A REVIEW OF THE USE OF GEOPHYSICS IN BASE- AND PRECIOUS-METAL EXPLORATION

by

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INTRODUCTION

The object of geophysical surveys in mineral exploration has traditionally been to detect subsurface geological features, which may reflect the presence of mineralization in depth and, if possible, to measure the dimensions of the causative body. Geophysical methods may also be used to locate extensions to known mineralization and for determining the size, depth and internal characteristics of an ore-body. Marked improvements in geological concepts of ore genesis have led to a better appreciation, amongst geologists, of mineralized environments, and this has had an effect on the use of geophysics in recent years. Geophysical surveys are being increasingly used as an aid in environmental reconstructions and the results of regional surveys may be used to provide an indirect guide to ore. One of the main applications of geophysics lies in areas where the orebodies and associated structures are not exposed, as most geophysical measurements are more expensive than surface geological or geochemical surveys.

The detection of buried mineralization by geophysical means is dependent on the development of a distinctive physical characteristic which differentiates the ore deposit from the surrounding host rocks. Methods based upon variations in the magnetic properties of rocks were developed for determining the location of magnetic ore deposits in the latter half of the nineteenth century. Since this time the magnetic method has been considerably refined and the extreme sensitivity of modern magnetometers enable subtle variations in magnetic susceptibility to be recorded, thus facilitating lithological and structural mapping. The natural gravitational attraction that exists between different masses in the earth's crust produces local changes in gravity which are detectable using gravimetric survey methods. Variations in the natural and artificially induced electrical potentials in the ground, in electrical conductivities and resistivities, rates of decay of electrical potentials and radioactivity, all provide geophysical information which may be used to assess structure and lithological characteristics. These data may be of direct or indirect value in locating mineralization.

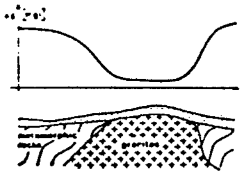
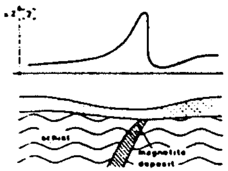
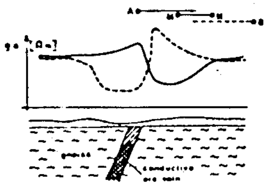
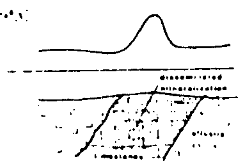
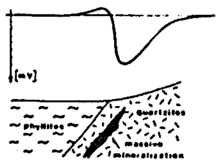
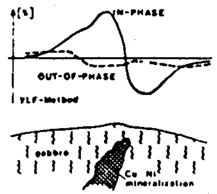
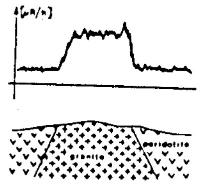
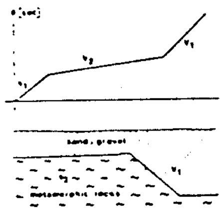
The most important geophysical methods that are employed in base-and precious-metal exploration include gravity, magnetics, self potential, and radiometric methods which are natural-field techniques.

Applied field surveys include induced polarization, resistivity, electro-magnetic and seismic methods. The characteristic features of these geophysical methods are summarized in Table I. All the geophysical survey methods were originally designed for operation on the earth's surface but more recent advances have facilitated the development of modified systems which can be used in surveys in the air, at sea, underground and down boreholes. This review focuses attention on the use of ground and airborne geophysical survey methods while the use of modified systems in borehole logging and exploration are considered beyond the scope of the dissertation.

Airborne surveys using magnetic, electromagnetic, radiometric and other devices, are the most rapid and commonly the most cost-effective means of covering large areas. The major cost component in conducting airborne surveys is the hire of the aircraft and it is therefore highly desirable to utilize integrated geophysical surveys wherever possible. Magnetic surveys are normally flown routinely in conjunction with electromagnetic and radiometric surveys and multi-channel digital recording systems are becoming increasingly popular. The comparatively low unit cost associated with airborne geophysical surveys has resulted in their widespread use in reconnaissance surveys, particularly in regions where accessibility on the ground is difficult. Although numerous anomalies are inevitably generated by regional airborne surveys, the characteristics and distribution of these anomalies can be used to locate priority areas which can be investigated using more detailed geological, geochemical or geophysical surveys.

In designing a geophysical survey it is desirable to develop a sound geological model because the results of geophysical investigation will ultimately have to be interpreted in terms of subsurface geology. In many instances the anomalous response of an orebody may be significantly lower than the strongest anomalies generated in the survey area. In order to effectively screen the geophysical anomalies, it is therefore imperative that the geoscientist should be thoroughly familiar with both the geology of the area and the geophysical properties of the rocks in the region. The most effective use of geophysics in mineral exploration necessitates the translation of a conceptual geological model into physical values at the outset of a geophysical programme as this will dictate the choice of the most suitable

