a vertical force.

The needle will not point directly toward the geographic or true north, as the earth's north magnetic pole is found on Prince of Wales Island, District of Franklin, Northwest Territories.

The horizontal angle between a suspended needle and true north is referred to as declination, or variation of the compass. The vertical angle between a suspended needle and the horizontal is called the angle of dip or inclination.

The dip needle is used to measure the angle of dip or inclination. The vertical magnetic force is measured with a magnetometer. The direction of the horizontal magnetic force is measured with a compass.

Identifying Minerals

All field men should be equipped with a compass, the simplest of all geophysical instruments. With it certain minerals can be identified, and certain rock types and buried geological contacts can be mapped.

Magnetite (a black oxide of iron) and pyrrhotite (a reddish-brown sulphide of iron) are two minerals which, when placed near a compass, will readily attract

*Consulting geologist-geophysicist, Toronto, Canada.
the needle. Franklinite, (an iron-zinc manganese oxide); chromite, (an iron-chromium oxide) and ilmenite, (an iron-titanium oxide) are minerals which attract the compass needle only feebly. When testing the magnetic attraction of a mineral, it is best to set the compass on a level place and bring the specimen up to the needle several times and in several different positions.

To trace buried formations with a compass, there must be a great relative difference in the magnetic attraction of the rocks so that the difference in attraction is readily apparent. This can be tested by bringing samples up to the compass and noting the deflection of the needle. If one sample moves the needle a great deal and other does not, a magnetic difference exists and can be mapped.

Although there may not be enough magnetite in the hand specimen to move the compass, the whole mass of a large formation may contain sufficient magnetite to deflect the compass.

Making the Survey

To test the magnetic differences between large rock areas and to map formations and contacts with a compass, the following field procedure is recommended.

Cut a picket line across the contact or formations, making sure that the line is long enough to extend well beyond the contact or beyond the formations to be mapped. Beginning at one end of the line, take the compass bearing of the line accurately every 100 or 200 ft. and record the readings. Small changes of 5° to 10° in the bearing of the line (i.e. deflection from normal) will indicate that there has been a change in the magnetic character of the underlying rock and very possibly there has been a change in rock type.

The deflection of the needle may be great, as shown in the accompanying figure. In this instance the bearing of north-south picket lines was taken at 100- and 200-ft. intervals across an iron-formation. The direction taken by the compass needle is shown by small arrows.

Diabase dykes, gabbros, syenites, granites, slates, and volcanics, as well as iron-formations, have been mapped in this manner.

If very strong magnetic deflections are observed over a small area, the chances of a local concentration of magnetite are great, but whether it is ore grade or not, can be determined only by sampling or drilling.

Using the Magnet

The common horseshoe or the bar magnet can be used by the prospector to great advantage, and because of their greater strength be of better use than the compass in identifying the minerals previously listed. They can be used to determine the amount of magnetic material present in a rock.

In using a bar or horseshoe magnet to identify minerals three methods may be followed: one is to balance the magnet delicately and bring the sample to the magnet; a second is to suspend the magnet on a string and move it to the sample; a third method is to powder the sample and test with the magnet. A surprisingly small amount of magnetic material can be detected by the third method.

To determine roughly the amount of magnetic material present in a sample, first crush sufficient material, then make a thorough separation by pulling the magnet through the sample several times, cleaning the magnet after each pass. When no additional material is picked up, compare the amount of concentrate to the amount of tailing.

The compass and the magnet are the basic tools used in geophysical prospecting to detect the presence of magnetic forces. The dip needle and the magnetometer are more sensitive refinements of these instruments.
THE DIP NEEDLE
by E. W. Westrick*

The original dip needle was known as a "dip circle", and consisted of a delicately balanced magnetic needle pivoted on a horizontal axis. With the balancing of the needle parallel to the magnetic meridian, the needle would align itself with the earth's magnetic lines of force (magnetic field), and thus provide a measure of the angle of dip of the earth's magnetic field.

The dip needle currently used for prospecting is a variation of the dip circle, in that the needle is provided with a movable counter-weight attached to one end. The counter-weight balances the needle at an arbitrary angle to the inclination (dip) of the earth's field when the dip needle is oriented in the plane of the earth's field. The use of the counter-weight introduces a gravitational force which acts on the needle along with the magnetic force. The gravitational force is relatively constant from one area to another, while the magnetic force varies in direction and intensity from one observation point to another, thus varying the position of rest of the needle.

Remove Metallic Objects

The counter-weight is so placed that the effect of the gravitational force opposes that of the magnetic force acting on the needle, and this makes it possible to rebalance the needle to a near horizontal position for the area being surveyed. The needle is balanced thus to increase its sensitivity.

It is very important in using all forms of magnetic instruments that the operator exercise extreme care in demagnetizing himself. Any pieces of iron on his clothes or body will affect compasses, dip needles and magnetometers, causing them to give false readings. Therefore, the individual should be sure his key chain, pocket knife, belt buckle, geological pick and other metallic objects are sufficiently removed from the dip needle that they do not interfere with the readings.

The dip needle readings will show the relative changes in the intensity or dip in the earth's magnetic field. Therefore, it is important that an operator establish a routine procedure in making observations, so that the only relative changes the dip needle reads are the changes in the earth's magnetic field.

Readings on the dip needle are taken with the instrument oriented so that the needle is swinging in the plane of the earth's magnetic field. This orientation and the reading may be obtained by the following procedure:

1. Hold the dip needle flat so that the needle is swinging in a horizontal plane and release the needle;
2. Observe the direction of magnetic north;
3. Get a firm footing facing magnetic west;
4. Raise the instrument to a position directly in front of the face so that the needle will swing in a vertical plane, thus making sure the vertical plane of the instrument is common with the plane of the earth's magnetic field;
5. Read the position of the north end of the needle;
6. When the position of the north end of the needle is below the horizontal the reading is given a plus sign. When it is above the horizontal the sign is negative.

A significant anomaly as indicated by a dip needle will vary with the geological problems to which it is applied. Bands of magnetite will cause strong anomalies while diabase dykes may give only a few degrees deflection.

Mapping the Results

If extreme care is exercised in manipulating the dip needle, the data that are observed may be plotted on a map and contoured. Let us assume that dip needle readings are observed at 200-ft. intervals along picket lines spaced at 400-ft. intervals and that the points of observation are carefully located. The locations of the observations can then be plotted to scale on a map and the actual dip needle readings plotted at the respective locations. Contour lines may be drawn to join readings of approximately the same magnitude and thus extend the effectiveness of the observations, as shown in the accompanying figure. One must, of course, exercise careful judgment in extrapolating such data.

There are many sources of error in the use of the dip needle which can be minimized by previous evalu-

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*Geophysicist, Dominion Gulf Company, Toronto, Canada.
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ation and care in operating. Some sources of error include the actual manipulation of the instrument, mechanical defects within the instrument, and certain magnetic factors.

Care Needed

Generally, the dip needle is held in the operator's hands, and its orientation and level are only approximate. Ideally, the instrument should be level, vertical, and exactly in the plane of the earth's magnetic field. Many dip needles are not provided with a level, but rely on near-level operations by suspending the instrument from a single point using gravity as a means of levelling. Experience has shown that the dip needle may vary up to 5° from vertical and up to 5° from being parallel with the earth's magnetic field before it affects the reading of the dip angle by as much as 1°. With a careful operating procedure, it is possible to place the instrument within 5° of being parallel with the earth's field and within a couple of degrees of the vertical, thus eliminating the effects of these errors.

Some of the mechanical factors that introduce errors in the operation of a dip needle are:

1. Defective bearings, such as pitted jewels, accumulation of dirt in the bearings;

2. Defects in the pivot point such as pits, irregularities, blunted ends;

3. Dust or particles of dirt between the jewels and pivot points;

4. Gradual demagnetization of the needle.

Recognizing Defects

The effects of defects can be observed in the use of the instrument. A failure of the dip needle to repeat its readings at any given location, the irregularities of the swing of the needle as it comes to rest, and any jerkiness in the needle are warnings of faulty operations, and when noticed should be taken into consideration in future use of the instrument, until such time as it can be repaired by a competent repairman.

The dip needle is most readily applicable to rapid reconnaissance investigation—for magnetic anomalies which in turn are associated with, or reflect, geological structures, rock types or mineral distribution. The dip needle is particularly applicable for locating ironformation: tracing faults in highly magnetic material; tracing dykes, and igneous contacts; and assisting in delimiting the scattered outcrops in general geological mapping. It is an invaluable aid to the prospector.

REFERENCES

Haanel, Eugene: On the Location and Examination of Magnetic Ore Deposits by Magnetometric Measurements, Department of the Interior, Ottawa, Canada, 1904.


THE MAGNETOMETER

by D. W. Smellie* and C. W. Faessler†

Magnometers designed for scientific observatories appeared about 100 years ago, but it was not until 1915 that Adolph Schmidt designed the first field instrument, which still stands as the basic model for nearly all magnetometers. It was a magnetic balance with a magnet pivoted near, but not at its centre of mass.

The magnetic field of the earth acting on the magnetic poles at the ends of the balancing element creates a torque around the point of support. This torque is balanced by a torque created by the gravitational pull on the centre mass of the element. An adjustable weight provides for varying the gravitational torque, or what is known as a “latitude adjustment”. A similar adjustable weight mounted on an aluminum screw provides for variable temperature compensation for the instrument. The balancing element is supported by a quartz knife edge resting on highly polished cylindrical quartz bearings, thus making a very sensitive measuring device. A small, adjustable screw permits raising or lowering its centre of gravity, thereby increasing or decreasing the sensitivity of the balance. The deflections of the magnetic balance, read by an optical system, are directly proportional to the magnetic field variations for small-scale deviations. The most commonly used magnetometer is the vertical force variometer which measures the variation of the vertical component of the earth’s magnetic field. Horizontal intensity instruments are useful in low geomagnetic latitudes.

The Schmidt type magnetometer combines precision and sensitivity with ruggedness. It can be adjusted to make readings to a precision of about 2 gammas; the gamma is a unit of magnetic intensity equal to $10^{-5}$ oersted. The workings of the magnetometer are delicate and should be adjusted by specialized technicians.

Magnometer surveys in mining exploration normally are done on traverse lines 400 ft. apart with initial reconnaissance readings at 100-ft. intervals along the lines. Detail in interesting areas usually is on lines 100 or 200 ft. apart and with readings at 25- or 50-ft. intervals.

The earth’s magnetic field changes constantly in a more or less regular daily pattern, known as the “diurnal variation”. This variation may range from a few gammas amplitude in low geomagnetic latitudes to variations of thousands of gammas in the near-polar areas during magnetic storms. All magnetic data should be corrected for diurnal variations. Should the geophysicist deem that the diurnal variations during any particular survey are likely to be small in comparison with the magnetic variations being measured, he may elect to dispense with the diurnal variation corrections, but this must be done with care.

Diurnal variations may be measured by reading a base station instrument at regular time intervals throughout the day, or by checking the field instrument at a base station frequently throughout the day. The accuracy required of the survey generally will be the deciding factor in determining whether or not a base station instrument is used. The diurnal variations are plotted against time to provide a curve for correcting the field station data.

Interpretation

The earth’s normal magnetic field varies in total intensity from about 0.3 oersted at certain points near the magnetic equator to about 0.6 oersted near the magnetic poles. In addition, the inclination or dip of the field varies from zero on the geomagnetic equator to 90 degrees at the geomagnetic poles. It is tilted downward in the northern (magnetic) hemisphere and upward in the southern and this gives rise to a change with latitude of the intensity of both the horizontal and the vertical components. Besides this broad latitude change, the magnetic field components are affected by contrasts in the magnetic properties of rocks in the area. In mining areas, the rock formations showing contrasts in magnetic polarization are close to the surface, and changes in magnetic intensity occur within a few hundred feet. Even more local changes, within a few feet, can be caused by contrast in magnetic polarization between portions of the same rock type, such as the banding found in ultrabasic sills. Iron-formation also gives rise to rapid spatial changes in intensity. Magnetic bodies give rise to magnetic field variations over horizontal distances of the order of the depth to the body. Deeply covered magnetic bodies may be masked by extraneous magnetic effects nearer the surface.

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*Consulting Geophysicist.
†Geophysicist, Hunting Technical and Exploration Services Ltd.
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Theoretical curves showing the magnetic field variations caused by magnetized vertical dykes and inclined tabular bodies are of great value in interpreting anomalies due to various geological features. Curves showing the magnetic effects of magnetic poles, polarized spheres, lines of poles and polarized cylinders are of value in estimating depth, dimensions and magnetization of certain orebodies. Thus anomalies of possible economic significance can be sorted out from the many closures obtained on a magnetic contour map.

Application

The ground magnetometer has been used in the search for orebodies, and to outline geological conditions masked by cover. It may detect directly magnetic orebodies, such as magnetite and complex sulphide deposits containing pyrrhotite. Examples are the Marnora magnetic deposit and the Quemont sulphide deposit, both in Eastern Canada. A second type of deposit that may be discovered by the magnetic method is one associated with a magnetic rock or magnetic alteration such as asbestos-bearing serpen-
tine. Thirdly, the magnetometer is used to locate concealed ore-bearing horizons when they lie at a known distance from a magnetic marker horizon. In the Cadillac district of Quebec, ore zones have been found adjacent to iron-formation bands. The magnetometer was also used in this way to trace the westward extension of the Witwatersrand in South Africa.

The foregoing examples deal with ore directly or indirectly associated with magnetic anomalies but the usefulness of the ground magnetometer is far from limited to such cases. In mining areas like the Canadian Shield where most geological formations are upturned and concealed by glacial deposits, an important application of the ground magnetometer is to outline geological structure and formations under the mantle of overburden.

REFERENCES


THE AIRBORNE MAGNETOMETER

by H. S. Scott*

The rapid industrial development of this century has increased demands upon sources of mineral materials, emphasizing the need for successful prospecting, which in turn relies increasingly upon sound geological knowledge of potential mineral areas. The traditional geologist, working by ground methods alone, has been hard pressed by the prospector, who now requires geological guidance in new areas of search. New, faster methods are necessary if the present pace of mineral development is to be maintained.

Some use was made of visual aerial reconnaissance as early as the 1920's. Aerial photography was useful from its inception, not only as a means of locating oneself and navigating on the ground, but for base mapping. More recently, aerial photography has been widely adopted for geological interpretation.

The breakthrough into successful airborne geophysics came only during World War II, when the airborne magnetometer was developed and employed by the United States Navy for submarine detection. It was developed in cooperation with several large electronics laboratories, notably that of Gulf Research and Development Company. Such was the incentive created by the development, that three additional methods of geophysics took to the air in the next decade.

Immediately after the war aeromagnetic surveying was applied to petroleum exploration, and then to exploration for metalliferous deposits. Results were encouraging in both fields, and its acceptance increased until the method is now commonplace in many branches of geological work.

A number of government geological organizations now conduct regular programs of aeromagnetic surveying. The Geological Survey of Canada, for example, since 1947 has published more than 700 aeromagnetic sheets covering a total area of approximately 2½ million square miles, and this work continues. (See Figure 1).

*Photographic Survey Corp., Ltd., Toronto.
Mining and petroleum companies have covered large areas of Canada and many parts of the world by aeromagnetic surveys. In the near future, after little more than a decade since its inception, the area of aeromagnetic mapping done in Canada may well exceed that of geological mapping at the equivalent scale. Other countries are recognizing the importance of the new data, and surveys are being conducted far afield.

It should be evident from these observations that "aeromagnetics" is here to stay, and that sooner or later everyone engaged in the search for mineral resources should be familiar with the method, its capabilities, its limitations, and its results. This chapter presents a brief review of the method and its applications.

The Popularity of Aeromagnetic Surveying

For many years geologists tended to regard geophysics with skepticism and suspicion. It is therefore gratifying that aeromagnetic surveying was warmly welcomed by most geologists almost since its inception. Indeed, the enthusiastic adoption of the airborne magnetometer by the exploration industry is without precedent.

The day of random prospecting is gone. Most outcrops within a reasonable distance of civilization have been examined in at least cursory fashion, and the prospector must turn either to more remote outcrop regions or to the vast areas of covered ground, where he is faced with the problem of overburden, whether
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glacial drift, water, sand, ice, or tropical residual soil. Even areas of bare rock may hide valuable clues to the mineral deposits below.

Exploration commonly begins with the geological mapping of large areas, to define zones of greatest promise. In general, the reliability of this work varies with the distribution of outcrops, for the observed data must be interpolated across covered areas.

Any means whereby the initial geological understanding of an area can be improved, and extended reliably into covered ground, deserves careful consideration. It was largely to meet this need that exploration geophysics was developed. Ground geophysical methods are detailed and flexible, but tend to be slow and expensive, and are usually confined to much smaller areas than is geological mapping itself. The airborne magnetometer goes a long way in helping to fill in the blank areas on a regional geological map.

In comparison with magnetometer surveying on the ground, the airborne magnetometer offers these advantages:

i. Almost any area is accessible, ground conditions being of little or no importance.

ii. The rate of survey is much faster.

iii. The cost is about one tenth per unit of profile.

iv. Measurements are continuous, automatically recorded, and of high precision.

v. Minor magnetic variations originating near surface are reduced or eliminated. It follows that the airborne magnetometer responds to conditions over a greater area, according to the flying height; in other words, it gives less resolution than the ground magnetometer.

vi. Areas surveyed are necessarily large, giving the advantages of broad interpretational techniques and concepts.

The last two factors favour the ground survey, when the requirement is for a detailed survey of a small area. The cost of such a ground survey is relatively small, although the cost per mile of profile is nonetheless much greater than that of aeromagnetic profiles covering a larger area.

The Instruments

Various types of airborne magnetometers have been devised, operating on different principles. None are based upon the ground magnetometer principle, in which a magnet system is delicately balanced against gravity.

Most airborne magnetometers measure variations in the earth’s total magnetic field. This is a fundamental and important distinction from ground instruments, which commonly measure the horizontal or vertical component only. Aeromagnetic results should not, therefore, be compared directly with ground results, and interpretational theories differ for the two methods.

The Gulf airborne magnetometer has achieved first place in aeromagnetic survey work. Briefly, it comprises an ingenious detection unit known as a “fluxgate”. Two adjacent strips of high magnetic permeability alloy are centred in coils, each wound in the opposite direction. An alternating current passing through these coils thus produces opposite polarities in each, and a coil surrounding both units will register no electromagnetic field. However, if an external magnetic field (the earth’s) be applied, the fields from the two primary windings will no longer balance each other due to the magnetic saturation effect in the cores of the coils, and a current will be generated in the secondary coil. The characteristics of this current form the basis of the magnetic measurement. The detector head incorporates two additional mutually perpendicular detectors, the trio being mounted in gimbals. The additional detectors actuate small motors which keep the principle detector aligned with the earth’s field.

The detector unit is either mounted on the aircraft, towed behind on a cable, or carried by helicopter. In common with all airborne magnetometers, the results are plotted automatically as a profile on a moving paper graph.

Recently the nuclear precession magnetometer has appeared. Here the sensitive unit is merely a bottle of water surrounded by a wire coil. Its operation depends upon the precession, as with a gyroscope, of atomic nuclei, which behave as tiny magnets. These tend to spin about and align with the prevailing magnetic field. A very strong magnetic field is created by direct current in the coil, approximately at right angles to the earth’s field, at short, regular intervals. When the current is turned off, the nuclei precess under the influence of the earth’s field, producing an alternating
current in the coil. The frequency of this current gives an accurate measure of the earth's field.

Other magnetometers use rotating or vibrating coils, the current so produced being a function of the external magnetic field.

The airborne magnetometer requires certain ancillary apparatus. Of prime importance is the positioning camera, usually designed for 35-mm. film and mounted vertically. Exposures are made automatically at regular intervals, and are numbered to correspond with fiducial marks on the aermagnetic profile. In some installations a continuous strip camera is used.

Commonly the aircraft is equipped with a radio-altimeter, to help the pilot maintain the correct ground clearance. If this instrument is of the recording type, it may also be of value in certain problems of interpretation.

In some survey work, a recording total field magnetometer is operated at a fixed base on the ground throughout the survey. The results from this are used in correcting the survey records for diurnal magnetic change, and to warn against magnetic storms which can render survey records valueless.

Survey Practice

Typical procedure for mineral surveys is to fly parallel lines across the regional geological trend, usually a quarter-mile apart. Half- and one-mile spacing is permissible, depending upon the requirements for detail of the survey. The flying height (ground clearance) for most mineral surveys is 500 ft., or occasionally 1,000 ft., again depending upon requirements of detail. The pilot attempts to maintain the specified clearance, but with most topographic relief some deviation is unavoidable. Petroleum surveys are commonly flown at a constant altitude (barometric); this practice is infrequently applied to surveys in areas of "hardrock".

After completing the survey lines, the aircraft flies widely spaced, transverse tie-lines, by means of which diurnal magnetic variations and instrument drift are reduced. A recording instrument on the ground may reduce or eliminate the need for tie-lines.

The navigator follows the required flight lines as marked on an aerial photographic mosaic, or upon a detailed map. The positioning camera is operated during flight.

Reduction and Plotting of Data

The magnetic profiles are corrected according to the tie-lines or other control data, and then adjusted for horizontal control (variations in ground speed). This requires the correlation of numerous points on the positioning camera photography, with the mosaic or base-map. The corrected profile data are then transferred in terms of intensity values (gammas) to the map, and contoured at specified intervals. Contour intervals of 10 or 20 gammas are commonly used, except where steep magnetic gradients necessitate wider intervals.

Such contour mapping is sometimes referred to as interpretation. However, with a sufficient density of flight lines and proper flying height, the interpretational element should be small. "Interpretation" should be reserved for much more variable stages in which the aermagnetic results are converted into geology.

The Significance of Aeromagnetic Data

Aeromagnetic surveying has two principal modes of application in mineral exploration which, although described separately here, should always be treated together in practice.

a) The direct detection of economic mineral deposits. This is the less important application. Mineral deposits may or may not be appreciably magnetic. The great majority are not, and this fact should help to reduce the enthusiasm commonly generated by the discovery of magnetic "anomalies".

Magnetic prospecting methods were developed originally to aid the search for magnetite, which is by far the most strongly magnetic of minerals. Ilmenite is slightly magnetic, and it appears to have a peculiar tendency for reverse magnetization which may aid in its detection. Franklinite, a weakly magnetic zinc mineral, is restricted to one known important locality in Canada.

Any ore that occurs in close association with a magnetic mineral is also amenable to direct discovery by magnetic means. Thus magnetic plays an important role as an indicator. In a similar category, the magnetic sulphide pyrrhotite is a valuable guide, for it is commonly an important constituent in copper and nickel sulphide ore. Pyrrhotite is a relatively strongly magnetic mineral, although less so than magnetite.

Where the ore being sought is non-magnetic, as compared with its surroundings, magnetic surveying
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may still prove useful. This is a negative sort of application which relies heavily upon other local evidence for correct interpretation.

b) The interpretation of general geology. In this lies the main application of aeromagnetic surveying. The airborne magnetometer has in a few short years established itself as the ideal complement to reconnaissance geological mapping. It provides a base of continuous data, regardless of whether it is flown over bare rock or overburden, for areas of great extent. In this respect it surpasses geological mapping itself. Aeromagnetic data are related to fundamental properties of the underlying bedrock, namely the magnetic properties, influenced by several factors such as variations in the distance between the source of magnetic changes and the measuring instrument. Unlike much geological observation, the measuring and recording of aeromagnetic data are not subject to personal experience and prejudice. Not even the best geological maps provide such a continuity of reliable observation.

The means by which the geological interpretation is made are discussed in the following section of this article. It is sufficient to note here that while they are the field of the geological-geophysical specialist, they are based upon common sense and experience, and most persons involved in mineral exploration can derive benefit by a careful study of aeromagnetic maps in the region of their interest.

Interpretation

The interpretation of aeromagnetic data may be considered under two headings: a) quantitative and semi-quantitative treatment, and b) qualitative treatment. In general, the former is applied to anomalies of possible direct economic significance, the latter having its principal use in general geological interpretation.

• Quantitative Treatment

This is the realm of the scientific prospector. It is concerned mainly with deposits of magnetite and pyrrhotite, and to a lesser extent with ilmenite, although the occurrence of other economic minerals associated with magnetic accessories may warrant quantitative assessment of the related aeromagnetic data.

Theoretically, a buried body of regular shape and uniform magnetic properties, in a host of uniform but contrasting magnetic susceptibility, can be defined geometrically by its anomalous effect upon the earth's magnetic field. That is, its dimensions, attitude, and even magnetic susceptibility can be determined with practicable accuracy. Much study and experiment has been devoted to this aspect of aeromagnetics, and the methods developed range from complex mathematical procedures, through calculations based upon "models" of possible conditions, to relatively simple rules of thumb.

For example, in assessing the relative importance of similar anomalies in magnetic prospecting for magnetite, W. G. Wall (personal communication) records the peak intensity of each significant anomaly and divides by its surface area. The resulting intensity per unit area offers a rough comparison of the magnetite content responsible for each anomaly.

![Figure 2. An example of a well-behaved anomaly in Newfoundland.](image-url)
Most quantitative investigations have been carried out for surveys at fairly high magnetic latitudes, and much remains to be done. Very little is known of the possibilities of quantitative analysis in low magnetic latitudes.

In combination with other geophysical data, as for example gravimetric, it is often possible to derive more quantitative information from an aeromagnetic anomaly than would otherwise be possible. The tonnage of several magnetic deposits has been calculated in this way before drilling.

- **Qualitative Treatment**

This is the field of general geology, the importance of which, as a background for mineral exploration needs no elaboration. The magnetometer helps to identify various rock units, and to outline their spatial relationships; this is equivalent to the geologist's mapping of lithology and structure.

**Lithology.** Most rocks contain a small percentage of the ubiquitous mineral magnetite, which for any one formation or body tends to be characteristic in amount and distribution. Dogmatic rules on this aspect are likely to be misleading, as a little experience will demonstrate. The best approach is to correlate known rock occurrences in the aeromagnetic map area with the magnetic map, to establish the characteristic intensity and pattern of the field. Magnetic susceptibility tests on field specimens are also helpful, if the specimens are truly representative. In the absence of known outcrop, however, some general considerations will prove helpful if used with proper caution.

![Figure 3. Two types of diabase cutting sedimentary strata in northern Ontario. The quartz diabase causes very little magnetic disturbance, and only the low magnetic relief of the country rock permits the identification of these dykes.](image)

Among *igneous intrusives*, the more basic rocks tend to have more magnetite, but there are some startling exceptions, as for example a granite with more than 10 per cent magnetite, and a "non-magnetic" serpentine. The associated magnetic field is typically quite uniform, with any prominent linearity parallel to the principal contacts; this is particularly true of sills and dykes (Figure 3). There may be low magnetic relief of a highly irregular pattern. The outline of the rock unit is commonly the best clue (Figure 4) to its intrusive nature. Individual bodies of the same rock type, occurring within a single geological province, tend to show similar magnetic characteristics.

![Figure 4. Aeromagnetic contours outlining a large granodiorite intrusive in Newfoundland.](image)
It is important to note that even where a formation cannot be identified by aeromagnetic interpretation alone, it is often possible to outline its extent and approximate nature—for example, whether it is a volcanic or intrusive rock. This will suffice to proceed with a general structural interpretation, and later field work may be planned to identify the formation specifically.

Structure. It follows that if the distribution and extent of the principal rock units in a region can be outlined, some general observations relating to their structure may then be made; the illustrations with this chapter demonstrate that statement.

Strike trends, folding, and faulting should be apparent, and they should be traced in preliminary fashion.

Volcanic rocks may be recognized generally by their contrasting susceptibilities from flow to flow, or across a single flow. The occurrence of parallel, linear anomalies is characteristic (Figure 5). Like igneous intrusives, the more basic varieties are apt to be the more magnetic.

Sediments are generally very low in magnetite content, with the outstanding exception of banded ironformation. There may be faint magnetic lineation of low relief, but otherwise these rocks underlie the open areas in a contoured aeromagnetic map (see Figure 3).

Metamorphism may affect a wide range of rock types in many different ways, so that few observations of general applicability are justified. In some rocks, magnetite may be developed from the effects of an adjacent igneous intrusive, thus helping to outline the intrusive (Figure 4). Magnetite may or may not form in a shear zone. Serpentization of ultrabasic rocks commonly produces a considerable amount of secondary magnetite (Figure 6), but exceptions occur. Granitized gneisses are generally of rather uniform magnetic character, with faint lineation parallel to the gneissosity (Figure 7).

Figure 5. Aeromagnetic contours outlining a belt of basic volcanic rocks, to the left.

Figure 6. Plan and profile showing the magnetic field over a serpentined peridotite sill in Newfoundland. The curves fill the theoretical requirements quite closely.
At this stage the aeromagnetic data should be studied for more details of structure. Faults may be outlined by displaced magnetic features, if displacement is sufficient. They may also be marked by a zone of magnetic anomalies, which are related to metamorphic changes in the fault zone, or may be related to the fact that when a magnetized horizon is broken, polarity tends to be concentrated near the break. In many cases the dip direction of a contact may be determined (Figure 6) and its approximate value estimated.

Several of the aeromagnetic examples illustrating this chapter have appeared in previous papers, but no apologies are offered because a good example never loses its value. With the exception of Figures 3 and 7, they were extracted or redrawn from a survey flown in 1950 for the Government of Newfoundland, which has kindly granted permission for their publication.

Concluding Remarks

The interpretation of aeromagnetic maps themselves cannot be unique; there are too many unknown variables in the interpretational equation. It is therefore important that the maps be studied in conjunction with data from other sources, but preferably of similar broad coverage. These include the compiled geology of large areas, other geophysical methods (particularly airborne electromagnetic survey), and aerial photography.

Aerial photographs are ideally suited to narrow down the degree of freedom of choice in aeromagnetic interpretation. Where for example the aeromagnetic data suggest faulting, the geological interpretation of aerial photographs will often show the surface expression of the fault (or faults), enabling the position and direction of faulting to be established. Similarly, mutual support may be obtained for postulating the presence and position of contacts, general strike, folds, dips, and the general nature of rock types.

Aeromagnetic surveying will continue to play a role of increasing importance in mineral exploration. The broad geological concepts which in the past have had to await many years of detailed mapping, are to some extent available in advance through this new field. Detailed geological observations may assume greater significance in the broader setting.

It must be remembered of course that interpretation from any source remains as a working hypothesis until it is substantiated in the field. It is strongly recommended that maps incorporating aeromagnetic or other interpretations should distinguish the source of all pertinent features. In this way the advantages of

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**Figure 7.** Typical total intensity field over Grenville-type gneisses in Quebec.

**Figure 8.** The abrupt horizontal displacement of magnetic contours is indicative of a fault in the underlying rocks.
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interpretation can be realized, without falling victim to the inherent dangers.

To obtain an initial geological appreciation of the area covered in a typically large aeromagnetic survey, it is extremely useful to reduce the results to a much smaller scale, such as one inch to four miles or more. Major features in particular are stressed, that might otherwise fail to be noted in the detail of individual, large-scale map sheets. Even the most complex portions of the survey tend to assume significance in the regional pattern. This procedure is ideal as a preliminary step to detailed interpretation, and it helps to make use of, perhaps, the most valuable contribution of aeromagnetics—broad, continuous measurement of a fundamental physical property of the formations in an area.

REFERENCES


Methods

B—Gravitational

GRAVITY METER SURVEYS
by Roger Pemberton

Fundamental Principles and Units

GRAVITY meter exploration falls in the category of "direct" geophysical procedures by which natural physical forces are measured at the earth's surface without the application of an artificial extraneous field.

Modern gravimetric surveying consists of measuring minute variations in the pull of attraction between a small mass and the earth. This pull is termed the force of gravity.

Everyone is familiar with the action of the force of gravity. We have all learned, perhaps unknowingly; that it is a fundamental property of matter. Sir Isaac Newton first stated the law governing the force of attraction in the year 1686.

It may be repeated: "Every particle of matter in the universe attracts every other particle with a force which is directly proportional to the product of the masses of the particles, and inversely proportional to the square of the distance between them."

This means simply that the closer two masses are to each other, and the larger they are, the greater is the force of attraction between them. Each time we weigh ourselves we actually are measuring the gravitational force or attraction between ourselves and the earth. In fact, if a sensitive weighing device were employed, it would be possible to measure the attraction between ourselves and a nearby mountain.

The instruments used now are capable of measuring extremely small differences in gravitational force. A good field instrument will measure to one part in 100,000,000; a massive sulphide orebody of 50,000 tons at a depth of 200 ft. in greenstone would give rise to an anomaly of about 1/100,000,000 of the earth's total gravitational force and hence is the minimum size of such an orebody likely to be detected at this depth.

As a force-measuring device, a gravity meter is therefore many times more sensitive than the finest chemical balance, and yet is sufficiently rugged for field use.

One common type of gravity meter may be likened to a spring balance. With this instrument, a mass is suspended from a spring; the stress on the spring depends on the attraction between the earth and the mass. Minute variations in the length of the spring are measured by optical and mechanical devices. The measurement of the length of the spring is proportional to the force of gravity at the point of observation and is usually expressed in terms of milligals, one milligal being roughly equivalent to one millionth of the total gravitational force at the surface of the earth. Modern field instruments will measure variations in the force of gravity of one hundredth of a milligal.

A number of reliable instruments are available today and the particular purpose for which the operator wishes to use the gravity meter mostly governs the type he uses. For instance, an operator might employ
one type for underwater surveying, where requirements call for a rugged and completely electronically operated instrument; another type where the survey can be conducted along a network of roads with the instrument mounted in a vehicle; and perhaps a third where the survey is to be over mining claims in bush country where portability is of prime importance.

**Application of Gravity**

The application of gravimetric surveying as an exploration method depends on the existence of differences in density between geological bodies and their surroundings. Any sub-surface structure of higher density than its surroundings will exert a greater gravitational pull which will add to the normal earth's force of gravity in its vicinity.

A positive gravity anomaly, or an area of greater gravitational force, indicates the presence of higher-density material beneath the anomaly than that surrounding it. A negative anomaly, on the other hand, indicates lower-density material beneath the anomaly.

Suppose, for instance, there is below the surface of the ground a large mass of very dense material, such as a massive sulphide body, surrounded by rock of lesser density; because of the mass of the denser body, the force of gravity directly over it will be greater than it will be to either side. Figure 2 illustrates the increase in the force of gravity caused by a lens of massive sulphide.

The gravity meter has been used mostly in oil exploration, to outline regional geological features, to determine basement topography, and to locate buried ridges. Because of its high degree of accuracy and the speed with which it can be operated, it is also used for more local problems of oil geology, for example, the detection and definition of domes, anticlines, salt domes and general structure.

Since the Second World War the gravity meter has been employed more extensively than before in the mining field, primarily in the search for large, near-surface orebodies. It should be noted that a heavy subsurface body not only is detected but actually is weighed, i.e., the excess density (or density deficiency) compared with surrounding rocks is used to determine the mass of the anomalous body. This mass determination is independent of any assumption as to shape, volume, and disposition. It can be translated to actual tonnage estimates by the appropriate assumption of densities for the mineral formation and the host rock.

Since 1953 the method has been used increasingly as a follow-up step to other geophysical techniques such as electrical, magnetic, seismic, geochemical, etc. It has become an invaluable aid in distinguishing massive sulphide bodies, electrically indicated, from graphite or sparsely mineralized zones.

**Field Procedure**

The procedure in any particular survey depends upon the object of the gravity program. In regional exploration for oil, the spacing of the gravity stations is usually such as to give a station density of one per square mile. For more detailed exploration where the object of the survey is to locate domes, anticlines, faults, etc., stations are usually at approximately 1,000-ft. intervals along available and suitably located roads covering the area; in cases where there are large areas without roads, cross-country lines must be run in order to divide the area into a reasonably close network of coverage.

In mining exploration the station interval for any particular survey will, in general, be much smaller than the spacing in oil exploration; for example, if the requirement is to trace an iron-formation, stations could be spaced at 100-ft. intervals along lines 600 to 1,000 ft. apart. To locate less extensive bodies, such as massive sulphide deposits, in an area of unknown rock types and geological conditions, the survey may be conducted with stations at 50-ft. intervals along lines 200 ft. apart. To check conductors located, for example, by electrical surveys, such as electromagnetic, resistivity or spontaneous polarization, lines may be
laid out across the interpreted conductor at right angles to the strike and extended 300 to 600 ft. on either side. Stations directly over the conducting zone should be at 25-ft. intervals, changing to 50-ft. intervals, and eventually to 100-ft. intervals, as the survey extends outward from the conductor.

In planning a gravity meter survey, gravity meter base stations are spaced as deemed necessary over the area to be surveyed. The gravity differences among the various base stations are determined by averaging several repeat observations at each. In the course of the survey all traverses are done in closed loops, returning to the base station once every hour or two. Base station observations provide data for plotting curves for use in correcting the observed data for instrument drift and diurnal variations of gravity.

The locations of the gravity meter stations may be surveyed by plane table or by transit. The elevations of the stations must be determined by accurate levelling. The surveying and levelling can be done independently of, or concurrently with, the gravity observations. These survey data are required to correct the observed gravity data.

For most gravity meters used in mining exploration, the actual time of setting up and reading the instrument is only a few (one to five) minutes. Normally, the instrument crew is one observer, but a helper may be used if conditions of weather or terrain are difficult.

Reduction of Data

Before there can be any interpretation of the nature of the subsurface, certain corrections must be applied to the observed gravity data:

(1) Because the gravity meter is sufficiently sensitive to be affected by the positions of the sun and the moon, the force of gravity at any particular station changes regularly throughout the day. The diurnal variation and the drift caused by instrument changes are measured by frequent observations at base stations throughout the day during the survey. The base station observations are calculated and plotted against time to produce a curve from which diurnal and drift corrections are read.

(2) Bouguer and free air corrections are applied to the observed gravity data to compensate for the differences in elevation between the gravity stations and the reference elevation.

The observed gravity data for stations above the reference elevation are too great because of the attraction of the mass of material between the station and the reference level. A Bouguer or mass correction of \(-0.01276 \sigma\) milligals per foot is applied to compensate for the effect of this mass. For stations below the reference level, positive corrections are made. (\(\sigma\) is the density of the material between the station and the reference level.)
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The free air correction compensates for the decrease in gravity with increase in elevation or in distance from the centre of the earth. This correction is \( +0.09406 \) milligals per ft. above the reference level. For stations below the reference level, negative corrections are made.

(3) The earth is a rotating oblate spheroid causing the forces of gravity to increase as one goes north or south from the equator because of the decreased radius and lower centrifugal force. Standard latitude correction tables are used for correcting all observed data for the effects of latitude. In order to apply these corrections, it is necessary to survey accurately the horizontal positions of all gravity stations.

(4) The gravity meter measures the effect of the surrounding gravitational field. It is, therefore, affected by the mass of any surrounding hills or valleys, and the effect of these must be compensated for by making what are known as "terrain corrections". Thus it is necessary to determine elevations of all local physical features surrounding each gravity station when these variations are sufficiently large to affect the gravity meter reading. The field work usually is completed with the preparation of a map showing the locations of the gravity stations accompanied by the gravity values corrected for latitude, elevation, mass and terrain effects.

Gravity measurements are not sensitive to vertical variations in density so long as they are constant in horizontal layers. However, any horizontal variation in density will cause a horizontal variation in gravity (and its derivations), and it is these horizontal variations which appear on gravity maps. Thus any geological condition that produces a horizontal variation in density will cause a horizontal gravity variation or a gravity 'anomaly'. A geological uplift of beds of different density will cause a gravity anomaly, the magnitude of which will depend on the density contrasts involved and the magnitude and form of the uplift.

The gravity meter is best applied where a high difference in density is one of the characteristics of the material sought. For instance, because the outstanding physical characteristic of a hard, high-grade hematite is its high density, a gravity survey will disclose the quantity of the mineral present, and hence whether it is a potentially commercial deposit. A fairly reliable estimate of the tonnage can be calculated regardless of the shape, size or distribution of the body.

The gravity meter can be used also to map structure because many rock types are distinguished by small differences in density. In general, the basic rocks are denser than the acidic. However, it must be emphasized that interpretation of structure on the basis of gravity data requires close geological control.

Depth Determination

From potential theory we learn that no interpretation of natural fields can be unique. It will always be possible to supply an infinite number of mass distributions that will give the same resultant field. For example, a large mass of given density near the earth's surface will give rise to observed gravitational data similar to those observed over a smaller mass with a greater density at a greater depth. Because of this, it is not possible to determine the exact position and shape of a disturbing mass, but upper and lower limits of depth can be set. In this way, interpretation of gravity data is similar to the interpretation of magnetic data. The depth limitation does not follow quite the same law and, generally speaking, it is possible to obtain useful data from sources at greater depth by a gravity meter survey than by most other methods. In fact, deep-seated heavy masses very often cause anomalies that apparently obscure the relatively near-surface anomalies for which one may be looking.

The gravity interpreter may make qualitative analyses of gravity data in terms of the probable size, shape, depth and type of material causing the anomalies. Within limits, quantitative calculations can be made on the volume, the mass and the depth of the sources of gravity anomalies. These interpretations may be most helpful in solving many geological problems.
THE application of geochemistry in the search for ore deposits is a relatively recent innovation in many parts of the world. Scandinavian and Russian geologists have made use of these methods since the early 1930s. In a sense, the panning technique that has been one of the most important tools of the prospector in his search for gold, tin, tungsten, platinum and precious stones, is the ancestor of geochemical exploration techniques.

It is true that the alluvial prospector did not use direct chemical analyses to identify and measure the amount of valuable material in his samples, but he did use a rough form of mineralogical analysis. Furthermore, he recognized clearly that these minerals formed a dispersion pattern leading up to the main zone of concentration of the minerals in the bedrock source. Thus the alluvial prospector made use of the same basic exploration approach that is used now by the exploration geochemist, and traced the sought-after element to its bedrock source by sampling upstream or upslope in the direction of increasing values until a cut-off point was reached. At this point the prospector knew he was close to the lode, therefore he resorted to trenching, pitting and tunnelling to locate the ore zone. Modern geochemical exploration makes use of the same principle of search, but instead of panning the products of weathering (such as soil, sediment and water), these are chemically analysed for the valuable metal. Because this metal normally is present in trace amounts, very sensitive analytical methods must be used.

Dispersion Phenomena

In the zone of weathering, rocks and minerals are broken down by mechanical disintegration and chemical decomposition. Part of this weathered material forms the soil but the remainder is taken into solution and carried away by ground waters. Both soil and groundwater move down slope under the influence of gravity into the nearest drainage channel and thence are moved downstream by the running water.

If a limited area of the bedrock contains an abnormal concentration of a valuable metal then the soils and solutions derived from that area also will contain an abnormal concentration of the metal. As these products of weathering move away from the source, they become mixed with similar products derived from barren areas. The concentration of the metal is thereby decreased by dilution with this barren material. The dilution becomes greater as the distance from the mineralized zone increases until eventually the slightly higher concentration of the valuable metal no longer can be distinguished from the general background value for the metal in barren areas. Thus there is a limit beyond which it is not possible to detect indications of mineralization.

Terms Defined

The metalliferous zone derived from a weathering source is spoken of as a “secondary dispersion halo,” a “secondary dispersion fan,” or a “secondary disper-
tion train”, depending on the pattern of metal values developed.

A dispersion halo is a more or less symmetrical pattern of increasing metal values centred about the source. Dispersion halos if developed in the wall rocks surrounding an ore zone, and therefore presumably formed at the same time as the ore zone was formed, are spoken of as “primary dispersion halos.” Dispersion halos developed in soils above an ore zone are spoken of as secondary dispersion halos. Secondary dispersion halos may develop in residual soils or in transported soils and are characteristic of flat terrains. In transported soil the metal has been transferred in ion form from the weathering metal deposit to the clay minerals of the overlying transported soil. Such transfer apparently takes place by diffusion through the ground water. Secondary dispersion halos developed in transported soils normally are much weaker than those developed in residual soils.

A dispersion fan is a pattern of decreasing metal values leading away from one side of the source, and characteristically is developed on sloping ground. A dispersion train is an elongated pattern of decreasing metal values leading away from the source and frequently confined to the drainage channel from the area. Glacial soils might be expected to contain poorly-developed and erratic dispersion fans or trains leading away from the source in the direction of glacial movement.

**Plants Absorb Metals**

During recent years much attention has been directed to the possibility of using vegetation as an indicator of secondary dispersion phenomena. Vegetation derives its nourishment from soils and ground waters and hence should reflect variations in the soil composition. Trace amounts of various metals appear to be essential for healthy plant growth, although in some cases plant poisoning may result from abnormal concentrations of metal in the soil. Some species of plants will accumulate metal in their wood and fruit in direct proportion to the amount of metal available in the plant soil. Where this soil is enriched in metal, the metal content of the plant material also will be increased. This increase in metal can be detected by analyzing selected portions of the plant. Comparison between plants can be made only by comparing the metal content of the same type of plant material of the same plant species. For example, a survey might use the second-year growth of twigs taken from balsam fir. Plants which can accumulate varying amounts of metal but which show no external evidence of their increased metal content are spoken of as covert indicator plants. Overt indicator plants on the other hand directly reveal the presence of abnormal amounts of metal in the soils, by symptomatic changes or by preferential growth where such metal is present. Only a few such overt indicator plants are known at the present time and their distribution appears to be relatively limited.

**Geochemical Surveys**

Geochemical surveys may be divided into four groups on the basis of the material sampled and analyzed. These groups are:

(a) surveys of bedrock;
(b) surveys of soils;
(c) surveys of water;
(d) surveys of vegetation.

In general there are two more or less distinct methods of applying geochemical surveys to the problem of mineral exploration, depending on whether the object of the survey is a broad reconnaissance of a large area or whether the object is a detailed study of a much smaller area.

Reconnaissance geochemical surveys are carried out by making use of the drainage system as the major control of the sampling pattern. In this type of survey, soils, sediments and waters are sampled and areas of general interest containing dispersion fans or dispersion trains are outlined. Such reconnaissance methods are applied most effectively in well-drained areas of moderate relief. In flat, poorly-drained terrains such methods cannot be employed with any assurance of success.

**Collecting the Samples**

Detailed geochemical surveys are carried out by sampling rocks, soils, or vegetation at regular intervals on a definite grid pattern. The proper interval between sampling points is determined by such factors as expected width of mineralized zone, depth of overburden, and slope of the ground. If the strike of the mineralized zone is known, then a greater sampling interval may be used in the strike direction. The base line of the grid pattern should be established parallel to the strike of the mineralized zone. Soil samples should be collected at uniform depths below surface. A very satisfactory soil zone for sampling purposes is the upper part of the B-zone. This zone is marked by the development of a brown color slightly darker than that of the underlying parent soil. The B-zone usually is overlain by
a grey leached zone (A-zone) in most areas of the Canadian bush. This may vary in other parts of the world.

The range of readily extractable base metals in soils derived from nonmineralized areas appears to be less than 100 parts per million for copper, zinc or lead. On the other hand, soils derived from mineralized zones may contain over 10,000 parts per million of the base metals.

Water samples may be collected from stream waters or from ground waters, and are analysed in the field. Ground waters normally contain higher base metal values than do running waters flowing in open channels. Therefore, values for ground waters cannot be compared with values for streams. In areas devoid of base metal sulphide mineralization the stream waters and the ground waters are negative with respect to the base metal and contain less than one part of metal in one thousand million of solution. Stream values in waters draining from areas containing base metal mineralization may contain up to several parts per million of base metals.

In biogeochemical surveys, i.e. geochemical surveys of the metal content of vegetation, it is essential that the sampling of plant material be confined to similar parts of the same species of plant. Research has shown that the optimum sampling conditions are achieved when the second-year growth of the plant twig is selected for sampling. The choice of species of plant is restricted of course to the plants growing in the area to be explored. At the present time it appears that the coniferous species are more reliable indicators than are most of the deciduous varieties. However, it should be noted that there is a marked variation in the ability of plant species to accumulate metal, and it is necessary to take into consideration both the distribution of the plant species and the type of metal that is being sought.

Simple chemical analyses of stream or lake waters can be carried out by the prospector using prepared water-testing kits. More detailed analyses of waters, soils, twigs, etc., must be done by trained chemists in modern laboratories using precise quantitative chemical and spectrographic analyses.

**Interpretation of Anomalies**

After an area has been sampled thoroughly and the samples have been analysed for the sought-after metal, or for an indicator metal, the results of the analyses and sampling are plotted on a geochemical survey map. It is of considerable assistance if the results of geophysical and geological work in the area are shown on the same map. In interpreting such a geochemical map one must consider the following points: (1) the characteristic behaviour of the metal in the zone of weathering and dispersion, (2), the type of material sampled and the range of values obtained on analysis, (3), the relationship of topographic highs and drainage channels to the zones containing geochemical highs.

For many metals and a wide range of physical conditions the basic data are not available to formulate general rules for the interpretation of geochemical anomalies. Each survey must be interpreted on its own merits, so to speak. However, in the case of base metal deposits, overlain by secondary dispersion halos, in relatively flat-lying terrains, the following generalizations appear to be valid. Lead and copper values are highest in soils, vegetation and waters in the immediate vicinity of the bedrock source. Lead values diminish rapidly away from this source; copper values diminish less rapidly. Therefore the copper halo normally is larger than the lead halo. Zinc values, on the other hand, normally are somewhat erratic and extend for long distances from the source in the direction of ground water. Movement for zinc is relatively mobile in the zone of weathering. There is a tendency for zinc values in soils and vegetation to increase in areas where there is an abundance of clay minerals, because of ready absorption of zinc in such minerals.

Zones containing humus, such as peat-bogs and muskegs, frequently show enrichment in zinc and copper where these metals are present in abnormal amounts in the drainage of the area.

**Migration from Source**

In areas where the slope of the land leads away from a mineralized zone, the zone of high metal values extends downhill for a considerable distance from the actual source, but on the uphill side the zone is terminated abruptly. Generally speaking, when interpreting geochemical survey maps one must keep in mind that although the highest metal values quite probably are near the bedrock source, there is a possibility that the source lies upstream or up-slope from the zone of maximum concentration of such values in soils and vegetation.

In glaciated terrains there is a distinct possibility that false anomalies may be produced by the transportation of metal-rich soil from its original position immediately over an orebody to some other location.
Another cause of false anomalies in glaciated areas is the presence of erratics derived from mineralized zones which upon weathering will contaminate the enclosing moraine. A false anomaly of this type is likely to be of very limited extent.

Field of Application

Geochemical exploration may be applied to the majority of unglaciated areas as an aid in the location of a variety of metalliferous deposits, the sole consideration being that the metalliferous deposits shall be undergoing weathering and that suitable analytical methods for the determination of the metal shall be available. This search may be on a regional basis for one or more metals and it is conceivable that in the not too distant future geological survey parties will carry out routine soil and vegetation analyses as a means of establishing the economic potentialities of an area.

On a more restricted scale the geochemical survey technique may be employed to evaluate the worth of geophysical anomalies and geological structures.

Although geochemical exploration will yield direct evidence of the presence or absence of metals in the soil, vegetation or water, provided that a suitable source is exposed to weathering and erosion, it is important to remember that a very limited thickness of barren cap rock overlying a mineralized zone probably will conceal that zone, for here there will be little if any opportunity for weathering of the deposit and the consequent dispersion of the metal.

Geochemical exploration techniques are most effective when applied in conjunction with geophysical and geological surveys. Intelligent use of such combined methods undoubtedly provides a most powerful and efficient means of locating new mineral camps and pinpointing new orebodies within those camps.

HEAVY METALS IN STREAM SEDIMENT
AS AN EXPLORATION GUIDE

by H. E. Hawkes* and Harold Bloom**

Streams and rivers are the principal channels into which the weathering products of rocks and their contained ores are funnelled. The inorganic load of a stream system is, therefore, a crude sample of all the earth materials in the drainage basin of the stream, and under favourable conditions can be used as a guide in reconnaissance mineral explorations.

The heavy mineral assemblage of sediments is, in fact, one of the oldest and most successful guides to certain kinds of bedrock ore in unexplored terrain. The early application of this method of reconnaissance exploration was occasioned by the ease of separation and identification of heavy minerals in the field with the simplest equipment.

Water analysis for traces of base metals became a practical possibility about eight years ago with the development of rapid chemical tests that could be carried out at the field site. Since that time the water method has been used widely in mineral reconnaissance, and a substantial number of discoveries have been reported. Here again, the techniques developed for this work were relatively simple and could be performed easily at the field site.

Sediment analysis by chemical methods, as distinguished from mineralogical, has received less attention. Some experimental work was done by Lovering and others; but, to the authors' knowledge, chemical analysis of sediment samples has not been used in routine exploration programs until very recently. In spite of the obvious promise of this method, it was not pursued vigorously because of the lack of a simple and portable chemical test that could be used conveniently at the field site or in a field camp.

Recently an extremely rapid and simple test was developed by Bloom. The extractant in this procedure is a cold solution of ammonium citrate. Elements measured are the heavy metals, principally zinc, lead, and copper. This method differs from the established procedures for soil analysis in that it measures only a small fraction, about five per cent, of the total metal content of the sample. It has been found, however, that the significant pattern of metals in the sediments of streams below a base-metal deposit can be brought

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*Lecturer, Dept. Geology & Geophysics, Massachusetts Institute of Technology.
**Dept. Geology, Colorado School of Mines.
out as well and sometimes better by this simple cold-
extraction procedure than by the more tedious methods
requiring hot acids.

To understand fully the significance of the relation
between the readily extractable and the total metal
content of sediments, it might be helpful to review
briefly the various ways in which metals can occur in
stream sediments.

* Geochemistry of Stream Sediments

Stream beds serve as a temporary resting place
for materials in transit between the site of weathering
and erosion and the site of ultimate deposition. Solid
materials temporarily deposited either in the active
channel of the stream or over the floodplain may be
grouped as follows:

1. Rock fragments;

2. Primary resistant minerals. These consist
principally of quartz and the heavy accessory minerals
of igneous and metamorphic rocks, but may include
native metals, cassiterite, columbite, and other resistant
ore minerals;

3. Secondary minerals formed at the site of
weathering of rocks and ores: clay minerals, hydrated
oxides of iron and manganese, and the secondary
oxidation products of the ore metals;

4. Inorganic matter precipitated from stream
water solutions. This may occur as relatively insoluble
secondary minerals or as ions absorbed into the struc-
ture of minerals already present in the sediments;

5. Inorganic matter withdrawn from ionic solu-
tion by living organisms and by the formation of
organic complexes;

6. Exchangeable ions in relatively active equili-
rium with the aqueous solutions in contact with the
sediment.

It should be noted that material in the first three
of these groups travels as clastic fragments, whereas
that in the last three travels predominantly in solution
in the water.

The readiness with which these various kinds of
material can be dissolved for chemical determination
depends on the kinds of bonds that hold the atoms
in place. The primary rock-forming minerals (Groups
1 and 2) commonly require a strong chemical attack,
such as alkali fluxes or hydrofluoric and perchloric
acids; the secondary minerals (Groups 3 and 4) com-
nonly are soluble in hot acids; metals held in living
organisms and organic complexes (Group 5) can be
released by ashing or wet oxidation; and exchangeable
ions (Group 6), with the weakest bonds, will go into
solution promptly on treatment with neutral cold solu-
tions of any one of a number of salts, including am-
monium citrate. Thus, by modifying the extraction
treatment, it is possible to get at least a qualitative idea
of how a given chemical component is partitioned
between the different kinds of material making up the
sediment.

Analytical Procedures

* Exchangeable Metals

Exchangeable metal, for these purposes, is defined
as that fraction of the total metal content of a clastic
sample that can be put into aqueous solution by treat-
ment with a cold dilute solution of ammonium citrate.
The analytical procedure for determining the exchange-
able metal content of soil or sediment samples is
described in detail in an earlier paper by Bloom. In
essence the procedure is as follows:

1. For analysis in the base-camp laboratory, dry
and sieve the sample, discarding the coarse fraction;
for analysis at the field site, use a moist sample after
pulverizing and fragments of wood have been removed by
hand. (2) Measure the dry or moist sample into a
volumetric scoop of about 0.15 cc. capacity and tap
into a test tube. (3) Add 3 ml. of an aqueous solution
containing 5 per cent ammonium citrate and 0.8 per
cent hydroxylamine hydrochloride adjusted to a pH
of 8.5. (4) To the same tube, add 1 ml. of a 0.001
per cent solution of dithizone (diphenylthiocarbazonine)
in xylene. (5) Shake vigorously for five seconds,
observing the colour of the dithizone solution that col-
llects at the surface of the aqueous citrate solution. If
the colour is green, green-blue to blue, record 0, ½, or
1 ml., respectively. If the colour is blue-purple to red,
(6) titrate with 1 ml. or larger increments of dithizone
solution, shaking for three seconds after each addition,
until a blue colour is obtained. Record the volume
of dithizone solution used as an index of the heavy
metal content.

Calibration of these values shows that for zinc,
commonly the most abundant of the heavy metals en-
countered, the conversion factor of millilitres of dithi-
zone solution to micrograms (millimilliols of a gram)
of metal is 0.34. Thus, if 10 ml. of dithizone solution is
required to reach the blue end point, the sample con-
tains 3.4 mg. of exchangeable metal expressed as zinc.
If the volume of the scoop is known, the exchangeable
metal content of the sample may be computed in
absolute values as micrograms per cubic centimeter of
sample (parts per million weight/volume, or ppm w/v). Inasmuch as the bulk density of dried samples is commonly about 1, the value of parts per million weight/volume is a fair first approximation of parts per million weight/weight.

The exchangeable metal content of moist, unsieved sediment samples is in general comparable with that in the same samples after systematic drying and coarse sieving. This was shown in a study of a set of forty-six samples representing both low and high contents of exchangeable metal. These samples were first analysed as collected, and then dried, sieved to-12 mesh and reassayed. The median of the ratios of exchangeable metal content of the moist sample to that of the same sample after drying and sieving was 1.20.

Total Metals: In the experiments described below, the total metal content of the sediment samples was determined by digestion with hot nitric acid for one hour, following a procedure described in detail by Bloom and Crowe. Attack by nitric acid will remove the metal from virtually all components of the sediment except the primary resistant minerals and rock fragments.

Metals in Water: Water analysis has a unique advantage over sediment analysis in that the component to be determined is already in solution. Thus errors due to inhomogeneities of sample and variations in rigour of the extraction procedure do not affect the precision of the data. In the field experiments described here, water was analysed for traces of heavy metals by a method requiring most of the reagents used for the test for exchangeable metals in sediments.

- Test for Heavy Metals in Water

Reagents: Water. This refers to metal-free water, usually obtained by passing water through a resin demineralizer.

Dithizone (diphenylthiocarbazole) of reagent grade.

Dithizone in carbon tetrachloride, about 0.01 per cent. This used to purify the sodium acetate solution. Dissolve approximately 0.01 g. of dithizone in 100 ml. of carbon tetrachloride a few hours before using.

Dithizone in xylene, 0.001 per cent, work solution. Prepare a work solution of 0.001 per cent by diluting 10 ml. of stock solution to 100 ml. with xylene.

Carbon tetrachloride, ACS grade.

Xylene, ACS grade. The xylene is further purified in the following manner: 500 ml. of xylene are extracted with about 30 ml. concentrated sulphuric acid by vigorously shaking for one minute. Allow phase to separate completely and discard the acid. Add demineralized water to the xylene (ratio 1:10) and mix vigorously. Separate the xylene and distill in an all-pyrex still.

Sodium acetate (anhydrous) solution 8 per cent.

Dissolve 4 oz. of anhydrous sodium acetate in 500 ml. water and adjust the pH to 6.7 with acetic acid if necessary. Remove heavy metals by extracting the solution with successive 20-ml. portions of the carbon tetrachloride solution of dithizone until the dithizone is no longer red. Wash the aqueous solution with about 3-ml portions of carbon tetrachloride until the carbon tetrachloride is colourless.

Apparatus: Necessary equipment consists of two wash bottles, polyethylene, 8-oz. capacity; one glass-stoppered cylinder, pyrex, 50-ml. capacity; four reagent bottles, pyrex or polyethylene, 16-oz capacity; and one graduated cylinder, 100-ml. capacity.

Procedure: Add the sample of water to the 40-ml. mark of the glass-stoppered cylinder, followed by 5 ml. of sodium acetate solution. Add ten drops of 0.001 per cent dithizone in xylene from a wash bottle, cap the cylinder and shake vigorously for twenty seconds. Observe droplets as they collect on the water surface. If purple or red, add ten more drops and shake only ten seconds. If a blue colour is not obtained, repeat the latter step until it is obtained. This blue colour is known as the end point. As an index of the heavy metal content, record the number of drops required to reach the end point.

A chart for converting drops of dithizone solution to parts per million heavy metal was constructed by connecting the following three points as plotted on graph paper: 0 drops-0 ppm; 40 drops-0.0025 ppm; 150 drops-0.0125 ppm. In normal surface water, zinc is the only member of the heavy metal group present in significant quantities.

The geochemical principles and analytical techniques described in this paper were applied in the province of New Brunswick during the summers of 1953, 1954, and 1955. A comparison paper by Hawkes, Bloom, and Riddell in this volume illustrates in detail some typical results. For application of the water test for heavy metals see reference.

REFERENCE

**Methods**

**D—Radioactive**

**NUCLEAR RADIATION IN PROSPECTING**

by G. M. Brownell*

The discovery of numerous commercial deposits of uranium in recent years has been made possible by the development of portable instruments capable of detecting and measuring radioactivity. The two instruments that have best served the prospector and the mining engineer are the Geiger counter and the scintillation counter. Dr. Gordon Shrum at the University of British Columbia was the first to construct a portable instrument incorporating a Geiger-Muller tube which he tried out in field experiments in British Columbia in 1932. The batteries to operate this first field instrument weighed about 50 lb.

The earliest commercial Geiger counters for prospecting became available about 1940 and were used to a limited extent in the Colorado Plateau area, but these suffered from an excessive weight of batteries (1). With the sudden demand for atomic war materials in 1944, Dr. A. W. Joliffe of the Geological Survey of Canada was sent that summer with a field party to search for uranium in the Great Bear Lake area, and took with him three Geiger counters made by the National Research Council which incorporated Dr. Shrum’s circuit. Also on that field party was Dr. W. J. Hushley, a physicist who worked with those first crude field instruments during the summer months. From this close collaboration between field geologist and physicist evolved the modern light-weight portable Geiger counter.

The ordinary Geiger tube is not an efficient detector for gamma rays because less than one per cent of the rays passing through it are counted. Also, cosmic radiation is responsible for a high proportion of the total count recorded as normal background. Consequently the Geiger counter has been largely superseded by the much more efficient scintillation counter for geophysical work.

The scintillation counter principle was first used in the construction of portable geophysical instruments early in 1949 by Dr. R. W. Pringle and Dr. K. I. Roulston, both at the University of Manitoba. These two physicists accompanied the author in the Beaverlodge area during the summer of 1949 and again under field conditions a new type of equipment was developed into a practical geophysical instrument (2).

Gamma rays produce scintillations or flashes of light in “phosphors” in much the same manner as ultraviolet light produces fluorescence. The phosphors most used in field instruments are: (a), crystals of thallium-activated sodium iodide, and (b), plastic phosphors. Scintillations produced by radioactivity in crystalline salts have been known since the time of Sir Ernest Rutherford but it was the development of the modern photomultiplier tube during the 1940’s which made the scintillation counter possible. These tubes have a photo-sensitive cathode on the inner surface at one end of the glass envelope against which the crystal is placed. Each flash of light from within the crystal as it falls on the cathode is converted into a minute current pulse which, by a series of dynodes, is multiplied a million times or more so that it issues from the tube as a pulse of sufficient magnitude to be

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*Professor of Geology, University of British Columbia.
of practical use in the instrumentation. These pulses are amplified before being passed on to a discriminator.

Gamma rays of high energy (or short wave-length) produce brighter flashes than do the rays of lesser energy (or longer wave-length) and in consequence current pulses emerge from the photo-tube of greater or lesser voltages according to the intensity of the flashes. By discriminating between these pulses of different voltage levels it is possible to employ the scintillation counter as a gamma ray spectrometer.

The discriminator can be employed in two ways:
(a) as an integral discriminator by which all voltage pulses above a certain value are counted. All low-voltage pulses due to instrument or tube noise are eliminated or "biased out" and only genuine gamma rays are counted. This is the common type of scintillation counter used in field prospecting that measures total gamma radiation. For this type of instrument either the sodium iodide crystal or the plastic phosphor may be used.
(b) as a differential discriminator, pulses above and below chosen voltage levels are eliminated and only those voltages in a narrow band between these limits are counted. The width between these upper and lower limits is the "window" and not only may the width of the window be varied, but the window may be moved to select any band of radiation from the gamma ray spectrum. For example, the only gamma ray from potassium (K40) has an energy of 1.45 MEV (million electron volts) so by setting the discriminator to select gamma rays between say 1.42 and 1.48 MEV, only radiation from potassium would be counted. Likewise by another setting the radiation from potassium would be cut out and only that from uranium or from both uranium and thorium would be counted.

Sodium iodide crystals are used in spectrometers because they possess a pronounced "photoelectric effect" in which an appreciable fraction of the gamma rays gives up all its energy to the crystal. This results in a fairly narrow band of pulse height. Plastic phosphors, on the other hand, do not possess a pronounced photoelectric effect and so are not suitable for use in gamma ray spectrometry unless very large volumes are used.

The final recording in the instruments used for field work is the rate meter and, for aircraft models, the pen recorder. In contrast to Geiger counters, the effect of cosmic radiation on scintillation counters is negligible and therefore may be ignored. One big advantage of sodium iodide NaI(Tl) crystals is their high density which provides great stopping power for gamma rays. However, such crystals are extremely hygroscopic and their perfect cubic cleavage makes them sensitive to shock so they must be sealed in airtight containers having a transparent window to fit against the photomultiplier tube, and be shock-mounted. The failure of an instrument to function properly can frequently be traced to leakage of moist air into the cell with consequent deterioration of the crystal, or to its cleavage by shock. But these hazards are overcome for the common type of instrument by the use of the plastic phosphors. However, about two and one half times the volume of plastic is necessary to secure an equivalent counting rate.

The use of the scintillator as a geophysical instrument in the search for mineral wealth finds extensive use in three separate fields of activity, namely:
(a) hand instruments;
(b) aircraft instruments;
(c) oil well logging.

Radioactivity in the Field

Before discussing field observations, it is well to have in mind some of the principles applied in this type of geophysical work. Three forms of radiation emanate from naturally occurring elements:
(a) Alpha particles—which have a range of the order of one inch in air and are of little significance in prospecting;
(b) Beta particles—which may have a range of the order of one foot in air;
(c) Gamma rays—which may be detected up to several hundred feet through air or even a thousand feet or more from strong sources.

Gamma radiation, therefore, is the one particular type of radiation that is of use in both ground and aerial prospecting for radioactive minerals because it is the only one that can be measured at a reasonable distance from the source. Gamma rays are similar to X-rays but are shorter in wave-length and have more penetrating power. Penetration is definitely limited, however, and a strong radioactive source suspended in water to a depth of 5 ft. can barely be detected at the surface; likewise a cover of rock or dense clay two or three feet thick will blanket out the radiation.

Uranium. This element occurs most abundantly in minerals such as pitchblende, uraninite, brannerite, carnontite, etc. and their oxidation products.

Uranium by itself would not be detected by the ordinary instruments used in prospecting were it not
that it is constantly undergoing radioactive decay into daughter products that are in themselves also radioactive (Table I). This series begins with uranium—238 and by a series of disintegrations is transformed into thirteen successive radioactive daughter elements and finally ends with inactive lead. When each of these radioactive daughter elements is present in such amount that it decays at the same rate as it is produced, the series is then in equilibrium. The “half-life” of any member is the time required for each radioactive member to lose half of its radioactivity, hence the half-life is a measure of the speed of decay. In five half-lives it loses 96 per cent of its original activity and is essentially exhausted.

<table>
<thead>
<tr>
<th>Element</th>
<th>Radiometric designation</th>
<th>Half life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium—238</td>
<td>U1</td>
<td>4,510,000,000 years</td>
</tr>
<tr>
<td>Thorium—234</td>
<td>UX1</td>
<td>24.1 days</td>
</tr>
<tr>
<td>Proctactinium—234</td>
<td>UX2</td>
<td>1.1 minute</td>
</tr>
<tr>
<td>Uranium—234</td>
<td>U11</td>
<td>250,000 years</td>
</tr>
<tr>
<td>Thorium—230</td>
<td>Ionium</td>
<td>80,000 years</td>
</tr>
<tr>
<td>Radium—226</td>
<td>Radium</td>
<td>1,600 years</td>
</tr>
<tr>
<td>Radium—222</td>
<td>Radium</td>
<td>3.8 days</td>
</tr>
<tr>
<td>Poilonium—218</td>
<td>Radium A</td>
<td>3.1 minutes</td>
</tr>
<tr>
<td>Lead—214</td>
<td>Radium B</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>Bismuth—214</td>
<td>Radium C</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>Poilonium—214</td>
<td>Radium C'</td>
<td>0.0002 second</td>
</tr>
<tr>
<td>Lead—210</td>
<td>Radium D</td>
<td>22.2 years</td>
</tr>
<tr>
<td>Bismuth—210</td>
<td>Radium E</td>
<td>4.9 days</td>
</tr>
<tr>
<td>Poilonium—210</td>
<td>Radium F</td>
<td>138 days</td>
</tr>
<tr>
<td>Lead—206</td>
<td>Radium G</td>
<td>Stable</td>
</tr>
</tbody>
</table>

Radium is the fifth product of disintegration and formerly was an important economic constituent. Radium decays to form radon gas which, to the prospector, is one of the most important daughter elements. Radon is the only member of the series which is a gas and it has a half-life of 3.8 days. Radon is extremely active as a source of gamma rays by its rapid disintegration to successive short-lived elements, and is responsible for much of the observed activity of uranium ores. Should a mass of pitchblende be pulverized or heated, its radioactivity will decrease due to the escape of gas and it will not again reach a state of radioactive equilibrium until it has remained undisturbed for several weeks.

Prospectors frequently encounter a surface zone of increased radioactivity only to discover after digging or blasting into it that the radioactivity is much reduced. Usually radon gas is responsible for this phenomenon. Where rocks are fractured or porous it seems quite likely that a number of anomalies otherwise difficult to explain may be traced to the activity of radon which has diffused into cracks from disseminations of small quantities of radioactive minerals. On the other hand, where radon escapes from a vein or deposit of possible commercial value, an overlying porous soil will permit the upward migration of radon thus causing a recognizable radioactive anomaly at the surface even through 5 ft. or more of overburden, whereas a dense clay or water-soaked soil would restrict the movement of radon and effectively obscure the deposit at a depth of perhaps only 1 or 2 ft.

One must keep in mind the fact that uranium is relatively soluble and tends to be removed by the leaching effect of ground waters from surface outcrops. The sulphides present with pitchblende will oxidize to form sulphuric acid which dissolves uranium and carries it away in solution. However, the radium present in the pitchblende is much less soluble and tends to remain behind in the leached outcrop. Therefore the outcrop may be strongly radioactive due to the presence of the gamma-emitting elements RaC and RaD although a chemical analysis proves that the uranium content is low. This was the situation at Blind River where the discovery of commercial ore was delayed until diamond drilling revealed the presence of uranium in commercial quantities below the zone of leaching.

It has been observed elsewhere that migration of uranium in solution may cause some of it to spread as a halo around the deposit, or down one side if the vein is located on the side of a hill, thus giving a much broader zone of increased radioactivity. While with a hand instrument at ground level such a broad zone may indicate an anomaly of low intensity due to the small area scanned by a hand instrument, an airborne instrument scanning a much greater area might detect this occurrence as a very strong anomaly because of the mass effect.

The prospector must ever keep in mind that in discovering an anomaly he has merely found a place worthy of his attention. The vagaries of radon gas and the soluble character of uranium introduce an element of uncertainty into any discovery, and these plus local geological conditions may combine either to reveal or to obscure the presence of a uranium ore deposit. Should an anomaly be of sufficient magnitude to encourage detailed investigation, then exploration by some method to a depth below surface leaching is essential to determine its value.

There are two other elements besides uranium which occur in rock formations in sufficient abundance
dark or basic varieties. In sedimentary rocks it is present in clays and shales but is low or absent in sandstone and limestone.

Potassium in nature is made up of three isotopes—$^{40}K$ (93.44%), $^{41}K$ (0.01%) and $^{42}K$ (6.55%) of which only $^{40}K$ is radioactive. However, since $^{40}K$ makes up such a small proportion of the total potassium content, its effect in small samples is negligible, but the mass effect of a potassium-bearing rock formation in place is appreciable. Granites characteristically carry trace amounts of uranium but some of the background count registered on an instrument in normal locations is from $^{40}K$ in the underlying rock. Operators on ground surveys may observe an increase of several times in background when passing on foot from a basic rock to a granite; and likewise an airborne scintillation counter may record a sudden high increase in radioactivity far exceeding that from many a uranium-bearing vein when flying over the contact from greenstone to a potash granite. Pegmatite dykes may give a particularly high radioactive signal due not only to a relatively high $^{40}K$ content but commonly also to varying small amounts of both uranium and thorium to the mass.

*Thorium* is currently of little value commercially. It may occur in association with other metals, in places providing a method of discovery. Deposits of niobium in carbonatites, for example, usually contain small amounts of thorium and/or uranium and this has led to the discovery of a number of such deposits in North America and Africa.

**Ground Surveys**

Hand instruments used in prospecting may have the meter scale read directly in millionths (mR) per hour; or in gamma ray counts per second. A normal background might be 0.005 millionths per hour*. Wherever a pronounced increase in radiation is

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*The roentgen (R) is defined as that quantity of X-radiation which will produce one electrostatic unit of ions in one cubic centimeter of air under standard conditions of temperature and pressure. The roentgen is a measure of the quantity or amount of radiation, regardless of whether that quantity is produced quickly by intense radiation or slowly by moderate radiation. Therefore, the rate of gamma ray production—or, in other words, the intensity of radiation—must be expressed as roentgens per unit of time.

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zone, such a reading should lead to a close examination of the anomaly. High readings fifty to several hundred times background or more will be recorded over strong anomalies and especially where veins are exposed by excavation.

Systematic radiation surveys with hand instruments may readily be carried out over local areas where uranium-bearing veins occur or may be suspected. Lines should be run at 50- or 100-ft. spacings and readings recorded periodically along these lines at 25- or 50-ft. intervals, and at closer spacings in critical places. From the resultant grid it is a simple matter to connect points of equal radiation intensities and draw "isorads" or lines of equal radiation intensity. It has been noted that some veins show a pattern of decreasing radiation for a distance of 100 ft. or more away from the vein. One group of small pitchblende-bearing veins, for example, was enclosed within a clearly defined area of enhanced radioactivity. Such systematic ground surveys, carried out after an anomaly has been discovered, provide the pattern of a vein system and guidance in development work.

**Airborne Surveys**

Scintillation counters used in aircraft must have a much larger mass of phosphor than instruments used at ground level (3). Since the counting rate is proportional to the mass of crystal, this increase in size compensates for the decrease in radiation at a distance from the source. Such instruments provide for continuous roll chart recording of the gamma radiation. Also, the detector head must be placed at the rear of the aircraft away from the luminous (radioactive) dials of the instrument panel or effectively shielded from them. In measuring radioactivity from aircraft, it is important to keep in mind the theoretical difference in intensity from three types of source as it would apply in a vacuum:

1. **A Point Source**—The intensity of radiation emanating from a point varies by the well-known inverse square law; that is, at double the distance, one quarter the strength of the radiation.

2. **A Line Source**—The intensity of gamma radiation from a line varies approximately inversely as the distance (not the square). Thus, by doubling
the distance between a line source and the detector, the intensity drops by one half.

(3) Sheet Source—The intensity of radiation from an infinite sheet of radioactive material does not decrease so rapidly with increasing height. This is because a larger area is scanned at greater height.

The above theoretical considerations must be amended in practice, however, because of air absorption. Gamma radiation is reduced 50 per cent by absorption in passing through 400 to 500 ft. of air and this effect must be added to that of distance. Figure 1 shows actual measurements made by the author with an aircraft model scintillation counter in a helicopter making successive flights over a small pit on a narrow pitchblende vein in the Beaverlodge Lake district. This illustrates graphically the rapid drop in radioactivity with increasing height from a relatively small source.

- Height of Aircraft:

   An elevation of 500 ft. above the surface is about the maximum height for any radioactivity survey and at this distance from the ground an instrument with a large phosphor is essential. Lower level flying in the range 250 to 350 ft. is much more practical and can more readily pick out a strong anomaly. However, in regions where pitchblende-bearing veins are small or where closely detailed surveys are desired, the helicopter offers the greatest advantage of low-level flying down to 100 ft. and with speeds as slow as 40 miles per hour.

   There are two types of flight: (a) straight line or grid flying; (b) contour flying.

   Straight line flying is employed generally by geophysical companies on contract surveys not only because it is the most economical for covering extensive areas, but it also permits the orderly presentation of recorded data on a map. Over flat terrain it is a simple operation to obtain a reasonably accurate record on a continuous chart recorder, but each flight record must be lengthened or shortened to fit the map. This is most readily accomplished by using a “transcriber”.

   The flight of an aircraft over an irregular land surface, however, involves the problem of compensating for variations in radiation intensity due to the constantly changing distance between the detector and the ground. The aircraft pilot may attempt to follow the topographic profile along the line of flight, but for more accurate surveys the aircraft is maintained on a level course and a radar altimeter is employed to make a continuous recording of the aircraft-to-ground distance. The radiation record is later adjusted by visual comparison with the altimeter record, or the radiation signal as received by the scintillation counter can automatically be compensated for distance electronically by a coupling of the two instruments.

   Major surveys of this type generally follow flight lines spaced at quarter or half-mile intervals using twin-engine aircraft. However, detailed work with small fixed wing aircraft or helicopters has been carried out along lines as closely spaced as 200 and even 100 ft. apart. In either case, as the aircraft passes over specific points recognizable on the air photo or map these points are marked on the roll chart of the recording instrument simply by pressing a button that operates a side chronograph pen. Air photos provide many more check points over recognizable topographic features than do maps and they also offer much better guidance along planned flight lines.

   Navigation along fixed lines frequently presents a problem. In Precambrian territory where numerous lakes dot the surface, the intersection of flight lines with lake boundaries or other topographic features recognizable on air photo or map, usually gives sufficient control. But in the Radium Hill district of
South Australia where about 2,000 square miles were surveyed by flying north-south traverses at 500-yard intervals, ground pegs were placed at the end of traverse lines and during the survey a ground-to-air control was maintained by positioning a jeep at these terminal points (6). The jeeps were equipped with Aldis lamps which could be seen at considerable distance from the air and served to guide the aircraft to the correct positions at the beginning and the end of each traverse. Surveys over settled areas in Western Canada find ample control by following the rectangular system of road allowances. Smaller areas involving groups of mining claims in the Beaverlodge area, Saskatchewan, were surveyed by helicopter along lines spaced at 100- and 200- ft. intervals where pilot control was provided by brightly coloured cloth targets tacked to the cross-arms of tall poles erected every 400 ft. along the property boundaries. These examples indicate that a choice of method must depend upon the character of the survey and nature of the terrain.

*Contour flying* is commonly used in prospecting by small, relatively low speed airplanes or helicopters. An irregular course is followed which endeavour to maintain the aircraft at a uniform height above ground level and to fly along the length of depressions and escarpments. This overcomes the greatest risk of straight-line flying, that of passing across a narrow depression or at right angles to a cliff or escarpment which marks the site of a mineralized shear zone or fault, and where the sudden increase in distance to the detector offsets the radiation signal from a possible anomaly. Where air photos are available, the method of planned flights along lineaments or parallel to escarpments, is a good prospecting technique. It is not possible to prepare a good geophysical map from contour flying yet this method is more thorough in its search and can be used with the minimum of equipment. Even in contour flying a chart recorder, while not essential, is highly desirable because the operator has before him the readings over several minutes of flight and an anomaly will stand out clearly against the general background level. Also, the operator is not compelled to keep his eye on the dial continuously but may observe geologic and topographic features during the flight. However, when an automatic recorder is not used, an attachment may be provided to give an audio signal when a selected minimum radiation intensity is encountered.

Uranium in the Colorado Plateau area of the United States, is found almost exclusively in nearly flat-lying terrestrial sediments. The topography consists of buttes, mesas and deeply dissected plateaus. The best mineral outcrops are along the steep escarpments which border the mesas and canyon walls and to examine this area a system of contour flying has been adopted, locally referred to as "rim flying", by the U.S. Atomic Energy Commission. In rim flying, outcrops on the vertical cliff faces are investigated by flying at a distance of about 50 ft. from the outcrop at various stratigraphic levels, depending upon the horizon of interest. In addition to rim flying, grid patterns are flown when a mineralized horizon outcrops on a mesa or plateau. The gridlines are spaced 200 ft. apart, the pattern depending on the geologic problem involved. Operations in this region are usually carried on at about 70 miles per hour in light, fixed-wing aircraft, and the separation of the detector from the ground is maintained remarkably constant by an experienced pilot.

Helicopters are favored by some operators, especially in rugged territory. They enjoy one great advantage in that one can usually make a landing close to the site of any anomaly discovered in flight, thus permitting an immediate ground check. However, their operating costs are high and this has restricted their use.

*Spectrometers.* The airborne gamma ray spectrometer now in use is an improvement over the common scintillation counter which, in the latter case, records the total gamma energy spectrum. Exploration in Precambrian territory has previously been hampered because of the mass effect of the potassium isotope K\(^{40}\) over outcrops of granite because the radiation from the potassium was not distinguishable from that due to the variable uranium content of such acid rocks. The spectrometer, however, makes it possible to evaluate these signals in terms of the uranium content as distinct from the radiation due to potassium. Likewise over sedimentary areas where surveys are carried out for oil exploration purposes in an effort to map the variations in uranium and radium concentrations in surface layers, it is extremely important to be able to eliminate the masking effect of the potassium isotope K\(^{40}\) that pervades most soils. For these and other types of survey the scintillation spectrometer is of particular value though its greater complexity requires competent technical skill for successful operation.

*General.* Flights over a body of water give the lowest background reading and a lake in the vicinity of an area being surveyed provides a means of checking and standardizing the instrument. It also serves to detect a general increase in background count over a land area which results from the fallout of radioactive
dust from a nuclear explosion. Thus the testing of atomic weapons has affected broad continental areas and airborne radiometric surveys have been interrupted for periods as long as thirty days before work could be resumed. Likewise any swamp or water-soaked land will give low readings. Unfortunately many scintillation counter surveys have suffered from being run simultaneously with magnetometer surveys. In such cases the height above ground or other arrangements, have been governed by the requirements of the other equipment which have not been favourable for radiometric measurements. Such a radioactivity survey is not only unsatisfactory but may be misleading.

Radiometric surveys may provide data of indirect value. For example, the uranium content of sedimentary phosphate beds, although low, is sufficient to permit them to be located by radiometric methods; activity patterns may determine zones of water saturation, or formation contacts, etc., all of which contribute to the interpretation of geologic structures. The full scope of radioactivity surveys has yet to be determined.

REFERENCES


Methods

E—Electrical

SPONTANEOUS POLARIZATION, OR SELF-POTENTIAL METHOD
by Sherwin F. Kelly*

As our knowledge increases of the structure of the universe and of the forces that keep it spinning, moving, expanding, supporting life, it becomes ever more evident that the mysterious force of electricity is an all-pervasive and ubiquitous power extending from the sub-atomic microcosm to the super-galactic macrocosm. The earth, intermediate in this scale, is permeated by electrical fields originating within and without its body, fields which are affected by discontinuities and irregularities within and on the surface of the globe. Therein lies the wide utility of electrical studies for revealing some of these hidden discontinuities, irregularities, “anomalies” lying near the accessible surface of the lithosphere.

However, fast increasing knowledge of terrestrial phenomena will broaden the horizon of interest of the exploration geophysicist in the future. His preoccupation with the discovery of near-surface deposits of minerals currently confines him to the study of minute discontinuities, and of the small anomalies to which they give rise. Although these anomalies may loom large on the maps of the geophysicists, on a global scale they are truly tiny, insignificant departures from the usual.

Long before the physicists had any sound knowledge of terrestrial electrical phenomena, efforts were made to utilize electrical observations in the study of mineral deposits. They were initiated in Cornwall by Robert W. Fox in 1830. He discovered a body of “sulphurets” of copper in one of the Cornish copper mines about 1835. The work was picked up in the United States in 1881 by Carl W. Barus, who first applied the non-polarizing electrode in his studies in Nevada. Not until Professor Conrad Schlumberger of the School of Mines, Paris, France, perfected his apparatus and technique about 1912, did the spontaneous polarization or self-potential method for prospecting come into practical use. The first geophysical discovery of modern times (aside from work with older, magnetic techniques) was made by Schlumberger at the pyrite mine of Sain Bel, in France. His work there in 1913 resulted in the discovery of a new lens of pyrite. The first discovery in the western hemisphere was during a survey in 1924 on the Noranda mine, in Quebec, Canada, credited with revealing the “E” and “G” orebodies which form part of that famous assemblage of copper sulphide ore deposits.

These weak electrical currents which everywhere circulate in the crust of the earth, owe their origin to a variety of processes,—chemical, physical and electromagnetic induction phenomena. The exploration geophysicist is interested mainly in those spontaneous polarization currents which arise from chemical activity in sulphide deposits. Currents owing their origin to the other causes nevertheless play their part in his investigations, sometimes as an assistance and sometimes as a nuisance.

The great circulatory system of weak terrestrial currents, known as telluric currents, which permeates
the earth's crust is presumed to be due, in part at least, to solar influences. When solar flares and sun spots produce particularly violent magnetic disturbances and auroral displays on earth, these telluric currents sometimes suffer such violent fluctuations as to preclude reliable observations with the spontaneous polarization technique. On the other hand, milder fluctuations in telluric currents have been employed as an exploration technique.

Primarily, however, exploration procedures based on the flow of natural currents, rely on the "self-potential" currents which arise spontaneously in certain mineral bodies, due to the polarization of these bodies. In other words, such mineral deposits are natural batteries, buried in the ground. In utilizing this phenomenon, the geophysicist is profiting from a natural field of force offered ready to his hand. He is spared the necessity of taking into the field apparatus, more or less cumbersome, to apply an artificially created field of force to the earth. On the other hand, he can neither vary the place of application nor the magnitude of the force, but must accept it as nature provides it.

The manner of origin of spontaneous polarization currents may not be fully understood, but enough is known to permit correcting some misconceptions and to give a general idea of the processes involved. The statement is often made that these currents arise from the oxidation of sulphide bodies. That this is partly erroneous is demonstrated by the fact that deposits of graphite, with very small amounts of sulphides, yield remarkably strong currents. Beds of anthracite, but not bituminous, coal also give moderately strong currents. Furthermore, currents noted in underground workings, far below the surface, have actually been found to arise from sulphides apexing well below those working levels.