TABLE 1 Summary of the main Geophysical methods. From Kuzvart and Bohmer, 1978

Method	Parameter, characteristic physical property	Main causes of anomalies	Applications: direct investigation	Applications: indirect investigation
GRAVITY ground, marine 	gravity, milligal (1 gal = 1 cm/s^2), density	deposits of heavy ores, differences in the distribution of densities	iron ore, chromite, pyrite, chalcopyrite	geological structural mapping, placer configuration
MAGNETIC ground, airborne, marine, logging 	earth magnetic field: total intensity, vertical gradient, $1\gamma = 10^{-5}$ gauss, magnetic susceptibility	magnetic content of the material, contrast of magnetization	magnetite, pyrrhotite, titano-magnetite	iron ore, chromite, copper ore, kimberlites, geological structural mapping
RESISTIVITY ground, marine, logging 	apparent resistivity, Ωm, resistivity, conductivity	conductive vein, ore body, sedimentary layer, resistive layer, limestone, volcanic intrusion, shear zone, fault, weathering	massive sulphides, quartz, calcite, special clays, rock salt	detailed tectonics, base metals, phosphates, uranium, potash, coal
INDUCED POLARIZATION ground, logging 	time domain, chargeability, ms, polarizability, %, frequency domain, frequency effect, %, metal factor, ionic-electronic, over voltage	conductive mineralization, disseminated or massive	conductive sulphides, oxides	associated minerals, zinc, tin, gold, silver
SELF-POTENTIAL ground, logging 	natural potential field, mV, conductivity, oxidability	massive conductive ores, graphite, filtration	sulphides pyrite, pyrrhotite, chalcopyrite, galena, pentlandite	associated minerals, tin, cobalt, gold, silver
ELECTROMAGNETIC ground, airborne, marine, logging 	electromagnetic field induced by energizing coil or wire, natural electromagnetic field, standard VLF transmissions, pulse EM field, electrical conductivity	conductive mineralization, surficial conductors, shear zones	conductive sulphides, oxides, graphite, magnetite	ground follow-up, associated minerals, shear zones, weathered zones, kimberlites
RADIOACTIVITY ground, airborne, logging 	gamma radiations, μ Roentgen, radioactivity	radioactive elements uranium, thorium, potassium	radioactive minerals, coal, phosphates, monazite	ground follow-up, geological structural mapping, differentiation in granites
SEISMIC ground 	refraction, reflection, travelling time of elastic waves, m/s, elastic wave velocity, dynamic modulus	contrast of velocity, marker at variable depth, fissured rocks	buried channels, faults, general tectonics, sand, gravel deposits, heavy minerals	tin, heavy minerals placers, coal, uranium

geophysical method. On completing the survey the results must be translated back into the geological model. The reliability of the geological picture which ultimately develops will be in large part dependent on the geologist's ability to interpret the geophysical data in terms of the local geology.

The choice of a geophysical method will depend on the characteristics of the mineral sought, including the deposits anticipated size, shape and depth extent. The nature of the host rocks and the immediate ore environment are other important considerations, together with the depth and degree of weathering. The magnitude and nature of the physical contrast between an orebody and its host rock, considered in conjunction with the resolution powers and limitations of the geophysical methods available, are equally important factors. Many ore deposits may contrast in a number of their physical properties, as for example massive nickel sulfide deposits, which are normally characterized by high magnetic susceptibilities, density contrasts, conductivities and resistivities; consequently they form good geophysical prospecting targets. In these instances the choice of the most suitable geophysical method will normally be, in large part, dictated by the most economical survey method applicable. As ore search progressively aims at locating deposits at ever increasing depths the basic limitations of the various geophysical techniques becomes increasingly important.

The sensitivity of a geophysical survey is primarily dependent on the signal to noise ratio. The noise levels associated with different geophysical methods impose important limitations on the resolution powers of geophysical instruments. Many of the recent advances in instrumentation are designed to enhance the response from the buried source and dampen the effects of noise. Routine corrections are necessary in most gravity and magnetic surveys in order to correct for many effects which contribute to unacceptably high background noise levels. However in the electromagnetic, resistivity and induced polarization methods, natural electromagnetic noise levels often limit the application of these methods and necessitate the use of large generators and phase lock receivers. The various types of noise include geologic noise, instrumental noise, location and orientation errors as summarized in Table 2. Noise levels are an important consideration in geophysical exploration because the signal to noise ratio is the most important factor in limiting the depth penetration characteristics and sensitivity of the different methods.

Table 2

Method	Geologic noise	Topographic noise	Location and orientation errors
gravity	—local density inhomogeneities —regional gradients —bedrock relief	incomplete topographic correction due to lack of detailed knowledge of subsurface density distribution	elevation errors, latitude correction errors
magnetics	—local susceptibility inhomogeneities —regional gradients —bedrock relief —remanence inhomogeneities	topographic correction extremely difficult to make with any assurance due to irregular magnetization of irregular shapes	usually are insignificant except irregular terrain clearance in airborne surveys
resistivity	—local conductivity inhomogeneities —regional gradients —bedrock relief —buried contacts —broad shear zones —graphite horizons —masking effect of highly conductive or highly resistive overburden	topographic correction extremely difficult to make with any assurance due to irregular distribution of subsurface conductivities	usually are insignificant but see under induced polarization
electro-magnetics	—local conductivity inhomogeneities —faults, shears —graphite horizons —masking effect of highly conductive overburden	usually are insignificant in inductive methods but same as for resistivity with conductive methods	erroneous orientation of transmitting coil relative to receiving coil
induced polarization	—minor magnetite in country rock or overburden —graphite horizons —clay minerals in overburden or country rock —masking effect of highly conductive or highly resistive overburden	usually insignificant but all our theory assumes electrodes on flat earth. Gullies can and do give resistivity and induced polarization anomalies.	usually insignificant but all our theory assumes electrodes placed on flat earth. Must correct for irregular surface if theory to be strictly applicable.

TABLE 2 Summary of factors that adversely effect the sensitivity of the main geophysical survey methods.
From Ward and Rodgers, 1967.

The limitation in detecting bodies in depth is due to the decrease of the anomaly strength with depth, coupled with the increasing effects of noise, which tend to increase with electrode separation and with the area of the anomaly. In general, with certain exceptions, airborne electromagnetic and ground methods are limited to approximately 150m of penetration, induced polarization methods and resistivity methods to about twice the minimum dimension of the body sought or half the potential electrode separation, gravity methods to about 100 metres for most massive sulfide bodies and magnetic methods about five times the minimum dimension of the responsive body.

Applied geophysics is a relatively new science which is rapidly evolving, so much so that it is difficult to acquire information relating to the potential value, efficiency and limitations of the latest geophysical equipment. Field techniques, instrumentation and data interpretation are also undergoing rapid developments, largely due to the tremendous advances that have been made in electronics over the past decade. The continued expansion in demand for metals should provide the necessary impetus for the development of many new geophysical techniques of ever increasing sensitivity for the detection and mapping of buried ore deposits and structures. Technological advances over recent years have also greatly enhanced the interpretation of geophysical data. Interpretation normally involves making certain assumptions concerning the form, position and physical property difference of the causative body and this function has been greatly enhanced by the widespread application of the digital computer.

The following chapters will provide the reader with a geologically orientated review of the most important geophysical methods currently available for use in base and precious metal exploration. Emphasis has been placed on the application of the geophysical techniques in different geological environments and extensive reference has been made to case history studies wherever possible. The topic is relatively broad and the use of geophysics in certain geological environments has been superficially covered in many instances. Reference to relevant papers has been made whenever possible in order to provide more details about geophysical applications in specific regions. In a review of this nature, it is difficult to avoid presenting an unbiased account of the role of geophysics in mineral exploration. The final chapter discusses the role of geophysics in mineral exploration, with the emphasis on the use of geophysical surveys in integrated exploration programmes. Indeed, much of the criticism that has been levelled at geophysics by the geological fraternity, stems from the use of geophysical methods in poorly conceived exploration programmes. Most geophysical survey methods are expensive in comparison with equivalent geological and geochemical surveys. As such, it is desirable for the explorationist to have a good idea of the use, potential value and probable results of a geophysical survey before initiating such an investigation. The purpose of this review is to provide the exploration geologist with a better insight into the use of geophysics in the exploration and evaluation of base and precious metal deposits.

THE GRAVITY METHOD

The gravity method of geophysical exploration measures directly the gravitational forces that exist at the surface without application of an artificial field. This local source method detects and measures lateral variations in the earth's gravitational field. The application of gravity surveys in mineral exploration is dependent on the existence of a density contrast between a mineral deposit and its surroundings. The density variations encountered in the earth's crust, cause diagnostic anomalies in the earth's gravitational field that are detectable by extremely sensitive gravimeters. In order to obtain the required precision, numerous corrections must be made to gravity readings and this makes the method relatively expensive. This fact has tended to restrict the use of gravity in mineral exploration and most surveys are usually designed to solve specific problems which cannot be resolved through the application of other cheaper geological or geophysical techniques.

Gravity methods used in mineral exploration can be broadly subdivided into regional and local surveys. Regional surveys are commonly undertaken by the Geological Survey Departments of most countries. The results of regional surveys usually bring out the major structural and lithological variations in an area and this information may be of direct metallogenic significance. More detailed regional surveys are used extensively in petroleum exploration to map sedimentary basins and structures within these basins. The use of the gravity method in sedimentary basin mapping has been successfully applied in coal exploration and in the search for sedimentary gold-uranium deposits in the Witwatersrand and Pongola basins of South Africa. The method has not been utilized extensively in base metal exploration, but the technique could find future application in the exploration for sedimentary copper-uranium and carbonate hosted lead-zinc deposits.

The use of gravity methods in mining geophysics is generally of a local nature and its application is largely confined to the immediate orebody environment. Gravimetric prospecting can be applied directly in the delineation of heavy ores, and it is particularly valuable in prospecting for many iron, manganese and chromite ores which cannot be detected by other geophysical methods. In many parts of the world gravity data provide the best means of differentiating between graphite and massive sulfides and it is used routinely to follow up electromagnetic and induced polarization anomalies in suitable environments. The information obtained from detailed gravity surveys over an orebody can be used to make preliminary estimates of the total tonnage of the deposit. The results of a detailed survey of this nature can also be used to locate the centre of gravity of the causative mass, knowledge of which is potentially valuable in designing a suitable delineation drilling programme and during subsequent mine development.

Numerous problems have been encountered in the practical application of gravity surveys in the field. The main factors that limit the use of gravity surveying in mineral exploration include :

1. The demands for high sensitivity which impose important economic constraints on the use of gravity methods.

2. The accuracy of the gravity result is adversely effected by topography and this limits the use of gravity methods in mountainous terrain.

3. Gravity surveys are particularly sensitive to variations in overburden thickness and even modest 2-3 metre changes are sufficient to produce anomalies of 0.10 - 0.15m gals. In the majority of detailed surveys, it is therefore necessary to measure the depth of overburden by conducting small-scale seismic refraction or surface resistivity surveys.

4. The gravity method should not be used in regions where deep sulfide weathering is anticipated. Sulfide weathering is commonly accompanied by a density decrease and the results of gravity surveys may therefore be ambiguous and inconclusive.

5. The effectiveness of gravimetric surveys in detecting an orebody is proportional to the density contrast between the ore and its host rock, and the depth of burial. The magnitude of an anomaly decreases rapidly with increasing depth and gravity surveys are not normally very effective when the orebody lies at depths greater than 100m. This figure may be extended when dealing with exceptionally large deposits.

6. The complex nature of gravity surveying makes interpretation difficult and this constitutes a very serious problem. Strong gravity anomalies may also be produced by faults, anticlines, synclines, dikes, folds, overburden and other geological features and the sifting of significant from non-significant gravity anomalies can be exceedingly difficult. As with most geophysical techniques the interpretation of gravity data relies heavily on sound geological input without which considerable ambiguity may exist in the geophysical interpretation. A relatively detailed geological map should therefore be available to facilitate interpretation of the gravity data in most situations.