For an electrical current to be generated in a manner similar to the process taking place in a galvanic cell, one or more metallic conductors of electricity must be in contact with one or more electrolytes (solutions of salts, acids or alkalies that are themselves electrically conductive). Most of the sulphides are metallic conductors of electricity, the general rule being that minerals possessing metallic lustre are metallic conductors of electricity, thus excluding sphalerite and cinnabar. An exception is stibnite, the antimony sulphide, a non-conductor in spite of its metallic lustre.

The oxides are mostly non-conductive, except for the manganese minerals pyrolusite and psilomelane. Graphite is a good metallic conductor, and anthracite coal owes its electrical activity to the sooty layers of conductive, graphitic material often interleaved with the bright, shiny, non-conductive portions. This sooty, graphitic material is absent from the lower orders of coal (and occasionally from some anthracites) which therefore yield no currents.

Metallic conductors, such as those just described, are bathed by various electrolytes in the rock forma-
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...ions enclosing the mineral deposit. These electrolytes are formed by the ground water, which has dissolved various salts from soils and rocks, and near the surface carries acids derived from humus and from the atmosphere. The major factor in the generation of spontaneous polarization currents appears to be the difference in acidity (pH) between near-surface electrolytes (usually acid, with a low pH number, sometimes as low as 1, 2 or 3), and the solutions at depth which normally are somewhat alkaline (carrying a higher pH number, usually 7 or 8 or more). It is in this phase of the phenomenon that actively oxidizing sulphides enter to give a boost to the current generation. The acids formed during oxidation of sulphides lower the pH of near-surface solutions, and increase the contrast between them and the less acid, neutral, or alkaline electrolytes at depth. The differences in pH between near-surface and deep-lying electrolytes largely control the actual strengths (potentials, or voltages) of the electrical currents excited by that contrast.

From near the apex of the sulphide body, the electrical current travels down the vein, lens, or other form of deposit, to some point in depth (the lower terminus of the deposit, or possibly the zone of minimum acidity or of maximum alkalinity) where it passes into the wall rocks. It spreads through the country rock as it returns towards the surface, finally to converge on the sulphide apex. Its return into the sulphide apex to complete the circuit creates a negative pole there, and produces a centre of negative polarity at the ground surface in that vicinity.

The flow of galvanically generated currents acts to destroy the contrasts to which they owe their birth, —the reason why a dry cell wears out eventually, and a storage battery has to be recharged. In nature, the recharge of the sulphide battery is achieved by the continuous movement of the ground water bringing new electrolytes into contact with the conductive sulphides. But the current flow tends to liberate nascent hydrogen, or metals, near the surface, and nascent oxygen at the pole in depth. This may explain native metals in some gas sands, and cases of oxidation at great depth, far below the water-table, in some sulphide deposits.

Two factors are of prime importance in the practical use of the phenomenon of spontaneous polarization: first, the strength of the potentials generated; and second, the magnitude of the potentials observable at the ground surface.

The strength of the current potentials generated depends on the electromotive potential of the sulphides (or other metallically conductive minerals) against the acid electrolytes (near surface) compared to the electromotive potential of the metallically conductive minerals against the less acid, neutral, or alkaline electrolytes (at depth). Thus, the nature of the metallically conductive minerals and the chemical natures of the electrolytes are the factors controlling the magnitude of the potentials created. The maximum potentials likely to be generated by the combinations encountered in nature, appear to be of the order of one volt, more or less, but usually less.

Two potentials observable at the surface of the ground will not show the total magnitude generated, because measurements at the surface can be of potential differences in only a part of the total circuit. The deeper the overburden covering the mineral body's upper, negative pole, the smaller is the proportion of the circuit observable at the surface to the total circuit. Deepening overburden therefore reduces the reactions recorded at the surface, and spreads them over a greater width. Normally, sulphides whose apices lie deeper than 300 ft. are unlikely to give an interpretable reaction at the ground surface.

A second factor influencing the potentials observable at the surface, is the electrical continuity of the metallically conductive mineral deposit. A body of massive sulphides, for example, will yield a higher potential than a body of disseminated mineralization. This is presumably due to higher internal resistance offered by a vein structure in which the conductive mineralization is not in sufficiently close contact to offer a continuously good conductive path for the current. In consequence, the voltage drop within the resistance vein structure itself is considerably more pronounced than in the case of more massive, conductive sulphides. This causes proportionately lower potential drops in the "exterior", or near-surface, portion of the circuit available for observation.

As a rough rule-of-thumb, disseminations carrying less than 5 per cent total conductive sulphides, are unlikely to yield interpretable reactions. It should nevertheless be noted that a mineral deposit can contain less than 5 per cent total conductive sulphides and still offer good conductivity if the sulphides, instead of being scattered through the vein material, are present as an interlacing network of veinlets, as thin platings along intersecting cracks and fissures. Under these conditions, interpretable reactions can be expected.

A rough correspondence often exists between the percentage of conductive sulphides present, and the maximum potential observable at the surface, above a
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shallow sulphide body apex. A potential of 50 millivolts (1 millivolt is 0.001 volt) usually indicates about 5 per cent total conductive minerals, or possibly less. Increasing content of conductive mineralization is suggested by higher potentials, and when potentials of 300 mv. and higher are recorded, it may be assumed that the causative body carries heavy sulphide mineralization, say 30 per cent or more.

A third factor in the strength and distribution of potentials observable at the surface, is the extension in depth of the reacting body. A well-mineralized sulphide, or other conductive body, extending to considerable depth will have its upper and lower ends bathed in contrasting electrolytes, and will generate strong potentials. The negative (near surface) and positive (deep-lying) poles of this natural battery will be widely separated, and the current will spread far into the country rock in its return to the surface. This will produce a broad electrical field centred more or less above the mineral apex, with noticeable increases in ground potentials, commencing as much as 300 ft. or so away from the vein, in the wall rocks on each side. The potentials increase in value from there to a rounded maximum over the vein apex. This maximum will be a maximum of negative potentials.

Where the sulphide (or other conductive mineral) body is small vertically, measured say in a few tens of feet, the results are different. In the first place, contrasts between the electrolytes around the upper and the lower portions of such a body are likely to be minimal, and the potentials generated may be lower than in the case of a body whose vertical extent is measured in hundreds of feet.

In addition, the two poles of the mineral battery are fairly close together, with the result that the current, in flowing up from the lower, positive pole to the near-surface, negative one, does not spread widely into the wall rocks. The electrical field at the surface is therefore confined to a narrow zone along the vein; the rise in potentials may be detectable only 10 or 15 ft. away from the apex, and the plotted profile of the potentials will rise abruptly to a sharp peak, and drop off as abruptly on passing beyond the apex. This type of reaction can be masked by a relatively shallow overburden, only a few tens of feet deep.

Since the strength of the potentials generated depends on the chemical nature of the elements in contact, not on their volume, the quantity of sulphides present or the thickness of the vein exert no effect whatever on the voltage observable at the surface. Also, since the normal distribution of electrolytes is acid near surface and alkaline at depth, the result is always to produce a negative centre over the apex of a reactive deposit, whether the mineral be conductive sulphides, graphite, coal or rare conductive oxides. If a centre of positive potentials at the surface is definitely associated with a conductive deposit, then the explanation must be sought in an anomalous reversal of the normal space relationships of acid and alkaline electrolytes, a most unusual but not unknown circumstance.

In résumé, electrical currents are spontaneously generated by the electrochemical reactions between metallically conductive minerals (mostly the sulphides, arsenides, antimonides, tellurides, etc.) and electrolytes in the surrounding rocks and soils. The strength of the electrical potentials thus created depends on the chemical nature of the metallic and the electrolytic conductors in contact with each other. The strength of potentials observable at the surface, over a deposit, depends also on the percentage of sulphides present, on the vertical size of the deposit, and on the depth of overburden.

The electrical field thus emanating from a mineral deposit is mapped at the surface by making observations of the potentials naturally present in the ground, on a systematic grid of observation points. The usual practice is to take readings at regularly spaced stations, along straight lines crossing the prevailing structural trends as nearly at right angles as is convenient. The stations may be at intervals as small as 5 ft. to as great as 100 ft., depending on the nature of the problem.

The instrument used for measuring spontaneous polarization potentials is a potentiometer-voltmeter, sensitive to 1 millivolt. In this apparatus, a measured current is drawn from some flashlight batteries and used to neutralize the ground current between two contacts with the earth, a "null method" of measurement. By opposing the ground current with an equal and opposite current from the batteries, no current is drawn from the ground. Were the current drawn from the earth, a new, and unrelated, circuit would be set up, distorting the original electrical field and invalidating the observations.

Since a metal in contact with the ground will be in contact with electrolytes and will set up a current, non-metallic contacts must be used when measuring earth potentials. The usual form consists of porous porcelain pots, a little larger than a coffee cup, filled with a saturated solution of copper sulphate, containing an excess of the sulphate crystals to insure satura-
tion at all times. A copper bar is plunged into this solution, and is connected by wire with the measuring apparatus. By this arrangement, the electromotive potential of the bar against the solution is equal in both pots or electrodes. The copper sulphate solution percolates through the porous bottom of the pot and makes electrical contact with the earth. No significant potentials are set by this action. These porous pots are therefore known as “non-polarizing electrodes”.

By keeping one electrode at a fixed spot and moving the other systematically along the various traverse lines, making contact with the earth at predetermined intervals, measurements of ground potentials are made which can be assembled to picture the distribution of these potentials within the area studied. The values recorded can be plotted along each traverse against the stations occupied. If the negative potentials are plotted above the line, the resulting profile will rise to a peak over a centre of electrical activity connected with a mineral deposit. Some geophysicists plot the negative below the line, producing a trough instead of a peak over a reactive deposit.

An equipotential contour map can be drawn up if a series of traverses has been made with the lines sufficiently close together. In this map, each contour joins the points showing the same potential, so it is essentially a contour map of the “mountain of electricity” centered on the deposit. In addition measurements can be taken to advantage in underground workings, provided metallic pipes and rails have been removed or insulated from the rocks, in those drifts and crosscuts to be utilized. This is necessary as the metallic rails and pipes would be in contact with electrolytes in the wall rocks and floor, and thus would generate currents. They are capable of generating fairly strong currents, but fortunately the effect usually is limited to a radius of a few tens of feet. Hence, such metallic material needs to be removed only from those workings actually to be traversed by the observations.

Wherever reactions of interest, or “anomalies”, are encountered, measurements must be extended well beyond the anomalous area. This is necessary since there is no such thing as a zone of zero reaction, because weak electrical currents circulate everywhere in the earth’s crust. Therefore, it becomes essential to continue the observations well into the zone of these weak reactions in order to pick, by inspection, a zero or datum to which to refer all measurements. It is like determining sea level on a wave-washed coast where the ever-rolling breakers continually produce crests and troughs above and below the true mean sea level.

In surveys covering large areas, a regional gradient may be encountered, sometimes amounting to a few, even 10 or more, millivolts per kilometer. In this case, a “sloping zero” correction can be applied.

Another disturbing factor is occasionally encountered in mountainous country, namely, the “topographic effect”. This effect is to be suspected when the profiles of electrical potentials show striking similarity to the topographic profiles. Unfortunately, it produces negative centres on or near hill tops. It has been ascribed, on occasion, to the potential gradient in the atmosphere. Since neighbouring hills of similar slope and altitude can show radically different topographic effects, and since the topographic effect is frequently absent altogether, nothing as uniform as the atmospheric potential gradient is likely to be the cause. Rather, the factor to be considered is the phenomenon of electro-filtration.

Where the rock and soil formations are such as to promote ready, downslope flow of ground water, the movement of the water through the porous soil and rocks will produce a negative zone in the area from which it is flowing (top of the hill). If the formations are of such nature or lie in such an attitude as to inhibit downslope flow, no topographic effect will be recorded.

Electro-filtration, or electro-capillarity is probably the cause of another disturbing factor occasionally encountered in tropical areas having strongly contrasting wet and dry seasons. In regions of steeply tilted, thinly bedded formations, especially shales and shaley sandstones, a pronounced and irregular increase in positive potentials is sometimes observed during the dry season. This effect is not so noticeable in areas of more massive rocks, either sedimentary or igneous. The phenomenon seems to be due to the capillary rise of deep-lying moisture to the arid surface where rapid evaporation is taking place. This movement carries positive potentials with it, thus augmenting positive values at the surface. The same phenomenon can happen in faults and shear zones, and may be employed to help map them.

Positive zones may also mark faults and shears under other circumstances. If a fault, especially a wet one, passes close to or intersects the lower portion of a reacting sulphide deposit, it may serve as a conductive “conduit” in which the outflowing current is concentrated in its return to the surface. This will produce a positive centre when the current flows out of the fault zone to return to the negative centre over
the sulphide apex. The phenomenon can thus be useful in unravelling some of the structural features of an ore-bearing region.

Under some circumstances, spontaneous polarization currents may fail to appear around a sulphide body, for example, in a sulphide deposit when the percentage of sphalerite is quite high in comparison with the percentage of conductive sulphides such as galena, pyrite, chalcopyrite, etc. The sphalerite may then insulate the grains and crystals of the conductive sulphides, destroying the electrical continuity of the deposit.

Spontaneous polarization currents apparently do not arise where sulphides lie beneath lake waters. The explanation lies probably in the natural character of lake waters, neither acid nor alkaline, so that there is practically no contrast in pH between the waters surrounding the upper and the lower portions of the sulphide body.

Sometimes swamps exert the same blanketing effect, but since swamp water is likely to contain humic acids it follows that sulphide bodies beneath swamps may yield spontaneous polarization potentials; cases in point are known. The fact that an area is swamplike is, therefore, no reason to rule out spontaneous polarization work; however, it is advisable to check, say with resistivity, those areas lacking self-potential anomalies but which appear to be favourable, especially on strike of any spontaneous polarization indications.

It is evident that there are many factors which will influence the results obtained in a spontaneous polarization or self-potential survey. As with other geophysical techniques, no one method is ever likely to yield a unique solution. This desirable end can be approached only by a multiple-attack technique employing a variety of applicable geophysical methods. Spontaneous polarization is a most valuable and direct attack on the discovery of sulphide bodies. Its usefulness is as an intermediate step in the progressive narrowing of the search for ore, and the extent to which it can be made to serve this end depends on the ability and the experience of the geophysicist. He must have a sound knowledge of geology, and a keen appreciation of how various geological factors can effect the results obtained. He must have a wide experience to enable him to meet, and overcome or circumvent where possible, the sometimes confusing indications arising from phenomena extraneous to his objectives. If these confusing indications cannot be eliminated, he must have a clear understanding of the extent to which they may be clouding his data.

Some of the more important problems to be faced in a survey follow:

1. Choice of base point ground contacts from which to conduct the measurements, in order to minimize disturbing effects; this involves evaluation of topography, vegetation and geology;

2. Orientation and spacing of the lines of observation in order to gain the maximum benefit from the data; this requires an evaluation of the structure of the formations involved;

3. Appreciation of what potential values may be significant; the significant values may vary from a few tens of millivolts for thinly mineralized deposits, to 100 millivolts or more when looking for massive sulphides of major dimensions;

4. Decision where and how much detail work must be done to give the maximum of valuable data without excessive cost;

5. Finally, decision whether or not the data obtained warrant recommending further exploration by drilling, trenching, or underground work, and where the work should be done in order to determine rapidly and cheaply whether or not an orebody exists beneath the anomalies.

In the search for sulphides and related minerals (sulpharsenides, sulphantimonides, arsenides, antimonides, tellurides, etc.), the spontaneous polarization method furnishes a rapid and economical spearhead for the attack. In competent hands, such a survey can be and should be thoroughly integrated in the program of geological exploration and diamond drilling. Correlated also with findings by other geophysical techniques, such an overall program furnishes a powerful tool for economy of time and money in the finding of new ore deposits and, of equal importance, in lessening the cost of not finding ore.

REFERENCES


THE RESISTIVITY METHOD

H. O. Seigel*

WHEN an electrical voltage is applied across a sample of a substance, a current is caused to flow through the substance. The ratio of the applied voltage to the current is related to the "resistivity" of the substance, i.e., it is a measure of the resistance the substance offers to the flow of electric current, in units of resistance times unit of distance. In this volume all resistivity measurements are given in meter-ohms. Other units sometimes employed are ohm-meters or ohm-centimeters.

Most rock materials, when perfectly dry, are excellent insulators. In all rocks, however, the individual aggregates of minerals, or grains, are separated by microscopic holes called pore spaces. The ratio of the volume of the solid mineral grains to the pore spaces within the entire rock mass is dependent upon the size and shape of the grains and the degree of compaction of the rock. The pore spaces contain appreciable amounts of water with salts in solution even above the permanent water table. It is because of these solutions that all rocks in their natural states conduct electricity to some extent. This type of conduction is called "ionic". Naturally the greater the porosity or fissuring of a rock the more water it can contain and the lower will be its resistivity. Different formations often can be distinguished by their difference in resistivity, reflecting a general change in average porosity. However, because the physical condition of a rock mass often will vary from place to place within the mass it cannot always be said that a specific narrow range of resistivities characterizes a particular rock type. A ten-fold variation may often be encountered within one rock type.

Surface Water Conductive

Soils, swamps, lakes and streams usually have much lower resistivities than the underlying consolidated rocks.

In general, igneous rocks have higher resistivities than sedimentary rocks. The resistivity of sedimentary rocks frequently rises with the age of the rocks, since advancing age generally means greater compaction.

The rocks of the Precambrian Shield in Canada are among the most highly resistive in the world, with resistivities up to one million meter-ohms. At the other end of the scale, saline shales of much more recent age exhibit resistivities of less than one meter-ohm.

Many rock constituents have the ability to conduct electricity, even in a perfectly dry state. These include graphite, a wide variety of metallic sulphides, and a.

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*Consulting Geophysicist, Toronto, Ontario.
few metallic oxides; they have the property of “electronic” conduction. This is the manner in which metals themselves conduct. As a class, these minerals are much better conductors than barren rock and hence can be readily differentiated from the rocks by their greatly decreased resistivity.

**General Field Procedure**

Current may be caused to pass into the earth by connecting a direct current or a low-frequency alternating current generator to two contact points, such as metal stakes driven into the ground. If the medium between the two stakes is homogeneous the current will flow through it in a manner predictable by theory. The passage of current will cause voltage differences in the region about and between these stakes and these voltages are predictable, once again by theory, since they are dependent on the distance between the stakes, the total current, and the resistivity of the medium. By measuring these differences it is possible to determine the resistivity near the stakes, knowing the other factors involved.
Since, in nature, no rocks are perfectly homogeneous, the value of "resistivity" which may be computed from such measurements will depend on the region in which the measurements are made. With this information, it is possible to make the same calculations as in the case of a truly uniform medium, but calling the resultant values the "apparent resistivity" of the medium in the region of measurement.

The apparent resistivities will decrease near areas of increased porosity, shearing and brecciation, and also in the presence of concentrations of the electronic conductors referred to.

**Canadian Practice**

The system usually employed in Canada involves two current stakes about 7,000 to 15,000 ft. apart, with the line joining the stakes being perpendicular to the regional strike. (Figure 1). Voltage measurements are made in the central region along survey lines also running perpendicular to the formational strike, with the current stakes remaining fixed throughout the survey.
A second form of survey, widely employed elsewhere, moves both the current stakes and the voltage measuring points, with fixed relative spacing, throughout the area to be surveyed. (Figure 2). The latter system has the advantage that its “depth of penetration” can be controlled by varying the relative spacing of the ground points. That is, it can be made sensitive to effects arising preferentially from a certain range of depths. It is not widely used in Canada, however, because usually it is affected adversely by the relatively well conducting soil mantle present over most of the Shield area.

The resistivity methods are used in mining exploration primarily for base metal sulphides, although they have been employed in the search for high resistivity materials as well, such as certain hematite occurrences and quartz veins. They find increasing use in engineering problems, such as determining the depth of drift at dam sites and elsewhere, and also in the search for water-bearing formations where surface water supplies are inadequate.

Interpretation

The greatest limitation to a satisfactory interpretation of a resistivity survey is that the variations from the normal or background values, i.e., the so-called “anomalies” could be caused not only by the materials sought, such as metallic sulphides, but also by non-economic structures. A narrow, highly conductive zone, such as a massive sulphide body, may give rise to the same type of anomaly as a broad zone of lower conductivity like a shear zone. This is an instance of the “saturation” effect to which the resistivity measurements are susceptible. This does not apply when the width of a zone is much greater than its depth below surface, for then we can get a measure of the true resistivity of the zone from the surface measurements and hence can differentiate between concentrated sulphides and a shear or fracture zone having no sulphides. Even under these favourable circumstances we cannot always distinguish between concentrated sulphides and graphite, nor between disseminated sulphides and a shear or fracture zone.

Valleys in the bedrock under 50 to 100 ft. of overburden also can give rise to resistivity anomalies which may be of the same magnitude as those to be expected from small sulphide bodies in the bedrock.

All too often these limitations are ignored in practice and interpretation, with consequent disappointment when all the resistivity anomalies in an area are drilled and do not disclose sulphide mineralization. It is only when these factors are understood both by those who carry out the surveys and by those for whom the surveys are performed, that the resistivity methods find their proper appreciations as simple, inexpensive and relatively rapid tools for base metal exploration.

REFERENCES


ELECTROMAGNETIC SURVEYING — GROUND METHODS
by S. H. Ward* and T. R. Gledhill*.

The electromagnetic method of geophysical prospecting is based on the interrelation of the two fundamental physical phenomena, electricity and magnetism.

Early geophysical work employed these phenomena in prospecting for sulphide mineralization by passing a current through the ground via two metal stakes and measuring the resulting magnetic field at the surface of the earth. By this procedure, it was possible to determine whether or not an excellent conductor of electricity existed under the surface of the ground.

Subsequently, subsurface conductors were energized inductively rather than conductively, with the result that lighter weight equipment and reportedly greater differentiation against extraneous conductors became possible. Most modern electromagnetic surveys employ inductive energy sources. They are very efficient and have led to the discovery of several substantial base metal deposits. However, at least one exploration company currently is obtaining satisfactory results with a conductive source method.

This paper outlines the principles and operation of two of the commonest forms of inductive electromagnetic survey techniques.

Theory

In nearly all present-day electromagnetic work, an electrical field is established when a strong alternating current passes through a transmitting coil and, in turn, produces an alternating magnetic field (referred to as the primary field) about the coil. If there is a highly conductive mass near the coil the primary alternating magnetic field induces electrical currents in the conductive mass, which in turn produce another alternating magnetic field, known as the secondary field. This secondary magnetic field distorts the primary magnetic field and it is measurements of the distorted primary field (i.e. total field), that are used in electromagnetic surveying.

In addition to an obvious directional distortion of the primary field, the time reference or the “phase” is usually changed so that a portion of the total field is “in-phase”, that is, similar in time to the transmitted field; and a portion is “out-of-phase”, that is, changed in time reference. In general, the poorer the conductivity of a body the greater the time distortion, or the greater the out-of-phase portion of the total field. In a perfect conductor the total field is all in-phase (no time distortion).

Secondary electromagnetic fields are set up in all conductive bodies surrounding the transmitting coil.

Common conductive bodies encountered are: (i) overburden; (ii) clays; (iii) electrolytes filling fault zones, shears or porous horizons; (iv) graphitic shears; (v) carbonaceous sediments; (vi) sulphide mineralization.

For an electromagnetic survey to be of greatest use, the interpretation of data from it should involve the assessment of the most probable cause or causes of an anomaly from among the several possible causes listed above.

The effect of any one of these conductive bodies can easily be masked by another, or by a combination of the others. On the other hand, with a careful choice of coil system and operating frequency, the effect of any one conductor often may be magnified or reduced. Hence some sorting of conductors is possible on the basis of electromagnetic survey data alone.

Measuring the Magnetic Field

With the systems in use today, the following measurements of the resultant magnetic field are employed:

(a) Direction of the magnetic field and the width of the null (the latter is a measurement of the out-of-phase):
   1. "strike angle" in the horizontal plane;
   2. "dip angle" in the vertical plane which is perpendicular to the plane of the transmitting coil.

(b) Magnitude of the magnetic field:
   1. total field amplitude;
   2. amplitude of in-phase component;
   3. amplitude of out-of-phase component.

The measurements in case (a) are those commonly made with the vertical transmitting coil system; those

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*Geophysicists, Nucor Limited, Toronto, Canada.
in case (b) commonly are made with the horizontal transmitting coil system.

These measurements are usually made with a “search” or “receiving” coil. At any point in a magnetic field, a search coil will have an induced voltage which is dependent upon the frequency of the alternating current in the transmitting coil, the number of turns of wire in the search coil, the area of the search coil, and the angle the search coil makes with the lines of force.

The “dip angle” measurement employed with the vertical transmitting coil system is illustrated in Figure 1A. The directions of the primary and the secondary fields are indicated by arrows whose lengths are proportional to their respective field strengths. The direction and the intensity of the resultant or “distorted” field are found by employing the so-called “parallelogram of forces” as shown. The resultant arrows are parallel to the plane of a search coil when it is rotated into a position where it is not cut by any of the lines of force of the resulting field. In these positions, no voltage is induced in the search coil and hence, if a pair of earphones is connected across the search coil, no signal is heard. A signal is heard when the search coil is tilted in either direction away from the position of minimum voltage.

The angle between the resultant arrow and the horizontal at any point is termed the “dip angle”, and its determination often is the only measurement in this system of surveying.

Sometimes, however, the “strike angle” is measured in addition to the dip angle. In these instances, the plane of the search coil is turned to the vertical and the coil is rotated about a vertical axis until a minimum signal is heard in the earphones. Then the direction of the plane of the search coil is recorded. The difference in angle between the observed direction of the search coil plane and a plane perpendicular to the transmitting coil plane is termed the “strike angles”. This is illustrated in Figure 1B.

The amplitudes of the total field, in-phase component, and out-of-phase component in any direction may be determined with the aid of search coils where the transmitting coil is horizontal. Usually, however, these measurements are recorded with the plane of the search coil being horizontal and hence those secondary magnetic fields having a vertical direction or component are measured. In order to provide a ready reference, the amplitudes of the resulting vertical fields are compared with the amplitude of the transmitted field at the transmitter. Thus the effects of variations of the transmitted field strengths are unimportant.

**Equipment**

In selecting the electromagnetic system best suited to surveying a given area, the geologist should have the following information on the typical conductor (sulphide orebody) sought:

(a) attitude and configuration of conductor; (b) maximum and minimum dimensions of conductor; (c) physical properties of the conductor; (d) physical properties of the host rock; (e) depth and conductivity of overburden; (f) topographical relief.

All these factors will influence the choice of the electromagnetic equipment for a particular exploration program. It is possible for the geophysicist to alter two significant variables in the design of ground electromagnetic equipment in order to obtain optimum performance under any given set of the above conditions.
These variables are:

- **Frequency**

  The frequency of the alternating current is an important consideration in the choice of equipment. By selecting the correct operating frequency, responses from extraneous conductive bodies, such as faults, shear zones, swamps, etc., may be reduced and the response from the conductive sulphides may be raised.

  To visualize the frequency dependence of a conductor to an electromagnetic field, consider the simulation of a sulphide lens by a conductive sphere in a space occupied by a uniform alternating magnetic field. The in-phase and out-of-phase responses are plotted as functions of frequency in Figure 2. The in-phase response rises gradually from negligible at very low frequencies to maximum in a region of “saturation”, where any increase in frequency has no noticeable effect on the amplitude of the response. The out-of-phase response from this body rises from zero more quickly with increasing frequency than the in-phase component, levels off at some critical frequency where it equals the in-phase component, then drops until it becomes negligible. The forms of these curves remain the same if the size or the conductivity is chosen as the variable, instead of the frequency.

  The practical range of frequencies for most of Canada is from 60 to 5,000 cps. The upper limit is set by geological considerations, since all faults and shears are conductive at these higher frequencies; the lower limit is set by equipment weight considerations.

  An examination of Figure 2 shows that measurement of the in-phase response of a body at two discrete frequencies will provide a quantitative evaluation of the body’s conductivity if this conductivity lies below the saturation portion of the in-phase curve. Similar measurements of the out-of-phase component at two frequencies would lead to ambiguity, but on occasion might be used for evaluation of conductivity.

  Figure 3 shows the response from poor, moderate, good and excellent conductors surveyed with a vertical transmitting coil system at 1,000 cps and 5,000 cps. The separation between the transmitter and the receiver-traverse, normally termed the “spread”, was 400 ft. for these examples.

  Similarly, it is possible to evaluate the conductivity of a buried mass by measuring the ratio of in-phase response to out-of-phase response at a single frequency.

- **Coil Configuration**

  In choosing a suitable coil configuration we should keep in mind the following:

  (a) finding an orebody is a three-dimensional problem;
### A Comparison of the Two Common Coil Systems for Ground Surveys

<table>
<thead>
<tr>
<th>Survey technique</th>
<th>System 1—Vertical Transmitting Coil</th>
<th>System 2—Horizontal Transmitting Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td>Transmitter usually is stationary and traverses with the receiving coil are carried out normal to the geological structure. The system has been used by traversing the transmitter along one line and the receiver along a parallel adjacent line, or the two coils are moved in steps of 100 feet as a unit along one line. Orientation of the transmitting coil is required.</td>
<td>Transmitting and receiving coils are linked by a reference cable and this fixed array then traverses along lines normal to the geological strike. No orientation of this system is employed other than levelling.</td>
</tr>
<tr>
<td>Quantity measured</td>
<td>Direction of the resultant magnetic field in one plane.</td>
<td>The change in the in-phase and out-of-phase components of the resultant vertical magnetic field.</td>
</tr>
</tbody>
</table>
| Dimensions of coils | (a) Transmitting Coil  
—Triangular up to 15 feet to the side.  
(b) Receiving Coil  
Nominally of the order of 12 inches in maximum dimension. | (a) Transmitting Coil  
—Circular, 30 inches in diameter.  
(b) Receiving Coil  
—Circular, 30 inches in diameter. |
| Topographic effect | There is no effect from topographic relief since the measurement is made in the plane of the transmitting coil. | Irregular topography results in the coils moving closer than the separation for which the compensator is adjusted. Excessive positive in-phase readings follow. If the coils are at different elevations, negative in-phase readings occur because of the change in coupling but may be minimized by turning both coils off the horizontal, until they are estimated to be coplanar. Reference to topographic maps may permit evaluation of the importance of these two effects. |
| Depth of exploration | The depth of exploration in both cases is proportional to the separation of the coils. As a general rule this depth is one half of the separation.  
Separation ranges from 400 feet to 1,600 feet would give depths of exploration of 200 to 800 feet. | Separation ranges from 100 feet to 400 feet would give depths of exploration of 50 to 200 feet. |
| Estimating conductivity | Dual frequency surveys are possible and customarily are employed. Comparison of dip angles at the two frequencies yields information regarding conductivity of body. | Dual frequency surveys are possible but customarily are not employed.  
Conductivity information is supplied by in-phase to out-of-phase ratio. |
| (a) Dual frequency | | |
| (b) Out-of-phase measurements | Out-of-phase measurements are qualitative, being recorded as null width in degrees plus amplitude of signal over this null. They provide a qualitative confirmation for the conductivity analysis furnished by the dual frequency dip angle comparison. | |
| Response to conductive sheets | (a) Vertical sheet  
Strong response.  
(b) Horizontal sheet of limited extent, equivalent to small swamp or flatterlying sulphide body.  
Good response from edges only. | Strong response.  
Good response for entire sheet.
(c) **Horizontal sheet of infinite extent** (conductive overburden equivalent).

(d) **Horizontal sheet overlying vertical sheet** (equivalent to vertical ore-body underlying swamp or conductive overburden).

(c) **Large vertical sheet** to one side of grid.

**Effective coverage**

(a) **Area consideration.**

(b) **Depth.**

(c) **Overall consideration**

**Economy**

**Resolution of adjacent conductors**

**General**

The system would have an advantage where topographic relief is greater than 10% of the separation in system 2 between the two coils, or where the overburden is fairly conductive, or where great depth of exploration is required.

Neither system requires lines on open plains or on ice surfaces of lakes where visual orientation is possible.

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No response.

Good response to corresponding vertical sheet. Response over edges of horizontal sheet.

Detects large sheets as much as 500-1,000 feet off grid, depending on spread.

In both cases the effective coverage depends on the size of strike length of the conductor is of the order of the traverse line conductor sought and on the coil separation. Assuming the interval, the effective coverage in the case of 400 foot line is:

With 200 ft. coil separation effective coverage of an area is 50%.

The average depth of exploration is: 400 feet.

9 units of volume.

100 feet.

1 unit of volume.

Under average conditions of moderate vegetation coverage and topographic relief, the two systems are equal in cost per mile of line traversed.

Conductor closest to transmitter will often partially mask effect of more distant conductors. It is necessary to erect transmitter independently on each conductor in order to provide comparative evaluations. This fact can be put to good advantage in tracing one interesting conductive bond in presence of others of no commercial interest.

Without special detailed surveying the method will resolve and define conductors 200 to 400 feet apart or more and will emphasize each proportional to its size and conductivity.

The system would have an advantage in an area where the vegetation is light enough to traverse without lines and the topographic relief is not enough to confuse readings. It would have an advantage also in surveying an area containing several closely spaced conductors, since the short spread normally used leads to high resolution. Further the station interval may be adjusted as desired during the course of a survey.

The system would have an advantage in detecting small conductors whose size is of the order of the separation between the two coils provided the traverse lines were spaced sufficiently close together (100 feet, say).
(b) depth of exploration is dependent on coil separation;

(c) if the overburden is conductive, the coil configuration should reduce the response from the overburden;

(d) the coil configuration should provide for adequate response from the typical orebodies of the region.

In considering (a), it is necessary to employ a coil configuration that will give the highest response from a body of certain dimensions. This body may be on the plane of exploration, but more probably will be at some variable depth below the plane. The optimum coil separation for maximum response is of the order of the body's greatest dimension provided the distance of the coil system from the body is less than this dimension.

With regard to (b), the physical separation of the transmitting and the receiving coils should be sufficient to ensure depths of exploration varying from 75 to 500 ft. or more. The field technique for the coil configuration chosen must be adapted to the coil separation or vice versa. Thus with the vertical transmitting coil, separations of 400 to 1,600 ft. are common and permit depths of exploration from 200 to 800 ft. However, the coil separation commonly in use with the horizontal transmitting coil is 100 to 400 ft., with consequent depths of exploration of 50 to 200 ft.

Concerning (c), Wait\textsuperscript{*} has made an analysis of coil systems which indicates that maximum rejection of the response of infinite flat horizontal conductive sheets can be expected from the vertical transmitting coil, while a fairly large response is obtained over the same conductor with the horizontal transmitting coil. An infinite flat horizontal conductive sheet is a first approximation to a uniform layer of overburden.

With respect to (d), either the vertical transmitting coil or the horizontal transmitting coil provides for adequate responses from most typical orebodies in the Canadian Shield or in the Palaeozoic deposits of New Brunswick, the commonest areas of application of electromagnetic surveys.

Field Procedure

As mentioned above, both electromagnetic systems are in general use. Each has its advantages and its


limitations. In the following paragraphs the field techniques are described and the systems are compared.

- System 1 — Vertical Transmitting Coil

With this system, measurements are usually restricted to a quantitative recording of "dip angles" as described earlier and a quantitative recording of width of null (related to amplitude of out-of-phase).

Figure 4 shows idealized dip angle curves for 1,000 cps and 5,000 cps, obtained across a massive sulphide orebody and a swamp. Over barren ground, the dip
angles are practically zero. The approach to a conductor is marked by rising dip angles which in turn drop to zero directly above the conductor and then rise again, but in the opposite sense, beyond the conductor until far away from the conductor they reduce once more to zero. Note that the edges of the swamps sometimes show up as individual conductors (on the 5,000 cps only).

In operation, the transmitting coil is set up at a convenient location and traverses are made perpendicular to the assumed geological strike, on either side of the transmitter.

With the transmitter located on line 0, traverses normally would be made of lines 4, 8, 12W and lines 4, 8 and 12E as shown. Then the transmitter would be moved to line 12E and line 0 and three additional lines 16, 20 and 24E would be traversed.

To overcome extraneous dip angles (or strike angles if measured) arising from elevation and topographic effects, the plane of the transmitting coil is oriented on each observation so as to contain the point of observation. If relative positions of the transmitting coil and the receiving coil are known to within a few feet, the transmitting coil can be oriented to make errors negligible, even in the most rugged terrain. Hence the dip angle profiles are directly interpretable and require no topographic or other correction. When the coils are properly oriented, the occurrence of a dip angle indicates a conductor.

Orientation of the transmitting coil is effected by employing a plane table at the point of rotation of the coil. This requires use of a reliable scale drawing of the grid lines.

**System 2 - Horizontal Transmitting Coil**

This system comprises two horizontal coils spaced at a fixed distance with the coils held in the same plane. The primary field is produced by a horizontal transmitting coil which in turn produces secondary fields in all nearby conductive bodies. The vertical component of the resultant of the primary and the secondary magnetic fields is picked up by the horizontal receiving coil. The effect of the vertical magnetic field is cancelled out in the receiver with a compensator. The field at the receiver is comprised of two portions, the in-phase and the out-of-phase components. By means of a phase-shifting device and a reference lead from the transmitter, it is possible to cancel these two components with the compensator until there is no signal in the headphones. The in-phase and the out-of-phase components are read directly on the compensator as percentages of the primary field strength.

Investigations in the field as a rule are along straight lines perpendicular to the general strike. Observations are made with the coils at an arbitrary fixed separation which varies from 100 to 400 ft. The system as a unit is moved in intervals of 100 ft. (or 50 ft. for detail), new readings are taken, and the procedure is repeated until a line of desired length has been surveyed.

Anomalies appear as variations of the signal from the normal. As the unit is moved along a traverse line, the approach to a conductor is marked by an increase
Mining Geophysics

in both the in-phase and the out-of-phase readings until the receiving coil is directly over the conductor, when the readings will be zero again. After this they are negative while the conductor lies between the coils. When the transmitting coil is directly over the conductor the readings are zero again and become positive when both coils are beyond the conductor. By the so-called “principle of reciprocity”, the same anomaly profiles would result if the positions of the receiving and the transmitting coils were interchanged. This means that the same profiles would be traced regardless of the direction of traverse.

Figure 5 shows idealized response, for 400 cps and 1,600 cps, obtained across a massive sulphide orebody and a swamp.

Conclusion

It is believed that either of the two electromagnetic prospecting techniques discussed here can be used to advantage in an exploration program, provided that the limitations of the techniques are understood fully by both the geologist and the geophysicist employing them.

Of the conductors usually found in electromagnetic surveys, one might optimistically expect one in one hundred to be caused by sulphide mineralization. Pessimistically, this figure might be raised to one in one thousand. Obviously with such a profusion of extraneous conductors some grading or sorting must be done. On the basis of dual-frequency ground electromagnetic data in New Brunswick, the following qualitative “grades” of conductors have been found.

<table>
<thead>
<tr>
<th>Media</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive sulphides—mostly pyrrhotite, graphitic shear zones, pyrrhotite stockworks.</td>
<td>Excellent</td>
</tr>
<tr>
<td>Massive sulphides—mostly pyrite, graphitic shear zones, coarsely disseminated pyrrhotite.</td>
<td>Good</td>
</tr>
<tr>
<td>Pyrite stockworks—coarsely disseminated pyrite, highly carbonaceous sediments, graphitic partings on shear faces.</td>
<td>Moderate</td>
</tr>
<tr>
<td>Carbonaceous sediments—disseminated pyrite, pyrrhotite, solution-filled faults and shear, swamps, lakes, overburden.</td>
<td>Fair to poor</td>
</tr>
</tbody>
</table>

Further sorting of the conductors is done best by employing secondary exploration procedures such as gravity surveys or geochemical surveys, and/or by diamond drilling. An electromagnetic anomaly is just a starting point for specific discriminatory techniques.

Permission to publish this paper was kindly authorized by the management of the Exploration Division, Mining and Exploration Department of The American Metal Company, Limited.

REFERENCES


AIRBORNE ELECTROMAGNETIC SURVEYING

by S. H. Word*

Part I - The Method

AIRBORNE electromagnetic prospecting is one of the newest geophysical techniques to be made available to the mining industry. The first successful totally airborne electromagnetic system was placed in operation in 1950, but intensive and extensive use of such devices by more than one company was delayed until mid-1955. However, one or more semi-airborne electromagnetic prospecting devices were in operation on a limited scale from 1950 onwards. By late 1956 there were probably ten different airborne electromagnetic (AEM) systems in part or full time operation throughout the world.

The purpose of all of the totally airborne systems is to locate, rapidly, good conductors of electricity within the top 100 or 200 ft. of the earth’s surface. Such good conductors might be expected to include graphitic schists, carbonaceous sediments, fault and shear zones, swamps, etc., as well as the primary target, massive sulphide mineralization. Normally, the AEM equipment does not respond to changes in rock type as the airborne magnetometer does. Rather, it produces discrete anomalies only over such conductive media as listed above. Thus, in the normal sense, it is not a device for mapping structure. If, however, the structure in question contains such conductive media as massive sulphides or graphite, then the structure may be mapped because of this association—that is, indirectly.

AEM is intended to be a rapid reconnaissance survey technique which will locate most, but not all, of the economic deposits of massive sulphide mineralization within 100 to 200 feet of surface. The results of one survey over any area should not be expected to duplicate the results of a second survey over the same area unless the same instrument is flown at the same height, the same speed, and in the same direction, along the same flight lines for both surveys. This fact must be accepted by the geologist employing AEM equipment. Justification for the use of equipment which will reproduce results only under such stringent conditions lies in the undeniable fact that AEM surveys can and have found orebodies. AEM surveys have also missed some interesting sulphide bodies while detecting a host of extraneous conductors. The

*Geophysicist, Nucor Limited, Toronto, Canada.

The probability of locating all the economic massive sulphide bodies in an area can be raised by decreasing the flight-line spacing and by ensuring that the aircraft flies at a constant terrain clearance. Both factors are controllable, but both affect the cost per square mile of any survey. A reasonable balance between economy and effective coverage, as determined by these factors, must be established by the exploration team before commencing an AEM survey.

Principle of Operation

Most AEM systems in operation today are based on the measurement of the mutual impedance between two coils as this impedance is affected by the presence of nearby naturally occurring conductive bodies. Figure 1 illustrates this phenomenon.

Current (I) flowing in the transmitting coil causes a voltage (E) to appear across the receiving coil. The ratio \( \frac{E}{I} \) of the voltage in the receiving coil to the current in the transmitting coil is known as the mutual impedance between the two coils. If a conductive body
is brought near the two coils, distributed currents (Ic) will be caused to flow in it. These latter currents will cause a voltage (Ec) to appear in the receiving coil. Then the total voltage appearing across the receiving coil will be \( E + E_c \), and the measured mutual impedance between the transmitting and receiving coils will be \( \frac{E + E_c}{1} \); a change in measured mutual impedance occurs thus when the coils are brought near the conductive body. The process whereby a current flowing in one circuit causes a voltage to appear in an adjacent unconnected circuit is known as induction.

**Equipment**

It is not within the scope of this paper to describe in detail the equipment used in any particular AEM system but reference to the block diagram of Figure 2 indicates the basic components used in most systems.

A rotary or electronic generator, termed the transmitter, is employed to supply a single audio frequency (sometimes two frequencies) to a transmitting coil. The audio frequency current in the transmitting coil causes a voltage to appear across the receiving coil and causes currents to flow in adjacent conductive bodies. The voltage developed in the receiving coil then is compared with the voltage induced in a reference coil. This comparison takes place in the “compensator”. Because of the proximity of the reference coil to the transmitting coils, the voltage induced in it will not be affected materially by the presence of conductors. By using a “reference” system of this sort, variations of the strength of the transmitter output and of the gain of the amplifiers are unimportant. Further, it permits cancellation of the voltage normally appearing across the receiving coil, thereby facilitating more accurate measurement of the anomalous voltages developed across the receiving coil by currents flowing in nearby conductors.

Upon amplification, the output of the compensator is applied to a multiple pen, paper tape recorder. Variations from the normal voltage appearing across the receiving coils then cause the pen to deflect and an anomaly is traced on the moving paper. An illustration of a typical paper tape is shown in Figure 3.

![Typical Paper Tape](image)

**Figure 3.** Typical paper tape.

Because of the need to maintain accurate aircraft terrain clearance control, a radio altimeter is provided whose output also appears on the paper tape (Figure 3).

Since position of the aircraft must be known at all times in order to permit accurate mapping of the survey data, a continuous-strip camera is operated throughout the survey. An intervalometer provides conveniently spaced time marks or “fiducials” on the photographic strip film and on the paper tape. The strip film is compared with photographic mosaics or maps of the survey area in order to retrace the flight paths of the aircraft.
Sometimes two or more voltages from the receiver system are applied to two or more pens in the recorder. Thus measurement is possible of those portions of the anomalous voltages which are in-phase and out-of-phase with the normal voltages across the receiving coil. Sometimes two receiving coils and two transmitting coils operating at two discrete frequencies are employed, then two complete receiving channels are often used. Both the above dual-recording instruments are used in order to provide a measure of the conductivity, in addition to the location and the extent of the conductive bodies detected.

Survey Techniques

The AEM aircraft is flown at constant elevation along equally spaced lines forming a uniform grid across the area of interest. For most AEM surveys the aircraft flies at a mean terrain clearance of 500 ft. and along flight lines spaced 1,000 to 1,500 ft. apart. For greater detail and to facilitate the use of equipment designed for operation at lesser mean terrain clearance, some surveys are flown at altitudes as low as 150 ft. and along lines spaced as closely as 400 ft. The results of the survey, as recorded on the paper tapes, are positioned, interpreted and plotted on plan maps of the area surveyed. The reliability and interpretation of airborne electromagnetic data pose complex problems, which are discussed in the succeeding portion of this paper.

Part II - Reliability and Interpretation of Data

Airborne electromagnetic (AEM) systems are intended to serve as reconnaissance exploration tools in areas that are known or inferred to contain deposits of minerals which exhibit the basic physical property of high electrical conductivity and may be important commercially. The intelligent application of these systems presupposes a sound knowledge, on the part of the exploration geologist, of the general geology of the area to be surveyed. Such information needs to be conveyed in comprehensive form to the geophysicist and/or the electrical engineer before the latter can adapt the system to provide the most efficient exploration of any specific tract of land in which the geologist is interested. For, unlike airborne magnetic systems, AEM systems may be designed to provide optimum performance under a given set of geological conditions. The implications of such flexibility in an exploration tool require careful consideration before an adequate understanding of the reliability and interpretation of AEM data may be gained.

Problems Inherent in Design

For illustrative purposes, it is convenient to compare operational problems of AEM systems with those of an airborne magnetometer. In aeromagnetic surveying, the geophysicist has few significant variables with which to control the quality and the utility of the aeromagnetic data. Such variables include: (1) terrain clearance at which aircraft is flown; (2) sensitivity of magnetometer; (3) determination of flight direction; (4) flightline spacing.

On the other hand, with AEM systems the geophysicist is confronted with the task of choosing the optimum combination of these four variables, plus the following: (1) frequency or frequencies of operation; (2) coil configuration, including orientation of the transmitting and receiving coils and separation distance between the coils; (3) limiting air turbulence (this factor affects aeromagnetic systems also, but not to the same extent).

The choice of one factor very frequently limits the range of choice of the other factors and therefore it is not possible merely to “tune-up” each variable for optimum operating efficiency. It is customary at the outset to treat the last three factors simultaneously in designing an AEM system to suit any particular geological setting. The first four factors, then, are usually dictated entirely by the resulting optimum combination of the last three. Following are some of the effects brought about by varying the latter.

- Frequency

Usually, the frequency of AEM systems is chosen to lie between 150 cps and 250 cps. The upper limit is imposed strictly by geological considerations, while the lower limit may be imposed by geological conditions and/or the weight of equipment. In general, the lower the frequency the higher is the weight of the equipment. Also in general, the lower the frequency, the higher must be the electrical conductivity of any geological unit for it to respond in terms of a recognizable anomaly.

To illustrate the frequency dependence of the response to electromagnetic energy of a geological unit, consider the very simple case of a conductive sulphide lens in a strictly non-conductive rock as approximated by the response of a conductive sphere, suspended in space, and subject to a uniform alternating magnetic field. The in-phase and out-of-phase responses of the spheres are plotted as functions of frequency in Figure 1. The physical constants and the dimension of the
sphères are selected to approximate those which may be found in nature. It should be noted that the in-phase response of the sphere is negligible at very low frequencies, then gradually increases with frequency until a “saturation” limit is reached beyond which any increase in frequency has a negligible effect on the magnitude of the response. On the other hand, the out-of-phase response is zero, at zero frequency, and rises more quickly with increasing frequency than the in-phase component; it then levels out until, at some critical frequency, the in-phase and the out-of-phase responses are equal. Beyond this point, the out-of-phase response declines until it becomes negligible. The form of these curves is fundamental to the design and the operation of AEM systems. Similarly, the frequency may be considered fixed and the conductivity of the hypothetical geological unit varied systematically. The forms of the response versus conductivity curves are identical with those shown in Figure 1. Finally, if both frequency and conductivity are fixed and the size of the hypothetical geological unit be varied, the same curves will again be traced. Although the curves of Figure 1 were calculated for a spherical conductive body, the same general form of response curves applies to a body of arbitrary configuration in a uniform alternating magnetic field.

Practically speaking, this means that whether we measure in-phase or out-of-phase, it is possible to vary the operating frequency so that excellently conductive bodies, like massive sulphide lenses, will give rise to a large anomaly, while swamps, lakes, patches of overburden, etc., exhibit predominantly negligible anomalies. However, it should be obvious that because of the great extremes of variability of conductivities of geological materials, some lakes and swamps can give rise to significant anomalies, while poorly conductive sulphide bodies, particularly those involving silicous, finely disseminated sulphide grains and crystals, can give rise only to negligible anomalies. The discrimination between the wanted and the unwanted geological conductors can never be perfect. Further, the ideal frequency for one locality might not be at all suitable for another locality. Emphasis, therefore, is placed upon the necessity of knowing something about the physical properties of pertinent geological media before commencing an AEM survey. In the search for massive sulphide bodies in the Precambrian and in the Ordovician sediment-volcanic complex of New Brunswick, the lowest practical frequency (about 150 cps) appears to be the most suitable. This frequency may be too low if disseminated sulphides are being sought.

Emphasis on the desirability of the lowest practical frequency is afforded by flight record 1 of Figure 4. Note that a lake has given rise to an anomaly above background level, despite the use of a frequency as low as 150 cps. In New Brunswick, some AEM anomalies obtained with apparatus operating at 2,000 cps have been attributed to such poorly conductive media as solution-filled faults and shears, carbonaceous sediments, and disseminated pyrite or pyrrhotite.

An anomaly obtained over a stockwork of pyrrhotite with a 1,000-cps helicopter system clearly stands out above the background of the flight record of Figure 5.

The fact that the AEM response of geological materials is a function of frequency can be theoretically put to further use in attempts to identify the cause of the AEM response. Although width of conductor exerts a considerable influence on the response of near-spherical masses, it is not nearly as important for large, dyke-like conductors. The response of such conductors is dependent largely upon their conductivity at any fixed frequency. Thus, if an AEM system is designed to operate at two discrete frequencies simultaneously, the difference in response at the two frequencies theoretically is a qualitative measure of the conductivity of the causative body.

Rather than use two frequencies simultaneously, it is theoretically possible also to compare the out-of-phase response with the in-phase response at a single frequency in order to estimate conductivity.
In practice, the theoretical state of affairs indicated here can be only partially realized in any known operating AEM system. The qualitative determination by AEM of conductivity of geological units is not too reliable. Comparison of the responses at two frequencies infers maintenance of identical behaviour and amplification of two separate electronic systems (one for each frequency). Further, it infers that the zero level of response is known absolutely for each electronic system, so that the amplitudes of responses which are being measured can be compared intelligently. Finally, it ignores the influence of the overburden on the amplitude of responses.

Similar comments apply, if one should wish to measure the ratio of in-phase response to out-of-phase response, as an indicator of conductivity. On the optimistic side, some "grading" of conductors directly from airborne data has proved successful on the basis of conductivity analysis. However, there is a tendency to overrate its reliability. In contrast to this, such grading of conductors on the basis of dual-frequency ground electromagnetic surveys has proved about 80 per cent successful in New Brunswick, during the last four years.

**Coil Configuration**

Having chosen the frequency which he considers optimum to obtain maximum response from sulphide bodies and minimum response from extraneous features typical of the region to be surveyed, the design engineer then chooses a coil system which magnifies geometrically the response of typical sulphide bodies and reduces that of extraneous features. In the Palaeozoic regions of New Brunswick and in the Precambrian of Canada, the geophysicist begins with the basic assumption that most sulphide orebodies have longer depth than width, i.e., are nearly vertical sheet conductors. He also realizes that overburden, lakes, and swamps are essentially flat-lying sheet conductors. The response of the latter may be reduced by the appropriate choice of coil configuration as Wait* has shown.

Five coil systems are listed in Figure 2 in order of increasing magnitude of response to flat-lying, infinite conductive sheets (a first approximation to extensive uniform overburden). If the conductive sheets are finite (e.g. flat-lying orebody) the analysis illustrated in Figure 2 does not necessarily hold true.

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However, with greater coil separation comes an inherent response to more poorly conductive materials; the effect is similar to increasing the frequency of operation. A decision then has to be reached to provide that the depth of exploration is adequate to reach at least through the overburden, but that the separation does not lower the frequency of operation to ridiculous extremes in order to minimize the response of the poorly conductive extraneous materials. However, this decision must include also consideration for the next item, limiting air turbulence.

- Limiting Air Turbulence

Any of the coil systems mentioned above may be mounted at opposite ends of a rigid structure in order to prevent relative motion between the coils when in flight. This is done in all current helicopter electromagnetic systems, for example. The rigid structure may be the aircraft itself or a towed or mounted beam. Alternatively, the coils may be allowed to move relative to one another (towed bird systems), in which case either the relative motion is recorded and applied as a correction to the response record, or measurement is made of only the out-of-phase response (which cannot arise from the transmitter in a perfectly balanced electrical circuit).

Whichever approach is used, there is some limiting air turbulence beyond which the relative movement of the coils will produce false responses on the recording apparatus of such magnitude as to obscure any true anomaly. Recognition of an anomaly then is simply distinguishing the anomaly from a general background “noise” from this and other sources. Other systems of limiting or allowing for noise due to air turbulence have been devised but are somewhat complex and not pertinent to the current description. It should also be mentioned that several other sources of noise arise with any mobile electromagnetic system but all of these can be suppressed adequately.

It should be mentioned that the relative motion between coils may be either rotational or translational; in either case a spurious noise is created in the recording equipment.

Thus AEM surveys might best be performed in the very early morning or in the late evening when winds and thermal air currents are lightest, giving minimum air turbulence. Some days are entirely unsuitable for AEM surveying because of turbulence.

Most rigid-structure coil systems involve coil separations of the order of 20 to 50 ft., while most towed bird systems involve coil separations of the order of 300 to 500 ft.

“Maximum coupled” coil systems (2, 3, and 4 in Figure 2) offer least trouble from relative coil rotation, insofar as the spurious noise response so introduced is a function of the cosine of the angle of rotation rather than the sine of the angle of rotation, as applies to “minimum coupled” systems (1 and 5 in Figure 2). Hence, even though System 1 is by far the best for reducing the effect of overburden, it has not been used yet in any AEM device. System 2 has been limited largely to rigid-structure, mobile electromagnetic devices for three reasons: first, the area of the transmitting coil is a function of the maximum fuselage cross section for interior coil mounts; second, because the aircraft metal parts have a greater effect on this system than on System 3; and third, because in practice the receiving coil in trailing bird systems is towed beneath the aircraft so that the resulting system is a combination of Systems 2 and 4 (as shown in Figure 3), and hence is subject to fairly large overburden response.

System 3 is one of the best compromises for practical AEM devices. One device which employs this system moves the two coils in line (transmitter in aircraft and receiver in trailing bird); another device moves the two coils broadside (each coil mounted on a wing tip).

Coil systems 4 and 5 are very sensitive to flat-lying conductors and thus are strongly affected by extensive flat conductive sheets such as overburden.

Having discussed coil configuration, frequency, and limiting air turbulence, it is now appropriate to consider the first four variables; aircraft terrain clearance, sensitivity, flight direction, and flightline spacing.

The choice of coil systems as above often dictates the flight direction. For instance, System 3 is flown at 45 degrees to geological strike and System 2 usually perpendicular to strike in order to obtain maximum response from linear conductors.

Also, the choice of coil system to a certain extent determines the aircraft altitude above the ground surface. All current helicopter systems must be flown at 150 to 200 ft., because of the short coil separation utilized, in order to explore to depths of 50 to 100 ft. Sensitivity usually is set so that normal background noise is just recognizable on the flight records. Very
Often a good AEM system is capable of measuring and distinguishing anomalous fields of the order of $10^{-3}$ gammas.

Flightline spacing on reconnaissance surveys usually is of the order of $\frac{1}{4}$ mile. Detailed surveys are carried out, particularly with AEM systems, at smaller flightline intervals. The effect of varying the flightline interval is discussed below.

**The Significant Data**

Having discussed briefly some of the problems inherent in the design of airborne electromagnetic systems, little more need be added to complete a study of the reliability and interpretation of AEM data. The data are only as reliable as the ability of the interpreter to recognize a true anomaly as distinct from the noise background. This is illustrated by the typical AEM records of Figures 4 and 6.

The physical interpretation of the data involves a qualitative appraisal of the following features:

1. Anomaly character (compared with anomalies obtained over typical orebodies of the district and with scale-model data);
2. Anomaly amplitude;
3. Anomaly width;
4. Anomaly grouping on adjacent flight lines;
5. Indicated conductivity as based on the comparison of anomalies at two frequencies or on the comparison of in-phase with out-of-phase response at a single frequency;
6. Anomaly contrast with background noise.

This physical assessment is limited because of its qualitative nature. Of far more importance is the correlation of the AEM data with such other information as geology, photogeology and aeromagnetic data. By this correlation, the geologist and the geophysicist as a team can plan a systematic approach to the investigation of the causes of the AEM anomalies.

Two other factors which must be borne in mind when applying AEM to the exploration of any specific tract of land are line spacing and the sharp decrease

**Figure 4.** Data obtained with system 3.
in anomaly amplitude with altitude. Both these factors have led to blank records in the immediate vicinities of massive sulphide orebodies. Agocs** has shown that in aeromagnetic surveying, the detection of an anomaly is a statistical problem unless the line spacing is less than the least horizontal dimension of the anomaly. Similar considerations apply to AEM surveys; it is possible to “miss” conductive orebodies.

Depending upon the configuration of the conductive body detected, the amplitude of an AEM anomaly decreases as the inverse fourth to sixth power of the altitude of the centre of the coil system. Thus, rigid control of altitude is essential in order to ensure that anomalies are not “lost” because of high altitude.

**W. B. Agocs, Geophysics, Vol. XX, No. 4, October 1955, pp. 871-855.

![Vector Relationships in E.M. Measurements](image)

E.M. Fields in Surveying with an Aircraft

Figure 6A. System employed in obtaining results shown in Figure 6A.

Also, because of this rapid decrease, contouring of AEM data is considered by many to be impractical.

Thanks are due to The American Metal Company Limited and to Aeromagnetic Surveys Limited for permission to publish the flight records of Figures 4, 5 and 6 respectively, and to The American Metal Company Limited for permission to publish this paper.
Methods

F—Seismic

THE SEISMIC REFRACTION METHOD

by P. D. Brown* and J. Robertshaw*

Principle of the Method

All geophysical methods depend upon measuring the variations in the physical properties of the earth, from which deductions can be made regarding the subsurface geology. The seismic method is based on variations in the elastic properties of the earth and measurements are made of the speed of transmission of the longitudinal elastic waves. In seismic refraction an explosive charge is fired close to the surface of the ground. The resultant elastic waves transmitted through the ground are picked up by a number of vibration detectors (geophones) which are located in line with, and at known distances from, the shot point. The geophones transform the ground vibrations into electrical impulses which are conducted by cable to the recording equipment. The impulses are then amplified and recorded on photographic paper moving at high speed. The photographic paper records also the instant of shot and a series of timing lines which enable the interval of time between the explosion and the arrival of the elastic wave at each geophone to be determined accurately. A typical layout of the recording equipment and geophones in the field is illustrated in Figure 1(a), and the corresponding photographic record obtained for this layout is shown in Figure 1(c). On this record the faint vertical lines are the time markings, spaced at equal time intervals of 1/100th second. The uppermost horizontal trace on this record shows the instant at which the shot is fired. The twelve horizontal traces beneath it record the amplified signals from twelve geophones, and the point where each of these traces disappears indicates the time when the vibration from the shot has reached the corresponding geophone.

If the ground consists of a single homogeneous material the first vibrations to reach the geophones will be the "direct waves" travelling directly from the explosion along the surface of the ground to the geophone. The travel times of these waves to each geophone will be proportional to the distance of the geophone from the shot, and the slope of the time-distance curve (plot of travel time against distance) will give the velocity of transmission of the elastic waves in the material. However, if the surface formation is underlain by a different formation which transmits the elastic waves at a higher velocity, the direct wave will arrive first only at geophones placed close to the shot point. At the more distant geophones, the elastic waves which have been refracted through the underlying high-speed formation will overtake and arrive ahead of the direct waves travelling near to the surface, and the corresponding part of the time-distance curve will be a function of the velocity of the higher speed formation. The paths of the direct and refracted waves are illustrated in Figure 1 (a), and the corresponding time-distance curve is shown below in Figure 1 (b). The first part of this curve indicates the velocity of transmission in the unconsolidated surface formation, and the slope of the second half indicates the velocity in the underlying rock formation. The

*B. Sc., A. M. I. C. E.
point at which these two parts of the curve intersect is called the critical distance and occurs when the direct waves in the surface formation arrive at the same instant as the waves refracted from the underlying rock. The depth to the refracting rock surface is obtained from the curve by using the following formula, usually referred to as the “time-intercept” method:

\[ H = \frac{t_i}{2} \sqrt{V_2^2 - V_1^2} \]

- \( H \) = depth to rock surface beneath the shot point.
- \( V_1 \) = velocity of transmission of elastic waves in the upper formation.
- \( V_2 \) = velocity of transmission of elastic waves in the underlying rock formation.
- \( t_i \) = the intercept on the time axis of the \( V_2 \) branch of the time-distance curve (see Figure 1(b)).

The case illustrated shows only a single refracting boundary, but in practice many refracting layers can be present. Each layer will show up on the time-distance curve if its velocity of transmission is greater than the overlying layer so that in consequence refraction is possible. The slope of each segment on the curve will correspond to the velocity of transmission in each successive layer, and the thickness of each layer can be obtained from a simple extension of the above formula. In the case of dipping beds the velocities of the refracting beds indicated on the time-distance curves are not the true velocities but are functions of the angle of dip. In this case a shot is fired at each end of the line of geophones, and thus two time-distance curves are obtained. One will indicate the up dip velocities, and the other the down dip velocities, from which the true velocities can be calculated.

REFERENCES


Case Histories in
Mining Geophysics

1 — Australia
2 — Canada
3 — Great Britain
4 — India
5 — Jamaica
6 — South Africa
7 — Tanganyika
8 — Uganda
Case Histories

1—Australia

PEKO COPPER OREBODY, TENNANT CREEK, NORTHERN TERRITORY, AUSTRALIA

by D. W. Smeillie*

Abstract

A magnetic survey in the vicinity of the Peko shaft near Tennant Creek, Northern Territory, Australia, revealed a strong localized anomaly immediately over the outcropping quartz-hematite lode and a 5500-gamma anomaly from a source which appeared to top at about 300 ft. subsurface. Drilling and subsequent mine development disclosed that the anomaly was due to the unoxidized portion of a pipe-like ore zone where chalcopyrite and other sulphides had partially replaced a banded quartz-magnetite rock.

Geophysical prospection has been going on for some 20 years in the Northern Territory of Australia. At Tennant Creek, magnetic surveys were first conducted in the vicinity of the quartz-hematite gold-bearing lodes in 1935 by the Aerial, Geological and Geophysical Survey of Northern Australia. The results of one of these surveys and the subsequent discovery of ore are described.

General Geology

The geological structure of the Northern Territory and its relation to mineralization has been described by Noakes (1953). Other papers in the volume Geology of Australian Ore Deposits, published by the Fifth Empire Mining and Metallurgical Congress (1953), describe in more detail selected areas of economic interest, and in addition the bulletins and reports of the Bureau of Mineral Resources, Geology and Geophysics of the Commonwealth of Australia, contain much pertinent information. The structural framework and metaliferous provinces are shown in Figure 1 (Noakes, 1953). Mineralization in the Arunta Block is believed to be Archaean in age, while that in the Carpentaria, Warramunga and Pine Creek geosynclines is presumed to be associated with orogenies toward the close of Lower Proterozoic time.

The geology of the Tennant Creek area has been described recently by Ivanac (1954). The ore deposits occur in the folded and brecciated sequence of sandstones, siltstones, mudstones and shales making up the Lower Proterozoic Warramunga group. In the centre of the Tennant Creek gold field are stock-like intrusions of soda-granite (adamellite). Folding is generally along east-west axes.

In the weathered zone, quartz-hematite lodes are gold-bearing. Below the oxidized zone, which generally extends to about 270 ft., structurally similar lodes are of quartz-magnetite, with the magnetite bands partly replaced by chalcopyrite and other sulphide minerals. These lodes are localized in breccia zones on the limbs and crestal regions of anticlines and are in a mudstone or shale zone generally flanked by competent sandstones.

The Magnetic Survey

In 1936, the Aerial, Geological and Geophysical Survey of Northern Australia conducted a magneto-
meter survey in the vicinity of the Peko No. 1 shaft. The original purpose of the survey was the detection of concealed gold-bearing quartz-hematite lodes, which were slightly magnetic due to traces of magnetite. The plan of vertical magnetic intensity shown in Figure 2 is adapted from their report (Richardson, Rayner and Ny, 1936). This is a smoothed contour map and does not show the strong local anomaly immediately over the outcropping quartz-hematite lode (cross-hatched in Figure 2). It is clear from the profile of the anomaly that it is caused largely by a highly magnetic body possibly of pipe-like form topping at about 300 ft. subsurface.

Initial testing of the anomaly was done by diamond drill holes No. 3 and 6 of the Aerial, Geological and Geophysical Survey of Northern Australia; they intersected the oxidized portion of the main lode. A revival of interest in the property led to the drilling of D.D.H. No. 1 by the Bureau of Mineral Resources in 1950 which intersected the primary magnetite-chalcopyrite ore. The drill hole findings and subsequent
Figure 2. Magnetic survey of Peko area.
Figure 3. Peko Mines Ltd., S-N cross section.
Figure 4. Plan of 530-foot level, Peko Mine, Tennant Creek, Northern Territory, Australia. (For cross-section along line A-B see Figure 3).
mine development are shown in section in Figure 3, kindly provided by Peko Mines Limited.

The Peko Copper Orebody

The Peko lode was worked as a gold mine between 1935 and 1942 from levels at 62, 120, 170 and 210 ft.; the first three were in a gold-bearing quartz-hematite lode. The 210-ft. level encountered oxidized copper ore consisting chiefly of cuprite and native copper. Development after 1950 found copper ore in three zones. Oxidized ore extends from 200 to 270 ft. From 270 to about 315 ft. is the zone of secondary sulphide enrichment, consisting largely of chalcocite and covellite with varying amounts of residual chalcopyrite and pyrite. The wall rocks in this zone are mainly massive magnetite rock, the magnetite being in the form of corroded and hollow crystals (Edwards, 1956). Below 315 ft. the ore consists of primary sulphides, essentially chalcopyrite and pyrite. The wall rocks are a slightly banded magnetite rock, and in the main ore zone the sulphides appear to have replaced the magnetic rock along the banding. Structurally, the lode occurs in a crush zone in mudstone, probably on the north flank of a west-pitching anticline.

For purposes of correlation, Figure 4 shows a plan of the 530-ft. level of the Peko mine as of October 1955. It is understood that further mine development has disclosed ore reserves estimated (Nov. 1956) at 207,000 tons proved about the 530-ft. level grading 9.9 per cent copper, and 878,000 tons indicated averaging 7.5 per cent copper between the 530- and 864-ft. levels.

Correlation

The rather unique geological situation of partial replacement of a quartz-magnetite zone by sulphide minerals, chiefly chalcopyrite, allows detection of the primary copper ore at the Peko mine by means of a magnetic survey. The magnetic anomaly correlates well with the position of the top of the unoxidized ore zone, the anomaly maximum being displaced to the north of this position as expected in this area of inclined normal magnetic polarization (magnetic dip I = 48°). The geological situation at the Peko mine probably is repeated in other parts of the Tennant Creek gold-field, and magnetic anomalies of suitable intensity may be worth testing.

Acknowledgments

The preparation of this paper would have been impossible without the published papers referred to as sources. The author gratefully acknowledges courtesies extended by the management of Peko Mines Limited during a visit to the mine in August, 1954.

REFERENCES


GEOPHYSICAL INVESTIGATION OF A COPPER-NICKEL FIELD
NEAR ZEEHAN, TASMANIA, AUSTRALIA

by J. Horvath*

Abstract

The Copper-Nickel, or Cuni field, lies on the west coast of the island of Tasmania, about 5 miles northeast of Zeehan. The deposits are in a marshy basin where the bedrock consists of Lower to Middle Cambrian shales, argillites and tuffs with steep easterly dips, intruded by dykes and sills of pyroxenite and gabbro 20 to 60 ft. thick and generally paralleling the bedding. The copper-nickel orebodies are on the footwall side of the ultrabasic dykes, and are small but extremely rich. They consist of massive sulphides up to 4 ft. thick, and containing as much as 17 per cent nickel, with sulphides disseminated as much as 20 ft. into the hangingwall dykes.

Electrical methods had been tested over part of this area in 1929, with encouraging results. In 1952-53 the Bureau of Mineral Resources conducted self-potential and electromagnetic surveys over a larger area. A test with magnetic instruments yielded no anomalies, so the magnetic method was not used.

The self-potential profiles revealed only a small anomaly around the Cuni South shaft, but a persistent one around the Cuni North workings. An electromagnetic survey was then done in the north portion of the area. The indications obtained agreed with those yielded by the self-potential work, but with the anomaly displaced slightly to the east by the eastward dip of the ore formations.

Drilling disclosed thicknesses of 3 to 4 ft. of high-grade ore, and greater thicknesses of disseminated copper-nickel sulphides. Preparations are being made to re-open the field.

The Copper-Nickel (or Cuni) area lies about 5 miles northeast of Zeehan, on the west coast of Tasmania (Figure 1). The deposits are in a marshy basin about 2 miles in diameter, surrounded by hills rising several hundred feet above marsh level. The rainfall on the west coast of Tasmania is about 100 inches per year. The country is thickly covered with button grass on the low-lying portions, with dense scrub and rain forest on the ridges.

Geology

The geology of the area has been described by Taylor and Burger (1952).

The Cuni area consists mainly of Lower to Middle Cambrian sedimentary rocks which extend for several miles. The sediments are shales, argillites and tuffs; usually they are fairly uniformly fine grained and are grey, green or red. In the mineralized part of the area the rocks strike a few degrees west of north and dip steeply to the east; the strike changes to east of north in the north part of the area.

Basic and ultrabasic rocks, mainly pyroxenite and gabbro, intrude the Cambrian rocks. The intrusions generally trend parallel to the bedding of the sediments and only at a few places do they cut across the bedding. They are relatively narrow dykes or sills about 20 to 60 ft. thick and are probably related to a large serpen-

*t Bureau of Mineral Resources, Geology and Geophysics, Melbourne, Australia.

tine mass which outcrops in the hills east of the basin. In the underground workings, several small crossfaults have displaced the dykes. The intrusion of the basic and ultrabasic material occurred during Devonian time. All the materials in the subsidiary dykes appear to have been derived by differentiation from one parent magma.

The Copper-Nickel Deposits

The copper-nickel orebodies are on the footwall side of the ultrabasic dykes, and are small but extremely rich. They comprise massive sulphides (violarite, pentlandite and chalcopyrite) in widths up to 4 ft., and some of these sulphides are disseminated through the lower part of the dykes in widths up to 20 ft.

The ultrabasic dykes extend over more than 1½ miles, and contain several orebodies on which small shafts have been sunk. Massive ore containing 9 to 17 per cent nickel was mined from these shafts and shipped without concentration. The main shafts are the Vaudeau, Cuni South and Cuni North Shafts, but only a few thousand tons of rich ore were produced from each.

Geophysical Surveys

As the known orebodies are sulphides, it was assumed that it would be possible to detect them, and any others that might exist, by electrical methods of prospecting. Electrical methods were used over a restricted area by the Imperial Geophysical Experimental
Figure 4. Electromagnetic data and drilling results in the northern part of the area.
Survey in 1929 (Edge and Laby, 1931). This survey gave encouraging results, which were confirmed by drilling, but, owing to prevailing economic conditions, it did not lead to the re-opening of the area.

A survey over a larger area was undertaken by the Bureau of Mineral Resources in 1952-53, using electromagnetic and self-potential methods. Test magnetometer traverses showed that there is no magnetic anomaly associated with either the ore or the basic dykes, and, therefore, magnetometer surveys were not used in the exploration program.

Results

Examples of the self-potential profiles are shown in Figures 2 and 3. The profiles on Figure 2 were obtained near the Cuni South Shaft and the only anomaly is confined to a small area around the shaft. The profiles on Figure 3, around the Cuni North workings, show a persistent, well-defined anomaly. As these results indicated that the prospects for more extensive orebodies are better in the north portion of the area, electromagnetic surveys were made in that portion only.
The results of the electromagnetic survey are shown in Figure 4. A continuous anomaly was obtained, ranging from very weak indications at the south end through strong indications in the central portion, to weaker indications again at the north end. The position of the electromagnetic anomaly agrees in general with the position of the self-potential anomaly, although the electromagnetic anomaly is east of the self-potential anomaly. This would be expected as the ore has an easterly dip.

This relationship, and the fact that the electromagnetic anomaly follows closely the approximate position of a basic dyke, suggested the presence of a sulphide body. The variation in intensity of the electromagnetic anomaly along the strike suggested that the sulphide content is not uniform, but may consist of sections of more massive sulphides separated by weakly mineralized or barren sections.

Testing

The results of drilling to test the indications of the various surveys are shown in Figure 4, and more detailed sections through two of the latest holes (M. 6 and EM. 1) are given in Figure 5. It will be seen that the results indicate thicknesses of 3 to 4 ft. of high-grade copper-nickel ore, and greater thicknesses of disseminated copper-nickel sulphide ore. Based on these results, preparations are now in hand for reopening the area.

REFERENCES


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GEOCHEMICAL PROSPECTING AT MOUNT ISA, QUEENSLAND*

*by A. H. Debnam†*

Abstract

Geochemical anomalies in soils over zones of lead mineralization were studied, both in known mineralized areas and in areas of suspected mineralization. The anomalies were readily detected and outlined by using a dithizone technique on acid extracts of soil samples collected from grid systems.

By assuming the principles of mechanical mixing of the mineralized rock with other material during soil formation, and of downhill migration of soils, the anomalies were correlated with the zones of their origin; the asymmetric anomalies discovered are typical of such conditions.

Applied to areas of suspected mineralization, the geochemical prospecting was responsible for the discovery of two new bands of lead mineralization and several large lead and copper anomalies. The method proved extremely useful for indicating the most favourable areas for more detailed prospecting such as diamond or channelling and geophysical methods.

Introduction

GEOCHEMICAL prospecting is one of the newer scientific tools, having been developed over the last fifteen years. It finds its principal application in the search for hidden mineral deposits. Workers in various countries, in particular Russia (Sergeev, 1941), United States (Huff, 1952.), Scandinavia (Rankama, 1940), and Nigeria (Webb and Millman, 1951), have applied the methods with varying degrees of success. Hawkes (1949) gives a summary of the work which had been carried out up to the end of 1949.

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†Chemist, Bureau of Mineral Resources, Geology and Geophysics, Canberra.

The main advantages of the geochemical methods are speed and economy. A team of three men can collect and test up to 50 samples per day. The results are available immediately and if an anomaly is discovered further sampling can be carried out to define its boundary. Colorimetric analytical methods require only a small quantity of inexpensive chemical materials and equipment which can be transported with ease in suitably packed boxes. Experienced personnel with high technical qualifications are not necessary for sampling and testing; an assistant of sub-university chemistry standard can be trained to perform the tests satisfactorily in two weeks. One member of the team should be sufficiently qualified in chemistry and geology to enable any unexpected difficulties in procedure to be overcome quickly and to be able to interpret the results rapidly and correctly.
Soil was the sampling medium used in the Mt. Isa investigations and the amounts of trace metals, lead and copper, were determined by a colorimetric method using the organic reagent dithizone. The survey occupied a period of nine weeks, during which time a total of 1,334 samples were collected and tested. It was planned to coincide with an extensive prospecting program being carried out by Mt. Isa Mines Ltd., embracing two areas of suspected lead mineralization, one north and the other south of Mt. Isa.

Work at the northern area, 11 miles from Mt. Isa, was well advanced when the geochemical studies began in October, 1952. Many coteans had been cut to bedrock by bulldozer, several diamond drill holes were completed or in progress, and five shafts were being sunk. Bands of high-grade lead mineralization had been uncovered in some of the coteans and this known mineralization served as an ideal test-area for the geochemical method. Anomalies were established in the sub-surface soils in the vicinity of the known mineralized bands. Thus the results from the test-area served to provide the prospecting criteria for the district as a whole. Further work at the Northern Prospect, an area not recently investigated, led to the discovery of two new mineralized zones, and the possible rejection as unpromising of other areas.

The Southern Prospecting Area, 12 miles south of Mt. Isa, was then studied in order to determine the most favourable areas for more detailed coteaning and drilling. Previously only one small section had been geologically investigated and samples assaying over 20 per cent lead were obtained from one cotean. Geological mapping of the area, which covered over 3 miles length of gossanous outcrop, was being carried out by Mt. Isa geologists while the geochemical work was in progress.
Climate, Topography, and Vegetation

Mt. Isa is situated at 20°40'S. latitude and 139°30' longitude. It is at the southern fringe of the monsoonal region, and has a mild dry winter and a hot to very hot summer. The average annual rainfall is 13 in., most of which falls during the 'wet' season, between December and March.

Both the Northern and the Southern Prospecting Areas are flanked by prominent quartzite ridges on their west sides. From the foot of the quartzite ridge the Northern Area has a gentle slope to the east with numerous local undulations, but this topographical pattern is rather sharply interrupted by the prominent hills formed by the ferruginous jasper outcrops.

The topography of the Southern Prospect is characterized by a series of sharp ridges with a general north-south trend and a number of quartz 'blows'. The principal drainage channels run north or south into larger creeks which run west to east through breaks in the ridges at several places.

Vegetation in the area is rather sparse. Trees grow to a height of 30 ft., the most common species being Eucalyptus brevifolia (snappy gum), Eucalyptus pruinosa (silver-leaved box), Eucalyptus argillacea (box), and Acacia spp. (wattles). Acacia lysiphylla (turpentine) is abundant on the alluvial soils. Triodia spp. (spinifex) and Aristida spp. (spear grass) are common.

Geology of the Prospecting Areas

The geology of Mt. Isa and its immediate surroundings, and the emplacement and paragenesis of the lead-zinc ores, have been summarized in a paper by S. R. Carter (1950). The lead-zinc mineralization is localized in the western limit of a west-dipping, north-plunging, isoclinal syncline of Mt. Isa shales. These are the uppermost formations of the Mt. Isa group, which is Lower Proterozoic in age.

Immediately to the west of the isoclinal the Mt. Isa shear, a thrust striking north-south and dipping at about 60° to the west, brings the next lower formation, the eastern Creek formation, against the shales; and about two miles west of the thrust a region of extensively granitized sediments of the Eastern Creek formation grades into the Templeton granite, the emplacement of which is pene-contemporaneous with pressure from the west.

Sullivan (personal communication) considers that the Templeton granite is very significant for the occurrence of ore at Mt. Isa. In the area north and west of Mt. Isa the granite-sedimentary contact forms a north-pitching anticlinal structure along which local reversals of pitch occur. Both the Mt. Isa and the Northern Prospect deposits are associated with a swing in the granite contact, which is convex to the eastward, representing an anticlinal pitch change in the dominantly north-pitching fold. A similar swing in the granite contact south of Mt. Isa led Sullivan to predict the probable occurrence of lead-zinc ore in an area 12-13 miles south of Mt. Isa. He considers that the granite pitches beneath Mt. Isa, and the anticlinal pitch changes in the sediments correspond to the positions of buried cupolas in the granite gneiss.

The Mt. Isa shales consist of brown and grey shales and slates, in part dolomitic and in some places carbonaceous. They are strongly crenulated and strike faults and cross-fractures provide ore-channels through which the mineralizing solutions had access to the fine-grained shales in which they are emplaced.

The general geology of the Northern Prospecting Area is very similar to that of Mt. Isa and the rock formations are continuous with those of Mt. Isa. The area is bounded on the west by a prominent quartzite ridge. Adjacent and parallel to the eastern margin of this quartzite in the shear zone which is at least 19 miles in length and has an average width of 500 ft. at the Northern Prospect. As far as is known the shear zone is barren throughout its length. It is occupied by phyllite, sericite schist, and some quartzite and shale.

The western limit of the mineralized zone is approximately 1,000 ft. east of the quartzite ridge. The area between is occupied by various groups of shales. The rocks which contain the mineralized zone are predominantly thinly bedded shales, hundreds of feet in width. They have a general north-south strike, and have large gentle flexures and some tight folding. Dips average about 60° to the west. The mineralized zone has a heavily pyritic hanging-wall section averaging 50 ft. in width and carrying numerous narrow sphalerite-galena seams. This section is represented at the surface by prominent but discontinuous ferruginous jasper outcrops. At Offset Hill, however, the ferruginous jasper occurs in the footwall beds. To the east more mineralized and pyritic beds occur with intercalated barren beds, but the mineralized bands decrease in width, and 800 ft. east of the jasper ridges the shales are completely barren.

Diamond drilling has proved that the main section of the mineralized zone has a length of at least 2,500 ft. and an average width of 440 ft.; the mean depth...
of the drill hole intersections is about 1,000 ft. below the surface. Although the overall grade is low, there are several lodes of commercial grade and of minable width within the zone. Some of the mineralized beds are galena-rich, but in most of them sphalerite predominates.

There are a few points of similarity between the Southern and Northern Prospecting Areas. Each is bounded on the west by a prominent quartzite ridge; in both the mineralization occurs in shales; prominent ferruginous jaspers mark the mineralized zones of each, and in each area the shales have a general north-south strike and steep westerly dip. Here, however, the similarity ends.

At the southern end of the Southern Area, Window Ridge is 300 ft. east of a large ridge of quartzite which swings to the northwest from the northern end of Mt. Novit, so that it is 2,000 ft. west of Gouger Ridge. The quartzite thereafter resumes its north-south strike. The area between the western quartzite and the jasper ridges is temporarily designated as siliceous shale.

The mineralized beds are contained in shales and are represented by the sharp, rough ferruginous jasper ridges—namely Window Ridge, Mt. Novit, Cork Ridge, Haney’s Ridge, and Bradshaw’s Ridge. The ferruginous jaspers are closely associated with beds that have obviously contained a high percentage of pyrite. Another belt of siliceous shales forms the footwall of this group and immediately below this is the so-called ‘footwall quartzite’. This gradually transgresses the shales in a manner which suggests that it has been formed by silicification along a strike-fault zone. This impression is heightened by the fact that prominent quartz ‘blows’ occur at intervals throughout its length.

The ferruginous shales and jaspers of Cork Ridge are cut off against the ‘footwall quartzite’ at the southern end of Gouger Ridge, and the remainder of Gouger Ridge and the whole of Smoko Ridge represent part of the ‘footwall quartzite’ group. Previous study of these two ridges yielded no indications of mineralization, and they were considered to be barren. The geochemical results indicated that they are favourable for lead mineralization.

**Sampling Procedures**

All testing was carried out on soil samples as surface waters were not available and rocks, although easy to sample, require crushing, which is a time-consuming operation, and, mainly because of shortage of time, the sampling of vegetation was not attempted.

The presence of costeans greatly facilitated the establishment of the prospecting criteria in the early part of the survey. The chief problem was to decide on the minimum depth at which samples could be collected and still give a true representation of the conditions at bedrock. Tests on samples from the sides of the costeans, in soils up to 8 ft. deep, revealed that for each sampling position uniform results were obtained irrespective of the depths at which the samples were taken. As the humus layer was not sampled, the depth of 9 to 15 in. was used for sampling throughout the project, except in special cases. In one case, for example, the topsoil to a depth of 18 in. consisted of very recent alluvium which gave negative results, whereas deeper soils at the same point gave high results. To obtain truly representative samples it was necessary to penetrate the upper alluvium with a posthole digger before collecting the sample.

Most of the samples were collected from traverses laid out by compass and tape, survey pegs being used as positioning points. Pick and shovel were used as sampling tools, but the posthole digger was found more convenient for soils free of large rock fragments.

**Testing Procedures**

The testing procedures used throughout the project were similar to those introduced to Australia in 1948 by Dr. V. P. Sokoloff (Sokoloff, 1951) of the United States Geological Survey. These methods seem to have lost popularity during the last few years, preference being given to those which seek total amounts of the metals in question and which present the results in numerical form. However, the writer’s experience in other Australian studies has shown that acid-soluble forms of the metals are quite useful in establishing the geochemical expression of mineralization more rapidly than, and as accurately as, the other methods. Testing procedures differ considerably and depend on the forms of the metals being investigated. Acid-soluble forms include ‘free’, ‘exchangeable’, ‘occluded’, and, perhaps, some ‘organic’ forms (Sokoloff, 1951). Metals present in the crystal structures of the soil components are not as useful in establishing the geochemical expression. In any case, time-consuming operations, such as prolonged aqua-regia extractions or fusions, are required to release these forms as soluble compounds.
**Mining Geophysics**

Colorimetric analytical methods have invariably been used in Australian studies and this practice was continued at Mt. Isa. The colorimetric reagent, diphenylthiocarbazone (dithizone) has been thoroughly investigated by Sandell (1944) and others. The chief advantages of colorimetric methods for field prospecting are speed, small apparatus requirements, and economy. A two-man team can test up to 80 samples per day. The equipment required at Mt. Isa consisted of: balance, 200-ml. breakers, filter funnels and stands, filter papers, 'Hydron' pH papers, 500-ml. and 25-ml. burette stands, and clamps, clock glasses, 50-ml. graduated glass-stoppered cylinders, reagent bottles, and spatulas. Chemicals used were hydrochloric acid, carbon tetrachloride, dithizone, ammonium hydroxide, and potassium cyanide. Distilled water was not required as the Mt. Isa tap water was entirely free of copper and lead. Zinc did not have to be removed, as it did not interfere with the tests. If required, suitable metal-free water could be produced in aluminium stills (glass has proved unsatisfactory in the field) or with ion-exchange resins (Lakin, Stephens, and Almond, 1949).