The use of regional gravity surveys is of limited value in mineral exploration, but these surveys may be utilized to locate major structural trends that may be of direct metallogenic significance. Regional surveys provide fundamental information about the nature, structure and composition of the earth's crusts and the junctions between major lithospheric plates are commonly discernable. A number of major metallogenic provinces are spatially related to major gravity trends. In South Africa the Kalahari Manganese and Sishen-Postmasburg iron ore fields are closely associated with a prominent gravity high that trends northwards into Botswana. In Canada, the structural boundaries between the Superior, Churchill and Grenville provinces are defined by major gravity features which are broadly coincident with the two major copper-nickel producing areas of Canada, namely Sudbury and the Thompson nickel belt.

The nature of the gravity field in the region of the Thompson nickel belt is illustrated in Fig. 1. The boundary between the Churchill and Superior province is marked by a strong gravity low that is bounded to the southeast by the Nelson River gravity high. The gravity high is developed over dense granulites of the Superior province and the adjacent gravity lows are associated with a number of granitoid bodies. The nickel sulfide deposits in the Thompson-Wabowden areas are hosted by peridotites that are associated with a number of alkaline intrusive rocks. The distribution of the basic bodies is confined to the regions outlined by the elongate gravity low. Wilson and Brisbin (1961) have noted that the copper-nickel ores of the Thompson Belt lie scattered along the axis of the regional gravity

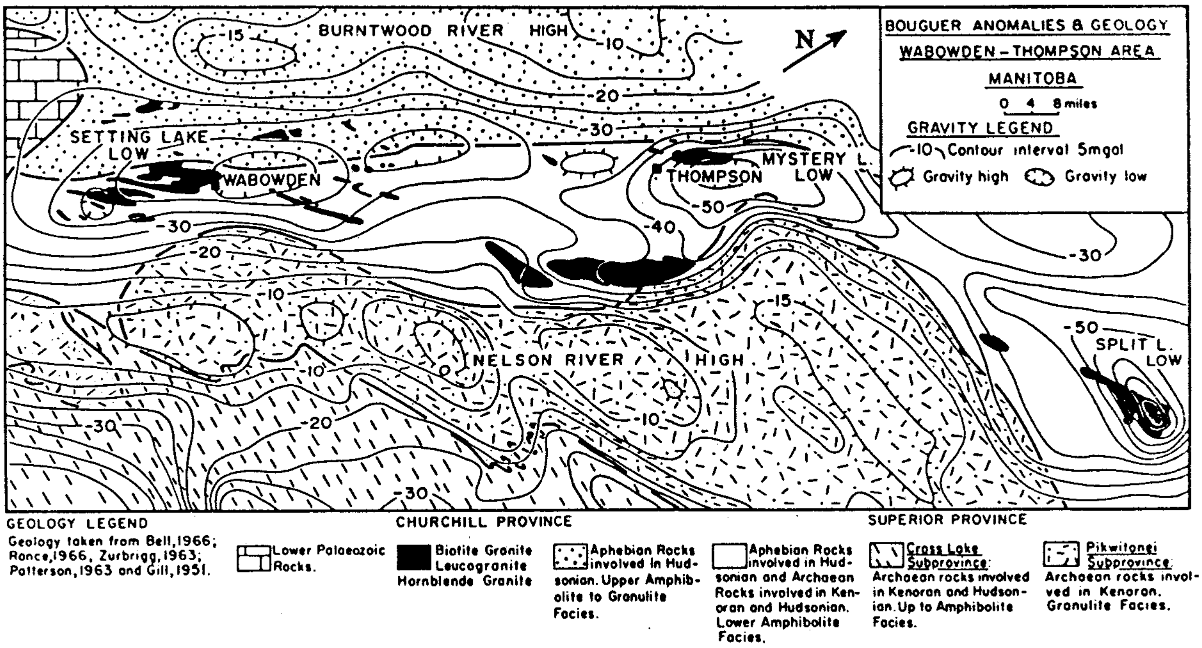


Fig. 1 Bouger anomalies and geology over the Thompson Nickel Belt, northern Manitoba. From Innes, 1967.

low and the deposits normally fall within a few kilometres of the centre of the lows.

Another prominent gravity feature in Canada, the Kapuskasing gravity high, forms a 600 km long feature within the Superior province. The character of the gravity anomaly as depicted in Fig. 2, comprises a 30 km wide zone in the south and the gravity high broadens to more than 100 kms in the north (Innes, 1967). The attitude of the anomaly strikes directly across the predominantly east-west structural trend and on average the anomaly rises 35 milligals. above the background. The anomaly is broadly coincident with the western limit of the Porcupine-Quebec Belt of basic volcanic rocks and the eastern limit of the Ontario Belt of metasedimentary rocks. The geological map shows the presence of a number of carbonate complexes along the axis of the high. Some narrow elongate belts of high grade metamorphic rocks are exposed over the central peak of the anomaly to the north-east of the alkali ring complexes. Local gravity highs within the main gravity high correlate with areas containing intrusive masses and occurrences of granulites. Geophysical model calculations indicate that the gravity feature can be explained as being due to a