The testing procedures were both simple and rapid. Ten g. of soil, selected with a spatula from the finer portion of the sample (grain size up to 0.5 mm.), was weighed on a rough balance, and transferred to a 200-ml. beaker; 50 ml. of 0.01N hydrochloric acid was added, and the mixture swirled at intervals for 2 min. to allow extraction of the acid-soluble forms of the metals. If the pH increased above 3 during the extraction, a suitable adjustment was made with hydrochloric acid. Failure to adjust the pH when extracting alkaline soils would cause incomplete extraction of the ‘acid-soluble’ forms of the metals with consequent low results. After filtration, the filtrate (called the test solution) was ready for the colorimetric determinations.

The reactions of the reagent dithizone, as applied to geochemical prospecting, have been fully described by Sokoloff (1950).

Thirty ml. of the test solution at pH3 were transferred to a 50-ml. cylinder, and 5 ml. of 0.01 per cent dithizone solution (in carbon tetrachloride) added. A change of colour in the dithizone layer to grey or purple after shaking for 30 sec. was attributed to copper. Without removing the copper by replacing the dithizone in the cylinder two drops of concentrated ammonium hydroxide were added to bring the solution to a pH of 8-9. At this stage shaking for 2 sec. revealed intense pink colours in the organic layer, caused by the large amounts of zinc present. However, all copper and zinc colours were removed by the addition of 0.5 ml. of a 10 per cent potassium cyanide solution. Any pink colours remaining in the organic layer after shaking for 15 sec. were considered as being due to lead, the only possible interfering elements being divalent tin, monovalent thallium, and bismuth (Sandell, 1944), all of which could be disregarded in the area under investigation. If large amounts of lead were indicated in the 30-ml test the aliquot of test solution was reduced to 5 ml. or even to 1 ml. to give a more accurate semi-quantitative appraisal of the results.

The interferences referred to by Sokoloff (1950) for testing as pH8 did not appear to be operative in the lead tests carried out at Mt. Isa. The intensities of the pink colour given by standard lead solutions increased in proportion to the amount of lead in the solution. It was found that if the pH was raised above 9 the lead colours were suppressed, and low results were obtained. Large amounts of copper caused a mixture of the yellow oxidation product of dithizone and the brown enol copper dithizonate to form in alkaline solution, and these colours were not completely removed by the potassium cyanide. In such cases the copper had to be removed before the lead test could be carried out.

The only troublesome interference encountered in the testing procedures was caused by dust which contained a high proportion of copper and lead minerals, presumably derived from the mine crushing plant which was only 200 yards from the laboratory. On windy days it was difficult to keep dust out of the solutions during extraction and filtering operations. However, a blank test run concurrently with each batch of tests gave warning of this interference.

**Method of Reporting the Results**

When assessing a test, it is necessary to emphasize that the search is for prospecting indications and not for exact quantitative results. Colour intensities were most conveniently recorded as negative, low, medium, high, and very high. For copper estimations the results were assessed from the time taken for the purple colours to appear and from the intensities of the colours after 30 sec. agitation. The values for lead tests were assigned according to the aliquots of test solutions used and the resulting colours after shaking for 15 sec., as shown in Table 1.
Table 1
VALUES ASSIGNED TO COLOURS IN LEAD TESTS

<table>
<thead>
<tr>
<th>Alligant of test solution ml.</th>
<th>Colour observed in carbon tetrachloride</th>
<th>Value assigned to the test</th>
<th>Approx. p.p.m. acid-soluble lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Coloured</td>
<td>Negative</td>
<td>Less than 0.2</td>
</tr>
<tr>
<td>30</td>
<td>Faint pink</td>
<td>Low</td>
<td>0.2–1.0</td>
</tr>
<tr>
<td>30</td>
<td>Intense pink</td>
<td>Medium</td>
<td>1.0–6.0</td>
</tr>
<tr>
<td>5</td>
<td>Faint pink</td>
<td>High</td>
<td>6.0–30</td>
</tr>
<tr>
<td>1</td>
<td>Intense pink</td>
<td>Very high</td>
<td>Greater than 30</td>
</tr>
</tbody>
</table>

From Table 1 it will be seen that a very high percentage error can be tolerated without appreciably affecting the final result. In the case of borderline results, it is of real consequence into which of two adjacent brackets they are placed. In such circumstances nothing is gained by introducing refinements into the method, which at first may have appeared a little rough to the analytical chemist.

The results obtained in an extensive survey, such as that carried out at Mt. Isa, are of little use in tabular form, and are best presented on plans. The original plans were on a scale of 100 ft. to the inch, but these were reduced to 400 ft. to the inch to facilitate drafting and handling. Each circle and dot on the plans represents a sampling point, the size of the dot increasing with the strength of the test (see reproduction on reduced scale, Figure 1).

Two grades of geochemical anomalies have been outlined. In general, the strong anomalies embrace all the very high results, and the weak anomalies include the high and medium tests.

Results

Of the 1,334 samples collected and tested during the nine weeks of the survey, 744 were from the Northern Prospect, and 590 were from the Southern Prospect.

Northern Prospecting Area

The preliminary prospecting criteria were obtained from samples collected in No. 4 costean, situated between Handlebar and Tombstone Hills (Figure 4). The results are shown diagrammatically in Figure 2.

It will be seen from Figure 2 that the bands of high-grade mineralization are represented by a distinct geochemical anomaly in the overlying soils. The anomaly is asymmetric, the highest values being over and immediately downhill from the mineralized bands; downslope the values steadily decrease, so that within 300 ft. of the seams they have almost returned to the normal background value.

Figures 3, 4 and 5 present the results obtained at the Northern Prospect. Figure 4 shows two large and three small anomalies outlined in the Handlebar-Tombstone area. Most of the mineralization was already known before the geochemical prospecting commenced, and the anomalies demonstrated the correlation between the traces of lead minerals in the soils and the underlying mineralized material from which the soils were derived.

The northern boundary only of the large anomaly on the eastern slope of Handlebar Hill has been outlined. Further sampling to the south was not possible owing to the presence of dumps near the prospecting shafts. However, the anomaly would certainly continue to the south, over and downhill from the high-grade mineralized bands shown in Figure 4. An unexpected strong anomaly crosses the eastern end of No. 2 costean on Handlebar Hill; further investigation revealed mineralized bands which previously were not known to exist.

The two weak anomalies over Nos. 4 and 5 costeans between Handlebar and Tombstone Hills were discovered during the preliminary testing at the beginning of the survey. The small western anomaly may be due to weak lead mineralization associated with pyrite. The soil cover was very thin, and substantial mineralization should have produced higher results. The other anomaly, 700 ft. in length, is more important, as it represents seams of high-grade mineralization (2 ft. of 35.8 per cent, and 8.5 ft. of 21.3 per cent lead). The reasons for the presence of only a
weak anomaly over these seams and the existence of apparently negative areas on either side are discussed later.

The large, strong anomalies at Tombstone Hill bear a striking resemblance to those at Handlebar Hill (Figure 4). Mineralized seams were known to be present and the geochemical results give a guide to their extent. A south extension of the mineralized bands to No. 3 cotean was first indicated by the geochemical prospecting. Later assay results proved that a 1-ft. band of 7 per cent lead mineralization existed in No. 3 cotean a short distance uphill from the place where very high geochemical results were obtained. Soils were only 2 ft. deep over this band.

The weak and dispersed results obtained at Gidyea Hill suggest either that the mineralized bands do not extend north of Tombstone Hill, or that they do not reach the surface in that area.

The Termite Flat-13 Mile Hill area (Figure 5) had been prospected many years previously, apparently without success, and the old coteans, with supplementary traverses, were used for sampling. The geochemical prospecting showed no more success, although many weak anomalies were established. Closer and deeper sampling, due to the deep soils encountered, would be necessary before more conclusive results for the area could be obtained.

Pick Hill was the most southerly portion of the Northern Prospect to be studied. The area was untouched except for two hand-dug coteans which had been prepared many years previously. An anomaly over 1,600 ft. in length (Figure 3) was discovered; the northern boundary has not been established owing to the presence of a creek bed. The strong anomaly was over 800 ft. long, and at its northern end a small cotean was cut in an attempt to discover the source of the anomaly. A cotean less than 10 ft. long was required to reveal a mineralized band which contained crystallized cerussite in the decomposed bedrock. Further geological work has traced the band for many hundreds of feet to the north, almost to Offset Hill. This was the second discovery made solely by geochemical prospecting methods of lead mineralization in the Northern Prospecting Area.

- Southern Prospecting Area

The lead results for this area are also presented on Plate 1 in Figure 6, which represents the 3½ miles of almost continuous gossanous outcrops covered by the survey. Several areas, for example, Bradshaw's Ridge, Mt. Novit, and Window Ridge, were considered as being geologically favourable, because of structure or the presence of favourable types of gossans, for the discovery of ore-bearing seams. Contrary to expectations, these areas gave only small weak anomalies, which appear to indicate an almost complete lack of lead mineralization.

However, on Smoko Ridge a large and strong geochemical lead anomaly was discovered. This ridge and the northern part of Gouger Ridge fall into the 'foottall quartzite' group, and have the appearance of a non-ferruginous jasper. The anomaly differs from all the other lead anomalies in that it extends to both sides of the ridge; the mineralization must occur at the top of the ridge or on both sides, being more extensive on the western side where the strong anomaly occurs.

Another lead anomaly, possibly associated with that on Smoko Ridge, was outlined on Haney's Ridge, north of Smoko Ridge. The two ridges are separated by Sybella Creek. The surface indications of mineralization thus extend over a length of 5,000 ft. A seam containing payable lead ore had been discovered in one of the coteans at Haney's Ridge before the geochemical work commenced.

Although the Mt. Isa work was chiefly an investigation of lead mineralization, the possibility of detecting copper anomalies was not overlooked, and all lead tests were preceded by an examination for copper. At the southern section of the Southern Prospect, from Gouger Ridge to Window Ridge, the number and intensity of positive copper tests increased considerably, and they have been recorded separately in Figure 7. Three separate strong copper anomalies were outlined, each at least 1,600 ft. in length. It is interesting to note that they occur in areas in which the lead results were lower than expected on geological grounds. Some reasonably high, but very dispersed copper tests at Bradshaw's Ridge have not been recorded on the plans.

Interpretation of the Results

The preliminary investigations were carried out in the area of known mineralization chiefly to establish a correlation between the geochemical anomalies located in the soils and the ore occurrences from which they originated. In each of the areas studied the mineralization occurs in bands which are usually parallel or almost parallel to the ridges. Abnormal amounts of
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lead are found in the residual soils associated with the seams containing oxidized lead minerals, and the ratio of acid-soluble lead in these soils to that in soils derived from barren rock, is as high as 200 : 1; in a few exceptional cases the ratio exceeded 1,100 : 1. This is a much higher ratio than that of 170 : 1 given by Huff (1952) who used strong acids and fusions to extract the metals. It may indicate that the acid-soluble forms of the metals, extracted by dilute acid, give a much sharper geochemical anomaly than the corresponding total amounts of the metals, as extracted by aqua regia or fusion.

There is little doubt that the lead anomalies discovered in the Mt. Isa study are similar to those originally described by Sergeev (1941) and discussed by Huff (1952). There are the typical asymmetric anomalies produced by mechanical dispersion and downhill creep in soil over a seam parallel to the topographic contours. The seam must be present at bedrock for the anomaly to exist, as solutions play no part in the formation of the anomaly. The detection of a previously known mineralized band (for example at Pick Hill) is relatively simple, as the upper topographic boundary of a strong anomaly is almost certain to be directly over the band under investigation.

The width and strength of the anomalies are influenced by the following factors: the width and grade of the mineralized seams, the topographical relief and depth of soil over the seams, the relative proportions of residual and alluvial soils in the anomalous areas, and the mobilities of the metals in the soil horizons. It is obvious that a wide, high-grade seam will introduce more mineral into the soil than a narrow, low-grade seam, thus producing a larger and stronger anomaly. It is probably a reasonable assumption that the acid-soluble forms of the metals are correspondingly increased. Webb and Millman (1951) also suggest, from the results of a biogeochemical reconnaissance in Nigeria, that an increase in the total amount of an element in the soil will increase the available portion of that element. The acid-soluble forms of the metals are equivalent to the available portions which are taken up by vegetation (Hawkes, 1950).

Owing to the shallow residual soil cover, seams at or near the tops of ridges should produce anomalies of maximum strength. A seam of similar dimensions and grade, but farther downslope, would produce a weaker anomaly, because much soil from barren rocks above the band would be mixed with that derived from the band itself, with consequent dilution of the seam mineral dispersed in the soil. In general, soils increase in depth on passing down a slope, causing further dilution of the ore minerals.

At Haney's Ridge (Figure 6), the strongly mineralized seam occurs in an almost flat outcrop with very little soil cover. The anomaly is very strong, but narrow. Had several feet of soil overlain this seam the anomaly would have been weaker but much wider, owing to increased mechanical dispersion.

As the ferruginous jasper outcrops at the Northern Prospect represent the western margin (hanging wall) of the mineralized zone, it follows that positive lead tests can be expected only on the eastern slopes, and not on the western slopes of the hills. This was proved to be the case. The jasper ridges, where they occur, effectively protect the metalliferous soils in their vicinity from dilution by barren soil from the west, and ensure that the soil on their eastern slopes is derived wholly from the mineralized zone. In the gap between Handlebar and Tombstone Hills, and that between Pick and Offset Hills, the diluting effect of soils from the west is very extensive. At Offset Hill, where the ferruginous jasper occurs in the footwall, the strong geochemical anomaly could be expected on the western side of the hill. Five samples were collected from a coastean on the western side of Offset Hill and they gave very high results. The remainder of the hill was not sampled.

The Smoko Ridge anomaly occurs on both sides of the ridge, although the strong anomaly is confined to the western side (Figure 6). At Window Ridge two low lead values were given by samples collected from residual soil on the top of the ridge only a few inches deep but covering mineralized rock assaying 0.25 to 0.5 per cent lead. If soils representing mineralization of this grade are favourably placed at the top of a ridge, and give only a low result, it is reasonable to assume that the very high results at Smoko Ridge represent relatively high-grade mineralization, possibly in the order of 5 to 20 per cent lead, also situated close to the top of the ridge.

It is possible that the geochemical results not only indicate the mineralized areas, but also the grade, in general terms, of the mineralization. If this assumption is correct, the only areas in the Southern Prospect where commercial-grade lead mineralization is likely to be found near the surface are Smoko Ridge and Haney's Ridge, and possibly at the south end of Window Ridge.

The results at Smoko and Haney's Ridges suggest that the footwall quartzite is in some way associated
Figure 1. Index map.
with mineralization; whether it has had a local concentrating effect on the mineralization in the shales, or whether it indicates that the postulated strike-fault zone is mineralized, can only be conjectured at this stage of our knowledge (A. A. Gibson, personal communication).

The weak lead anomalies at Window Ridge, Mt. Novit, Cork Ridge, and Bradshaw's Ridge cannot be overlooked completely. It is safe to conclude that substantial surface mineralization will not be found in these areas but the possibility of the presence of commercial grade ore at depth still remains. Unfortunately the geochemical prospecting at its present stage of development cannot assist in the solution of this problem.

The strong anomaly on the eastern side of Handlebar Hill (Figure 4), where new mineralized seams were discovered, need not necessarily be due to high-grade mineralization. Thus, it is seen from the plan that the soils uphill from the anomaly already give high results and that the mineralization in the newly discovered band merely increases the values to very high. The increase, however, is sufficiently well defined to allow detection of the band, but it may be below commercial grade.

At the Northern Prospect, the presence of only a weak anomaly over the two high-grade seams (up to 35 per cent lead) which cross Nos. 4 and 5 costeans (Figure 4), is readily explained when the nature of the soils in the anomalous area is considered. A large proportion of eluvial material, characterized by angular and some rounded pebbles and obviously derived from barren rocks to the west, has been intermixed with the soils derived from the seams, causing dilution of the lead minerals in the soils. What would have been a strong anomaly, in residual soil only, is thus reduced to a weak anomaly.

The negative areas north and south of this anomaly were unexpected, as deep drilling revealed that the seams were continuous at depth and similar conditions were expected at the surface. The lack of positive tests was later found to be due to the presence of old, deep water channels, now completely concealed beneath the eluvium. At a churn drill hole on the northern side of No. 3 costean the depth of soil is 27 ft. The resulting decrease in concentration of the lead minerals in the deep soils over the veins was sufficient to cause negative geochemical results in these areas. Before the correct results could be obtained for such cases a new sampling technique would have to be adopted, the depth of 9 to 15 in. as in the present survey being obviously inadequate.

It is possible that the old drainage channels, filled as they are with a large percentage of coarse material, still contribute largely to the drainage of the area, and they would tend to drain to a reasonably dry state after rains. This combination of deep alluvial cover with leaching by fresh water each rainy season and rapid drying out of the soil, might tend to prevent indications of mineralization from reaching the shallower layers of the soil. The rate of soil shift is also likely to be more rapid in such channels.

Groundwaters, even when they are present for short periods during the summer, appear to play little or no part in the solution and dispersion of the lead ore minerals. The stability of oxidized lead minerals in the zone of weathering is well known, and even for other minerals Huff (1952) suggests that after incorporation in the soil the ore metals are practically insoluble in soil moisture.

The sphalerite and galena in the seams at the Northern Prospect are ultra-fine-grained and intimately mixed. Very few of the mineralized beds show visible signs of mineralization at the surface and it is probable that when the sulphides were oxidized at the surface the sphalerite was rapidly leached out, leaving the lead minerals in a finely divided state which allowed them to be easily dispersed.

The interpretation of the copper anomalies is more difficult than that of lead anomalies, because of the greater mobility of copper in the weathering zone. Copper minerals would have to be present at bedrock to allow mechanical dispersion; visible traces, as oxidized copper minerals, would be present in the soil, and no such traces were observed. On the other hand, without circulating groundwater, copper would not rise from a non-outcropping orebody at depth. Earlier extensive leaching of a sulphide orebody, in a more humid climate, might have left sufficient vestigial copper above the water table to produce a geochemical anomaly at the present surface. Alkaline conditions in the present soils, as noted in many samples from the copper anomalous areas, would help to hold the copper in an immobile form.

In a study of the dispersion of copper from the San Manuel copper deposit, Arizona, in a climate similar to that of Mt. Isa, Lovering, Huff, and Almond (1950) state that wherever the soil is derived from the immediately underlying rocks, as on ridges, the copper
content of the soil bears an especially close relationship to the copper content of the parent rock. Whether or not this is true at Mt. Isa cannot be proved until more prospecting has been carried out.

Conclusion

The survey was a test case for the prospecting for lead by geochemical methods; as far as is known it was the first time they had been applied successfully in Australia to lead mineralization.

The chief use of the geochemical prospecting was to separate a large area into smaller favourable and unfavourable areas. Advanced prospecting could then be carried out with less expense and with an increased possibility of locating commercial-grade mineralization. Thus at the Southern Prospect, of the 3/4 miles length of probably mineralized outcrops, only Smoko and Haney's Ridges were shown by the geochemical work to be suitable for more advanced prospecting. Smoko Ridge was previously considered unfavourable for any type of mineralization and would probably have been overlooked during the costeaneing and drilling program.

The weak lead anomalies in the other parts of the Southern Prospect indicate that mineralization is not present at the surface in commercial quantities and that examination of the bedrock by costeaneing would be of no avail.

Interpretation of the three copper anomalies in the Southern Prospect proved rather difficult as an anomaly over known copper mineralization, with which a comparison could be drawn, was not available. The value of the results can only be assessed when the drilling results are known.

At Pick Hill, in the Northern Prospect, the discovery of a mineralized seam demonstrated the rapidity of the method and its advantage of day-to-day planning of the work. In less than three days a team of three was able to sample the area (86 samples), test the samples in the laboratory, indicate the lateral extent of the mineralization, and locate the mineralized seam by digging a short costean.

The success of this project should encourage further work of this type, both in the Mt. Isa area and in other areas of similar climate and topography.

Acknowledgements

The author is indebted to the Commonwealth Bureau of Mineral Resources which made the survey possible and permitted publication of the report, and also to Mount Isa Mines Ltd., for the use of laboratory and office space. Thanks are due to S. R. Carter, chief geologist of Mt. Isa Mines, for his assistance throughout the project, and to A. A. Gibson of Mt. Isa Mines and K. A. Townley of the Bureau of Mineral Resources, for their contributions on the geology of the area.

REFERENCES


Sandell, E. B.: Colorimetric determination of traces of metals (N.Y., Interscience), 1944.


The Chairman invited Mr. Tooms to introduce the paper in the absence of the author.

Mr. J. S. Tooms said that the paper was the first on geochemical prospecting in Australia to be presented to the Institution. It illustrated the usefulness of applied geochemistry as an additional tool in the
prospector's hands, the adaptability of the analytical techniques to a given problem, and the care required in interpreting the results.

He felt that two points could not be over-emphasized: first, that geochemical prospecting was not a prospecting method to replace established methods but an additional aid in locating orebodies which should be used in conjunction with all other available data; second, that while interpretation of the results required, among other things, a knowledge of geology, modifications of the analytical method should only be carried out by personnel with a knowledge of chemistry.

The speaker then summarized the main points of the paper. He called attention to the importance of carrying out an orientation survey over known mineralization in an associated area if the results of the survey were to be interpreted with any confidence. That was illustrated in the area prospected, because it was not possible, except in a very general way, to interpret the copper anomaly in the southern area covered by the survey.

Judged on the results, he thought it would be agreed that the survey had been a success. Areas of probable mineralization had been delimited. Some of those areas were previously thought to be geologically unfavourable and it was unfortunate that while costeans had been bulldozed on either side of Smoko Ridge to within 40 ft. of the top, without positive result, it had not been possible, owing to a hard jasper capping, to test the author's interpretation of the anomaly as due to mineralization at or near the top of the ridge. It would be necessary to costean by hand to the foot of that capping before the supposedly mineralized beds could be uncovered. However, an anomaly on Pick Hill had been tested by trenching, and a mineralized bed, which was believed to be of economic grade, had been located.

Finally, he suggested that the cost of the survey, including the small outlay on equipment, would compare very favourably with the cost of obtaining the same information by other methods.

Dr. S. H. Shaw said that the paper was a workmanlike account of a practical job and served well to show the usefulness of that type of work in suitable circumstances. He was glad to note that Mr. Tooms had drawn attention to the limitations that must be taken into account, both for the method generally and for the particular area under examination. Geophysical prospecting certainly requires an appreciation of such limitations, as was true of geochemical prospecting. Among those mentioned by the author was the necessity for a relatively thin soil cover for a successful operation of the method in the Mt. Isa area; they emphasized that where the soil was thick the results had to be treated with a certain amount of caution. If sufficient caution was not exercised, an area with economic possibilities might perhaps be rejected. As long as that point was known it did not mean that the method as a whole should be rejected; because there would be other areas where valuable positive results would be obtained, and others where negative results could be safely taken as eliminating that particular ground from the necessity for further examination.

There was one detail in the paper on which he would like a little enlightenment. It was stated that 'The seam must be present at bedrock for the anomaly to exist, as solutions play no part in the formation of the anomaly'. That seemed to suggest—in fact it was claimed earlier in the paragraph—that the whole question of lead dispersion was one of the mechanical breakdown of the lead vein. He found that difficult to reconcile with the statement earlier in the paper that it was the acid-soluble mineral which was used to determine the geochemical anomaly in that particular prospecting operation. The author appeared to envisage a purely mechanical disintegration and dispersion of his vein material, assuming solution processes to have played no part; yet he relied on the acid-solubility of a part of the mechanically-produced debris to give him his geochemical anomaly. That would appear to be the more remarkable, in that the outcrops of those veins were of an oxidized character, with the lead mineral being largely cerussite, resulting presumably from the breakdown of primary galena. Was it suggested that solutions had played no part in the process, or that the acids resulting from the oxidation of the lead and other sulphides were, and had been, inert as far as their power to influence a geochemical anomaly was concerned? It would be a matter of scientific interest and possibly of practical importance to have some clarification of that point.

During the Fifth Empire Mining and Metallurgical Congress in 1953 he had been fortunate enough to visit Mt. Isa, and Mr. Carter, the mine geologist, had shown him some of the prospecting areas. In one case Mr. Carter had led him to a prospecting trench where he said that there was lead mineralization outcropping with the rather uniform-looking steeply dipping slaty sediments that had been exposed, but it required a most minute examination to determine where the thin
and inconspicuous mineralization actually was. If the unfortunate geologist had to go over the country with a toothcomb he would certainly welcome the advent of a method such as that described, which would relieve him of some part of that labour or increase the chances of its being rewarding.

Dr. D. R. Grantham said that under conditions of tropical weathering, massive galena veins below surface might make only a miserable showing of oxidized lead minerals on surface and be hardly recognizable. A geochemical method was welcome in such circumstances.

As a general statement one might say that the chief advantage of geochemical work, in contradistinction to geophysical, was that the results obtained were directly related to what was sought; in geophysical work the results might be useful or might be related to something entirely extraneous.

Mr. T. Eastwood said that he was a little worried about some of the statements in the paper with regard to the ‘two-men-and-a-boy’ outfit. He thought there was danger in trying to make some of the work far too simple. The actual sampling might be carried out by that small body, but interpretation, he thought, should be done carefully and by experienced men.

The method had much in common with the soil mapping used for agriculture, and one of the difficulties of the geologist was that the agriculturalist looked at a geological map and thought that the soil would stay put on a particular formation. In the area under discussion the soils had moved in all cases and some had moved a very great deal—that was where sound geological mapping and sound geological understanding of the geological history of an area was essential. There was an instance of a thick alluvium which gave negative results, caused obviously by transported soil, which, geologically, should be obvious.

He wished to query: ‘What is soil?’ All knew the difficulties with regard to the engineer and soil. Samples taken about 15 in. or so below the surface would be more or less ‘agricultural soil’. In one or two places, however, the author still spoke of soil after he had gone down quite a depth to the bedrock; that might be ‘engineering soil’, but geologically it would be ‘subsoil’.

He also asked whether or not there had been poisoning of animals in any degree in the relatively rich areas which had been surveyed. He knew of cases in Great Britain where sheep and fowl had been poisoned in pecking over old lead dumps. Seeing that it was largely a mechanical breakdown of minerals, as had been pointed out, there were probably some grains of galena and cerussite in the soils. The analyses were related to materials easily dissolved in acids, and in view of the fact that most animals had acid in the stomach which would also dissolve those minerals, they could pick up and absorb poisonous substances.

He was very much interested in that particular method of geochemical investigation, which certainly would assist prospecting in some places by at least warning the prospector of areas which were probably no good at all. It was easily applied and easily organized. The author was particularly fortunate in dealing with an area where neighbouring workings provided keys to the results straight away.

Mr. J. B. Dennison said he had heard a lot of talk of animals being poisoned by lead occurrences but never met it. He thought the reference might be to one of the mines where they were trying to sell the tailings, in which there was as much as 0.1 per cent of lead, as fertilizer. That was not very high from a metallurgical standpoint, but agriculturalists were rather afraid of it. Even if there were any doubts about 0.1 per cent lead, surely there could not be anything amiss in material with nine parts per million. He could not imagine animals taking hurt from eating grass growing on the top of one of those deposits depicted in Figure 2 as ‘V.H.’, for example.

He had had some experience of geochemical prospecting at Matlock. There were two people present that evening who were actually doing it, and the results in that area were satisfactory in that they showed what might be there. The work described in the paper might be interesting to those familiar with what had been done in Derbyshire.

Mr. Eastwood wished to direct Mr. Dennison’s attention to the infinitesimal amount of molybdenum which had had a disastrous effect on horses and cattle in some parts of Great Britain. In the reverse direction the lack of cobalt in small areas overlying granite in Cornwall, had had disastrous effects on sheep. It was beginning to be realized that the presence or absence of traces of minerals might have pronounced effects on plants and animals.

Mr. Dennison replied that those were two good points. It was known that a shortage of cobalt was bad for sheep particularly and led to a disease called ‘pinning’. The amount which was supposed to be bene-
Solution processes certainly played a part in the breakdown of galena and, indirectly, in the formation of the cerussite. At the time when, and places where, galena was actually being decomposed, the solutions would be acid (at present depth). But these acid solutions have no influence on the geochemical anomaly now existing at and near the surface, where the distribution of lead is due to mechanical breakdown and dispersion of the secondary lead mineral.

The weak (0.01 N) hydrochloric acid used for the extraction would dissolve sufficient lead from the secondary mineral to give positive tests with dithizone. Under the controlled conditions of the dithizone tests, the amount of lead dissolved (extracted) should be directly proportional to the amount of secondary mineral in the samples.

Mr. Eastwood's remarks on the danger of trying to over-simplify, apparently refer to the interpretation. Fortunately in this survey, the interpretation was simple. The anomalies were on sloping ground and the sources could be located within a few feet, as demonstrated at Pick Hill. Anomalies on flat terrain may present more difficulties in interpretation.

In the survey no distinction was made between 'agricultural soil' and 'engineering soil'. The latter was sampled during the orientation survey, the fine fraction of the decomposed bedrock having been collected and referred to as soil. In general, samples were taken from the 'upper B' horizon, or 'agricultural soil'.

The writer has not heard of any poisoning of animals in the lead-rich areas covered by the survey. In general grass does not grow in sufficient quantity to allow grazing of cattle, and no other animals were seen at the time of the survey.

Mr. Tooms asked whether any comparative results for total lead content of the soil were obtained. Unfortunately they were not, although the author now considers that it would have been of interest to have run a series of tests designed to establish the relationship between total lead (or other metal) content and amounts shown under the controlled conditions of the dithizone test. In a recent survey carried out at Natioona, Northern Territory, a comparison was made between results obtained by the cold dilute acid extraction (Mt. Isa method) and by a hot concentrated acid extraction (U.S. Geological Survey method.) As expected, the latter method gave the higher results, expressed as parts per million. However, when referred to their respective background values the results for each method showed a close similarity.
No further work has been carried out in the vicinity of the old drainage channels between Handle-bar and Tombstone Hills.

Mr. W. Domzalski's question regarding the influence of the thickness of soil or overburden on an anomaly is one which is often asked. In the surveys carried out to date the writer has found that for residual soils up to 10 ft. deep the lead results are reasonably uniform for all sampling depths. There is possibly a limiting depth for which this would hold, but it has not yet been met in practice. The author considers that, provided suitable conditions prevail in the soil, an ore-grade lead seam of reasonable dimensions (greater than 1 ft. wide) would be readily detectable at the surface of residual soil up to 20 ft. deep. Extensive high-grade mineralization at the base of soils over 30 ft. deep should be easily detected by the geochemical methods. The anomaly may be displaced at the surface in the direction of soil movement. The intensity of the anomaly would depend on the width and grade of the mineralization, and on the ratio of the amount of barren soil moving over the seam to the amount of soil being formed in the immediate vicinity of the seam, i.e. containing a high concentration of lead mineral.

The writer visited Mt. Isa in November, 1954, to investigate the results of drilling and surface operations which have been carried out at the geochemical anomalies since the survey in 1952.

Four diamond drill holes, ranging in depth from 385 ft. to 900 ft. were drilled at the Southern Prospecting Area, but no mineralization of commercial grade was disclosed. Information supplied by the holes indicated that the ferruginous ridges originated from sulphides contained within an extensive shear zone. Pyrite is the predominant sulphide, and is accompanied by minor amounts of galena and sphalerite (personal communication).

At the Smoko Ridge anomaly two drill holes to depths of 385 ft. and 420 ft. intersected only narrow zones of lead mineralization. In the first of these massive pyrite occurred between 227 ft. and 273 ft., with small amounts of galena and sphalerite showing between 227 ft. and 247 ft. In the second two ½-in. stringers of galena were intersected at 263 ft. and 289 ft. Traces of lead (determined by assay) were located in surface coteans. However, the coteans terminated at least 30 ft. from the jasper capping, although it had been pointed out that the lead mineralization causing the anomaly could be expected below this capping.

A drill hole passing beneath Window Ridge, where a strong copper anomaly was found, intersected dolomitic shale with traces of pyrite and chalcopyrite in places between 300 ft. and 990 ft. Lead assays ranging from 0.1 to 2.8 per cent were obtained on core samples between 660 ft. and 724 ft. Copper assays were not reported. In the presence of dolomitic shale traces of copper would be retained and concentrated (as carbonate) near, but not necessarily at, the surface. Soils derived from such a rock are generally slightly acid or neutral at the surface, but where active decomposition of dolomite is taking place in weathered rock they would have a pH of between 8 and 9, and this is where the copper would be held. This phenomenon could explain the copper anomaly at Window Ridge.
MAGNETIC SURVEY OF RYE PARK SCHEELITE DEPOSIT,
NEW SOUTH WALES, AUSTRALIA

by J. Horvath*

Abstract

The Rye Park scheelite deposit lies 1½ miles north of the village of that name, and 12 miles southeast of the town of Boorowa, in New South Wales, Australia. The bedrock consists of gently dipping Silurian porphyries and dacitic tuffs, intruded by two small granite cupolas. Although the soil cover is shallow, there are few outcrops, which hindered geological mapping and prospecting. It was found that magnetite accompanied scheelite ore, which has selectively replaced certain beds in the volcanic suite, probably originally calcareous tuffs. A magnetic survey was used to delimit the areas of magnetite-scheelite occurrence.

Magnetic anomalies were found in the marginal area around the north granite cupola. These anomalies were strong but limited in extent, and were interpreted to indicate near-horizontal magnetic bodies at shallow depth and of limited dimensions. Drilling revealed one main, nearly horizontal body, ten to twenty feet thick, overlain by a smaller one. Values in tungsten were found to vary more or less with the magnetic intensities.

The Rye Park scheelite deposit is about 1½ miles north of the small village of Rye Park and about 12 miles southeast of the town of Boorowa in New South Wales, Australia. (Figure 1).

Although the depth of soil cover is only a few feet, reaching a maximum thickness of about 20 ft. in the alluvial flats, the lack of outcrops seriously hindered geological mapping and prospecting of the deposit. However, as the ore contained some magnetite, it appeared that a magnetometer survey would be the most satisfactory means of mapping these deposits.

Geology

The scheelite deposit lies in an area of rather gently dipping (0°-15°) Silurian porphyries and dacitic tuffs, which are intruded by two small granite stocks. Outcrops showing high-grade metamorphism indicate that granite may underlie the Silurian rocks at relatively shallow depth. The main geological features in the immediate vicinity of the deposit are shown in Figure 2 (in pocket).

Mining Geology

Certain beds within the volcanic suite which appear to have been calcareous tuffs, have been selectively replaced by ore. The mineral deposits are confined to a relatively narrow margin around the granite intrusion, and appear restricted to the east edge of the granite stock. Near the granite, the ore-bearing beds have been converted rather extensively to hornfels.

The ore is complex and includes such contact metamorphic minerals as garnets, micas, scheelite, wolframite, magnetite, apatite and fluorite. Most of the ore minerals are aggregates of fine grains.

Geophysical Methods Used

In the course of the preliminary mining exploration, magnetite was found only in association with the scheelite-tungsten orebodies, and it was assumed that the extent of the magnetic anomalies would coincide roughly with that of the scheelite mineralization.

The magnetometer survey was done with a Watts vertical magnetic balance (scale constant 27.6 gammas per division).

Although the ore beds were considered too small to give rise to detectable gravity anomalies, it was thought that there might be a sufficient difference in density between the granite and the porphyries or tuffs to enable the main boundaries of the granitic intrusions to be located by gravity methods. A few tests
were sufficient to show that such was not the case, and the gravity method was abandoned.

**Interpretation of Results**

The data read during the magnetometer survey were plotted as profiles and as a contour map. Over most of the surveyed area the magnetic intensity shows little if any variation. Magnetic anomalies were found only in the marginal area around the north granite stock. The contoured magnetic data of this part of the area shown on Figure 2.

The anomalies are strong but limited in extent. They indicate, by their pattern, that the magnetic bodies are lens-shaped. Several such bodies were indicated, and the interpretation suggested near-horizontal magnetic bodies at shallow depths and having limited dimensions. For that reason it was recommended that the magnetic anomalies should be tested by several short diamond drill holes.

**Testing of Indications**

Thirty holes were drilled with an average depth of about 100 ft. The positions of these holes are shown on Figure 2, which shows also whether the holes revealed good ore (i.e. above 0.5 per cent WO₃), low-grade ore or no ore.

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**Figure 3.** East-west section near open cut.
The drilling proved the presence of a nearly horizontal body containing magnetite and scheelite which corresponds approximately to the shape indicated by the outline of the principal magnetic anomaly. This body is about 20 ft. thick in the south part of the anomaly and about 10 ft. thick in the north part, and is about 40 ft. below surface south of the central shaft, about 80 ft. near the shaft, and from 80 to 100 ft. thick north of the shaft.

In the area of the open cut (Figure 2), a second, smaller horizontal body lies above the larger one, and scheelite in mineable quantities outside the zero magnetic relief of the anomaly (Figure 3). Despite the fact that the magnetic anomalies are caused only by the magnetite and not by the scheelite, there is good agreement between the magnetic data and the drilling results. Values of more than 0.5 per cent WO₃ were found within contours of high magnetic intensity in drill holes 1, 2, 3, 4, 5, 8, 9, 10, 11, 12, 22 and 32, and near the boundary of higher intensities in drill holes 7, 18, 20 and 21, but no drill hole encountered scheelite in mineable quantities outside the zero magnetic contour, e.g. drill holes 29 and 30.

The narrow zone extending south from the south part of the main magnetic anomaly was investigated by drill holes 26, 27 and 28. None showed more than traces of scheelite, and it is assumed, therefore, that the main orebody terminates near drill holes 1 and 2.

The main anomaly is almost divided into two parts by a marked narrowing near No. 2 shaft. The grades of ore in drill holes 7, 20 and 21 are almost as good as in the other drill holes, and the narrowing seems to be caused by an abrupt increase in the depth to the orebody near the shaft.

The drilling results on a small anomaly about 150 ft. east of the north shaft illustrate the close agreement between them and magnetic data. One hole, drilled in the centre of the anomaly, intersected 22 ft. of good ore; but of four holes around the first, one showed very low grade ore and the other three no ore.

No explanation is given for the small but intense magnetic anomaly checked by drill hole 17; no magnetic material was reported from this hole although it was drilled in the centre of the anomaly. The rapid variations in the magnetic readings and the very limited extent of the anomalies at this location could be caused also by strongly magnetic boulders in the creek bed. The creek prevented a more complete magnetic investigation of that particular area.

Testing and development (including the drilling described) were carried out in accordance with the interpretation of the data observed on the survey. Mining and treatment of the ore were undertaken but later were stopped because the operations seemingly were not a financial success.

GEOPHYSICAL EXPLORATION FOR COAL IN GIPPSLAND, VICTORIA

by F. J. G. Neumann*

Abstract

Hard, brown coal occurs in Tertiary strata, at shallow depth, in Gippsland, Victoria, Australia. Seams have been worked since 1889, and reserves have been diminishing rapidly in recent years. Early exploration drilling failed to discover appreciable reserves, largely because bores must be accurately placed to intersect the seam where it lies on the flank of a steeply dipping monocline.

Gravity studies were used to trace the eastward and northeastward extension at this monocline. Drilling carried out in accordance with recommendations made on the basis of the gravity survey results, subsequently revealed new coal reserves in excess of one hundred million tons, and showed that the coal seam continues for a distance of at least nine miles.

THE East Gippsland basin, near the southeastern corner of the Australian continent, contains enormous reserves of Tertiary brown coal, occurring mainly in the Latrobe syncline. Detailed descriptions of the geology of the basin have been given by Thomas and Baragwanath (1949-1951), and Herman (1952).


The coal occurs in several seams with an aggregate thickness exceeding 1,000 ft. It is generally soft and of low grade, has a high water content, and is suitable only for local power generation and briquetting.

However, hard brown coal of better quality (lower water content) is also found in Gippsland. This coal is contained in the “Latrobe Seam”, which is strati-
mining geophysics

graphically below the soft coal seams; it was early known to occur at shallow depth and in a relatively high tectonic position on the northern fringe of the main coal basin.

The Latrobe seam has been worked in the Yallourn-North open cut since 1889. In recent years this coal has been widely used by Victorian industry, firstly because it is the cheapest coal, based on fuel value, that is available in Victoria, and secondly because it can be used commercially without briquetting.

As a result of increased demand, coal production from the Latrobe seam has risen to more than one million tons a year, and known reserves were rapidly decreasing prior to the recent geophysical survey, described in this paper.

The coal seams of the Latrobe syncline crop out at only a few places; in these places they have been exposed by river erosion. In general, the coal measures throughout the East Gippsland basin are covered by sand, clay, and gravel of thickness ranging from a few tens to several hundreds of feet.

Mining by open-cut methods is carried out near Yallourn and Morwell, where the coal seams occur under a thin overburden in monoclines and anticlines. The tectonics involved have been described as a combination of gentle folding in the Tertiary sediments with almost vertical faulting in the underlying Jurassic rocks. Details of the concealed tectonics along the northern fringe area of the Latrobe syncline have recently been developed as a result of an intensive drilling campaign carried out after an earlier geophysical survey.

Earlier exploration drilling initiated without geophysical guidance failed to locate appreciable coal reserves in the Latrobe seam. This is not surprising when it is realized that the Latrobe seam, although more than 200 feet thick in places, occurs mainly on a steeply-dipping monocline, and that bores must be very accurately placed to intersect the coal.

This monocline is irregular and at many places is intercepted by folds and minor cross-faults. Strike variations are frequent and are independent of topography. Commercial coal reserves which have been found recently occur at several places miles apart, so that large blocks of coal suitable for mining appear as several separate lenses rather than one deposit continuous in strike.

Geophysical exploration of the Gippsland coal areas was initiated about 12 years ago, mainly by the gravity method. Correlation of gravity anomalies with known geology shows that the anomalies are caused mainly by the density contrast between the Tertiary brown coal measures and underlying Jurassic and pre-Jurassic (Silurian) rocks. The density of the Tertiary sediments ranges from 1.41 gm/cc (coal) to 1.9 gm/cc (clay); the Jurassic sediments average 2.5 gm/cc and Silurian rocks 2.7 gm/cc.

By the end of 1953 the whole of the Latrobe syncline and much of the adjoining regions of East Gippsland had been covered by a reconnaissance gravity survey, the results of which clearly showed the major tectonic features of the area.

A feature of note is the gravity high shown on the Bouger anomaly plan (Figure 1) and on the cross section (Figure 2) which coincides with the Morwell anticline. Detailed drilling in this region has shown that the gravity anomaly agrees closely in position, strike, and pitch with the anticline. Of particular interest is the zone of steep gravity gradients on the northern side of the Latrobe syncline, coinciding with the steeply dipping monocline in which the Latrobe seam occurs. The zone of steep gradients was attributed mainly to the sudden decrease in thickness of the Tertiary sediments (including the coal measures) and to a lesser extent to a thinning of the underlying Jurassic sediments.

The reconnaissance results showed clearly that this zone persists to the northeast of the Yallourn North open cut, but, owing to the wide spacing of the gravity stations used in the reconnaissance survey, its exact position and course were not well defined. Its coincidence with the Latrobe seam suggested that this zone would be a useful guide to prospecting for extensions of the Latrobe seam.

Early in 1954, the Commonwealth Bureau of Mineral Resources, Geology and Geophysics and the State Electricity Commission of Victoria started geophysical and drilling programs respectively to investigate a possible eastern extension of the Latrobe seam. Drilling results obtained up to the middle of 1954 indicated only a small coal deposit in the area adjoining the present open-cut workings to the east.

Detailed gravity surveying was extended further eastwards to include areas considered favourable, on the basis of an earlier gravity reconnaissance survey, for an extension of the Latrobe seam. The results reveal a comparatively narrow zone of steep gravity gradients similar to those obtained over the monoclinal feature with which the Latrobe seam is associated at the present open-cut. (see Figure 1).
Figure 2. Bouger anomaly profile ABC.

Figure 3. Bouger anomaly DE.
The zone of steep gravity gradients continues east and northeast for at least 9 miles. It indicates a probable extension of the monocline, and by inference the associated Latrobe seam, over this distance at shallow depth.

Since the middle of 1954, drilling has been carried out in accordance with recommendations made by the Bureau and based on the gravity results; to the end of June, 1956, additional coal reserves in the Latrobe seam exceeding one hundred million tons had been proved by drilling. It is evident from the drilling results that the Latrobe seam, earlier considered to be an isolated block of coal, follows the trend of gravity contours eastward over a distance of at least 9 miles from the original Yallourn North open-cut area.

Figure 1 shows the pattern of Bouguer anomalies found in the westernmost section of the East Gippsland brown coal basin, together with locations of significant exploration bores.

Section ABC (Figure 2) indicates the correlation of observed Bouguer anomalies with the main tectonic features and present open-cut workings of the Yallourn-Morwell area.

Section DE (Figure 3) shows a cross-section of the recently discovered Yallourn North extension coal field with gravity anomalies and estimated depths to Jurassic and pre-Jurassic rocks as deduced from gravity results.

REFERENCES


MINING GEOPHYSICS AND ITS FUTURE IN CANADA

by L. W. Morley

FOR a century is was thought, in many European countries, that most of the available mineral wealth had been discovered. About 30 years ago, however, geophysics began to be used more widely and many new orebodies were found in unexpected places.

In Canada, while it is still a worthwhile venture to prospect with pick and hammer in the remote areas, the chances are slight of finding promising showings in outcrop areas for a surprisingly large area of the Canadian Shield and other mining districts, and the diamond drill is often employed to probe under lakes and below overburden. Wildcat drilling has been successful but is an extravagant way to prospect.

Informed prospectors and mining companies prefer to have their drilling guided by indications—geological, geochemical, or geophysical—and in areas of widespread cover, geophysical methods hold most promise for success. From reconnaissance mapping and from study of aerial photographs it is known that the relatively unexplored central parts of the Canadian Shield have greater overburden than the better known outward fringes. Thus, to prospect these areas for their minerals will require greater reliance on geophysical methods than in the past.

The direction of the other, newer, frontier is vertically downwards and here again geophysics must play its part. The deeper the target, the harder it is for the geophysicist to detect it, but when the economic need arises, refined geophysical methods, both on the surface and in deep drill holes, will be used.

To predict trends in mining geophysics, one need only review the history of geophysics in petroleum exploration. Oil fields first were indicated by surface seepages. Later a combination of drilling and geological knowledge followed. Then primitive geophysical methods were added and easily detected structures were found. At present, improved geophysical techniques, both surface and drill-hole, are combined with geology and drilling to find the deeper and more elusive structures.

It is interesting to compare the worldwide geophysical investment in petroleum geophysics in 1956 ($370,000,000) with the corresponding investment for mining geophysics ($11,200,000). For Canada the corresponding figures are about $37,000,000 and $3,400,000 respectively. Thus, while the expenditure for mining geophysics in Canada in 1956 was only about 9 per cent of that for petroleum geophysics, it is more than 30 per cent of the world total for mining geophysics. It is worthy of note also that, while total mineral prospecting in the United States exceeds considerably that in Canada, mining geophysical prospecting in Canada surpasses that done in the United States.

Thirty years ago geophysical prospecting in Canada was regarded by the established mining companies as an expensive fad. Most of the techniques were understood only by a few physicists interested in geophysical prospecting and the methods were regarded by geologists as well as by prospectors as too difficult to use and to understand. As mineral deposits became more difficult to find, and as mining engineers, geologists and prospectors grew familiar with the methods, they began to accept the aid of geophysics. Today most major mining companies spend, on the average, about 25 per cent of their exploration budget (including the cost of drilling) on geophysics. Instead of being regarded as separate and distinct from normal prospecting and geological methods, it is woven into the overall exploration programs, along with reconnaissance mapping, detailed geological mapping, geochemistry and drilling.

The prosperity enjoyed by the Canadian mineral industry since the end of World War II has helped to advance the science of geophysical prospecting because more money has been available for its continued use. Because of favourable natural, economic, and political conditions in Canada, large foreign controlled mining companies with fairly big exploration budgets have been attracted to Canada and these companies spend most of the money on mining geophysics in Canada.
Not only do they spend more on geophysics, but their outlays are more effective than those of smaller companies.

Recent Geophysical Successes in Canada

The present acceptance of geophysical prospecting is largely the outcome of the successes achieved since World War II, caused in part by the introduction of airborne geophysical devices, followed up effectively by ground geophysical work and by drilling. The airborne magnetometer was used extensively in the search for magnetic iron ore in Ontario and Quebec and led to the discovery of a large magnetic iron deposit at Marmora, Ontario. Ground magnetic and electrical methods played an important role in the discovery of the base metal deposits at Lynn Lake. Both airborne and ground magnetometers were used in the Eastern Townships to extend the known deposits of asbestos. The original outlining of the Steeprock iron deposit was helped considerably by the ground magnetometer. Ground magnetic and electrical methods were used extensively to trace geological structure in the Kirkland Lake-Val d'Or area but geophysical surveys met their greatest successes in New Brunswick. In 1949 an airborne magnetometer survey was conducted by the Geological Survey of Canada over an area which had been prospected extensively on the surface. The maps, which were published in 1952, outlined many magnetic features which suggested promising geological structures. Much of the area was covered by overburden and ground geophysical instruments followed the airborne magnetometer. The ground electromagnetic survey outlined a base metal deposit of about 28,000,000 tons near the old Austin Brook iron mine, and two other base metal deposits, the New Lander U (1,173,540 tons) and the Brunswick Number 6 (28,312,000), also were found in a ground electromagnetic survey. Airborne electromagnetic surveys were then conducted over most of this interesting area and a fourth substantial base metal deposit (7,000,000 tons minimum) near Little River Lake was located. Thus the discovery of this New Brunswick mining camp was important to the prestige of geophysical surveys in Canada because it was attributable almost entirely to geophysics.

Now mining geophysics is on a new threshold; it has recognition and can take its place among the other engineering fields, or it can, as in the late twenties, fall into disrepute because of malpractice. It still is prey to stock promotion because of its glamorous appeal to the public, but a certain amount of this must be accepted. It is the responsibility of individual geophysicists and geologists to maintain a high standard of professional ethics. Another danger is that geophysics may become a proud and independent science divorced from geology. When most of the depositions easily detected by geophysics alone have been found, geophysicists will remember its essential relationship to geology.

Cost of Geophysical Surveys

Geophysical prospecting has been criticized as too expensive in relation to benefits derived. Again, if we look to the experience of the petroleum geophysicists, we find that actual costs have risen markedly in recent years, but success has increased to the point that costs relative to benefits derived actually are less. So, in mining geophysics, outlays may be expected to rise but through improved methods the final or effective charges will be lower. Geophysics will be hurt if costs are cut at the expense of the quality and detail of the work done. Airborne geophysical surveys have contributed substantially towards lowering reconnaissance expenditures but there always is a temptation to spread the work thinly to cover larger areas. Then the risk is run of missing entirely not only possible orebodies but in some cases fairly large geological structures.

It is unfair to talk about the cost of geophysics alone; the real issue is the cost of overall exploration, including reconnaissance geological mapping, airborne geophysics, ground geophysics, detailed geological mapping, geochemistry, and finally drilling. Thus it is the job of the exploration executive to determine the appropriate exploration sequence in any given area, and the extent of geophysical surveys that should be engaged in for an overall efficient exploration program. The geophysical work should tie in with the geological knowledge in the area. Because geophysics and geology must work hand in hand, they should complement each other; the geophysical survey alone will simply pose more problems than can be answered without further geological work. Since the cost of labour is most likely to continue to rise, actual costs of geophysical surveys can be reduced largely by developing lighter weight equipment which can be operated more efficiently. Instrument manufacturers have achieved and will continue to achieve great things along these lines.

Organization of Commercial Mining Geophysics in Canada

Geophysical prospecting methods are used in Canada by all types of people ranging from "weekend prospectors" with Geiger counters and dip needles to
highly qualified geophysicists. There are consulting geologists who specialize in geophysical contracting, consulting geophysicists who do contracting and consulting, prospectors who do contracting, and aerial survey companies that specialize in airborne geophysical surveys and their interpretation. Many of the larger mining companies employ their own geophysicists who work with their geologists as a team. Generally speaking, the larger the companies, the more of their own geophysical surveys they will do. In such cases geophysical consultants often are brought in for special problems and contracting companies are employed for special types of surveys or in cases where they are better equipped to do the work economically. When mining companies venture into a new area, or start a method of geophysical prospecting new to them, frequently they will use the services of consultants or contractors. The smaller mining companies that do not employ their own geophysicists may do the simpler work themselves but employ contracting companies for the more complicated surveys. No doubt there will be a tendency for mining companies to do more geophysical surveys with their own staffs, both ground and airborne, as men and equipment become more readily available. Because of the present shortage, they will have difficulty in getting geophysicists, but the combination of an electrical engineer or technician and a geologist enables them to accomplish much on their own. This combination, however, usually is at a loss when an assessment must be made of the capabilities and the limitations of the particular method used. Nevertheless, because the volume of geophysical work and the diversity of mining geophysical methods are expanding, there will be a growing need both for consultants and for contractors in geophysical prospecting in Canada.

Government Geophysics

There is almost unanimous agreement amongst prospectors and mining companies that the Government of Canada should contribute to mining geophysics in two ways: first, by continuing regional aeromagnetic and gravity surveys; and second, by research and development to improve existing methods as well as to devise new practices.

Since 1948 the Geological Survey of Canada has surveyed an average of 20,000 square miles a year with the airborne magnetometer, bringing the total area covered in Canada to about 210,000 square miles. Taking a total annual rate of surveying of 40,000 square miles a year by both private companies and the Survey, it would take about 35 years to complete the Canadian Shield alone; this does not include the Cordillera, which presents special problems.

Aeromagnetic work, to be of most value, should be available not only in advance of prospecting but in advance of geological mapping. If the aeromagnetic surveying of Canada could be completed in 15 years (the geological mapping will take about 20 years), the waste of great expenditures by government in geological mapping and by private companies on ineffective prospecting could be avoided. It is considered, therefore, that the rate of aeromagnetic surveying should be speeded up.

In the interpretation of geophysical maps, geophysicists constantly require data on the physical properties of rocks — their magnetic, electrical and elastic properties, as well as their density. This important work could be fittingly done by government agencies.

Training of Personnel

The future of mining geophysics in Canada depends more on the calibre of men attracted to the science and on their training, than on any other factor. Some Canadian universities, and particularly the University of Toronto, have done an outstanding job in inducing students to study geophysics, and then training them. More universities have started in the field and it is now possible in seven Canadian universities to pursue a course of studies leading to the degree of doctor of philosophy in geophysics. It is natural that graduates tend to specialize in phases of geophysics in which their professors are most interested. However, there appears to be sufficient diversity of study in the different universities to ensure that the field of geophysics will be well covered.

Now that the geophysics departments are in existence in the universities, they require support from the industry. Specifically, the universities need scholarships to attract the good students, at both the undergraduate and the graduate levels. They should be given grants for equipment. Geophysical instruments are costly and the universities do not have the funds for their purchase.

The physicists made the start in geophysical prospecting. A few are still being attracted, but they tend to be interested more in the fundamental problems and in the applications of modern physics to geology. This is as it should be. Now it is the duty of the geo-
physicists and the geologists to develop and apply the methods bequeathed to them by the physicists of 30 years ago. There is a realization of this and students in economic geology are receiving more advanced training in mathematics and physics to better prepare them for this work. In some universities geologists may proceed directly to graduate degrees in geophysical prospecting. Thus the gap between physics and geology is slowly being closed from both sides.

In the past, geophysics graduates were used as instrument operators which was wasteful of manpower. Now there is a tendency to use high school graduates trained on the job, but with the growing complexity of instruments and techniques there is need for better trained technicians. Courses in geophysical methods and instrument maintenance should be available to technical or high school graduates.

Research in Mining Geophysics

- Instrumentation and Technique

This phase of geophysical research has enjoyed much activity since World War II. Because of the vigour of the electronics industry, encouraged by defence and consumer requirements, and because of present-day interest in electronics, it is unlikely that this aspect will be found wanting in the next few years. Its development has opened and will continue to open new vistas in geophysics in the direction of gathering and processing great masses of data. The geophysical contracting companies and the larger mining companies are doing most of the research of this character.

- Research in Interpretation of Geophysical Data

It is one thing to gather and compile geophysical data and make shrewd guesses at their meaning; thorough interpretation is another. The need for research in this phase of mining geophysics is only too obvious. Again it is the private companies that are doing most research in interpretation, but under the stress of business they find it difficult to pursue long, unified research problems. Government agencies and the universities might undertake this work. It is done best by geophysicists who have training in both physics and geology. A common failing is to allow the mere collecting of data to become an end in itself and to minimize the importance of interpretation. This work is unattractive because it involves spending money to obtain information which it is known will have no immediate economic value. That is the type of research that needs to be attacked from both the physics and the geological sides. The physical side involves the mathematical treatment of force field instruments to delineate anomaly sources. On the geological side it involves investigating the petrological and structural nature of anomaly sources, to the end that causes of anomalies may be predicted.

Fundamental Research

Fundamental research may include the previous two categories except that its economic value is even more remote. Into this category would fall such subjects as isotope geology, the regional interpretation of geophysical data as an aid to delineating geological and metallogenic provinces, and the measurement of physical rock properties, magnetic, electrical, thermal, elastic and radioactive, etc. Some advanced instrument work also could fall into this category. While oil companies in the United States do this work, mining companies do not, neither in the United States nor in Canada. It is the sort of work in which the people of this continent generally are backward, more because of inclination and training than of lack of opportunity. It is difficult and financially unrewarding.

The University of Toronto has engaged in fundamental research in geophysics for about nine or ten years and six other Canadian universities have started within the last two or three years. The Dominion Observatory perhaps is the largest organization in Canada doing fundamental gravity, seismic and geomagnetic research. The Geological Survey recently has initiated research in isotope geology.

It is important that the mining companies support basic research. One way is by the release of regional geophysical data to organizations interested in regional interpretation. Such release would ensure also that the data, which are expensive to gather, would not be lost. Often this type of data bears re-interpretation again and again in the light of new geological knowledge.

Research directed toward the possibility of subdividing the Canadian Shield into geological and metallogenic provinces might be given as an example of the possible long-range application of basic research. In the light of present knowledge, such subdivision is speculative, but as more information becomes available, geological, geophysical and mineralogical, no doubt it will be possible. When this situation is recognized, mining companies will have more confidence in spending greater sums on geophysical prospecting and drilling to locate the more
deeply buried deposits. Such research is needed for the benefit of future generations.

Conclusions

An attempt has been made to illustrate the impetus that mining geophysics has received in Canada in late years. It was suggested that the explanation for this increased activity is the coincidence of a number of factors: firstly, the high demand for minerals, due to the depletion of reserves in the United States and Europe; secondly, the willingness of mining companies to spend more on geophysical prospecting because of recent and perhaps somewhat fortuitous successes achieved by geophysical methods; and finally, the favourable natural and political conditions for prospecting and mining in Canada. In these respects, Canada has been fortunate indeed. It is the responsibility of the individuals and the organizations participating directly in this activity to record their experiences faithfully and objectively and to do their part in helping to mould geophysical prospecting into a more coherent science for the benefit of all nations and future generations.

MAGNETIC PROSPECTING METHODS IN ASBESTOS EXPLORATION

by John H. Low

Abstract

The accompanying paper describes the outcome of magnetic surveys made in 1949 in two important asbestos-producing areas in Eastern Canada, the Thetford Mines-Black Lake area of Quebec and the Munro-Beatty townships area, Ontario. (Figure 1).

The results demonstrate that in the Thetford Mines-Black Lake area, especially in the Pennington dyke, asbestos deposits are characterized by magnetic field intensities greater than those over surrounding, barren serpentinitized peridotite. The method is not fully diagnostic, and other non-economic, geological features which also give rise to magnetic anomalies have been described. However, combined with available geological data, the magnetic results proved of great help in exploring this area.

In the Munro-Beatty area, magnetic results per se were found less directly applicable, but an indirect approach by which the fault pattern was determined from the magnetic data, and the probable locations of new deposits were deduced from the fault pattern, yielded useful information.

THE association of magnetite with chrysotile asbestos in the most important producing area of the world, the Thetford Mines-Black Lake area, has been recognized since the ores of that region were first known. However, magnetic methods were not employed extensively in exploration for asbestos until about the beginning of 1949. Since then, large areas of Ontario, Quebec, and the eastern United States have been prospected both by aeromagnetic and by conventional ground magnetic methods.

Prior to 1949, only limited magnetic work had been done, notably that of A. H. Miller (1940), carried out in conjunction with Cook’s (1937) geological survey of the Thetford area. At that time, Miller pointed out that the asbestos is associated with very large magnetic ‘anomalies’ and that, within the Pennington dyke, an area of asbestos-bearing peridotite could be distinguished, by the anomalies, from adjacent areas of non-asbestos-bearing peridotite. Since he also observed large anomalies in what were believed to be barren areas, Miller concluded that the magnetometer could hardly be of much or any direct value in finding asbestos. However, war and post-war demands on known reserves of asbestos ore stimulated the search for new deposits, and an economical and rapid method of directing speculative drilling became desirable. Although Miller showed that magnetic anomalies do not indicate asbestos concentrations exclusively, the fact that known asbestos deposits do give rise to magnetic anomalies was, from an exploration standpoint, sufficient encouragement to warrant further tests of the method.

Preliminary Tests of the Method

- Tests on Drill Cores

Some simple tests were made prior to field application of the method. In the first of these, the relative magnetic effects of the more common rock types to be expected in the Thetford Mines-Black Lake area were
checked by measuring the deflection of the magnetometer needle caused by specimens of diamond drill core about 5 inches long.

The results are shown graphically in Figure 5, and it was readily apparent that asbestos-bearing peridotite of the types represented can be distinguished from the types of barren peridotite represented; also, of course, that the peridotite can be clearly distinguished magnetically from the sediments which border it on the northwest. Less obvious from these specimens was the suggestion that granitic bodies intruding the peridotite could be detected.

Field Tests

The second of the tests comprised surveys over asbestos deposits which had been thoroughly investigated by vertical diamond drill holes on 200-ft. centres; the results of this drilling were unknown to the investigators at the time. In each of these areas, magnetic observations were made at 50-ft. intervals along lines spaced at 200 ft.

Figure 3 illustrates the magnetic conditions pertaining at Asbestos Corporation's Black Lake asbestos
and chrome property, where an irregularly shaped, low-grade ore deposit had been outlined by drilling. The deposit is about 1½ miles east of the village of Black Lake, and close to the west side of the irregular granitic intrusive which surrounds the Reed hills. Overburden is shallow everywhere within the surveyed area.

The results here demonstrate the association of magnetic anomalies with the asbestos-bearing peridotite. Although the boundaries of the favourable area suggested by the magnetic results alone would differ somewhat from the limits indicated by drilling, it is apparent that in this case diamond drilling, guided by magnetic indications, would have encountered the asbestos-bearing rock and outlined it more economically than the original program. Several drill holes in massive granite could have been entirely eliminated since the granite masses are clearly shown by areas of low and uniform magnetic intensity.

The second test was over the 'H' orebody of the Vinny Ridge mine (now the Normandie orebody), which is about 3 miles southwest of Black Lake village. The apex of the 'H' orebody at rock surface is about 500 ft. across and is covered by about 60 ft. of overburden. From the apex, the ore dips away flatly beneath a capping of barren peridotite, and the back of the deposit is more or less dome-shaped.

As shown in Figure 4, the anomaly here conforms closely with the known outline of the orebody, par-
particularly if certain minor irregularities of the contours, due probably to magnetite-bearing sludge from the drill holes, are eliminated.

The field tests therefore confirmed in these cases the magnetic relationships suggested by the specimen tests, and it appeared feasible to indicate concealed bodies of asbestos ore by magnetic methods. Areas underlain by massive granite within the peridotite apparently also could be outlined magnetically.

**Areas and Method**

The encouraging results of these tests led to field application of the magnetic method which eventually covered the most promising areas of the Thetford Mines-Black Lake district, the vicinity of what is now the Munro mine of the Canadian Johns-Manville Company in Ontario, and many other areas in eastern Canada.

Magnetic observations were made with a standard vertical variometer at intervals of 50 to 100 ft. along traverse lines spaced usually at 300-ft. intervals. Magnetic maps were compiled at a scale of one inch equals 200 ft., together with pertinent geological data from surface geology, drilling, or mining, all of which were used in interpretation.

In the Thetford Mines-Black Lake area, most of the work was concentrated on the mile-wide zone along the northwest side of the peridotite, which generally is considered the productive zone in the camp, and was extended with some gaps from the northeast side of Belmina ridge to the town of Thetford Mines, a distance of almost 10 miles (Figure 5). Following the work on the main intrusive, the southwest portion of the Pennington dyke was surveyed for about 7 miles.

In the Munro mine area, the ultrabasic sill which contains the asbestos deposit was surveyed for a distance of 3 miles. Because of the complex geology in this area, traverse lines were spaced at 200 ft., and semi-detailed outcrop maps were prepared in conjunction with the magnetometer survey.

**Geology of the Thetford Mines-Black Lake Area**

The asbestos deposits of the Thetford Mines-Black Lake area occur within peridotite intrusives, with associated pyroxenite, forming parts of the "serpentine belt" of southern Quebec. The serpentine belt is a narrow zone of intermittent, ultrabasic intrusive bodies extending northeast from the Vermont-Quebec border for 150 miles through the Appalachian region of Quebec province.

The peridotite intrusions are thought to be of late Ordovician age, occurring as sills, dykes or laccolithic bodies penetrating middle Ordovician or older
sediments, volcanics and schists. Small, irregularly shaped bodies of granite intrude the ultrabasic rocks.

The Thetford Mines intrusive body is about 13 miles long and 6 miles across at its widest part. Its southeast portion is made up of pyroxenite and gabbro, with minor amounts of dunite or peridotite (Figure 5). The northwest portion is composed for the most part of olivine-rich peridotite with some dunite and minor pyroxenite. Of similar character is the Pennington dyke (or sill) which extends for 15 miles northeast from Thetford Mines with widths varying from less than 10 ft. to over 500 ft.

The peridotites which make up the greater part of the Thetford Mines intrusion are massive, dark grey to green rocks, consisting of olivine with from 10 to 15 per cent pyroxene (enstatite), and accessory chromite and magnetite.

Dunite is an olivine rock, virtually free of pyroxene, containing disseminated chromite. Most of the dunite in the area is completely serpentinized and is a dense, dark olive-brown rock with somewhat conchoidal fracture.

Pyroxenite is generally coarse-grained and contains crystals of enstatite and diagge. A fair proportion of pyroxene-rich peridotite and a good deal of dunite are included in the pyroxenite bodies.

Serpentinization of the ultrabasic rocks is widespread. The main mass of peridotite is from 40 to 70 per cent serpentinized throughout; in the pyroxenite
area the degree of development of serpentine has been dependent largely on the relative abundance of olivine. In addition to this general serpentinization, certain zones in the peridotite have been completely serpentinized. These zones lie along contacts of the peridotite with country rock, with granite, or with zones of fracturing not related to contacts.

- Asbestos Deposits

Asbestos was discovered in the Thetford Mines area in 1876; production commenced in 1878 and has been increased ever since. In 1952 there were nine producing mines in the area, of which two were in the Pennington dyke, and the others in the main intrusion.

The asbestos deposits of economic value, with minor exceptions, are near contacts, preferably the contacts of peridotite with country rock or granite. The northwest margin of the intrusive is particularly significant as the most important deposits of the area are within half a mile of this contact.

Riordan (1954) believes that the granite bodies so frequently associated with the asbestos deposits have promoted fracturing in the surrounding peridotite by buttressing action and also have served as traps for circulating solutions. Cooke (1937) thinks that the great function of the granitic intrusive rocks was in supplying heat to the neighbouring peridotite.

Asbestos vein-formation has shown a preference for the partly serpentinized, comparatively brittle peridotite. Dunite itself contains only minute slip-fibre and very narrow cross-fibre veins, but where dunite bodies are present they may have aided in localizing fracturing in surrounding peridotite.

Chrysotile asbestos occurs both as slip-fibre and as cross-fibre, but cross-fibre is of much greater value than the slip variety.

The presence of magnetite intimately associated with the fibre is an important characteristic of the asbestos veins of the Thetford Mines area. Cooke (1937, pp. 92-94) describes magnetite as occupying the central fissure in a 2-fibre vein, following the vein-wall in a single fibre vein or as fibres and bundles of fibres running the full width of the vein, and he concludes that there is little doubt but that the magnetite was later than the asbestos and was introduced after the fibre was formed. It is upon this relationship of magnetite and asbestos that the chief usefulness of the magnetic method depends in the Thetford Mines-Black Lake area.
Two areas which best demonstrate the features of the district have been selected for discussion in this paper, namely, the Black Lake property of Johnson's Company, and the southwest portion of the Pennington dyke.

**Johnson's Company Black Lake Property**

The Black Lake property of the Johnson's Company comprises three lots in Coleraine township, a short distance east of the village of Black Lake and adjoining the British-Canadian property on the east (Figures 5 & 7).

The property is just within the northwest margin of the peridotite intrusion but includes a small area of Caldwell series volcanic rocks and sediments in the northwest corner. No granitic intrusive rocks of appreciable size outcrop, but the large, Reed hills granite mass is near the east corner and other small intrusives occur on British-Canadian ground near the south boundary. In the southwest corner of the property lies the main orebody, the limits of which have been determined by detailed drilling and stripping.

Outcrops are relatively abundant on the slopes of Murphy Hill in the south and southwest portion of the ground, but most of the north and northeast portion is drift-covered.

Thus, the Johnson's Company property is an almost ideal demonstration area, since most of the major rock types of the area, as well as a large and important asbestos deposit, are represented. In addition, the principal magnetic features of the property were investigated subsequently by drilling and an accurate appraisal of the merits of the magnetic work is possible.

- **Anomaly Zones**

Figure 6 is a geomagnetic contour map of the property. As shown on the map, six areas of anomalous magnetic intensity were observed which were indicated in the original interpretation as areas possibly underlain by asbestos-bearing peridotite. Four small areas of low magnetic intensity were considered to indicate areas underlain by granite. In the northeast portion of Lot 31, the area underlain by Caldwell volcanic rocks and sediments is shown by a low and uniform portion of the magnetic field.

Anomaly Zone 1, in the southwest corner of the property, coincides remarkably with the known outlines of the main orebody, and stands in contrast to the large area in Lot 29 to the southeast, in which sufficient drilling has been done to indicate the barrenness of the rock. In the latter region, occasional isolated high readings were observed, probably over exposed peridotite, but no continuous anomalies were encountered similar to those which characterize the main orebody. Thus a third instance is recorded of the association of magnetic anomalies with asbestos-bearing peridotite.

Anomaly Zone 2, about 400 ft. northeast of Zone 1, provides an interesting example of how magnetic indications may influence interpretation of drilling results. Only one vertical hole had been drilled in this area prior to the magnetic work; it encountered no asbestos to a depth of 100 ft. and poor rock to a depth of 288 ft. On the strength of the magnetic results, however, a second hole was tried along the strike of the anomaly less than 100 ft. to the northeast. The first 255 ft. of core from this hole averaged 3.3 per cent asbestos. A third hole, 300 ft. to the northeast, gave 1.5 per cent to a depth of 307 ft. Thus a small block of ore was outlined in an area not previously given much consideration.

Zone 3, a short distance east of Zone 2, showed similar irregularity in drilling. Two holes on the margins of the zone encountered good ore; two holes well within the anomaly yielded less than half per cent asbestos. With the addition of the new ore from Zone 2, Johnson Company engineers however, believe that a block including both zones can be mined profitably.

Zone 4, about 350 ft. east of Zone 3, comprises a narrow area of high intensity about 900 ft. long. At the southwest end, 3.5 per cent asbestos was found in drilling, but 500 ft. to the northeast, the core from a second hole ran no better than 4.5 per cent. No further drilling has since been done on this anomaly but experience in Zone 2 suggests that this zone still has possibilities.

Zone 5, in the northeast section of the property, is an irregularly shaped area within which several anomaly zones were grouped. Three widely separated holes had been drilled within this zone prior to the survey, of which two at the northeast contain 1.5 per cent asbestos or better. The third hole, near the southwest end, gave 0.5 per cent. Eight holes were drilled on the magnetic indications, all of which encountered some asbestos but nowhere in concentrations over 0.5 per cent.

Zone 6, is a single, continuous, strong anomaly lying close to, and for most of its length, parallel to,
the contact of peridotite and Caldwell series rocks. Of the six anomaly areas observed, this one showed most promise of indicating a sizable new orebody in an unexplored portion of the property. One hole had been drilled here previously, at the extreme southwest tip of the anomaly, and returned 1.0 per cent asbestos to a vertical depth of 203 ft., which encouraged speculation that more and better grade material might be encountered in the anomaly zone to the northeast.

However, later drilling revealed entirely different conditions. The anomaly was found to arise from strongly sheared and brecciated serpentine containing picrolite, slip-serpentine, talcose minerals, minute cross-fibre asbestos veinlets, and a great deal of magnetic. From a mining standpoint, this zone was barren; from a geological standpoint, the existence of a zone of strong shearing in close proximity to a major orebody is of marked interest and will be discussed further:

- Granitic Intrusives

Available information from drilling suggests that the granitic intrusive areas, as indicated by the magnetic results, are roughly correct. One diamond drill hole in the indicated granite area in the northeast corner of Lot 29 went through 118 ft. of granite in the first 203 ft. of core. A vertical hole within the indicated granite area between anomaly Zones 3 and 5 encountered granite at a depth of 165 ft. The surface area of this intrusive would appear therefore to be smaller than shown and to have steeply dipping contacts. Neither of the two remaining areas has been directly investigated, but a hole about 300 ft. to the south of the granite mass, near Zone 6, was in granite, possibly a tongue extending southward from the intrusive indicated by the magnetic results.

Discussion of Results

Within its boundaries, the Johnson’s Company property encompasses most of the important geological and magnetic features found in the Thetford Mines-Black Lake region and the discussion below is valid therefore for the whole general area.

The results obtained are thought to demonstrate amply the value of magnetic surveying as an exploration technique in the area. Three well-documented cases show that commercial asbestos deposits are attended by strong magnetic anomalies, and it seems a valid assumption that any near-surface deposits in unexplored areas likewise will be directly indicated by their magnetic effects.

In areas partially explored by drilling, magnetic indications may justify further investigation where earlier results were inconclusive or even discouraging.

Favourable sites for permanent buildings, railway rights-of-way, or other surface structures, can be selected economically by the magnetic method and a minimum of check-drilling.

Some of the limitations of the method are obvious. Firstly, magnetic results give no indication of grade of material. Secondly, magnetic anomalies do not arise exclusively from asbestos-bearing rock but may be due to other causes. Chief among these in the productive zone of the main Thetford-Black Lake intrusive are strong zones of shearing which contain much magnetite.

- Sheared Zones

Three major zones of anomalies of the Thetford Mines-Black Lake area were found to be due to material resembling that which underlies Zone 6 on the Johnson’s Company property. In addition to their similar composition, these zones have certain other common characteristics. In the first place, all are close to or against the northwest contact of the peridotite with Caldwell series rocks and are elongated parallel to the contact. In the second place, each occurs near an important producing asbestos deposit (Figure 7). One is a little over half a mile northeast of the Vimy Ridge ‘H’ orebody; another is about three-quarters of a mile from the Beaver orebody; and the third is close to the Johnson’s and British-Canadian deposit. It is possible that other similar zones may be present along the considerable stretches of the contact not covered by magnetic surveys.

The material comprising these zones is similar to that described by Cooke (1937, p. 120) as present in the fault zones observed in or near the major asbestos deposits, that is, picrolite, ‘slip serpentine’ which approaches slip-fibre, talcose minerals, minute veinlets of cross-fibre asbestos, and much magnetite. It seems reasonable to assume, therefore, that these zones probably are large faulted or sheared zones formed by differential movement along the contact of the peridotite during post-Lower Devonian folding movements.

What connection, if any, there is between these sheared zones and asbestos deposits remains to be proved. In one case, excellent ore has been found in deep drilling below the zone, which is in agreement with Cooke’s observation (1937, p. 117) that asbestos veins tend to occur beneath thrust faults. No deep drilling has been done yet in the other two zones.
Until more information is available, the one case in which there appears to be a connection between ore and sheared zone must be regarded as coincidence.

Another field for speculation about the role played by these sheared zones is presented by the fact that the major asbestos deposits of the region are confined to a relatively narrow zone along the northwest side of the peridotite. This relationship is interpreted by Cooke (1937, p. 125) as an indication that the asbestos-forming agent entered the peridotite from outside and originated northwest of the present peridotite boundary. However, the large faults or sheared zones now known in places along the peridotite boundary conceivably could have provided access for the asbestos-forming agent, and also would account for the localization of the principal asbestos deposits to the northwest side of the intrusion. The asbestos-forming solutions, therefore, might indeed have entered along the northwest side of the peridotite but need not have originated northwest of the present boundary.

- The Pennington Dyke

A section of the Pennington dyke extending from Lot 5 to Lot 24, Thetford township, a distance of about 7 miles, was surveyed in detail by the magnetic method.

The total extent of the dyke is about 14 miles in a northeast-southwest direction, the width varying along strike from less than 10 to over 500 ft. In places there are gaps where the peridotite is absent entirely. The dyke contacts with the enclosing Bennet schist dip to the southeast at from 45° to 85°.

Asbestos deposits have been found and mined at several localities along the dyke, the ore being characterized by much fibrous and considerable amounts of magnetite. Compared with the deposits in the main intrusive, the orebodies here are small and of less desirable quality. Obviously, mineable deposits may be expected only in wider portions of the dyke, so that even the simple function of determining the contacts of the dyke by magnetic methods is important.

Several traverses of the Pennington dyke were made by Miller (1940, pp. 186, 209-223) in the course of his investigations, and a portion of the Quebec Asbestos Company property at East Broughton was surveyed by him in some detail. This work showed that the contacts of the dyke with the Bennett schist could be determined by magnetic methods with much accuracy, and further that an area of asbestos-bearing peridotite at the Quebec Asbestos property could be distinguished from adjacent barren rocks.

Figure 8 shows the results of magnetic surveying along the southwest half of the dyke, and these confirm fully that the course of the dyke can be reliably traced magnetically and the contacts indicated with much accuracy. Small errors in the placement of the contact were introduced by the presence of a subsidiary dyke south of the main dyke in Lot 14 and perhaps also by masses of soapstone, which is magnetically inert, along the north margin of the dyke. For exploration purposes, these errors were of little importance.

The results indicate that the dyke persists without interruption for about 6 miles from the west boundary of Lot 4 to about the middle of Lot 21, Thetford township, where it ends abruptly. No magnetic indication of the dyke was found to the southwest for about 3,200 ft. and peridotite is presumed to be absent. The dyke anomaly was encountered again in Lot 23 and persists for an additional 3,700 ft. to the southwest, where it again seems to die out.

The proposition that asbestos-bearing sections of the dyke are characterized by abnormally high magnetic intensity received confirmation in several places. High readings were observed at both ends of the abandoned Federal pit in Lots 9 and 10, apparently the termination of what was once a continuous anomaly over the orebody. In Lot 17, intensity is abnormally high near sections of good ore in a trench across the dyke. In Lot 15, an orebody has been partially outlined by test-pits and drilling, and here again ore sections were indicated by strong magnetic anomalies.

On the basis of this observed correspondence between sections of high magnetic intensity and asbestos-bearing rock within the dyke, several zones in unexplored areas were indicated as favourable for occurrence of ore. Most of these are small and, from an economic standpoint, unattractive at the present time, so that only the largest has yet been drilled. This is in Lot 14 and consists of a series of high anomalies in a zone from about 100 to 300 ft wide along the south or hanging-wall contact of the dyke. Closely spaced drill holes here confirmed the interpretation of the magnetic results both as to the occurrence of asbestos in this zone and as to the dimensions of the asbestos-bearing portion.

Conclusions

Experience in the Thetford area establishes magnetic prospecting as useful exploration technique if employed with a recognition of its limitations and if full use is made of geological information in interpretation of magnetic data.
Figure 2. The Pennington dyke—magnetic contour map.
In the foregoing discussion it has been shown that magnetic anomalies may arise from: (1), asbestos-bearing peridotite both in the main intrusion and in the Pennington dyke; and (2), from sheared and brecciated zones near the peridotite contact.

Causes of anomalies not previously mentioned are: (3), at the extreme southwest end of the main intrusion (Figure 5) a large area of very fine-grained, dark-coloured serpentine, probably once dunite, which is seamed with numerous, tiny cross-fibre veinlets; (4), along the south margin of the peridotite, near the pyroxenite, abnormally high and erratic reading over barren, pyroxene-rich peridotite are the rule rather than exception. Thus magnetic data in this region are of little value, but fortunately the rocks are generally well exposed and can be eliminated by inspection of outcrops.

The Munro-Beatty Area

The presence of chrysotile asbestos in the Haileyburian type serpentine bodies which is quite common in the Precambrian areas of Ontario, especially in the renowned gold-producing Porcupine area, has been known for 40 years or more. Although minor amounts of asbestos were produced from four properties in Ontario prior to 1949, it was not until that year that an effort to outline a major deposit culminated successfully in the development of the Munro mine of Canadian Johns-Manville Company which in 1955 was treating 2,000 tons of ore per day.

The prominent outcrop in which part of the ‘A’ orebody of the Munro mine was exposed in Lot 10, concession II, Munro township, had been recorded since 1915 in government reports and later by Satterly (a, 1944) who mapped the southwest portion of Munro township in 1944. The extent of neither the asbestos deposit nor of the ultrabasic sill which contains it were apparent at that time because of numerous cross-faults and because of heavy overburden in the valley of Barton Creek which masks the presumed westerly course of the sill.

Early in 1949 therefore, geological and magnetic surveys of the area were commenced in conjunction with a diamond drilling program, to determine whether the relationship between magnetic anomalies and asbestos deposits which obtains in the Thetford Mines-Black Lake area could be usefully applied in the Munro area. A secondary but important objective was to trace the ultrabasic sill westward beneath the overburden and work out the complicated fault pattern.

Geology of the Area

The Munro-Beatty area is in the east extension of the Porcupine belt, a wide zone of early Precambrian volcanic and sedimentary rocks which extends from west of the town of Timmins eastward into northern Quebec.

Volcanic rocks predominate in the vicinity of the Munro mine, chiefly basic to intermediate lavas with associated fragmentals but including a narrow band of rhyolite. About one mile south of the mine the volcanics are in faulted contact with a series of sediments, predominantly greywacke.

Intrusive rocks in the area of the Munro mine have been classified by Hendry (1951) as:

(a), Differentiated, sill-like bodies of dunite, peridotite, pyroxenite, gabbro and diorite; the dunite and peridotite have been serpenitized;

(b), Narrow, discontinuous pyroxenite dykes, now largely altered to prehnite;

(c), Dykes of lamprophyre and olivine diabase.

Hendry (1951) describes the Munro sill in the vicinity of ‘A’ orebody as composed of a narrow band of pyroxenite, a band of gabbro grading into pyroxenite, and a band of serpenitized peridotite containing a central core of highly serpenitized dunite. The width of the sill varies from 650 ft. near the Munro ‘A’ orebody, to 1,000 ft. about 2 miles to the west (Figure 9, in pocket). The zone of commercial mineralization is roughly 1,500 ft. long and 300 ft. wide.

Here, in contrast to the Thetford Mines-Black Lake area, the chrysotile asbestos is confined almost entirely to serpenitized dunite which forms a light green, granular core in the ultrabasic portion of the sill. Magnetite is disseminated throughout the serpenitized mass.

Perhaps the most striking geological feature of the Munro-Beatty area is the complex fault pattern. The Munro mine is about 4 miles north of the Porcupine-Destor fault zone which has been traced for more than 100 miles; also it lies between two parallel major strike faults, the Munro and the contact faults which trend about N60°W. Satterly (b, 1951) suggests that the stresses between these two faults may account for the great extent of fracturing in the peridotite sill. Certainly the 1½-mile wide strip between these two faults is marked by numerous closely spaced cross-faults which strike east or west of north and offset the strike faults.
Hendry (1951), in describing the 'A' orebody of the Munro mine, remarks that cross-fibre veins from 1/32 of an inch to a maximum of one inch occur in three major sets. One set parallels the strike of the sill; another is normal to this, that is, parallel to the directions of the strike faults and cross-faults of the area. The third set is horizontal or nearly so. In addition, many narrower and shorter veins occur in regular and irregular patterns within the blocks determined by the major vein sets. Veins may be composed of one fibre vein or may contain two or more fibre veins.

Magnetite, which is present in abundance, is found in seams along the margins of every asbestos vein, as a filling in the breaks in compound veins, as seams up to half an inch wide, and in disseminated form within the limits of fibre mineralization.

Magnetite is abundant in the 'B' area also, which extends from the Johns fault at the west end of 'A' orebody for several hundreds of feet westward along the serpentine band.

In the areas of asbestos mineralization respectively one and two miles west of 'A' orebody, which were discovered later, there is a much lower magnetite content, relative to 'A' orebody, either in association with the veins or in the serpentine. (Hendry, 1951).

Magnetic Data of the Munro-Beatty Sill and Original Interpretation

In discussing the results of the magnetic survey it should be remarked that since the original geological and magnetic work was done in 1949, much detailed geological information has been accumulated from diamond drilling, underground exploration and mining. As the purpose of this paper, however, is to record the application of magnetic data to the exploration of the portion of the Munro sill west of the outcrop of 'A' orebody, then unexplored territory, it is proposed to discuss the magnetic-geological relationship as it developed at the time and apply the results of later exploration to check the accuracy and the value of the interpretation.

Magnetic results have been correlated with all published geological reports of the area.

Extent of the Sill: Preliminary magnetic work around the 'A' orebody, where good geological control was available, indicated that all rocks except the serpentine and the younger diabase were relatively non-magnetic so that, although contacts between the older diabase and gabbro fraction of the sill and the volcanic rocks could not be detected with any degree of certainty, the serpentine belt could be indicated accurately, (Figure 9). Thus the sill was traced beneath heavy overburden for about 2½ miles westward from 'A' orebody. It had been assumed previously that an outcrop of serpentine in the north part of Lot 1, concession III, Beatty township, might indicate the westerly continuation of the sill but the magnetic data clearly showed this to be part of a separate intrusion, the sill itself having been faulted southward for over 1,000 ft. in that vicinity. A dyke of diabase, which postdates the serpentine, and which does not outcrop near the sill, was clearly marked by a magnetic depression where it intersected the ultrabasic rocks east of 'A' orebody.

Faulting: Geological mapping in conjunction with the magnetic survey in the vicinity of 'A' orebody showed that irregularities in the magnetic contours of the sill almost invariably indicated the presence of cross-faults trending from north to slightly east of north. One exception was the marked indentations caused by the younger diabase dyke at the east end of the 'A' orebody; even in this case it appears that the dyke may follow a pre-existing fault as the offset of the sill contact is much greater than that which might be caused by straight, lateral thrusting during dyke injection.

Applying this observation where the sill is covered by overburden, and checking in some cases by extrapolation of faults mapped by Satterly on an outcrop area south of the sill, thirty-five faults were indicated in the 3-mile length covered by the survey.

Three of these faults showed much greater displacements than the others. The Johns fault, which bounds the 'A' orebody on the west, had an apparent horizontal displacement of about 600 ft. and movement was right-hand (west side north). The Manville fault is about 7,000 ft. to the northwest. Displacement is in the order of 300 ft. and again movement was right-hand. The largest fault, the Barton Creek fault, is 2,500 ft. farther west where a left-hand movement displaced the sill about 1,000 ft. south.

The smaller faults show offsets in the sill contact of from 25 to 200 ft., and undoubtedly there are many smaller faults which were impossible to resolve from the magnetic data. Recent detailed mine-mapping of 'A' orebody confirms this inference and shows a complex pattern of cross and oblique faults (Hendry, from paper in preparation). However, the magnetic data did indicate the loci of the more important cross-faults, particularly along the north margin of the ser-
pentite. Movement on northerly-trending cross-faults almost invariably was right-hand from the east boundary of the area up to the Manville fault where left-hand movement begins, and ends in the Barton Creek fault. West of the Barton Creek fault only two small faults were detected which resume right-hand movement. The area between the Manville fault and the Barton Creek fault therefore is thrust northward like the keystone of an arch.

Indicated faults tend to occur in groups. In Lot 10, concession II, Munro to the east of the Johns fault, five well defined faults, including that probably occupied by the diabase dyke, occur in a horizontal distance of 1,700 ft. To the west of the Johns fault, four smaller faults occur in a distance of about 1,300 ft. For 1,500 ft. to the west faults are small and are not well defined but in the west portion of Lot 11, four prominent faults occur in a distance of 1,100 ft. One of these displaces the serpentine contact more than 200 ft. Across Lot 12 only minor, widely spaced faults were indicated until the Manville fault is reached. Here there are five faults in a space of 1,000 ft.

West of this group, incidence of minor faulting apparently lessens until in the 3,700-ft. length of sill west of Barton Creek fault only two minor faults were indicated. Due to increasing depth of overburden westward along the sill to at least 120 ft. near Barton Creek fault, these groupings may be more apparent than real through the difficulty in resolving the magnetic data where overburden is deep.

Asbestos Deposits: In view of the abundant magnetite associated with the asbestos in the 'A' orebody it was hoped at the outset that magnetic results would be helpful in locating new asbestos deposits, as in the Pennington dyke. But it was soon learned that barren serpentine in the vicinity of the 'A' orebody also gave high anomalies, and further that relatively little magnetite accompanied the chrysotile veins seen in the few outcrops in the west portion of the area. It was concluded therefore, despite the outline of 'A' orebody being quite well indicated by magnetic data, that magnetic results per se should be treated with reserve.

A more promising line of attack was suggested by the structural conditions indicated by the magnetic data. As noted above, two of the main sets of veins in 'A' orebody parallel the strike faults and cross-faults of the area. The 'A' orebody itself apparently consisted of a series of fault blocks close to a major right-hand offset. It appeared reasonable therefore, that asbestos-filled fractures and faults probably were manifestations of the same or closely related deformation.

On these observations it was postulated that favourable areas for asbestos should be characterized by the presence of a major cross-fault accompanied by minor faults. Other factors might influence individual selection such as the relative directions of movement on faults, the presence of magnetic anomalies, the presence of quartz veins and mineralization in association with certain faults beyond the sill boundaries, and the width of the ultrabasic portion of the sill as indicated by the magnetic data.

Applying this working hypothesis, the following areas were selected for investigation by diamond drilling:

(a), The section of the sill westward from the Johns fault for about 1,500 ft.
(b), The faulted area in the west portion of Lot 11 east of a well defined fault.
(c), The section of the sill between the Manville and the Barton Creek faults which was considered the most favourable zone, excluding the known 'A' orebody, in the 3-mile portion of the sill covered by the survey. This zone lies between two major faults with opposite displacements at a point where a change in the regional strike suggests that it could be a focal point of deformation and fracturing favourably for asbestos vein formation. In this area the ultrabasic sill is 900 ft. wide as compared to a maximum of 600 ft. near 'A' orebody.
(d), The portion of the sill eastward from the Manville fault for about 1,500 ft. was considered to be less favourable than the three areas listed above.

The sill westward from the Barton Creek fault was considered uninteresting, being relatively undisturbed both structurally and magnetically.

Discussion: Figure 9 shows the location of the four orebodies and potential orebodies (fibre zones) located by subsequent diamond drilling with respect to magnetic data and structure interpreted from the magnetic data.

The association of orebodies and potential orebodies with major cross-faults is illustrated very clearly. The 'A' orebody and the 'B' fibre zone adjoin the Johns fault; the 'B Extension' fibre zone adjoins the large fault near the west boundary of Lot 11; and the 'Barton Creek' fibre zone adjoins the Barton Creek fault. The first postulate therefore appears to have
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some validity in this area although no important fibre zone was found near the Manville fault.

The association of fibre with groups of indicated minor faults is less clearly apparent. The 'B' zone does occur in an anomaly area associated with a group of minor faults to the west of the Johns fault. In the case of the 'B' Extension zone, however, although several ill-defined minor faults were indicated in its vicinity, the more favourable grouping according to the hypothesis lies east of the fibre zone in Lot 11 where an anomaly zone occurs in a faulted area.

Again, although the Barton Creek zone embraces three minor faults, the more favourable area would appear to lie to the east, close to the Manville fault.

In assessing these relationships however, the effect of overburden depth on resolution of minor structures from the magnetic data should be taken into account. Overburden depth on the 'Barton Creek' zone, for instance, ranges from 120 ft. at the west end to 60 ft. at the east end. It is questionable therefore if displacements in the order of 100 ft. or less could be detected, and more faults actually may be present than are shown. In the vicinity of the Manville fault, on the other hand, nearby outcrops and the magnetic data suggest shallower overburden (a few drill holes indicate about 45 ft.), therefore more definite resolution is obtained and a more favourable grouping is suggested. The same may hold for the 'B Extension' zone which is overlain by an average depth of 50 ft. of overburden.

As described in a previous section, abundant magnetite is present in the area of the 'A' orebody, both intimately associated with the asbestos veins and as separate veinlets. In consequence abnormally high anomalies occur over the 'A' orebody area and also over the adjacent 'B' fibre zone.

The 'B' Extension' and the 'Barton Creek' zones, however, are not marked by any abnormal increases in the magnetic field. In this portion of the sill, reliance upon abnormal magnetic anomalies as possible indications of asbestos occurrence would be entirely misleading as the highest anomalies occur near the Manville fault where no fibre zones of importance have been found. Some relatively small fibre concentrations were intersected in one hole through the anomaly zone west of the Manville fault and it is possible that more detailed drilling or depth drilling might show that the anomaly bears a relationship to a fibre zone.

Eight holes have been drilled west of Barton Creek fault. Only one hole, which was within 100 ft. of the fault, encountered asbestos fibre though not in commercial concentrations.

Conclusions

Experience with magnetic prospecting in the Munro-Beatty area demonstrates even more vividly than in the Thetford Mines area: firstly, that magnetic data to be useful in asbestos exploration, must be interpretable in geological terms. Secondly, it is apparent that although experience in different areas is of value in such interpretation, each area presents its own particular problems, and ideas preconceived from experience in another field may prove misleading. For example, if the magnetic data of the Munro sill had been interpreted exactly as were those of the Pennington dyke, the important Barton Creek and 'B Extension' fibre zones would have been completely overlooked.

All available geological information must be taken into account to arrive at the best interpretation of the magnetic data. This is a rule which applies to virtually all applications of magnetic prospecting and is particularly important in asbestos exploration.

Acknowledgments

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Most of the first section on the Thetford Mines area was published first in Transactions, Vol. LIV, 1951, Canadian Institute of Mining and Metallurgy.

REFERENCES


MAGNETIC PROSPECTING FOR ASBESTOS DEPOSITS

by H. K. Conn†

Abstract

A ground magnetic survey was carried out on an asbestos prospect in Garrison Township, Ontario. The data from part of the survey are shown and the basis of the interpretation is presented for comparison with the actual interpretation. A drilling program planned from the interpretation of the ground magnetic data discovered and localized an important chrysotile asbestos deposit buried under more than 20 ft. of overburden.

The geological occurrence of chrysotile asbestos deposits in ultrabasic intrusive rocks is a worldwide phenomenon. The persistent presence of magnetite within these rocks, resulting from serpentinization of olivine, produces a relatively high magnetic susceptibility contrast with adjacent formations. This factor has made magnetic surveys a basic and valuable technique for asbestos exploration.

Field Procedure

The quickest and most economic method of outlining ultrabasic belts in unmapped regions, or in overburdened areas, is an airborne magnetometer survey. This instrument locates these magnetic formations and associated geologic structures with reasonable accuracy, thereby directing attention to specific areas of possible interest. These areas are then explored in detail by ground surveys.

Survey control for ground magnetic work normally consists of a base line parallel to the strike of the ultrabasic body with cross lines at 50- to 300-ft. intervals. Stations are established along the lines by chaining at 25- to 100-ft. intervals. Spacing of lines and stations depends on the degree of magnetic detail desired; in some cases a grid system is advantageous.

Magnetic readings are taken at the stations with any standard-type magnetometer, measuring local variations in the vertical component (in Canada) of the earth’s magnetic field. All readings are tied to a local control station or stations to record diurnal variation and day to day corrections, to permit the reduction of all readings to a common base. Constant checks at control stations also give warning of magnetic storms.

The magnetic readings are plotted and contoured on a large-scale base map comprising a plan of the area surveyed. This may normally show all relevant detail which can be used to interpret magnetic results, including control lines, stations and readings, pertinent geological data, and generalized topography and culture.

Interpretation of Data

A preliminary geological interpretation of the map area is made, using all available magnetic and geological information. Under ideal conditions* the data are amenable to interpretation for the following features. The “degree of doubt” of each interpreted feature should be indicated.

(a) Location of the geological contacts between the ultrabasic body and surrounding formations;

(b) Generalized dip of the above contacts from magnetic profiles. (If the ultrabasic body is a sill, knowledge of regional and local folding is desirable to check magnetic interpretation);

(c) Location of geological contacts within the ultrabasic body. The approximate contacts separating rock types such as serpentinized peridotite, serpentinized dunite, pyroxene-rich serpentinized peridotite, pyroxenite, and acidic dykes, can be determined, in most cases, by magnetic interpretation.

The bedrock in the area is of early Precambrian age, and is composed of sediments, volcanics and intrusive rocks, ranging in composition from granite to peridotite. The sediments include quartzite, arkose, argillite and iron-formation, and occur in a narrow east-west belt across the north section of the township. Volcanic rocks, including meta-andesite, meta-basalt and minor rhyolite, bound the sediments to the north and south. A stock of hornblende granite with associated dykes and sills of quartz and feldspar porphyry, felsite, syenite and lamprophyre, intrudes the volcanics south of the sedimentary belt. A complex ultrabasic sill of serpentinized peridotite and dunite, with a narrow border zone of gabbro, intrudes the volcanics north of the sediments. A few younger diabase dykes, with a northeast trend, are present. Carbonatization is

*Ideal conditions would include flat or gently rolling topography with a uniform thickness of overburden of 25 to 50 ft., sharp magnetic contrast between adjacent rock formations, steeply dipping geological contacts, absence of remanent magnetism, etc.

†Chief Geologist, Canadian Johns-Manville Company Limited.
widespread in the sediments and is present locally in the ultrabasic sill.

The structure of this area is extremely complex. The volcanics in the northwest section appear to be part of an east-pitching anticline. The sediments are highly contorted but suggest an anticlinal structure. Faults and shears are found everywhere, the faults may be described generally as strike faults or cross-faults. The major strike faults are associated with the east section of the sedimentary belt where the regional Destor-Porcupine fault zone and the Munro fault zone are believed to converge. These fault zones are characterized by wide zones of talc-chlorite schist, green carbonate rock, and acid dykes, together with remnants of lava and sediments. Cross-faults are typified by the Garrison Creek fault, a distinct topographic feature which offsets the ultrabasic sill. Numerous smaller cross-faults have been mapped along the exposed north contact of the ultrabasic sill.

(d) Location of cross-faulting by offset of contacts and termination of local anomalies parallel to the contacts and within the intrusive. Major cross-faults frequently result in the erosion of valleys or other marked topographic features. When the bedrock is mantled with glacial overburden, such buried valleys may be diagnosed from irregular, moderate cross-cutting magnetic "lows".

(c) Location of strike faults and shear zones within the ultrabasic. These structures may cause local lenslike magnetic anomalies.

(f) Generalized delineation of zones of talc-carbonate rock or carbonatized peridotite. Such replacement zones are extremely irregular and are characterized by relatively low anomalies. Magnetite is scarce or absent in these altered zones.

(g) Location of structurally favourable zones for the formation of asbestos deposits and the significance of magnetic anomalies in these locations. Such anomalies may result from the formation of additional magnetite in a zone of late intense serpentinization, coincident with the development of asbestos veins.

Case History

Garrison Township was mapped in detail by Satterley (1) in 1947. Further generalized magnetic information on the north section of the township is available from Geophysics Paper 45 (2). The following description of the general geology was taken largely from Satterley's report. Many supplemental data on the ultrabasic rocks have been derived from work done by Canadian Johns-Manville Company (see Map No. 1).

The calculated curve is for a body 275 ft. wide of infinite depth under 50 ft. of overburden and dipping to the west at 80 degrees, using a susceptibility contrast of 0.075 c.g.s. units with the enclosing rock.

This calculated curve is in very good agreement with the observed values. The cause of this magnetic low was interpreted as a relatively nonmagnetic diabase dyke traversing the iron-formation.

Comparison of Drilling Results and Calculated Data: A short drill hole from the west side of this magnetic anomaly confirmed this interpretation and indicated that the iron-formation enclosing the diabase dyke contained about 17 per cent magnetite. The depth of overburden was about 40 ft.

Based on the 17 per cent magnetite content the susceptibility of the iron-formation would be of the order of 0.085 c.g.s. units. Since a contrast of 0.075 c.g.s. units gives a calculated curve in good agreement with the observed values it would appear that the susceptibility of the diabase is quite normal and probably less than 0.01 c.g.s. units. No laboratory determinations of the susceptibility of the diabase were made.

The drill hole was not extended to the footwall side of the dyke, but the intersection with the hangingwall side had been predicted to occur at 70 ft. and actually was obtained at a hole length of 61 ft. In the horizontal plane, the error in positioning the hangingwall of the dyke amounted to only about 6 ft.

Magnetic and Electromagnetic Surveys at Jeffries Lake

- General Features of Data

From the correlation of aeromagnetic data, photographic interpretation and some regional geologic investigations, it was deduced that zones of sulphide mineralization might be present.

Exploration of the sill by Canadian Johns-Manville Company and others followed publications of the report by Satterley, and resulted in the acquisition of several claim blocks by the former company. A detailed exploration program has been undertaken intermittently since that time.

Ground magnetic surveys and geological mapping were done, as described under Field Procedure, and
provided a basis for further exploration by drilling. Since bedrock over most of the sill is covered by 20 to 100 ft. of overburden, the importance of magnetic interpretation is apparent.

The attached Map No. 2 covers a small portion of the south section of the sill. Preliminary interpretation of magnetic data by N. W. Hendry, with supplemental interpretation by the writer, was tested in a two-stage drilling program and the discovery and delineation of an asbestos deposit resulted. The interpreted features are described herewith:

(A) & (B) The contact of the ultrabasic sill with volcanic rocks to the south was determined with reasonable accuracy from the first major inflection point of the magnetic profiles. The exact position of the contact at sub-surface bedrock is subject to interpretation error, due to station spacing and the moderate northerly dip of the sill, as indicated by Satterley, and confirmed by drilling. The dip of the south contact of the sill is not readily discernible from the magnetic profiles, in this case.

(C) Differentiation of ultrabasic rock types within the sill is not applicable to the map-area. That section of the sill within the detailed map-area is composed largely of serpentinized dunite. The acidic dykes present are too small to be interpreted from existing magnetic maps.

(D) No cross-faults with significant horizontal displacement have been defined accurately within the area of Map No. 2. A cross-fault with a northeast strike may explain (1) the westward pinching of the fibre zone and the carbonate zone; and (2) the abrupt termination, on the west, of the local magnetic “high” (6,000 gamma contour line), several hundred feet north of the carbonate zone. Detailed magnetic work in this area, now in progress, will confirm or disprove the existence of this postulated fault.

The major north-south cross-fault along Garrison Creek, as described by Satterley, is readily interpretable on the aeromagnetic map (Geophysics Paper No. 45), and ground magnetic maps. East of this fault the ultrabasic sill splits into several parallel segments (see Map No. 1).

(E) A strong strike fault is present within the serpentinite and adjoins the volcanic contact within Map No. 2. This shear zone was discovered first by drilling; subsequent re-interpretation of the profiles shows a small “shoulder” on the south slope of the major magnetic “high”, probably due to the increased magnetite content of this shear, (see magnetic profiles B-1-B-1-A-1-A).

![Magnetic Profile](attachment:image.png)

Figure 1.
Magnetic profile A-1-A.
(F) Zones of carbonatized serpentinite and talc-carbonate rock are shown on the detailed magnetic map. These are late alteration features of the serpentinite and post-date (and replace) the asbestos fibre veins. They are characterized in most cases by a relatively low magnetite content. These zones were intersected during preliminary drilling and were readily extended by magnetic interpretation, as shown, and confirmed by later drilling.

(G) The interpretation of the strong northeast-trending magnetic anomaly as a “zone of possible fiberization” was made on the basis of contact location, and “texture” of the anomaly. Drilling confirmed the interpretation by discovering a chrysotile asbestos deposit. Further study suggested that the east end of the zone raked north-east at a moderate angle; this interpretation has been partially confirmed by limited deeper drilling. A moderate magnetic anomaly in the upper left corner of the map, interpreted as interesting, was drilled and revealed a minor asbestos fibre zone.

The discovery of this asbestos deposit, a result of the magnetic interpretation described in the foregoing, has been duplicated in numerous other ultrabasic areas, both in Canada and in other parts of the world. This fact suggests that magnetic surveys can be regarded as an essential and valuable tool in asbestos exploration.

REFERENCES


"Texture" in this context is the degree of fluctuation of the magnetic readings as revealed by the general appearance of the local magnetic anomalies on a contour map.
THE DISCOVERY OF LARGE LEAD-ZINC DEPOSITS AT BUCHANS, NFD.

by Hans Lundberg†

basic lavas are from 100 to 1,000 ft. thick. Between the flows are beds of arkose, agglomerate, tuffs and other fine-grained siliceous sediments which together may reach a thickness in some places of 1,000 ft.

The old rocks have been intruded by granite, diabase and quartz porphyry of pre-Carboniferous age. Folding and shearing of tuff, agglomerate and arkose accompanied and followed these intrusions. Sulphide and barite mineralization was introduced after the intrusion of the quartz-porphyry. Subsequently the pyroclastics, porphyry and ore were cut by diabase and lamprophyre dykes.

Tuff is the principal host rock for the barite-sulphide mineralization. The agglomerate carries only minor amounts of relatively coarse-grained lead, zinc and copper sulphides. The lavas and the arkose contain few sulphides, even at contacts with quartz porphyry.

The rocks at Buchans are gently folded. The Lucky Strike orebodies are on the axis of an antcline plunging westward: the orebodies at Old Buchans and Oriental are on the north limb of the same antcline, which at Oriental plunges eastward.

Equipotential Surveys Using Line Extracts — 1926

Early in June 1926, an equipotential survey was started, a method considered antiquated today but the first geophysical method using successfully an artificially applied field of force*.

The fundamentals of the method were simple (2). The current from induction coils and storage batteries was supplied between long, parallel wires grounded at suitable intervals. In the first lay-out (designated Square One) the electrodes were placed in a north-south direction; one was laid over the mine and the other was placed approximately 3,000 ft. to the west. The equipotential lines were traced by using two movable probes or searching rods connected to a telephone receiver. In this way points having the same potential were located (where no sound was heard in

†President, Lundberg Explorations Limited, Toronto, Canada.

**Vice-President, American Smelting and Refining Company.

*In Sweden, 1916.
the telephone); these were marked out on the ground by stakes and later were mapped on a plane table with transit and stadia rod.

In Square One (Figure 2) besides indicating local deflections of the equipotential lines around the known orebody, the survey located a small conductor a few hundred feet to the west. Near the south end of the west electrode the equipotential lines were pinched together, strongly indicating a conducting zone continuing westward.

Although this suggested a westward continuation of the mineralized zone, the area east of the mine was surveyed first in an attempt to trace the zone of mineralization from the mine in that direction. Consequently, the west electrode was moved to the east, while the first electrode remained in its original position. The new area thus prepared for survey was called Square Two. The equipotential lines showed a very strong conductor in the east part of the square and detail lines enabled us to outline the conductor.

Trenching was started with the hope of reaching bedrock within a few days but over 30 feet of overburden with layers of quicksand defeated this intention. No experienced miners were available but the Newfoundland fishermen who helped us were interested, willing, very efficient and handy with any kind of tool. They managed to build cribs to hold up the walls of the trenches and in spite of this, the trenching became too difficult when greater depth was reached. Even the sinking of a small shaft had to be abandoned after reaching nearly 30 feet. Finally, an exploratory diamond drill hole encountered massive lead-zinc mineralization. This location was named Oriental.

We then transferred our attention to the westward continuation of the conducting zone found in Square One. For Square Three the electrodes were placed in a N30°W direction (approximately magnetic north and south). The conducting zone continued and very high conductivity was indicated near the west electrode. The effect of the conducting zone appeared to increase westward and outside the square. To investigate this continuation meant going beyond the limit of one square mile — no more, no less — originally assigned for the survey. However, after a conference with J. Ward Williams, the company exploration manager, it was decided to take a chance on a new lay-out, Square Four, still further west. Confidence in the method had been strengthened by another good result on the anomaly indicated west of the Buchans River Mine in Square One, where a small shaft had encountered a conglomerate-like deposit at bedrock with pebbles of massive lead-zinc mineralization.

The survey of Square Four was very difficult. Although the electrodes were laid only 1,200 ft. apart, low-current density made the sound in the telephone receiver almost inaudible, but after a few days an anomaly appeared gradually, indicating a very strong conductor in the middle of the square. This was finally outlined and mapped, despite weak signals and the curiosity of a bear and two cubs aroused by the sound of the induction coils.

Although this was the beginning of July there still were patches of snow here and there on the big bog to the west. Because of the wetness underfoot, the muggy atmosphere, and thick swarms of black flies which made it difficult to see the pickets through the telescope, work was almost unbearable. But our reward was to come soon. While finishing the survey of the anomaly a trench near the east electrode had disclosed promising lead-zinc mineralization. This location was appropriately named Black Fly.

Then we searched for a favourable place to reach bedrock on the major indication in the centre of the square. The area here was flat and even, like the bottom of a dried-out lake, and appeared easy to get through. Just below the surface bright yellow and red clay with a few boulders of lead-zinc carbonate was encountered. The bedrock, about 2 or 3 feet down, was massive lead-zinc mineralization. Throughout the night my assistants and I kept on digging, sometimes with our bare hands, convinced that our indication was going to make mining history by the discovery of this large lead-zinc deposit. During the night my assistant, Hjortzberg-Nordlund, said in his broken English: "This is sure a lucky find". Williams corrected him, "not a lucky find, but a lucky strike". The name Lucky Strike has remained with the mine ever since (Figure 3).

Extra men were put to work trenching and within a few days an ore width of about 300 ft. had been uncovered, the mineralization resembling that at the Buchans River mine. Later a shaft was started and carried through over 100 ft. of massive ore.

At Lucky Strike the orebodies are found mainly replacing the tuff beds where fractured or intruded by quartz porphyry. The main orebody, which is at the centre of the anticline, totals 5,300,000 tons of ore of which 85 per cent is high grade. Fifteen per cent of the ore is found in lower-grade bodies down the dip of the anticline. The average assay of the main
Figure 2. Map showing layout of equipotential squares, June to July 1926, including Lucky Strike, Buchans River, and Oriental orebodies.
ore bodies was: Au, .06 oz.; Ag, 3.6 ozs.; Cu, 1.2 to 6.1%; Pb, 9.9%; Zn, 20.8%; Fe, 8.0%, with a barite content of approximately 30 per cent.

These important discoveries took place during the first week of July 1926. The following week, when our assigned work had been completed, a very large quantity of ore was in sight and plans were laid for immediate development.

The building of the mill and the railway was finished in 1928, (Figure 4). Harbour facilities for large boats were built at Botwood on the north coast of Newfoundland, and the first ore was shipped from Buchans in 1928. Shipments to early 1956 of 10-000,000 tons of ore testify to the importance of these discoveries which rate as one of the largest lead-zinc-copper mines in North America.

Comparison of the 1926 Interpretation

The following maps have been prepared to demonstrate the early results and their interpretation compared with the shape and size of the ore developed over a period of 30 years:

Figures 5 and 6—the west part, Lucky Strike, Square Four;

Figures 7 and 8—the east part, Oriental, Squares Two and Nine;

Figures 9 and 10—the centre part, Buchans River mine, Squares One and Two.

The original interpretations submitted in 1926 are shown on one set of maps, and on the other set the ore that has been outlined as known from mining operations.

The interpretation of Lucky Strike (Figures 5 and 6) is fairly accurate; however, while the trend of the north side of the conductors is correct, it is quite evident now that the sharp southeast turn of the contact was missed. This does not detract from the value of the discovery or the technique, but proves how necessary it is to survey sufficient territory around the area of interest to enable the geologist to make a true and definite interpretation.

The Oriental ore picture (Figures 7 and 8) is fairly simple and shows good confirmation of the first interpretation. The orebodies replace a series of weak, incompetent tuff beds intruded by sills of quartz porphyry, situated on the north limb of the anticlinal fold. The orebodies at Oriental aggregate 2,220,000 tons with an average assay of: Au, .05 oz.; Ag, 3.7 ozs.; Cu, .9 to 5.9%; Pb, 8.6%; Zn, 15.7%; Fe, 4.1%. The barite content here is around 25 per cent.

The discovery of Oriental No. 2 orebody was announced in a paper presented at the American Institute of Mining and Metallurgical Engineers’ meeting in New York early in 1956. This orebody, which is flat-lying and about 200 ft. below surface, caused only vague disturbances on the equipotential lines in 1926. Compared with the other strong anomalies, the effect over Oriental No. 2 was not recognized. Such a flat-lying lens, of course, can be indicated now with the modern equipment and experience at our command.

The anomalies around the Buchans River mine (Figures 9 and 10) correspond very closely with the
Figure 5.
Details of equipotential survey of Square Four showing interpretation, 1926.

Figure 6.
Details of equipotential survey of Square Four showing Lucky Strike orebodies developed to 1956.
Figure 7. Details of equipotential survey, parts of Squares Two and Nine, showing interpretation, 1926.

Figure 8. Details of equipotential survey, parts of Squares Two and Nine, showing Oriental orebodies developed to 1956.
mineralization known from trenching and underground workings. The "conglomerate body" west of the Buchans River mine is a thin, flat-lying lens at bedrock and corresponds well with the equipotential anomaly.

Later Detail Studies and Other Methods 1927-1934

Detail studies of the potential drop were made in order to obtain more information on individual orebodies. Profiles of the "potential drop per unit of length (3)" are shown on Figure 11. Sharp peaks mark the boundaries of the conductor, and the lows indicate the best part of the conducting body. The depth of overburden is indicated by the sharpness of the curves.

The results from these curves obtained in 1926 were well confirmed by subsequent drilling (1929).

Later, in 1933, some tests were made aiming at deeper penetration with the so-called "ratiograph" method (4), whereby the ratio in potential drop between successively adjoining sections is observed. It is possible to eliminate surface effects to a certain extent by taking the observations in opposite directions along the same line and in that way to obtain assurance that the anomaly is caused by deep-seated effects and not by shallow features.

When the mining development at Lucky Strike had advanced to such a stage that a westward plunge appeared to be certain, geophysical exploration for the westward extension at depth was attempted by

Figure 9. Details of equipotential survey, parts of Squares One and Two, showing interpretation, 1926.
means of this ratiograph method. As waste dumps covered portions of the ground north and west of Lucky Strike orebody, the available space for such depth studies was somewhat restricted. However, some profiles were run and effects from deep-seated extensions were traced clearly. Figure 12 shows a cross-section west of Lucky Strike, and Figure 13 a longitudinal section fairly close to the central axis of the main Lucky Strike orebody and its continuation at depth. Figure 14 shows two profiles across the Oriental ore zone.

North of Lake 1, about 2,000 ft. west of Lucky Strike, a very strong east-west-trending conducting zone was found in the ratiograph survey, and was interpreted as caused by mineralization or shearing. However, drill holes encountered only patchy and slight lead-zinc mineralization, so the follow-up result remained uncertain. It must be remembered that at the time, 1933, lead and zinc prices were very low and rigid economy restricted exploratory drilling. Consequently the drill holes were stopped as soon as they ran into dark lava, which was considered the footwall of Lucky Strike. At a later date, however, a new ore body, the Rothermere, was developed well below 1,000 ft. from the surface. Figures 15 and 16 show the comparison between the old indications and the orebodies developed to 1956, including the eastern portion of the Rothermere bodies.
Figure 11. Detail studies of 'potential drop per unit of length' across sections of Lucky Strike and Oriental, 1926, in comparison with results from mine development, 1929.
Electromagnetic surveys (5) with both high and low frequencies were tried out but the fairly high conductivity of the surface water (in the rocks and swamps) prevented deep penetration (Figure 17).

An attempt to search for additional lead-zinc showings was made by analyzing the metal content in plants, trees, and the oxide-rich layers at the bottom of the lakes (6). A lead-zinc content of two to three per cent was observed in Lake I, for instance, but no pattern could be worked out that would serve as a guide for exploration. This method, however, was bound to fail as apparently the ore comes to the bedrock surface only in very few places.

To the southwest of Lucky Strike, in particular, a great number of lead-zinc-rich boulders had been found exposed or buried in the moraine deposits.

Figure 12. Reticograph observations over west end of Lucky Strike orebody, 1932.
Mining Geophysics

(Figure 13, in pocket). Some of these boulders were large, perhaps several tons in weight, and had a very high content of lead-zinc-copper (7). At the beginning we believed that several other orebodies might exist in the area but after several years of careful study of the various directions of the glacial movement, and mapping the lead-zinc-copper boulders and the trends of the moraine material containing grains of galena, pyrite and zincblende, we reached the sad conclusion that Lucky Strike and Oriental could be the source of all the boulders.

Boulders very rich in copper had been seen near the lower portion of Buchans River in the early exploration stages, but unfortunately a severe flood, caused by the breaking of the dam at Sandy Lake, covered all boulders and glacial evidence. Only a very sensitive method with deep penetration could determine definitely whether an orebody existed somewhere near the lower portion of Buchans River.

In conclusion, I wish to express my gratitude for the good fortune of being assigned this work. I am pleased to have lived long enough to see the results of 30 years of mining bear out so successfully the predictions made in 1926. The hard work and the cooperation of the mining staff deserve the great credit of having developed these large ore deposits in the wilderness into a profitable and interesting mining operation.

REFERENCES

Geology and Ore Deposits on Buchans, Newfoundland, W. H. Newhouse, Econ. Geol., 1931, No. 26, pp. 399-414.


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Figure 14. Refractograph profiles across the Orient ore zone.
Figure 15. Map showing indications from gravimetric survey, 1926, and radiograph anomalies over Lucky Strike waters extension, 1933.


Figure 17. Aerial photograph: Lucky Strike glory-hole in foreground, Rothermere shaft in background.
[George Hunter photo.]
AIRBORNE MAGNETOMETER SURVEY DISCOVERS MARMORA MAGNETITE DEPOSIT

by W. G. Wohl* and S. Lake**

Abstract

This property was surveyed by compass, dip needle, magnetometer, gravity meter and by the airborne magnetometer. After mining had started, magnetometer and dip needle surveys were done on the floor of the pit which at that time was approximately 100 ft. sub-surface.

The data from the compass survey when contoured show that certain deductions can be made which will define the causative body. This is true also of the dip needle survey results when mapped on the surface. In neither case was the source directly underneath the peak of the anomaly but was offset some 900 ft.

The magnetometer and the gravity surveys defined the ore body as to location, attitude, length, width and depth of burial.

The data from nine airborne magnetometer surveys flown at elevations of 100 ft. to 5,000 ft. are presented. It was found that the intensity varied inversely as the square of the distance. A method is presented whereby anomalies from causative bodies of the same or different depths of burial may be ranked according to their relative worth. The following formula is used to determine the intensity per unit area of a magnetic anomaly:

\[
\frac{\text{depth}^2 \times \text{anomaly intensity}}{\text{area}}
\]

Introduction

The magnetic deposit now being mined by Bethlehem Steel Company near Marmora, Ontario, was discovered with the airborne magnetometer. It is a contact replacement body in Grenville "limestone", completely covered with a capping of flat-lying Palaeozoic sediments; its occurrence was unknown prior to the airborne magnetometer survey.

Marmora, is roughly midway between Toronto and Ottawa on Highway Number 7. The deposit lies 2 miles southeast of Marmora, in Lots 4 and 5 of the 5th Concession of the township of Marmora in Hastings county, Ontario.

Above is an aerial view of the Marmora open pit and general surroundings, including the stripping dumps, the tailings area and the plant site as of October 1954. The view, looking northwest, shows a large portion of the 20,000,000 tons of stripping which were removed. The stripping distributed in the linear pattern on the right is dykes built to confine the tailings pond. The entire surface plant was completed in 1955 and mining and milling were started. The concentrates are pelletized for use in the blast furnace and are shipped to Picton where the pellets are transferred to Great Lakes ore carriers for delivery to Bethlehem's Lackawanna plant near Buffalo, N.Y.
Geological mapping by M. E. Wilson, (Geol. Surv. Canada, Map No. 560A), shows that a limestone assigned to the Black River series of Ordovician age outcrops in this area. No magnetic or Precambrian material are found in this limestone and drilling indicated the limestone to be approximately 90 to 150 ft. thick.

A ferruginous, carbonaceous shale up to 15 ft. thick underlies the Black River series. Beneath the shale a thin basal conglomerate lies unconformably above the Precambrian. The Palaeozoic rocks are arched in a gentle supratenuous fold trending N45°W.

Diamond drilling and open pit development show the magnetite body as a replacement deposit trending N45°W with a 75° dip to the southwest, in metamorphosed Grenville "limestone" northeast of a very irregular intrusive contact with a Precambrian syenite. The syenite is characterized by a coarse-grained rock consisting predominantly of plagioclase feldspars with a very low content of quartz and amphiboles.

The Grenville "limestone" outside of the zone of metamorphism is banded into beds of almost pure dolomitic limestone and beds of argillaceous dolomitic limestone. Within the zone of metamorphism the Grenville "limestone" is altered to a garnet, epidote, or zoisite scarn. Magnetite occurs as disseminated grains in the scarn or as relatively pure masses or blobs within the scarn. The zone of magnetic enrichment is up to 400 ft. wide and 2,100 ft. long, and drilling has outlined 20,000,000 tons of material assaying 37 per cent Fe to a depth of 500 ft.

The anomaly caused by the Marmora magnetite deposit is shown on the Campbellford aeromagnetic map sheet released by the Geological Survey of Canada in May, 1950. This sheet was one of four flown by Canadian Aero Service on a joint project of the Geological Survey of Canada and the Ontario Department of Mines. The survey was flown at an elevation of 500 ft. with quarter-mile spacing between north-south flight lines. Figure 2 shows the anomaly as mapped.

Visual inspection of this airborne magnetometer anomaly discloses that the anomaly is a dipole and has a peak intensity of 8,500 gammas and a low of 1,500 gammas for a total value of 7,000 gammas. The trend of this anomaly, as determined by peak intensities on adjacent flight lines, is approximately N45°W; the symmetry suggests a near-vertical dip. The lack of resolution into two or more peaks indicated that the cause was a single, continuous mass. The distances between inflection points on a profile across this anomaly give a probable width of 700 ft. and a length of 2,000 ft. The depth to the cause of the anomaly is approximately 700 ft. sub-flight level as determined by measuring the horizontal distance across the zone where the isomagnetic lines of equal intensity are closest together. This places the cause of the anomaly at a maximum of 200 ft. below ground level.

Another method of determining the depth is to note the maximum value of 8,500 gammas and the low of 1,500 gammas, and measure the horizontal distance from half the anomaly value (which is at the 5,000-gamma contour line) to the peak of the anomaly. This horizontal distance approximates the depth. In this case the depth equates to approximately 600 ft. sub-flight elevation for the cause of the anomaly, or to a sub-surface depth of 100 ft.

To evaluate more fully the significance of this airborne anomaly it should be compared to other anomalies in the immediate area whose causative bodies are at the same depth of burial. This may be done by measuring the surface area covered by the anomaly and dividing this figure into the value of the anomaly. This gives a ratio for the intensity per unit area which is an indication of the magnetic susceptibility of the mass causing the anomaly. It was found that the Marmora anomaly had approximately 10 times the intensity per unit area of any other anomaly in the region. An anomaly over an intrusive carrying approximately 5 per cent magnetite had a value of one-tenth the intensity per unit area of the Marmora anomaly.

Based on the foregoing discussion it could be assumed that the cause of the Marmora anomaly was a mass trending N45°W, with near-vertical dip, approximately 2,000 ft. long and 700 ft. wide, buried up to 200 ft.
ft. sub-surface, and carrying about 50 per cent magnetite or 35 per cent iron. This in essence is what was found.

Dip Needle Survey

After the ground was optioned, a dip needle survey was completed (Figure 3) using a Lake Superior type dip needle. The values recorded were made by reading zero when the north-seeking end of the needle in a vertical position pointed up and 180° when pointing down. The instrument was held in the plane of the local magnetic meridian, thus recording the direction of the total field. Prior to the survey the instrument was adjusted over an area known to be free of local anomalous magnetic effects. This adjustment consisted of counter-weighting the needle so that at rest position the needle was normal to the earth magnetic lines of force. That is to say, the north-seeking end of the needle came to rest at 72° or 18° above the horizontal.

The survey was carried out on taped picket lines 300 ft. apart and readings were recorded on 50-ft. stations.

Figure 3 shows the contoured results of the dip needle survey. On this figure and on subsequent figures the base line, trending N45°W, and a traverse line form lines of reference. The locations of diamond drill holes also are included.

The peak of the dip needle anomaly lies approximately 300 ft. northwest of the intersection of the two lines of reference, and is marked by an area in which the north-seeking end of the needle points vertically down. To the north of this peak a sharp negative was mapped over an area on which the north-seeking end of the needle pointed almost vertically up. The dashed line marks the axis of the positive dip needle anomaly.
The dip needle results indicated that the cause of the anomaly was a single, continuous mass. The trend of the axis of the anomaly showed that the mass trended N25°W towards the south end of the anomaly and N45°W at the northwest end of the anomaly. A vertical dip is indicated at the south end of the anomaly, and a steep dip to the southwest at the northwest end of the anomaly. A length of 2,400 ft. and a width of 100 ft. at the south end and 400 ft. at the northwest end can be inferred. A depth of 100 ft. sub-surface to the top of the cause of the anomaly may be deduced from the dip needle results.

The first diamond drill hole was put down on the crest of this dip needle anomaly. A garnet-epidote scarn with a very low tenor of magnetite was encountered underlying the Palaeozoic limestone. Additional drill holes southeast along the axis of the anomaly returned more favourable results. It should be emphasized that the dip needle used in this survey measured only the direction and not the strength of the total field.

**Horizontal Declination Survey**

Abnormally high horizontal deflections of the compass were noted during the course of the dip needle survey. The horizontal deflection of the compass was measured by taking the bearing of the picket line at each dip needle station with the expectation that usable information could be gathered (Figure 4). The results first were plotted by drawing an arrow in the direction of the local magnetic meridian. This showed a converging of the magnetic lines of force at a point 300 ft. north of the intersection of the two lines of reference. The results were then compared to the regional magnetic declination and the amount of the deflection from the regional was calculated. A positive value was assigned to those deflections which were to the west, and a negative value to those with a deflection east of the regional magnetic meridian.

**Magnetometer Survey**

It was observed that the greatest horizontal deflection occurred at the peak of the dip needle anomaly, and that the axis of the dip needle anomaly followed the line of zero deflection from the regional magnetic meridian. Lines drawn along the axes of the positive and the negative of the horizontal deflection anomaly would define the extreme outside limits of magnetic mineralization and appear to mark the line of zero curvature of the contoured dip needle results.

A magnetometer survey, using a Schmitt type instrument, was completed over part of the magnetic deposit (Figure 5). The grid system established for the dip needle survey was followed. For illustrative purposes the magnetometer data are shown superimposed on the dip needle results.

The peak vertical intensity as mapped by the magnetometer is 900 ft. southeast of the area of maximum dip needle readings, and the axes of the magnetometer anomaly and the dip needle anomaly are the same.

The magnetometer data on visual inspection indicate that the cause of the anomaly may be a single, homogeneous mass or, if banded, that the bands of magnetite are not separated by a distance equal to or greater than the depth of burial. A first derivative of these data shows that the tenor of magnetite is not constant and that zones of differing magnetite concentration do occur.

The source of the magnetic anomaly is approximately 100 ft. sub-surface. It may be zoned into magnetite-rich and magnetite-lean bands; has a vertical dip near the south end of the anomaly and a steep dip to the southwest at the northwest end; has a trend of N25°W at the south end and N45°W at the northwest end; and has a width of up to 400 ft. These results
agree in part with the interpretation of the dip needle results.

Diamond drilling confirmed the magnetometer results in that the greatest concentration of magnetite nearest the surface was found directly under the crest of the anomaly.

The results of a gravity survey are shown in Figure 6. A Worden gravimeter was used and an 8 milligal positive anomaly was mapped. This anomaly is coincident with the magnetic anomaly, as well it should be, since both anomalies are the results of measuring vertical components of natural forces derived from the same mass of material.

Interpretative techniques employed in the study of the magnetometer data may be used on the gravity data, and the size and attitude of the causative body are found to be the same. The gravity data indicate that there is a great excess of mass underlying this area and that there is an uneven distribution of the mass within the ore body. Diamond drilling confirmed the irregular distribution of magnetite suggested by the gravity survey.

Figure 7 shows the results of a reconnaissance gravity survey. The only purpose this survey served was to indicate the location of an area of excess mass over which more detail work should be undertaken, and the results when contoured showed a similarity in form to that obtained by the airborne magnetometer flown at 2,000 ft. This illustration is included to show the reconnaissance nature of airborne surveys and to emphasize the need for more detail work when a significant anomaly is found.

After most of the Palaeozoic capping had been removed, and when the floor of the pit reached a depth of approximately 100 ft., dip needle and magnetometer surveys were done over the accessible parts of the pit.
The results of this survey should be compared with the results of the dip needle survey carried out on the surface, (Figure 3). It will be noticed that the peak values as shown on Figure 8 are less, caused in part by the instrumental differences between the two dip needles used, and in part by the fact that these instruments measured only the direction and not the intensities of the total field. It should be pointed out also that the area of maximum readings on Figure 8 is approximately 600 ft. southeast of the area of maximum readings recorded at the surface.

![Diagram](MARMORA.png)

Figure 9.

The results of the magnetometer survey on the floor of the pit are shown in Figure 9. It will be seen that the magnetite is present in at least four zones and that within these zones large differences in the tenor of magnetite exist. The stations and traverses are not close enough together to place the distribution of the magnetite in this deposit but the results do show the outside limits and the variable character of the mineralization. Comparison of these data with those in Figure 5 will show the degree of resolution of the magnetic anomaly. Different instruments were employed and it was not possible to occupy the same base station as used on the previous survey, so the base level difference between these two surveys is not known. The base level of the second survey is estimated to be approximately 1,000 gammas greater.

A compilation of the geology and the magnetites across the mineralized zone along the vertical line of reference is prepared in section in Figure 10. The profiles of the dip needle and magnetometer results, for both the previous ground level and along the floor of the pit, are given in the upper part of the figure. The geology as interpreted from diamond drilling is outlined in the lower part. It will be observed that the magnetometer indicates the zone of mineralization in greater detail, and that, in general, the inflection points on the curves mark the edges of the magnetite concentration.

Figures 11 through 18 present the contoured results of airborne magnetometer data recorded over the Marmora anomaly at different flight elevations. It will be observed that major changes in the anomaly appear as its source is approached. First, there is an increase in the intensity at a rate which approximates the inverse of the square of the distance. Second, the area of the anomaly decreases directly as the distance. Third, the negative to the north of the anomaly becomes more pronounced. The negative anomaly is not apparent at a great distance because of the dispersion of the strong positive anomaly which completely masks the weaker anomaly.

The peak of the anomaly seems to be at a different location in each figure. This is caused by the inability of the aircraft to retrace the same flight pattern at the different elevations. Indeed, it is impossible to map the same anomaly exactly even when an attempt is made to fly at the same elevation; comparison of the results shown in Figures 2 and 14 emphasizes this point; both illustrations are compiled from data recorded at 500 ft. terrain clearance. As the flight pattern was not duplicated the intensity of the anomalies differs by 300 gammas, and the peaks of the anomalies are separated by approximately 500 ft.

As pointed out previously, a method to determine the relative significance of an anomaly can be made by comparing the intensity per unit area with that of other anomalies whose source is at the same depth. This series of airborne magnetometer maps show that it is possible to adjust the intensity per unit area for sources at different depths. In general, the intensity varies inversely as the square of the distance between the recording instruments and the cause of the anomaly. For purposes of illustration reference is made to Figures 2, 11 and 14.

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<th>Distance Squared × Intensity Area</th>
<th>Area</th>
<th>Result</th>
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<tr>
<td>Figure 2 . . . . (500)² × 6700</td>
<td>16,000,000 sq. ft.</td>
<td>104</td>
</tr>
<tr>
<td>Figure 11 . . . (5000)² × 140</td>
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<td>70</td>
</tr>
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<td>Figure 14 . . . (500)² × 4100</td>
<td>14,500,000 sq. ft.</td>
<td>70</td>
</tr>
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</table>

The discrepancy in the above results is caused by the inability of the aeroplane to duplicate the flight paths. However, the results are sufficient to show that the method has merit.
MARMORA
GROUND AND -100' LEVEL

DIP NEEDLE

MAGNETOMETER

Figure 10.

5000'

140°

2000'

900°

Figure 11.

Figure 12.
THE NEGATIVE MAGNETIC ANOMALIES OF RIVIÈRE PORTNEUF AND LAC PAULINE, CHICOUTIMI COUNTY, QUEBEC

by Louis Moys*  

Abstract

Airborne magnetometer, ground magnetometer and dip needle surveys were used in conjunction with geological mapping in exploration for titanium in anorthositic areas in eastern Quebec. Several negative anomalies, — diagnostic of titanium mineralization — were mapped and drilled. The surveys showed that localized disseminations of hematite-ilmenite caused the negative anomalies and titaniferous magnetite the positive anomalies.

Petrographic studies and measurements of the magnetic properties of core specimens were made to explain the negative anomalies and their association with ilmenite mineralization.

Two of these causes are discussed.

In the early 1950's, airborne and surface magnetic surveys were made of many anorthosite masses in Quebec and in Labrador in the search for titanium deposits. These surveys were based primarily on the fact that the large deposits of hematite-ilmenite which occur in anorthosite near Allard Lake, Saguenay County, Quebec, were found to be represented by negative anomalies of high intensity (1).

Several anorthositic areas in eastern Quebec were investigated for Crane Company by the author and in the course of these surveys, numerous occurrences of hematite-ilmenite and of titaniferous magnetite were found. In general, it was learned that positive anomalies

*Consulting Geologist, Yonkers, New York.
represent occurrences of titaniferous magnetite and negative anomalies (pole inversions) represent occurrences of hematite ilmenite, but there are exceptions. It was learned also, particularly in the case of hematitic ilmenite occurrences, that the intensity of the anomaly is not necessarily proportional to the content of the ore minerals. In the Rivière Portneuf and Lac Pauline areas, negative anomalies of about the same intensity as those of the Allard Lake deposits were found to be caused by ore disseminations of very low grade. The information gained from the investigation of these anomalies is presented here as an aid in the study and evaluation of negative anomalies.

Location

Both occurrences are in Chicoutimi County, Quebec, the one at Lac Pauline about 40 miles northeast of the town of Chicoutimi on Saguenay River, and the other near Rivière Portneuf, about 10 miles farther to the northeast (Figure 1). Their geographic coordinates are:

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lac Pauline</td>
<td>48° 46'</td>
<td>70° 21'</td>
</tr>
<tr>
<td>Rivière Portneuf</td>
<td>48° 52'</td>
<td>70° 13'</td>
</tr>
</tbody>
</table>

Program

The areas that were surveyed by airborne magnetometer were selected primarily on the basis of relative accessibility. Limits were based on the indicated extent of anorthosite occurrences as shown on published geological maps. In general, flight lines were spaced at half-mile intervals and flown with a flux-gate magnetometer at about 500 ft. above the ground. Isogam maps were prepared on a scale of one inch to one-half mile, with a contour interval of 100 gammas. The aeromagnetic patterns of the Rivière Portneuf and Lac Pauline negative anomalies are shown on Figures 2 and 3 respectively.

On the Rivière Portneuf anomaly, the 1952 ground program included the establishment of a grid of lines cut on a one-quarter-mile square pattern, geological reconnaissance, dip needle traverses, and the compilation of a magnetometric plan at a scale of one inch to 500 ft., contoured at 20° intervals. A copy of this plan is shown in Figure 4 (in pocket). The 1953 program included magnetometer traverses, topographic mapping, and diamond drilling in the zone of highest negative intensity. The magnetometric plan is shown in Figure 5 (in pocket). The drill cores were given petrographic, magnetic and chemical analyses.

To obtain information in the field which would aid in the exploration of the anomaly area, the magnetic properties of a series of drill core specimens were tested by rotating the specimens in an aluminum jig mounted under the north-seeking pole of an Askania magnetometer. The core specimens, which were 3/8 inch in diameter and ranged from 2 to 8 inches in length, were rotated around their long axes. In initial tests, both ends of several of the specimens were checked in order to determine the orientation of the polarity. The results of this investigation, correlated with structural and assay information, are shown on the section in Figure 6 (in pocket).

On the Lac Pauline anomaly, the ground program conducted in 1954 included reconnaissance lines, the establishment of a grid with cross lines at 500-ft. or closer intervals, magnetometer traversing, geological mapping, preparation of a geologic and magnetometric plan at a scale of one inch to 2,000 ft., and trenching and sampling across the zone of highest negative magnetic intensity. The geologic and magnetometric plan is shown in Figure 7 (in pocket). The samples were given petrographic, magnetic, and chemical analyses.

Geology and Mineralogy

• Anorthosite Masses

Very early in the program it became apparent that the anorthosite areas of the Lake St. John region are far more complex than is indicated on the available geological maps. In general, the anorthosite is represented by weak magnetic fields showing very little "relief". Individual masses of anorthosite are more or less rectangular in plan, up to tens of miles long and up to about 10 miles wide, with long axes generally trending northeastward. The anorthosite masses are parallel to sub-parallel, with intervening zones consisting of several types of gneiss, marble, and massive to strongly foliated igneous rocks ranging from granites to gabbros. Locally, the anorthosite grades into norite. The field work connected with the investigation of the anomalies was, of necessity, too limited to determine the relations between these various rock types. However, it was found that the Rivière Portneuf and Lac Pauline occurrences, as well as many others, are not within anorthosite bodies.

• Rivière Portneuf Anomaly

The general terrain in this area consists of dark gneisses showing various stages of injection and alteration by granite. Magnetite is disseminated through the gneisses and gives rise to positive magnetic anomalies. Local zones enriched in magnetite are represented by strong dipole anomalies. The negative anomaly zone is underlain by a steeply dipping, tabular mass of hyper-
stheni-augite diorite. The mineralogy of the mass is fairly constant, but there is a wide range in mineral proportion and textures. The mineralogical composition shows the following range:

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesine</td>
<td>50 - 84%</td>
</tr>
<tr>
<td>Augite</td>
<td>3 - 15</td>
</tr>
<tr>
<td>Hypersthene</td>
<td>2 - 25</td>
</tr>
<tr>
<td>Biotite</td>
<td>2 - 14</td>
</tr>
<tr>
<td>Hematitic Ilmenite</td>
<td>3 - 17</td>
</tr>
<tr>
<td>Apatite, spinel, serpentine, sphene, magnetite, pyrite, and chalcopyrite</td>
<td>Minor</td>
</tr>
</tbody>
</table>

The diorite is medium- to coarse-grained and generally granitoid. Porphyritic zones are common, with rounded Carlsbad twins of andesine up to several inches long. Evidences of dynamic metamorphism are widespread and include undulatory extinction and granulation of the feldspars, and mortar and suture textures. Dykes of similar composition cut the main mass and show chilled borders.

Within the diorite mass, several thick layers are enriched in disseminated hematitic ilmenite, and these layers cause the strong negative anomalies (to minus 9,000 gammas on the ground, through about 50 ft. of overburden). The individual grains of the ore mineral are closely intergrown ilmenite and hematite, showing a typical exsolution texture, with about twice as much ilmenite as hematite. The ore grains, which are anhedral, occur in patchy enrichments locally connected by ore stringers, and appear to be later than the gangue minerals.

As shown on the section in Figure 6, the titania and iron contents throughout the mineralized zones are relatively constant, ranging from 5.03 per cent to 7.54 per cent TiO₂ and 14.44 per cent to 16.40 per cent total iron. A layer about 130 ft. thick averages 6.13 per cent TiO₂ and 15.00 per cent total iron. A typical specimen of the highest grade material showed a magnetic susceptibility of 854 x 10⁻⁶ c.g.s. units and a density of 3.28 gms/cc. The south-seeking pole was found to be at the bottom of the oriented core specimens, indicating a true negative anomaly or pole inversion.

- Lac Pauline Anomaly

The general terrain of the Lac Pauline area consists of coarse-grained, strongly foliated, porphyritic granite. The negative anomaly zone is underlain by an elongated mass of less strongly foliated hypersthene diorite. Anhedral grains of hematitic ilmenite are disseminated through the diorite. Localized irregular enrichments of the ore minerals cause the strongest negative magnetic intensities. The ore grains consist of closely intergrown ilmenite and hematite as sub-parallel exsolution lamellae. Within the large lamellae of each of these minerals occur tiny lamellae of the other mineral, indicating more than one stage of exsolution. The ore grains are anhedral and enclose grains of the gangue minerals. In the zone of highest intensity (minus 11,600 gammas on the ground), the rock through a 10-foot width has the following mineralogical composition:

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesine</td>
<td>55.5%</td>
</tr>
<tr>
<td>Albite</td>
<td>11.0</td>
</tr>
<tr>
<td>Hypersthene</td>
<td>9.0</td>
</tr>
<tr>
<td>Biotite</td>
<td>4.0</td>
</tr>
<tr>
<td>Apatite</td>
<td>8.5</td>
</tr>
<tr>
<td>Hematitic Ilmenite</td>
<td>11.5</td>
</tr>
<tr>
<td>Chlorite</td>
<td>0.5</td>
</tr>
</tbody>
</table>

This rock assayed 4.69 per cent TiO₂ and 13.17 per cent total iron. A typical specimen showed a magnetic susceptibility of 720 x 10⁻⁶ c.g.s. units and a density of 3.15 gms/cc.

Zones of Zero Magnetic Intensity

In the Rivière Portneuf area, check traverses with the magnetometer showed that dip needle traverses were adequate to delineate the zones of maximum intensity. However, a peculiar phenomenon was encountered. Along each cross line, as the zone between high positive and high negative intensity was entered, the dip needle did not respond, the magnetized needle going round and round and eventually stopping at any place along the circle. In general, the effect was similar to that shown when a compass or a dip needle, in horizontal position, is held directly over a strong, vertically polarized zone. In this zone, the needle shows no preferred orientation in the horizontal plane. By analogy, therefore, it might be considered that a similar situation may exist in the vertical plane, with a truly zero magnetic field obtaining. This would differ from the usual "zero-reading" field in that the latter, either directly or through the aid of the adjustable counterweight, has the effect of pulling the needle into the horizontal plane. In the latter case, readings are readily duplicated, whereas in the former the needle rarely comes to rest in the same position. Although satisfactory readings could not be obtained in such zones, the uncertain action of the needle was, in itself, an indication of the zone of zero intensity.
Discussion of Results

The field and the laboratory results indicate that the negative anomalies are true pole inversions representing localized disseminations of hematite ilmenite. The mineralized zones are far too low in grade to be of economic importance although the associated anomalies are of the same order of magnitude as those of the Allard Lake orebodies which assay about 35 per cent TiO₂ and 40 per cent Fe and are now being mined. On the basis of presently available information, it might be inferred that the intensity of the negative anomalies is more closely related to the kinds of magnetic minerals present and the way in which they are intergrown, rather than to the total amount of titania and iron present.

The dip needle surveys encountered a vertical-plane equivalent of the commonly observed lack of needle response that obtains in the horizontal plane immediately above strong magnetic poles.

Acknowledgments

Permission of Crane Company for publication of this material is gratefully acknowledged. During the course of the field programs, geophysical advice and interpretations were obtained from Dr. W. B. Agocs, Chief Geophysicist, Aero Service Corporation. Maurice Lauzon, now geologist for Coulée Lead and Zinc Mines Ltd. and Headway Red Lake Gold Mines Ltd., gave notable assistance in the field. Petrographic analyses were made by Dr. C. C. Woo and O. G. Alessio of Crane Company Chemical, and analyses were made by the staff of the Quebec Department of Mines.

REFERENCES


DISCOVERY OF COPPER-NICKEL OREBODIES AT THE TEMAGAMI MINE, ONTARIO

W. R. Bergey*, A. R. Clark†, J. C. Frantz‡, N. B. Keevil§, F. Gordon Smith¶

Abstract

Geological study, aeromagnetic surveys and detailed ground geophysical surveys by magnetic, electromagnetic, resistivity, and self-potential methods were used in the Lake Temagami area in the discovery of the large copper-nickel orebodies at the Temagami mine.

Selection of the particular area for prospecting was based on the hypothesis that the relatively narrow belt north and west of the Huron-Mistassini line was much more favourable for base-metal occurrence than the region as a whole.

Aeromagnetic surveys outlined major formational features. Self-potential surveys were useful on land portions, indicating the intensity of sulphide mineralization and pointing the sub-outcrop. The resistivity survey indicated deposits as a whole, and the combined use of self-potential and resistivity gave information regarding dip and plunge of deposits. The electromagnetic surveys outlined the margins of the massive portions of the deposits and were used mainly to check self-potential and resistivity anomalies.

The Temagami mine was found by combining, along with conventional prospecting and development, three processes for selection of areas of economic interest. These were: 1) setting up hypotheses of regional geology near so-called Huron-Mistassini geological boundary; 2) surveying by aerial magnetic and electromagnetic methods a belt on the northwest side of the Huron-Mistassini line; and 3) surveying by detailed surface methods, including magnetic, electromagnetic, resistivity, and self-potential, selected parts of the belt. Each in turn allowed much discrimination between areas of no apparent interest and areas of possible interest, and led to the discovery of copper and copper-nickel orebodies now being developed and mined by Temagami Mining Co. Limited.

Regional Geological Rationale

The regional structural geology of the area from Lake Huron northeast to the Quebec boundary (Figure 1) until recently has been somewhat puzzling, but
many age determinations have eliminated most of the controversies. The remaining possible hypotheses were synthesized in a self-consistent theory of structure of this part of the North American continent by J. Tuzo Wilson, Professor of Geophysics, University of Toronto. While agreement with all of the details of the theory is not complete, there seems little doubt that its broader aspects are correct. The principal points which have a bearing here are concerned with a line which runs from the north shore of Lake Huron eastward and then northeastward to Lake Mistassini; the highly metamorphosed rocks to the south and east of this line are younger by over a billion years than the highly metamorphosed rocks to the north and west. In other words, this line can be taken to be the boundary between two orogenic provinces, Grenville and Superior respectively.

When the important base-metal occurrences of this part of the provinces of Ontario and Quebec are plotted on a map, it becomes evident that a relatively narrow belt north and west of the Huron-Mistassini line is much more favourable than the region as a whole. This favourable belt could be called a copper-nickle-cobalt-platinum metallogenic province. Accordingly, the area selected as of most interest was parallel to that line, extending across the line but mostly on the northwest side, the total width being 20 miles.

The geology of the selected belt is too complex to discuss here, but in general, on the northwest side of the Huron-Mistassini line, the rocks are mostly flatly dipping Huronian clastic sediments with one or more large diabase sills, lying on a basement of Archaean age. The basement, which appears as windows at Emerald Lake and Lake Temagami, is metamorphosed, Keewatin-type basic and acidic lavas and pyroclastics and banded magnetite-hematite-quartz iron-formation, Timiskaming-type clastic sediments and basic and acidic intrusive rocks of several kinds. The trend lines in the basement rocks are substantially parallel to the Huron-Mistassini line in this belt. The rocks on the southeast side of the line are various types of high grade gneisses, many of sedimentary origin. An irregular and light mantle of recessional glacial deposits covers the entire area.

**Regional Aeromagnetic Survey**

The area shown in Figures 1 and 2 was surveyed by Mining Geophysics Corporation. Aircraft altitude was 500 ft. The geological contacts, faults, etc., were interpolated and extrapolated, using the magnetic data, and the generalized magnetic contour map is shown in Figure 2.

The principal features of the magnetic map of the region are, first, the broad, large anomaly which has a centre or centres a short distance from the northwest corner of Emerald Lake; and, second, the narrow, linear anomalies present from Emerald Lake to Lake Temagami.

Ground magnetometer surveys, geological mapping and diamond drilling in the vicinity of the large anomaly northwest of Emerald Lake, failed to indicate the reason for the presence of the anomaly. Nipissing diabase and clastic sediments of presumed Cobalt age were the only rock types encountered on surface or in diamond drilling.

The area around Emerald Lake and east to Lake Temagami was prospected. Ground magnetometer, gravimeter, self-potential, resistivity, electromagnetic and geological surveys were made by Mining Geophysics Corporation Limited in selected portions of the area, and a limited amount of exploratory diamond drilling was done. Sulphide mineralization was found in several localities, but no mineral deposits of economic importance were indicated.

The occurrence of pyrite with copper-nickel minerals on Temagami Island has been known since 1897, when it was mentioned first in government reports. These showings occur along the strike of one of the linear aeromagnetic anomalies. A preliminary program of ground geophysical surveys, geological mapping and diamond drilling of anomaly zones indicated that:

1. The linear aeromagnetic anomaly was caused by a gabbroic intrusive rock containing variable amounts of magnetite;

2. Pyrite with copper-nickel mineralization occurs along the south (footwall) side of the gabbro and is the cause of the linear electrical anomalies. Local magnetite with the sulphides is a small contributing factor to the magnetic anomaly;

3. Local electrical anomalies, in the volcanic rocks south of the gabbro are the expression of chalcopyrite mineralization with very little other sulphide mineralization.

The Temagami Mining Co. Limited was formed to take over the holdings of several other companies in 1954 and an extensive program of detailed electrical geophysical surveying and diamond drilling followed under the direction of Mining Geophysics Limited.
Figure 1. Location map and general geology.

Figure 2. Generalized aeromagnetic map, Temagami Lake area, Ontario. Note: isogram values in gammas.
This work indicated approximately 2,250,000 tons of ore assaying 1.6 per cent combined copper and nickel and over 50,000 tons of nearly massive chalcopyrite assaying over 20 per cent copper. Mining has since started and shipments of high-grade ore are being made.

Electrical resistivity and vertical-loop electromagnetic surveys were done on the water-covered sections of the property, and resistivity, electromagnetic and self-potential surveys on the land portions. The electromagnetic method was used mostly for additional information in the anomaly areas outlined by the other surveys.

Figures 3 and 4 show the results of the resistivity and the self-potential surveys over the main orebodies (Figure 5) of Temagami Mining Co. Limited. With the exception of part of the K-D zone ("3" in Figures 3 and 4), bedrock in the vicinity of all the orebodies...
shown on these figures was hidden by overburden or by the waters of Lake Temagami. It was found that negative self-potentials of over 500 millivolts were obtained over the massive pyritic ore, and approximately 300 to 350 millivolts over the massive chalcopyrite ore.

Figures 6 and 7 show the results of detailed resistivity and self-potential surveys over the massive chalcopyrite bodies on Temagami Island (No. 1 and No. 2 deposits), together with detailed surface geology revealed after stripping of the overburden. Figure 8 shows a typical cross-section of the No. 1 deposit, together with geophysical profiles across the deposit.

Figure 9 compares self-potential and resistivity profiles over the pyritic ore of the Keevil zone. It will be noted that the centre of the self-potential anomaly is over the sub-outcrop of the orebody whereas the centre of the resistivity anomaly is down dip from the sub-outcrop.

Typical geophysical profiles over pyritic and chalcopyrite deposits under the lake are shown in Figures 10 and 11.

Remarks

The self-potential method was found particularly useful on the land portions of the property, giving an indication of the intensity of sulphide mineralization and pin-pointing the sub-outcrop of the sulphides. The method outlined the margins of the massive portions of the deposits, but did not differentiate between the shallow and the deep parts of the massive orebodies. It may be significant in this regard to note that the tops of the deposits are only a few feet above the water-table.

The resistivity survey indicated the presence of the deposits as a whole, but gave a rather weak indication over the largest cross-section of massive ore (east part of No. 1 orebody). At this location, however, the orebody is cut by several dykes that are poor conductors. In the case of the No. 2 orebody the more distinct anomalies may be due to the fact that the massive ore occurs in a continuous zone of conductivity (mineralized breccia) extending downward and to the east for a good distance, uninterrupted by dyking.

Combined self-potential and resistivity surveys were used to interpret dip and plunge of the sulphide deposits.

Small sulphide deposits under the lake were difficult to detect by very closely spaced readings in resistivity surveys.

The electromagnetic survey outlined the margins of the massive portion of the deposits, the response being greatest over the largest cross-sections of massive ore.
Figure 10. Resistivity profile, Phillips Bay zone.

Figure 11. Geoelectrical profiles over No. 3 high-grade orebody.
MAGNETOMETER SURVEYS IN THE AREA OF THE BOURLAMAQUE BATHOLITH AND ITS SATELLITES

by T. Koufomznne and Leo Brossard*

Abstract

Ground magnetometer surveys have played an outstanding role in the development of the Val d’Or mining camp. The data observed on many of the individual surveys were used in preparing a large map of the Bourlamaque batholith and its satellites, the information so gained combined with the knowledge of the surface geology and the geological information provided by the diamond drilling permitting the contacts of the batholith to be outlined.

Several rules are presented for guiding the interpretation of ground magnetic data in this area.

The Geological Survey of Canada covered the Val d’Or district with their aeromagnetometer. Some of the data observed are presented and compared with the ground magnetic data. The complementary roles of the two methods are clearly established.

Introduction

THE Bourlamaque batholith forms the core of the Val d’Or mining district which is 330 miles northwest of Montreal. At present, there are three producing gold mines and three producing base metal mines in the area, all of which are associated with the Bourlamaque batholith and its satellites. The combined output in 1956 was valued at $20,408,000, with the base metal mines accounting for $11,695,000.

Gold was first found in the district in 1911, and production began in 1929 at the Siscoe mine. The presence of copper had been noted since 1928, but recovery of base metals started only in 1942. The total value of metals recovered during the last 28 years amounts to almost $312,000,000, of which slightly more than two-thirds is represented by gold.

Geophysical prospecting has played an outstanding role in the development of the Val d’Or mining camp. The East Sullivan orebody, now the largest mine of the district, was discovered by a magnetometer survey in an area totally devoid of rock outcrops, and electrical surveys were helpful in the early stages of development of the Rainville copper orebody. These are the direct geophysical discoveries of orebodies presently in production. However, even more important to the development of the area has been the contribution by geophysicists to the understanding of the geological structure which is masked almost entirely by glacial overburden.

Most of the ore deposits of the area are intimately related to the intrusive masses of the Bourlamaque granodiorite batholith and its many satellites. Ground magnetometer surveys led not only to a complete re-shaping of the contours of the Bourlamaque batholith itself, but also to the discovery of three previously unknown satellites, two of which were found subsequently to contain gold deposits; the third was the Centre Post, the outlining of which resulted in finding the East Sullivan deposit. Figure 2 shows the Val d’Or mining area, and the location of the producing mines and prospect shafts; it also gives some figures on the output of the mines.

The area covered by Figure 2 contains over 150 individual mining properties, most of which have now been surveyed geophysically; our organization alone has surveyed 58. In 1948 the Geological Survey of Canada published compilation maps of the results of ground magnetic surveys in the townships of Louvicourt, Bourlamaque, Dubuisson and Vassan and in 1952 issued the aeromagnetic map of Val d’Or. These publications provide the main source material for this article, the principal object of which is to state what can be gained by the application of ground and airborne magnetometer techniques to geological and mining exploration problems of the type encountered in this area.

General Geology

With the exception of glacial overburden, all the rocks of the district are of Precambrian age. The earliest rocks are lavas, volcanic tuffs and agglomerates of Kee watin or early Temiskamian age. The south part of the map-area is underlain by a thick belt of sediments also of early Precambrian age. Both the volcanic rocks and the sediments have been tightly folded and at the present time are vertically upturned.

The volcanic rocks and the sediments are invaded by a variety of intrusive rocks, ranging from peridotite to syenite and granite. The largest intrusive masses

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*Koufomznne and Brossard Ltd., Val d’Or, Que., Montreal, Que., Toronto, Ont.
are formed by granodiorite and associated rocks. Ore deposition is controlled by faults, intrusive rocks and dragfolds. All the known gold deposits are of the quartz vein and stringer zone types, and most of them are within and along the edges of the large or small intrusive masses. The three presently worked base metal deposits are in zones of disseminated mineralization, two of which, the Golden Manitou and the Rainville, are in shears; the East Sullivan deposit seems to be controlled mainly by the large Centre Post intrusive mass.

At the present time, the most complete geological maps of the district are published by the Quebec Department of Mines in the form of ozalid prints called
Figure 2. Showing principal mines, granodiorite type Intrusions and main known fractures of the Val d'Or area.
Figure 3. Three successive government geological maps showing gradual working out of geological picture largely through ground magnetometer work and drilling.
Mining Geophysics

"geological compilation" maps; each sheet, on a scale of 1,000 ft. to the inch, covers 25 square miles representing one quarter of a township. These maps show not only the surface geology mapped from outcrops, but also all the diamond drill holes ever bored in the area of the map. We estimate that around 10,000 exploration holes have been put down in the 280-square-mile area covered by Figure 2.

The contribution of this drilling to the understanding of the geological structure has been immense because of the extreme scarcity of rock outcrops. It must be borne in mind, however, that in most cases the exploratory diamond drilling has been done to follow up, confirm or disprove indications furnished by the geophysical, mainly ground magnetometer, surveys. Thus it can be said that geophysical prospecting and diamond drilling were about equally responsible for performing the task, still unfinished, of working out the geological structure of the area.

The geological knowledge of the district was not always as complete as it is today. Figure 3 reproduces the main features of three government geological maps printed respectively in 1929, 1930 and 1943; the first two were issued before any geophysics had been done in the district. The rapidly changing shape of the Boulamaque batholith, as shown on these maps, is not a geological phenomenon, but rather is a change of interpretation by different geologists, based on extremely few rock outcrops. The last of the three maps on this figure was issued in 1943; it was drawn after many ground magnetometer surveys were done and is almost up-to-date.

Ground Magnetic Surveys

About three-quarters of the length of the outside boundary of the Boulamaque batholith, as shown on the lower map of Figure 3, has been traced by ground magnetometer work. The Centre Post and the Snow Shoe intrusive plugs were found and outlined by magnetometer surveys. The location of the Cadillac Break zone and many basic intrusive dykes, some of which are ore-bearing, were also found and outlined by ground magnetometer.

The outlining of geological structures in general, and the tracing of granodiorite contacts with the magnetometer in particular, is not easy. In most cases the granodiorite is less magnetic than the surrounding volcanic rocks, (Figure 4), though this is not a general rule; on the contrary, sometimes the granodiorite is strongly magnetic. The basic intrusive rocks usually are magnetic, but on the other hand many bands of volcanic rocks are also magnetic, which may lead to confusion. In many cases greywacke sediments have the same strength of magnetization as granites. Actually, the sorting out of the magnetic variations and the final geological interpretation becomes a laborious study, a synthesis of many facts, and the selection of the geological hypothesis that could best fit the magnetic pattern obtained on the ground.

To enumerate all the rules of interpretation would hardly be possible in an article such as this. We may note, however, some of the guides to the interpretation:

1. Intrusive batholiths and plugs, whenever they contain magnetic variations, have them either as irregularly shaped, more or less rounded areas, or as criss-crossing patterns reflecting the fracturing of the mass. On the other hand, the upturned volcanic rocks always present a magnetic pattern having a banded appearance.

2. Intrusive batholiths and plugs present two types of contacts with the volcanic rocks. Occasionally the volcanic rocks are digested, especially when the intrusive contact strikes at right angles to the formations, notably at the east end of the Boulamaque batholith. Here the contact is fringed, with the intrusive and the volcanic rocks forming embayments into each other. More often, and this is true especially of smaller intrusive masses, the intrusions displace the volcanic beds, pushing them away, and giving a characteristic "flowing around" pattern of the irregularly magnetic banded volcanics around the intrusive plug.

3. When the average strength of magnetization of the acid or the intermediate intrusives is identical with the surrounding sediments, the only clue to the presence of an intrusive mass is a different magnetic profile: over the granitic masses the magnetic profiles usually are smooth, but over sediments small variations reflect the banded character of the rock, (Figure 5).

It is well to mention here that although magnetic contours seem to be the favourite presentation of the results of a survey, a series of magnetic profiles drawn on a map affords a much better means of interpretation, as it permits a better correlation of beds from one profile to the other even when the magnetic variations are small. As soon as one notices the impossibility of correlating individual profiles to form a pattern of parallel beds, the presence of an intrusive mass must be suspected. It is our opinion that, for a complete interpretation, both contours and profiles should be drawn on a map; however, most of the effort should be directed to the study of profiles.
(4). To distinguish sill-like basic intrusive dykes from beds of magnetic volcanic tuffs or lava flows, we recommend a careful study of the shape of the magnetic profiles. The profiles over intrusive dykes and sills are more likely to conform to theoretical profiles and therefore are more regular than the profiles usually obtained over volcanic rocks.

The contributions of the ground magnetometer surveys to the outlining, in the Val d'Or area, of the geological structure under the overburden, are far too numerous to be listed here, but we should mention that the extension of the Cadillac shear zone from Malartic into the south part of the map-area was first suggested by magnetometer work. Other important faults and shears, such as the "K" zone and the Blouin Lake fault, have been extended and traced under the overburden by ground magnetometer surveys. That the Boulamaque batholith is formed by two adjacent masses also was established by the ground magnetometer. Finally, the basic dykes which contain the Louvicourt Goldfield, Lapaska, and Vicour gold deposits have been outlined magnetically.

However, the most important contributions were the identification of the Centre Post intrusive plug and the discovery of the Snow Shoe and Crangold plugs. In the first instance, the few rock outcrops were so far apart and so small that the presence of a well-defined rounded mass was not suspected by the geologists who mapped the area. The Snow Shoe and the Crangold plugs did not have a single outcrop. Two additional plugs have since been indicated by ground magnetometer work in the Val d'Or area, but they are not shown on Figure 2 because one lacks confirmation by diamond drilling and the other is still confidential information.

The three magnetometer-discovered plugs mentioned are economically important. Both the Snow Shoe and the Crangold plugs have been drilled and found to contain many gold-bearing veins. In both
cases shaft-sinking was recommended but was not implemented because of the generally depressed condition of the gold mining industry. The identification of the Centre Post mass led to the exploration of its outside boundaries and to the discovery of the East Sullivan orebody by drilling a magnetic anomaly in the immediate vicinity of the plug contact.**

**The East Sullivan deposit was found in 1945 during a survey by G. H. Dumont for East Sullivan Mines Ltd. The Centre Post intrusion was identified by T. Koulomzine in 1940 while working for Central Mining Corporation which at the time controlled all the ground except the few claims which later became the East Sullivan.

Airborne Magnetic Data

The advent of airborne magnetic equipment was followed by an extensive program of airborne surveying initiated by the Geological Survey of Canada. The Val d’Or district, where so much ground magnetic surveying already had been done, and where compilation of information from ground magnetometer surveys was in process, offered an unrivalled opportunity to test the advantages of wide, regional use of the newly invented technique, and northwest Quebec was one of the first areas flown by the Geological Survey of Canada. Geophysics Paper 73 (1952) presents part
Figure 6. Airborne magnetometer survey results reproduced from Geophysics Paper 73G, Geological Survey of Canada. The general outline of the Boulamaque batholith and of the Centre Peak intrusive mass is shown.
Figure 8. Comparison between ground and airborne magnetometer results over the East Sullivan orebodies. The airborne survey missed the orebody mainly because of the flightline location.
of the results of this airborne survey. While most modern, commercial airborne magnetometer surveys are flown at 500-ft. terrain clearance and with profiles spaced at quarter-mile intervals, this survey was flown at 1,000 ft. and with half-mile spacing, thus losing much of the resolving power of the airborne magnetometer. Figure 6 is a reproduction of the part of Map 73G covering the area of Figure 2, with the 20 and 10-gamma contours omitted.

Figure 6 shows the west part of the Bourlamaque batholith outlined quite well by the airborne magnetometer. In the northeast and southeast sections of the batholith, the contrast of the magnetic properties of the granodiorite and of the adjoining non-magnetic volcanics is weak and in places is nonexistent, so that the airborne magnetometer data obtained with 1,000-ft. terrain clearance and profiles at half-mile intervals are not sufficient to permit an accurate deduction of the position of the contacts. The ground magnetometer data did lead to the outlining of the contact, but even with these more detailed measurements it was necessary sometimes to use indirect methods of interpretation. The Centre Post mass shows very well on the airborne map as an intrusion, mainly because of its rounded shape.

The airborne map emphasizes the presence of some very magnetic intrusive rocks west of the Bourlamaque batholith, and also suggests the separation of the batholith into two parts, which already had been established by the ground surveys. The airborne survey map is quite useful in showing the broad outlines of the general geology. Had this map been studied before the orebodies were found, it certainly would have led a competent geophysicist to explore the areas where the Sullivan, the East Sullivan and the Perron mines now are. However, one can say that without systematic large-scale ground work, the other deposits of the district would not have been found because, on the basis of these aeromagnetometer data alone, the areas where they are would not have been singled out for further exploration.

Figure 7 (in pocket) shows, side by side, a small section of the Val d’Or aeromagnetic map and the corresponding section of ground magnetometer compilation maps. The outline of the intrusive rocks drawn on the aeromagnetic map is taken from geological compilation maps and has been confirmed by several hundred drill holes. Study of these two maps shows that the ground magnetometer outlines the Snow Shoe, Siscoe and Crangold plugs and marks with much detail the shape of the west end of the Bourlamaque batholith.

The aeromagnetic data over the Bourlamaque batholith do not permit delineating the contact of the intrusion as accurately as does the ground magnetic survey. The possible errors in locating the main contact would be as much as 2,000 ft. in some spots. Qualitative interpretation could have led to the identification of the Snow Shoe plug, but the Siscoe and the Crangold plug would have been missed.

The study of the airborne data may suggest the existence of deeply buried intrusive rocks, for instance, between the Snow Shoe and Siscoe, but existing diamond drilling and known geological information does not lend support to this.

It must be admitted that part of the difficulty here is that we are dealing with intrusive rocks that are non-magnetic and form a low magnetic anomaly which always is harder to find or identify than a positive anomaly. Nevertheless, aeromagnetic surveying, done on half-mile profile spacing, can miss geological features that have dimensions of up to one mile. This is unfortunate because such features quite often are extremely important.

Figure 8 shows side by side: a) the results of ground magnetometer work, b) the East Sullivan orebodies under the overburden as outlined by diamond drilling, and c) an enlargement of a small portion of the aeromagnetic map covering the same area. The flight lines of the aeromagnetic survey missed the area of the East Sullivan orebodies by about 1,000 ft. on each side, and this will explain why no anomaly was picked up. Thus a major ore deposit, which produces a strong ground magnetic anomaly, has been missed in the course of this routine aeromagnetic survey.

Conclusions

Airborne magnetometer surveys of entire districts have important roles in mineral exploration because they bring out geological information of a general nature quickly and cheaply, in comparison to ground geological and ground magnetometer surveys. Had airborne surveys been possible in 1929 and 1930, the gross errors in geological interpretation of the outline of the Bourlamaque batholith, which can be seen on the two top maps of Figure 3, would have been avoided. The large-scale airborne maps draw attention to areas favorable for further exploration, but airborne surveys frequently miss many important details, and it would be wrong in mineral exploration—except for iron—to lay emphasis on airborne magnetic work.
Airborne and ground magnetometer surveys have companion places in a program of mineral exploration, and the recent tremendous expansion of geophysical work, as applied to the search for metals, is proof of the usefulness of both techniques.

REFERENCES
3. Cadillac-Bourlamaque Area, Preliminary Map, Geol. Surv., Canada, No. 43-6, 1943.

INTEGRATED EXPLORATION FINDS COLUMBIUM DEPOSITS IN CHEWETT AND COLLINS TOWNSHIPS, ONTARIO

by E. W. Westrick* and G. E. Parsons†

Abstract

Study of available data indicated a predominantly circular habit for alkaline plugs and diatremes with associated columbium mineralization. A magnetic aureole corresponding to a zone of metasomatic alteration surrounding these alkaline intrusions suggested that magnetic methods might be used to locate similar occurrences. Such phenomena had been observed in the vicinity of Lackner Lake, Ontario. On the basis of these facts, an area of gneissic near the town of Chapleau, Ontario, about 170 miles northwest of Sudbury, was selected for investigation.

An area of eight townships was surveyed with an airborne magnetometer at 1,000 ft. altitude on flight lines half a mile apart. Resultant data indicated an aureole of alteration surrounding an alkaline plug in the vicinity of Lake Nemegosenda in Chewett township. Detailed ground magnetometer work was carried out on the area, together with geological mapping and scintillation meter observations. The detail magnetometer observations defined the magnetite-bearing zones and areas of light overburden. The scintillation meter readings assisted in outlining areas carrying columbium by reason of the slight radioactivity associated with pyroxene, the columbium-bearing mineral of this area. Drilling was undertaken on zones indicated by the magnetic and radioactivity observations, and scintillation meter readings were used in evaluating the cores for sampling and assaying. A pyroxenite zone, in the form of a “basic front” around the syenitic contact zone, was found to be the principal carrier of the columbium mineralization.

Two principal ore areas have been discovered to date, one of which probably will be a major open-pit operation. A large area which appears to be favourable for columbium mineralization, from geological considerations and magnetic evidence, awaits further testing.

Location

The property is at Nemegosenda Lake, Chewett township, Ontario, about 16 air-miles northeast of Chapleau, a divisional point on the Canadian Pacific Railway’s transcontinental line, 170 miles northwest of Sudbury. It is not accessible by public roads although lumber roads in the general area penetrate to within a few miles.

Introduction

Dominion Gulf Company became interested in this general area in 1952 and staked a group of claims on the southeast part of a magnetically anomalous area in McNaught and Lackner townships (Figure 1), following the announcements of mineral finds by other exploration groups operating in those townships. The anomalous area was shown in the data observed in an aeromagnetic survey done by Dominion Gulf Company in 1952. Exploration on these claims and general prospecting thereabouts found columbium miner-
alization to be in association with the hybrid rocks surrounding a large alkaline intrusion centred on Lackner Lake in Lackner township.

Government surveys in this part of Ontario have been limited, and in 1952 permitted only a very generalized geological map showing several unmapped townships around Lackner to be surrounded by granite gneiss.

**Planning**

The following significant conclusions were drawn from the evaluation studies of the exploration in Lackner township:

1. The aeromagnetic surveying revealed the presence of a distinct magnetic aureole around the alkaline intrusion in the vicinity of Lackner Lake;
2. Columbium mineralization was found to be associated with the rocks within the magnetic aureole;
3. The Lackner intrusive body, occurred as an isolated intrusion in an otherwise extensive area of gneisses;
4. The Lackner intrusion did not appear to be associated with regional faulting or folding.

Based on these conclusions and geological evidence from boulders found northwest of the Lackner intrusion, it was assumed that other alkaline intrusive
Figure 2. Aeromagnetic data observed over parts of Chewett, Collins, McGee and Pattison townships. Flight interval, 1,320 feet; flight altitude, 1,000 feet; flight direction, north-south; contour interval, 20 gammas.
rocks existed in the extensive area of gneiss to the north. An aeromagnetometer survey covering eight townships north of the previous survey, was flown in 1954,—the objective being to locate any such intrusive rocks that might exist, within the area surveyed, through the observance of the characteristic magnetic aureole.

On the assumption that any significant alkaline intrusion would be indicated by a magnetic aureole at least 2 miles in diameter, the aeromagnetometer survey was planned to be flown at one-half mile profile spacing with adequate assurance of detecting any target of this type that might exist. Following the rule-of-thumb used in planning aeromagnetic surveys, the aircraft height equal to profile spacing, the average flight elevation was set at 1,000 ft. These conditions permitted a substantial economy in the reconnaissance program.

**Interpretation of the Aeromagnetic Data**

The aeromagnetic data observed over parts of Chewett, Collins, Pattinson and McGee townships are shown in Figure 2. The strikingly independent and circular character of the anomalous area centred on Nemegosenda Lake indicated a possible alkaline intrusion. A study of aerial photographs gave support for a plug-like area of rocks in the form of a circular lineament northwest of the lake, the curving lake shore itself, and the high topographic relief immediately east of the lake.

On the basis of this interpretation, a group of 41 claims was staked in February, 1955, to include what was assumed to be that part of the magnetic aureole most favourable for the occurrence of columbium mineralization. The outline of this original staking also is shown in Figure 2. Twenty-five of the claims were under Nemegosenda Lake, and the remaining 16 claims lay east of it. This staking later proved to contain all of Zone D, the largest deposit discovered on the property, and a part of the east area zone of mineralization.