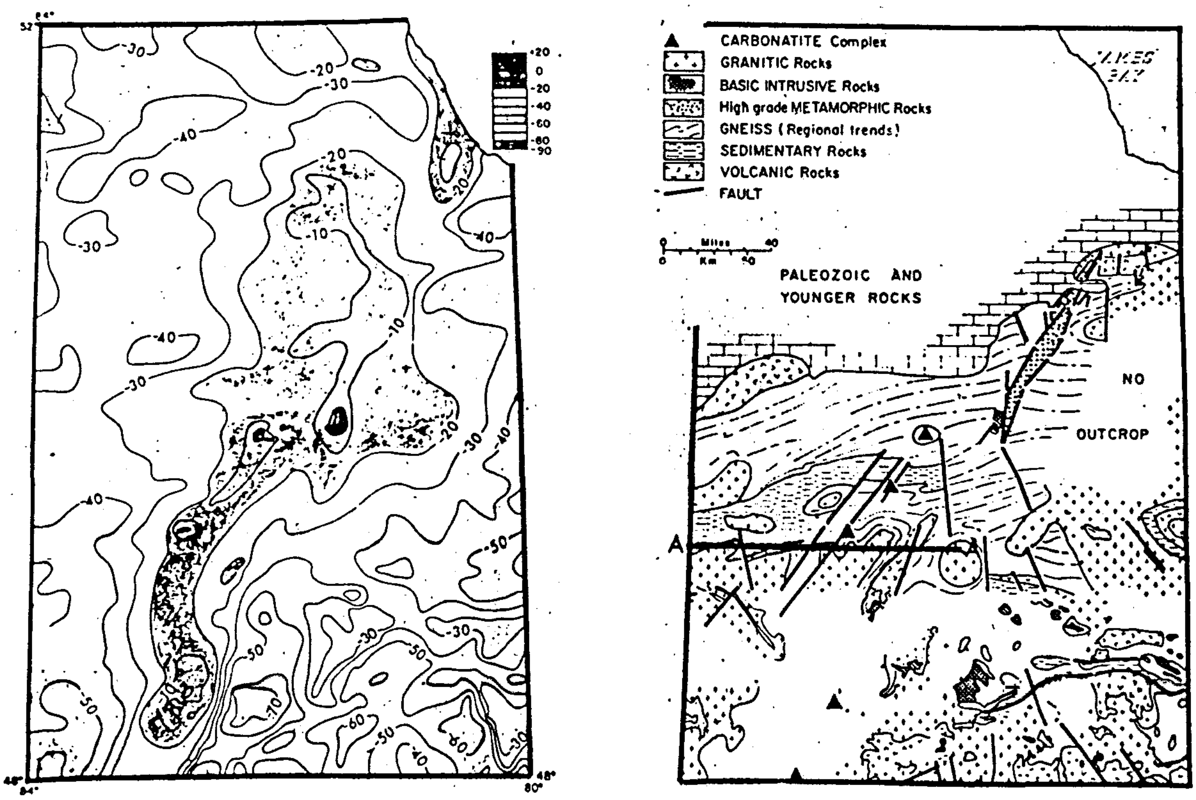


Fig. 2 Geology and Bouguer anomaly maps in the region of the Kapushasing High, Superior Province, Ontario.
From Innes, 1967.

local rise of the Conrad discontinuity of approximately 8 kms. Geological evidence supports the view that the anomaly belt is due to a deeply eroded rift zone which extended through the entire thickness of the crust.

The prominent linear distribution of the carbonatite-alkaline ring complexes along the axis of the Kapuskasing gravity high is of economic interest because the carbonatites are important sources of numerous minerals including niobium, rare earths, uranium, vermiculite and base metals. Volcanic piles that are commonly well developed along rift zones are potential hosts for massive sulfide deposits. Although few orebodies have been discovered as a direct result of regional gravimetric surveys, the results of reconnaissance surveys are valuable. The gravity anomalies provide information about both the near-surface and deep crustal structure and this information is of direct value in locating deposits of economic interest.

Integrated gravity and magnetic surveys have been used routinely in the Okiep Copper District in South Africa, a detailed account of which is presented by Hugo et al. (1975). The copper deposits of the Okiep district occur within basic bodies that intrude an extensive gneissic complex. The distinct contrast in the density and magnetic susceptiblity between the pipelike basic intrusives and the gneissic country rocks is readily detectable by gravity and magnetic methods. The geophysical data is analysed in detail to provide information about the subsurface configuration and probable composition of the basic bodies. The composition of the intrusives is an important factor that controls, to a large extent, their economic potential. The geophysical data are considered in conjunction with geological and geochemical evidence in planning an effective delineation drilling programme to establish the potential of the copper-bearing bodies. It should be noted that the detailed geophysical programme does not attempt to detect the sulfide mineralization, but its main function is to delineate the size and nature of the basic bodies in depth.

A typical example of an integrated geophysical survey in the Okiep district is presented in Fig. 3 for the Waaihoek prospect. The geological plan of the prospect (Fig. 3A) outlines the distribution of the irregular diorite that is intrusive into Concordia granite. The results of a ground magnetometer survey (Fig. 3B) indicate that the body is dike-like in plan, and magnetic profiles show that the diorite is inclined steeply to the south. The gravity survey was confined to the western part of the prospect due to adverse topographic effects in the east. The results of this survey are outlined in Fig. 3C. Analysis of the gravity profile plots indicate that the body has a density contrast of 0.17 $g.cm^{-3}$ with the Concordia granite, suggesting that there is no appreciable change in composition with depth. The gravity data indicated that the diorite extended vertically for a depth of approximately 100m and these results were subsequently confirmed by drilling.