**Field Work**

A geologist visited the staking party for a few days late in February 1955, and located an outcrop of nepheline-bearing syenite on the east shore of Lake Nemegosenda. A few magnetite grains were found in the syenite, indicating that magnetite-bearing syenite might be the cause of the anomaly. Outcrops of gneiss were found on the north shore of the lake, and petrographic study of one specimen of the gneiss in our laboratory showed sodic alteration away from the fractures.

One of the stakers, while cutting the east boundary of the original claim block, recognized a rock as being similar to one he had seen while assisting on geological reconnaissance in Lackner township the previous year, and this rock was identified as a pyroxenitic soweite. Semi-quantitative spectrographic analyses of both the nepheline-bearing syenite and the soweite gave traces of columbium.

With the assurance of alkaline rocks on the claims, and consistent with the decision to use magnetics as the preliminary reconnaissance method of exploration, a ground magnetometer survey of the claims was done on the ice covering the lake claims immediately after staking, and over the land claims immediately thereafter and during the spring break-up. The survey was done on lines 200 ft. apart with observations at 100-ft. intervals, using an Askania-type magnetometer having a scale constant of about 25 gammas.

A geologist and two assistants arrived on the property on May 16, 1955; their objectives were:

1. To prove that we were dealing with an alkaline syenite intrusive;
2. To locate columbium mineralization;
3. To correlate the geology with the magnetics; and
4. To define general areas for detailed investigation.

Radiometric anomalies up to fifty times background and typical alkaline boulders and rocks were found during the first few days of scouting while completing the staking along the east edge of the original claim group. ’Finds’ were almost a daily occurrence for the next two weeks. Many of the ’finds’ were in boulders and rubble, and the physical character and distribution of the boulders indicated that they were not far out of place.

Prospecting outward from the claim group encountered extensive areas of high radioactivity in the area of the magnetic high just off the southeast corner of the staked claims. Additional staking followed promptly to cover the area of high radioactivity and magnetics. Staking continued as exploration progressed through the summer until 196 claims were staked. The outline of the 196 claims is shown on Figure 2.

Magnetic surveys followed in close conjunction with geological mapping and prospecting of all the claims. The detailed ground magnetometer data defined the magnetite-bearing zones and assisted in
Figure 3. Ground magnetometer survey of variations in the intensity of the vertical component of the magnetic field over the eastern area. Contour interval, 500 gammas.
Figure 4. Ground magnetometer survey of the variations in the intensity of the vertical component of the magnetic field over zone B and its environs. Contour interval 500 gammas.
identifying areas of light overburden. The ground magnetometer data covering the east area are shown in Figure 3. Zones of mineralization as indicated by diamond drilling are marked. It is important to note the association of the columbium mineralization and the magnetics in Zones A, B, E, F and G. Zone A carries significant amounts of rare earths of the cerium group. Zirconium is another associated mineral which may be of economic importance.

Figure 4 presents the ground magnetometer data in the vicinity of Zone D. Figure 5 presents in more detail the ground magnetometer data on the north part of Zone D and a number of the drill holes cutting Zone D are shown. It should be noted that the mineralization outlined in Zone D is on the outer edge of the large magnetic anomaly within the alteration zone. Rare earths are not present in the mineralization of Zone D in any consistently significant quantity. The physical relationship of Zones C and D to Zones A, B, E, F and G can be seen on the map of generalized geology shown in Figure 8.

During the magnetometer survey of the east area, (Figure 3), it became evident that it would be necessary to make magnetic observations at 20-ft. centres, or less, if one wished to define the magnetic data in detail. The complex nature of the data was interpreted as reflecting magnetite replacement in zones of brecciation and rim-ripping. It was decided that under such circumstances the data should be used qualitatively to define geological trends and in planning locations for diamond drilling. Consistent with this decision, magnetic data were observed in sufficient detail to define, to the geologists' satisfaction, the trends and extent of the zones of alteration. Eight X-ray diamond drill holes were drilled from outcrops to intersect some of the magnetic trends in order to determine the rock types present for assistance in the interpretation of the magnetic data. The evidence from this X-ray drilling, plus that in the widely scattered outcrops and boulder erratics, indicated that the higher concentrations of columbium mineralization were associated with aegirite-rich and garnet-rich rocks, and that these rocks normally were accompanied by magnetite. Accordingly, the initial AXT drilling was planned to cross-section at widely spaced intervals the areas in which these rocks were interpreted as probably occurring, i.e., the area between the intrusive core and the alkaline fenite. The first AXT drill hole (hole 9) in Zone D cut a narrow zone of high-grade columbium mineralization beneath the highest magnetic relief. Hole 10 cut a very substantial width of ore-grade mineralization in the area of lower magnetic relief. The locations of these holes with respect to the magnetic data of Zone D are shown in Figure 4. When holes 11 and 12, 170 ft. to the east, proved the continuity of the ore zone to the east, additional magnetic observations were added to define the north extent of Zone D in more detail (Figure 5).

The geologists used scintillometers while engaged in prospecting and geological mapping. The scintillometer proved an invaluable aid in locating near-surface rock, boulders and soil carrying significant columbium values. Pyrochlore, the columbium mineral present in Chewett township, contains small amounts of uranium and thorium, thus its ore is slightly radioactive. Systematic records of the measure of radioactivity were kept during the reconnaissance and detailed-mapping periods. The scintillometer served one purpose by leading the geologist to columbium-bearing rocks and boulders; later it served a second purpose as an aid in logging drill core by indicating the presence of the radioactive columbium-mineral pyrochlore. All samples cut for assay were checked for radioactivity and records of these measurements were kept. A typical diamond drill core log, showing the geology, radioactivity and \( \text{C}_{2}\text{O}_{3} \) values, is seen in Figure 6 (hole 53).

**Geology**

- **General**

  The geology as interpreted from the few scattered outcrops, magnetic data and the geology of the drill core, consists of an alkaline intrusion surrounded by a metasomatic aureole in an area of gneisses. The main concentrations of columbium mineralization occur in the metasomatic aureole and apparently exclusively as the mineral pyrochlore. The columbium-bearing aureole has an indicated inner circumference of 7 miles, and an outer circumference of 11 miles. The aureole may be divided into four units from the intrusive core outwards, namely: 1. syenitic contact zone, 2. pyroxenitic zone, 3. alkaline fenite zone, 4. fenitic gneiss zone.

  The fenitic gneiss zone is transitional between the unaltered country rock and the alkaline fentes.

  The alkaline fenite zone contains the oldest alkaline rocks in the area. The term 'fenite' (from Fen, Norway) is used to describe the in situ metasomatically altered country rock surrounding an alkaline intrusion. The original gneiss minerals have been destroyed in the development of the alkaline fentes. They are red,
Figure 5. Ground magnetometer survey of the variations in the intensity of the vertical component of the magnetic field over zone D, showing drill locations and ore zones. Contour interval, 500 gammas.
foliated rocks composed of aegirite and hydrated feldspar with varying proportions of fresh feldspar and nepheline, and often with fresh feldspar metacrysts; the red colour is due to hematite. They are always radioactive and columbium-bearing; their $\text{Ce}_2\text{O}_3$ content varies from 0.15 to 0.5 per cent. The extent of the alkaline fennites is quite important because there are strong indications that a higher temperature type of metasomatism, superimposed on these rocks, has produced the main concentrations of higher grade pyrochlore.

The pyroxenitic zone is the chief producer of, or locale for, the higher grade columbium-bearing bodies. It takes the form of a "basic front" around the syenitic
contact zone of the alkalic intrusive plug. On the east flank of the intrusive, i.e., in the east ore area, the pyroxenitic zone is in the form of a dark green pyroxene-rich fenite with linear zones rich in magnetite, garnet and/or wollastonite. On the north flank of the intrusive in Zone D area most of the columbium-bearing material is in the form of a rock called malignite; this rock consists of aegirite and orthoclase, with the former generally existing as acicular needles; it occurs as stringers or dykes, and masses replacing highly fractured and brecciated fenites.

The syenitic contact zone marks the transition from the true intrusive rocks of the core to the metasomatic rocks. It is characterized by an increase in orthoclase, biotite, felspathoids and low to erratic high columbium values.

Figure 7 illustrates these zones in a diagrammatic cross-section of the metasomatic aureole. The section presents schematically the relative build-up of magnetite and pyrochlore across Zone D. The relative location of such a section might be A-B as shown on the map of the generalized geology shown in Figure 8.

- **Columbium Mineralization**

Pyrochlore is the only columbium-bearing mineral identified in the Nemeosenda area to date. The main higher grade concentrations of this mineral are confined to the pyroxenitic zones.

The pyrochlore, in certain areas, as in Zone D, is always visible, while in others it is seldom seen. It shows a marked affinity for aegirite (the soda-pyroxene mineral), garnet, magnetite, wollastonite and graphite. Nevertheless, it is present in quantity under a rather wide range of mineral combinations. For example, it has been encountered in grades over 0.5 per cent \( \text{Cb}_2\text{O}_6 \) in rocks consisting chiefly of the following: 1. aegirite; 2. aegirite and felspar; 3. aegirite and calcite; 4. garnet and magnetite; 5. garnet and wollastonite; 6. graphite; 7. rocks consisting of varying proportions of apatite, magnetite, orthoclase, biotite and aegirite; 8. orthoclase and biotite; 9. orthoclase, apatite and calcite.

- **Ore Zones**

Two major ore areas are indicated to date: Zone D area and the East Ore area. There can be little doubt that still others exist. The ore zones were lettered in the order of their discovery once it became reasonably apparent that they were rather distinct, continuous and defineable units. These areas are seen in Figure 8.

**Conclusions**

The airborne magnetometer survey located successfully the contact zone of an alkalic intrusion in an extensive area of gneisses. Ground magnetometer surveys and radiation surveys were responsible for locating near-surface rocks and trends favourable for testing by diamond drilling. Radiation measurements were used profitably in core logging and to guide the selection of the drill cores for assay purposes.

Thirty-four thousand feet of AXT diamond drilling has been done, based on the geological deductions...
Generalized geology of the alkalic plug, showing the zones of alteration and the known mineralized areas.
from the geophysical data and the very scarce rock outcrops.

Numerous orebodies of substantial dimensions have been discovered. Very extensive potential ore-bearing areas remain untested.

The Zone D orebody represents a probable major open pit mine with over 20,000,000 tons of ore averaging 0.5 per cent C₂O₆, and very substantial additional tonnage averaging down to 0.3 per cent has been indicated. The orebodies in the east area hold similar reserves and appear favourable for underground mining, although it is conceivable that additional drilling may prove that they can be combined into another open pit.

Acknowledgment

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REFERENCE


THE BOSTON TOWNSHIP IRON RANGE

by J. H. Rattcliffe

Abstract

The Boston township iron range has been prospected for gold, non-ferrous metals, and iron since 1902 or 1903. In 1951 concentrated exploration based on aeromagnetic surveys, geological mapping and ground magnetometer surveys, led to the development of 213,600,000 tons of iron ore averaging approximately 20.6 per cent magnetite which can be magnetically concentrated to produce a high-grade product suitable for blast furnace use. However, not all of this material is economic under present conditions.

Some interesting features of the geomagnetic surveys which came to light during the exploration, were the steep magnetic gradients encountered in the area, the extreme magnetic intensities, both positive and negative, measured by the ground magnetometer, and the possibility of outlining potential magnetic ore zones on the basis of ground magnetometer data and detailed geological mapping.

While the exploration was designed primarily to outline iron orebodies, several problems of academic interest were met. Detailed ground magnetometer profiles measuring anomalies in the vertical component of the earth's magnetic field of 250,000 gamma and 65,000 gamma are shown in conjunction with the accompanying angles of inclination, magnetic deviations, and geology.

By comparing the detailed geology with the ground magnetometer data, it was possible to select a cut-off value of 40,000 gamma above base level as an aid in outlining possible magnetite ore zones. Recent diamond drilling has shown that this succeeds in locating all the ore zones, thus justifying the use of this rule of thumb method on this property.

Location

OSTON township lies about 6 miles southeast of the town of Kirkland Lake, in the District of Timiskaming, Ontario. Dane station, on the Ontario Northland Railway, is on the west boundary of the township. Highway No. 11, providing direct access to North Bay (165 miles) and Toronto (390 miles) to the south, cuts across the southwest corner of Boston township. Highway Number 66 and a branch of the Ontario Northland Railway about 3 miles north of the north boundary of the township provide direct access to Kirkland Lake, Ontario, and Rouyn-Noranda, Quebec, as shown in Figure 1.

*Geophysicist, Lundberg Explorations Ltd.

History

The Boston iron range was discovered in 1902 or 1903, the earliest report on the area being attributed to Dr. G. A. Young (1) of the Geological Survey of Canada, in 1904. In 1905, Dr. Willet G. Miller (2) of the Ontario Bureau of Mines, visited the area and reported on the iron ore deposit on which twenty one mining locations had been staked. In this report, Dr. Miller stated, "The formation consists of iron ore, which in Boston is magnetite, interbanded with jasper and other closely related siliceous material... This formation has a length in Boston of approximately seven or eight miles. Another point in its favour, in addition to its length, is that it has been subjected to considerable disturbance by intrusions of igneous..."
rocks... The width of the Boston iron-formation usually is not more than 90 or 100 feet. The greatest width we saw in the township was about 300 feet."

The mining locations to which Dr. Miller referred were allowed to lapse in time but sporadic examination of the iron range for iron, non-ferrous metals and gold continued. In 1947, Gulf Research and Development Company initiated a program of airborne magnetometer surveying in Canada, using a Grumman Goose aircraft, fitted with the Gulf airborne magnetometer. The first survey including Boston township covered the area between the Ontario-Quebec interprovincial boundary and the Porcupine gold mining camp. The flightlines were spaced at half-mile intervals, and were flown at an altitude of 500 ft. above the terrain. Upon reducing these data it was recognized that the Boston township iron range produced a magnetic anomaly of higher intensity than any recorded with the airborne magnetometer up to that time. To obtain further information, additional flight lines were flown in December, 1948, reducing the flightline spacing to one-quarter mile intervals in both north-south and east-west directions.

Dominion Gulf Company geologists did reconnaissance geological mapping in Boston township in 1949 to evaluate the economic possibilities of the iron range. While mapping was in progress, a new airborne magnetometer capable of recording much steeper magnetic gradients, became available from Gulf Research and Development Company, and this instrument was flown over the Boston township magnetic anomaly on several test flights in June, 1949.
The results of the reconnaissance geological mapping in 1949 were not encouraging. The very strong magnetic anomalies apparently were caused by a number of rather continuous, banded iron-formations up to 600 ft. wide. Few of these bands, however, exceeded 20 per cent iron over a width of 100 ft., which at that time was considered to be a minimum width for an economic deposit of iron ore. Interest in the area diminished.

By 1951 the demand for iron had increased and exploration for iron was intensified. These changes in the iron ore picture prompted Dominion Gulf Company to re-evaluate their information concerning the Boston township iron range. Following a re-study of the aeromagnetic information 31 claims were staked by Dominion Gulf Company in the extreme northeast corner of Boston township, in January, 1951.

Detailed geological mapping and a ground magnetometer survey were completed over the banded iron-formation on picket lines spaced at 200-ft intervals. These surveys indicated that the 1949 preliminary evaluation of the area had been ultra-conservative in regard to both grade and potential tonnage, so an additional 62 claims were acquired. Detailed geological mapping and ground magnetometer surveys were conducted on the new claims. Based on the results of these surveys, 14 diamond drill holes, totalling 5,724 ft. were drilled to test the banded iron formation. Upon assessing the results of the surface exploration, 24 of the 62 acquired claims were dropped and present holdings comprise the remaining 38 acquired claims and the original group of 31 claims.

The Jones and Laughlin Steel Corporation became interested in the property and arranged to continue exploration with a view toward ultimate production. Jones and Laughlin's diamond drilling to date consists of eighteen holes for a total of 11,924 ft. Bulk sampling, assays and concentration tests have been done, and it appears that the property may yield an economic tonnage of high-grade iron ore concentrates.

Geology

The geology of the Kirkland Lake-Larder Lake area has been mapped by the Ontario Department of Mines at a scale of 1 inch equals 1,000 ft. A summary of this project has been published by Thomson (3). Although Boston township was not included in the detailed study, the east quarter of the township was mapped by Abraham (4) in conjunction with the detailed survey of McElroy township. Other maps showing the geology of parts of Boston township are the "Kirkland Lake Area" (Ontario Department of Mines No. 32c) and the "Boston-Skead Gold Area" (Ontario Department of Mines No. 30d). A generalized geological map of the area based on these published reports and maps is shown in Figure 2.

The oldest rocks in the area have been named Keewatin, and include acid, intermediate and basic volcanic, with interbedded tuffs, fragmental and siltaceous, banded iron-formation. Timiskaming-type sediments, such as greywacke and conglomerate, overlie the Keewatin-type rocks unconformably. Folding and faulting of the Keewatin-type and Timiskaming-type rocks resulted in the formation of a strong east striking syncline, the south limb of which was removed by faulting and erosion, particularly in the west part of the area. Intrusive activity consisted of Haileyburian-type diorites, gabbros, serpentinite, etc., followed by Algoman-type granites, syenites, and more basic derivatives, and Matachewan-type or Keweenawan-type diabase. The well-known gold deposits of the Kirkland Lake region are associated with competent rock types which have been faulted by pre-ore "breaks" subsidiary to the main Larder Lake break.

The greater part of Boston township is underlain by typical Keewatin-type rocks. Timiskaming-type sediments, prominent in McElroy township, extend about a mile into the east central part of Boston township. An Algoman-type syenite mass occupies the south half of Lebel township and the north part of Boston township. The Round Lake batholith, a syenitic rock of Algoman age, encroaches on the west boundary of Boston township. Minor stocks and dykes of Algoman-type syenite or granite, and Matachewan-type or Keweenawan-type diabase dykes intrude the Keewatin-type rocks throughout the township.

The structural geology of Boston township is complex. In the north half of the township the Keewatin-type rocks more or less follow the south boundary of the Lebel syenite mass from the northeast corner of Boston township to the northeast corner of Otto township. A similar structure exists in the south part of Boston township where the Keewatin formations follow the trend established by the margins of the Round Lake batholith. The central part of the township is a transitional zone, the rocks striking generally easterly but assuming the trend of the nearest major intrusive.

The detailed geology of part of the Boston township iron range as mapped by Dominion Gulf Com-
pany geologists is shown in Figure 3. Topographic relief in the area is marked, some hills rising up to 300 ft. above swamp level. The banded iron-formation, together with some of the andesite and gabbro, tend to form the higher ridges, where outcrops are numerous. Even in the lower sections between the hills, the overburden depth is believed to be less than 20 ft.

Essentially the property is underlain by Keevatin-type volcanic rocks and sedimentary rocks, which are intruded by minor dykes and stocks of serpentine, gabbro, granite and diabase. The Keevatin-type volcanic rocks are intermediate to basic, massive flows, and acid to intermediate tuffs and agglomerates. From an economic viewpoint, the Keevatin-type sediments, consisting of banded iron-formation, are the most important rocks found on the iron range.

For convenience in geological mapping the banded iron-formation was broken into two components: recrystallized chert (or in field terminology, quartzite), and iron-formation. The term iron-formation was reserved for those formations in which magnetite comprised 20 per cent to 45 per cent of the volume of the rock. The iron-formation and the recrystallized chert are, therefore, related formations, having gradational contacts. Most of the recrystallized chert contains some magnetite, either as a fine dissemination or as local concentrations in stringers or blebs. As the magnetite content increases, the rock may be called a lean iron-formation.

In the iron-formation, silica occurs in grains averaging between 0.1 and 0.2 mm. in size. The interstitial magnetite varies from 0.02 mm. to 0.1 mm. while the magnetite stringers consist of granular magnetite averaging 0.02 to 0.04 mm. in grain size. Garnet is a very common mineral in some sections and usually is associated with the high-grade iron-formation. The individual quartz and magnetite bands are seldom over 3 inches wide, with quartz predominating. The magnetite stringers vary from a hair line to a maximum of 2 inches wide, the predominant width being about ½ inch.

The iron-formation vary greatly in width. The linear masses range from 10 to 300 ft. wide, the usual width being about 150 ft. A combination of folding and coalescence of narrower beds, particularly in the south part of the area, localizes thickening of the iron-formation, creating widths up to 700 ft. A southwesterly plunging syncline located near the north boundary of the claim group is the major structural feature.

While the foregoing account of the area in general and of the claim group in particular is by no means complete, it may illustrate the complexity of the problem confronting those charged with the responsibility of assessing the economic potentialities of this and similar taconite or banded iron-formation bodies.

Airborne Magnetometer Data

The Gulf Research and Development Company’s airborne magnetometer has been described by G. Muffly (5) and R. D. Wyckoff (6). The instrument has proved very adaptable to mineral prospecting the world over; perhaps its severest test was encountered in Boston township. A map of the magnetic data observed 500 ft. above the terrain and obtained from profiles flown one-quarter mile apart on both north-south and east-west flightlines is shown in Figure 4.

The highest intensity observed was 17,400 gammas above base level, which may be much less than the true field at this altitude because the horizontal gradients of the total field encountered over the Boston iron range were greater than the recording speed of the airborne magnetometer then in use.

Quantitative interpretation of the Boston township aeromagnetic anomaly was not attempted since the data themselves are hypothetical. Qualitatively it was possible to assume that the Boston township anomaly must represent a substantial volume of highly magnetic material.

During the detailed geological mapping, the geologists found that the aeromagnetic data led them directly to the banded iron-formation. The aeromagnetic data were not observed in sufficient detail to indicate directly the higher grade portions or the detailed structure of the iron-formation. The contacts of the banded iron-formation, as interpreted from the aeromagnetic data, were found to lie beyond the true contacts determined from geology. The aeromagnetic survey accomplished its purpose by drawing attention to banded iron-formation which, as events later proved, was worth detailed investigation.

Ground Magnetometer Data

In 1951, Dominion Gulf Company performed a ground magnetometer survey over the entire claim group. Basic coverage over the banded iron-formation consisted of stations 50 ft. apart on picket lines 200 ft. apart. In the more complicated sections additional detail stations were observed.
Figure 4. Aeromagnetic survey, Boston township iron range. Flight elevation, 500 ft. above terrain, contour interval 500 gammas.
Mining Geophysics

An Askania Schmidt-type magnetic balance, having a sensitivity of about 25 gammas per scale division, was used for the survey. It was evident immediately that very intense magnetic fields would be encountered throughout the survey of the banded iron-formation which would necessitate many latitude adjustments of the magnetometer, particularly in areas characterized by exceedingly steep magnetic gradients. To increase the range of the magnetometer, and to reduce the number of latitude adjustments, special equipment consisting of larger latitude weights and two extra strong auxiliary compensating magnets were provided. In this manner it was possible to increase the range of the magnetometer to about 35,000 gammas at any one latitude adjustment or to a total range of 500,000 gammas employing latitude adjustments.

A map of the main anomaly zone showing isomagnetic contours as derived from the ground magnetometer survey, is presented in Figure 5. The magnetic values shown on this map may be related to the vertical component of the earth's field by adding 55,396 gammas to the observed measurements. To facilitate data reduction, the general non-anomalous magnetic level was chosen to be about 2,400 gammas. The strongest positive anomaly measured during the course of the routine survey was about 146,000 gammas above the base level, while the strongest negative anomaly measured was about 58,700 gammas below the base level. When the earth's normal field is added to these values, the vertical component of the earth's field at the two particular stations becomes 203,856 gammas and -901 gammas respectively.

In many cases maximum or minimum values of anomalies were not observed because the information obtained did not justify the time and effort involved. If the anomalous magnetic field was either 100,000 gammas or more above base, or 30,000 gammas or more below base, it was assumed to reflect a zone rich in magnetite. Consequently no attempt was made to record maximums or minimums above or below these limits, in the course of the routine survey. In some detail work, to be discussed later in this paper, (Figures 6 and 7), the maximum magnetic anomaly measured was 249,260 gammas above base level and the minimum magnetic anomaly observed was 65,450 gammas below base level.

The extreme variations in magnetic intensity require some consideration. Even qualitatively one would assume that part of the anomalous field was caused by remanent magnetization. This also may be shown quantitatively. The equation for the maximum induced magnetic field due to a vertical dyke, having infinite magnetic north strike and depth extent, may be written

\[ \Delta V = 4 K \sin i \tan \frac{m}{h} \]

where \( \Delta V \) is the vertical component of the anomalous induced magnetic field in gammas;

\( K \) is the apparent magnetic susceptibility difference in c.g.s. units, between the dyke and its surroundings;

\( I \) is the normal earth's total magnetic field intensity (i.e. the induction field, in the vicinity, in gamma); 

\( i \) is the angle of inclination of the earth's total field;

\( m \) is the half width of the dyke;

\( h \) is the depth to the top surface of the dyke from the plane of measurement and \( \sin i = \sin \) the normal vertical component of the earth's magnetic field in gammas.

In order to obtain a minimum value of \( K \), we may select a body infinitely wide compared to its depth so that \( \frac{m}{h} = \frac{\pi}{2} \) and \( \tan \frac{m}{h} \). Thus \( K_{min} = \frac{\Delta V}{2 \pi I \sin i} \). I sin i as established at the Dominion Observatory base station in Larder Lake is 57,794 gammas. The maximum positive anomaly was 242,200 gammas above its immediate environs, which in turn were about 7,000 gammas above the regional base level, (Figure 6). Supplying these values to the equation we obtain a minimum apparent susceptibility \( K_{min} = .667 \) c.g.s. units.

The susceptibility of pure magnetite has been measured (or inferred) by many observers, and while there are wide variations (0.3 to 0.8 c.g.s. units) (7) in the results, the figure usually accepted for magnetic interpretation calculations is of the order of 0.3 c.g.s. units (8), (9). Assuming that the susceptibility of the magnetite in Boston township is average, there is reason to believe that remanent magnetization is producing part of the anomalous magnetic field, the remanent magnetization and the induced magnetization adding together to produce a minimum apparent susceptibility \( K_{min} = 0.667 \) c.g.s. units.

Let us consider now the case of inverse remanent magnetization, where the direction of the remanent magnetization vector opposes the induced magnetization vector. Assuming that the largest positive magnetic anomaly observed on the property is caused by a magnetite distribution similar to that causing the largest negative anomaly observed, (Figure 7), only
Figure 5. Ground magnetometer survey, Boston township claim group.
the direction of the remanent magnetization vector being reversed, it may be shown that induced magnetization (susceptibility) accounts for 0.25 c.g.s. units, and remanent magnetization provides 0.42 c.g.s. units or 68 per cent more than the induced magnetization. The induced magnetization factor suggests that the strongest anomalies, both positive and negative, are caused by rocks containing about 80 per cent magnetite. This figure undoubtedly is too high. Assay results from the critical sections of diamond drill holes G-3 (Figure 6) and G-4 (Figure 7) indicate that the rock immediately under the strongest positive anomaly grades about 36 per cent magnetite over a horizontal distance of 64 ft., while that under the strongest negative anomaly grades 33 per cent magnetite over a horizontal distance of 29 ft.

If the induced magnetization factor is reduced to 0.10 c.g.s. units to fall in line with the observed percentage of magnetite, the remanent magnetization factor will be raised to 0.57 c.g.s. units. On these figures, it would be possible to obtain negative anom-
ties up to -170,000 gammas over an infinitely wide dyke. This is about 2.5 times greater than the largest negative anomaly actually measured but the discrepancy may be easily explained. Remanent magnetization varies widely in magnitude, direction and sense. Extreme variations in all of these components were observed in the diamond drill core, on a minute scale. Furthermore, the size factor is unrealistic and any reduction in width will tend to reduce the anomaly.

It has been suggested that the negative anomalies may be the normal lows associated with strong positive anomalies due to dipping or depth-limited dykes, or easterly striking bodies. While many of the strong lows, particularly in the south part of the area, definitely are associated with the north flanks of iron-formation, these lows have not been considered true negative anomalies. The calculations above were based on figures from the magnetic anomalies due to northerly striking, steeply dipping iron-formation. In the case of the negative anomaly, (Figure 7), diamond drilling proved that the west half of a continuous iron-formation was negatively polarized while the east half was positively polarized.

The ground magnetometer data were studied in the field in conjunction with rock outcrops across which visual estimates of the iron content were made. From a careful correlation of the geology and magnetic data over available outcrop, the value of 40,000
gammans magnetic intensity above level was selected arbitrarily as a cut-off value for purposes of outlining potential ore zones for detailed mapping. All areas of over 200-ft minimum width within which the anomalous magnetic intensity was over 40,000 gammans, were mapped in detail. It was found that the use of this magnetic guide provided a relatively quick, yet accurate, method for defining the potential ore zones without carrying out detail stripping, trenching, mapping and diamond drilling over the entire claim block.

While the 40,000-gamma cut-off was determined from visual comparison of magnetic data and outcrop, it is interesting to note that if the induction theory formula for the vertical dyke is considered again, 40,000 gamma corresponds to a rock susceptibility \( K = 0.11 \) c.g.s. units, which in turn corresponds to a rock containing 37 per cent magnetite or 27 per cent iron. Because of remanent magnetism, however, the mere fact that the magnetic relief exceeded 40,000 gammans over a mineable width was no guarantee that the causative body could be considered ore. Conversely there were several instances in which economic deposits were found in areas where the magnetic relief was less than 40,000 gammans over the required width. In general, these exceptions tended to cancel one another and permitted the geologist to make estimates of the potential tonnage and grade of the iron ore deposit prior to diamond drilling.

Two detail ground magnetometer profiles are shown in Figures 6 and 7. Stations were observed at 10-ft. intervals along these profiles, which were run along the horizontal projections of two diamond drill holes, G-3 and G-4, the locations of which are shown in Figure 5.

Values of the anomalous part of the vertical component of magnetic intensity, the dip of the earth's magnetic field, the magnetic deviation, and the relative elevation of the stations were observed. Surface geology where known and diamond drill hole data were added for the purpose of studying the magnetic data.

In Figure 6, the most prominent feature is the strongest magnetic anomaly recorded on the property, the anomaly in the vertical component of magnetic intensity being 249,260 gammans. While the dip of the earth's magnetic field remains relatively constant in magnitude in the vicinity of the anomaly, the magnetic deviation varies widely, the direction of magnetic north swinging through 360° in the vicinity of the anomaly. The strong anomalous area corresponds with an iron-formation, which in diamond drill hole G-3 produced a true width of about 160 ft. of material ranging from 19 per cent to 36 per cent but averaging about 21.4 per cent iron.

Figure 7 shows a similar profile along the horizontal projection of diamond drill hole G-4. The interesting feature of this profile is the sharp positive-negative reversal (giving rise to a gradient in excess of 14,000 gammas per horizontal foot) just west of the diamond drill hole collar. It will be noted that the maximum value (217,942 gamma) was obtained over the west side of a small outcrop, 10 ft. west of the diamond drill hole collar, above a section of iron-formation grading about 35.5 per cent magnetite over a horizontal width of 21 ft., while the minimum value (63,045 gammans) was obtained over the west part of the same iron-formation above a zone which graded 33 per cent magnetite over a horizontal width of 29 ft. Since the magnetite content in the rocks causing the negative anomaly is only 2.5 per cent less than that causing the positive anomaly, it would appear that the only solution to the problem of the intense high-low combination is a reversal in remanent magnetization. Further evidence of this is seen in the behaviour of the magnetic meridian and the angle of inclination as illustrated in Figure 7. A definite negative pole coincident with the negative anomaly is indicated by these data. An associated positive pole is coincident with the positive anomaly.

The primary purpose of the ground magnetometer survey was to provide a basis for the extension of possible ore determined from outcrop information into those areas which were covered by overburden. This led to the selection of the 40,000-gamma cut-off value previously mentioned, and an estimate of indicated ore reserves. In the south part of the area the iron-formation may have been tightly folded, causing the widening of the ore section. The geology and the ground magnetometer data for this area are compared in Figure 8. A comparison of these data with those on Figure 6 demonstrates the evident contradiction that the strongest magnetic anomalies are not necessarily associated with either the highest grade material or the widest ore sections. Again, the unpredictable nature of remanent magnetism must be a contributing factor to this contradiction.

Conclusions

The airborne magnetometer survey cannot be credited with finding the Boston township iron range because it had been indicated by geological mapping.
about 45 years prior to the first airborne magnetometer traverse over it. The airborne magnetometer survey did bring the iron-formation to the attention of the Dominion Gulf Company, and, in a general way, outlined its boundaries and thus provided a guide for the acquisition and detailed examination of the property. The ground magnetometer survey which followed, provided an aid for extending the known geology into overburden-covered areas. Without the knowledge gained from extensive detailed geological
mapping, the value of the ground magnetometer survey would have been greatly lessened. By combining the information gained from geology and magnetic data, it was possible to outline a number of potential ore zones in which to localize and thereby reduce the footage of diamond drilling.

A block plan of these potential ore zones, as interpreted by Dominion Gulf Company personnel, is shown in Figure 9. Calculations of "indicated" and "possible" ore were based on the assumptions that open pit mining can be carried on to a depth equal to the width of the ore zone, and that the grade of ore as estimated from outcrop data remains continuous along strike for the distance indicated by the magnetic data.

In the original calculations, based entirely upon surface geology and ground magnetometer data, "indicated" ore was defined as those zones greater than 200 ft. wide grading better than 20 per cent iron, and "possible" ore those sections of the iron-formation which are less than 200 ft. wide but have a grade better than 20 per cent iron, and also those zones which are greater than 200 ft. wide but grade less than 20 per cent iron. The "indicated" ore zones are designated on Figure 9 by letters; "possible" ore zones are indicated by numbers.

Following diamond drilling by Dominion Gulf Company and Jones and Laughlin Steel Corporation, Dominion Gulf Company made a second tabulation of the ore reserves. The drilling results were used for calculating ore grade and width, but as there were several zones with only one drill hole intersection, the lateral extent was estimated by a study of the combined results of surface work and the ground magnetometer survey. Several zones presumed to be ore in the original estimates were rejected in the second estimate; only those zones intersected by diamond drill holes were considered. Several of these were eliminated due to unfavourable drilling results, and still more were reduced in size or grade, only the odd one being increased in either tonnage or grade.

The two estimates made by Dominion Gulf Company personnel may be compared in Table 1. Because the ore must be concentrated by magnetic separators to produce a usable product, the grade is expressed in terms of magnetic iron. It must be emphasized that tonnages and grades in the table represent ore material in place, and do not necessarily reflect the quantities which can be extracted economically.

<table>
<thead>
<tr>
<th>Tonnage (Mag.Fe.)</th>
<th>Grade</th>
<th>&quot;Indicated&quot; Ore</th>
<th>Tonnage (Mag.Fe.)</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Estimate</td>
<td>168,000,000</td>
<td>26%</td>
<td>88,000,000</td>
<td>21.5%</td>
</tr>
<tr>
<td>Present Estimate</td>
<td>143,000,000</td>
<td>21.8%</td>
<td>70,000,000</td>
<td>18.1%</td>
</tr>
</tbody>
</table>

Taking the present calculations, 213,000,000 tons of "indicated" and "possible" ore, averaging 20.6 per cent magnetite, have been outlined. However, in estimates of this nature the personal factor plays a large part. The selection of cut-off grades, widths and lengths varies between individuals, particularly in respect to the category of "possible" ore. For example, an independent analysis of the data upon which the "present" estimate is based reduced the ore reserves to 132,000,000 tons averaging about 22 per cent magnetite. All these estimates must be considered preliminary, due to the limited amount of diamond drilling. It is believed that further development will prove them conservative both in grade and tonnage.

In the final analysis, the evaluation of the economic possibilities of the property was the primary consideration of the magnetic surveys. Certain interesting academic problems were encountered in the course of achieving this end. The outstanding features were the intense magnetic lows which were met in the ground magnetometer surveys. The strength of these negative anomalies, one of which is at least 63,000 gammas less than the normal vertical component of the earth's magnetic field, required inverse remanent magnetization of the rocks to account for the values observed. The question which arises is: "How did some of the iron-formation become inversely polarized while the rest retained normal polarization?"

None of the normal structural solutions appears to answer the question fully. No titanium oxides were observed in association with the magnetite. All of the iron-formation is highly contorted, minor folding being prominent but faulting rarely seen. One feature which appears to be peculiar to the negative magnetic areas is the formation of an iron-rich garnet. The presence of this high-temperature metamorphic mineral suggests the possibility of high-grade metamorphism possibly associated with the granitic intrusions in Lébel and Otto townships. It would seem likely therefore that at the time of the formation of the garnets, the magnetite was heated well beyond the Curie point, thus removing its prior remanent magnetism. If this magnetite was allowed to cool in a reversed magnetic
field, possibly caused by the return path of the magnetic field generated by neighbouring unheated bands of iron-formation, it is possible that a reversed polarization could result.

The problem of reverse remanent magnetism has received much attention in the past few years and some progress has been achieved. However, it is suggested that the ultimate explanation must provide for negative anomalies of the order of magnitude observed on this property. Perhaps the publication of these data will assist future investigators in the search for the true cause of reverse remanent magnetization.

Acknowledgments

The author wishes to acknowledge the assistance of the members of the staff of Dominion Gulf Company for their help in the preparation of the material contained in this paper. Much of the material was drawn from reports prepared by those who were responsible for the ultimate success of the project.

Credit for suggesting the preparation of this paper for inclusion in this volume must be given to E. W. Westrick, whose energies have played a large part in the development of the volume itself.

Finally the co-operation of the managements of Dominion Gulf Company and Jones and Laughlin Steel Corporation in releasing this information for publication is gratefully acknowledged.

REFERENCES


MAGNETIC AND ELECTROMAGNETIC INVESTIGATIONS IN PASKA TOWNSHIP,
DISTRICT OF THUNDER BAY, ONTARIO

by H. W. Fleming*

Abstract

The results of an exploration program organized to investigate some large aeromagnetic anomalies which indicated large extensions to the known Onasam iron range, are discussed and compared with the predictions made from the interpretation of the magnetic data.

It was found that a high apparent susceptibility of about 0.50 c.g.s. units for magnetic was required to satisfy the anomalies when compared to the true magnetite content of the iron-formation. This susceptibility factor, in conjunction with variations in overburden cover and magnetite content in the iron-formation, appeared adequate to satisfy even the larger variations in the anomalies where overburden cover was light, but was inadequate where overburden cover was heavy and the extreme variations were encountered.

It is, therefore, concluded that normal and inverse remanent magnetization must play an important role, and that the apparent high uniform susceptibility in regions under heavy overburden is due to the integrated effect from relatively narrow zones having widely different values for remanent magnetization.

After regional geologic investigations and photographic interpretation, a reconnaissance ground electromagentic survey and a magnetic survey were carried out in regions adjacent to the iron-formation and subsequently test flights were made with aereoelectromagnetic equipment to obtain a general comparison with the ground data. These surveys and the interpretations from the data are discussed in relation to the drilling results obtained.

Such combined survey methods are shown to possess a good degree of accuracy and can give technically satisfactory results if properly interpreted and reassessed as exploration progresses.

*Chief Geophysicist, Kennec Explorations (Canada) Ltd.
Introduction

The geophysical data was obtained from two separate ground surveys done to investigate aeromagnetic anomalies indicated by an airborne magnetometer survey of a larger area.

The first survey consisted of ground magnetometer work and was used to outline in detail an extension of the Onamak iron range into an area extensively covered by overburden, indicated by the airborne magnetic survey.

The second survey combined magnetic and electromagnetic methods and investigated some drift-covered areas adjacent to the iron-formation where aeromagnetic, geological and photographic evidence indicated that bodies of sulphide mineralization might be found.

Diamond drilling followed to test the economic potentialities of the area and to obtain data as a basis for the revision and re-assessment of the geophysical interpretations.

Some test flights with airborne electromagnetic equipment were made later over portions of the region to learn the type of response from these bodies of sulphides, and to determine whether or not sulphide mineralization was present in unsurveyed portions of the property.

From the point of view of indicating the dimensions, locations and character of the anomalous bodies, the initial interpretations of the geophysical data possessed a high degree of accuracy. However, in the case of predicting the percentage of magnetite present, results were not too satisfactory and some revisions were necessary. Re-interpretation in the light of additional data made possible an early decision that further work was not justified.

The geophysical data presented in this paper are only a portion of those obtained from the surveys conducted, but cover areas that have been checked by diamond drilling and include the information used as a basis for the interpretations.

General Information

The portion of Paska township which was surveyed is roughly 50° 11’ north latitude and 87° 20’ west longitude. This is about 25 miles west of the village of Nakina, a divisional point on the transcontinental line of the Canadian National Railways in the District of Thunder Bay, Ontario, and about 500 miles east of Winnipeg, Manitoba.

The region is extensively covered by a mantle of overburden varying generally from 40 to 75 ft. thick and in places up to 100 ft. thick. Outcrops are only locally abundant.

Topographically, the region alternates between broad areas of wet muskeg where forest growth is predominantly stunted spruce and tamarack, and lesser areas of low sand hills up to 100 ft. high where growth consists of poplar and birch with minor amounts of spruce and pine.

Regional Geology

The geological features of this township have been interpreted from aeromagnetic and photographic data supplemented by data from diamond drilling and the few rock outcrops that could be mapped.

The underlying rocks are Precambrian and consist of a west-trending assemblage of volcanic and sedimentary units which have been intruded by northerly and northwesterly-trending diabase dykes and a small stock of granite, bounded on the south by paragneiss.

The volcanic unit includes basalt, andesite and rhyolite flows and carbonaceous tuffs. Some medium-grained diorite and gabbro appear to be conformable.
with the regional trend and probably are coarser grained portions of andesite and basalt flows.

The sedimentary rocks are predominantly arenaceous chlorite-biotite schists intimately interbanded with iron-formation units consisting principally of magnetite and quartz. The iron-formation has been found to contain locally appreciable amounts of jasper, garnet and hornblende and sporadic small amounts of pyrite, pyrrhotite and chalcopyrite. Sparsely mineralized quartz veins are not uncommon.

**Structural Features**

The region has been interpreted as a volcanic assemblage overlain by sedimentary units both of which have been subjected to stresses from the north resulting in two west-trending divergent folds, with the sedimentary units occupying the synclinal portions of the folds and the volcanic units the anticlinal portions. All dips noted are greater than 50 degrees and to the north, so it is evident that these folds have been overturned to the south.

It is quite possible that some strike thrust faulting has taken place, although the only positive evidence of movement has been the development of graphite in the tuffaceous horizons. Offsets of some of the magnetic anomalies may possibly indicate the presence of northerly striking faults.

**Part I—Magnetic Surveys at Sandhill Lake**

*General Features of Data*

The airborne magnetic data for this region, obtained at a mean flight elevation of 500 ft. above ground and at a mean flightline spacing of 1,320 ft., on north-south lines, are shown in Figure 1. They are total field intensity measurements and the most salient features are the two slightly divergent west-trending zones of high magnetic intensity in which the peaks are "off-scale" and in excess of 13,000 gammas. It is probable that the horizontal magnetic gradient was greater than the recording speed of the magnetometer in addition to the peak value of the anomaly being considerably beyond the range of the instrument at the sensitivity employed. A few flights at an elevation of 1,500 ft. above ground showed the measured anomalies to be still of a magnitude of 13,000 gamma at this height.

The fact that these peaks were lost through being "off-scale" prevented any direct calculations being made from them. However, the inferred width, length and intensity of the anomalies were of such magnitude that the cause could only be iron-formation and further investigations on the ground were deemed warranted.

A portion of the ground magnetic survey done in the area south of Sandhill Lake is shown in Figure 2. This survey, which measured the variations in the vertical component of the earth's field, checked very closely with the airborne survey as to the location and dimensions of the magnetic body and outlined a broad zone up to about 1,500 ft. wide in which the magnetic values average between 30,000 and 40,000 gammas, broken by peaks up to 70,000 gammas and troughs as low as 5,000 gammas against a base level of about 5,000 gammas.

These extreme values are all local features with the exception of one persistent trough which traverses the high anomalous zone along the 0+00 section line (section line in this paper refers to a picket line run at a right angle to a base line), and has an anomalous value some 20,000 gammas below the average of the adjacent anomalous zone.

**Magnetic Anomalies Along Section Line 8+00 East**

(a) Comparison of Observed and Calculated Data:

A profile across the magnetic zone along section line 8+00 east and facing in a westerly direction is shown in Figure 3. The profile is located south of Sandhill Lake. Three curves are plotted, the first being the observed magnetic data and the second and third calculated curves based on the assumptions enumerated below.

The observed magnetic values indicate an average anomaly of about 30,000 gammas, the base level being taken at about 5,000 gammas. The maximum anomaly within this zone is about 44,000 gammas and the least value is about 13,000 gammas. These peaks and hollows were assumed tentatively to be due either to a variation in the magnetite content of the zone itself or to sharp variations in the depth of overburden if the magnetite content was found to be relatively uniform.

The dotted curve No. 2 was calculated before any drilling was done and shows the anomalous magnetism to be due to a body 1,500 ft. wide and 1,000 ft. deep, under 50 ft. of overburden, which dips to the north at 80 degrees and has an assumed uniform susceptibility of 0.10 c.g.s. units.

This calculated curve gives fairly satisfactory agreement with the observed data inasmuch as the
Figure 1. Airborne magnetic anomalies in part of Paska township.

Figure 2. Ground magnetic anomalies south of Sandhill Lake.
maximum anomaly is slightly greater than 30,000 gammas in magnitude. However, the maximum appears on the south side of the body and does not duplicate the higher shoulder shown on the north side of the observed curve. As is to be expected, the sharp peaks and hollows are not duplicated. It was inferred, therefore, that the average susceptibility of the iron-formation was about 0.10 c.g.s. units.

Curve No. 3 was calculated after drilling the section and shows the anomalous magnetism to be due to a body 1,600 ft. wide and 1,000 ft. deep, dipping north at 55 degrees. The overburden varies in depth from 40 to 100 ft. The susceptibility factor is 0.09 c.g.s. units for the south block and 0.11 c.g.s. units for the north block, and was arrived at by determining the relative amounts of magnetite in the blocks from assay results and using a figure of 0.50 c.g.s. units for the susceptibility of magnetite.

This curve gives closer over-all agreement with the observed data. The anomaly varies from a maximum of 30,000 gammas near the north edge to about 20,000 gammas at the south edge of the body.

The sharp peaks and hollows are still not explained but it seems likely from assay data that these could be reproduced, in part at least, if a curve was
calculated using a series of 50- or 100-ft. wide bodies of varying susceptibility and making allowable changes in depth of cover.

(b) Comparison of Drilling Results with Calculated Data: When curve No. 2 was calculated it was assumed that the susceptibility of the magnetite was 0.30 c.g.s. units and the average susceptibility of the body 0.10 c.g.s. units. Under these conditions, there might be present in the assumed body an enormous tonnage of material averaging 33 per cent magnetite or about 24 per cent iron. Alternatively, based on the magnitude and the distribution of the higher magnetic peaks, it was considered that the iron-formation might contain mineable sections of higher grade material averaging 35 to 40 per cent iron since it was necessary to use a susceptibility factor of about 0.15 to 0.18 c.g.s. units to satisfy certain anomalies. This appeared to indicate 50 to 60 per cent magnetite content.

However, when drill core and rock samples from trenching became available for susceptibility tests and comparative assays, it was evident that a figure of 0.50 c.g.s. units for the average susceptibility of the magnetite itself would not be greatly in error.

A recalculation of the potential of the iron-formation using a susceptibility of 0.50 c.g.s. units indicated that it would average about 20 per cent magnetite or about 14 per cent iron, and that any higher grade zones could not be expected to average over 33 per cent magnetite and about 24 per cent iron.

This final assessment was verified precisely by the drilling results, which indicated that the average magnetite content of sizable blocks of the iron-formation was very uniform and varied between 19 and 22 per cent. Only narrow sections were found to attain a 40 per cent magnetite content and these were not in sufficient quantity to raise the average grade of the block appreciably.

As previously mentioned, it had been postulated that the sharp peaks and lows could be due to one of two factors or a combination of both, namely: the presence of relatively narrow, high-grade bands of magnetite within the iron-formation or the presence of buried ridges in the bedrock surface.

However, the drilling results indicated that the bedrock surface had only minor local variations in height above sea level. Assay data indicated further that there was no section of iron-formation of a width of 20 ft. or more that would contain more than 30 per cent magnetite or less than 12 per cent magnetite.

It was concluded, therefore, that most of these sharp peaks and lows could be caused by a combination of these two factors, that is, the occurrence of low ridges in the bedrock surface composed of slightly higher grade material. This is compatible with the physical properties of the iron-formation, inasmuch as the higher grade sections composed essentially of magnetite and quartz would be more resistant to erosion and glacial action than the surrounding more schistose members.

However, it does seem likely that the very large positive anomalies and the true negative anomalies of the order of 10,000 gammas must be due to variations in the normal and the inverse remanent magnetization.

It is of interest to note in this respect that these very sharp positive and negative anomalies occur only in regions where the overburden is 20 ft. or less thick. It is probable, therefore, that if the overburden was generally of this thickness greater extremes would have been measured in many additional cases. The rather obvious conclusion from this reasoning is that where the overburden is heavy, the effects of remanent magnetization due to narrow bodies are integrated, resulting in a relatively uniform apparent susceptibility which in this case is about 0.50 c.g.s. units; and that where overburden is light the individual effect of the various bodies having widely different values from remanent magnetization, dominates.

Unfortunately, the results of the exploration were not sufficiently encouraging to warrant further work and enable this question to be investigated more thoroughly.

- Magnetic Anomaly Across Section Line 0+00

(a) Comparison of Observed and Calculated Data: The broad magnetic trough coincident with section line 0+00 (Figure 2) and within which the peak magnetic intensities are some 20,000 gammas below the level established by the iron-formation, could not be readily explained by topography, small variations in the magnetite content of the iron-formation, or remanent magnetization.

As it seemed odd that such a low should parallel and coincide with a section line it was regarded at first rather skeptically as possibly due to operational errors. Consequently, the line was checked and three east-west profiles were run with stations at 50-ft. intervals across it. The profile run along the 0+00 baseline is reproduced in Figure 4 along with a calculated curve.
electromagnetic survey was done over a large area, including detailed work in anomalous areas using McPhar vertical loop equipment. All conductors located were further investigated with a magnetometer.

(a) **Comparison of Airborne and Ground Magnetic Data:** Figure 1 shows also the airborne magnetic data for the region about Jeffries Lake. By comparing with the ground magnetic data for the immediate area about the lake, as shown in Figure 5, it is readily apparent that only the most prominent magnetic feature was detected by the airborne magnetic survey, namely, the band of iron-formation whose presence is indicated by the steep magnetic gradient in the northwest quarter of Jeffries Lake.

Unfortunately the smaller, localized anomalies beneath Jeffries Lake and to the northeast outlined by the ground survey were in such position that no flightlines passed near their centres and they were not detected.
However, these anomalies have been found to be caused by bodies of the order of 100 ft. wide and of limited strike length. Such bodies, producing an anomaly of about 2,000 gammas at ground level, could be expected to produce an anomaly not greatly in excess of 120 gamma at 500 ft. above ground. An anomaly of this magnitude could be detected only if the regional gradient were flat and if the flightline passed very close to the body. In the existing cross gradient varying from 30 to 200 gammas per 100 ft., their magnitude becomes relatively insignificant and at best a small bulge would be produced in the contours.

(b) Comparison of Airborne and Ground Electromagnetic Data: An airborne electromagnetic profile across the conductors in Jeffries Lake is shown in Figure 6; its location is found in Figure 5.

![Figure 6. Aeroelectromagnetic anomalies over Jeffries Lake, showing relation to the conductors indicated by ground surveys.](image)

These data were obtained with the Acromagnetic Surveys Limited equipment which reportedly measures simultaneously at two frequencies the phase angle between the applied primary field and the horizontal component of the resultant field.

Figure 6 shows the responses obtained at frequencies of 400 and 2300 c.p.s. at a flight level of about 400 ft. above ground. On the airborne record, a significant indication across the whole extent of the lake was obtained on both frequencies, while the ground electromagnetic data shown in Figure 7 indicate four distinct conductive zones.

Later experience has indicated that it is likely that the mildly conductive overburden and water in and about Jeffries Lake may have reduced the sharpness of the airborne anomalies and, as this effect is more pronounced on the high frequency, lowered the ratios of the low frequency to high frequency responses which are of the order of 0.5 to 0.75. It is possible, however, that the conductors are too close for complete resolution.

(c) Ground Magnetic and Electromagnetic Data:

It was found that there was a close correlation between the location of the conductors and the position of the moderate magnetic anomalies about Jeffries Lake, inasmuch as the conductors invariably were associated with a magnetic anomaly varying from a minimum of 300 to 500 gammas to a maximum of about 2,500 gammas. It was further shown that the best conductors on the basis of the magnitude of the response were present in association with the strongest magnetic anomalies. These stronger magnetic anomalies frequently were found at intersections of two conductive zones or where a conductor was offset due either to faulting or to folding.

Interpretation of the data from these surveys indicated that the dimensions of the bodies causing the larger magnetic anomalies in association with the conductors were of the order of 100 ft. wide, possibly 400 to 600 ft. long, and of rather limited vertical extent.

It was postulated that the conductors were sulphide mineralization in shears or beds, and that the mineralization along these zones would be local concentrations of pyrrhotite in association with other sulphides in folds or along faults.

Since the magnetic and the electromagnetic responses varied directly, it seemed likely that the percentage of pyrrhotite would rise as the total percentage of sulphides rose.

It was recognized that the presence of magnetite and/or graphite could alter the true situation, but after considering all related factors it was decided that the presence of appreciable amounts of disseminated to heavy sulphide mineralization offered the most logical explanation.

Diamond drilling was done to test a number of those localities where strong magnetic anomalies coincided with good conductivity, and the drilling later was extended to include investigations of good conductors with only small magnetic anomalies and even some poorer conductors in favourable structural situations.
Anomalies Along Section Line 108±00 East

(a) Comparison of Observed and Calculated Data: The data obtained for the conductor and the magnetic anomaly present near 38±00 north on section line 108±00 east are shown in Figure 7.

Here the observed magnetic anomaly is slightly in excess of 2,000 gammas and multi-frequency electromagnetic data indicate a conductor axis 50 to 75 ft. south of the magnetic peak.

The electromagnetic response on a frequency of 500 c.p.s. is somewhat less than on 1,000 c.p.s. and quite low on the 60 c.p.s. frequency. These data were interpreted by McPhar Geophysics Limited as indicating a good conductor but not massive sulphide mineralization. The poor response on the 60 c.p.s. frequency was thought to be due to the high magnetization of the conductor.

A calculated magnetic curve for a body 100 ft. wide and 350 ft. deep under 50 ft. of overburden, dipping to the south at about 57 degrees and having a susceptibility contrast of 0.012 c.g.s. units, also is shown in Figure 7. This curve fits the observed curve reasonably well, but it is possible that the actual magnetic body may be slightly narrower or have a somewhat greater concentration of magnetic material toward the footwall.

The magnetic data therefore indicate a body of limited vertical extent dipping steeply south. This con-
clusion conflicts with the electromagnetic data which indicate that the conductor has at least a moderate vertical extent and is either vertical or dips steeply north.

At the time of the interpretation, it was postulated that the distribution of the magnetic material did not conform exactly with the attitude of the conductor, nor persist over its full extent, but that it exists as a concentration near the present surface and rakes across the conductor at a slight angle.

On the basis of past experience in the area, it was assumed that the pyrrhotite itself has a very high susceptibility and the round figure of 0.10 c.g.s. units was used. The pyrrhotite content of the assumed body therefore was indicated to be about 12 per cent. Since this was hardly high enough to account for the observed conductivity, other conductive material such as other sulphides and/or graphite were inferred to be present. If other sulphides should be present, then the possibility of locating concentrations of economic metals would be reasonably good.

(b) Comparison of Drilling Results and Calculated Data: A drill hole on an azimuth of 330 degrees was drilled through this conductor. The hole began at an angle of 45 degrees but flattened to 32 degrees at the bottom, and cut through a graphic sulphide zone over a core length of 131 ft. The last 113 ft. of this zone were estimated to contain 40 per cent total sulphides including about 17 per cent pyrrhotite.

The sulphides are in nodules and blebs locally coalescing to form irregular seams of massive sulphides. The graphite is present for the most part as thin partings on slickensided surfaces and bedding planes.

Assuming 17 per cent pyrrhotite, a calculation of the susceptibility of the pyrrhotite itself indicates a value of the order of 0.07 c.g.s. units. This value is greater than normal but appears consistent with experience in this region.

The only other sulphide present in appreciable quantity is pyrite which was predominant in the first 18 ft. of the core and present in quantities up to 50 per cent with only very small local showings of pyrrhotite. In estimate, the pyrite averaged 23 per cent of the last 113 ft. of the intersection.

A possible explanation of the apparent disagreement in dip of the body as indicated by the magnetic and electromagnetic data, was found when logging the core. About halfway through the sulphide zone a 30-degree change in the angle of banding was noted, deeper in the hole the banding reverts to nearly the original angle. This change may be interpreted as a roll in the sulphide zone and is sufficient to change the dip of the body from about 70 degrees north to about 80 degrees south for a short distance as indicated by the dashed line in Figure 7.

General Comparison of Geophysical Data and Drilling Results

As previously mentioned, the drilling program included the testing of different combinations of magnetic and electromagnetic data. The results of these tests can be summarized as follows:

(1) All the conductive zones contained pyrite, pyrrhotite and graphite. No magnetite was noted in the core.

(2) Where the magnetic anomalies were low and the conductivity relatively poor, the zone was less than 50 ft. wide, contained little pyrrhotite, and was not highly graphitic.

(3) Where the magnetic anomalies were low and the conductivity good, the zone was broad and over 100 ft. wide. The better conductivity, however, could be due to either a greater percentage of sulphides or to more graphitic character. Pyrite in this case predominated over pyrrhotite.

(4) Where the magnetic anomalies were high and the conductivity was good, sulphides comprised 30 to 50 per cent of the material in the conductive zone and the pyrrhotite to pyrite ratio approached one to one. Graphite invariably was present but not dominant.

Since both the visual examination of the core and the assay results indicated that no appreciable amounts of economic metals were associated with the pyrrhotite and none whatsoever with the pyrite, the drilling was stopped after sufficient data were obtained.

In addition, the geophysical and the drilling data indicated that the pyrrhotite was limited both horizontally and vertically. It was further indicated that the great vertical extent of the conductors most likely was due to the consistent presence of graphite and that therefore there was little likelihood of encountering economically important mineral concentrations at depth.

Conclusions

These surveys, while a failure in the economic sense, point out that satisfactory and reasonable predictions can be made by the proper interpretation of
data from combined surveys of these types. Regional geological investigations and photographic interpretation often can provide important additional data upon which to base geophysical work.

The following points are worth consideration and although some have been pointed out in other publications are deemed worthy of being repeated here:

(1) The flightline spacing of an airborne survey is very important and should be considered in relation to the size of anomalous bodies sought or likely to be present.

While careful interpretation is important in assessing the data, in many cases small important magnetic features located by ground surveys and found to be important are not detected by airborne surveys because of inadequate flightline spacing. This points up the advisability of considering either closer line spacing or adequate follow-up methods on the ground in areas of interest.

(2) The airborne electromagnetic unit appears to be capable of indicating the presence of conductors which may be due to sulphide mineralization, and of locating them with a good degree of accuracy provided adequate topographical control is available for flightline positioning. A series of parallel conductors however, apparently produce a composite anomaly when their separation is less than one quarter of a mile and the individual peaks may not be recognized readily.

(3) When a number of one-line anomalies are obtained on a ground magnetic survey, it is advisable to obtain detailed data by running intermediate lines and lowering the station interval in critical regions to indicate the true magnitude, extent and trend of the anomalies.

(4) If detailed data are available and reasonably close approximations of existing conditions can be made, calculations based on magnetic data can give very good indications of the percentages of magnetite and pyrrhotite actually present. Valid geological data and reasoning play an important role at this stage.

(5) When considering the fine-grained early Precambrian types of iron-formation in Ontario, the susceptibility of the magnetite itself often seems to be quite high and of the order of 0.50 c.g.s. units. In many cases, notably where overburden cover is relatively thick, this value has given a satisfactory comparison between calculated and observed magnetic data when positive information such as drilling results are available. This high value for the apparent susceptibility may be due to the integrated effect of a large percentage of remnant magnetization. Where overburden cover is thin the effects of the remnant magnetization both normal and inverse are more noticeable and calculations are much less precise.

(6) Combined geophysical surveys employing electromagnetic and magnetic methods both in the air and on the ground often can be used to advantage in conjunction with geological and photographic data in locating and determining the character of sulphide mineralization at shallow or moderate depths. Of course, if no magnetite or pyrrhotite is present in a sulphide body it is doubtful, for example, that pyrite or galena could be distinguished readily from a graphite shear without resorting to supplementary methods such as a gravity survey, or to diamond drilling.

Generally it is advisable in mineral exploration to obtain positive data from drilling at a reasonably early stage. Frequently this can be done as cheaply as employing supplementary geophysical methods which still do not provide positive evidence of the type of anomalous body under consideration. The test drilling, furthermore, may provide information which would indicate which geophysical method is most applicable in the particular region under exploration.

(7) A continual and careful re-consideration of the geophysical data in the light of data acquired from drilling can be of great importance in determining the advisability of continuing or terminating a specific exploration program.

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THE ROLE OF GEOPHYSICS IN EXPLORATION IN NEW BRUNSWICK

by S. H. Ward*

Abstract

Over the period 1952-57, geologists, geophysicists and geochemists have gradually accumulated basic information concerning the impact of climate, topography, overburden, bush conditions, travel difficulties, ease of acquisition of property, and of specific geological and geochemical conditions, on exploration in central New Brunswick. Consequently there has been a gradual but persistent transition in the exploration procedures used during the period in question. Throughout this transition, more and more emphasis has been placed on the adaptation of geochemical and geophysical techniques to the search for sulphide mineralization. The typical result is a scientific exploration program differing radically from the previous custom of adding geophysical and geochemical techniques as appendages to an exploration program built around geological knowledge. Ore has been found by the new types of exploration programs.

In this paper, some of the exploration sequences used during the last five years in New Brunswick are discussed and illustrated with examples of both successes and failures. There is serious doubt concerning the economic advisability of uniform application of one fixed exploration sequence. The paper concludes with the observation that any exploration technique and sequence should be subject to constant review and revision for it to meet the economic, geological, and physical demands of the area of application.

CERTAIN basic facts must be faced by the exploration engineer when embarking upon any exploration program and full appreciation of these is essential to an intelligent undertaking. The following is a list of those pertinent facts which, taken as a whole, are peculiar to central New Brunswick.

1. There is a uniform, shallow, semi-residual drift, seldom exceeding 40 ft., throughout the area;

2. The rainfall, temperature, and drainage are such that this drift normally does not contain excessive dissolved salts or acids. This results in fairly low electrical conductivity in the soils. The same conditions are ideal for producing clear-cut abundance of metallic ions near sub-surface concentrations of metallic sulphides. Evidence of these abnormal metallic ion concentrations in the soils is projected over considerable distances by the heavy rainfall and the drainage pattern;

3. Topographically, the area is a plains of low relief with only minor local exceptions;

4. Generally, the bush is thick and overland travelling consequently is difficult;

5. Much of the country is difficult of access because of the few lakes, navigable streams, and all-weather roads;

6. The area is largely unpopulated and uncultivated and consequently the natural physical and chemical properties of the soils are undisturbed and uncontaminated.

7. Property acquisition in 1952 was not seriously complicated by special Crown grants, concessions or homesteading. Claim staking at first was limited only by transportation problems. Although much of central New Brunswick is staked solidly today, ground acquisition problems probably are simpler than in most of the older mining districts in Canada.

(8) Geological information over much of the area generally has been limited by the paucity of outcrops. Although structural controls on ore deposition are only being worked out today, certain other features are known which help formulate exploration programs. The country rocks are known to include: (a) slates and argillites, some of which are carbonaceous and graphitic; (b) rhyolites; (c) basic volcanic rocks; (d) greenstone-porphyrhy complex; (e) minor basic intrusive rocks; (f) the central granite “core”.

(9) Knowledge of the physical properties of the rock units listed above is of primary importance in the application of geophysical methods. To date, we have learned that the slates, argillites, rhyolites, basic volcanic rocks, and the greenstone-porphyrhy complex are of remarkably uniform density. With the exception of the basic volcanic rocks, these latter rock units are also of uniformly low magnetic susceptibility, except where sulphide mineralization is introduced.

We have learned also since 1952 that the typical massive sulphide bodies of the district possess the following characteristics: (a) high electrical conductivity; (b) high density; (c) direct or indirect association with magnetic minerals.

Over the last 5 years, the geologist, the geophysicist and the geochemist have gradually adjusted their approach to exploration as the above facts became known. Hence, there has been a gradual transition
from a simple, limited-scope type of exploration program to the broad-scale, highly technical programs exemplified by the work of such companies as The American Metal Company Limited and Kenno Explorations (Canada) Limited. Throughout this transition, more and more emphasis has been placed on the adaptation of geochemical and geophysical techniques in the search for sulphide mineralization. For the geophysicist this has meant a period of experimentation and opportunity.

Some geophysicists having had the opportunity of participating in this sequence of events have assessed the aforementioned list of facts and added an additional observation: that any ore found to date in New Brunswick has been associated with massive sulphides. This basic assumption, rightly or wrongly, has become an essential part of their exploration philosophy.

If one is willing to accept this assumption, then the list of facts suggest that several geophysical methods will prove advantageous and that an exploration program can be built around geophysical techniques. This has been done even though it meant a radical departure from the time-honoured custom of adding geophysical techniques as adjuncts to an exploration program based on geological knowledge. This new approach, then, owes much to the exploration opportunities offered by central New Brunswick. That it has been successful can be best attested to by the record of discoveries partially or wholly attributed to geophysical techniques. The two Brunswick Mining and Smelting Company orebodies and the Heath Steele orebodies fall in this category. Many other examples have been suggested.

**Typical Exploration Programs in New Brunswick**

Because of the gradual and persistent transition from small-scale to large-scale exploration programs, and because of the many different basic approaches employed, a complete study of all exploration sequences used to date in central New Brunswick is practically impossible. However, reference to several typical sequences probably will suffice to indicate the manner in which the exploration engineers have adapted themselves to changing conditions, facts, and new techniques.

Around 1952 a typical exploration program might consist of: (1) office study based on sketchy regional geology and government aeromagnetic maps which had just become available; (2) property acquisition, largely on the basis of the aeromagnetic data; (3) ground electrical survey, either electromagnetic, resistivity, or self-potential; (4) diamond drilling.

These early programs were based on true, reported or interpreted "facts" concerning the discovery of ore at the Brunswick, No. 6 orebody at Austin Brook. This massive sulphide ore at first was believed to be associated directly with magnetic iron-formation and hence large and intense anomalies on the government aeromagnetic sheets were prime targets for staking. Although the association between massive sulphide ores and magnetic minerals was shown later to be indirect, the approach did lead to at least one discovery: the Brunswick Mining and Smelting Company No. 12 body on Pabineau River. Some of the aeromagnetic anomalies on which staking was done were due to iron-formation interbanded with carbonaceous and/or graphitic slates, basic intrusive rocks and extrusive rocks, and a very few to pyrrhotite. For the most part, however, aeromagnetic maps merely reflected variations in the content of magnetite in the country rocks.

The experience at the Austin Brook property indicated that the massive pyritic ores had very high electrical conductivity relative to the host rocks and were readily located by electrical surveys of one form or another. Hence, subsequent to ground acquisition, an electrical survey was usually done, most often without the benefit of any detailed geological examination of the property. The reported complete lack of outcrop was responsible for this approach. The approach was modified when it was known that a few outcrops were available and that mapping of float could prove beneficial. Some electrical surveys could have been avoided and ground subsequently dropped if even cursory geological examination had been made.

Later, as most electrical anomalies were found to be carbonaceous and/or graphitic sediments, secondary methods such as geochemical soil sampling and gravity surveys were introduced, after the electrical survey and before drilling. This helped to avoid much drilling of graphite, but knowledge of the utility of gravity and geochemical surveys in this application was limited. Gradual experimentation with these techniques led to their efficient application.

As development of ground exploration techniques and sequences continued, interest was aroused in 1954 over the airborne electromagnetic (AEM) program conducted jointly by The American Metal Company Limited and by the International Nickel Company of
Canada, Limited. Although the latter had been employing AEM for 4 years prior to their entry into New Brunswick, their advanced approach had failed to attract much attention. However, with the discovery of the Heath Steele Mines orebodies at Little River, the rapid coverage of the AEM inspired many companies to embark upon large-scale exploration programs. These took several forms, some of which did not involve AEM as the primary field exploration tool.

A typical exploration sequence including AEM might be as follows:

1. Preliminary office study, based on available geological information, government aeromagnetic data, and aerial photographs;

2. Airborne electromagnetic survey;

3. Secondary office study; this involves a correlation of geological, aeromagnetic and AEM data;

4(a) Reconnaissance geochemical sampling of streams and/or soils;

4(b) Reconnaissance geological examination near AEM anomalies.

5. Ground acquisition;

6. Ground electromagnetic survey;

7. Detailed geological examination including pitting and trenching;

8. Detailed soil sampling;

9(a) Limited gravity surveys;

9(b) Limited magnetic surveys;

10. Diamond drilling.

In some instances steps 4(a) and/or 8 have been omitted; in other instances 4(a) and 4(b) have been combined in one operation under a field geologist. The choice of a limited gravity or a magnetic survey usually has been dependent upon the correlation, or lack thereof, between the AEM and aeromagnetic data. In only a few instances have both been applied.

In those programs where geochemical soil and stream sampling was the primary field tool, the AEM survey was dropped or changed positions with 4(a) in the above sequence.

As an example of what might be done with such an exploration sequence consider the sequence of events illustrated by Figures 1 to 4 inclusive.

A government aeromagnetic survey disclosed the anomaly outlined by the closed contours on Figure 1.

A subsequent helicopter electromagnetic survey on a large tract of land blanketing this area resulted in several anomalies, the peaks of which fall within the tight aeromagnetic closure of Figure 1. Geological examination of this anomalous area on the ground disclosed no evidence for the cause of the coinciding AEM and aeromagnetic anomalies; outcrops were very scarce. Confirmation was obtained, however, that the area probably was underlain by argillaceous sediments as was indicated by available government geological maps. Although geochemical soil sampling at the time of the geological study failed to disclose any significant anomalous metallic ion concentrations, the coinciding geophysical evidence warranted further work. Consequently the conductive zones causing the AEM anomalies were delineated by a ground electromagnetic survey (Figure 2). The conductors so delineated were mostly of good conductivity and at shallow depth.
Hence a limited gravity survey was planned to determine whether or not the cause of the conductors was high-density material such as massive sulphides. The gravity contours of Figure 2 were interpreted to indicate either a broad, disseminated sulphide body near surface, or alternatively a massive sulphide body at a depth perhaps as great as 1,000 ft. This property then appeared to be a "borderline case", probably demanding a small drilling program. Disseminated pyrrhotite near surface was the most probable cause of the geophysical anomalies observed. Diamond drilling was done to test both possibilities. Approximately 2 per cent sulphides, mostly pyrrhotite over a width of 500 ft., was encountered in the drilling. As illustrated in Figures 3 and 4, theoretically such mineralization was adequate to explain all the geophysical data. No economic values were returned from assays of the core (probably accounting for the lack of geochemical anomalies), and hence all work on the property was suspended.

Although this example illustrates the progressive narrowing down of the possible causes of the cumulative anomalies to probably barren, disseminated pyrrhotite, other instances have been noted where the successive steps in the sequence failed to eliminate the extraneous. One case is noted where interbanded iron-formation and graphite were drilled despite the following coincident anomalies: (1) aeromagnetic; (2) airborne electromagnetic; (3) ground electromagnetic; (4) geochemical (soil); (5) ground magnetic.

The "iron-formation" was finely banded and very lean in magnetite, but contained enough magnetite to produce magnetic anomalies of the order of those normally observed over large massive pyrrhotite "dykes." This iron-formation was found to contain abundant manganese which probably reacted as zinc in the routine geochemical tests. However, later detailed work did indicate that zinc ions were in the soil, but the amounts were such as might be explained as concentrations (of the normal zinc content of the inter-
bedded slates) brought about by accumulation in a drainage basin.

Figure 5 illustrates the last example. Perhaps the application of a gravity survey rather than a magnetic survey in this case might have shown that a large tonnage of massive sulphide mineralization was improbable, but in any event the large observed geochemical anomaly would have demanded some drilling.

In still another disappointing case, the gravity survey was applied only after substantial drilling had indicated both graphite and disseminated sulphides. Earlier application of the gravity survey might have lessened the drilling done, especially if the basic geophysical assumption of a persistent association between ore and massive sulphides in central New Brunswick had been accepted at the time.

**Conclusion**

Modern exploration in central New Brunswick involves progressive elimination of possible causes of primary geochemical or geophysical anomalies by the application of multiple exploration techniques. The typical causes of anomalies obtained with the various methods, provided these are employed in the latter sequence listed above, are as follows:

**Relevant Causes and Comments**

1. **AEM**
   - 1st group—massive sulphides, mostly pyrrhotite; graphitic shear zones; pyrrhotite stockworks.
   - 2nd group—massive sulphides, mostly pyrite; graphitic shear zones; coarsely disseminated pyrrhotite; massive magnetite.
5. Magnetic survey

All ore in New Brunswick has so far been directly or indirectly associated with ground magnetic anomalies. Since magnetic anomalies automatically infer the presence of pyrrhotite and/or magnetite, the presence of a magnetic anomaly coincident with anomalies found by electromagnetic, gravity and geochemical methods lends considerable weight to the probable occurrence of ore-grade mineralization.

There may be exceptions to the above analysis, as possibly is the reported ore at the Kenneo Explorations Clearwater property. However, no definite contradictory evidence currently is available to the writer provided the end result is ore as measured by 1957 prices.

This procedure of successive elimination of extraneous causes of anomalies sounds simple, but the vast mass of data to be dealt with in large-scale exploration programs in New Brunswick has not necessarily permitted all steps to be taken. Economic considerations and time factors often have dictated drilling prior to a complete technical sorting of the anomalies and/or to the complete sequence.

The lesson to be learned from the role of geophysics in exploration in New Brunswick is that the science of geophysical techniques and the art of interpretation of data should not be considered static. Both should be under constant review and revision as the knowledge of any specific mining camp grows.

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EXPLORATION OF A FORTY-SQUARE-MILE TRACT NEAR CAMERON LAKE, QUEBEC

by H. V. McMurry

Abstract

Electromagnetic and magnetic surveys were employed to survey a 40-square mile claim block near Cameron Lake, Quebec. Numerous conductors were found in areas underlain by volcanic tuffs and flows. Iron-formation bands in a belt of metamorphosed sediments also were mapped. The conductors tested by drilling were chiefly graphitic schists or carbonaceous sediments. Some sulphide mineralization was found, none of which approached ore grade, and minor amounts of gold were found in association with structurally disturbed portions of certain iron-formation bands.

IN 1948 The New Jersey Zinc Company optioned a block of 108 claims in Desjardins and Currie townships, Quebec and the following year an agreement was reached with Dominion Gulf Company for the joint exploration of areas surrounding this block. The Gulf-Zinc holdings were staked for the most part between 1949 and 1951; they amounted to about 450 claims in addition to the original 108. The total area explored covered almost 40 square miles.

Figure 1 is a key map which gives the geographical location of the claims. They lie in a belt of greenstones known to extend from the Quebec-Ontario boundary northeastward into the Chibougamau district. The belt was considered to be favourable for prospecting on the basis of a number of base metal and gold discoveries for the most part northeast of Cameron Lake. In addition, the Cameron Lake area itself was held to be attractive because of a history of minor gold production from a property just west of Cameron Lake. The Cameron Lake granite stock in the immediate vicinity of the lake was looked upon as a possible source of ore-bearing solutions.

Summary of Geology

Figure 2 is a generalized geological map showing the major features of the property. All the rocks are Precambrian, and are part of a persistent belt of variable, Keewatin-type flows and pyroclastics bordered and invaded by granitic rocks. Between Rose and Cameron lakes are some rocks of sedimentary origin, chiefly arkose, greywacke and iron-formation, enfolded with the Keewatin rocks. The latter are intruded by a group of much altered diorites and gabbro, massive and gneissic granite, and a variety of dykes of related origin.

The volcanics and sediments have been closely folded along axes which trend west on the west part of the property, and southeasterly on the east part.
The schistosity follows these trends, in general, but around the granite stock north of Cameron Lake corresponds roughly to the contact. The dip of the schistosity and the bedding is generally steeply to the north, though some vertical and southward dips also are recorded.

Initial prospecting interest in the area was prompted by generally favourable geological conditions and the discovery of gold in quartz veins or in sheared and silicified zones in volcanics and tuffs. The latter are often heavily carbonated and impregnated with pyrite, pyrrhotite and minor sphalerite and chalcopyrite, and were the chief centre of interest in the New Jersey Zinc exploration program.

Geophysical Methods Employed at Cameron Lake

The amount of outcrop present on the Cameron Lake claims was small in comparison to the area to be explored and for this reason it was necessary to emphasize geophysical methods for the exploration of the property. Electromagnetic and magnetic surveys were used extensively.

- Electromagnetic Methods

*Vertical Coil Apparatus:* Most of the electromagnetic reconnaissance involved the measurement of the inclination of the electromagnetic field at stations in the plane of a large, vertical source loop, fed by a 900-cycle, 3 k.w. generator driven by a 5-h.p., 2-cycle engine. Observations were made on the inclination of the electromagnetic field at 100-ft. intervals, starting from 100 and ranging to about 2,000 ft. from the source. Receivers were employed on both sides of the loop. Traverse lines were oriented north-south and were spaced at 500-ft. intervals. East-west base lines were cut at intervals of about 4,000 ft. in order to provide access to the traverse lines. The base lines were also covered by the electromagnetic survey.

Five men were required to operate the equipment efficiently, two for the receivers and three to transport,
assemble, and operate the source equipment. Two source loops were provided so that one could be moved and erected at the next station while a survey was in progress.

Approximately 400 miles of reconnaissance survey was done with this type of equipment, and the average rate of work was about 2½ miles of line per day.

The effect of the currents induced in conductors is such as to cause the electromagnetic flux to pass over or around the conductor much as water flows over or around a dam or impermeable barrier. The inclinations observed at the surface are therefore directed away from the conductor.

In the Cameron Lake area the basement rocks are steeply dipping, metamorphosed sediments and flows, and the conductors present in this environment usually have the same dip as that of the host rocks. When a traverse passes over a steeply dipping conductor, a reversal of inclination takes place above the conductor; Figure 3 is an example of this behaviour. The results from four adjacent profiles are shown.

The anomaly caused by a steeply dipping planar body tends to be small if the source loop is aligned at right angles to the strike of the conductor. This is because the conductor under these circumstances intercepts very little primary flux. When the traverse lines were laid out at Cameron Lake, it was judged that in general northeasterly strikes would be encountered and that north-south traverse lines would be acceptable. Actually it developed that in Desjardins township, many of the strikes were about east-west and therefore were unfavourably disposed for detection by north-south traverse lines. In spite of this disadvantage many conductors were found; furthermore, check data obtained with Boliden equipment to be described, did not disclose any major occurrences not indicated on the north-south traverses. To the east in Currie township southeast strikes were the rule. The vertical loop data in this area were found to be generally somewhat superior to the average of results obtained where east-west strikes were the rule.

The inclinations, in general, did not return to zero at large distances beyond the apexes of conductors; this can be ascribed to the fact that the conductors were in the form of large sheets. The eddy currents induced in these sheets circulate in such wide loops that their effects persist for long distances from the conductor.

*Boliden Electromagnetic Apparatus:* The vertical coil apparatus, though effective for reconnaissance purposes, was bulky and not well suited to the detailing of anomaly zones. Accordingly, much of the detail follow-up to the reconnaissance work was done with Boliden loop-frame electromagnetic apparatus obtained from the Boliden Mining Company of Sweden. This equipment was used also for reconnaissance over many of the north claims during the latter part of the exploration.

The Boliden equipment measures variations in the magnitudes of the in-phase and out-of-phase components of the vertical component of the field from a horizontal source coil; the measurement is made at a point exactly 40 meters from the source coil. Variations in field intensity are expressed in terms of per cent of the normal “free air” field at the receiver. A 3,600-cycle vacuum tube oscillator supplies power to the source loop.
MINING GEOPHYSICS

Figure 4 is a contoured presentation of the in-phase Boliden data over the same traverses as shown on Figure 3. The strong, elongated, negative anomaly zones coincide with the locations of inclination reversals for the 900-cycle vertical loop survey shown on Figure 3.

Boliden detail data involving about 250 miles of traverse were worked out on lines about 160-170 ft. apart, that is, two intermediate lines were cut between each of the 500-ft. separated reconnaissance lines in areas where detail was desired. In addition about 125 miles of reconnaissance was done using Boliden apparatus rather than vertical loop equipment. An average of about 2 miles per day was achieved over long periods of time. Four men are required to operate the Boliden equipment; hence, the amount of line covered per man-day was comparable to that obtained with vertical loop apparatus.

The Boliden apparatus appeared to be as effective at disclosing conductors at Cameron Lake as was the vertical coil equipment. However, most of the conductors which were tested by drilling were, relatively shallow (under 100 ft. deep). It is likely that the vertical loop equipment would have been more effective than the Boliden apparatus in areas where target depths exceeded 100 ft., but no comparisons under such conditions are available.

- Magnetic Surveys

Ground magnetometer data were obtained over lines 500 ft. apart on most of the areas in which conductors were found from the reconnaissance electromagnetic surveys. Little was inferred from these data other than that some electromagnetic anomalies were associated with magnetic anomalies and some were not. The magnetic anomalies tended to be less continuous than were the electromagnetic anomalies.

Areas which were detailed with the Boliden equipment on lines 160-170 ft. apart were covered also with a magnetometer and in such cases the magnetometer results sometimes added to the structural picture of the host rocks containing the conductors. In other cases where detailed data were obtained, the distribution of magnetic anomalies appeared to be rather haphazard as compared to the distribution of electromagnetic anomalies.

Almost all the conductors found by the electromagnetic surveys were associated with volcanic tuffs and flows. Large areas underlain by metamorphosed sediments were present in which almost no conductors occurred. However, interest in these rocks was de-
Developed as a result of the discovery in 1950, by a prospecting team, of gold in a thin band of iron-formation lying in the metasediments. Accordingly, reconnaissance magnetic surveys were done over much of the territory underlain by the meta-sediments and several bands of iron-formation, both extensive and local, were mapped.

It was hoped that gold concentrations might exist in areas where iron-formation bands had been strongly folded, and with this in mind, several local iron-formation bands, including the one in which the gold discovery had been made, were subjected to detailed magnetic surveys. Evidence of structural deformation was readily obtained and a few promising cases were tested by drilling or trenching, but the results, though not completely negative, were disappointing.

**General Results**

Many conductors were found by the electromagnetic surveys; their distribution is shown in Figure 5. For the most part the conductors occur in west- or northwest-trending bands although a few isolated groups of conductors were found.

The locations of iron-formation bands as deduced from reconnaissance ground magnetometer data also are shown on Figure 5. Several of the bands are over 2 miles long but none extends across the entire area. The manner in which the iron-formation bands come and go suggests that the magnetite was concentrated by sedimentary deposition.

The distribution of conductors and of iron-formation bands indicates regional structural trends present in the area. The changes in strike of the conductors which take place on the Currie-Desjardins boundary line and in the southeast portion of the claim block are particularly noticeable.

The contact between the volcanic rocks which are the host rocks for the conductors which were found, and the meta-sediments in which the iron-formation bands occur could not be established accurately, because the magnetic contrast between the volcanics and the meta-sediments is not always appreciable. The iron-formation bands themselves constitute only a small part of the section of metamorphosed sediments.
Examples of Areas Studied in Detail

Case 1—An Area in the Southeast Part of the Cameron Lake Claim Block in Which Geological and Electromagnetic Reconnaissance Had Disclosed Conductors Lying in Volcanic Rocks.

This area was chosen for discussion because its exploration history is typical of work done elsewhere on the Cameron Lake claims where base metal sulphide conductors were sought.

Figure 6 is a location map of the area in question. Geological data are shown on this map, based on scattered outcrops which were found in varying abundance. The rock types consist of volcanic flows and intrusives.

Figure 7 depicts the locations of conductors deduced from the vertical coil reconnaissance electromagnetic survey. The conductors are widely distributed save in the northeast portion of the area where none at all were found; this is also an area where outcrops were relatively scarce.

Figure 8 gives the results of a detailed electromagnetic survey using Boliden equipment over north-south lines spaced about 165 ft. apart (two new lines cut between the reconnaissance lines). The detail survey did not extend into the northeast part of the area because of the negative results obtained there with the reconnaissance survey. It was not possible to reproduce the Boliden contours in exact detail on a map of the scale of Figure 8 but the general nature of the contoured data is well represented. As might be expected, the conductors are outlined in greater detail by the Boliden data than by the reconnaissance vertical coil data.

Magnetic data were obtained over the same traverses as were followed using the Boliden equipment and are shown on Figure 9. The magnetic contours were too irregular to be readily displayed on a map of the scale of Figure 9 and for this reason only the outlines of the magnetic highs are shown.

Both the electromagnetic and the magnetic maps show a change in regional strike from northwest to about west in passing from the west to the east parts of the map. The magnetic bodies to the east are smaller and less regular in distribution than are the
magnetic bodies to the west. The conductors, though somewhat more complex in distribution in the east than in the west, nevertheless are more regular and continuous than are the magnetic bodies. The magnetic and electromagnetic anomalies are not obviously related to each other; in some instances they coincide and in others they do not. Neither type of anomaly appears to be associated with a given rock type and even the diorite bodies are not especially magnetic. The geological trends indicated by the magnetic and the electromagnetic data agree well. In general, these trends are in harmony also with the trends shown on the geological map. Although the correspondence is not exact, it is felt that some disagreement is to be expected merely on the basis that the amount of outcrop present was limited.

Figure 10 gives the results, to an enlarged scale, of Boliden and magnetic surveys over a small part of the area covered by Figures 6-9. The three drill holes shown were selected to test zones in which magnetic and electromagnetic anomalies coincided and where the magnetic data indicate structural deformation in the host rocks. The fault shown on the figures was deduced from geological observations. None of the drill holes encountered ore-grade mineralization although much pyrite and pyrrhotite were found. Many carbonaceous beds were present.

Case 2—Example of a Small Area in the Iron-Formation Which Was Detailed Magnetically for the Purpose of Guiding Exploration for Gold.

Data from a detailed survey over part of an iron-formation band are shown on Figure 11. The contours are based on a survey over lines about 165 ft. apart with stations taken at intervals of 50 ft. The data are suggestive of a strong local fold in the iron-formation. The two drill holes shown on the map failed to find significant gold associated with this structure.