Gravity methods have been applied extensively in the exploration of podiform chromite deposits. Geological mapping of the host serpentinites should always form an integral part of exploration programmes for chromite deposits in order to interpret the data obtained by the

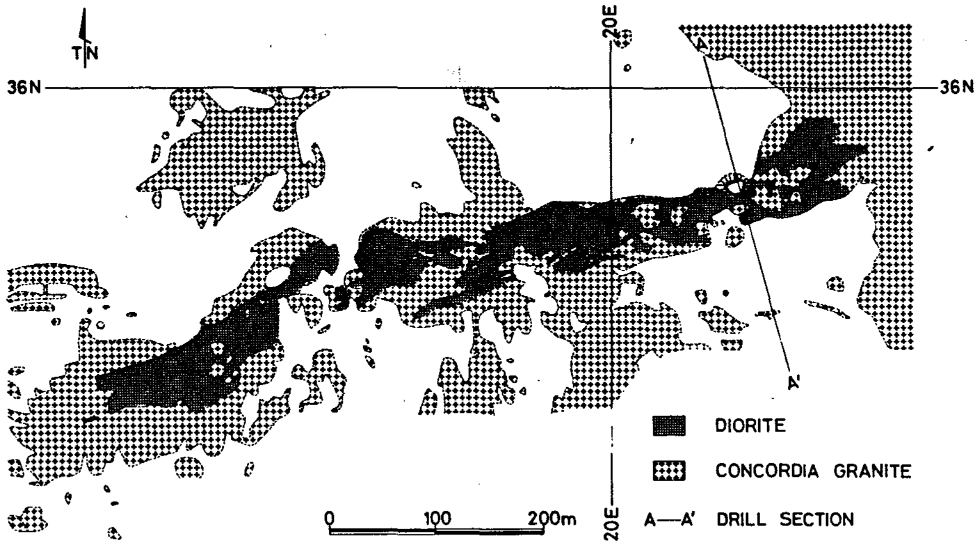


Fig. 3A

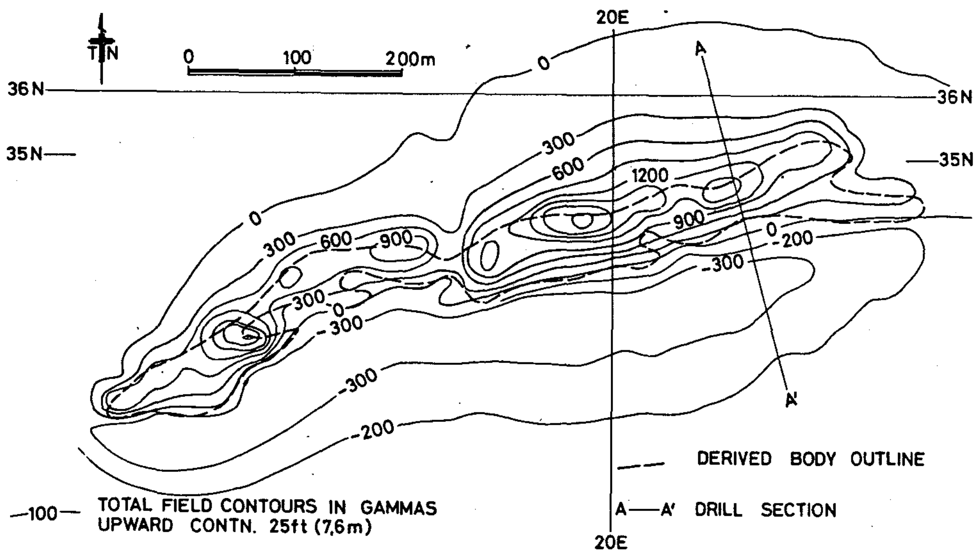


Fig. 3B

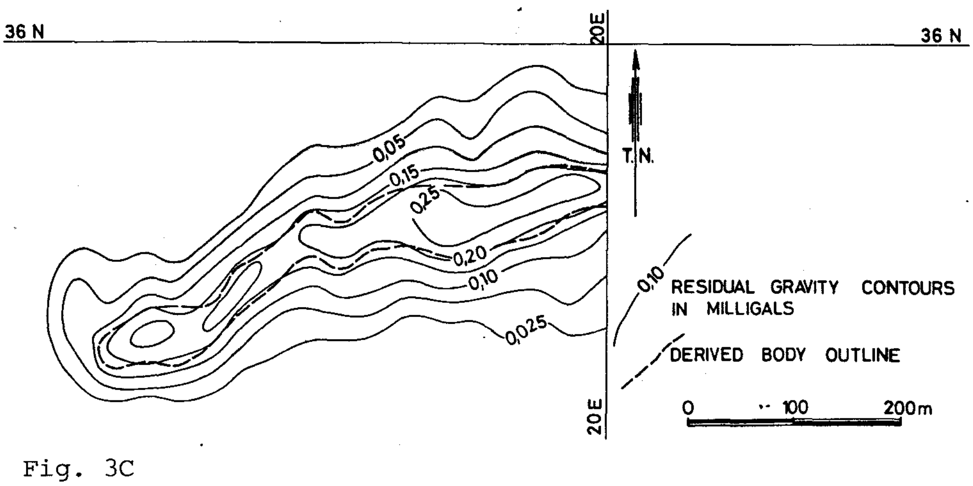


Fig. 3C

Fig. 3 Geology, magnetic and gravity data over the Waaihoek prospect, Okiep Copper District, South Africa.
From Hugo et al., 1975.

gravity surveys. Case studies are available in Davis et al. (1960), Yungul (1956) and Klichnikov et al. (1967), to which the reader is referred for more comprehensive details. The density contrast between podiform chromite ores and their host rocks is generally of the order of about 1.5 gm/cc and this difference is sufficient for chromite masses lying at commercially exploitable depths, to cause positive gravity anomalies of more than 0.05 m.gals. Similar anomalies may also be produced by the more feldspathic and dunitic masses within the serpentinized peridotite host, and this necessitates geological control in the form of detailed mapping.

An extensive exploratory drilling programme designed to test potential gravity anomalies in the Camaguey chromite district of Cuba, revealed 10 chromite deposits (Davis et al., 1960). In total, 106 gravity anomalies were tested and the drilling revealed that 47 of the anomalies were located over feldspathic rock, 40 over dense parts of the serpentinized rocks, 2 over deposits of magnesite-talc-quartz rock, and 7 anomalies were unexplained. In this example the drilling programme was not geologically orientated and the resulting expenditure on drilling was excessive. It was concluded that the evaluation of the anomalies on the basis of geology, aerial extent, and magnitude offered the best means of screening the anomalies, but the presence of spurious anomalies, caused by unexposed masses of high-density rocks, remained a problem.

Information relating to the detection limits of the gravity method in chromite exploration are provided by Yungul (1956) and Parasnis (1966). Given homogenous overburden conditions, a 200 000 ton podiform chromite deposit should be detectable if its top lies below a depth of 45 metres. This depth will be approximately halved if moderate, 2-3m variations in overburden thickness are evident over the body. The result of a gravity survey over a 115 000 ton chromite deposit is outlined in Fig. 4. The deposit comes within 3m of the surface and it dips steeply towards the southwest. The bulk of the ore lies below 23m and the body extends to a depth of 75m. The anomaly is broadly outlined by the 0.9 g.u. (0.09 m.gal) contour and it peaks at 0.16 m.gal.

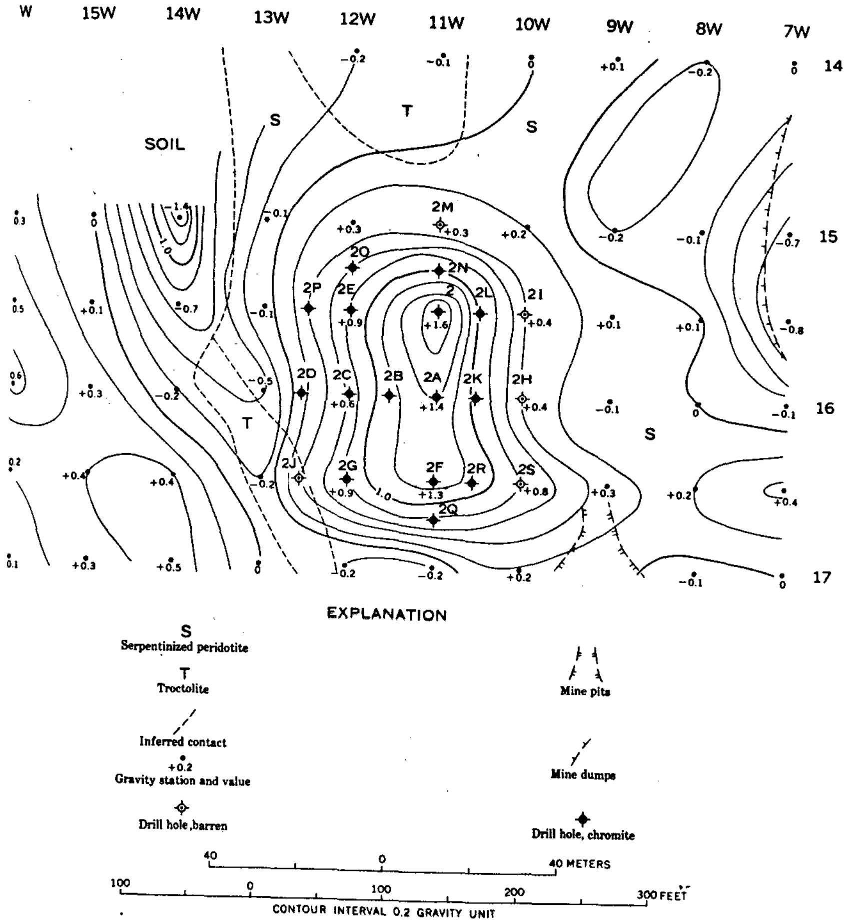


Fig. 4 Residual gravity anomaly over a podiform chromite deposit in Camaguey Province, Cuba. From Davis et al., 1960.

The marked density contrast that is normally developed between the basal zone of major basic intrusive complexes and the adjacent wall rocks, is readily detectable by gravity surveying. The form and attitude of the intrusive contacts, and the distribution of the footwall rocks underlying the basic intrusive, can be effectively mapped using gravity methods. Surveys of this nature may be contemplated in exploring for Sudbury type nickel sulfide ores that are concentrated in footwall depressions of the intrusive host. Surveys of this type have also been used to ascertain the nature of the contact of the Bushveld Igneous Complex with the adjacent wall rocks (Campbell, personal communication). Gravity methods have also been applied over the basic lobe of the eastern Bushveld in order to map the distribution and nature of the Transvaal sediments below the complex. This information was of value in assessing the probability of locating chromite layers or platiniferous Merensky reef at shallow depth, in areas overlying updomed Transvaal floor rocks.

Only limited use has been made of the gravity method in prospecting for mineralization in granitic terrains. Large scale, regional gravity surveys may be potentially valuable in granitic terrains in locating major faults and fracture zones which are often closely related to tin-bearing granites. Deep faults in granitic terrains are frequently marked by linear zones of high gravity gradients and by noticeable variations in the nature of the gravity (and magnetic) fields.

The routine application of regional gravity and magnetic surveys in the U.S.S.R. on scales of 1:200 000 and smaller, indicated a strong correlation between the distribution of tin, tungsten and molybdenum mineralization and the peaks of gravity lows (Klichnikov, 1967). The gravity lows correspond to the updomed roof of the underlying granite pluton. In the majority of tin-producing districts these areas can normally be easily recognized due to a marked increase in the amount of quartz and tourmaline veining, together with other signs of alteration. In areas covered by substantial thicknesses of overburden or snow, the distribution of the underlying granite dome could be more effectively and economically defined by airborne magnetics and/or radiometrics. In the majority of situations therefore, the use of gravity surveys in tin exploration is not justifiable.