Drilling Results

The number of conductors greatly exceeded expectations and it was not possible to drill all; accordingly, the drilling program was planned with the objective of sampling conductors widely distributed over the entire area. Each drill site was selected on the basis of the strength of the anomaly associated with the conductor, on structural information provided by electromagnetic and magnetic data, and upon other geological factors such as the proximity to intrusive rocks. Two intrusions were of special interest: the Cameron Lake stock, and the small diorite plug in the southwest part of the area.

Over 100 drill holes totalling over 40,000 ft. of drill-core were put down in testing the conductors at Cameron Lake. Most of the conductors penetrated consisted of carbonaceous or graphitic material with or without pyrite and/or pyrrhotite. Traces of base metal mineralization were found here and there but none approached ore grade.

Only a few diamond drill holes were used to test for gold associated with structures in iron-formation, but much stripping, trenching, and X-ray drilling were done on iron-formation prospects. No deposits of commercial interest were found.

Electrical Surveys in Drill Holes

Resistivity measurements were made in 16 widely scattered, representative drill holes on the Cameron Lake claims to obtain quantitative information on the resistivities of conductors responsible for the strong electromagnetic anomalies disclosed, and to determine whether significant differences in resistivities existed between carbonaceous conductors and dominantly sulphide conductors.

Each hole was first surveyed by the single-electrode resistance method with observations being taken at 5-ft. intervals. This permitted the rapid identification of conductive zones in the holes. Resistivity measurements were then confined largely to the conductors.

The electrode system used with the resistivity apparatus comprised two narrow cylindrical metal bands mounted 12½ inches apart on a ¾-inch di-
Figure 10. Large scale maps of detailed magnetic and Boliden data.
Figure 11. Detailed magnetometer survey over iron-formation.
ameter, cylindrical insulating rod. The 12½-inch electrode interval was large in terms of the drill hole diameters (EX holes) but short compared to the thicknesses of many of the conductors penetrated. It was judged that this design should minimize effects caused by the upper and the lower boundaries of the conductors penetrated and by the water in the hole.

Figures 12 and 13 illustrate typical single-electrode resistance and two-electrode resistivity data from three representative holes, including Hole No. 5 which appears on Figure 10. No strong distinction exists between the resistivities of the dominantly carbonaceous conductors and the resistivities of conductors which contain relatively high percentages of sulphides. This held true for data from the other holes which were surveyed. The resistivities of the best conductors were on the order of 5 meter-ohms as compared to 10,000 meter-ohms or more for the barren host rock.

Revised Prospecting Tactics

Prospecting tactics have changed from those described here partly as a result of experiences at Cameron Lake. Lightweight electromagnetic equipment has been developed which can be operated by two men at a somewhat faster rate than five men using the large, vertical loop equipment or four men with Boliden equipment. There is a growing tendency to defer diamond drilling as long as possible in order to determine how many, if any, conductors are shallow enough to be exposed by trenching. Gravity surveys are coming into favour as a means for discriminating against conductors in the form of carbonaceous or graphitic rocks.

Acknowledgments

The courtesy of Dominion Gulf Company and The New Jersey Zinc Company in releasing the geophysical information on Cameron Lake for publication is acknowledged. Helpful criticism and advice from the many Dominion Gulf and The New Jersey Zinc personnel who worked on the Cameron Lake venture were of great importance to the preparation of this manuscript and are much appreciated.
DISCOVERY OF THE MOBRUN COPPER LTD. SULPHIDE DEPOSIT
NORANDA MINING DISTRICT, QUEBEC

by H. O. Seigel*, H. A. Winkler**, and J. B. Boniwell†

Abstract

The Mobrun sulphide deposit was discovered by geophysical methods in an area which has been prospected intensively for forty years. The initial discovery was made by vehicle-borne electromagnetic instruments, and the conductor was determined to be of interest by virtue of a 1.3 milligal gravity anomaly with which it correlated. After the discovery, detailed electromagnetic, gravimetric, resistivity, magnetometric, spontaneous polarization and geochemical soil surveys were employed to give additional information. Quantitative interpretation of the results of the electromagnetic, gravimetric and resistivity surveys enabled accurate estimates of the following features of the sulphide body to be made prior to the drilling:

(a) Depth of cover;
(b) Average percentage of sulphide content in the central sections;
(c) Length, width and attitude;
(d) Total tonnage of sulphides.

The magnetometric, spontaneous polarization and soil sampling surveys gave no useful results as the body is non-magnetic and buried under the permanent water table beneath a shallow mantle of leneustrine clay. The nearest outcrop, non-mineralized rhyolite, is 1,600 ft. distant from the sulphide body.

![Locational plan of Mobrun sulphide deposit, Quebec](image)

The Mobrun deposit was found by vehicle-borne electromagnetic instruments and checked by auxiliary ground gravimetric and electromagnetic surveys. The conductor was located in November, 1954, but because of snow-blocked roads it was not ground-checked until May, 1955.

The sulphide body straddles the road between ranges VII and VIII at the southeast corner of Lot 52, in Dufresnoy township, about 10 miles northeast of the town of Noranda, Quebec, (Figure 1).

The deposit has been outlined to a depth of 600 ft. The tendency of the deeper drill holes to flatten caused considerable difficulty, but after wedging, one hole was drilled to 1,000 ft. vertical depth.

Geology

The geology of the Clericy district is depicted on Map 635A accompanying Geological Survey of Canada Memoir 233 (Ambrose (1)). In addition, the Quebec Department of Mines has published a geological compilation map, on a scale of one inch equals 1,000 feet, but this is essentially an enlargement of G.S.C. Map 635A.

The sulphide mass occurs mainly as a replacement of sheared rhyolite at a rhyolite-basic tuff contact. The rocks to the south are rhyolites, rhyolite breccia and rhyolite tuffs, and to the north are basic volcanics and basic tuffs with occasional rhyolite members. The formations dip almost vertically and strike about N80°W, or somewhat more westerly than the regional strike (N50°W). The deposit is on or near the axis of the Clericy syncline.

The body is roughly 1,000 ft. long and averages 56 ft. wide. The mineralization comprises a core of fine-grained, massive, "cherty" pyrite containing sphalerite as a contemporaneous mineral, and chalcopyrite as a later stage on joint planes and in areas of brecciation. Disseminated pyrite is present in both

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*Consulting Geophysicist, Toronto.
**Chief Geophysicist, Rio Canadian Exploration Ltd.
†Geophysicist, Rio Canadian Exploration Ltd.
walls to as much as 100 ft. on the south side of the body, and into rhyolite on the north wall but normally does not penetrate much farther than 20 ft. into the well-bedded basic tuff.

History

Geological surveys, from reconnaissance to detailed claim mapping, have been carried on in the Clericy area since 1918, and a dozen reference reports are mentioned by Ambrose (1).

Mineral prospecting, not documented, has been done for at least that long and must have been rather intense in the vicinity of Mobrun prior to 1928 when the Harvie shafts were sunk. The Copper Hill shaft is a scant mile southeast of the Mobrun deposit, and on its strike. Some self-potential and electromagnetic surveys were done in this vicinity about 1935.

The Clericy area was prospected by Rio Canadian Exploration Ltd. geophysical crews in the winter of 1954-55, during the normal course of reconnaissance of northwest Quebec.

The decision to investigate northwest Quebec was based on the favourable geology and on an abundance of roads along which the crews could work.

An effective geophysical system had been developed and tested during the previous year in New Brunswick and the Eastern Townships area of Quebec.

Geophysical Sequence

The prospecting program consisted of a primary electromagnetic reconnaissance along public roads, followed by routine gravimetric and geochemical soil surveys also along the roads, but only in the vicinity of conductors. Those conductors which coincided with anomalous soil analyses or positive gravity anomalies, or both, were tested further with a magnetic survey and repeated electromagnetic, gravimetric and geochemical traverses.

Geological reconnaissance was restricted to anomalous conductors in summer, and was omitted altogether in the winter months. Its greatest value was found to be in the identification of anomalies due to graphite zones, man-made conductors, man-laid chemical contaminants, and the effects of sub-surface topography on the gravity measurements.

It was recognized at the outset that this type of exploration, restricted to public roads, is at best only random sampling of the geological possibilities of a large area, but it was reasoned that the very casual nature of the sampling might, statistically, be as fruitful in the long run as a thorough investigation of a much smaller area. The results seem to have proved the strength of this reasoning.

Mobile Reconnaissance Unit

The geophysical crews and their equipment, operating in the sequence described above, were collectively identified as the mobile reconnaissance unit, conveniently abbreviated to M.R.U.

The M.R.U. operated throughout the year, regardless of snow and road conditions, by the use of snowmobiles, power wagons and skis, and by the practice of deferring the examination of impassable roads until their surface became firm.

The three sequential phases of conductor location, gravity-geochemical testing, and re-examination were termed the primary reconnaissance, the follow-up, and the re-check respectively, and are described below. Differences from routine practice are described in some detail.

- Primary Reconnaissance

The mobile electromagnetic reconnaissance equipment consisted of a transmitter and a receiver, each mounted in enclosed trailers. The trailers were pulled by trucks or snowmobiles; the receiver trailer was separated from its truck by a 20-ft. boom to reduce the effect of engine noise.

The transmitter coil was suspended from a damped pendulum mount so that the plane was always vertical, and was manually oriented so that its plane passed through the receiving coil position. It was energized by a 1,000-watt, gasoline-driven motor generator set, at a frequency dependent on the type of soil in the search area. In the Noranda area, the frequency employed was 400 c.p.s.

The multiple coil receiving system, mounted on a damped pendulum, automatically produced a signal related to the tilt of the resultant electromagnetic field, and this signal was recorded on an Esterline Angus instrument. A fiducial pen was actuated automatically by a bicycle wheel tachometer unit, at 200-ft. intervals. Manual control was provided for recording road tie-points on the record trace. Signal amplitude and zero balance were adjusted periodically as dictated by power line and other noises.

The separation of transmitter and receiver units was kept at approximately 200 ft., but this was not critical because of the nature of the receiver system.
Laboratory model studies showed that the system’s records could be analyzed to provide conductor-road intersection locations to within 50 ft., and that the conductivity, the depth, and the strike direction could be determined qualitatively.

Figure 2a shows that portions of the record over the Mobrun deposit, with the traverse direction, amplitude scale (in degrees of tilt), fiducial marks, and tie-point mark indicated. The fiducial marks are not equidistant on the record since constant truck speed could not be maintained. Interpolated distances between successive fiducial marks had to be judged on the assumption of constant speed, which introduced some error.

The conductor-road intersection point is shown by an arrow (Conductor 96). This point resulted from two trace analyses and represents the average of two locations obtained from different parts and properties of the anomalous curve. The distance between the nearest tie-point (No. 210) and the Conductor 96 arrow is shown; this distance had to be used by the follow-up gravity crew to locate the conductor on the road. This trace was obtained on November 2nd, 1954.
• **Follow-Up**

The follow-up crew were given a tie-point map, and a list of conductors and their distances and direction from these points. The instruments comprised car (or snowmobile)-mounted Heiland gravimeters, Cooke level and stadia rod, soil sampling augers, sample bags, and an axe. The vehicle was equipped with a precision tachometer graduated in hundredths of a mile, friction-driven by the rim of a tire, and manually engaged only when measuring distances from tie-points.

The conductor-road intersection was located and permanently blazed on a convenient post or tree.

The gravity traverse was made on 100-ft. stations, paced out and marked on the road (or the shoulder) by scratching furrows. The soil samples were taken while the gravimeter was being read and after the stations were marked. The two-man crew then completed this phase of the work by levelling the traverse.

The gravimeter operator made visual estimates of terrain corrections to Zone “C” (2) and also estimates of road-fill effects with the aid of standardized charts. For these calculations, and also for the Bouguer corrections, it was assumed that rock density was uniform at 2.65 gm./cc. and road-fill uniform at 2.0 gm./cc.

No attempt was made by this crew to estimate the probable topographic contours on the sub-surface rock overburden interface; this was done by the geologist during his subsequent examination of anomalous conductors.

The soil sampling presented difficulties in the winter and in swamps where the road surface was above ground level. Wherever possible, samples were taken above the road and on the far side of the ditch to avoid contamination by mine dump road metal and metalliferous ditch water. Sampling depth normally was 24 inches. Samples were analyzed for total loosely bonded ions of copper, lead and zinc, sometimes in the field office, but generally in the laboratory. A laboratory analysis was made in any case, and anomalous samples were further analyzed by a digestion method and by spectroscope.

**Figure 3.** Electromagnetic and soil sampling surveys over Mobrun orebody.
Figure 2b shows the gravity profile (Bouger anomaly) for Conductor 96. This curve was obtained in May, 1955, the road being impassable through the winter. The asymmetric station distribution about the conductor was the outcome of incorrect tie-point selection; the tie-point was one of two culverts within 600 ft. of each other. This error was eliminated, and conductor-gravity anomaly coincidence was established by the next phase of the reconnaissance program.

- Re-checks

The re-check crew were given a descriptive list of blaze marks in addition to the tie-point maps, and worked from the blaze mark, testing the conductor with a standard 1,000 c.p.s. vertical loop electromagnetic instrument. Where power line noise interfered, the primary mobile unit was employed for this check, and the conductor-road intersection was related accurately to the previous blaze mark so that the gravity and the geochemical anomalies could be referred to the conductor. The gravity traverse was repeated, in part at least, and a magnetic traverse was made with a Watt or Sharpe vertical intensity balance.

Also, fresh soil samples were taken. A geologist scouted the area for outcrops, estimated the configuration of the sub-surface topography on the rock overburden interface, and evaluated the prospect on geological evidence.

- Extended Surveys

(a) Electromagnetic and Soil Sampling: Figure 3 shows the detailed electromagnetic survey (vertical loop) with lines at 200-ft. intervals which indicated that Conductor 96 was about 1,000 ft. long. The asymmetry of the curves indicated that the conductor dipped steeply northward, or at variance with the original belief that the location was on the north flank of the Cleric syncline.

The locations of forty-three deep soil samples, taken at 50-ft. intervals across the conductor axis, also are shown on Figure 3. These samples were recovered from as great a depth as possible, generally below 5 ft. Some samples were analyzed both by the "total heavy metals" method and chemically, yielding individual copper-lead-zinc content. Only three samples gave more than normal background amounts of copper or

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Figure 4. Contour plan of vertical magnetic intensities over Mobrun orebody.
zinc, and these were of low magnitude and, lying on
the north or "up glacier" side of the conductor, were
regarded as not significant. However, their locations
down the present drainage direction from the body
may be of importance.

(b) Magnetometer Survey: Power and telephone
lines, fences, metal-roofed barns, etc., made magnet-
tometer measurements erratic in the immediate
vicinity of the sulphide body; however, Figure 4
shows what is believed to be a reliable set of obser-
vations. There appears to be a magnetic depression,
of the order of 100-gamma maximum, generally (but not too
faithfully) associated with the conductor.

(c) Gravimeter Survey: The results of a gravity
survey near the conductor are shown on Figure 5.
From the observed gravity values a uniform gradient,
increasing at the rate of 0.79 milligals per 1,000 ft.
N33°E, has been removed as expressing empirically
the regional gravity gradient in the area. The correla-
tion of the residual gravity anomaly, of the order of
1.6 milligals peak magnitude, with the projection of
the sulphide body is worth noting.

By simple graphical integration of the area within
the various contour intervals (Hammer, 3) an estimate
was made of the total excess mass of the gravity
anomaly source down to about 1,000 ft. A figure of
4,000,000 tons of massive sulphides or a larger ton-
age of less concentrated sulphides would be required
(down to about 1,000 ft.) to explain the observed
gravity anomaly.

To obtain some idea of the shape of the body the
section S-N of Figure 6 was "curve fitted". The best
two-dimensional fit, obtained by interpolation of two
trial theoretical curves, was a body about 100 ft. wide,
20 ft. to upper surface, and about 650 ft. to the lower
surface, with an excess density of about 1.65 gm./cc.
At this stage, it became almost certain that we were
dealing with a concentrated pyrite body, for no known
rock type is of such high density (and non-magnetic).
Assuming that pyrite has a density of 5.0 gm./cc. and
that the country rock has a density of 2.8 gm./cc.,
this deduced density contrast implies a pyrite content
of about 85 per cent over the 100-ft. width. Actual
measurements on core samples have indicated an
Figure 6. Gravity profile and geological section, S-N Mobrun orebody.
average density of 2.70 gm./cc. for both the rhyolite to the south and the basic tuffs to the north of the orebody. The massive sulphides may have an average density of about 4.63 gm./cc. (83 samples), but possibly this figure is not representative of the body as whole.

(d) Resistivity Survey: Alternating current resistivity methods, using 1,000 c.p.s. for expediency, were used to determine the depth of drift in the vicinity of the conductor and away from it (Heiland 4). For this purpose a standard expanding four-electrode (Wenner) array was used, and the results were interpreted by matching two- and three-layer theoretical resistivity curves. The direction of expansion was always taken parallel to the conductor direction so as to keep conditions as uniform as possible. In this way depths ranging from about 20 ft. to 40 ft. were obtained. Figure 7 shows the expanding resistivity curve No. 2 and its theoretical fit obtained 300 ft. north of the body on the centre line. A depth of 19 ft. to bedrock was deducted. This agrees well with 25 ft. of overburden in Hole 22, fifty feet to the north and down slope from this point.

A profile across the centre of the conductor, using a Wenner array with a fixed electrode spacing of 80 ft., gave an indication of the conductor presence but, because of power line interference, an independent estimate of the width of the body could not be obtained.

(e) Spontaneous Polarization: A limited spontaneous polarization survey was carried out, largely as a matter of interest, prior to the drilling. It gave no appreciable indication of the presence of the conductor. The presence of the lacustrine clays and the high water table makes this lack of indication not surprising. No oxidation is thought to be on the surface of the sulphide mass.

Summary

At the close of the detailed geophysical program it had been established that a body of near-massive pyrite had been found, containing about 4,000,000 tons above 1,000 ft. depth, dipping steeply northward, about 1,000 ft. long and 100 ft. wide at its centre, and probably at least 600 ft. in depth.

These deductions were made in June, 1955, about four months before the first drill hole was put down. The degree of accuracy of the predictions is remarkable to the point of being fortuitous in some respects (e.g. depth extent of the massive sulphide zone).

All that was needed to fire the imagination in anticipation of the drill results was verification that the body contained appreciable base metal values. On
Investigation it was found that a farmer had drilled a 6-inch hole ("A" on Figure 4) to bedrock right on the sulphide zone. He had intended to probe for water but finding none, had moved to point "B", drilled 140 ft. into bedrock, and got a good flow from a fissure. This latter hole is within 30 feet of the north margin of the sulphide body which has very little disseminated material. A few fragments of pyrite carrying significant gold, copper and zinc showings were obtained from hole “A" by driving a hardened steel bit into bedrock.

Drilling was begun on October 26, 1955. In all, twenty-three drill holes, totalling about 15,000 ft., have been put down to date. The tonnage included in the ore estimates (to 600 ft. depth), (published in The Northern Miner, June 28, 1956), is as follows:

<table>
<thead>
<tr>
<th>Tons</th>
<th>Cu</th>
<th>Zn</th>
<th>Au</th>
<th>Ag</th>
<th>Sulphur</th>
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<tr>
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<td>0.69</td>
<td>2.18</td>
<td>0.052</td>
<td>0.62</td>
<td>37.4</td>
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Conclusions

A statistical approach to exploration for large, massive sulphide deposits by random sampling of a generally favourable geological area has resulted in the discovery of the type of target sought, albeit low grade. The detailed geophysical investigation prior to drilling proved useful in guiding the drilling program, and led to remarkably accurate predictions.

Acknowledgment

The authors wish to express their gratitude to the management of Rio Canadian Exploration Ltd., and particularly to Dr. D. R. Derry, president, for permission to publish, and for generous assistance in the preparation of this paper, The details of the geology in the vicinity of the sulphide body are furnished by C. W. Pegg, geologist for Rio Canadian Exploration Ltd.

The specific gravity determinations on core samples quoted above were made by J. Goetz, a student at the University of Toronto.

REFERENCES

1. Ambrose, J. W.: Clericy and La Pause Map Area, Quebec, Geol. Surv., Canada, Memoir 233, 1941.
A SULPHIDE DISCOVERY, ROBB-JAMIESON AREA, ONTARIO

by N. R. Paterson

Abstract

The Robb-Jamieson area, just west of Timmins in northern Ontario, was prospected for gold in the early years of this century. More recently, attention has been directed at the search for base-metal sulphide deposits, particularly of copper and zinc.

The bedrock consists of Precambrian lavas and volcanic fragmentals, tightly folded and intruded by both acidic and basic igneous rocks. The sulphide bodies are hydrothermal replacement deposits in the lavas, controlled by shearing and brecciation, and probably are related to intrusive rocks. A deep mantle of glacial clay and sand covers much of the bedrock and for this reason geophysical techniques were used extensively, and were relied upon in the search for new deposits.

A large area was surveyed first by a detail aeromagnetometer survey, next by reconnaissance geological mapping, and then by extensive ground geophysical investigation. These surveys were used to guide the staking, optioning and purchasing of claims and the lines cut for the geophysical work were employed in detail geological mapping.

Most of the claims acquired have been subjected to examination by one or more of the geochemical, self-potential, resistivity, gravity, magnetic and electromagnetic techniques. The magnetic method was valuable in resolving geological problems; electrical methods showed the positions and dimensions of sulphide bodies; gravity measurements helped in the differentiation of electrical conductors. Subsequent drilling verified the presence of a sulphide deposit estimated to contain at least 7,000,000 tons running 25 per cent combined pyrite, chalcopyrite and sphalerite.

History

The area, referred to as the Robb-Jamieson area, comprises roughly 120 square miles, embracing all of Jamieson and Robb townships and roughly half of Godfrey and Turnbull townships. Kamiskotia Lake, near the centre of the area, is 19 miles west by road from Timmins, Ontario. A location map is shown in Figure 1.

Prospecting commenced shortly after the discovery of important gold deposits in the Porcupine camp in 1908, and has been continued at intervals since then. For many years efforts were directed chiefly toward the discovery of gold, and though many small gold-bearing deposits were found, none were brought into production.

The most important discovery to date, and the only one from which metals have been recovered on a commercial basis, is a copper-zinc deposit on the property of Kam-Kotia Porcupine Mines Ltd. in Robb township. This deposit was explored in 1928 to a depth of 150 ft. by underground workings, and in 1943 and 1944 189,064 tons of ore averaging 2.02 per cent copper were mined from an open pit.

Another important copper-zinc discovery is on G. Jamieson’s property in lot 9, con. VI, Godfrey township. This deposit has been explored by trenching and diamond drilling over a length of 300 ft. The sulphide minerals exist in lenses and the maximum width is about 12 ft. Other less promising copper and zinc showings are scattered throughout the area.

Three geological reports, covering various parts of the area, have been published by the Ontario Department of Mines within the past 30 years. Findley’s (1925) report gives an excellent description of the geology; Gledhill (1928), Berry (1944), and Ferguson (1944), deal with the economic geology.

Jones (1947), described in detail his electrical and magnetic work over twenty-one claims in the vicinity of the Kam-Kotia mine; these claims adjoin some acquired later by Dominion Gulf Company and referred to in this paper. Jones dealt with a different set of conditions and it is hoped that the two papers will present a fairly comprehensive picture of the geophysical methods that have been used in this area.

The reader may obtain the reconnaissance aeromagnetic data, flown by Dominion Gulf Company in 1947, from recently published maps (1956), of the Department of Mines and Technical Surveys, Ottawa.

A further reference to geophysical problems in the Robb-Jamieson area is found in Jakosky’s (1929) paper on inductive geophysical methods.

Dominion Gulf Company’s interest in the area started in 1949, with a detail aeromagnetic survey. Reconnaissance geological mapping was done in 1950
and 1953, and these surveys led to the staking of claims in Godfrey, Jamieson and Robb townships. Ground geophysical surveys were commenced in October 1953, and were done almost continuously until 1956. This work led to further staking and by September 1956, 384 claims had been staked, optioned or purchased by Dominion Gulf Company in the area. After these, 293 claims had been surveyed by ground magnetometer, and 203 claims had been covered at least once by ground electromagnetic survey. Detail geological mapping followed, using cut lines for control, as claims were acquired. Geochemical, self-potential, resistivity and gravity surveys have been conducted over many of the claims. Thirty-two diamond drill holes have been drilled to date, with a total footage of 16,915 ft. Fifteen of these, totalling 6,687 ft. of drilling have been used in outlining or delimiting a sulphide body discovered in earlier exploratory drilling.

All the exploratory holes were located to test geophysical anomalies. Estimates based on a gravity survey over the sulphide body indicate a minimum of 7,000,000 tons of sulphide material containing 25 per cent combined pyrite, chalcopyrite and sphalerite.

**Geological Setting**

Berry (1944), gives the following introduction to the general geology of the area:

"The consolidated rocks in the area consist of early Precambrian lavas and fragmentals of Keewatin type, which have been tightly folded and intruded in turn by basic igneous rocks, granite and related acid dykes, and diabase dykes. A thick deposit of glacial clay and sand obscures the bedrock over large areas, especially in MacDiarmid township and the east part of Jamieson township."

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TABLE OF FORMATIONS
(after Berry)

CENOZOIC

Pleistocene: Clay, sand, gravel, boulders.
Great unconformity

PRECAMBRIAN

Keweenawan (?): Olivine diabase.
Intrusive contact
Matachewan: Quartz diabase.
Intrusive contact
Algoman: Granite, quartz porphyry, aplite.
Intrusive contact
Haileyburian: Gabbro, hornblende.
Intrusive contact
Keewatin: Transition zone: intermediate rocks between normal Keewatin types and normal gabbro.
Rhyolite.
Greenstone, pillow lava, volcanic fragmentals.
Iron-formation.

Apart from the Kam-Kotia mine, the nearest economic metal production has come from the Porcupine gold camp 20 miles east. Here gold, silver and scheelite are associated with quartz veins which occur mostly in altered Keewatin lavas. The ore appears to favor tight antiformal folds; is most abundant where east-west faulting is most intense; and to some extent is associated with quartz porphyry or similar intrusives. The east-west faulting is believed to have occurred during a period of intense regional folding which probably was at the start of the Algoman period. Hydrothermal alteration with gold, silver and sulphide mineralization is believed to have occurred later in the period. The most intense faulting is confined to a narrow belt which has been named the Porcupine Creek fault and most of the orebodies occur within 4 miles of this fault. The westward extension of the fault is believed to lie well to the south of the Robb-Jamieson area.

There is no evidence in the Porcupine area of any appreciable folding, faulting, or vein formation either during or after the intrusion of the Matachewan dykes.

Methods and Interpretation

• Aeromagnetic Surveys

Reconnaissance aeromagnetic coverage of the Robb-Jamieson area was obtained in 1947 as part of a program involving roughly 4,000 square miles in the Porcupine-Kirkland area. These data, gained on north-south flightlines half a mile apart at a flight elevation of 500 ft., later were compiled at a scale of one inch to the mile and are being released now through the Department of Mines and Technical Surveys, Ottawa.

Detail aeromagnetic surveys were flown in 1948 and 1949 over areas selected on the basis of geology and the reconnaissance aeromagnetic data. The Robb-Jamieson area was surveyed in June, 1949, with north-south profiles at one-eighth mile spacing, and east-west profiles at one-quarter mile spacing. Flight elevation was again 500 ft. above terrain. The data were plotted at a scale of a quarter-mile to the inch and contoured at 20-gamma intervals. Figure 2 (in pocket) shows a reduction of the detail aeromagnetic data for the Robb-Jamieson area.

The pronounced northerly trends, which obscure to a large extent the other features, are produced by swarms of diabase dykes. The strong anomaly southwest of Kamiskotia Lake coincides with a hill of gabbro known as Robb Mountain. It is surrounded by a plateau of medium to low magnetic values which covers an intrusive complex of gabbro and granite. Minor magnetic trends are noticeable outside the area of intrusive rocks, more or less parallel to the periphery. Of these, the northwest striking lineaments in Jamieson township and the easterly trends in the north part of Robb Township are the most obvious. They were interpreted as bands of magnetic greenstone, and have since been identified as such. Interruption in the dykes and in the intrusive contacts are indicative of west to northwest faulting. In the absence of ground data, they could not be defined accurately.

Figure 3 shows the detail aeromagnetic data for an area 2½ miles by 2 miles including the Kam-Kotia mine and the recent Dominion Gulf Company sulphide discovery. This area is termed detail area 'A'. Superimposed on the map are the outlines of diabase dykes interpreted from closely spaced ground magnetic data. The lack of resolution in the aeromagnetic map is most apparent where the dykes are close to one another, as in the eastern part of the area.

• Reconnaissance Geological Surveys

The reconnaissance geological surveys made in 1950 and 1953 were undertaken to study the environment of the known base metal deposits, and to evaluate the chances of discovering other deposits. The mapping was done at a scale of a quarter-mile to the inch using aerial photographs for control.

The 1950 field work in Godfrey township failed to reveal any encouraging indications of base metal
mineralization. The geology of that township is exceedingly complex, and the structural picture is still obscure.

The mapping of the remainder of the area in 1953 revealed a less complicated picture. C. G. MacIntosh, geologist, Dominion Gulf Company, made the following comments, which have been proved since to be remarkably accurate:

"Rocks outcropping within the area mapped are predominantly Kewatin lavas. A large area immediately west of the lavas is occupied by an intrusive complex of gabbro and granite. Regionally, the lavas trend southeasterly and southerly, roughly parallel to the intrusive contact. The tops of the flows face north-easterly and easterly away from the intrusive masses. In Jamieson and Godfrey townships minor folds are superimposed on the major structure. The axes of these folds strike and plunge southeasterly.

"There is no direct evidence of appreciable faulting. However, the locations of probable fault planes have been inferred from topographical lineaments, shearing and aeromagnetic data. These inferred faults strike southeasterly, parallel to the principal direction of shearing and to the axes of the minor folds.

"Hydrothermal alteration is indicated by carbonatization and silicification of the volcanic formations.

"The Kam-Kotia and the G. Jamieson sulphide bodies occur in intermediate formations a short distance below a rhyolite horizon. They are hydrothermal replacement deposits and probably are related in origin to the intrusive rocks that outcrop to the west. The location of the deposits apparently is controlled by
shearing and/or brecciation of the host rocks. It is possible that there is a significant relationship between the location of the deposits and the rhyolite contact.

"It may be concluded that there are likely to be other locations favourable to the deposition of sulphides and that these should be sought below the rhyolite horizon, where there is some evidence of faulting or shearing.

"Much of the potentially favourable area is covered by overburden. Outcrop areas have been fairly well prospected. Any undiscovered ore deposits therefore will have to be detected by geophysical methods or by diamond drilling."

Staking began in October, 1953, in Jamieson township, half a mile southeast of the Kam-Kotia mine. It is interesting to note in retrospect that not only did later events prove MacIntosh's geological summary to be correct, but that Dominion Gulf Company's sulphide discovery was made in the second of 384 claims acquired by the company in the area.

- **Detail Geological and Geochemical Surveys**

As claims were acquired, picket lines were cut and detail geological surveys were made. Since the strike of the country rocks and the shearing is northwest to west in Jamieson, Robb and Turnbull townships, picket lines were cut north-south from east-west surveyed base lines. In Godfrey township the lines were cut east-west. Preliminary line spacing was 400 ft., but this was dropped to 200 ft. or less as extra detail was required. A careful search was made for outcrops between picket lines.
Very little was revealed in the detail geology that was not noticed in the reconnaissance surveys. The value of the work was chiefly in providing geological maps that could be tied in exactly with the geophysical data obtained on the same grid. Topographical information also was found useful.

Outcrop areas in detail area 'A' are shown on the ground electromagnetic compilation, Figure 5. Outcrops form less than 1 per cent of the surface area. Overburden varies from a few feet to about 200 ft. deep, averaging about 60 ft., and consists of interbedded clay and sand. Most of the area, particularly in Jamieson township, is swampy, flat and heavily timbered with small spruce, balsam, poplar and alder.

Geochemical soil sampling was done in 1955 along picket lines over parts of the area. The samples were analyzed for zinc, copper and lead in the Company's Toronto laboratory. Values generally were very low and the few variations encountered were considered smaller than the probable error of the method. The heavy overburden apparently prevented sufficient upward migration of the metallic ions. The geochemical soil sampling was discontinued in 1956.

- Ground Magnetometer Surveys

Until 1956 ground magnetometer surveys were routine procedure on all claims acquired by the company in the Robb-Jamieson area. The reasons were:

i. Accurate detailing of diabase dykes helps to interpret faults and shear zones, and sometimes assists in making overburden depth estimates.

ii. Magnetic trends in the country rocks may represent bedding or alteration in shear zones.

iii. Intrusive rocks may be indicated; gabbro as highs and granite as lows.

iv. Sulphide bodies containing appreciable pyrrhotite will be indicated by anomalies, possibly distinguishable from those due to the more homogeneous flows and intrusions.

Interpretations of the data confirmed the usefulness of the surveys. Though it was seldom possible to identify
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... anomalies positively as shear zones, volcanic bands or intrusive rocks, nevertheless, a structural picture was obtained which was invaluable where outcrops were scarce. The magnetic data made it possible to extrapolate surface geological information a fair distance from outcrops.

Diabase dykes were used extensively for identifying faults and contacts. Deflections in the dykes were found to be sub-parallel to contacts between different volcanic members or contacts between volcanic rocks and intrusive rocks. Usually the dykes were only partly deflect at shear zones, and often suffered several jogs if the zone was wide. This strike of the shear usually was hard to interpret. Major faults may be indicated by abrupt terminations in the dykes, but it was not clear whether the termination was due to the destruction of magnetite by later movements on the fault, by erosion in the fault zone, or by actual termination of the dyke.

Rock types were seldom identifiable by magnetic data alone, since gabbros, granites, andesites and rhyolites were found to have very variable and generally low magnetite content. Laboratory determinations of susceptibility were made of some specimens from the area and some results are given in the following table:

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Average density and number of specimens</th>
<th>Susceptibility range and number of specimens (x10^-6 c.g.s. units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andesite</td>
<td>2.89 (26)</td>
<td>30 - 275 (9)</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>2.73 (8)</td>
<td>12 - 231 (5)</td>
</tr>
<tr>
<td>Gabbro</td>
<td>2.90 (8)</td>
<td>62 - 6140 (8)</td>
</tr>
<tr>
<td>Granite</td>
<td>2.66 (4)</td>
<td>0 - 29960 (4)</td>
</tr>
<tr>
<td>Diabase</td>
<td>3.03 (2)</td>
<td>2610 - 3875 (2)</td>
</tr>
<tr>
<td>Sulphides</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Kam-Kotia ore</td>
<td>3.48</td>
<td>8120</td>
</tr>
<tr>
<td>(45% pyrrhotite by magnetic separation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. DGC sulphide body</td>
<td>3.41</td>
<td>158</td>
</tr>
<tr>
<td>(25% pyrite—usual estimate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. DGC sulphide body</td>
<td>3.55</td>
<td>4840</td>
</tr>
<tr>
<td>(40% combined pyrite and pyrrhotite—usual estimate)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. DGC sulphide body</td>
<td>3.86</td>
<td>1270</td>
</tr>
<tr>
<td>(40% combined pyrite and pyrrhotite, 13% sphalerite—usual estimate)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Susceptibilities calculated from the anomalies themselves fall within the range of the above figures. Generally, however, the diabase dykes in the area seem to be more magnetic than the one sampled, having apparent susceptibilities of up to 18,000 x 10^-6 c.g.s. units.

The susceptibility of sulphides in the Robb-Jamieson area depends almost entirely upon the pyrrhotite content. Little magnetite is associated with the sulphides. One of the premises upon which the geophysical program was based was that pyrrhotite probably would be present if an economic body of sulphides existed. Certainly this was the case at the Kam-Kotia mine, but it was found later that pyrrhotite was not a necessary constituent in many of the smaller bodies of sulphides. The Dominion Gulf Company sulphide discovery contains only minor pyrrhotite and is in a magnetic depression. Probably this is because of destruction of magnetite by carbonatization and oxidation.

Figure 4 is a compilation of the ground magnetic data in detail area 'A'. An anomaly is seen over the Kam-Kotia mine but not over the Dominion Gulf Company sulphide body. The increase in resolution, particularly of the diabase dykes, is seen by comparison with the aeromagnetic data of Figure 3. The contour interval of the data presented in Figure 4...
has been increased from 100 to 500 gammas for clarity, so only the major features are indicated. Features of interest are: (1) the northwest trending anomalies in Robb township which are believed to indicate bedding in the volcanic rocks; (2) similar features in Jamieson township, concession IV, which are due mainly to shearing; and (3) deflections and terminations of the diabase dykes.

The strong deflection in the diabase dyke immediately south of the Dominion Gulf Company sulphide body, was interpreted in 1954 as representing a strong northwest trending shear. A later interpretation postulated a more westerly shear zone causing the jogs near the south end of the deflection, and an andesite-rhyolite contact causing the main, straight part of the deflection. Further shearing was thought to be the cause of the termination north of the concession line.

The advantage of separating features caused by shearing from features caused by bedding or contacts cannot be stressed enough. Magnetic features paralleling the shear direction are of considerable interest, while those in the bedding direction probably are non-economical as they are produced almost invariably by bands of basic or altered volcanic rocks. The 500-gamma anomaly half a mile east of the township line and a quarter-mile north of the concession line was drilled by New Kelore Mines Ltd. following an interpretation which connected it with the shear zone at the Kam-Kotia mine. It was hoped also that the rhyolite-andesite contact present at the mine might strike through the anomaly. The shear zone was found as predicted, as was a minor band of rhyolite. However, the formations outcropping at the mine appear now to swing well to the south of the anomaly drilled, and in fact are believed to be the host rocks for the sulphides found by Dominion Gulf Company in concession III.

In 1955 several magnetic anomalies in Robb township were drilled and found to be due to the magnetite in altered volcanic rocks. There were no electromagnetic conductors over these anomalies. After this experience it was decided to conduct electromagnetic surveys before magnetic, and do the latter only in areas where conductors were found.

All the magnetometer work was done with modified Askania Schmidt-type vertical magnetic balances with sensitivities of about 20 gammas per scale division. This sensitivity was needed in the detailing of some of the weaker anomalies. Surveys were run first at 100-ft. station spacing on lines 400 ft. apart.

In the vicinity of anomalies, detail lines were cut 200 ft. apart, and the station interval was dropped to 50 ft., closing to 25 ft. where steep gradients were next encountered. Cross lines were cut and surveyed where extra control was required, especially in the detailing of anomalies running parallel to the picket lines. In this regard, it was unfortunate that the main magnetic features of the area, the diabase dykes, paralleled the picket lines in Robb, Jamieson and Turnbull townships. Many cross lines were required to define the anomalies adequately.

- **Ground Electromagnetic Surveys**

Inductive electromagnetic methods have not changed much since Jakosky (1929) applied them to similar problems in the same area. The operating principles of the vertical coil electromagnetic method presented in Figure 13 of Jakosky's paper are the same as those used by Dominion Gulf Company and most other operators today.

Dominion Gulf Company commenced electromagnetic work in the Robb-Jamieson area in August, 1954, the purpose being to search for massive sulphide bodies in these overburden-covered portions considered most favourably located geologically. The geological premises outlined under "Reconnaissance Geological Surveys" above, assisted by magnetic interpretations of structure, were the basis for choosing survey areas.

The electromagnetic apparatus consisted of a vertical, 16-ft. diameter, collapsible, hexagonal transmitting coil, fed by a 900-cycle-per-second, 2200-volt-ampere, gasoline motor-driven generator, and two tripod-mounted receiving coils with amplifiers and earphones. The receiving coils were traversed along the line containing the transmitter or on lines either side of the transmitter, with the transmitting coil oriented continuously in the plane of the receivers. In the absence of 'anomalous' conducting bodies, the field at the receivers is normal to the vertical plane containing the transmitter and receivers. Conducting bodies radiate secondary fields which change the direction of the field at the receivers.

These changes in dip and strike are measured in degrees and are used to interpret the positions of the conducting bodies. Measurement is made by rotating the receiving coil about a vertical axis until it is parallel to the horizontal component of the resultant field, and then about a horizontal axis perpendicular to the last or strike direction to obtain the dip of the
resultant field. The strengths of the minimum signals thus obtained and the ‘widths’ of the minima in degrees are recorded and used qualitatively to assist in interpreting strike, dip and conductivity of the conducting bodies.

The relatively powerful transmitter employed by Dominion Gulf Company provided audible signals up to 5,000 ft. from the transmitting coil. Since depth penetration is proportional to transmitter-receiver distance in homogeneous ground, this was a distinct advantage. The routine operating procedure developed was to read lines 400 ft. apart, starting 800 ft. from the transmitter and continuing out to 2,000 ft. or up to 3,200 ft. in some cases. Lines varied from 3,000 ft. to 5,000 ft. long, depending upon the area being surveyed; for clarification of the procedure, the reader is referred to Figure 6. Station spacing usually was 100 ft. The crew comprised four or five men, and survey speed was roughly 1½ miles per day.

The 1954 field work failed to show any significant conductors. The drilling program, following the field work, was based on ground magnetic data. Magnetite only was encountered.

Field work was resumed in 1955, and portions of detail area ‘A’ were covered in close detail. The preliminary survey located numerous conductors and lines were repeated from several set-ups to help detail the conducting bodies. It was found that a fixed transmitter orientation provided more easily interpreted information than the usual ‘fan’ when many conductors were present. Lines were run closer to the transmitter in the detail work than in the preliminary survey, but the reduction in depth penetration brought a loss in sensitivity.
Dual-frequency electromagnetic surveys were carried out in 1955 by McPhar Geophysics Ltd. on some of the company's ground in the area. Operating procedures were the same though the less powerful unit limited the detectable distance of the transmitter to 1,200 ft. The two frequencies, 5,000 and 1,000 cycles per second, were radiated simultaneously and two sets of data were recorded and compared to obtain conductivity information.

By the end of 1955 roughly 14 miles of conductor had been located on ground held by Dominion Gulf Company in the area. Exploratory drilling was begun in January, 1956, to test a number of the conductors. The first six holes are shown, together with conductors, outcrops, and dykes and faults interpreted from magnetic data, in Figure 5. The cause of the conductor in each of the first five holes was found to be massive sulphides. In the sixth hole a fault was found which drill-hole electrologging proved to be the conducting 'body'. Five holes drilled further south in Jamieson township met faults which correlated well with the electromagnetic anomalies.

Drill hole resistivity surveys were done in all holes to ensure that the conductors had indeed been penetrated. In the case of sulphide conductors, resistivity contrasts of between 100 to one and 1,000 to one were usual between conductor and host rock. Where water-filled faults were the conductors, resistivity contrasts were between 10 to one and 100 to one.

Electrologging was done at 60 cycles per second with a three-electrode, fixed spacing system, similar to that discussed by Clark and Salt (1951). An 'expanding' system (after Clark and Salt) was used to explore outward from the drill holes and was found to give lower resistivities than the fixed system where sulphides existed, and higher resistivities where a single fault zone was present. In the case of drill hole 171-56-1 (Figure 5) the expanding system showed the presence of a large sulphide mass which had been 'under-shot' by the drill hole.

Electromagnetic surveys continued in 1956, using Dominion Gulf Company and McPhar Geophysics equipment. More detailing of the sulphide zone assisted in planning the detail drilling. A new, triangular transmitting coil and two new amplifiers fitted with rectifiers and meters for quantitative amplitude determinations were brought into use. With these instruments the ratio of the signal maximum to the signal minimum could be recorded and was used to interpret phases of the secondary field. The crew was reduced from four or five to three or four men.

It is beyond the scope of this paper to discuss the relative values of amplitude measurements, dual-frequency dip-angle measurements, null-width or direct-phase measurements in interpreting types of conductors. However, it should be said: firstly, that to be able to distinguish the conductor from another by any electrical method, electrical property differences must exist; secondly, that size and conductivity work together in producing an induction field; and thirdly, to separate the two, either phase or dual frequency methods must be used.

A few data are presented to show the type of results obtained over sulphides. Figure 6 shows dip-angle profiles in a detail survey over a 2,000-ft. by 1,600 ft. area named detail area 'B'. Also shown on the map (stippled) are the bands of massive sulphides proved or (in the case of the dashed lines) projected from the drilling. In these bands the average sulphide content exceeds 15 per cent. The bands dip from roughly 50° north to nearly vertical and, for the most part, pinch out rapidly with depth. Disseminated sulphides are present over a much larger area than shown on the map. Bedrock depth varies from 40 ft. in the southwest to about 150 ft. in the northeast. The surface is swampy.

The correlation between the 'cross-overs' and inflections of the dip-angle curves and the sulphide bands is fairly good. It is seen that the cross-over position is influenced strongly by transmitter location. The position of steepest dip-angle gradient is a better criterion of conductor position. This is influenced partly by depth to conductor surface. For example, the south sulphide band on Line 18E shows the steepest gradients on profiles 2-3 and 2-16 as the overburden is shallower there than at the north band. In the profiles read from set-ups 1, 4 and 5, the north band is favoured by transmitter location and better continuity between transmitter and receiver. Significant on all profiles is the rapid return from large to small angles at a short distance from the cross-over. This is indicative of limited depth extent and normally is not found over faults or shears.

Two electromagnetic profiles read with the same apparatus in the vicinity of the Kan-Kotia mine are shown for comparison in Figure 7. The reader is referred to Figures 12 and 18 of Jones' (1947) paper for ground magnetometer and resistivity data for the same area. The sulphide zones shown roughly in Figure 7 correlate quite well with the cross-overs and inflections on profile number 1. The anomaly on profile number 5 correlates with a band of weakly
mineralized andesite. It coincides with a resistivity anomaly discovered by Jones.

A large number of electromagnetic conductors were found in the 1956 work, most of which appeared to be due to buried valleys and shear zones. Some samples of ground water were taken and analyzed in Toronto for pH and conductivity. Swamp waters were found to be the most acid and the poorest conductors. Streams were roughly neutral and of medium conductivity. A single sample of bedrock circulating water (from a flowing drill hole) was slightly basic and had the highest conductivity. The overall range in resistivity of the samples was 220-meter-ohms to 1450-meter-ohms. Surface resistivity surveys over a portion of detail area 'A' showed a minimum resistivity in the overburden of 250 meter-ohms. These determinations confirmed the suspected conducting quality of overburden and bedrock waters. They served also to point to areas where these effects might be most severe.

- **Self-Potential Surveys**

  Some experimental self-potential work was done in detail area 'A' in 1955 in the hope that this method might be used to detail electromagnetic anomalies and distinguish metallic conductors from those due to ground water. The results were negative. Thick layers of sand and clay effectively short-circuited any voltage differences that may have existed on the bedrock surface. A few positive readings of up to 150 millivolts were obtained over a dry sand plain, but in the low areas voltages seldom exceeded plus or minus 50 millivolts. No correlation was found with electromagnetic conductors.

- **Gravity Surveys**

  Following the exploratory drilling in early 1956, in which faults were proved to be the cause of several conductors, gravity surveys were run, using a Warden gravimeter, to check all the more promising looking electromagnetic anomalies. This instrument was capable of distinguishing gravity anomalies as low as 0.2 milligals. It was recognized that this sensitivity was insufficient for the detection of the smaller or more disseminated sulphide bodies under deep overburden, but it would show up both large (or shallow) sulphide bodies and sharp bedrock depression. The gravity surveys proved exceedingly useful when combined with careful electromagnetic procedures.

  Besides checking electromagnetic anomalies, which consisted usually of a 2,000-ft. profile with 50-ft. station intervals, the gravimeter was used for detailing the sulphide zone in detail area 'B'. For this work station spacing was reduced to 25 ft. over the anomaly and lines were read 100 ft. apart. Elevations were measured with a level and each station was marked by a 'hub' from which an exact height of instrument could be obtained for connecting the gravity data.

  The Bouguer gravity data for detail area 'B' showed a marked negative regional gradient to the northeast, due to the dipping bedrock surface which obscured to a large extent the anomaly caused by the sulphides. Graphical removal of the regional effect showed residual anomalies of from 0.3 to 0.6 milli-
gals over the sulphide zone. A grid residual was calculated by averaging the values 200 ft. north, south, east and west of 100-ft. stations and subtracting this from the values at the stations. These data are shown in Figure 8. The anomaly is reduced greatly in size but shows excellent correlation with the sulphide zone. This map was found to be of value in the detail drilling which was carried out during May to October, 1956.

An estimate of the excess tonnage of the causative body was made by graphical integration of the residual gravity, determined graphically on a number of profiles over the anomaly. The areas under these curves were plotted against position on a central line along the axis of the anomaly. A second integration provided a figure which could be related to the excess mass. The actual mass of material based on 25 per cent combined sulphides appears to be of the order of 7,000,000 tons. This is in rough agreement with drilling results to date. Density differences between rock types did not cause significant anomalies. The densities presented in the table of susceptibilities above show a total range of 0.37, but this was seldom experienced. Dykes caused minor anomalies which could be recognized easily with the aid of the magnetic data. The density contrast between rhyolite and andesite, the two main rock types, is so small that only the major volcanic bands showed up, and these were readily distinguishable from the local sulphide anomalies.

Bedrock valleys and ridges produced marked anomalies and these were a continual source of trouble. The trouble is more acute in the grid-type survey than in the check profile where a yes-no answer in the vicinity of the electromagnetic conductor is all that is required.

- **Surface Resistivity Surveys**

It was considered from the start that electromagnetic methods would be more useful than surface resistivity methods in this area. Since the two respond to the same body properties, there was little point in following one with the other. A small number of Wenner profiles were read in detail area 'B' in an attempt to measure overburden depth for use in interpreting gravity data. The results were unsatisfactory, probably because the rock surface over much of the area is mineralized or rusty, providing an insufficient contrast in conductivity with the wet overburden.

After drilling holes numbers 1 and 2, (see Figure 5), it was considered that resistivity methods could be applied with considerable advantage. Current electrodes could now be lowered into the conducting bands in the drill holes, thus directly energizing the interesting zone. Potential measurements were made along profiles on the surface. Sixty-cycle current was provided by a 250-watt gasoline motor-driven generator, and was maintained by a rheostat at 300 milliamperes. Voltages were measured between the casing of the drill hole containing the near-current electrodes or electrodes and a field electrode moved along the traverse lines across the conductors. A vacuum tube voltmeter near the fixed-voltage electrode was used to measure the potential.

With this configuration, voltage highs were found over the conductors. Clear definition of the zones was possible only a few hundred feet on either side of the near-current electrode and best definition on the side of the electrode farthest from the far-current electrode. The profiles in Figure 9 were read from three different electrode configurations. The conducting zones are interpreted from inflection points on the profiles. Conductor axes correspond to the profile peaks and correlate well with the bands of most massive sulphides. Cross-faults are interpreted from a detailed comparison of adjacent profiles. Only the voltages obtained from a deep-current source are shown in Figure 9. Profiles were read simultaneously with a shallow-current source and comparison of the results helped to resolve the bands and indicate their continuity and dip.

Drilling of the bodies showed almost perfect correlation between the resistivity anomalies and the sulphide bands. Disseminated sulphides were found under all the resistivity anomalies tested. A slight displacement of some of the bands to the north of the anomalies is due to the projection of the mineralized sections vertically from the drill holes whereas the bands actually dip north.

Comparison of Figure 9 with Figure 7 shows the increase in resolution of the resistivity method over the electromagnetic. Probably even better resolution could have been obtained if a 1,000 c.p.s. source had been used, as in the electromagnetic method.

**Conclusions**

Exploration using a combination of geology and geophysics found a sulphide body in a swamp area under roughly 100 ft. of overburden. Problems in the interpretations were successfully overcome by using a variety of geophysical methods. The magnetic method was a valuable aid in interpreting geology.
Figure 9. Detail area B, resistivity survey, voltage profiles.
Electrical methods showed the position and the extent of sulphide bodies. Gravity helped to distinguish conductors due to sulphides from those due to surface waters and shear zones.

Acknowledgments

The writer wishes to express his thanks to the management of Dominion Gulf Company for permission to publish these data and for use of the Company’s time and facilities. Special recognition is given to E. W. Westrick without whose persuasion the paper would not have been written.

Credit for guiding the exploration program through its early phases is due to G. E. Parsons and C. G. MacIntosh; the latter also supervised geological work in the area throughout the entire program. The geological work was performed by a variety of field engineers and operators. J. H. Ratcliffe did the work in 1954, G. F. West followed in 1955 and D. W. Strangway in 1956. R. Hodgins gave invaluable assistance throughout. The writer is indebted to these and to other members of the Company’s field and office staff for their help in the work described.

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STREAM SEDIMENT ANALYSIS DISCOVERS TWO MINERAL DEPOSITS†

H. E. Hawkes*, Harold Bloom** and J. E. Riddell***

Abstract

Reconnaissance geochemical surveys based on sediment analysis were carried out in the streams in an area of over 27,000 square miles in the province of New Brunswick and the Gaspé peninsula, Quebec. These surveys located nine areas of above normal soluble heavy metal content and these areas were then covered by extensive integrated exploration programs.

The exploration techniques applied to two of the areas are discussed, and conclusions are drawn on the effectiveness of geochemistry in mineral exploration.

A RECONNAISSANCE geochemical survey based on the analysis of modern stream sediments for traces of readily soluble heavy metals was conducted over an area of 27,000 square miles in New Brunswick and the Gaspé peninsula of Quebec, throughout the 1953, 1954 and 1955 seasons. In the 1954 and 1955 seasons, the writers were joined by Dr. John S. Webb of the Royal School of Mines.

†This paper has been compiled from part of a paper which was published in Mining Engineering, with further added material. That portion of the paper is reprinted here by permission of Mining Engineering and of the American Institute of Mining, Metallurgy and Petroleum Engineers, Inc.

The principles of the method used in this survey are described in a companion paper by Hawkes and Bloom (1); the analytical procedures are related elsewhere by Bloom (2); and the sampling techniques and the organization of the program are detailed in a paper presented at the International Geological Congress in Mexico in 1956, by Hawkes, Bloom, Riddell and Webb (3).

*Professor, Division of Mineral Technology, University of California, Berkeley.
**Special Lecturer, Geology Department, Colorado School of Mines, Golden.
***Professor of Geology, McGill University, Montreal.
Two examples of mineral discoveries based on reconnaissance by stream sediment analysis have been chosen from nine that were sufficiently promising to warrant recommendations for intensive physical exploration. Information on the other areas either is confidential, or is not sufficiently instructive to deserve detailed discussion here. The description of the field experiments at the Nash Creek prospect is reprinted with minor modifications from a previously published paper by Hawkes and Bloom (4); the material on the Mount Pleasant prospect, assembled by Hawkes and Riddell, is original.

**Nash Creek Prospect**

The Nash Creek prospect, near the south shore of Chaleur Bay in north New Brunswick (Figure 1), was the first mineralized area found by systematic sampling and analysis of modern stream sediments for exchangeable heavy metals. The samples that led to this discovery were part of a reconnaissance suite collected in 1953 from the streams that crossed provincial highway 11 between Bathurst and Campbellton.

The reconnaissance samples, which were analyzed a few days after collection, showed anomalous amounts of exchangeable heavy metals in a number of the streams entering Chaleur Bay from the south. The areas in question were then resampled in greater detail from the network of farm roads running inland from the main highway. The original anomaly at Nash Creek was confirmed by samples taken from the south branch of Nash Creek, about 2 miles upstream from the discovery site on the highway. The other reconnaissance anomalies were not confirmed by further upstream sampling.

The source area was located after about two hours of follow-up, during which sediment samples were analyzed on the spot with a field kit. The ground had not been prospected previously, and was staked immediately. Within a few months, the claims were optioned to a large exploration company, whose staff conducted an extensive program of drilling. The presence of widespread zinc and lead mineralization was established but the option was dropped because of the low grade and the absence of continuity.

In 1955, the Nash Creek prospect was selected as an experimental area to determine precisely what kind of sample would give the strongest indication of mineralization and at the same time minimize errors caused by erratic distribution of the metals in different sedimentary material. This was a question that could be answered only by a study of the distribution of metals in stream sediments below a known area of mineralization where the drainage had not been contaminated by metal leached from mine workings and ore dumps. The experimental results would be easier to interpret if the patterns in such an area were not confused by more than one source of metal. In other words, the mineralized area should show a relatively sharp boundary with non-mineralized terrain.

The Nash Creek prospect appeared to be well suited for this study, because no other strong geochemical indications of mineralization were known within a radius of several miles, no source of contamination was present, and the boundaries of the mineralized area were well defined.

Figure 2 shows the drainage pattern and the experimental sample sites in the immediate vicinity of the Nash Creek prospect.

It will be noted that the stream draining the mineralized area, known locally as the South Branch of Nash Creek, is relatively small and is joined by a much larger stream, the Main Branch of Nash Creek, about 6,000 ft. downstream from the edge of the known mineralized area. The combined drainage of the two
branches flows into Chaleur Bay about 3,000 ft. below this confluence.

- **Experimental Results**

Samples of both active sediments from the present stream bed and of floodplain sediments near the edge of the active channel were collected at 200-ft. intervals along the South Branch of Nash Creek from Site 1 (Figure 2), above the mineralized area, downstream as far as tidewater at Site 9. Samples were also taken from other streams within the area of Figure 2 for the purpose of showing the background (or normal) distribution of exchangeable metals in the stream sediments draining unmineralized areas. At selected sites in the drainage below the Nash Creek prospect, suites of experimental samples were taken for special purposes, as described in detail below.

- **Background**

Within the area of Figure 2, samples of both active and floodplain sediments were taken at 23 sites on streams outside the sections of the streams which gave anomalous amounts of soluble metals in the reconnaissance sampling. The median of these values is 2 ppm w/v (equal to micrograms per cubic centimeter) in both the active and floodplain sediments and in both the —12 and —200 mesh fractions. From experience elsewhere, this background for the content of exchangeable metals in sediments appears normal for non-mineralized terrain.

The metal content of the stream water also was determined at most of these sites; the median of these values was 0.0006 ppm (0.6 µg/l) of heavy metal expressed as zinc.

- **Distribution of Metal in Active Sediments**

The error in sampling active sediments was investigated by collecting multiple samples of similar material within a few feet of one another and comparing the exchangeable metal contents, as shown in Table I. These results show that if samples of the same kind of material are collected, the sampling error is relatively small.

<table>
<thead>
<tr>
<th>Material</th>
<th>Site</th>
<th>Exchangeable Heavy Metal ppm w/v*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ooze</td>
<td>6</td>
<td>21, 25, 28, 30</td>
</tr>
<tr>
<td>Ooze</td>
<td>8</td>
<td>5, 7, 8, 10</td>
</tr>
<tr>
<td>Silt</td>
<td>5</td>
<td>22, 24, 32, 52</td>
</tr>
<tr>
<td>Silt</td>
<td>6</td>
<td>18, 20, 21, 21</td>
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<tr>
<td>Sand</td>
<td>5</td>
<td>12, 14, 16, 17</td>
</tr>
<tr>
<td>Gravel</td>
<td>5</td>
<td>16, 16, 17, 18</td>
</tr>
<tr>
<td>Gravel</td>
<td>6</td>
<td>8, 11, 12, 12</td>
</tr>
</tbody>
</table>

*Weight/volume: 1 ppm w/v is equal to 1 µg per cc.

Samples representing two vertical profiles below the active stream bed were collected at Site 5. No significant variation with depth was revealed, indicating that for routine work a sample from the surface of the stream bed is as satisfactory as a deeper sample.

The variation of metal content with type of sample was investigated by collecting suites of samples of different kinds of sedimentary material at three sites, 5, 8, and 6, all lying in the anomalous drainage below the Nash Creek prospect where anomalous amounts of soluble metal were obtained. The analytical data, given in Table II, show that the —12 mesh fraction of fine-grained samples and of samples with a high content of organic matter are slightly higher in their content of exchangeable metal than similarly prepared samples of sand or gravel.
Sizing studies were run on a bulk sample of gravel collected at Site 5, with results summarized in Table III. Exchangeable metal was determined on weighed samples (ppm w/w) as well as on samples measured in the volumetric scope (ppm w/v), for the purpose of obtaining more accurate comparison between exchangeable and total metal. These figures show a pronounced inverse relationship between content of exchangeable metal and grain size. The same relationship is borne out by the data of Table II, on samples of different grain size collected from the same sites.

Normal operating errors, where samples are taken without regard to grain size and texture, may be estimated by comparing the exchangeable metal content of contiguous samples of active sediment taken at 200-ft. intervals along the South Branch of Nash Creek between Sites 3 and 7 (solid lines of Figure 3). Of these samples, almost two-thirds were sand and gravel, the remainder silt. In all, 49 pairs of samples 200 ft. apart were compared. The median of the ratios of the higher to the lower value for exchangeable metal in these pairs is 1.50 for the —12 fraction, and 1.33 for the —200 mesh fraction.

This means, for example, that if a given sample of active sediment contains 12 ppm of exchangeable metal, a sample taken 200 ft. either up or down-
stream will have a 50 per cent chance of falling within the range from 8 to 18 ppm for — 12 mesh fraction, or 9 to 16 ppm for the — 200 fraction.

- **Distribution of Metals in Floodplain Sediments**

In a similar way, the error in sampling floodplain sediments was estimated by comparing data on corresponding samples of floodplain sediment (broken lines of Figure 3). Here the median of the ratios of the higher to the lower value for exchangeable metal is 1.21. Thus if a given sample of floodplain sediment contains 12 ppm of exchangeable metal, a sample taken 200 ft. either up or down stream will have a 50 per cent chance of falling within the range from 10 to 15 ppm. The lower sampling error of floodplain sediments as compared with active sediments unquestionably is due in large part to the more uniformly fine-grained texture of the floodplain samples.

The relation of the content of exchangeable metals in floodplain material to distance from the active channel of the stream is shown in the data of three traverses crossing the floodplain at Sites 5, 6, and 8. The results are summarized in Figure 4. The data of the first two traverses indicate that in the absence of a lateral source of metal, the exchangeable metal content of floodplain samples is highest near the active channel. Where several active channels are present, as at Site 8, the relationship becomes confused.

Samples comparing humus-rich silt with organic muck from the floodplain were collected near Site 5; no significant relation between these types of sediment and the content of exchangeable metal was apparent.

Samples representing a vertical profile of the floodplain sediments to a depth of 18 in. were collected at Site 6. These determinations showed no significant variation in metal content with depth.

Ratios of the exchangeable metal content of floodplain samples to that in the corresponding active sediments were computed on the basis of data shown in Figure 3. For the — 12 mesh fraction the median ratio is 1.33, whereas for the — 200 mesh fraction it is 1.06. Ordinarily, the active sediment is coarser grained than the corresponding floodplain sediments, and has a lower content of exchangeable metal. Fine sieving, however, reduces the disparity.

- **Distribution of Metal Within Source Area**

Figure 3 shows the variation in the metal content of the stream sediments as the stream enters and passes through the source area. At Site 1, upstream from the mineralized area, the metal content of the sediments is near the background value. The content of metals increases sharply as the stream enters the source area, at a point commonly known as the cutoff (Site 2 in Figure 3). Immediately below this point, the metal content of the active sediment apparently increases faster than that of the floodplain sediments. As the stream flows through the source area, the exchangeable metal content fluctuates in response to local increments from lateral drainage, ground water, and springs. Metal-rich tributary streams are known to enter the main channel at Sites 3 and 4 where they can be correlated with local increases in the metal content of the floodplain sediments.

- **Distribution of Metals Downstream from Source Area**

The reduction in the metal content of sediments downstream from the Nash Creek prospect is, in a very general way, a reflection of simple dilution, as shown by the data of Figure 3 between Site 5 and tidewater at Site 9.
At Site 7, the South Branch of Nash Creek is joined by the Main Branch, with about four times the drainage area of the South Branch. By a straight dilution factor, the exchangeable metal content of sediments below this point should be 5 and 7 ppm w/v for 12- and 200-mesh fractions respectively. Averages of the values actually observed in the section below this confluence are 3 and 6 respectively, indicating a slightly more rapid decay of the pattern than can be accounted for by simple dilution, particularly for the coarser fraction.

Tidewater extends up the stream channel for a distance of 600 ft. from the end of the traverse. Comparison of data on total and exchangeable metals in sediments above and below tidehead shows no significant contrast.

- **Comparison of Total and Exchangeable Metal in Sediments**

Table IV summarizes the data on samples where determinations have been made of both total and exchangeable metal. It is seen that, at least for the Nash Creek samples, a fairly close ratio exists between exchangeable and total metals, although in the more anomalous samples the ratio of exchangeable to total metal is somewhat higher.

- **Exchangeable Metal in Sediment Compared with Metal Content of Water**

The metal content of stream water was determined at a total of 23 sites, of which 6 were in drainage from parts of the mineralized area, and 17 were in unmineralized terrain. Measurements were made on the same day to avoid changes due to fluctuations in weather. The data of the 6 samples from streams draining the mineralized area are given in Table V.

In general, it is seen that all anomalous water samples of high metal intent are associated with anomalous sediment samples of high metal content; beyond this, the correlation is not strikingly close. The median metal content of the other 17 water samples is 0.0006 ppm.

At Site 5, water was sampled and analyzed for metals at periodic intervals. Results varied from 0.0017 ppm, when the water level was relatively high, to 0.005 ppm when it was low. This variation suggests that dilution during periods of higher rainfall and runoff can cause a relative decline in the metal content.

- **Water Sampling vs. Sediment Sampling in Geochemical Reconnaissance**

Both water and sediment sampling have advantages and disadvantages as prospecting tools that should be carefully weighed before being used for a given problem. Both media apparently can be used effectively in the search for geochemical anomalies. The obvious advantage of water sampling is its freedom from sampling errors. In favor of sediment sampling, it should be pointed out that: (1) the metal content is not affected by short-term variations; (2) drainage channels may be sampled and tested even though no water is present at the time the samples are taken; (3) a much less sensitive test is required, reducing the necessity for extreme cleanliness of reagents and glassware; (4) small samples are collected, and may be analyzed at a central laboratory with greater precision and efficiency; and (5) the sample may be kept indefinitely for future reference.

In the authors' experience, sediment sampling with analysis by the cold-citrate test is more suitable for geochemical reconnaissance work where large tracts of ground are to be scanned quickly and cheap-
ly. When exploration based on sediment sampling has led to a strongly anomalous area where the water test need not be particularly sensitive, a detailed survey by water analysis may be more satisfactory.

Conclusions

Comparative studies of the distribution of heavy metals in sediment and water from streams in the vicinity of the known mineralized area near Nash Creek, New Brunswick, have shown that:

(1) In sediment from the active channel of a stream draining a mineralized area, the content of exchangeable metal varies inversely with grain size but is independent of depth below the stream bed;

(2) In sediment from the floodplain of a stream draining a mineralized area, the content of exchangeable metal (a) is comparable with that in samples of active sediments of the same grain size taken at the same site; (b) varies inversely with distance from the active channel; and (c) is independent of depth below surface;

(3) The background content of exchangeable metals in both coarse and fine fractions, and in both active and floodplain sediments, is about 2 ppm w/v;

(4) Exchangeable metal content of sediments is unusually high where the metal content of stream water also is high. Analysis of sediments for exchangeable metals, however, has distinct practical advantages over water analysis as a method of reconnaissance mineral exploration in that (a) effect of variations in weather is eliminated, (b) dry stream channels may be tested, (c) the chemical test is simpler, (d) large-scale operations are more efficient, and (e) samples may be stored for future reference.

Mount Pleasant Prospect

The reconnaissance samples that led to the discovery of the Mount Pleasant prospect (Figure 1) were collected in the early part of the 1954 field season, in the course of traversing all the passable roads in south New Brunswick. Two streams showed relatively high indications, and an adjoining stream showed a slightly weaker indication, as illustrated on Figure 5. The samples were brought for analysis to the field headquarters in Fredericton. A field follow-up of the reconnaissance anomalies immediately confirmed the presence of an extensive area of strong geochemical indications, but about eight man-days of reconnaissance soil sampling and further sediment testing with the field analytical kit were necessary before the outside limits of the mineralized area could be established.

The ground was then staked, and Selco Exploration Company of Toronto, who sponsored the geochemical reconnaissance, continued with an intensive examination of the property. Over a period of a year, the geology was mapped; soil samples were collected at 100-ft. intervals on lines spaced at 400 ft. intervals and were analyzed for total copper, lead, and zinc; an electromagnetic survey was run; and four diamond drill holes totalling 1,000 ft. were drilled. As this work gave no promise of massive sulphides, Selco Exploration Company abandoned its interest in the property. Further drilling was done in 1956 by another sponsor with a view to appraising the chances of a large body of disseminated copper mineralization. While the presence of base metal sulphides over a large area was confirmed, no rock was found that would qualify as ore.

Figure 6 summarizes the pertinent geological, geochemical and geophysical information from the Mount Pleasant prospect. This material was collected largely by A. R. Barringer and Alan Warren of Selco Exploration Company, whose work the writers gratefully acknowledge.

The mineralized area underlies and partially surrounds Mount Pleasant, one of the conspicuous landmarks of southwest New Brunswick. The total relief from the summit of the mountain to the west edge of the claim block is over 700 ft. The ridge crest and the fire tower at the summit of the mountain are shown on Figure 6.

Although the Pleistocene ice masses undoubtedly overrode Mount Pleasant, the surficial cover is almost entirely a rubble of angular blocks of local origin. Drill cores show strong oxidation of sulphides at depths of 50 ft. or more. The bedrock in the area of Mount Pleasant is poorly exposed, and geological mapping must depend almost entirely on examination of the surficial rubble. The only feature of the geological structure that is beyond dispute is a fairly well-defined boundary trending roughly magnetic north, and separating a series of rhyolites and felsites that underlie the mountain from argillites and other sedimentary rocks in the lower country to the west.

A well-defined line of springs and seepage areas almost coincident with the geological boundary between rhyolites and sedimentary rocks, lies along the base of the steep, west slopes of the mountain for
about 4,000 ft. This zone of seepages represents the emergence at the surface of ground water that has percolated through the rhyolites higher on the mountain, and is of considerable significance in interpreting the geochemical soil patterns.

The critical contours for the copper, lead, and zinc content of the soil over the Mount Pleasant property are shown on Figure 6. Individual geochemical soil values mostly are highly erratic and not amenable to contour mapping; and the figures on which the contours are based represent the averages of the metal content of all samples within a square 1,000 ft. on a side.

The soil pattern cannot be positively correlated with the bedrock distribution of metals until much more drilling has been done. A conspicuous feature of the pattern, however, is the tendency for the lead anomalies to be best developed on the ridge crest, and
for the zinc anomalies to be concentrated west of the line of springs and seepages along the west base of the mountain. The strongest part of the copper pattern is in an intermediate position, partly on the steep, west slope of the mountain, and partly on the flatter ground west of the zone of seepages. Particularly high zinc and copper anomalies are observed in soils collected from the seepage zone itself. Presumably at least a part of the metal content of these soils is precipitated from ground water solutions that have percolated through the mineralized rhyolites higher on the mountain. The distribution pattern of the various metals at Mount Pleasant is consistent with the general observation that lead is relatively immobile in
the weathering cycle and tends to stay near the bed-
rock source, that zinc is extremely mobile and will
migrate in the direction of ground water movement,
and that copper shows an intermediate behaviour.

The electromagnetic survey revealed only very
weak and discontinuous electrical conductors. All the
electromagnetic anomalies within the area of Figure 6
are very close to the contact of the rhyolites and the
sedimentary rocks with the associated zone of seep-
ages. These anomalies, therefore, could be interpreted
as reflections of electrolytically conducting fractures
associated with the contact. No indications were found
that could be ascribed to massive sulphides.

In the drill cores, sphalerite was found to occur
as high-grade pockets containing up to 25 per cent
zinc, up to a foot wide. Galena was observed only as
extremely fine-grained crystals disseminated through-
out the rock. Chemical analyses showing lead contents
up to 1.25 per cent in material containing no visible
galena, suggest that the lead minerals are extremely
fine-grained. Copper is seen frequently in the fresh
rock of the drill core, usually as fine disseminations of
chalcopyrite, and locally as conspicuous veinlets of
chalcopyrite and other sulphides. Unweathered sedi-
mentary rocks in drill hole 6 averaged 0.06 per cent
copper over 65 ft. and unweathered rhyolite in drill
hole 10 averaged 0.16 per cent copper over 85 ft.
Bornite and chalcocite have been found in weathered
rock from both drill cores and surficial float. Well-
developed crystals of fluorite are common in both
surficial material and drill cores. Accessory minerals
include widespread pyrite and arsenopyrite, and some
topaz and molybdenite. Spectrographic analysis of two
grab samples showed tin above normal quantities. A
Geiger counter survey of the mountain indicated a
radioactivity only slightly above background.

Whether the very widespread and intense geo-
chemical anomalies can be fully explained on the basis
of the tenor of material so far seen in the drill holes
is still not certain. Altogether, 21 localities have been
found where the copper content of the soil exceeds 0.1
per cent (1000 ppm). The 200-ppm contour in Figure
6 encloses an area of more than one-quarter square
mile, and one locality in the zone of seepages shows
an average of 1 per cent copper over about an acre.
In contrast with this, the nonweathered mineralized
rock rarely contains more than 0.15 per cent copper.
This uncertainty of the source of the metal in the
geochemical anomalies can be resolved only by fur-
ther drilling, particularly in the area between the ridge
crest and the line of seepages.

REFERENCES

(1) Hawkes, H. E. and Bloom, Harold: Heavy Metals in
Steam Sediments as an Exploration Guide, (See
"Methods—Geochemistry," this volume).

(2) Bloom, Harold: A Field Method for the Determination
of Ammonium Citrate-Soluble Heavy Metals in Soils
and Alluvium, Econ. Geol., Vol. 50, p. 533-541, 1955.

(3) Hawkes, H. E., Bloom, Harold, Riddell, J. E., and
Webb, J. S.: Geochemical Reconnaissance in Eastern
Canada: XX International Geological Congress, 1956,
In Press.

(4) Hawkes, H. E. and Bloom, Harold: Heavy Metals in
Stream Sediments Used as Exploration Guides. Mining
GEOPHYSICAL EXPLORATION OF A LEAD-ZINC DEPOSIT IN YUKON TERRITORY

by Edward O. Chisholm*

Abstract

Self-potential and magnetometer surveys were followed by a gravimetric survey in the northwestern Cordillera to outline successfully a flat-lying lead-zinc sulphide replacement deposit beneath 50 ft. of glacial overburden. This site of the survey is 125 miles northeast of Whitehorse, Yukon Territory, in mountainous terrain. Detailed diamond drilling verified the accuracy of the survey both as to boundaries and estimated tonnage of the deposit. Auxiliary surveys were carried out by aeromagnetic and geochemical methods. Graphitic schists interfered with the self-potential readings, but geochemical and magnetic results were helpful for indicating favourable terrain.

Location, Topography, Etc.

The lead-zinc sulphide replacement body investigated by geophysical techniques described here is located on the headwaters of Vangorda Creek, a tributary of Pelly River, on the Vangorda Mines property of Prospectors Airways Company Limited. The surrounding country is mountainous but the deposit is in the centre of an intermontane valley approximately 2½ miles wide. Differences of elevation within the area of the survey are less than 100 ft., a feature which facilitated gravity work.

The replacement body lies beneath a glacial sand and boulder ridge varying in thickness from 25 to 80 ft. The ridge is traversed by Vangorda Creek, a small glacial stream, and a smaller tributary. Outcrop is exposed in the area of the survey at one location only on the bank of the stream, and consists of massive sulphides 100 ft. in length, 10 ft. in height. Permafrost, though usual in this latitude, was not encountered. Overlying the glacial material is a persistent layer of volcanic ash approximately 4 inches thick. The climate is sub-arctic and the soil profile is immature with zones of leaching and oxides penetrating less than a foot below surface. This results in a smaller, residual base-metal content of the soil and water than is normal to central latitudes.

The geophysical methods were started in advance of drilling, but were broadened in kind and magnitude as the drilling progressed and as different characteristics of the deposit were revealed. Initially the simplest methods, the self-potential and the magnetometer, were used. When it was apparent that graphitic schist was present, the electrical methods were discarded and magnetometer work was increased. The detail of this method was completed during the second season in time to indicate possible extensions of the deposit.

Further drilling indicated, however, that the magnetometer could not be relied upon solely to indicate sulphides because of the presence of other magnetic zones. At this stage gravimetric work was initiated and was completed over the deposit at the same time as the drill program. The results coincided so well that further drilling to extend the margins of the deposit was considered unnecessary. The excess mass calculation agreed so closely with the tonnage figure arrived at by drilling that it was decided also that further deep holes to explore the possibility of underlying zones were unnecessary.

Geology, Mineralization, Alteration

The deposit comprises an overlapping series of horizontal lenses of sulphides that appear to replace a favourable sedimentary bed; longitudinal section of the body is shown in Figure 1. Seventy-three diamond drill holes indicate a length of 3,200 ft. with an average width of 490 ft., and 9,400,000 tons of sulphide containing 3.16% Pb, 4.96% Zn, 0.27% Cu, 1.76 ozs. Ag, and 0.02 oz. Au; also, an additional 12,600,000 tons of low-grade to barren sulphides. The total mass of sulphides is estimated from diamond drilling to be in the order of 22,000,000 tons. The mineralized body extends from bedrock surface to a depth of 300 ft. Drilling to 1,000 ft. encountered no underlying body.

The host rocks comprise a flat-lying sedimentary assemblage which can be divided into two main zones, namely, one predominantly chloritic sericite schist, and the other predominantly graphitic schist. They are intimately associated with much intercalation at the edges of the graphitic horizon. The graphitic schist is minutely crumpled, breaks easily along cleavage planes, and contains narrow (up to 1 m.m.) quartz stringers.
which often are mineralized with pyrrhotite, with minor chalcopryite and pyrite. In thin section, it consists of minutely folded bands of white mica (sericite) and black carbonaceous matter intercalated with bands of anhedral, interlocking quartz grains, and isolated siliceous lenses. Sparse mineralization is confined to the siliceous bands, pyrrhotite apparently replacing quartz. This graphitic schist seems to have been produced by strong metamorphism of impure carbonaceous slate interbedded with thin, sandy layers. Calcite is present in small amounts and may have been introduced with the sulphides.

The sericitic zone consists of light greenish-grey, chlorite schist and appears less deformed than the black schist. It is sparsely mineralized in siliceous bands (mainly pyrrhotite with some galena and chalcopryite). In thin section, it appears to be a succession of thin bands of sericite, alternating with somewhat wider layers of quartz and chlorite containing minor amounts of orthoclase and sericite. The serite-chlorite schist appears to have resulted from strong regional metamorphism of a succession of thin sedimentary beds, probably of impure sandstone interbedded with shale. Occasional siliceous lenses containing sulphides may originally have been small pebbles in the sediment.

No intrusive rocks were found within the area, although granite, gabbro, diorite and porphyry are present elsewhere on the claims.

The mineralization is a fine-grained aggregate of sulphides in a siliceous matrix. Sulphide content is variable but might average 60 per cent overall. Minerals present in their order of abundance follow:

- Pyrite .................. 35%
- Sphalerite .................. 25%
- Galena .................. 15%
- Pyrrhotite .................. 10%
- Chalcopyrite .................. 6%
- Arsenopyrite .................. 5%
- Magnetite .................. 3%
- Marcasite .................. 1%
- Tennantite .................. Small amount

The assemblage indicates a hypothermal replacement deposit.

Alteration is predominantly sericitic and chloritic and is intensified in an envelope surrounding the mineralized deposit.

The control of deposition appears to be lithological rather than structural, but at this stage there is insufficient evidence to decide. There is a suggestion that the northwest extremity of the deposit is terminated by a fault along Vangorda Creek. Brecciation and carbonatization of the ore in drill holes in this section indicate faulting. There is also a suggestion that the long axis of the deposit is controlled by faulting and/or folding. No post-ore displacement of the sulphide mass in a horizontal or a vertical plane was indicated in the drilling and it would seem that any structural elements reflected in the magnetometer and gravity surveys may indicate pre-ore controls. It is reasonable to assume that the presence of feeder faults in the area and the displacement of contours in the magnetic and gravity surveys in the vicinity of Vangorda Creek and its tributary to the east near Line 19E, may be caused by this. However, part of the displacement of the gravity contours along the creeks is due to thinning of the overburden in this locality.
Gravimeter Survey

The outline of the residual gravimeter anomaly and its relation to the mineralized zone is shown in Figure 2 (in pocket).

Readings were taken with a Worden gravimeter with sensitivity of 0.10024 mgs. per scale division, at 100-ft. intervals with varying line separation. Gravity and elevation runs were made in closed loops with all errors being adjusted. Elevation misclosures were kept under 0.5 ft. and gravity misclosures under 0.5 milligals. Drift, elevation, latitude and terrain corrections were applied to the gravity readings.

Density measurements on both surface and core specimens gave the following values:

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<th>Specimen</th>
<th>Depth</th>
<th>Type of Material</th>
<th>Density</th>
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<td>Surface</td>
<td>Granite</td>
<td>2.64 gms./cc.</td>
</tr>
<tr>
<td>2</td>
<td>139'</td>
<td>Sericite schist</td>
<td>2.69</td>
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<tr>
<td>10</td>
<td>—</td>
<td>Massive sulphides</td>
<td>4.62</td>
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The schists are of relatively uniform density, with the granite slightly lighter and gabbro slightly heavier.

**Conclusions**

The disturbance of the deposit indicated by the gravity anomaly are noticeably sharp, others are gradual; this may be a reflection of faulting, especially in the northwest end of the deposit.

Approximately 500 ft. southwest of the mineralized deposit, and parallel to it, is a small, broad low; this appears to be a reflection of a graphitic schist zone which outcrops in this area. Its overall density is lower than surrounding schists.

No anomalous regional effects that might be expected in the disturbed zone of intermontane terrain were noticeable in the gravity survey.

**Observations**

The mineralized zone was clearly detected by geophysics and its edges are well defined. The results show a remarkable coincidence with the zone as outlined by drilling.

Tonnage calculations from the residual anomaly (total anomaly minus regional anomaly) gave in excess of 6,000,000 long tons. Transferred into actual tonnage, on the assumption that the schist's average density is 2.8 gms./cc. and the mineralization averages 4.0 gms./cc., a total of 20,000,000 tons is indicated. This is remarkably close to the 22,000,000 tons of sulphides indicated by drilling.

The regional gravity, not shown on the accompanying map, slopes gradually southwest and is caused by a series of gabbro intrusions in this direction.

The shape of the anomaly indicates that the mineralization is banded in parallel zones along its length. The portions of greatest thickness near Vangorda Creek, (as shown on the longitudinal section on Figure 1), are reflected in high-gravity values up to a peak of 2.02 milligals. The lensing out of the deposit to the edges is reflected also in lower-gravity values.

Some of the edges of the deposit indicated by the gravity anomaly are noticeably sharp, others are gradual; this may be a reflection of faulting, especially in the northwest end of the deposit.

Approximately 500 ft. southwest of the mineralized deposit, and parallel to it, is a small, broad low; this appears to be a reflection of a graphitic schist zone which outcrops in this area. Its overall density is lower than surrounding schists.

No anomalous regional effects that might be expected in the disturbed zone of intermontane terrain were noticeable in the gravity survey.

**Conclusions**

Near-surface deposits of massive sulphides enclosed in light schists that provide a marked density contrast, produced sharp high-gravity anomalies. Values about 0.5 milligals are considered anomalous.

The gravimetric method is a definite tool for outlining sulphide masses in the geological conditions described here.

Self-Potential Survey

The outline of the self-potential survey and its relation to the mineralized zone are shown in Figure 3 (in pocket). Readings were taken at 50-ft. intervals along lines 200 ft. apart.

**Observations**

The self-potential survey of the mineralized zone showed several large anomalies seemingly caused by graphitic schist. Readings over the deposit itself generally were flat and appeared to be blanketed by overburden where it exceeded 25 ft. in thickness.

**Conclusions**

The self-potential method, although cheap and fast, would be of use under the present geological association only in tracing the block schist zones under overburden less than 25 ft. thick. Where depth of overburden is unknown, interpretation of results would be difficult and the electrical-magnetic method would offer a more effective technique because of its greater penetration.

Aeromagnetic Survey

A series of lines approximately 5,000 ft. apart were flown over the central part of the claims at a
height of 500 ft. to test the effectiveness of this type of instrument for reconnaissance.

- **Observations**
  
  No higher than normal readings were obtained over the mineralized zone, but a generally higher level of readings was noted over the basic intrusive rocks one mile to the southwest of the deposit.

- **Conclusions**
  
  Insufficient lines were run over the zone to test the airborne instrument conclusively; with closely spaced flightlines at a low altitude, results comparative to the ground magnetometer survey might be expected.

**Magnetometer Survey**

The outline of the magnetometer survey and its relation to the mineralized zone are shown in Figure 4 (in pocket).

Readings were taken by the Askania instrument at 50-ft. intervals on lines 200 ft. apart. Sensitivity was 25.6 gammas per scale division. No magnetic storms or side hill effects from surrounding mountains were noted.

- **Observations**
  
  Six anomalies were found within the area of mineralization, with residual magnetic values ranging from 800 to 2,000 gammas.

  Contours are lenticular along the length of the deposit.

  The most intense anomalies were obtained where overburden is shallow.

  Anomalies of similar magnitude and shape were found outside the mineralized zone.

  Certain sections of massive mineralization gave no magnetic anomalies.

  Magnetic contours show displacement along Vangorda Creek and its tributary to the east.

  Sufficient spot drilling has been done to indicate the cause for most anomalies.

- **Conclusions**
  
  The magnetometer alone would not produce definitive anomalies signifying underlying sulphide mineralization because of the variable magnetite content of the sulphide deposit itself, and because of the presence within the confines of the survey of other factors contributing to a magnetic condition of magnitude similar to that encountered over the mineral deposit. These factors are:

  1. Concentration of magnetite in residual gossan material underneath an eroded section of sulphides;

  2. Small gabbro intrusive plugs outside the confines of the mineralized zone;

  3. Widely disseminated magnetite in certain sections of the graphitic schist zone which, when near surface, produced a mass effect equal in magnitude to the magnetic section of the main mineralized zone.

  The magnetometer proved useful in indicating favourable terrain; in determining the strike of mineralized zones; and in pinpointing thick sections of sulphide containing magnetite. It indicated also a possible fault that terminates the deposit abruptly along Vangorda Creek between anomalies 1 and 2; drilling confirmed this fault. A possible pre-ore fault is indicated along the creek at Line 19E.

  The magnetometer is best used under the above geological conditions in conjunction with other exploration survey methods.

**Geochemical Surveys**

The outlines of geochemical heavy-metal surveys in the soil surrounding part of the deposit and in the drainage system cutting through it are shown on Figures 5 and 8 respectively. Geochemical profiles showing the relationship between heavy-metal content in the soil, topography, location of sulphides, gravity and magnetic determinations, are shown in cross-sections 6 and 7.

Soil samples were taken at 100-ft. intervals on lines 200 ft. apart at uniform depth of 2 ft.; this represents the “C” or parent soil zone. It was tested for heavy-metal content by the cold extraction method devised by Bloom. Surveys were conducted in July after the seasonal run-off had taken place and the water table had reached a state of equilibrium.

The method is a rapid and simple field technique that involves extraction of (Zn, Cu, Pb, Co, Ni) ions from a soil sample with a cold solution of ammonium citrate in the presence of dithizone-xylene solution.

Figure 5. Geological map—soil survey.
Figure 6. Geochemical profile of line 0+00.
The method may be used also for water samples taken at regular intervals along streams.

- Observations

Figure 5 shows distinct heavy-metal anomalies in the soil near the mineralized zone on the downslope side.

The higher contours generally follow the water channels.

Deep overburden blanketed out anomalies.

Similar results are noted also in Figures 6 and 7 where sharp increases were obtained in the heavy-metal content of the soil on sections 0 plus 00 and 4
Figure 8. Geochemical map, Vangorda Creek.
plus 00 east at 12 plus 00 south, down-slope from the mineralized zone.

Figure 6 shows a sharp rise in the heavy-metal content of the soil at 0 plus 00 south where the massive sulphides are near surface and where overburden is light. In these conditions a heavy-metal content of over 200 parts per million was considered significant for the soil and over 0.01 part per million for water.

There is a rough correspondence between heavy-metal soil contours and the self-potential contours which trend along water courses. Both may be due in part to the concentration of ions along these channels.

Figure 8 shows a gradual build-up in the heavy-metal content of the water in Vangorda Creek up to the point where it cuts through the mineralized zone. Similar increases in heavy metals were noted in the tributaries of the main creek on proceeding upstream and approaching the mineralized zone.

**Conclusions**

The geochemical water test is a cheap and useful prospecting method for testing streams and tracing heavy metals to their point of maximum concentration. The soil testing is useful as an auxiliary exploration tool where overburden is light.

The main usefulness of geochemical methods lies in the quick determination of large targets for subsequent exploration by methods other than time-consuming investigation within narrow limits. This is because of the large inherent sampling error in any soil sample.

**General Conclusions**

The results of geophysical and geochemical surveys over the sulphide deposit at Vangorda Creek indicate that the optimum combination of preliminary exploration techniques elsewhere on the property would consist of a geochemical soil and water reconnaissance followed by electro-magnetic and gravity survey.

The assistance of the following is gratefully acknowledged: Radar Exploration Company (gravity survey); and R. W. Baker, (engineering and diamond drilling data), D. R. S. Doal (magnetometer survey), V. Papezík (geological survey), G. Novák (geochemical survey), and F. A. Campbell (self-potential survey), of Prospectors Airways Company Limited.

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**GEOCHEMICAL ANOMALIES RELATED TO SOME BRITISH COLUMBIA COPPER MINERALIZATION**

by Harry V. Warren, Robert E. Delavouct and Christine H. Cross

**Abstract**

Geochemical techniques were applied to prospecting for copper in three areas in the south part of British Columbia. Soil and vegetation samples were collected along profiles over strong, medium and weak copper mineralization. The analyses were plotted on profiles, and the mineralization, as determined by various methods, is shown. Large geochemical anomalies were obtained over the areas of significant copper mineralization. The ratios of the p.p.m. of copper to the p.p.m. of zinc present in the samples were computed and plotted as aids in interpretation. The techniques were found to be effective for exploration in the section of British Columbia under study.

**Recent** interest in low-grade copper deposits has induced a wave of intensive exploration in the vicinity of Kamloops, Ashcroft, Merritt, and Aspen Grove, British Columbia (Figure 1). Much of this section is geologically favourable and heavily drift-covered, making it a natural setting in which to use geochemical techniques.

The examples which follow were not collected originally with the intention of publication, and some data, which would have served to develop a more complete picture, are not available. However, through the kindness of the companies on whose properties the samples were collected, sufficient results have been released to illustrate the type of anomaly which may be looked for over mineralization of different intensities in some sections of south-central British Columbia. Biogeochemistry and pedogeochemistry, particularly the latter, have been shown to be of value in any search for mineralization buried by overburden less than 20 to 30 ft. thick.
MINING GEOPHYSICS

Three different areas have been selected to illustrate the different magnitudes of the anomalies which may be encountered over strong, medium and weak mineralization respectively. These areas will be referred to as (a) Bethlehem, (b) Afton, and (c) Dutchman, the names selected being those of known showings or claims in the immediate vicinity. The rainfall in these areas varies between 10 and 20 inches annually. The soils are poorly developed and vary greatly. The soil in the Afton area is pedocalcic and in the Bethlehem area it is pedalfertic, while the soil in the Dutchman area is an intermediate type.

Wherever practical, A₄ horizons were sampled (1). Laboratory determinations of the soil samples involved extraction by boiling in normal sulphuric acid after heating the soil to red heat and holding it there for two hours. Plants were ashed at low red heat. In both cases, dithizone was used for copper and zinc determination.

**General Geology**

The general geology in all the areas involved in this discussion has been well described (2) (3) (4).

(a) Bethlehem. The Iona and the Jersey orebodies, with large reserves grading between 0.5 and 1.0 per cent copper, were found in the Highland Valley. The ores consist of varying amounts of disseminated chalcopyrite and bornite in a brecciated and highly fractured igneous complex which roughly approximates a quartz diorite in composition. Over 90 per cent of the mineralized area is covered by a mantle of drift which varies in thickness from a few inches to 40 ft.; in places it amounts to 200 ft. or more.

(b) Afton. Plutonic and volcanic rocks are in contact a few miles west of Kamloops. The former are represented by syenitic and dioritic facies in which scattered mineralization occurs, usually associated with shearing. The copper mineralization consists primarily of chalcopyrite but native copper, malachite, and bornite have been reported. A high percentage of this area is covered by till and glacial gravels which are only a few inches thick in many places, but occasionally are a hundred feet or more thick. This glacial material has not been converted to a well-zoned soil, but usually it has a well-defined humus layer which is inches thick in some places. The grade of the mineralization, where it occurs, is low and where it has been determined by drilling it runs from 0.1 to 0.5 per cent.

(c) Dutchman. A mile or more east and north of Aspen Grove, the varicoloured lavas, approximating andesite in composition, contain small areas of coarser textured rocks. Grains of chalcocite are visible in some of these lavas. Occasionally veinlets of native copper, chalcocite and bornite are found in some shattered areas of which the Dutchman may be considered an example. In this particular showing considerable copper staining can be noted, but the overall grade of copper runs only about 0.05 per cent. Drilling in the vicinity failed to discover material of a better grade. Overburden of varying thickness is widespread and makes prospecting particularly difficult.

**Methods**

The samples were, wherever practical, taken at 100-ft. intervals with the exception of the Afton sagebrush and soil suite in which instance the samples were taken at 50-ft. intervals. The laboratory results obtained from the above areas are presented on the accompanying graphs (Figures 2 and 3).

The vertical columns represent the copper content of ash of various trees and lesser plants, distinguished by the following symbols: T=Douglas Fir (Pseudotsuga taxifolia); P=Spruce (Picea Engelmannii); A=Alder (Alnus sp.); S=Sagebrush (Artemisia tridentata). The normal contents of each species are indi-
Figure 2. Geoc chemical profiles (copper content)
Figure 3. Geochemical profiles (copper:zinc ratio).
cated by diagonal hatching. One solitary plant sample from the Jersey was below normal and has been omitted from the graph for the sake of simplicity.

The Bethlehem soil samples were also tested for copper by a simple field method. Copper was extracted by a cold acetic solution with a pH close to 4 and crudely estimated by spot-testing with rubeanic acid paper. The accompanying illustration (Figure 4) shows clearly how the highly anomalous samples contrast with the much weaker background. Incidentally, every one of the samples containing a high copper content as determined in the laboratory, is also readily recognized on the rubeanic acid papers.

Discussion

The above diagrams and the illustration bring out several points. It should be noted that in the soils of this area normal amounts of metal available to a sulphuric acid attack tend to run from 35 to 70 p.p.m. copper and 150 to 300 p.p.m. zinc. Furthermore, in a crude way zinc would tend to be from four to five times as abundant as copper. Dashed lines indicate "normals" in the diagrams.

Bearing the above in mind, the following facts emerge:

(a) The presence of even weak mineralization soon shows up in soil both in its copper content, which rises to as much as 150 p.p.m., and in its copper-to-zinc ratio which can reach from 0.4 to 0.8 without necessarily indicating any valuable mineralization. Naturally the deeper the overburden or the farther it has been transported the less likely it is that geochemical techniques will reflect mineralization directly below.

(b) Where several samples are taken, unless a significant number run more than 300 p.p.m. of copper and have a copper-to-zinc ratio of more than 1.0, it is not wise to expect commercial mineralization. Erratic highs should never be taken too seriously; they may be caused by mineralized fragments occurring in the drift. White (5) drew attention to this warning in a previous paper.

(c) Where large bodies of commercial mineralization are present, many soil samples will run hundreds of p.p.m. of copper and, occasionally, even thousands. Furthermore, copper-to-zinc ratios vary from several units to more than fifty on rare occasions. This, of course, is only true where there is no significant zinc mineralization accompanying the copper.

(d) The copper content of vegetal ash which normally ranges from 100 to 300 p.p.m., depending

Figure 4.
Illustration of geochemical profiles, rubeanic acid field method. All the above check well with geochemical profiles obtained by laboratory analyses.
on the species involved, also reflects the presence of mineralization, although to a less marked degree than the soil in which the vegetation is growing.

In the case of the Afton deposit, it can be seen that the copper content of the sagebrush ash parallels closely the copper content of the soil. At the Bethlehem deposit, the copper in the ash of the various trees also clearly betrays the anomalous conditions. Actually four species were used, their normal copper contents having been established by previous work (6).

(e) In the Bethlehem soil samples, the rubeanic acid field technique is all that is necessary to detect these anomalies. Laboratory analyses are quite unnecessary, merely confirming field methods.

The rubeanic-acid technique which was used in the above tests was developed by R. E. Delavault as an adaptation of a method initiated by the Geochemical Division of the United States Geological Survey (7). The technique has been fully described by Sawyer (8).

Conclusions

In the section of British Columbia under study, where overburden is not more than 20 to 30 ft. thick, geochemistry can be used to discover mineralized areas. Plants or soils will reveal anomalies, but soils tend to provide much greater variations from the normal.

Geochemistry should not be expected necessarily to indicate either the presence of ore directly below an anomaly, or the actual grade of ore. Ice and ground water movement, depth and nature of overburden may act to "displace" anomalies.

However, either plant or soil anomalies, if found in significant numbers, are usually caused by mineralization, and should never be ignored once they are discovered.

Acknowledgments

The writers are indebted to the companies and individuals who made the results presented in this paper available, and who assisted by furnishing geological and general information. J. S. Scott, J. Anderson, D. Barr, P. Hurst, J. Boyd and C. Godwin of Northwestern Explorations Co. Ltd.; C. Coveney of American Smelting and Refining Company Ltd.; and "Spud" Huestis, W. H. White and F. Cook of Bethlehem Copper Company Ltd., all contributed to the preparation of this paper although they are in no way responsible for the conclusions. The sagebrush and soil profile is taken from an unpublished undergraduate essay by L. Gonzales, prepared under the authors' direction at the University of British Columbia.

Geochemical Profiles (Copper Content)

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<th>Elevation</th>
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</tr>
<tr>
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<td>4000 W. - 1500 W.</td>
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<tr>
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<td>On 10 West Line</td>
<td></td>
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<tr>
<td>E. Dutchman</td>
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<td>South of Mineralized Showing</td>
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Geochemical Content (Cu:Zn Ratio)

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REFERENCES

RESISTIVITY AND MAGNETIC SURVEYS IN 1936 ON THE BROULAN-PORCUPINE GOLD PROSPECT, SOUTH PORCUPINE, ONTARIO

*by Sherwin F. Kelly*

Abstract

In 1936, the Broulan-Porcupine Mines, Ltd., held some claims in the newly developed eastern extension of the Timmins gold producing area in eastern Ontario. Paucity of outcrops made effective orientation of drilling difficult, so it was decided to utilize electrical resistivity and magnetic surveys to assist in outlining potentially gold-bearing zones. The magnetic results assisted in locating a lava-sediment contact near which most of the known mineralization in that district occurred. The electrical resistivity survey defined areas of high electrical resistivity which were presumably silicified zones. The gold mineralization in the region was known to be associated with quartz veins and zones of silicification. Therefore, high resistivity indications provided a logical objective for the drilling campaign, which resulted in subsequent discovery of the Broulan-Porcupine orebodies. Maps accompanying the article show the relationship of the orebodies to zones of high resistivity.

By 1936, the gold-producing zone of the Porcupine area around the town of Timmins in northern Ontario—the home of such famous mines as the Hollinger, the Dome, and the McIntyre—was being extended eastward by the development of new producers, the Parnour and the Hallnor, near South Porcupine. This is about 350 miles north of the city of Toronto.

In 1936, the Broulan-Porcupine Mines Ltd., of Toronto, Ontario, held seven 40-acre claims lying between the Hallnor mine on the west and the Parnour on the east, on which the paucity of outcrops made it difficult to orient a drilling campaign. The president of that company, Bert W. Lang, contracted for a geophysical survey over the northern part of the property for the purpose of obtaining more knowledge of the nature and structure of the concealed bedrock. In the summer of that year, the writer supervised and was in active charge of electrical resistivity and magnetic surveys on that property, which subsequently developed into an important gold producer, the Broulan-Porcupine gold mine.

Geological studies had indicated that the rocks in the Parnour-Hallnor area consist of Precambrian formations, mainly Keewatin lavas and sediments, and Temiskaming sediments lying unconformably upon the Keewatin (1). The lavas lie to the north, and consist principally of dacite, andesite, and basalt which have undergone chloritization and carbonatization. There are some thin, intercalated beds of slate, occasionally graphic when sheared and faulted. The Keewatin sediments consist of greywackes and slates.

The Temiskaming sediments are greywackes, arkoses, pebble conglomerates and slates. The unconformable contact between Temiskaming and Keewatin is nearly vertical, runs generally north of east, and skirts the northern boundary of the Broulan-Porcupine claims.

Major folding occurred after deposition of the Temiskaming sediments, with consequent differential movement between horizons in the lavas and in the sediments, together with some shearing. Subsequent faulting took place along shear zones parallel to the axes of the folds (N65°E) and also across the general strike of the formations. The introduction of the gold-bearing quartz veins followed movements along the shear-zone faults, and occurred in open fractures consequent upon these movements. The N-S fractures were post-mineral, and on the Parnour property produced displacements up to several hundred feet.

Ore occurs both in the lavas and in the sediments on the Parnour property, with a bed of conglomerate apparently the most persistent ore-bearing formation. The ore shoots consist of quartz veins together with pyritised wall rock. The veins and sulphide mineralization are apparently more likely to occur in fractured, competent horizons than in the sheared incompetent beds.

Serpentine rocks, probably altered phases of a basic rock such as peridotite, are occasionally encountered in this region.

The foregoing description sets forth briefly the general geological data available at the time of the geophysical survey. On the Broulan-Porcupine property, however, there were but few outcrops to assist in orienting that area within the general geological framework as outlined above. The principal exposures encountered, and practically the only ones on the property itself, were quartzite ridges in the eastern

*President, Geophysical Explorations Ltd., Toronto, Canada, and President, Sherwin F. Kelly Geophysical Services, Inc., Amawalk, New York.

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part of the area, on Claim 13794, shown on Figure 1. Just outside of the Broulan property, there were some showings of lava 500 ft. to 700 ft. north of the north boundary of the western claim, 14909. Also, some outcrops of greywacke, slate, and conglomerate lie just to the east, in the triangle formed by the railroad, the north boundary of Claim 14202, and the west boundary of Claim 13943. The strike of the latter sediments was a few degrees north of east. These outcrops, also shown on Figure 1, provided some useful geological data to assist in evaluating the geophysical results.

Formations common in the Pample district, namely lavas, slates, greywackes and conglomerates, cannot be expected to show remarkably different electrical resistivities because the lavas are not a particularly dense form of igneous rock, and both they and the sedimentary beds have undergone practically the same metamorphism since they were originally formed. Consequently, a wide difference in the porosities cannot be expected.

The probable lack of strong resistivity contrasts between the various formations rendered it unlikely that individual bands of greywacke, or slate, or conglomerate could be traced beneath the concealing overburden. It was hoped, however, that the patterns of resistivity ratios would fall into zones characteristic enough to warrant their differentiation and persistent enough to permit tracing them from one profile to the next.

An important feature of the geological setting was the fact that gold deposition accompanied silification, either as silification of the wall rocks or in the form of quartz veins, or both. Such silified formations would show high resistivities, and thus make their discovery and delineation relatively easy. The presence of silified zones is not, unfortunately, an invariable indicator of gold mineralization; many, many silified formations are barren. Hence, a high-resistivity band is not to be considered an infallible indication of a gold vein. It does indicate, of course, the most favorable location to drill, in order to determine if the quartz vein or silicified zone is gold-bearing.

The instruments used in the geophysical investigation were the Hotchkiss Superdip and the Ground Comparator. The Hotchkiss Superdip is a magnetic dip needle, modified by W. O. Hotchkiss, Noel Stearn, and associates (2), to give it a much greater sensitivity. The modification consisted of adding an adjustable counter-arm with a movable weight by which the sensitivity of the instrument could be set to a desired value.

The Ground Comparator was an instrument developed by the late Theodor Zuschlag. It was designed, not to measure ground electrical resistivities directly, but to derive the ratio (i.e., comparison) between such resistivities in two adjacent segments of ground (3). To do this, an alternating current of about 100 volts was passed through the ground, utilizing three current electrodes or power pegs. These were iron rods driven 2 or 3 ft. into the soil. One was placed at each end of the line or traverse to be worked over, and the third at a distance of 1,000 ft. or more from the line and approximately on its perpendicular bisector. Observations were made between three potential electrodes, or reading pegs (iron rods, similar to the power pegs), placed in series along the traverse, with a suitable distance between them—in this case, 50 ft. As the current was passed between the distant current electrode and the current electrode at one end of the line, an observation was taken which yielded a numerical value. This figure represented the ratio of the potential drop between the front and middle reading pegs to the potential drop between the middle and rear ones. The current was then switched to pass between the distant power peg and the one at the other end of the line, and a second reading was made of the potential drop ratio. This was done in order to compensate as much as possible for resistivity variations in the overburden.

Next, the potential electrode configuration was moved forward 50 ft. along the traverse, so that the rear electrode interval overlapped the front interval of the previous setup, (in the present survey, the movement was always from north to south), and the reading process was repeated. From the potential drop ratios and the spacing of the potential electrodes, corresponding ground resistivity ratios were calculated for each station occupied.

The Ground Comparator was a highly sensitive measuring instrument, but suffered from two drawbacks. In the first place, the Comparator itself was a temperamental instrument and difficult to keep in adjustment. In the second place, actual values of ground resistivities could not be obtained, and these quantitative figures are often of great diagnostic value. In spite of its useful service on this and other surveys of that era, the Ground Comparator was finally abandoned in favor of the Gish-Rooney type of equipment (4).

The area designated for geophysical investigation consisted of Claims 13943, 14202 and 14909 of the Broulan-Porcupine group, situated in Whitney town-
ship in the eastern portion of northern Ontario, near the town of South Porcupine. The claims were prepared by laying out and staking north-south lines spaced from 200 ft. to 400 ft. apart, as shown on Figure 1. Readings of magnetic intensities and of resistivity ratios were taken along portions of these lines, as indicated, at 50-ft. intervals. The spacing between the potential electrodes in the resistivity work was also 50 ft. The resistivity ratios as plotted represent the ratio of the resistivity in the 50-ft. interval ahead (south) of the station to that in the 50-ft. interval behind (north) of the station.

Diamond drilling commenced on the Broulan-Porcupine claims about the same time as the geophysical survey began. The first drilling was done in the northeastern part of the area, on Claim 13943, but failed to encounter any mineralization of interest. The geophysical work commenced in the western part of the area, on Claim 14909, and encountered zones of high resistivity ratios on the northern part of that claim (see Figure 1). The locations where peak ratio values indicated high bedrock resistivities on this claim were roughly outlined in discussions with the client while the field work was still in progress. A series of drill holes was spotted to test those resistant zones. The holes then drilled south from the north claim boundary delineated highly silicified zones carrying commercial gold values, under the high resistivity indications.

As drilling progressed, geological data from the drill holes were furnished to the geophysicists to assist them in correlating the geophysical results with the geological formations encountered. This brought out an additional factor of importance, namely that pronounced irregularities in the resistivity ratio profiles, as well as high peak values, corresponded to zones of silicification. This irregularity is due to frequent intercalations of silicified beds, as of greywacke, not very thick, in less silicified formations such as slates.

With this additional information, the outlining of high resistivity zones was completed, as shown on Figure 1.

In order to avoid complicating Figure 1, the drill holes are not shown. The positions of the ones referred to, however, are readily evident from the sections, Figures 2 and 3. Both holes No. 3 and No. 6 were drilled south from the north boundary of the western claim. No. 3 was drilled under line C, and No. 6 under line D. Hole No. 3 was spotted to test the high resistivity ratio peak on profile C, and the ratio profile and drill log are shown on Figure 2. The correlation of the geological and geophysical data made at that time stated that from 130 to 250 ft. in the drill hole, a predominance of silicified greywacke in the section was evidently responsible for the high ratio peaks at stations 0 + 50 N, 0 + 0, and 0 + 50 S. Following this peak there is again a series of interbedded slates and greywacke which produced but slight electrical variations. The few silicified portions are apparently too narrow to have much effect. It is interesting to note that the very well mineralized section (footage 130 to 150), did not produce a decrease in resistivity. This must be ascribed to the fact that the intense silicification of the beds involved effectively insulated the individual grains or masses of pyrite so that there was no continuous metallic path for the current to follow across the beds. The serpentinitised schist encountered toward the end of hole No. 3 falls beyond the end of the electrical profile, but was probably responsible for the intense magnetic anomaly found on the southern part of this claim.

The ratio profile along line D, and the log of hole No. 6 under that line, are shown on Figure 3. Of them, it was stated:

"In hole No. 6, which lies along a portion of profile D, the interbedded slates and silicified greywackes extending practically to the bottom of the hole produce a highly irregular ratio profile. Here again, the well mineralized but silicified greywacke exerts an effect predominantly resistant because of the intense silicification."

In examining the ratio profiles, it must be remembered that they are not profiles of resistivities, but of the gradient of resistivity. The peak on a ratio profile represents the location of the maximum increase in resistivity (i.e., maximum gradient); the maximum resistivity is south of that peak, where the ratio line approaches unity value. Resistivities decrease, of course, where the profile line dips below unity.

The strong peaks and irregularities in the resistivity ratio profiles along traverses C and D, indicative of silicification of the bedrock, were lacking in the profile along traverse E. This latter profile was noticeably smoother than those to the west, and it was reported that hole No. 16, drilled beneath traverse E, encountered only slightly silicified formations.

The pattern of the resistivity ratio profile along line C could not be clearly correlated with either profile B or D, from which it was concluded that a dislocation of some sort, or a marked change in formation occurred in the 400-ft. interval between lines B
Figure 1. Plan of geophysical survey on Bouloum Pass mine property. Principal deductions from geophysical results are indicated, together with location of orebodies and main faults subsequently encountered on the 175-ft. level in the Bouloum mine workings.
Figure 2. Magnetic and resistivity ratio profiles along traverse C, compared with formations encountered in diamond drill hole No. 3 beneath that traverse. Principal formations cut in drill hole are projected back to bedrock surface on an assumed northerly dip of 70 degrees, the average dip of formations in that area.

Figure 3. Resistivity ratio profile along traverse D, compared with formations cut in diamond drill hole No. 6 under that traverse. Principal formations encountered in the drill hole are projected back to bedrock surface on an assumed northerly dip of 70 degrees, as in Figure 2.
and D. It will be observed from Figure 1 that two major faults, the Hallnor and another one nearly parallel with it 150 to 200 ft. to the northeast, were subsequently encountered in the mine workings. They dislocated the formations in the interval between traverses B and D.

The Hallnor fault is of the normal type, and its east side had moved down to the southeast. The geological deductions as to the direction of movement in this area (east side carried north), quoted from the report in a summary at the end of this article, were therefore erroneous. The Hallnor fault would project to bedrock surface close to station 2 + 50 S on line C, and is therefore probably responsible for the dip below unity value of ratio profile C at that station. The No. 2 fault is a thrust fault whose projection to bedrock surface would bring it to the neighborhood of station 1 + 0 S or 1 + 50 S on traverse D. This fault zone is therefore probably responsible for the pronounced decrease in ground resistivity indicated at those stations on ratio profile D. These faults did not manifest themselves with sufficient consistency on all ratio profiles traversing them to permit mapping them in detail.

By correlating the ratio patterns from one profile to the next, the strike of the bedrock formations was deduced. This was shown on the map accompanying the report, but has been omitted from Figure 1 in order to keep that map from being overburdened with symbols (5). It showed that the strike was east-west in the area west of line G, and east of line K it was slightly north of east. No clear indication of strike could be found in the interval between lines G and K. Consequently, a break or dislocation was to be expected in the 800-ft. interval between those lines.

It may be seen from Figure 1 that lava outcrops were found north of the Broulan property on lines A, B, and G, some 600 to 800 ft. north of the base line whereas on lines L and M the electrical results indicated silicified zones in this position. Silicification extends to the north boundary of Claim 13943, or beyond, on line M and the successive lines to the east. This evidence points to a shift northward of the lava-sediment contact, amounting to some 600 ft. at least, and probably more, between lines G and L. Whether the shift was caused by faulting or by bending could not be decided as there were not enough lines of geological observation in the critical area west of Claim 13943.

The Broulan Mining Company carried out some exploration in the northwest portion of Claim 13943 and encountered a zone carrying a minor amount of silification with some gold values. Although it did not prove to be of profitable ore grade, a considerable tonnage was removed in testing the area, which corresponds approximately with the high resistivity band extending northeasterly from station 2 + 0 S on traverse M.

The magnetic profiles did not exhibit pronounced variations, except in two areas. The first, on Claim 14909, was marked by high values extending south from station 3 + 0 S on profiles A and B, culminating in a peak at station 8 + 0 S. See Figure 2 for magnetic profile C. This peak extended eastward with diminishing intensity to station 7 + 0 S on line E. The underlying, causative formation, it was stated, could consist of beds containing magnetite or pyrrhotite, or be an igneous rock of basic character. Drill hole No. 3, extending under line C from the boundary south, encountered “highly serpentinized sheared schist of a talc nature (basic origin)” under the magnetic high. The extent of the high magnetic values is indicated on Figure 1.

The second location was on Claim 13794, where similar magnetic anomalies were observed; leading to the conclusion that magnetic material could be expected to occur south of the quartzite outcrops in that area. It might be the same kind of serpentine rock, but the dislocations postulated between the two areas implied it would be in a different horizon.

A slight dip, or low magnetic reading at station 3 + 0 S on profiles A and B was believed to indicate the lava-sediment contact, or a horizon close to and parallel with it. On this basis, the contact was predicted at about 4 + 50 N on line C, and at 4 + 75 N on line E. The contact was encountered a few feet south of the predicted spots as shown on Figure 1.

The weak relief of the magnetic profiles prevented correlating from line to line where the spacing was wide, east of line E. Nevertheless, the magnetic profiles did seem to indicate a shift of some 650 ft. to the north for the formations east of line G, thus confirming deductions from the geological evidence and the electrical results. With more closely spaced lines, extending further north, it might have been possible to locate the area of shift more closely, and to determine whether it was due to a sharp bend or fault.

To summarize, the report stated that “The results of the magnetic survey indicate the presence of a tongue-like body of high magnetic permeability in the western portion of Claim 14909. This formation is
probably to be correlated with the serpentinised schist found in hole No. 3.

"The electrical results indicate a generally east-west strike of the formations on Claims 14909, 14202 and 13943. On the last named claim, the strike seems to follow a direction slightly more north of east.

"A possible bend or dislocation is postulated in the neighborhood of profile C on Claim 14909, carrying the east side a hundred feet or so north. On the western portion of Claim 14202, the question is raised as to whether or not there may be a fault or sharp fold carrying the formation east of profile G some 650 ft. to the north. Insufficient geophysical data make it impossible to answer this question clearly.

"On the basis of the electrical results certain zones have been outlined as probably underlain by formations more highly silicified than their surroundings. These silicified zones are particularly evident on the northern half of Claim 14909; on the northern boundary of Claim 14202; on the northern and southern boundaries of Claim 13943; and in the middle part of the latter claim and extending part way across it from its western boundary."

The orebodies of the Broulan-Porcupine mine were found in the silicified zones underlying the high resistivity bands on the northern part of Claim 14909, as shown on Figure 1. In the years from 1939, when it commenced production, to 1953, Broulan-Porcupine produced 1,146,059 tons of ore, yielding 243,639 ounces of gold, from workings extending to a depth of 900 ft.

About one quarter of the ore was found in a massive, coarse-grained bed of greywacke; the remainder in thinly bedded and drag folded slates and greywackes. The orebodies consisted of brecciated zones in greywackes and slates, which were filled with quartz-carbonate carrying gold and two or three percent of sulphides. The general trend of the orebodies paralleled the strike of the sediments, but the ore zones dipped steeply south, across the beds. The orebodies were found to be continuous in the massive greywacke bed, but discontinuous in the thinly bedded slates and greywackes. Flat, south-dipping stringers of quartz-carbonate ore extended into the walls between brecciated zones and, in places, off the main parts of the ore zone. The mine lies within a triangular fault block on the north limb of an overturned synclinal fold in the Temiskaming sediments (6).

Grateful acknowledgment is hereby extended to the management of Broulan Reef Mines, Limited for permission to publish the data in this article.

REFERENCES


The map accompanying this article presents the pattern of symbols indicating strike of bedrock formations and shows the correlation of early drill results with geophysical deductions.

SPONTANEOUS POLARIZATION SURVEY ON NORANDA MINES, QUEBEC, 1924
by Sherwin F. Kelly*

Abstract
The first systematic survey by the spontaneous polarization method in the Western Hemisphere was carried out in 1924 on the Horne Mine of Noranda Mines Ltd., in western Quebec. Drilling of this prospect was commenced, but as the pattern of mineralization was obscure, it was decided to try the then new electrical technique to see if it would assist in orienting the drilling program. Numerous centers of electrical activity were mapped, and their relationship to the subsequently discovered sulphide bodies is shown on the illustrations accompanying the article. The advantage is demonstrated of basing the interpretation on equipotential contours, rather than on the original technique of relying solely on peaks on the profiles. Maps originally presented with the report are reproduced for comparison with the modern type of representation.

The spontaneous polarization survey carried out in 1924 on a portion of the copper-gold claims of Noranda Mines, Ltd. in Quebec, was the first comprehensive and systematic investigation conducted by this technique in the Western Hemisphere. Some experimental work with this method had previously been conducted in 1921, in the mining areas of Sudbury, Cobalt, Kirkland Lake, and Porcupine in Ontario, and in the following year at the Flin Flon mine in Manitoba and at Lake Athapapuskow in Saskatchewan. The only prior application of this technique in North America had been made by Dr. Carl Barus (1), of the United States Geological Survey about 1880. He conducted some experiments near Eureka, Nevada, for the purpose of checking and following up the discovery, made 50 years earlier by Robert W. Fox (2) of Cornwall, England, of the spontaneous polarization phenomenon.

None of the 19th century experiments resulted in any commercial application of the method. It was not until the early years of this century that Conrad Schlumberger (3), Professor of Physics at the School of Mines in Paris, evolved the apparatus and technique for applying the phenomenon on a practical basis. It was his apparatus and technique which the writer introduced into Canada and the United States in 1921, employing them in the above experimental work and in making the survey on the property of Noranda Mines, Ltd., in western Quebec.

The phenomenon of spontaneous polarization and the technique for its practical application are described in an earlier chapter in this book. Suffice it here to recall that the method depends on detecting and mapping, at the surface, those weak, electrical currents, which are spontaneously generated by electrochemical reactions taking place within bodies of electrically conductive sulphides.

*President, Geophysical Explorations Limited, and President, Sherwin F. Kelly Geophysical Services, Inc.

The property of Noranda Mines Ltd. now under discussion had been staked in 1920 by E. H. Horne, and in 1922 he and his associates optioned it to a syndicate which later became Noranda Mines Ltd. Trenching in 1923 revealed the large body of copper and iron sulphides known as the "A" orebody. A drilling campaign was then started, but in early 1924, the pattern of mineralization and of the controlling structures was still obscure. In the spring of that year, the late L. K. Fletcher, consulting engineer on the project, approached the writer with a request to carry out a survey of the important part of the claims by the still unfamiliar and relatively unproven spontaneous polarization method.

The claims surveyed are located in Rouyn township, in western Quebec, on the west side of Osisko Lake, about 350 miles north of the city of Toronto. That the country rock consists of rhyolite and andesite lavas, with a strong dyke of later gabbro cutting north-south through the property, was known by 1924. The mineralization consists of pyrite, pyrrhotite and chalcopyrite in varying proportions, deposited in that order. It was then believed that the sulphide deposits were confined to the west side of the gabbro dyke.

As development has proceeded, it has become evident that the country rocks enclosing the sulphides consist of intrusives and extrusives of Keewegian age. The extrusives are quartz porphyry, rhyolite, rhyolite breccia and agglomerate, rhyolite tuffs and andesite. These have been introduced by diabase dykes, syenite porphyry dyke and stocks, and metadiabase. The sulphides replace the country rock, particularly the rhyolite tuffs and breccias, their emplacement having been largely controlled by the fault systems cutting through the area. Two strong, east-west breaks—the Horne Creek and the Andesite faults, some 2,500 ft. apart at the surface—bound the ore-bearing block on the north and south. The Horne Creek fault lies close to the north boundary of the survey area. Branching
Figure 1. Profiles of spontaneous polarization potentials observed on the Hoe mine of Noranda Mines Ltd. in 1924. They are plotted against the traverse lines along which they were observed. These profiles were not reduced to a common datum. Black symbols on the traverse lines indicate strong readings believed due to underlying sulphides. This figure reproduces the map made at the completion of the survey. The term "electro-potential profile lines" used at that time signifies the traverse lines along which observations were made of the spontaneous polarization potentials.
Figure 2. Probable locations of sulphide deposits underlying the Horne mine area, deduced from the positions of the profile peaks or strong readings depicted on Figure 1. This reproduces the map made in 1924 to accompany the one shown on Figure 1. An explanation of the term "electropotential profile lines" is given under Figure 1.
from these shears there are minor faults cutting the
down-faulted block between the two main faults. The
mineralizing solutions apparently followed the chan-
nelways offered by this branching system of faults (4.)

Some thirty-five orebodies are recognized here at
the Horne mine. They fall into four classes: massive
sulphides carrying copper and gold, siliceous rhyolite
flux ores bearing copper or gold, high grade gold de-
posits of chloritic type, and high grade gold deposits
of sericitic type. The gold ores consist of a wide variety
of tellurides which replace some of the earlier sul-
phides.

To prepare this property for the electrical survey,
a grid, 2,400 ft. north and south by 2,400 ft. east and
west, was laid out with marked stakes on 100-ft.
centers. Observations were then made of the sponta-
aneous polarization ground currents along the lines
thus prepared, with measurements being taken every
50 ft. On some portions of the property, detailed read-
ings were taken at closer intervals of 10 ft. and 20 ft.
Most of the east-west traverses were run along alter-
nate coordinate lines, so that they were spaced 200 ft.
apart, although in a few places intermediate lines were
run to give a 100-ft. spacing between traverses. Tra-
verses also were run along portions of a couple of
north-south lines.

The plan of the survey is shown on Figures 1 and
2. On Figure 1, the observed ground potentials are
plotted as profiles which clearly indicate the zones
of strong electrical reaction; in some areas, the spontan-
eous polarization potentials rise to values slightly
over 600 millivolts. The interpretation of these pro-
fies, as it was made at the time, is shown on Figure
2. Both Figure 1 and Figure 2 are reproductions of
the maps exactly as handed to the management of
Noranda Mines, Ltd., at the end of the survey.

It should be kept in mind that this was one of the
earliest surveys carried out by the modern techniques
and instruments, before the procedures of field op-
eration and of interpretation had been well developed.
At that time, it was customary to trace equipotential
curves on the ground. A suitable starting location
would be selected, and then the potentiometer-volt-
meter apparatus would be used to seek points of zero
potential difference from that station. The points
located would be marked with stakes, which would
subsequently be mapped by a transit survey. This was
not a convenient procedure to follow in heavy bush,
such as covered the Noranda area in those days.

Later, the technique was evolved of drawing equi-
potential curves from the plotted profiles. This neces-
sitated the development of a field procedure for tying
all profiles into a common zero or datum, by a process
akin to the "closed traverse" of land surveying. When
this is done, the individual profiles, if closely spaced,
can be used to draw equipotential contours, just as
topographic contours can be drawn from topographic
cross-sections.

The latter method of formulating the observations
would have greatly improved the presentation of the
results of this Noranda survey, and would have shown
more clearly where detail work was needed. It would
have outlined more closely the various near-surface
sulphide bodies and the pattern of mineralization, and
thus have indicated more convincingly the places re-
quiring investigation by trenching or drilling.

For the purpose of presentation in this article, an
effort has been made to draw such a contour map as
described above. The results are not completely satis-
factory, because it was not possible to reduce all the
profiles accurately to the same datum, since some
east-west traverses are not tied in by the two north-
south ones. Also there are numerous gaps which
should have been covered by detail work. After
zeroing the profiles as effectively as possible, the
equipotential contours were drawn as shown on
Figure 3.

The appearance of some of these contours indi-
cates that the zeroing of one or two of the profiles
still leaves something to be desired, but data for mak-
ing effective correction are lacking. The miscorre-
lations are very minor, however, and do not mar the
over-all picture of an area of considerable extent
wherein the spontaneous polarization potentials rise
to striking values. Examination of the contours de-
picted on Figure 3 reveals that this area of mineraliza-
tion could have been discovered by conducting re-
connaissance observations on traverse lines spaced
1,000 ft. or more apart. The deposits at the Horne
mine of Noranda Mines, Ltd., are, however, some-
what unusual—they are not many base-metal deposits
in the nonferrous category to equal it. From 1927 to
1955, the plant at Noranda smelted, from the Horne
mine, over 21½ million tons of ore and concentrates,
producing therefrom over 1½ billion pounds of cop-
per and over $5½ million ounces of gold. Reserves are
still in excess of 12 million tons.

The appearance of the equipotential contours on
Figure 3 provides an interesting comparison with the
erlier interpretation shown on Figure 2. It shows
that, in the earlier interpretation, the over-all picture was essentially correct, although it tended to indicate veins of some length, instead of separate, lens-like bodies.

To facilitate a comparison of both the older and the newer interpretations with the sulphide bodies as eventually outlined in the course of mine development, the pertinent data are shown on Figure 4. In order to keep this map as simple as possible, only the equipotential contours of 300 millivolts are depicted, except that the contours of 200 mv. are used in three places. These values are fairly high, so some of the areas of lower potentials do not appear. Thus, some of the details indicated by the zones of lower potentials are missing. The earlier method of deducing the positions of the sulphide zones from the peaks on the individual profiles is indicated by the solid-block and hollow-block symbols at the appropriate spots on the traverse lines. These are taken from Figure 1. Finally, to demonstrate the correlation between the electrical results, however indicated, and the causative sulphide deposits, the near-surface portions of the sulphide bodies are shown on the same map. This clearly indicates the extent to which the electrical results can be used as a guide in developing such a property.

The comment was made above that the older method of interpreting tended to indicate veins of considerable length, rather than separate, lens-like bodies. In some cases, the corresponding contours tended to do the same thing—particularly where detailed profiles were not run in an area where the sulphide bodies are closely spaced. A good example of this situation is provided by the contours in the vicinity of orebodies 26, 10, F, and those to the south of F (Figures 3 and 4).

In comparing the shape of an equipotential contour with that of the causative body, it should be kept in mind that the strong electrical activity is not necessarily distributed evenly over the apex of a sulphide body, but is more likely to be concentrated at the particular spot or spots where the sulphides come closest to the surface. The shape of the contour will then be affected by the number and distribution of these centers of strongest electrical activity. A single sulphide body may have more than one electrical center. This is shown by the 300- and 400-millivolt contours outlining the H orebody between grid coordinates 9E and 13F, and 9S and 13S (Figures 3 and 4).

In the case of bodies close together, the zones of strong activity may merge to give a contour picture which encloses several separate bodies, as illustrated by orebody F and its neighbours, previously discussed. Other cases may be found in which the electrical indications at the surface appear to be displaced with respect to the probable causative bodies. If it is kept in mind that the position of the electrical indication is controlled by the position of that portion of the body nearest the surface, this apparent displacement is readily understood, especially where the dip of the sulphides is not vertical.

There are also instances in which sulphide bodies seemingly have failed to give rise to strong electrical reactions. This failure may be more apparent than real, since most of the traverse lines were 200 ft. apart in the survey area. Thus, orebodies 317 and D (Figure 4) might well have been indicated, had closer spacing been used between the traverses.

Along with closer spacing of the traverses, it is also desirable to use a closer interval for the equipotential curves. With such closer spacing and closer interval, many more details of occurrence and shape become noticeable. In the light of our knowledge today the zones of reaction on this area of the Horne mine would be covered by traverses no more than 50 ft. apart and with readings about 25 ft. apart; this spacing would be cut down to 10 ft. or less in the vicinity of the peak reactions. With such details available, the contouring would be done at an interval of no more than 30 millivolts.

The equipotential contours depicted on Figure 3 nevertheless clearly indicate a zone of relatively closely-spaced bodies of heavy sulphide mineralization. The values recorded imply that the bodies, in general, consist of massive sulphides concealed beneath only a shallow overburden. Whether or not they carry commercial mineralization is, of course, beyond the province of geophysical techniques to say; this is a question which must be answered by drilling, oriented according to the geophysical results.

Again, it must be borne in mind that this was a survey conducted in the very early years of the application of the art of geophysical exploration. The results were consequently not presented in as emphatic and convincing a manner as is desirable—nor was the mining industry of those days prepared to accept and credit the geophysical results to the extent that it is today. The discovery of the E and G bodies on the east side of the dyke—where no ore deposits were expected—was, nevertheless, credited to the geo-
Figure 3. Equi-potential contours of the spontaneous polarization potentials recorded in the Horne mine area. This contour map, drawn for the present volume, was prepared from the profiles shown in Figure 1, plus a few minor ones not illustrated, after reducing all to a common datum, or zero according to present-day practice.
Figure 4. Relationship of near-surface sulphide bodies at the Horne mine to peaks on the potential profiles (block symbols from Figure 1) and to the higher values in the equipotential contour pattern (200 and 300 millivolt contours from Figure 3). The recent geological and mineralization data on this and Figure 3 were generously supplied by Noranda Mines Ltd.
The late Carl Erickson, engineer on the property at the time, was in charge of the exploratory drilling during the early development. He is reported to have stated that on the basis of the map of the geophysical results, he spotted the drill hole which revealed the sulphide zone in which the important "H" orebody was subsequently discovered. The near-surface sulphides cut in that drill hole and in the upper workings were barren, but in the downward extension of that zone, the "H" orebody was subsequently encountered in the 700-ft. level, off No. 3 shaft. Most of the orebodies of the Horne mine, however, were discovered without reference to the geophysical results; possibly the abundant indications of sulphide bodies looked too fantastic to be believed at that stage of the mine's development.

Even though the engineers in charge of Noranda Mines, Ltd. in those days did not fully exploit the data produced by the geophysical survey, it is a tribute to their enterprise and their willingness to experiment that they employed geophysical methods at all at that time—before these techniques had established themselves as a potent aid to the discovery and development of new mineral deposits.

Grateful acknowledgment is extended to the management of Noranda Mines, Ltd. for permission to publish this above data and for their kindness in providing the map of the near-surface portions of their sulphide orebodies.

REFERENCES


Case Histories

3—Great Britain

DETERMINING THE THICKNESS OF UNCONSOLIDATED DEPOSITS OVERLYING SHALLOW MINE WORKINGS BY SEISMIC REFRACTION

by P. D. Brown* and J. Robertshaw+

Abstract

Seismic refraction was used to determine the thicknesses of the weathered and unconsolidated glacial layers overlying the coal measures in two National Coal Board coalfields. Depths to the bases of these layers varied from 5 ft. to 25 ft., and from about 40 ft. to 150 ft. respectively. Standard 12-trace equipment was used. Profiles were read along five traverses laid out to cover existing boreholes. Roughly 6,000 ft. of profiling was done at a normal speed of one mile per week. Weathered layer velocity data were augmented by direct measurements made in auger holes. Depths were calculated by the time-intercept method.

Velocities measured at the two sites varied from 1,600 ft./sec. to 3,000 ft./sec. for the weathered layer, 4,200 ft./sec. to 5,500 ft./sec. for the glacial deposits, and 7,400 ft./sec. to 11,500 ft./sec. for the consolidated rock. A 50 per cent velocity anisotropy was shown in one sandstone bed by measurements made in two directions. A low-speed layer within the glacial deposits was interpreted from discontinuities in the time-distance curves. It was necessary to estimate both velocity and thickness of this layer in order to find the depth to the underlying rock.

Calculated depths to bedrock on the two sites agreed within 6 per cent with depths indicated by the boreholes.

Early in 1952 the National Coal Board instituted a program of research to assess the value of geophysics in determining the thickness of superficial deposits overlying the coal measures. As part of this program, a seismic refraction survey was made in the Northwestern Division of the National Coal Board as shown on Figure 1.

Seismic methods of subsurface exploration were developed originally on the oil fields, where they now are the most extensively used of all the geophysical surveys. They are particularly well adapted to the depth determination of formation boundaries, as in this respect they have a much greater resolving power than any other geophysical method. In recent years, seismic refraction has been developed for exploration at the relatively shallow depths encountered in mining and civil engineering problems, and this particular technique was employed on the survey described in this article.

Plan of the Survey

Two separate sites were investigated and these are referred to as Site 1 and Site 2. Site 1 is north of the Leigh branch of the Leeds and Liverpool Canal and adjoins the grounds of the Ince Moss colliery. The area is rough waste land on the banks of Pearson's Flash. Site 2 is south of the same canal, adjoining the abandoned Bamfurlong colliery. The area is arable farmland and meadows with a fairly level ground surface. Both sites are shown in plan on Figure 2. In this area the middle coal measures are close to surface

*B.Sc., A.M.I.C.E.
and are overlain by glacial deposits. A borehole to the west is shown on the 6-inch geological survey map (1934); it indicated 93 ft. of boulder clay overlying sandstone. In addition, some borings had been made by the National Coal Board on these sites but the results were withheld until after the completion of the seismic survey in order that they could be used later as an independent check. The seismic survey included as many of the boreholes as possible in order to obtain a maximum number of check points. The locations of the boreholes and the traverses along which the survey was made are shown in plan on Figure 2.

A seismic traverse is the line along which the geophone and the shots are placed, and usually consists of several overlapping profiles, a profile being the length of traverse covered by twelve geophones with a shot fired at each end. Three traverses were investigated on Site 1. Traverses 1 and 2 connected boreholes 1, 2 and 3, and traverse 3 ran from north to south across Pearson's Flash. On Site 2, boreholes 6 and 7 were connected by traverse 4, and traverse 5 ran east-west to the south of boreholes 5 and 7. It was not possible to link the survey with borehole 5 as it was surrounded by high waste tips. All the traverses were laid out to extend beyond the boreholes in order to obtain refractions from the rock under the boreholes. Each profile which constituted a line of twelve geophones was investigated with a shot at each end of the line, and the shots were spaced along the traverses to provide a 50 per cent overlap of the profiles. The length of each profile was 360 ft. on Site 1 with a geophone spacing of 30 ft., and 480 ft. on Site 2 with a geophone spacing of 40 ft. The choice of the length of profile is a function of the depth being investigated, the velocities encountered, and the amount of energy possible to obtain from the explosion. The geophones were laid at equal intervals starting from the shot point, so that the distance between the shot point and first geophone was 30 ft. or 40 ft.

It has been found in seismic prospecting that nearly always there is a surface layer of low-velocity material, generally referred to as the weathered or aerated layer, and on these particular sites it varied
in depth from 5 ft. to 25 ft. In order to measure accurately the thickness of this weathered layer, short profiles 100 ft. long were investigated along each traverse to provide the low-velocity data, the distance between geophones varying from 5 ft. to 10 ft. Additional velocity data were obtained for the weathered layer by firing small charges at the bottom of auger holes about 10 ft. deep and recording the time taken for the elastic waves to reach geophones placed at the top of the holes.

**Results on Site 1**

On this site the weathered surface layer had a velocity of transmission of 2,400 ft. to 2,500 ft./sec. These data were obtained from the time-distance curves constructed for the 100-ft. profiles, and also from the time measurements made in the auger holes. The velocity in the boulder clay taken from the time-distance curves varied from 4,200 ft. to 5,350 ft./sec. and 4,600 ft. to 5,500 ft./sec. on traverses 1 and 2 respectively. The velocity in the rock was 9,600 ft./sec. on traverse 1 and 8,900 ft. on traverse 2.

Traverse 3 was made across Pearson's Flash, a lake caused by mining subsidence. For this traverse the geophones were lowered to the bed of the lake, but the records were unsatisfactory due to a thick layer of mud covering the bed and preventing proper geophone reception. To improve the results the travelling shot point procedure was adopted in which the geophones were kept in the same position at the ends of the traverse and charges were exploded on the bed of the Flash at intervals equal to the geophone spacing. On this traverse the overburden velocity varied from 4,500 ft. to 5,000 ft./sec. and the rock velocity was 9,400 ft./sec. This is in close agreement with the rock velocity on traverse 1 which was parallel to traverse 3.

The time-distance curves for traverses 1 and 2 are given on Figure 3 together with the interpreted sections shown beneath them. The depth to rock was interpreted beneath each shot point by using the time-intercept formula. A typical calculation is given below for the depth to rock at borehole 1 on traverse 2.

Data from time-distance curves:

- Weathered layer velocity, \( V_1 = 2,400 \text{ ft./sec.} \)
- Velocity in glacial deposits, \( V_2 = 5,000 \text{ ft./sec.} \)
- Velocity in rock (coal measures), \( V_3 = 8,900 \text{ ft./sec.} \)
- Time intercept, \( t_1 = 0.002 \text{ seconds}. \)
- Time intercept, \( t_2 = 0.014 \text{ seconds}. \)

**Thickness of weathered layer,**

\[
H_1 = \frac{t_1}{2} \cdot \frac{V_1 \cdot V_2}{\sqrt{V_1^2 - V_2^2}} = \frac{0.002}{2} \cdot \frac{2400 \times 5000}{\sqrt{(5000^2 - 2400^2)}} = 2\frac{1}{2} \text{ ft.}
\]

**Thickness of glacial deposits,**

\[
H_2 = \frac{t_2}{2} \cdot \frac{V_2 \cdot V_3}{\sqrt{V_2^2 - V_3^2}} = \frac{0.014}{2} \cdot \frac{5000 \times 8900}{\sqrt{(8900^2 - 5000^2)}} = 42 \text{ ft.}
\]

Correction to be added to allow for depth of shot beneath ground surface

\( = 3\frac{1}{2} \text{ ft.} \)

Therefore total depth to rock beneath the ground surface

\( = 2\frac{1}{2} + 42 + 3\frac{1}{2} = 48 \text{ ft.} \)

On the time-distance curves for the south half of traverse 1 it will be noted that the rock refractor parts of curves are not straight lines. This probably
is caused by the uneven surface of the rock head. These curves were interpreted by drawing mean straight lines through the points on these parts of the curve in order to obtain the intercepts on the time axes at each shot point. The depth at each point was next determined in the usual way by using the time-intercept formula. The uneven rock profile between the shot points was then constructed graphically by drawing the ray paths of the refracted elastic waves so that the calculated time of the elastic wave to each geophone corresponded to the observed time.

- **Results on Site 2**

The velocity of transmission in the weathered layer on this site ($V_1$) varied from 1,600 ft. to 3,000 ft./sec. on traverse 4 and was a constant 2,600 ft./sec. on traverse 5. These data were obtained from the time-distance curves constructed for the 100-ft. profiles. The results of measurements on traverses 4 and 5 are shown as time-distance curves on Figure 4. In general three slopes are indicated on these curves. These represent the velocities of transmission in the upper weathered layer, the underlying unconsolidated layer, and the coal measures, and will be referred to subsequently as $V_1$, $V_2$, and $V_3$. The results are unusual in that some curves show a break in continuity resulting in an apparent upward displacement of the latter part of the curves. These breaks disconnect the $V_2$ and $V_3$ branches of the curves, and are indicated by dotted lines on the time-distance curves shown on Figure 4. The breaks are due to a time displacement on two adjacent traces on the seismic record amounting to 30 milli-seconds to 40 milli-seconds and occurring usually at a distance of 160 ft. to 200 ft. from the shot point.

To account for this phenomenon it is necessary to consider what may cause such a time delay, and why the $V_2$ branch of the time-distance curve disappears. The possibility that it is caused by a horizontal discontinuity, such as a fault, cannot be considered because it occurs repeatedly along both traverses between each pair of shots, and because the displacements of the curves are always upwards irrespective of the direction of the shooting of the profile. (When shooting across a fault a displacement in the curve occurs which is upwards when shooting from the upthrow side of the fault, and downwards from the downthrow side.)

The most probable explanation for the unusual result is that it is caused by an abnormal distribution of velocity with depth. Normally the velocity of transmission of elastic waves in the ground increases with depth below the surface, each successive layer having a velocity greater than the layer above it. If a velocity reversal occurs and an underlying layer has a velocity lower than the layer above it, refraction of the elastic waves will not occur at the boundary of the two layers, and consequently the lower velocity member would not be represented on the time-distance curve. However, refraction will occur at the base of the low-velocity layer, but if the layer is not very thick the refraction will be limited to the high-frequency elastic waves only. As the distance from the shot point increases, the high frequencies are attenuated, so that a stage will be reached when refraction from the base of the low-velocity layer will cease. This would account for the discontinuity of the curve $V_2$ part of the time distance, which occurs at a distance of 160 ft. to 200 ft. from the shot point. It will be noted on some of the time-distance curves on Figure 4 that at the discontinuity two times have been plotted against the same distance plot. In these instances on the seismic record two breaks were recorded on the geophone trace, indicating two times of arrival of elastic waves. This first time of arrival would be that of the partially attenuated elastic wave from the base of the low-velocity layer, and the second arrival that of the elastic wave refracted from the underlying rock.

Seismic refraction is based on the assumption that the velocity of propagation of the elastic waves increases with depth, in which case the velocities can be determined from the time-distance curves. If this assumption is not true and a lower-velocity layer is present at depth which does not show on the time-distance curve, some allowance has to be made for it in the interpretation. Otherwise, if the interpretation is based only on the higher velocities indicated on the curves the rock depths will be over-estimated.

The interpretation of the results on Site 2 was based on the assumption of an average velocity throughout the layer of unconsolidated material. The value of $V_2$ taken from the time-distance curves was 5,500 ft./sec., which is clearly the higher velocity of the unconsolidated material. In order to obtain a reasonable average velocity some assumption has to be made regarding the lower velocity of this material. This velocity must be less than 5,500 ft./sec., and probably is within the limits of 5,500 ft. and 1,500 ft./sec., as a velocity of less than 1,500 ft./sec. is unlikely in beds at depth. The average of these values is 3,500 ft./sec., which is a reasonable figure for the velocity of sandy beds that might occur in the glacial deposits forming the unconsolidated material. Assuming 3,500 ft./sec. as the velocity of the layer underlying
the 5,500 ft./sec. layer, the average for the velocity in the unconsolidated material will be 4,500 ft./sec. This average value will produce reasonable results if the thicknesses of the 5,500 ft./sec. and 3,500 ft./sec. layers are of a similar order. Although reference is made repeatedly to the low-velocity "layer" this probably is more of a low-velocity zone comprised of layers of different velocities. Such a conception would account better for the scattering and dispersion of the seismic energy resulting in the discontinuity on some of the time-distance curves.

The velocity of propagation of the elastic waves in the rock \( V_3 \) measured on the curves was 7,400 ft./sec. on traverse 4 and 11,500 ft./sec. on traverse 5. These two traverses were approximately at right angles to each other and a difference in the velocity values along different directions is to be expected, due to the anisotropy of the rock. It is rather large in this instance although 50 per cent differences have been recorded previously in shales.

The actual interpretation was made using the velocities referred to above and the time intercepts taken from the time-distance curves. A typical calculation is given below for the depth to rock at the borehole 7 on traverse 4.

Data from time-distance curves:
Weathered layer velocity, \( V_1 = 2,700 \) ft./sec.
Mean velocity in glacial deposits, \( V_2 = 4,500 \) ft./sec.
Velocity in rock (coal measures) = 7,400 ft./sec.
Time interception, \( t_1 = 0.005 \) seconds.
Time interception, \( t_2 = 0.042 \) seconds.

Thickness of weathered layer,
\[
H_1 = \frac{t_1}{2} \sqrt{V_1^2 - V_2^2} = \frac{0.005}{2} \sqrt{2700^2 - 4500^2} = 8 \text{ ft.}
\]

Thickness of glacial deposits,
\[
H_2 = \frac{t_2}{2} \sqrt{V_2^2 - V_3^2} = \frac{0.042}{2} \sqrt{4500^2 - 7400^2} = 120 \text{ ft.}
\]

**Case Histories — Great Britain**

Correction to be added to allow for depth of shot below the ground surface.
\[
= 5 \text{ ft.}
\]

Therefore total depth to rock below the ground surface.
\[
= 8 + 120 + 5 = 133 \text{ ft.}
\]

Similar calculations were made at each shot point along traverses 4 and 5, and the resulting profile of the rock head is given on the sections shown on Figure 4.

**Conclusions**

Site 2 presented an unusual problem in that it is considered that the anomalous results were caused by a reversal in velocity with depth in the glacial deposits. In order to interpret the observations on this site it was necessary to assume an average velocity of the elastic waves in the glacial material, since a direct measurement of the velocities was impossible. However, it should be mentioned that in normal practice one or more boreholes are available on a site in which a thorough check can be obtained on the velocities by making a direct measurement of them in the boreholes. On Site 1 the results were quite normal and a straightforward interpretation was possible. After the final interpretation of the results was completed the data from the holes previously bored on the site were revealed. This information is tabulated below against the corresponding depths determined by the seismic survey.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Depth to rock from seismic results</th>
<th>Depth to rock by drilling</th>
<th>Error Ft.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>46</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>53</td>
<td>57</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
<td>44</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>133</td>
<td>126</td>
<td>7</td>
</tr>
</tbody>
</table>

The mean error in the seismic results from the figures above is only 6 per cent., which is considered very satisfactory in view of the experimental nature of the survey. Under normal seismic survey conditions an error not exceeding 5 per cent can be expected where the depths are similar to those above.

Based on the results of the test survey it would seem that seismic refraction would be suitable for locating the thickness of unconsolidated materials overlying the coal measures. Such a survey should be preceded by one or two boreholes to rock head, which would act as a control on the survey and enable a
direct measurement of the velocities in the superficial deposits. The site then would be covered by a series of suitably spaced seismic traverses which would enable the rock head to be contoured. The spacing of the traverses would depend on the unevenness of the rock head. If a large rate of change in the level occurs, or if pre-glacial channels are likely, the seismic traverses would need to be sufficiently close to delineate these features. If, on the other hand, the rock surface was evenly contoured, only widely spaced traverses would be required. The normal rate of progress of survey is about one mile of traverse per week, which means that a continuous profile of the rock would be obtained over a section one mile in length. In terms of area this would amount to from 30 acres to 60 acres depending on the spacing of the traverses. This rate of progress is far greater than that by boring, and also is much more economical.

In doubtful areas that already have been investigated by borings it may still be worth while covering these areas by a seismic survey. The borings usually are spaced well apart and information regarding the depth to rock between the boreholes can be surmised only by interpolation. Should a survey be made between the boreholes, a more accurate profile of the rock head would be obtained and this may differ appreciably from that previously interpolated between the borings. Should the rock head be found closer to the surface than expected, a greater coal production may be possible, and if the rock is deeper than that expected the safety margin would be more adequately maintained.

Acknowledgments

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MAGNETIC SURVEYS FOR THE EXPLORATION OF MANGANESE ORES IN INDIA*

by M. B. Ramachandra Rao* and S. C. Sinha**

Abstract

Abundant resources of manganese occur in India, the most important field lying in Madhya Pradesh State (formerly the Central Provinces). This field is 150 miles long and the ores occur in large bands or reefs, but with outcrops often discontinuous and covered by alluvium. It was to fill in some of these gaps that geophysical work was carried out by the Geological Survey of India.

The manganese ores of this area are associated with the Gondite Series of Archaean age, consisting of mica schists, gneisses, cale-granulites and limestones. The rocks are mostly banded, with lenticular and ribbon structures. The ores generally follow the same trends as the rocks, and consist principally of braunite and psilomelane, with other manganese minerals. The deposits are believed due to the metamorphism of manganese-bearing sediments.

Although first attempts at using electrical resistivity and spontaneous polarization were disappointing, more recent studies have been reported successful. In the exploration reported here, however, solely magnetic anomalies were relied upon. The magnetic reactions varies from plus 100 to plus 25,000 gammas, and were of two kinds: one showed circular to irregular patterns of magnetic contours with irregular distribution; the other consisted of fairly strong indications with elongated contours and definite strike trends.

The strong, elongated contours usually are due to bands of magnetite-quartzite or magnetite-bearing schists, of no economic significance. The few places where it is thought they might be due to manganese mineralization have been designated for later exploration.

Investigation of the irregular anomalies of isolated character has located probably 50,000 tons of ore, mostly "float".

Several typical areas are selected for discussion of the magnetic anomalies and the results obtained by test-pitting are reported. The magnetic anomalies are believed due to the presence of jacobsite, a magnesium-iron manganese, although this being a supergene mineral, it presents difficulty in accounting for anomalous remnant magnetism. It is suggested that gravitational surveys could be used advantageously to supplement the magnetic work.

INDIA is one of the few countries which have abundant resources of manganese ores. The most important field, a 150-mile long belt of manganiferous rocks, occurs in Madhya Pradesh State (formerly known as Central Provinces) (see Figure 1 of the paper following this.)

*Published with the permission of the Director, Geological Survey of India.
*Chief Geophysicist, Geological Survey of India.
**Assistant Geophysicist, Geological Survey of India.
is covered by alluvium and such portions deserve to be explored.

The late Sir Lewis Fermor, who has made classic contributions to the study of the manganese ores of India (1), had suggested the use of magnetic methods to explore for the hidden deposits, and actually attempted to use a dip needle to investigate the anomalies produced by the ore deposits in the Chindwara district. This instrument of course proved unsuitable and the attempt was given up. During January 1947, B. L. Gulatee (2) of the Geodetic Survey of India, used a Watts magnetic variometer (vertical force) on the manganese ore deposits near Ramtek (Lat. 21°23′; Long. 79°18′) and found anomalies of the order of +4350 gammas.

Apparently encouraged by these results, the Central Province Manganese Ore Company approached the Geological Survey of India to undertake on their behalf a geophysical survey of some of their lease blocks at Tirodi (Lat. 21°42′; Long. 79°44′) where the known manganese orebodies had been mined out more or less completely. These properties were surveyed during 1947-48 and several magnetic indications were found. They were promptly tested by the company by putting down trial pits which led to the discovery of hidden manganese ore deposits. In the following years, several other companies requisitioned for similar geophysical surveys in their lease areas, and five more properties have been surveyed by the Geological Survey of India. A few blocks have been surveyed by private consulting firms.

In addition, the Geological Survey of India on their own initiative undertook two more investigations in the Ramtek area to study if the discontinuities in the exposed ore belts are 'bridged' by indications of ore under the alluvium. The present paper gives briefly a review of the results which have been obtained. Figure 1 shows the outlines of the manganese ore belt and the areas surveyed magnetically.

General Geological Features and the Nature of Magnetic Indications

The manganese ores of this region are associated with a series of metamorphic rocks termed the 'Gondite Series' (Archaean age). These ores appear to have been formed by the metamorphism of manganese bearing sediments deposited with the original sands, clays, and limestones; thus all are associated with mica-schists, gneisses, calc-granulites, and limestones. The rocks mostly are banded, often showing lenticular and ribbonlike structures. The ore deposits generally follow the strike trends of the rocks and are mixtures of braunite and psilomelane, but a host of other minerals, such as pyrolusite, manganite, jacobsite, hollandite, and several manganese silicates have been noted. Only a few of the latter have high magnetic susceptibility.

The magnetic surveys dealt with in this paper, have been conducted with Askania or Watts vertical force magnetometers with a sensitivity of 25 or 30 gammas per scale division. The observed anomalies varied from +100 to +25,000 gammas in places. The indications can be classed in two categories:

1. Isolated indications of very limited lateral extent and generally of irregular distribution. The magnetic contours appear in these cases as circular, oval, or irregular outlines, but without any distinctive strike trends;

2. Elongated indications of fairly strong intensity in narrow zones with definite strike trends resembling the topographical contours of a series of hills.

So far, only the first type of indication has been tested extensively by trial pits or boreholes. Usually these have revealed small patches or pockets of massive ore with a somewhat 'weathered' look, beneath the soil covering or debris. These ores exhibit remanent magnetization. Both positive and negative poles are noticeable, and in some cases the orientation is such that the positive and the negative points are nearly east-west instead of north-south. A few cases of 'inversions' of the poles compared to the earth's field also have been noted.

Some of the conspicuously elongated anomalies of the second type are manifestly due to bands of magnetite-quartzite, or magnetite-bearing schists, and it is doubtful if any manganese orebodies occur in such places. Nevertheless, there are a few magnetic anomalies in the alluvial tract of Ramtek, Nagardhan and Kachurwahi-Waregaon, which look like continuations of the large orebodies which have been worked out in the adjacent ground.

Isolated orebodies, located from the magnetic indications of the first type, in the six properties surveyed so far, may be said to amount to about 50,000 tons. On the other hand, if only a few of the indications of the second type (viz. the elongated magnetic anomaly zones), are proved to be due to manganese orebodies there is likelihood of locating far larger quantities. Unfortunately, none of this type of indication has yet been verified by drilling or shaft-sinking, although a few spots have been recommended for trial.
MAP SHOWING AREAS GEOPHYSICALLY SURVEYED FOR MANGANESE ORE IN MADHYA PRADESH STATE, INDIA.

Figure 1.
Areas Surveyed

The several areas surveyed geophysically in this region are distributed in four districts, namely, Balaghat, Bhandara, Nagpur, and Chhindwara Districts.

Table I gives the particulars of the surveys and the results obtained in different blocks.

Balaghat District, Tirodi Group

The known manganese ore deposits of this area occur as large bands or beds forming a more or less continuous belt which is folded repeatedly. The bands are missing abruptly in places, being either buried under the alluvium or else completely eroded. The geophysical surveys were done on the ground adjacent to or very close to the worked-out deposits. R. A. Nagarajaiah, P. C. Paul, and S. C. Sinha conducted the investigations during 1948-54.

In the initial stage, some experimental surveys using electrical resistivity and self-potential methods were carried out by P. C. Paul. The anomalies found thus were not, distinctive but were complicated by numerous factors which are not related to the orebody. However, more recently K. D. Jensen (3) has reported that electrical self-potential and resistivity surveys have been useful in this manganese belt. In all the cases recommended for trial pitting by the Geological Survey of India only the magnetic anomalies have been relied upon. The depths to the apex of the causative bodies in many cases were estimated by Nagarajaiah after taking magnetometer readings at different elevations, using a scaffolding, or inside the trial pits as the excavations progressed. The agreement between the estimated depths and the actual depth has been very good in a few cases but departures by 50 per cent or more were not uncommon. Most of the indications
Mining Geophysics

Table 1

<table>
<thead>
<tr>
<th>Locality</th>
<th>Lease</th>
<th>Extent of survey</th>
<th>Nature and number of magnetic indications</th>
<th>Results of trial pits reported</th>
<th>Investigated by</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Area (in acre)</td>
<td>No. of magnetic stations measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. Balaghat District, Tirodi group (Lat. 21°38' — 21°47'; Long. 79°43' — 79°47')</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Tirodi</td>
<td>Central Province</td>
<td>320</td>
<td>2,000</td>
<td>pocket type-6</td>
<td>11</td>
</tr>
<tr>
<td>2. Pawaia</td>
<td>Manganese Ore Co.</td>
<td>480</td>
<td>8,150</td>
<td>pocket type-36</td>
<td>20</td>
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<tr>
<td>3. Jamrapani</td>
<td>Shamlu Narainji</td>
<td>17</td>
<td>630</td>
<td>pocket type-18</td>
<td>2</td>
</tr>
<tr>
<td>4. Chikmara</td>
<td>Do</td>
<td>33</td>
<td>2,330</td>
<td>pocket type-48</td>
<td>25</td>
</tr>
<tr>
<td>5. Tirodi (south)</td>
<td>B. P. Bairamji Co.</td>
<td>92</td>
<td>1,238</td>
<td>elongated zone-1</td>
<td>—</td>
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<tr>
<td>6. Tirodi (east)</td>
<td>Sreeram Durgaprasad</td>
<td>10</td>
<td>300</td>
<td>nil</td>
<td>—</td>
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<tr>
<td>7. Garra</td>
<td>Do</td>
<td>160</td>
<td>2,000</td>
<td>elongated zone-1</td>
<td>—</td>
</tr>
<tr>
<td>8. Selwa</td>
<td>Do</td>
<td>10</td>
<td>300</td>
<td>nil</td>
<td>—</td>
</tr>
</tbody>
</table>

B. Bhandara District, Chikla area; (Lat. 21°33' — Long. 79°45')

<table>
<thead>
<tr>
<th>Location</th>
<th>Lease</th>
<th>Extent of survey</th>
<th>Nature and number of magnetic indications</th>
<th>Results of trial pits reported</th>
<th>Investigated by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chikla</td>
<td>M. P. Mines Ltd.</td>
<td>400</td>
<td>4,200</td>
<td>elongated zones-3</td>
<td>—</td>
</tr>
</tbody>
</table>

C. Nagpur District, Ramtek Group; (Lat. 21°29' — 21°23'; Long. 79°15' — 79°25')

<table>
<thead>
<tr>
<th>Location</th>
<th>Lease</th>
<th>Extent of survey</th>
<th>Nature and number of magnetic indications</th>
<th>Results of trial pits reported</th>
<th>Investigated by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ramtek</td>
<td>10,240</td>
<td>6,000</td>
<td>elongated zones-3</td>
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<td>—</td>
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<tr>
<td>3. Kachurwadi</td>
<td>M. P. Mines Ltd.</td>
<td>120</td>
<td>2,000</td>
<td>pocket type-16</td>
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<tr>
<td>4. Waregaon</td>
<td></td>
<td></td>
<td></td>
<td>elongated zone-1</td>
<td>—</td>
</tr>
</tbody>
</table>

D. Chiodara District, Gowari-Wadhora; (Lat. 21°31' — Long. 78°49')

<table>
<thead>
<tr>
<th>Location</th>
<th>Lease</th>
<th>Extent of survey</th>
<th>Nature and number of magnetic indications</th>
<th>Results of trial pits reported</th>
<th>Investigated by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gowari-Wadhora</td>
<td>Sreeram Durgaprasad</td>
<td>82</td>
<td>1,500</td>
<td>pocket type-2</td>
<td>—</td>
</tr>
</tbody>
</table>

proved by trial pits showed small but workable deposits of ore at depths varying from a foot to 73 feet below surface; the rest were caused by poor grade manganiferous or non-manganiferous rocks with magnetite.

Obviously it is not feasible within the limits of this paper to deal in detail with the results obtained in each of the blocks surveyed; three instances should suffice for the purpose of illustration.

Figure 2 shows the map of Pawaia blocks setting forth the magnetic anomalies noted in the survey. The anomalies are so localised that it is difficult to draw iso-gamma contours. Table II shows the results of trial pits referred to in Figure 2.

Figure 3, which is self-explanatory, shows the vertical anomalies in relation to the disposition of the orebodies below the indications for several cases in the Pawaia area. Figure 4 shows a typical profile of magnetic indications noted over superficial manganiferous rocks and sub-surface orebodies in the Tirodi block. All these illustrations and data have been based on the reports of Nagarajah.

According to information furnished by W. A. Hardy, general manager, Central Province Manganese Ore Company, the magnetic surveys done by the Geological Survey of India on the company's properties at Tirodi and Pawaia resulted in about 10,000 tons of manganese ore being raised from the several trial pits put down to test the geophysical indications; at least twice as large a quantity of ore remains to be won from the deposits newly located. Hardy considers that the geophysical survey may be credited with the discovery of some 30,000 tons of new ore which would have been overlooked in ordinary prospecting.

Of the remaining six blocks in this group, only two, the Chiklara and Jamrapani areas of Shamlu Narainji, have shown useful results. More than 60 indications were found, all pocket type; several thousand tons of ore are likely to be won from these indicated spots. The company raised more than 600 tons of ore from the pits put down on a few of the magnetic indications even during the progress of the surveys. This quantity of ore itself was enough to pay for all the expenses of the geophysical survey in these two blocks.

Bhandara District

In this group, only one block with an area of 400 acres of Chikla (Lat. 21°33'; Long. 79°45') was surveyed by S. C. Sinha and party during 1954. The area is mostly covered by alluvium, or laterite, though a few exposures of Gondite rocks, biotite gneisses, and mica-schists also are seen.

Magnetic measurements revealed several isolated groups of anomalies (— 100 to + 250 gammas) which appear to be connected with boulder or float ore deposits hidden under the alluvium. Another prominent anomaly zone manifestly was connected with magnetite-bearing schists of no economic importance.
A. Roy investigated the north portion near Ramtek while S. C. Sinha did the south part near Nagardhān and the east one near Kachurwahi-Wharegon. The results of the surveys in the first two blocks (combined) and the third one are given in Figures 5 and 6. Figure 5 shows, along with other details, the locations of the magnetic anomaly zones and the magnetic anomaly profiles across some of these zones in the Nagardhān and Ramtek areas. Figure 6 shows the magnetic anomaly contours and the anomaly profile of a part of the Kachurwahi block.

In the north part, the area surveyed by A. Roy, the exposures of the Kandri-Mansar band show magnetic anomalies of the order of +200 to +500 gammas, but at places there are negative and positive anomalies as high as a few thousand gammas on the exposed bands, possibly due to the localized effect of thermal metamorphism or to lightning discharges. Of the three magnetic zones, A, B, and C (Figure 5), in the north part, anomaly zone B (300 to 400 gammas) appears to be the continuation, under alluvium, of the manganese ore band of Mansor-Parsoda, though offset by about 2,000 ft. due to faulting (?). The third zone, C, recording a maximum anomaly of +400 gammas, occurs south of the town of Ramtek and it is thought that this might indicate either a flat-lying bed of float ore or some variation in the relief and/or magnetic susceptibility of the bedrocks under alluvium.

In the south part, namely, the Nagardhān area surveyed by S. C. Sinha, four distinctly elongated magnetic anomaly zones, D, E, F, and G (Figure 5) have been traced, all nearly parallel to each other, with an east-west strike in conformity with the trend of the country rock. The southernmost anomaly zones, F and G, have very strong magnetic anomalies of the order of −10,000 gammas to +13,000 gammas, and are associated with partially exposed magnetite-quartzite bands of no economic importance.

The central and north zones, D and E, are very conspicuous, stretching over 2 miles long and extending beyond the limits of the area surveyed. Zone E has anomalies of the order of −200 to −1,000 gammas to the north and +600 to +1,600 gammas to the south, indicating that the causative body is a single magnetic slab with its north and south poles corresponding to those of the earth’s field. The distance between the two poles is about 300 to 700 ft. and the body has a southerly dip in conformity with the dip of the country rock.

The trial pits were put down on selected points of the central anomaly of zone E. One, over an isolated negative anomaly centre, shown at 12 ft. depth,

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**Case Histories — India**

**Nagpur District, Ramtek Group**

Three blocks, namely, Hantex, Nagardhān and Kachurwahi-Waregon, have been surveyed in this group. The surveys in the first two blocks, coming within the large alluvial tract, were undertaken as a reconnaissance project by the Geological Survey of India with a view to locating unexplored orebodies and to trace the trend of the Kandri-Mansar-Parsoda belt (Lat. 21°25′N; Long. 79°16′E to Lat. 21°23′N; Long. 79°18′E) and the Satak-Beldongri-Lohdongri-Kachurwahi-Waregon belt (Lat. 21°20′W; Long. 79°16′E to Lat. 21°20′N; Long. 79°25′E).
calc-granulites with appreciable magnetite, but no manganese ore. The other pit, over a positive centre, was taken down to 2.5 ft. and showed mica-schist (non-magnetic) beneath 20 ft. of alluvium. The depth to the apex of the causative body was estimated, on the basis of line pole theory, at 55 ft. but owing to the incursion of water in the pit the excavation had to be discontinued. The cause of the indication still remains unverified.

The two zones D and E seem to hold some promise of containing valuable ore, because within these anomaly zones occur some of the abandoned mines of Beldongri and Satak from which immense quantities of high-grade ore have been obtained.

In the Kachurwahi-Waregaon blocks, surveyed by S. C. Sinha, both isolated or pocket type and the elongated zonal type of magnetic indications have been found. In Figure 6 is shown the magnetic anomaly map of a portion of the Kachurwahi area. All the isolated indications have been tested by the mining company by putting down trial pits. Pockets of ore have been found under the alluvium in each case, at depths varying from 13 to 22 ft. below surface. During the stay of the geophysical party, 500 tons of ore were recovered from the first four trial pits. The total quantity of ore to be expected from all the 18 indications would be very much more indeed. On the elongated anomaly zone in the area (zone H), where depth to causative body has been estimated at
MAGNETIC ANOMALY MAP, RAMTEK AREA

Figure 5.
70 to 80 ft., and where the body is expected to have a very steep dip, drilling has been recommended to explore the cause of the indication.

Zones E and H (Figure 5) in the Nagardhan and Kachurwahi areas respectively, are of similar type and if the country between the two zones is surveyed, probably a similar zone linking the two might be discovered.

### Chindwara District

The Gowari-Wadhena area, Chindwara District, on the extreme western part of the belt (Figure 1), was surveyed by S. C. Sinha during 1953. A manganese ore deposit about 6 ft. thick and extending over 3,000 ft. is being worked from open cast and by underground mining. The orebody is faulted on both sides of its strike length. The purpose of the geo-
physical survey was to locate hidden orebodies, if any, in the adjoining lands. Away from the known ore band, in the cultivated fields, several strong positive and negative magnetic anomaly centres were located. A trial pit put down on one revealed Deccan Trap boulders (basaltic rocks containing magnetite and ilmenite). The survey on this block failed, on the whole, to indicate anything of economic importance.

General Remarks on the Nature of Magnetic Anomalies and Association of Manganese Ore Bodies

There are many paradoxes—or apparent paradoxes—in prospecting for manganese ore by the magnetic method. While large bodies of rich ore yield little or no appreciable magnetic effects, we have achieved success in locating isolated patches of what looks like ‘weathered stumps’ or ‘float’ ore showing irregular magnetic anomalies. What appears to produce the large, striking anomalies is really magnetite in one or another form. The famous mines of Mansar, Kandri, Tirodi, etc., from which many hundreds of thousands of tons of ore have been obtained and where large tonnages still exist in the known bands, do not show appreciable high or even distinctive magnetic anomalies. The bulk of these orebodies comprises brailnite and psilomelane which are only feebly magnetic. In fact, most of the manganese ores do not show strong magnetization or very high magnetic susceptibility. The only manganese mineral which is strongly magnetic is what used to be called vredenburgite which is in fact a mixture of jacobsite (MnO, MgO, O. (Fe, Mn)O, Oa) and haussmannite (MnO, MnO, Oa). Most of the magnetic indications which have led to the discovery of manganese orebodies obviously are due to the presence of jacobsite. The origin of this mineral is, however, somewhat obscure but it looks, from what we have seen, to be a supergene ore. If this is really so, we shall have difficulty in accounting for its remanent magnetisation at comparatively low temperature, perhaps below Curie point. It is possible also that some of the ore pockets discovered under the alluvium are in the nature of ‘stumps’ which may have been struck by lightning and magnetized at some time when they were exposed as outcrops before the alluvium filled in. Research on this problem is still needed. It also is not certain if MnO, possesses strong ferromagnetism. There is always some amount of Fe in molecular combination with Mn, and it is still questionable whether the indications we have obtained are merely attributable to Fe in molecular or iso-morphous combination in the manganese ore.

In any case, it does not seem possible to tell whether or not any workable bodies of ore occur beneath magnetic indications, even in this manganese ore belt. The success which has attended our surveys in some of the blocks must be attributed to fortuitous circumstances. But even so, the success has been confined mostly to the minor indications of the isolated, very local type which can best yield only small patches or pockets of ore. On the other hand, the more conspicuous elongated strong magnetic anomaly zones seem to be caused by uneconomic magnetite-bearing rocks, but these anomalies have not yet been tested by drilling in places where manganese orebodies are likely to be met. Should even a few of these latter indications be shown to be due to hidden bodies of ore, there is a possibility of locating large quantities.

It is likely also that gravimetric surveys will be useful in scanning out manganese ore deposits from some of the noisy magnetic indications which are caused by uneconomic magnetite-bearing rocks. A test gravity profile on the known orebody at Parsoda, done by A. Roy, showed an anomaly of 0.4 milligals. B. L. Gulatee (2) also found measurable gravity anomalies, using a gradiometer in the same area. It is hoped that a further systematic magnetic-cum-gravity survey of the alluvial tract in this belt will lead to discovery of larger bodies of concealed manganese ore.

In conclusion, the writers wish to express their thanks to Central Province Manganese Ore Company and Madhya Pradesh Mines Ltd., for permission to use some of the illustrations relating to the survey of their lease blocks. Many of the illustrations, particularly Figures 1, 3 and 4 and part of Figure 5 have been based on the reports of R. A. Nagarajaiah and A. Roy. The writers are indebted to them for this and other information furnished during discussions of the surveys in the manganese ore belt.

REFERENCES

(1) Fermor, L. L.: (1909), Manganese Ore Deposits of India, Memoir, Geological Survey of India, Vol. XXXVII.
ELECTRICAL SURVEYS FOR EXPLORATION FOR SULPHIDE ORES IN INDIA*

by M. B. Ramachandra Rao† and M. M. Suryanarayana Rao‡

Abstract

Scattered indications of copper and numerous old workings in several mineralized belts in India attest the occurrence of ores which may not have been worked out by the ancient miners. In 1939 the Government of Mysore initiated geophysical investigations on some of these deposits, and in the last decade the Government of India has been carrying out systematic geophysical exploration for sulphide ores. Some 100 square miles have thus been covered in the States of Madras, Mysore and Rajastan. Numerous promising indications remain to be tested, but the results obtained in the Chitaldrug belt at Ingaldhal and G.R. Halli areas, Mysore State, are given in this paper.

At Guddasarangavvana Halli (G.R. Halli) spontaneous polarization surveys revealed numerous negative and positive centres with the same trend as outcrops of chalybite trap rocks. Sinking and crosscutting showed the underlying mineralization to be a lode of pyrrhotiferous graphitic schist. Its economic importance is improved but is considered promising.

At Ingaldhal both spontaneous polarization and resistivity were used, plus magnetic observations, and revealed a belt of anomalies about 2,000 feet long. Test-pitting and trenching disclosed a massive pyrite body estimated to contain over one million tons of pyrite suitable as a sulphur ore. This is the first massive sulphide body to be discovered in that area.

Figure 1. Map of India, showing the location of copper (and manganese) ore belts where geophysical surveys have been carried out.

*Published with the permission of the Director, Geological Survey of India.
†Chief Geophysicist and Geophysicist, respectively, Geological Survey of India.
Introduction

There are several large mineralized belts in India which show widely scattered surface indications of copper ore. The innumerable old workings and slag heaps spread over some parts of the country denote that the ores had been exploited in ancient times. In fact, it is a rarity to find a place in India where even the least visible occurrence of malachite or other ores of copper (also of lead and zinc) has not been prospected by the ancients by trenches, shafts, adits or other forms of excavation. In many places the easily workable portions of the orebody have been removed completely and the excavations have been filled up, but it is by no means certain that the resources of these ores have been exhausted. It is quite likely that where the ground surface is covered by thick soil or debris, the orebodies which may lie concealed even in the vicinity of the workings, have escaped the attention of early prospectors.

The first attempts to employ geophysical methods to prospect for orebodies, by private companies at two or three localities in India proved disappointing.

However, the Government of Mysore became keenly interested in getting some of the mineralized areas in Mysore surveyed geophysically, and during 1939, a section for this work was organized in the Mysore Geological Department. A few areas in the Chitaldrug district of the Mysore State were examined since 1939 and some success in locating massive sulphide bodies has resulted from these surveys.

During the past decade, the Geological Survey of India has engaged in systematic exploration for sulphide ores, using electrical and magnetic methods, in different parts of the country (1). More than 100 square miles in all have been covered in the mineralized belts of Madras, Mysore and Rajasthan States, and many promising geophysical indications have been noted, but no verification by drilling or shaft-sinking has followed, except in the case of one or two indications in the Chitaldrug belt of Mysore State. Therefore the contributions which these geophysical surveys have made can be assessed only after the test-drilling for which a comprehensive program has been laid out in the Second Five-Year Plan of the Government of India.

The purpose of this paper is to outline very briefly the nature of the geophysical indications obtained in the mineralized belts, and to mention the results in the test-drilling or shaft-sinking which has been done to follow up a few of these indications. Figure 1, map of India, shows the location of the copper ore (and manganese ore) belts on which geophysical surveys have been done.

The Singhbhum Belt, Bihar State

This belt is nearly 70 miles long, and comprises principally micaceous, chloritic and talc schists, quartzites, ancient lava flows, epidiorites and granites. There is a well marked shear zone which has some control over the mineralization of the area (2). Two important copper deposits are known, viz., the Mosa-bani Mines (N22°31'; E86°28') which at present are being exploited; and the Rakha Mines (N22°38'; E86°22') which were once in active production, but have since gone into liquidation. The orebodies mostly are steeply dipping lodes and stringers with chalcopyrite, pyrite, and pyrrhotite, mixed with apatite, magnetite, and several other gangue minerals. Massive sulphide bodies have not been met.

Electrical and magnetic surveys have been conducted at Baharamora (N22°18'; E84°41'), Surda (N22°33'; E86°26'), Rakha (N22°38'; E86°22'), Rajdah (N22°41'; E86°17'), Dudra (N22°45'; E86°08') and Narainpur (N22°44' 30"; E86°0')—covering about 50 square miles in all. Spontaneous polarization indications in this belt generally are poor, and promising centres were found only in the portion between Surda and Rakha. Magnetic anomalies are mixed up with magnetic quartzites and other iron-ore rocks of no economic importance.

Several strong negative centres of 300 to 400 millivolts have been outlined by P. C. Paul and party in the tract between Surda and Rakha mines. None of these indications have been verified by drilling, but the magnitude and the trend of the anomalies in relation to the shear zone suggest that important sulphide bodies are likely to be found when these are drilled.

The Gani Belt, Andhra State

In the Gani belt, about 20 square miles have been covered by spontaneous polarization and magnetic methods by the Geological Survey of India parties led by K. R. M. Simha and H. V. N. Rao. Twelve negative centres, 300 to 600 millivolts strong, have been located generally at the contact of basic traps with Tadapati shales, of Precambrian age, corresponding approximately to the Keweennawan. These negative centres follow a strike in close association with or parallel to the line of old workings for copper ore. Some of the spontaneous polarization centres have
shown also strong conductive anomalies when investigated by resistivity traverses, and it is quite probable that the indications are due to massive sulphide bodies at depth. However, the occurrence cannot be ruled out of carbonaceous shales in places which might cause the electrical anomalies. Drilling has been recommended to test these indications.

**Khetri Area, Rajasthan State**

This is perhaps the best known area in India where the ancients had exploited the copper ores on a fairly large scale (3). There are numerous old workings over a belt 16 miles long, striking roughly northeast and following the range of hills from Singhana (N28°6'5"; E75°59'10") to Babai (N27°53'20"; E75°45'50"). The copper mineralization consists principally of chalcopyrite, pyrrhotite, and malachite, mostly in thin stringers impregnating the slates and schists with the associated quartzites (of Precambrian age); massive sulphide bodies have not been reported. Some of the sulphides are said to be distinctly associated with amphibolites.

The geophysical survey parties led by S. N. Sengupta and M. N. S. Rao so far have covered about 25 square miles near Singhana, Banwas (N28°48'50"; E75°53'20") and Paprana (N27°55'50"; E75°48'20"). In the Singhana and Banwas areas, the spontaneous polarization anomalies are very weak and are distributed in narrow zones; at some of these indications, magnetic anomalies also have been noted. Near Paprana, spontaneous polarization indications are strong; two zones of negative potentials—each about 1,000 ft. long, and with centres of 300 to 400 millivolts—have been located very recently at the contacts of limestones with pegmatites and quartzites. These indications look very promising and have been recommended for drilling.

**Chitaldrug Belt, Mysore State**

This belt is an ancient schistose series of rocks known as the Dharwar system.
The presence in this belt of gold, copper, lead, zinc, antimony, arsenic, etc. has long been known but no workable deposits of any of these metals have been proved (4). In the north parts of this belt at Madalakkanhalli (N14°20′30″; E76°23′30″), G. R. Halli (N14°17′30″; E76°24′), Kunchiganahal (N14°11′50″; E76°26′48″) and Ingaldhal (N14°11′; E76°26′48″), geophysical surveys were conducted between 1939-1949, principally by the writers while in the Mysore Geological Department.

Since 1950, geophysical parties of the Geological Survey of India led by M. N. S. Rao, P. M. Mathew, V. L. N. Sastry and S. C. Nandi, have extended the surveys to the south parts of this belt. The survey work so far done covers the Belliguda (N14°10′; E76°26′30″), Kurubaramaradikere (N14°49′; E76°26′), Kallehadhu (N14°6′30″; E76°25′) and Yarchallar (N14°44′; E76°26′) areas, using self-potential, resistivity, and magnetic methods. In all about 25 square miles have been surveyed. These areas are shown in Figure 2.

While the north parts of this belt have shown spontaneous polarization indications of positive and negative centres 50 to 200 millivolts strong, the south portions have shown much stronger anomaly zones with negative centres of 300 to 500 millivolts. Many of these centres undoubtedly indicate massive sulphide bodies at depth but they have yet to be proved by drilling. So far, only a few of the north indications have been followed up with test pits, shaft-sinking or drilling.

Two of these case histories which are of some general interest, are reviewed below very briefly:

a) G. R. Halli: The spontaneous polarization surveys near Guddadarangavvanahalli (5) (G. R. Halli for short), showed that the area bristles with a number of negative and positive centres 50 to 200 millivolts strong. A detailed mapping of the geological features displayed remarkable agreement between the trends of the spontaneous polarization centres and the outcrops of chalybitic trap rocks occurring as isolated patches and dykes in the area. This trap rock carries disseminated pyrite but economically is unimportant. In one case, (Figure 1), the area of positive potentials corresponds very closely with the outcrops of shaly schists containing gossan materials and quartz stringers. The positive potential anomaly (only 60 millivolts strong) occurs right over the gossan; the negative centre (about 80 millivolts strong) was found over an outcrop of massive trap rock barren of mineralization.

In discussing the writer's original paper, Sherwin F. Kelly (5n) has furnished a very ingenious explanation for this peculiar positive centre. An equipotential line survey also showed a strong conductive anomaly corresponding to this positive zone (6).

Since the outcrop of gossan denoted a spontaneous polarization centre, supported by a strong conductive anomaly, it was chosen for further prospecting. An old prospecting shaft in the vicinity was deepened to 70 ft. below surface and a crosscut was driven westward from the bottom of this shaft (7) (Figure 4). This crosscut, after passing through the zone of indication, disclosed many thin ferruginous and quartzose stringers, all completely leached out, and a winze was then sunk at this point to 32 ft. below the level of the crosscut. About 100 ft. below surface, a well defined lode of pyritiferous graphitic schist was encountered and was followed up by a drive southerly for 12 ft. This lode is about 2½ ft. wide and dips westward at 60°, striking nearly north in conformity with the axis of the electrical indication. The lode is composed of a black, crumpled, clayey schist, carrying thin streaks and veins of fine crystals and irregular grains of pyrite. The lode material was found to contain about 20 per cent pyrite; a trace of copper but no other
metal of value was noted. The graphite is amorphous and more or less evenly diffused in the clayey material.

Further development of this prospect unfortunately was suspended in 1942 because of the war, and the economic importance of this discovery remains still unproved. Nevertheless, the results of the geophysical survey in this locality can be classed as successful, since the existence of a lode of a promising nature has been detected and proved at a depth of 100 ft. below the surface.

b) Ingaldhal: Ingaldhal is another locality in the Chitaldrug belt in which the geophysical surveys of 1945-46 led to the discovery of massive pyrite mineralization. The rock formations here (corresponding to the Kewatin?) are mostly chloritic schists with ancient volcanic rocks constituting greyish traps, agglomerates and tuffaceous beds. Bands of ferruginous quartzites and black cherty rocks also are found.

Prior to the geophysical survey, the presence in the region of a massive sulphide body was not known. The electrical surveys, using self-potential and resistivity methods in the vicinity of Ingaldhal, indicated a zone of negative potentials, about 2,000 ft. long, with three well defined centres 100 to 150 millivolts strong. Figure 5 shows the equipotential line contours and the location of pits and boreholes put down in a part of this area to prove the electrical indications. In 1946, a few shallow test pits were dug on the indications and some bands of massive pyrite were noted in one (pit No. 1). The Mysore Geological Department prospected this zone with a diamond drill during 1954 and has estimated that at least one million tons of easily workable pyrite may be obtained.

In order to illustrate graphically the nature of the geophysical indications obtained and the results of the verification by bore holes, Figures 6, 6A, 7, 7A, 8 and 8A are presented here to show the resistivity, the self-
potential and magnetic profiles, and geologic sections along lines A, B, and C marked in Figure 5.

The resistivity traverses noted in these figures were conducted with a Megger Earth Tester, keeping the four electrodes, C₁-P₁-P₂-C₂, on a line on which the interval between C₁-P₁ was 40 ft., between P₁-P₂ 20 ft., and between P₂-C₂ 40 ft. In another set of measurements these intervals were raised to 80 ft., 40 ft. and 80 ft. respectively. The idea in adopting an unequal electrode separations such as 40 ft., 20 ft. and 40 ft., or 80 ft., 40 ft. and 80 ft., was to minimize the interval between the potential electrodes (P₁-P₂) so as to pick up indications of narrow veins or sharply pinching out bands, while the current was, in effect, allowed to go down to a depth sufficient to exceed the thickness of overburden.

Referring to Figure 6, it should be pointed out that the very high electrical resistivity portion on the western side, up to about station 11, is due mostly to outcrops of hard schists. The sharp anomalies at stations 11, 10, 9 and 7½ are interesting; the one near station 9 coincides with the spontaneous polarization anomaly. The magnetic anomaly also indicates a strongly polarized body. The ground in this zone is composed of ferruginous rubble and soil. Three trenches had been sunk on this line. The trench on the west side, at station 11, denoted crumpled schist impregnated with fine granular pyrite and quartz blebs 12 ft. below surface. The excavations were deepened to 17 ft. but the mineralization was not promising. The central trench disclosed, at 10 ft. depth, a small vein of massive pyrite 1 ft. thick in a greenish, cherty rock. Although this vein was persistent, the excavations were discontinued at 15 ft. depth owing to the hardness of the rocks. In the east trench, a small, massive pyrite band was encountered below 5 or 6 ft. of ferruginous
Figure 6.
Spontaneous polarization, resistivity and magnetic profiles along line A, Ingolsthal, Chitaldug district.

Figure 6A.
Geological section along line A.
debris, and after going down about 25 ft., it was found that the sulphide body was much wider and extended both eastward and westward. Excavations had been stopped on account of hard rock, but very promising bands of massive sulphides were met here. The log of borehole No. 1 drilled at this place follows:

0 - 32 feet — Trap rock
32 - 52 " — Massive pyrite bands
52 - 120 " — Banded chert with disseminated pyrite.

As regards Figure 7, the spontaneous polarization anomaly was considered to suggest the existence of a massive sulphide body at depth near station 11. The resistivity anomaly also supported the existence of a conductive body, although the central peak on station 11 was difficult to understand. The magnetic anomaly is, however, shifted far to the east. A pit (No. 3) was dug here to 18 ft.; after passing through loose, ferruginous material, very hard bands of cherty rock were encountered and the excavation was discontinued.
without proving the indication. Recent drilling (borehole No. 3), however, has shown the following:

- 0 - 54 feet — Tuffaceous trap rock with sporadic pyrite
- 54 - 73 " — Massive pyrite
- 73 - 74 " — Banded chert
- 74 - 80 " — Pyrite bands
- 80 - 160 " — Banded trap with disseminated pyrite
- 160 - 224 " — Schists

At line C (Figure 8), the spontaneous polarization and resistivity indications were considered to point to the occurrence of a massive sulphide body at depth; but pit No. 2 showed only a thin stringer of pyrite and gypsum at 27 ft. below the ferruginous gossan. The excavations were deepened to 38 ft. and met only splashes of sulphides in the very compact, hard, cherty formation. Borehole No. 4, drilled to the east of the indication on the slope of the hill, showed:

- 0 - 140 feet — Trap rock
- 140 - 142 " — Pyrite
- 142 - 212 " — Banded trap with stringers of pyrite
- 212 - 214 " — Pyrite
- 214 - 235 " — Banded trap
- 235 - 236 " — Pyrite
- 236 - 249 " — Banded trap
- 249 - 250 " — Pyrite
- 250 - 264 " — Banded trap and chert with occasional stringers of pyrite

Apprently no large bands of massive pyrite occur here, although the electrical indications were fairly strong.

Borehole No. 2 (Figure 5), to the east of the electrical anomaly zone, met the sulphide body only after drilling through about 250 ft. of barren volcanic rock. The log of this borehole follows:

- 0 - 252 feet — Varicolitie and tuffaceous trap rock
- 252 - 260 " — Massive pyrite
- 260 - 323 " — Banded chert and trap
- 323 - 326 " — Massive pyrite
- 326 - 364 " — Banded chert
- 364 - 380 " — Massive pyrite
- 380 - 414 " — Banded chert and schist

Summing up, it may be stated that holes Nos. 1, 2 and 3 proved the existence of substantial sulphides, whereas borehole No. 4 on the south shows that the sulphide body has played out in that position.

According to the information furnished by Dr. B. P. Radhakrishna, geologist of the Mysore Geological Department, the mineralization in this area consists essentially of pyrite and marcasite. Practically no pyrrhotite or chalcopyrite has been noted. The magnetic indications are caused by magnetite in the black cherty rock mixed or associated with pyrite bands. The cherty formation has been pyritized very unevenly and the quantity of sulphides distributed in the cherty
rock, apart from the massive bodies, must also be considerable. However, for purposes of estimate, if only the massive bands are taken for a depth of 400 ft., the quantity to be expected is 1,200,000 tons, but from the disposition of the bodies it is obvious that they persist to much greater depths and the tonnage of sulphides available may be three to four times larger than this conservative estimate. Beneficiation tests have shown that a concentrate with 45 to 47 per cent sulphur can be obtained. Further development of this property and utilization of the ores are engaging the attention of the Mysore State Geological Department.

It can be claimed that this is the first discovery in India of a commercially important orebody in which geophysics played the leading role. We might expect also that the many stronger spontaneous polarization indications in the south portions at Kallehadlu and Yarehalli in the Chitraldrug belt will, when drilled, reveal the existence of vast quantities of sulphide ores.

Conclusion

The foregoing outline presents some of the attempts in India at geophysical exploration for ore deposits. In addition to the mineralized belts referred to above, geophysical investigations have been conducted by the Geological Survey of India on several isolated occurrences of sulphide bodies in different parts of the country, but most of them have failed to show any important indications of large bodies of ore.

Currently, the Geological Survey of India has formulated proposals for the Second Five-Year Plan in which a program of intensive and systematic geological mapping, geophysical and geochemical surveys of all the remaining parts of the areas potentially favourable for the occurrence of sulphide ores will be carried out. It is expected that the more promising indications already obtained in the Singhbhum, Ganj, Khetri belts, and also those which will be noted in the pursuance of this plan, will be drilled. One might, therefore, look forward confidently to a more illuminating picture of the contributions of geophysics in the discovery of new orebodies in India.

The author's wish to acknowledge their thankfulness to the Director, Mysore Geological Department, and to Dr. B. P. Radhakrishna, geologist, Bureau of Mineral Development, Mysore Geological Department, for information furnished.
REFERENCES


THE APPLICATION OF THE RESISTIVITY METHOD TO HYDROGEOLOGICAL PROBLEMS IN JAMAICA

by S. A. Vincenz* and H. R. Versey†

Abstract

Two examples of the use of resistivity measurements in locating water for irrigation purposes are described.

The first example deals with a resistivity survey of a waterlogged area, to trace gravel lenses and to locate the site for a borehole expected to give a higher yield of water than is obtained from the existing well. Resistivity curves obtained with Cooper’s electrode arrangement suggested two electrode separations for the Wenner arrangement used in constant electrode separation surveys of the area. The results of the 30- and 60-foot separation surveys are shown in the form of equiresistivity maps, and the interpretation of these is facilitated by a corresponding map of iso-ratios of the resistivities obtained with the two electrode separations. This procedure is shown to remove much of the disturbing influence of variable surface resistivity. In consequence, a site is suggested for another well, but it is pointed out that an output much larger than from the existing well can hardly be expected, and this conclusion is confirmed by a second borehole.

The second case is one of the determination of the thickness of an unconsolidated overburden resting on a limestone aquifer. Wenner and Cooper depth probes were done near the existing well and at the site where the information was required. The resulting two sets of resistivity curves are interpreted by curve matching and empirical (rule-of-thumb) methods. The conclusion is that the curves obtained with Cooper’s arrangement give on the whole more satisfactory results than those obtained with Wenner’s, though in both cases depths to rockhead of the same order of magnitude are obtained.

The maintenance of a high level of agricultural production in a tropical country depends largely upon the amount of water available for irrigation. In Jamaica, the problem of irrigation is of great importance in the low-lying alluvial plains where the rainfall is appreciably less than in the mountainous ranges. The seasonal variation of rainfall makes the shortage of water particularly acute when it is taken from rivers or streams which diminish during the dry season.

The best constant water supply in Jamaica is obtained from relatively deep-seated fissures in the 2,000-ft. thick limestone formation which constitutes two-thirds of the solid surface of the island. Traps for water are also formed where an alluvial blanket containing gravels overlies the limestone; however, these too are generally affected by seasonal variations.

From the geophysical point of view the problem of discovering a water supply is two-fold:

(a) to locate gravel lenses in the alluvium, and  
(b) where water from the deep aquifers in the limestone is sought, to determine the thickness of the unconsolidated overburden with a view to siting convenient spots for boreholes and thus reducing the drilling costs.

*Industrial Development Corporation, Jamaica, B.W.I.  
†Geological Survey Department, Jamaica, B.W.I.
MINING GEOPHYSICS

Both problems can be solved by the electrical resistivity method which frequently has been applied successfully to similar cases. For instance, gravel lenses in clay have often been detected by looking for resistivity "highs". Conversely, saturated gravel beds resting on an impermeable crystalline rock possess a low resistivity in relation to the resistivity of the rock. If both dry and saturated alluvial deposits are present, the water-bearing gravels will sometimes have a resistivity intermediate between the low resistivity of saturated clays and the high resistivity of dry gravels or dry sand. Although no definite rule exists for detecting gravel aquifers by the resistivity method, the necessary resistivity contrasts are usually present to permit its application.

Similarly, the determination of the thickness of an unconsolidated overburden resting on a hard, massive rock does not present any difficulties because the generally low resistivity of moist, unconsolidated deposits contrasts well with the high resistivity of the less porous, hard rock. A hope might be entertained also of using the resistivity method to locate the actual aquifers which would be expected to possess a lower resistivity than the surrounding massive limestone. Unfortunately, in Jamaica, water is present in zones usually only a few feet thick, at depths of the order of 300 ft, and it is improbable that their presence would materially affect the apparent resistivity observed at the surface of the ground.

In the two cases about to be described, geophysical methods other than resistivity could be used, but in each instance some very special conditions would have to be fulfilled to permit their application. For example, water-bearing gravels can be located by the equipotential line method, but only if their resistivity is markedly different from that of the surrounding medium. The electromagnetic or the potential-drop-ratio methods can be used if the very sharp resistivity contrasts occur only between the aquifers and the surrounding deposits. Fissures in massive rock can be detected by a new electromagnetic technique (Enslin, 1955 (1)), but the latter cannot be used to determine the thickness of overburden.

Subsurface topography can be investigated by the potential-drop-ratio method, by the telluric method, and by a seismic refraction technique adapted to shallow problems (Evson, 1952 (2)). None of these were practicable in the present case since either they were too costly (potential-drop-ratio and refraction seismic), or they have not yet been developed for the specified field use (refraction seismic), or their application was limited to the specific case of depth determination only (telluric).

The resistivity method thus emerges as the most versatile of all the possible techniques and it possesses the additional advantage of simplicity and low operational costs.

![Figure 1. Map of Jamaica, showing the positions of the sites.](image-url)
The Sites and Field Procedure

Two examples have been selected for description, each representing one of the two types of the problem. The first (described in Part I) deals with an attempt to trace gravel aquifers in an alluvial plain near Belvedere. The second (in Part II) concerns the determination of the thickness of an unconsolidated overburden overlying the massive limestone near Clarendon Park. The positions of the two sites are shown on the map in Figure 1.

The field procedure comprised the use of Cooper and Wenner configurations when depth probes were carried out, and of the Wenner configuration alone when observations with a constant electrode separation were made. Two types of equipment were employed: the Swedish ABEM equipment, and the Geophysical Megger manufactured by Messrs. Evereshed and Vignoles of London.

Part I—Location of Water-Bearing Gravels

- Description of the Site

An outline of the topography and geology of the site (No. 1 in Figure 1) is given in Figure 2. The site lies in the property of Bevedere on an alluvial plain where the latter abuts against the limestone hills. The main source of irrigation water is a system of canals leading from Morant River, but, because of seasonal changes in the level of the river, underground sources of water were sought. A well was drilled at the point shown as (B.H.) on Figure 2, but its output was found insufficient. It was necessary, therefore, to locate another site for a well, and a resistivity survey was carried out with this purpose in view.

The log of the existing well, B.H. in Figure 2, is as follows:

- Sand and fine gravel ................. 0-21 ft.
- Coarse gravel ........................ 21-30 ft.
- Dark grey clay with gravel ............ 30-50 ft.
- White sticky marl ...................... 50-70 ft.

The well was cased with a 12-inch strainer and pumping tests showed a drawdown of 17 ft. from the static level of 5 ft. below the surface of the ground for a yield of 150 cubic yards per hour. That the drawdown is not excessive suggests a fairly free movement of water in the gravel. If an expanding depth probe is carried out at the well, then, judging by the well log, the resulting resistivity curve will be expected to resemble the hypothetical curve shown in Figure 3. From experience it may be assumed that the apparent resistivities of the materials, in declining magnitudes,
are: dry surface materials, coarse gravels, sand and fine gravel and clays.

Hence by making observations with a constant electrode separation which was chosen on the basis of the well log and of several expanding depth probes, it should be possible to trace the water-bearing sands and gravels as regions of medium resistivity in comparison with the high resistivity of the surface layers and the low resistivity of the clays. Experience would show then whether it would be possible to discriminate between coarse gravels and finer gravel mixed with sand, though a decline in apparent resistivity would in the present case always indicate the presence of finer material.

Since a site for a new well had already been suggested on purely geological considerations (point S1, Figure 2), the resistivity work was undertaken to corroborate this or to propose an alternative.

- **The Depth Probes**

Three resistivity depth probes were made, using Cooper’s four electrode configuration (Cooper, 1934, 1950 (3)). One was located near the well, the second at the suggested borehole site, and the third to the east from the latter. The results are represented by the resistivity curves in Figure 4. The positions of the three depth probes are shown in Figure 5. In Figure 4 the apparent resistivity $R_a$ is plotted against the parameter $f$ of Cooper’s formula, with the current base fixed at 100 ft. For a brief description of Cooper’s electrode arrangement and the definition of the parameter $f$, the reader is referred toAppendix I.

The experimental curves do not conform with the hypothetical curve of Figure 3, since in all of them the apparent resistivity declines monotonously with the increasing current penetration and no peaks are associated with coarse gravels. Even in the resistivity curve No. 1, obtained at the well where coarse gravels are known to exist, there is only an insignificant irregularity at $f=0.8$. Furthermore, curve No. 2 reveals a fairly low resistivity of the uppermost surface layer. These results, however, do not materially affect the suggestion according to which zones of medium resistivity should be associated with water-bearing gravels, except that the chances of discriminating between the coarse gravel and the fine gravel with sand appear to have been reduced. All three resistivity curves are generally of the same shape and tend to coincide at large values of $f$. The differences between the curves, corresponding to small values of $f$, can be attributed to surface effects.

Unfortunately, interpretation of the curves with curve-matching methods (Cooper, 1950 (3)) did not yield any exact data relating to the thicknesses of the various layers, but it gave a satisfactory general correlation between the probes and the well log. Thus, in all probes the upper zone with a resistivity of about 120 to 250 meter-ohms appears to extend to a depth of about 25 to 30 ft and is followed by a layer with a resistivity of about 15 meter-ohms. The curves suggest further the presence of another interface at a depth of about 50 to 60 ft., below which there is a layer with a resistivity of less than 5 meter-ohms. Using the existing well as a marker, the following interpretation of the three resistivity curves is therefore feasible: the resistivity of 120 to 250 meter-ohms seems to be associated with gravels, sandy gravels and sands, including the surface layers; the resistivity of 15 meter-ohms appears to be that of more or less gravelly or sandy clays; and, finally, resistivities of less than 5 meter-ohms appear to correspond with marl and tight clay saturated with hard stagnant water.

Each resistivity curve gives, within limits, the same value for the resistivity of clays and marls and suggests that the interface between clays and the gravelly bed occurs at approximately the same depth. Hence by carrying out a survey-using the Wenner configuration (Wenner, 1916 (4)) with a suitably selected constant electrode separation, the lateral variations in the resistivity of the gravelly overburden can be determined. Since these variations will in principle reflect
the changes in porosity, including the factor of pore disposition which affects the degree of stagnation of ground waters, they will be expected to give a means of distinguishing between aquifers and the more clayey gravels and sands from which water cannot be extracted easily. The resistivity curves and the well log data suggest a 30-ft. electrode separation as being suitable for such a survey, and that the observations should be repeated with a 60-ft. separation to allow for possible changes in the thickness of the gravelly beds.

- **The Constant Electrode Separation Survey**

  The results of observations with a 30-ft. electrode separation are given in Figure 5 in the form of lines of equal apparent resistivity. The observations were made along parallel traverses 100 ft. apart and at intervals equal to the electrode separation. They were repeated with a 60-ft. electrode separation using a 60-ft. station interval along traverse lines 200 ft. apart. The results of the second set of observations are given in Figure 6.

Both equiresistivity maps reveal the same trend in the strike direction from southeast to northwest. The apparent resistivity generally declines from east to west, but the values obtained in the 60-ft. separation survey usually are about one half of those obtained with a 30-ft. separation. The 30-ft. separation map reveals a resistivity "high" of over 200 meter-ohms in the northeast quadrant near traverse No. 2, the lowest resistivities of 60 meter-ohms occurring in the west end of the site near traverse No. 8. Obviously, the contours obtained with a 30-ft. electrode spacing reveal greater extremes and are more complex than those obtained with a 60-ft. spacing, but the general picture presented by the two sets of observations is similar.

In both cases, due to the presence of outcrops, it was not possible to carry out any observations west of the depth probe D.P. 2 and traverse No. 8, and data for this part of the area consequently are not available.
Discussion and Interpretation of the Observations

The resistivity contours in Figures 5 and 6 appear to reflect a general trend in the alluvium, and their strike agrees roughly with the direction of flow of Morant River. The fact that both resistivity maps resemble each other and that the apparent resistivity measured with a 60-ft. separation varies less than the resistivity observed with a 30-ft. separation, confirms the deduction from the resistivity curves in Figure 4 that the surface of the clay is about horizontal. The map in Figure 5 should, therefore, mainly reflect the variations in the resistivity of the beds overlying the clay and marl formations, and, if the ground water table is everywhere at the same depth, these changes can be related to the average porosity and salinity of the beds.

The salinity of a saturated unconsolidated formation, if varying, does so with the degree of stagnation and therefore with the tightness of the formation. A high salinity and, therefore, a low resistivity are to be expected in clay and marl, and the depth probes provide a satisfactory confirmation for this interpretation. Hence the lowest resistivities obtained with a 30-ft. separation may be correlated with the presence in the gravel and sand of an appreciable admixture of clay and marl.

The data for the existing well have shown a fairly free movement of water in the gravel, and the corresponding apparent resistivity observed with a 30-ft. separation was found to be about 100 meter-ohms. It would appear, therefore, reasonable to accept a resistivity of this order of magnitude as an indicator of the presence of water-bearing gravels. However, this deduction based on empirical data may not be strictly correct and, since Figure 5 reveals the presence of resistivity "highs" with resistivities exceeding 200 meter-ohms, an alternative interpretation is possible. Thus, if there is a rapid circulation of water through the gravels, the observed resistivity will be high and the most suitable site for a new well would be inside
the 200 meter-ohms resistivity contour near traverse No. 2.

However, a different conclusion is suggested by considering certain hydrogeological aspects of the area. It is possible that the embayment in the limestone hill, adjacent to the site (Figure 2), has been carved out by stream action. This would imply that the accumulation of coarser gravel had taken place nearer the hill. Thus it seems that in the recent case the 200 metre-ohms resistivity high does not signify a rapid movement of ground waters and that, as suggested, the best aquifers are represented by medium resistivities.

Since the depth probes have shown much variation in the resistivity of the surface layers, two important conclusions emerge:

(a) the resistivity of the surface layers above the ground water table fluctuates and its variation affect the apparent resistivity observed with the two electrode separations, and

(b) even if this influence is eliminated by suitable treatment, the resulting picture will still not assure the finding of a yielding aquifer.

The second of these conclusions does not require any special explanation; and further, even if the required aquifer is there, the yield may be small and the drawdown very large if the aquifer is isolated, i.e., if there is no free movement of water into it.

The other conclusion, relating to the variation of surface resistivity, requires a more detailed investigation. Variable surface resistivity has been a source of interference in many surveys, particularly when relatively shallow structures have been examined. In the present case the observed apparent resistivity is also affected by the variation in the resistivity of the surface layers and this variation is demonstrated by observations with a 5-ft. electrode separation. The relevant resistivity profiles obtained along traverses Nos. 2 and 8 are given in Figures 7 and 8 respectively.

![Graph showing resistivity variations](image)

**Figure 7.** Results of surface resistivity measurements along traverse No. 2.
In each case, along with the variation of surface resistivity, the profile obtained with a 30-ft. separation is shown.

Clearly, in both cases the surface resistivity differs from the resistivity observed with a 30-ft. separation and this difference is illustrated by the variation of the ratio of the two resistivities ($\rho_{s(30)}/\rho_{s(5)}$), also represented in Figures 7 and 8. Each value of $\rho_{s(30)}$, used in calculating the ratio, was a mean of a set of three consecutive observed values of $\rho_{s(5)}$, the middle observation corresponding with the observed $\rho_{s(30)}$. Although at some points on traverse No. 2 the surface resistivity is either greater than the apparent resistivity $\rho_{s(30)}$ or equal to it, the observations along both traverses show that generally $\rho_{s(5)}$ is smaller than $\rho_{s(30)}$. This suggests that the surface layers above the ground water table contain some fine-grained material, the pore space of which, though not saturated, is partly filled with water of high conductivity. The true resistivity of the underlying gravels and sands therefore is on the whole higher than indicated by the resistivity contours in Figure 5.

Knowing the surface resistivity, it is possible to calculate the resistivity of the beds below the ground water table. This can be done by using Hummel's rule (Hummel, 1929 (5)) and assuming that the apparent resistivity $\rho_{a(30)}$ is equal to the average resistivity of the two media, i.e., of the relatively dry layer above the ground water table and the saturated gravelly beds below it. If $\rho_1$ and $\rho_2$ are the resistivities of two horizontal beds of respective thicknesses $h_1$ and $h_2$, and if $\rho_m$ is the average resistivity of the two upper beds, measured at large electrode separations, then Hummel's rule gives:

$$\frac{h_m}{\rho_m} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2}$$

where $h_m = h_1 + h_2$. In the present case $\rho_2$ is the resistivity of the gravelly beds, $\rho_m = \rho_{a(30)}$, $\rho_1 = \rho_{a(5)}$ and, using the data of the existing borehole, $h_1 = 5$ ft. and $h_2 = 25$ ft. Substituting these quantities in the formula and using, as before, averaged values of $\rho_{a(5)}$, the resistivity profiles giving the variation in $\rho_2$ have been obtained. These are shown by dotted lines in Figures 7 and 8.

Apart from the peaks on traverse No. 2, the calculated values of $\rho_2$ fluctuate between about 110-180 meter-ohms. Since, for Hummel's rule to apply, $\rho_m$ should have been obtained from observations at electrode separations large compared with $h_m$, these results cannot be strictly correct. This is because when the observations with a 30-ft. electrode separation were made, an appreciable portion of the current must have been flowing through the relevant conducting layers as through conductors connected in series.

Now, Hummel's rule has been based on the assumption that the conducting layers behave as conductors in parallel. It follows, therefore, that $\rho_m$ generally is smaller than $\rho_{a(30)}$ and hence that the true values of $\rho_2$ are smaller than those obtained above by calculation. The magnitude of the correction factor for $\rho_m$ at various points will depend on the resistivity contrast between the two layers, but generally speaking, since the calculated $\rho_2$ will always be greater than its true value, the latter will vary less and the sharp peaks on traverse No. 2 will be smoothed out. It would appear, therefore, that there are no great variations in $\rho_2$ in the whole of the area, i.e., that the resistivity of the gravel and sand beds varies little.

An obvious conclusion to the above deductions is that there are no significant lateral variations in porosity of the gravel beds, i.e., in the free movement of ground water. Hence it is not likely that at any point in the area a yield superior to the existing one can be found. Furthermore, since the variations in the surface resistivity are comparable with or greater
than the variations in \( \rho_2 \), the chances of locating a site for a better well are remote. Unfortunately, the variation of ratio \( \frac{\rho_{\alpha}(30)}{\rho_{\alpha}(60)} \) and the knowledge of \( \rho_{\alpha}(60) \) cannot be used in the exact determination of the true variation in \( \rho_2 \). Therefore, it is necessary to devise an interpretational technique with which it will be possible to eliminate the influence of surface resistivity and to study the small variations in \( \rho_2 \) with the view of locating a favourable site for a new well. An attempt at establishing such a technique is given below.

Assuming that the resistivities of the clays and marls do not vary, and that the beds investigated are horizontal and have thicknesses as revealed by the well log, it can be shown that the ratio of the apparent resistivity obtained with a 30-ft. separation to that observed with a 60-ft. separation should depend little on changes in surface resistivity, and its variation should in general reflect the changes in the conductivity of the intermediate layer. It is shown in Appendix II that this will be approximately true if the surface layer is thin and its resistivity varies between the limits of approximately 100 to 250 meter-ohms. Figure 9 gives the results of such an interpretation in the form of lines of equal ratio \( \frac{\rho_{\alpha}(30)}{\rho_{\alpha}(60)} \).

Clearly, the complexities exhibited by the equiresistivity contours have been reduced. The general north-westerly trend in the strike is still retained; some of the “highs” have disappeared but new “highs” have been created; and, though a great deal of smoothing has been achieved, the “highs” are still concentrated in the east part of the site and the “lows” in the south-west.

Bearing in mind that the ratio varies linearly with \( \rho_2 \) only if \( 100 \leq \rho_2 \leq 250 \) (see Appendix II), use must be made of the surface resistivity measurements on traverses Nos. 2 and 8. It is easy to show that the ratio \( \frac{\rho_{\alpha}(30)}{\rho_{\alpha}(60)} \) at points where \( \rho_1 \) is considerably less than 100 meter-ohms, is not representative for \( \rho_2 \). Thus at these points \( \rho_2 \) is either less or more, as the case may be, than suggested by the magnitude of the ratio. The true variation in \( \rho_2 \) can be calculated only
along the traverses Nos. 2 and 8 since the surface resistivities along these two lines are known. For this purpose use is made of the master curves in Figure 21 (Appendix II) and the values of $\rho_2$ are read off for the given values of $\rho_1$. This procedure shows immediately that the resistivity "highs" on traverse No. 2 (as shown for instance by the profile of $\rho_{2100}/\rho_{2100}$ in Figure 7) and the "lows" on traverse No. 8 are not real and that $\rho_2$ varies very little, the maximum variation not exceeding about 40 per cent. Although the surface resistivities along the other traverses are not known, a variation of this order of magnitude can be expected to occur in the whole of the area. Again the conclusion is reached that there is little hope of finding a favourable site for a well which would give a better yield than the existing one.

However, it is still possible to derive some information from the iso-ratio contours in Figure 9 by considering them from another angle. Careful examination of the contours shows that there is a region in the west part of the site where the ratio varies with position very little, its value remaining approximately at 2.3. The non-variability of the ratio over an area is indicative of settled conditions and in the present case may correspond with a relatively high permeability, i.e., with a free movement of water. Hence, taking into account the position of the existing well and of the site previously suggested (S1) on purely hydrogeological considerations, a site for a new well was selected at the point S2 (Figure 9). It was suggested that a 50-ft. borehole be drilled there, but that there was little hope of obtaining a supply better than about 200 cubic yards per hour.

The suggested borehole was drilled and its probable geological relationship with the first borehole is given in Figure 10. It is evident that the overall thickness of gravels pierced in the new borehole is greater than in the old one, though river gravel is mixed with marl and limestone pebbles. The thickness of sand also is greater, but the latter contains no fine gravel. The beds are not horizontal and hence the method of interpretation developed in Appendix II cannot be strictly valid. Finally, on testing the new well its output was found to be only 51 cubic yards per hour and eventually it was pumped dry. Although the gravels generally are thicker than in the first well, this aquifer appears to be isolated, thus cutting off the movement of water into it. In addition, the presence of marl will reduce its yield. Obviously, the assumption relating to non-variability of the iso-ratio and the mobility of water was not valid.

The result was disappointing, but, bearing in mind the conditions involved and the reservations made, is not surprising. A gravel bed thicker than the known one in B.H. 1 was located, and in this sense success could be claimed. Unfortunately, other factors such as the composition of the gravel which contained limestone pebbles and marl, and the possibility of this aquifer being isolated could not be foreseen. These factors appear to be responsible for its poor yield. Nevertheless the interpretation of the observations has been successful in showing that the site investigated was not suitable for establishing wells with yields greater than that found in the well at B.H. 1.

It is pertinent to describe at this stage the results of observations in an area a few miles north of the
above described site. This again was a case in which resistivity observations proved the unsuitability of a site. In the area investigated, a ridge of chalky limestone dips beneath the alluvium and reappears some 300 ft. away. The problem was to discover whether the alluvium included water-bearing gravels. About 3/4 mile west there was a well supplying 180 cubic yards per hour of water from gravel beds overlying a clay series. Figure 11 gives the results of three Cooper depth probes, two carried out at the site under investigation and one adjacent to the existing well to the west. The interpretation of the resistivity curves is simple and straightforward. The high resistivity (180 meter-ohms) of the relatively dry gravels in the well is not matched at the site, neither is the resistivity of the water-bearing gravels (90 meter-ohms). On the other hand, the low resistivities of the clay series approximately match the uniformly low resistivities obtained at the site. The conclusion is inescapable that there is no gravel at the site and that the site is quite unsuitable for siting a borehole. Constant electrode observations over the area merely confirmed this result.

**Conclusions**

The results of the observations, suitably interpreted, show that in the present case of a waterlogged alluvium it is difficult to locate the best-yielding aquifers, because coarse gravel cannot be differentiated reliably from finer gravel and sand. Although an aquifer, thicker than the known one has been located, the unforeseeable conditions relating to the composition of the gravel and its isolation deprive this result of its value. It is shown that it is unlikely that there are in the area aquifers which would give higher yields than that supplied by the existing well. The results show that a variable surface resistivity, which affects the observations with a constant electrode separation, can, under certain circumstances, be partly eliminated from the picture, and a method is suggested which permits such partial elimination. Finally, observations in a neighbouring area show that in the extreme case when the resistivity contrasts are great as between gravels and clays, the resistivity method is excellent in distinguishing between the two.

**Part II—Determination of the Thickness of an Unconsolidated Overburden**

**Description of the Site**

The sugar plantations in Clarendon Plain are irrigated by a network of canals because rainfall in that part of Jamaica is inadequate to supply the crop requirements. The main aquifers lie in massive Tertiary limestone. The limestone usually is covered by an unconsolidated alluvial overburden, the thickness of which varies from point to point. Since in the existing wells water rises to a uniform static level, an important criterion in siting boreholes is the thickness of this unconsolidated cover.

The details of the site investigated (No. 2 in Figure 1) are given in Figure 12. There is a well (B.H. in Figure

![Figure 12](image-url)
12) beside the Clarendon Park railway station, and an additional supply of water is obtained from a canal carrying water from another well. Because there was a possibility that more water would be needed, the Irrigation Authorities considered drilling another borehole at a point near the canal, and information was required of the depth to rockhead at that point. The log of the well at the railway station follows:

Yellow clay .......... 0-65 ft.
Yellow clay with marl ....... 65-78 ft.
Loose, bouldery limestone .... 78-110 ft.
Hard marl .............. 110-118 ft.
Massive limestone .......... 118-316 ft.
Loose, shelly limestone (aquifer) ... 316-318 ft.
Massive limestone ........ 318-348 ft.

Judging by these data it would appear that in principle the case should be a two-layer one, the overburden having a lower resistivity than the underlying layer, and the interface occurring at the depth of 78 ft. However, a second contrast might be expected to occur at depths between 110 and 118 ft. where the presence of hard marl and even harder massive limestone signify a further rise in resistivity.

The procedure therefore was that of carrying out two depth probes, one at the well for the purpose of calibration, and the other at the point at which it was proposed to drill a borehole. Comparison of the resistivity curve at that point with the calibrated resistivity curve would be expected to yield the required depth to rockhead.

- The Depth Probes and the Resulting Resistivity Curves

The depth probes were made using both the Cooper and the Wenner configurations. In the latter, the electrode system was expanded up to an electrode separation of 500 ft. In the Cooper depth probes, the current electrodes were maintained at 300 feet separation and the factor $f_i$ defined in Appendix I, was increased to 3.0 ft. In the observations at the well, owing to the presence of the pumping station, iron work, rails, etc., it was not possible to conduct the depth probe directly over the well and it was located at the point indicated on the map (D.P.I).

The results of observations are represented by the resistivity curves in Figures 13 and 14. Apart from the effect of near-surface layers in the Wenner probe at the canal (curve (b) Figure 13), all the curves reveal the presence of low-resistivity layers resting on higher-resistivity beds, the apparent resistivities observed varying from about 20 meter-ohms to 320 meter-ohms. Although the observed apparent resistivities vary somewhat irregularly, smooth curves have been drawn through the points to facilitate the interpretation.

- Interpretation of the Resistivity Curves

The interpretation used both the curve-matching methods and the empirical rule-of-thumb.

The results of the interpretation of the Wenner curves in Figure 13, obtained by curve-matching methods, are summarized in Table I. In this the resistivities of the successive layers counting downwards are denoted by $\rho_n$ where the suffix $n = 1, 2, 3 \ldots$, and the average resistivities of two or more layers are assigned the suffix $m$ with a number corresponding to the number of layers involved (Figure 13). The resistivity factors between the successive layers are denoted by $k$, i.e. $k_1 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$, $k_{m_1} = \frac{\rho_5 - \rho_{m_4}}{\rho_5 + \rho_{m_4}}$ etc. The thicknesses of the successive layers are denoted by $h$ bearing a suffix corresponding to the given layer, and the symbol $a$ is used to denote the electrode separation. All resistivities are quoted in meter-ohms and depths are in feet.

![Figure 13. Wenner resistivity curves obtained at site No. 2—(a) well; (b) canal.](image-url)
Figure 14.
Cooper resistivity curves obtained at site No. 2.

Table 1

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<th>Site</th>
<th>Method of interpretation</th>
<th>First four Points on curve</th>
<th>Fourth, fifth and sixth points on curve</th>
<th>Points on curve at a = 200, 300, 400 &amp; 500 ft.</th>
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</table>

335
The general procedure was first to apply Roman's logarithmic method (Roman, 1941(6)) to the various portions of the curves and obtain the resistivities of the upper layer or layers ($\rho_1$, $\rho_{min}$, etc.). These were then used in the calculations with Tagg's method of interpretation (Tagg, 1934(7)). This was found better than the series of approximations using Hummel's rule which in any case did not give satisfactory results. The calculations for some of the Tagg interpretations are given in Figures 15, 16, and 17. In all operations it was necessary to do a certain amount of smoothing. In particular, the apparent resistivity corresponding with $a = 70$ ft. (D.P. 1) had to be increased slightly to obtain a good intersection in the Tagg interpretation and a fit in the logarithmic plots. It was found also that by changing the apparent resistivity at $a = 150$ ft., the Tagg interpretation gave $k_1 = 0.9$, $\rho_2 =$ 1010 meter-ohms and $h_1 = 64$ ft. in full accord with the values obtained by Roman's method. Clearly, both Wenner curves reveal complexities which cannot be resolved by calculation. Thus at the well a low-resistivity layer follows the layer of 1010 meter-ohms, but the latter is too thin to permit an estimate of its thickness. Similarly, in the curve obtained at the canal, if the data for $a = 50$ ft. are included in the calculation (Figure 17), they do not yield any consistent results.

Generally speaking, the interpretation of the Wenner probes, as summarized in Table I, suggests the presence of the main interface at the depth of 64 ft. near the well and of 45 ft. at the canal. In addition, it indicates the presence of several other discontinuities at the well and the existence of a high-resistivity surface layer at the canal. Because D.P. 1 had to be located some distance away from the well, the interpretation of the resistivity curve in terms of the well log is not absolutely reliable. However, the interface at 64 ft. corresponds with the contact between the clay...
series and the high-resistivity, loose-bouldery limestone. The lower part of the latter presumably is saturated, giving a low resistivity which also may be associated with marl if the latter is not hard. An increase in resistivity occurs at a depth of 110 to 119 ft., representing the compact limestone or possibly also the hard marl. The deepest interface at 260 to 280 ft. may be associated with the aquifer itself, but this conclusion is problematic. The probe at the canal reveals no additional interfaces and suggests that the clay beds probably rest almost directly on limestone, without any appreciable thickness of intervening marls.

It is of interest to compare the above results with those obtained using a simplified calculation in which a two-layer case is assumed and the resistivity of the underlying medium is taken as infinite.

In this case, a well-known relation applies and \( h = a \) when \( \rho_2 = 1.5 \rho_1 \). In the present case the depths obtained are \( h = 70 \) ft. and \( h = 50 \) ft. for the well and the canal respectively.

The interpretation by a variety of rules-of-thumb gives a series of interfaces corresponding to the various types of change in the slope of the curves. The best and most consistent results are obtained by using the empirical rule due to Lancaster-Jones (1930(8)) according to which the depths of interfaces are equal to two-thirds of the electrode separation corresponding with the points of inflection on the Wenner resistivity curve. In the present case, this gives interfaces at the depths of 65, 133 and about 270 ft. at the well, and a single interface at the depth of 60 ft. near the canal.

Finally, the well-known cumulative resistivity method due to Moore (1945(9)) was applied. The increments of electrode separation were conveniently selected at 50 ft. and the results are given in Figure 18. In practice when \( a \to 0 \), \( \rho_2 \to \rho_1 \), but since \( \rho_1 \) is a constant it can be subtracted from all cumulative data without changing the positions of the breaks in the curve. In other words, the origin of the co-ordinates can be included in the data and the two main curves in Figure 18 have been constructed on this basis. Although there is no adequate theoretical justification for Moore’s method (Muskat, 1945(10)), surprisingly enough the present results agree fairly well with the interpretation by curve-matching methods as well as with results obtained by the use of Lancaster-Jones’(8) rule-of-thumb, as they both were applied to the curve obtained at the well. Presence of similar interfaces is revealed at the canal where an additional discontinuity is indicated at the depth of 400 ft. The main discontinuity is shown to occur at the depth of 75 ft. at the well and 74 ft. near the canal. Since the observations at the canal have been made using within the first 100-ft. interval increments smaller than 50 ft., an additional cumulative curve has been constructed with increments of 30 ft. This auxiliary curve (shown at the top of Figure 18) reveals the discontinuity at the depth of 60 ft. in exact agreement with the result obtained with Lancaster-Jones’ rule-of-thumb.

The results of the interpretation of the Cooper depth probes are summarized in Table II.

<table>
<thead>
<tr>
<th>Site</th>
<th>Method of Interpretation</th>
<th>( \rho_1 )</th>
<th>( k )</th>
<th>( \rho_2 )</th>
<th>( h )</th>
</tr>
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<tr>
<td>Railway Station</td>
<td>Logarithmic Ordinary</td>
<td>28</td>
<td>0.97</td>
<td>1840</td>
<td>60</td>
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<tr>
<td></td>
<td>Logarithmic Ordinary</td>
<td>28</td>
<td>0.97</td>
<td>1840</td>
<td>60</td>
</tr>
<tr>
<td>Canal</td>
<td>Logarithmic Ordinary</td>
<td>19.5</td>
<td>0.92</td>
<td>467</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Ordinary</td>
<td>19.5</td>
<td>1.0</td>
<td>( \infty )</td>
<td>63</td>
</tr>
</tbody>
</table>

As before, a logarithmic method was used to obtain the values of \( \rho_1 \), which were used in the ordinary curve-matching techniques developed by Cooper (3)
for use with his electrode configuration (Appendix 1). In the latter case, the five best values of \( f \) were selected for the given curve and the corresponding values of \( \rho_1/\rho_\alpha (k>1) \) were calculated. Then for each given \( f \) and \( \rho_1/\rho_\alpha \), Cooper’s master curves (Cooper, 1930 (3)) of \( k \) versus \( \lambda \) were traced directly, the intersection of five curves giving \( k \) and \( \lambda \) (Figure 14). The value of \( h \) was then obtained from the relation \( \lambda = h/a \).

Evidently, in the present case the resistivity curves obtained with the Cooper electrode arrangement are simpler to interpret and give more consistent results than those obtained with Wenner’s configuration. Apart from some irregularities, both Cooper curves are those of a two-layer case and no surface resistivities obscure the picture. Both curves suggest that the clayey overburden at the canal is about the same thickness as at the well, i.e., between 60 and 70 ft.

Conclusions

The problem posed has been solved successfully, that is to say that the thickness of the unconsolidated overburden at the given point has been determined. On the whole, both the Wenner and the Cooper electrode configurations have been found to give approximately the same results, though in the case of the canal the Roman and the Tagg analyses yielded different figures for the thickness of the overburden. The interpretation of the Cooper curves is simpler and gives more consistent results than obtained with Wenner’s probes. The reason for this probably is because, unlike in the Wenner arrangement, the overall current distribution in the Cooper arrangement remains unchanged.

Unfortunately no well has yet been drilled at the canal site, and hence the above results cannot yet be compared with its true geological section.

Acknowledgments

The writers thank the Industrial Development Corporation and the Director of the Geological Survey Department for permission to publish this paper and wish to record their indebtedness to the latter for the discussions which stimulated the investigations. They thank C. G. Ross of the Industrial Development Corporation and B. V. Bailey of the Geological Survey Department for assistance in the field. The diagrams in their final form were produced by C. G. Ross. Acknowledgments are due also to S. A. G. Taylor, Chief Engineer, Irrigation and Drainage Branch, Public Works Department, and to M. A. Rivera of Jamaica Antonsanti Well Company Limited for their good offices.

Appendix 1

Cooper’s electrode arrangement really is a modification of the Wenner four-electrode layout with the difference that in a Cooper depth probe the current electrodes remain fixed and the potential electrodes are moved successively to new positions. The principle of the method is illustrated in Figure 19. The current base \( C_1C_2 \) is fixed at a convenient length \( a \) depending on the required depth of penetration of the current. The potential electrodes \( P_1 \) and \( P_2 \) are moved by steps in a straight line on opposite sides of the current base, each at an equal distance \( f \ a \) from the respective current electrode, where \( f \) is a parameter which is varied from zero to a convenient value of a few units.

It is easy to show that the apparent resistivity is given by

\[ \rho_\alpha = \pi(f + 1) \ aR = FaR \]

where \( R \) is the resistance observed at a given value of \( f \), and \( F = \pi(f + 1) \).

This method of field procedure has the advantage over the Wenner method in that the observed apparent resistivity is affected less by local irregularities in the ground. Another advantage is the increased speed of field operations which are simpler, and require fewer field personnel.

The resistivity curves are obtained by plotting the apparent resistivity against the parameter \( f \), and the interpretation is carried out by curve-matching techniques. Suitable sets of master curves have been constructed by Cooper for various values of \( f \) and for various resistivity contrasts so that the interpretation is carried out simply by tracing the relevant master curves and determining their intersection, which gives the value of the resistivity factor \( k \) and of the parameter \( \lambda \), where \( \lambda \) is the ratio of the depth of the interface (\( h \)) to the length of the current base (\( a \)). In addition to this “ordinary” method of interpretation, a logarithmic technique has been developed which permits direct matching of the field curves with the master curves, both plotted on a logarithmic scale. For details of the interpretational techniques the reader is referred to Cooper’s original publications (Cooper, 1934, 1950 (3)).
Appendix II

(By S. A. Vincenz)

Experience has shown that when a constant-electrode separation survey is made using the Wenner configuration, the observations sometimes are difficult to interpret because they are affected by the variations in resistivity of the surface layers. If a fairly small electrode separation is used (e.g., about 50 ft. or less), a marked variation in the surface resistivity will seriously affect the observed apparent resistivity, and produce an incorrect picture of the variation in the resistivity of the underlying layers. In this case, to obtain any consistent results, resort has to be made to a dense network of depth probes.

A procedure which would not require a great number of depth probes and which also would avoid detailed measurements of surface resistivity would be instrumental in reducing the cost of an electrical survey and would be of great practical value. A simple procedure of this type is suggested below. It has been developed for the specific case under consideration and no general solution is offered, but in very broad lines a similar technique could be adapted to other cases. This technique is based on a series of assumptions and approximations and hence the results given also will be only approximate.

Consider three homogeneous and isotropic layers of resistivities $\rho_1$, $\rho_2$, and $\rho_3$ and respective thicknesses, $h_1$, $h_2$, and $h_3$. If observations are made with a 30-ft. and a 60-ft. electrode separation then, using Hummel's rule (Hummel, 1929 (5)), the respective apparent resistivities at any one point are given by

$$\frac{h_1 + h_2}{p\rho \alpha (50)} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2}$$

and

$$\frac{h_1 + h_2 + h_3}{q\rho \alpha (60)} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3}$$

where $p$ and $q$ are parameters which convert the apparent resistivity into the relevant average resistivity $\rho_m$, i.e., when the two or the three layers are considered as a single layer of resistivity $\rho_m$. Clearly, these equalities can be made strictly valid by adjusting $p$ and $q$. They can be rewritten

$$\frac{p\rho \alpha (50)}{\rho_1, \rho_2} = \frac{h_1 + h_2}{p\rho_1 h_1 + p\rho_2 h_2}$$

and

$$\frac{q\rho \alpha (60)}{\rho_1, \rho_2, \rho_3} = \frac{h_1 + h_2 + h_3}{p\rho_1 h_1 + p\rho_2 h_2 + p\rho_3 h_3}$$

The ratio $p\rho \alpha (50)/q\rho \alpha (50)$ is given by

$$\frac{p\rho \alpha (50)}{q\rho \alpha (50)} = \frac{h_1 + h_2}{h_1 + h_2 + h_3} + \frac{h_3}{h_1 + h_2 + h_3}$$

Now assume that the layers are horizontal, i.e., $h_1$, $h_2$, and $h_3$, and are constant throughout the area. Further, assume that $\rho_3$ is a constant and also (for the time being) that $\rho_2$ is a constant. The ratio of the parameters $p$ and $q$ can be assumed to be independent of the variation of $p\rho \alpha (50)$ and $q\rho \alpha (50)$, i.e., of the depth penetration of the current. Hence the surface resistivity $\rho_1$ will be the only variable and the only factor affecting current penetration. Thus now for any point in the area

$$r = A + B \left[ \frac{\rho_1 \rho_2 (h_1 + h_2)}{\rho_2 h_1 + \rho_1 h_2} \right] \ldots (1)$$

where $r$ is the ratio $p\rho \alpha (50)/q\rho \alpha (60)$ and $A$ and $B$ are constants.

Now take the following values: $h_1 = 5$ ft., $h_2 = 25$ ft. $\rho_2 = 100$ meter-ohms, and make $\rho_1$ vary from 50 to 250 meter-ohms. On substituting these values in the factor in square brackets, the factor will be found to change by 30 per cent when $\rho_1$ is changed from 50 to 250 meter-ohms. This variation will be 55 per cent when $\rho_2 = 200$ meter-ohms, but only 15½ per cent when $\rho_2 = 50$ meter-ohms. If in addition $\rho_3 = 10$ meter-ohms and $h_3 = 20$ ft. in agreement with the well log, equation (1) reduces to

$$r = 0.6 q/p + 0.04 q/p G \ldots (2)$$
where \( G \) is the factor in square brackets in equation (1) and the ratio \( q/p \) is now assumed to be a variable. If \( q/p \) is plotted against \( r \) for several values of \( p_1 \) and in each case \( p_1 \) is made to vary from 50 to 250 meter-ohms, a family of straight lines shown in Figure 20 is obtained. These show that, with indicated variations in \( p_1 \) and \( p_0 \), if the ratio \( r \) varies from 1.3 to 3.5, \( q/p \) generally assumes values between 0.15 and 1.35, and most values of \( q/p \) are less than unity.

Now, if \( r \) is plotted against \( p_2 \) for several values of \( q/p \leq 1 \), a family of curves shown in Figure 21 is obtained. It is evident that one group of curves fits best the range of ratios obtained experimentally, viz. 1.3 — 3.5, and corresponds with \( p_2 \) varying from 50 meter-ohms to about 180 meter-ohms. This is the set of curves for which \( q/p = 0.5 \). It shows that, when \( p_1 \) varies from 100 to 250 meter-ohms, the ratio \( r \) varies approximately linearly with \( p_2 \). For smaller values of \( p_1 \), the departure from linearity increases and when \( p_1 = 20 \) meter-ohms (the dotted curve in Figure 21) the departure becomes large. Thus if the surface resistivity varies between the limits of 100 to 250 meter-ohms, the ratio \( r \) will roughly represent the variation in the resistivity of the intermediate layer. When the surface resistivities are known, the values of \( p_2 \) can be read off the master curves in Figure 21. In the present case this can be done for the traverses Nos. 2 and 8. However, it is to be noted that since \( q/p \) to a certain extent has been selected arbitrarily, the values of \( p_2 \) as given by the curves in Figure 21 may not be absolute and may be only proportional to the true values of \( p_0 \).

Clearly, the above method of interpretation is open to a number of criticisms. For instance \( q/p \) may vary and, as a corollary, various factors such as the attitudes of the beds, a constant \( p_0 \), etc., may not be true. Further, it must be borne in mind that an electrical interface need not necessarily coincide with a geological interface and also, if two distinct beds possess the same resistivities, the electrical interface ceases to exist. In spite of these uncertainties, if \( p_1 \) varies within the prescribed limits and the beds are approximately horizontal, the contours of equal ratio \( r \) should reflect approximately the variation in the resistivity of the intermediate layer, and the exact relative changes can be estimated by using the master curves.

REFERENCES


GEOPHYSICAL SURVEYS DISCOVER STILFONTEIN GOLD MINE IN SOUTH AFRICA

by Oscar Weiss*

Abstract

Stilfontein and surrounding areas gave negative results in all prospecting since about 1904 when Goerz and Company, a forerunner of Union Corporation Ltd., first drilled in the region and on the farm Stilfontein. Subsequent efforts by African and European Investment Company and Anglo American Corporation from 1934-37 were unsuccessful. Holes drilled by these companies on the farms Rietfontein, Hessie, and Palmietfontein were stopped in the Lower Witwatersrand system without finding payable reefs.

The results of gravimeter, ground magnetometer, and aerial magnetometer surveys are presented in the area in and around the new Stilfontein gold mine, in the Klerksdorp district, Transvaal, Union of South Africa. The gravimeter and ground magnetic surveys were completed in 1947-48. The gravity anomalies suggested a block of Upper Witwatersrand quartzites faulted-up between denser rocks of dolomite and Ventersdorp lava. Boreholes S.T.1, 2, and 3 were drilled in 1948 and, after penetrating the dolomite and the Ventersdorp lava, entered Upper Witwatersrand quartzites and intersected the Gold Estates Reef and the Vaal Reef. Subsequent drilling delineated the sub-outcrop of the Vaal Reef and determined the main structure of this horizon. The gold content of the Vaal Reef was highly payable and shaft sinking was undertaken. Stilfontein Gold Mining Company was formed to develop and operate the mine. The Vaal Reef pay zone extends further south from Stilfontein, the reef descending at increasing depths. It is probable that at least another mine may be established on these deeper levels.

THE farm Stilfontein 39 is in the Klerksdorp district of the Transvaal. This farm and the surrounding areas have been subjected to repeated programs of prospecting dating back to about 1904, when Goerz and Company, the forerunner of Union Corporation, Ltd., first drilled on the farm and in the surrounding areas. From 1934 to 37, numerous boreholes were drilled on the neighbouring farms, Rietfontein, Hessie, and Palmietfontein, by African and European Investment Company and Anglo American Corporation. All these efforts were unsuccessful, and nobody suspected any possible gold-bearing area on Stilfontein until about 1947, when a gravity traverse run by D. D. Maree on the main road, showed a negative gravity anomaly.

*Consulting Geophysicist.
During 1947-48, the writer's organization completed gravimeter and magnetic surveys on Stilfontein and Rietfontein. An area of negative gravity anomalies was mapped, and it was suggested that this could be caused by blocks of Upper Witwatersrand quartzites, of the average density of 2.65, faulted-up between dolomites and Venterdsorp lavas, the density of both of these rocks being 2.8.

Figure 1 shows the geology of the area as mapped by L. T. Nel of the Geological Survey of South Africa. The boreholes on Stilfontein, with the exception of a single hole of Good and Company were drilled after the completion of the geophysical survey. The grouping of the first boreholes S.T., 1, 2, 3, 4, 5, and 6, clearly shows that these were in the zone of negative gravity anomalies. Figure 2 shows the gravity anomaly contours.

Figure 3 shows two sections across the gravity anomaly, together with the corresponding geological sections as obtained from boreholes. The close relation between gravity values and thickness of dolomite plus Venterdsorp lavas is striking. The two latter formations having the same density (2.8), act as one mass as far as gravity effects are concerned.

Figure 4 shows the magnetic anomalies observed on the ground by vertical magnetometers and at 500 feet.
Figure 1. Geology of the area, after L.T. Nel, Geological Survey of South Africa.
Figure 3.
Geophysical survey, Stilfontein gold mine, sections AB and CD.

Figure 4.
Magnetic anomalies, ground and air observations.
ft. above mean ground level by aerial magnetometer. The latter are anomalies of the total magnetic intensity. The magnetic results show that, on the farm Rietfontein and on the north half of Stilfontein, Lower Witwatersrand magnetic shales were to be expected at relatively shallow depths. As the strongly magnetic shales of the lower Witwatersrand system are in the Hospital Hill series and in the Government Reef series, below any known gold-bearing zones, the existence of magnetic anomalies beneath the dolomite and the Venterdorp systems was an indication of the probable absence of pay horizons. At the same time the lack of magnetic anomalies in the south portion of Stilfontein suggested the absence of major upthrows of the Lower Witwatersrand magnetic shales.

The geological plan, (Figure 1), shows that the oldest formation of the area, the contorted beds near the base of the Witwatersrand system, outcrops in the northwest corner of the plan. Moving southeasterly from this corner, the Witwatersrand system is faulted-up repeatedly by strike faults as shown by the repetition of Government Reef shales and tillites, so that, in this direction, the outcrops do not show horizons higher than the Government Reef series in the Witwatersrand system. This system is overlain by Venterdorp lavas and sediments and by black reefs and dolomites of the Transvaal system. This dolomite covers the entire area of Stilfontein with the Venterdorp lava and the black reef outcropping in a small portion of the northwest corner of this farm.

Starting again from the northwest corner of the geological plan and moving southward, we again find faulted repetitions of the Government Reef series, but the Witwatersrand system builds up to the Jeppesfontein series and even higher in the extreme south corner of the plan, where the Elsburg series is outcropping. As the Main Reef horizon of the Rand property, near Johannesburg, is above the Jeppesfontein series, exploration drilling by Anglo American Corporation (1934 to 37) in this part of the plan, on the farm Palmietfontein, was intended to intersect the Main Reef horizon. Unfortunately, in spite of systematic drilling no pay reefs of any kind were found and all the holes were stopped in Lower Witwatersrand beds (LWW).

On the farm Rietfontein, all the NMB holes were drilled by African and European Investment Co.'s subsidiary (New Machavie Mine) and by Anglo American Corporation, from 1934 to 37; boreholes 1, 2, 3. In addition, Goerz A.1 hole was drilled about 1903. The purpose of all the NMB holes and of boreholes 1 and 2 was to find the extension of the old Buffelsdoorn mine, which worked rich conglomerate beds correlated with Government Reefs. None of this drilling was successful.

Boreholes Goerz A.1 and Anglo American Corporation's boreholes 3 and 4 (on farm Hessie) were spotted to find the Main Reef Horizon. These holes also were failures.

It seems that the system of up-throw faults continues to the southeast in the areas tested by these holes. It is interesting to note that the Stilfontein farm was completely ignored by the companies who sponsored the drilling programs.

The gravity anomaly plan shows that, starting from Venterdorp lava outcrops in the northwest corners of Stilfontein and Rietfontein, the gravity anomalies increase as the Venterdorp lava, black reef and dolomite are piling up, but the southeast half of Stilfontein is an exception. Here, after reaching the value of 14 milligals, the gravity anomaly decreases to a minimum of 11 milligals and rises again to 15 milligals in the extreme southeast corner of the farm. Thus there is a negative anomaly of about 3 to 4 milligals and the total thickness of the Venterdorp lava and dolomite is less in this zone of negative anomalies than in the surrounding areas. Furthermore, as the density of Lower Witwatersrand magnetic shales is also about 2.8, no negative gravity anomalies could occur if the lava and dolomite were underlain by such shales. It was concluded therefore that the negative gravity anomaly was caused either by Upper Witwatersrand quartzite (density 2.65) or by a granite mass (density 2.63). As the aim of the prospecting was to test by drilling Upper Witwatersrand horizons for reefs, the obvious sites for such tests were located in the minimum zone of the negative anomaly. The grouping of the holes S.T. 1, 2, 3, 4, 5, 6, 8, 9, and 14 in the negative anomaly area proves the practical following up of the above ideas. All these holes intersected Upper Witwatersrand beds. Boreholes S.T. 7 and S.T. 11 were outside the negative gravity anomaly, and went into Government Reef, i.e., into Lower Witwatersrand beds. It should be mentioned that the last figure of footage next to any borehole gives the depth at which the hole was stopped.

Table 1 gives the widths and gold values intersected on Stilfontein.
| Table 1

<table>
<thead>
<tr>
<th>BOREHOLE NO.</th>
<th>THICKNESS OF VAAL REEF</th>
<th>GOLD VALUE PER INCH</th>
<th>TOTAL VALUE IN-OZ-WTS</th>
<th>REMARKS</th>
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<tr>
<td>ST 1</td>
<td>6-75 INCHES</td>
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**CASE HISTORIES — SOUTH AFRICA**

The approximate contours of the Vaal Reef are shown in Figures 1, 2, and 3; and, as can be seen, the reef extends southwards, although at increasing depths. It is very likely that at least another gold mine will be established in due course in the area south of Stilfontein.

Assuming 30,000,000 to 40,000,000 tons of potential ore reserves, we can expect a mine with the capacity of about 100,000 tons of ore per month and with a lifetime of about 30 to 35 years. The average grade, as a sheer guess, may be of the order of about 6 to 8 pennyweights per ton. Average cost per ton, allowing for the increasing costs of present times, should be about 3 pennyweight per ton, i.e., about 35 shillings per ton. Thus an average profit of 3 to 5 pennyweights, i.e., 36 to 60 shillings, per ton may be expected.

**Acknowledgment**

The writer wishes to thank Jack Scott and Union Corporation Limited for permission to publish the technical data of this paper.
A GEOPHYSICAL INVESTIGATION OF AURIFEROUS REEFS IN SOUTHERN TANGANYIKA*

by Anthony J. King**

Abstract

Electrical resistivity and magnetic methods were used to locate extensions of the gold-bearing Galena Reefs, in the Lupa Goldfield of south Tanganyika. These quartz reefs, or veins, occupy shears about 20 ft. wide in Archaean granitic gneiss, and were expected to yield high resistivity and low magnetic values. These characteristics were employed in an effort to trace the suspected extensions of the reefs to the south of an intersecting dolerite dike, and the results showed that the reefs lie probably a little east of their previously suspected position. Extraneous factors, namely, depth of soil cover, thickness of decomposed rock, and position of water-table, were found to influence the resistivity readings, and had to be taken into consideration when interpreting the results.

In the centre of the Lupa Goldfield in south Tanganyika is a small property known as Galena Reefs, the name arising from the fact that this is one of the few occurrences where galena is found in significant, although uneconomic, quantities. The reefs were originally worked during the “boom” days of the Lupa before World War II; they have been abandoned for about 12 years but recently have come under the control of one of the few remaining European operators on the field.

General Geological Setting

The reefs form the core of a low ridge running roughly north and south for about 2,500 ft. and terminating in the south in a flat stretch on the north bank of Itele River. The quartz reefs occupy shears, about 20 ft. wide, in granitic gneiss of Archaean age, and dip at about 35° to the west. They carry pyrite and chalcopyrite besides galena. Gold is said to run about 0.25 ounce a ton but very few records are available.

The property is divided by a nearly vertical dyke (either dolerite or meta-basalt), striking slightly north of east, which was proved underground but which has no visible outcrop. Movement along the line of this dyke is reputed to have displaced the reefs vertically by 20 ft.

North of the dyke, two reefs are known to extend for about 500 ft., swinging in a slight arc to the northeast. Previous development had suggested that only one reef occurs south of the dyke, but in a cross-cut from the foot of a new shaft (see plan) a reef was encountered which does not lie in the line of the known reef.

It will be seen that the sections shown in Figure 1 are both inaccurate and incomplete insofar as the locations and the depths of the shafts are concerned. They
were taken from the last available mine plan and as the shafts are now closed there is no means of correcting their depth or of obtaining a more accurate section of the reef.

Most of the property has been extensively worked over for open cast and dry-blowing operations and the disturbed nature of the ground hampers both geological and geophysical investigation.

**Purpose of the Geophysical Investigation**

The broken nature of the terrain made it necessary to confine the geophysical survey to the south part of the property, and even here difficulty was experienced in selecting stations. A trench, shown on the plan, had been dug to locate the outcrop of the south extension of the reef or reefs but failed to do so. The geophysical work was designed to determine whether
Figure 1. South extension of Galena Reefs.
GALENA REEFS
GEOPHYSICAL PROFILE YY
HORIZONTAL SCALE 1:1,000

(a) Apparent Resistivity at θ=40°

(b) Apparent Resistivity at θ=20°

(c) Differential Apparent Resistivity

(d) Vertical Magnetic Field

Figure 2. Geophysical extension YY', GALENA Reefs.
the reefs do continue southward and, if so, why the trench had failed to show them.

Methods

The electrical resistivity method, supported by a magnetometric survey, was employed. Silicified shears were expected to possess a higher resistivity and a lower magnetic susceptibility than the surrounding gneiss; on the other hand, a shear zone which was not well silicified would tend to act as a saturation channel for ground water and present a low resistivity. Naturally, the geophysical results cannot indicate whether the silicified shears, if present, are actually aniferous.

Measurements of apparent resistivity at two constant electrode separations were made along three parallel traverses using the Geophysical Megger Earth Tester. The two sets of observations were made in one operation by using the Wenner configuration of electrodes (spread along the line of the traverses) for the shallower current penetration (about 20 ft), together with a third power electrode trailing the Wenner spread so as to give effective penetration of the current to about 40 ft, when power was applied to the ground through this and the leading electrode.

The electrical and magnetic profiles obtained on traverse YY and which are typical are shown in Figure 2. The anomalies arising from the inferred reefs and the approach of bedrock to the surface are indicated by vertical correlation lines.

The object of this double-depth method is to reduce the surface effects, and the difference between the two observations of differential apparent resistivities gives, in qualitative terms, the effect of material in the vicinity of the leading power electrode.

One depth-probe, the position of which was dictated by terrain, was performed to obtain an estimate of the vertical distribution of resistivities and, if possible, to locate the reef in depth.

The magnetometric survey was made over the same traverses, using the Watts Vertical Force Variometer.

Interpretation and Results

The geophysical observations are influenced by the following factors in addition to the effects sought: i) depth of soil cover, ii) thickness of decomposed rock, and iii) position of the water-table.

The effect of the first factor is minimized by the use of the double-depth technique. Decomposition of the bedrock is accompanied by decreases in resistivity and susceptibility and thus the depth to bedrock is inversely proportional to both the apparent resistivity and the magnetic field. The third factor proved the most troublesome; it is essential that the whole of a resistivity survey be carried out under as uniform ground-water conditions as possible. During this work repeated torrential overnight rain necessitated the repetition of much of the operation.

The depth-probe results were analysed theoretically and found to agree closely with the model geoelectrical curve given by the following sequence:

<table>
<thead>
<tr>
<th>Depth (feet)</th>
<th>Resistivity (metre-ohms)</th>
<th>Geological Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1.6</td>
<td>220</td>
<td>Soil</td>
</tr>
<tr>
<td>1.6 - 13.2</td>
<td>50</td>
<td>Decomposed gneiss</td>
</tr>
<tr>
<td>13.2 - 140</td>
<td>2200</td>
<td>Gneiss</td>
</tr>
<tr>
<td>c.40 - c.50</td>
<td>2200</td>
<td>Silicified shear zone</td>
</tr>
<tr>
<td>c.50 + 60</td>
<td>2200</td>
<td>Gneiss</td>
</tr>
</tbody>
</table>

This interpretation is illustrated in Figure 3 where it will be seen that the enveloping trial curves give good agreement as far as "a" = 40 ft. Below that depth there is a significant departure which is assumed to be due to the silicified zone shown in the right-hand section.

The interpretation of the resistivity and magnetic profiles evolved into a search for points where small resistivity "highs" coincide with magnetic "lows". A profile of the bedrock surface was also constructed from variations in the same sense in the resistivity and magnetic field.

This interpretation results in the identification of a number of "geophysical indications" which, it is thought, may be due to silicified shears. These indications are neither exhaustive nor unambiguous but constitute a guide for further prospecting. They are shown on the plan and can be summarized as follows:

<table>
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<tr>
<th>Indication</th>
<th>Resistivity</th>
<th>Magnetic Field</th>
<th>Classification</th>
</tr>
</thead>
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<tr>
<td>Qx</td>
<td>Slight</td>
<td>Marked</td>
<td>Tentative</td>
</tr>
<tr>
<td>Px</td>
<td>Marked</td>
<td>Slight</td>
<td>Tentative</td>
</tr>
<tr>
<td>Qy</td>
<td>Marked</td>
<td>Marked</td>
<td>Strong</td>
</tr>
<tr>
<td>Py</td>
<td>Marked</td>
<td>Fair</td>
<td>Fairly strong</td>
</tr>
<tr>
<td>Sz</td>
<td>Marked</td>
<td>Fair</td>
<td>Tentative</td>
</tr>
<tr>
<td>Rz</td>
<td>Slight</td>
<td>Slight</td>
<td>Very tentative</td>
</tr>
<tr>
<td>Qz</td>
<td>Marked</td>
<td>Marked</td>
<td>Strong</td>
</tr>
</tbody>
</table>
The correlation between Ox, Oy and Oz is made on the basis of general collinearity and it should be noted that two of these indications are classified as "strong". Furthermore, if Oy be identified with the silicified zone located in the depth-probe, a value for the apparent dip (33°) is obtained which agrees well with the known dip of the reefs further north.

**Summary**

As a result of this investigation, fairly conclusive evidence was obtained for assuming the extension of the reefs southward from their known position, and probably swinging towards the southeast, thus explaining the failure of the trench to discover their outcrops.

The survey also demonstrated the limitations imposed on geophysical work by extraneous factors, in this case terrain and rainfall. The necessity is demonstrated for eliminating or identifying the effects of geological phenomena other than those sought (here, soil cover and decomposed rock), thus emphasizing that successful geophysical work is not possible without due reference to geological evidence.

At the time of writing, no further prospecting had been undertaken to confirm the geophysical results.
Case Histories

8—Uganda

EXPLORATORY GEOCHEMICAL SOIL SURVEY AT RUHIZA FERBERITE MINE, UGANDA

by R. H. C. Holman* and John S. Webb**

Abstract

Tungsten mineralization, from mesothermal to pegmatitic in type, exists in metamorphosed Precambrian sediments of the Kigezi District, Uganda, East Africa. At the Ruhiza mine, the orebody consists of ferberite in a ramifying mass of narrow quartz veins and stringers, which follow a steeply dipping shear zone in graphitic and sandy phyllites.

Samples of the residual soils obscuring the bedrock were tested for tungsten with a stannous-chloride-dithiol technique. Regional background concentrations of tungsten in soils overlying non-mineralized sedimentary rocks varied between 4 and 6 ppm, increasing to between 6 and 12 ppm near the Ruhiza deposit. Over the orebody, concentrations were erratic and rose to between 20 and 40 ppm, occasionally reaching 100 ppm.

GEOCHEMICAL investigations in Africa undertaken by the Geochemical Prospecting Research Centre, Imperial College, have included a brief exploratory examination of geochemical soil sampling methods in areas of tungsten mineralization in Uganda. The work described in this paper was done at Ruhiza in 1954 at the invitation of the Geological Survey of Uganda.

Location and Physical Features

Ruhiza tungsten mine is in the Kigezi district of southwest Uganda (Figure 1). Most Kigezi consists of an old plateau with a general elevation of 7,200 to 8,000 ft. The plateau is deeply dissected by steep-sided parallel valleys, the difference in elevation between hill crests and valley bottoms being about 1,500 ft.

The climate is typical of tropical highlands. Temperatures vary between 50 and 75°F, and the rain,

**Professor, Dept. of Geology, Imperial College of Science and Technology, London.
which falls mostly during thunderstorms, averages between 30 and 45 inches a year.

The steep hill slopes around Ruhiza are densely forested except where they have been cleared for native agriculture.

- **Geology**

  Lightly metamorphosed sediments of the Karagwe-Ankolean System (Precambrian) are widespread in the Kigezi district, but granites are exposed occasionally in the floors of large areas encircled by walls of steeply dipping sediments. Tungsten mineralization showing characteristics varying from mesothermal to pegmatitic is present in the sediments at a number of localities. In places the deposits are related spatially to nearby granites.

  At Ruhiza granite has not been found and the rocks exposed are entirely Karagwe-Ankolean mudstones and phyllites, with occasional arenaceous bands. The sediments dip steeply at the mine and have been contorted from the regional north-northwest strike into an east-west flexure. Faulting and shearing accompanied the folding, and the incompetent beds have been dragged.

- **Mineralization**

  The mineralized zone is very irregular and consists mainly of a ramifying mass of narrow quartz veins containing pockets of reinite and ferberite. These veins follow the general direction of a steeply dipping east-west shear zone in graphitic and sandy phyllites. Nodular ferberite without quartz occurs also along bedding planes in the more arenaceous horizons. The mineralized zone has a known strike length of about 1,000 ft., a width of about 300 ft., and a proved vertical extent of at least 500 ft. The grade of the deposit taken over the full width of the zone averages about 0.02 per cent WO₃. Across mineralized shears and veins within the zone the grade rises to 0.2 per cent WO₃ (Pargeter, personal communication).

- **Soil Cover**

  The residual soil cover is continuous, even on the steep slopes around Ruhiza mine. Soil thicknesses vary with the site and may reach 6 ft., or more, in local depressions or at the foot of slopes. Zones within the soil are poorly developed, except for a dark organic-rich surface layer about 12 inches thick. Most profiles consist of a red-brown lateritic loam showing only a gradual transition into the underlying weathered bedrock. Local terracing, probably due to slip, is fairly common.

- **Sample Collection**

  Soil samples weighing about 100 grams were collected from a depth of 18 inches below the surface along traverses over the ore-bearing zone. At a number of selected points in both background and anomalous areas soil profiles were sampled in detail from the surface down to bedrock.

- **Sample Preparation**

  The samples were oven-dried, screened, and the minus 80-mesh fraction used for analysis.

- **Analysis**

  The tungsten content of the sieved soils was determined by a method described by North.*

  In outline, the procedure involves the following steps:

  1. Fusing the sample with a sodium carbonate sodium chloride potassium nitrate flux;
  2. Leaching the fused mass with water and taking an aliquot part.
  3. Strongly acidifying, adding stannous chloride solution, and warming in a boiling water bath to reduce the tungsten;
  4. Adding a solution of dithiol in amyl acetate and shaking it with the aqueous phase. Heating is continued until the ester is almost completely removed by hydrolysis and evaporation. The green tungsten dithiol complex formed in the organic phase is thus concentrated into a small floating globule.
  5. Adding a small volume of kerosene to dissolve the tungsten complex;
  6. Comparing the green colour of the kerosene layer with standards prepared in a similar manner from solutions containing known amounts of tungsten.

  Using a 0.25-g. sample, the method is sensitive to 1 ppm. tungsten. The reproducibility is approximately ± 30 per cent. One operator can complete thirty determinations, including the preparation of the samples, in an 8-hour day.


A similar test using the same reagent, dithiol, has been described by P. G. Jeffery, in Records of the Geophysical Survey of Uganda for 1953. The field method described by P. N. Ward in U.S. Geological Survey Circ. 119, 1951, uses a thiocyanate-stannous chloride reaction.
Figure 2. Tungsten in soils, Ruhito ferberite mine, Uganda.
• Results

The usual low tungsten content or “regional background” for Karagwe-Ankolean sedimentary rocks and derived soils occurring in southwest Uganda was found to lie between 4 and 6 ppm. Pargeter and Jeffery† found similar concentrations, but noted higher values up to 420 ppm in black phyllites. High values of that order were not recorded in the limited number of samples collected during the present study, except over granite where the soils may contain up to 25 ppm. tungsten.

In the Ruhiza mine area, near ferberite mineralization, a slight rise in the tungsten background concentration in the soils was detected, and here the “local background” values commonly vary between 6 and 12 ppm. Similar, though slightly higher, values were noted for non-mineralized sedimentary rocks in the vicinity of mineralization. The extent of the area of high local background values was not determined, but the zone must be more than half a mile wide.

Anomalous concentrations of tungsten, i.e., greater than 12 ppm, were found in the near-surface soil within a broad band along the strike of the mineralization to the east (Figure 2). A weak anomaly rising to only 20 ppm. also was detected farther along the strike to the west.

†Personal communication.

Anomalous values within the stippled area shown in Figure 2 rise occasionally to 100 ppm., but the general level of the anomaly is 20 to 40 ppm. The values are very erratic both in lateral distribution and also vertically within the soil profile where, however, minimum contents were noted in the organic-rich surface soil. A similar erratic distribution of tungsten in the bedrock is shown by results obtained on chip channel samples taken underground near a small quartz-ferberite vein (Table 1).

In the absence of detailed knowledge of the distribution of tungsten in the bedrock immediately underlying soil-sampling traverses east of the known mineralization, it is difficult to draw a direct comparison between the tungsten contents of the soils and the rocks. However, speaking generally, peak values in the soils are much lower than those detected in the rocks. It is not clear to what extent this diminution of tungsten in the soils is due to mechanical dilution by barren material or to leaching. It is equally difficult to decide to what extent the hilly topography has caused the migration of metal downslope. From the results obtained by close sampling across an anomaly lying on a 15-degree slope (Figure 3), topography appears to have relatively little effect on the width of the anomaly in this particular instance.

![Figure 3. Localized tungsten anomaly in soils on a steep slope, Ruhiza, Uganda.](image-url)
Tentatively, however, it appears probable that under the local conditions tungsten is subject to a degree of leaching and removal in a relatively stable aqueous solution during weathering and soil formation. This inferred mobility of tungsten has not been tested yet and needs confirmation before the possible value of drainage (sediment and/or water) sampling as a geochemical reconnaissance for tungsten deposits in this area can be assessed.

Conclusions

1. An exploratory study in tropical highland terrain in Uganda has shown that anomalous amounts of tungsten exist in residual soils overlying a shear zone in phyllite carrying low-grade ferberite mineralization. Furthermore, the local background concentration in the vicinity of the mineralization is about twice as great as the regional background content of tungsten in similar soils from areas far removed from mineralization.

2. Over mineralization, the anomalous tungsten values in soils are distributed erratically, both laterally and in depth. Nevertheless, samples collected at 18 inches below surface (i.e., below the organic-rich layer) at intervals of 50 ft. along traverses spaced 400 ft. apart, would be adequate to detect an anomaly related to mineralization of the type considered. Closer sampling would be necessary to locate individual veins within the mineralized zone.

3. The relatively low intensity of the anomalies (20 to 40 ppm., excluding peak values, compared to the local background of < 12 ppm.) demand an analytical accuracy better than ± 40 per cent in the range 5 to 40 ppm. and a sensitivity of 1 ppm. This is achieved by the dithiol field method, which allows thirty samples to be treated by a trained non-technical operator in an 8-hour day.

4. Further work is necessary before a full assessment can be made, but the present study strongly supports the view that geochemical soil surveys can provide a useful additional source of information in the search for tungsten deposits concealed beneath deep residual soil cover in tropical terrain.

Acknowledgments

The writers are deeply indebted to A. Cawley, Director of the Uganda Geological Survey, Messrs. Pargetter, Jeffery, Seal, and to other members of the Survey staff for their help and co-operation in the field. Invaluable assistance was received also from T. Spyropoulos, owner and manager of the Ruhiza Mine. Assistance from Miss N. J. Crundwell and J. A. Gee, members of the Imperial College technical staff, is gratefully acknowledged.
### CROSS-REFERENCE BY METHODS

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<td>Titaniferous Magnetite</td>
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Figure 2. Geology and geomagnetic contours, Rye Park scheelite deposit. (See page 110.)
MUNRO MINE AND VICINITY
Magnetic and Geological Map
MUNRO and BEATTY TOWNSHIPS, ONTARIO

Figure 9. The Munro-Beatty 4th. (See page 131).
MAGNETOMETRIC PLAN
RIVIERE PORTNEUF CLAIMS
CHICOUTIMI COUNTY, QUEBEC
LM ML HGP
TO ACCOMPANY REPORT BY LOUIS MOYD
AUGUST 1953

SCALE

0 100 200 300 FEET

LEGEND
READINGS TAKEN WITH TRIPCO MOUNTED XBE DIP-NEEDLE AT INTERVALS OF 25 OR 50 FEET ON ALL LINES. EACH DEGREE = APPROXIMATELY 100 GAMMAS.

Figure 5. (See page 164.)
MAGNETOMETRIC DETERMINATIONS ON DIAMOND-BRILL CORES

Maximum and minimum readings in diagram were taken during rotation of specimens in a jig under an airborne magnetometer.

Temporary or in-situ magnetism taken as max - (2/3 max - min).

Remnant magnetism taken as max - min.

The ratio of remnant to temporary magnetism should give a rough indication of the ratio of siltstone to magnetite.

Data were projected upward, on dip, to approximate top of bedrock.

All specimens were obtained from DDH PR-1.

SURFACE TRAVERSES

ASARCO magnetometer

DDH PR-2

DDH PR-1

TRUE WIDTH: 130'

T.O.C. CONTENT: 6.1%

KEY

SAMPLE T.O.C. LENGTH

ZONE A

T.W. = 55'

T.O.C. = 3.4%

T.G. = 7.0%

ZONE B

T.W. = 55'

T.O.C. = 3.4%

T.G. = 7.0%

SECTION PR-1 AND PR-2

RIVIERE PORTNEUF CLAIMS

CHICOUTIMI COUNTY, QUEBEC

LM WBA ML HGP
Figure 7. Comparison of the details of the airborne and the ground magnetometer surveys at the west end of the Bourlamaque batholith. The airborne survey fails to outline the three smaller intrusions. (See page 182.)
Figure 2. Plan of residual gravity over the lead-zinc deposit. (See page 27).
Note: Self-potential values are in millivolts.

Figure 3. Self-potential survey of the lead-zinc deposit. (See page 271.)