Gravity surveys have not been used very extensively in the exploration for, and delineation of, porphyry deposits. This is largely due to the fact that the majority of porphyry deposits are generally associated with other barren intrusive masses and no significant density contrasts exist that could be effectively utilized to outline the mineralized porphyry. Furthermore, the majority of the world's porphyry deposits occur in mountainous orogenic belts and gravity surveying in these environments is inherently difficult. Magnetics, radiometrics and induced polarization-resistivity methods, are of far more potential value in porphyry exploration and gravity is generally only utilized to solve specific structural problems (e.g. to estimate the amount of displacement along post-mineralization faults).

The gravity technique has been used fairly extensively in prospecting for buried porphyries in the Basin and Range Province of California. Exploration in this region is hampered by the development of thick pediment gravels, and gravity traverses are conducted across the valleys to quickly establish the location of the faults bounding the pediments. The gravity data also provide adequate estimates of the depth to basement over the pediment covered areas and this information may be utilized to confine further exploration efforts to areas of comparatively shallow cover.

A rather unusual but highly successful use of gravity has been in the underground exploration of major, porphyry associated, replacement deposits, in the Warren-Bisbee mining district of Arizona. Exploration on the Bisbee copper mine has been guided by underground gravity surveys and a full account of the method is described by Sumner and Schnepfe (1966). The orebodies occur as irregular replacement masses in carbonates that have been invaded by a large porphyry stock. The copper orebodies occur as small, 10 000 - 30 000 ton bodies around the peripheral edge of large 100 - 250 000 ton pyrite lenses. The gravity method is applied because of the significant density contrast that exists between the essentially uniform host carbonates (2.65 - 2.7 gm/cc) and the massive sulfides (4.0 gm/cc). The ore tends to be localized along fault and dike structures, and along other major structural and lithological boundaries, many of which are difficult to predict using geological indications. The routine use of underground gravity surveys assists in both exploration and mine development by indicating the size and extent of concealed density contrast boundaries. The application of the method entails the calculation of residual gravity values for a network of closely-spaced underground stations. These values are plotted on level plans and contoured in the manner illustrated in Fig. 5. The copper-rich masses tend to be localized on the flanks of large pyritic bodies and geophysically these zones tend to occur in areas of steep gravity gradients on the flanks of gravity highs and lows (Fig. 5). Cavernous areas and above average density garnetiferous and dolomitic zones tend to complicate interpretation but the use of gravity has,nevertheless, been effective. Of the recommended drill holes that have been completed over the past 15 years, 80% have encountered sufficient sulfides to account for the anomaly. In Southern Africa, the use of underground gravity surveys may be of potential value in exploration for large, high grade tin replacement deposits on the Rooiberg A mine. Although the majority of the cassiterite-bearing pockets are too small to be detected, collectively they may produce a subtle gravity effect and some of the larger pockets may be more readily located.

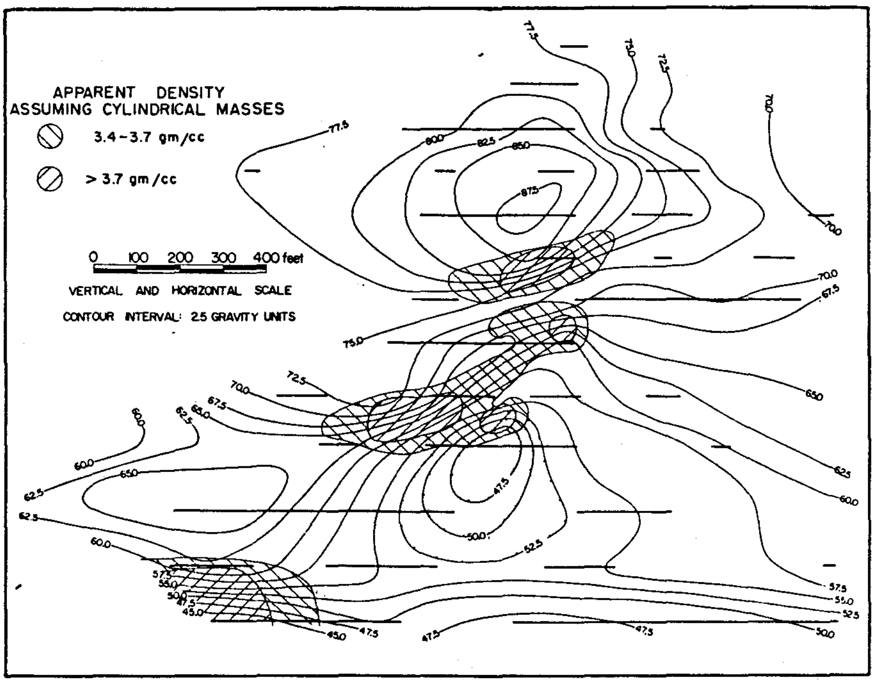


Fig. 5 Vertical gravity section through localized mineralization, Bisbee Copper Mine, U.S.A. From Sumner and Schnepfe, 1966.

The Mary Kathleen uranium deposit in Australia provides a somewhat unusual example of the successful application of a gravity survey. The orebody occurs in a metamorphosed sedimentary sequence and the reserves amount to 9.5 million tons at an average grade of 0.13 percent U_3O_8 . The orebodies are ultimately associated with extensive zones of garnetization which display a substantial (0.7 gm/cc) density contrast with the adjoining meta-sediments. The results of a gravity traverse over the mineralized zone are illustrated in Fig. 6. The orebody and its garnetized halo were clearly outlined by a 2.0 milligal anomaly despite the adverse effect of topography.

The gravity method has been applied with varying degrees of effectiveness to massive-sulfide exploration. In environments where relatively fresh sulfides are found close to the surface, gravity methods can be used effectively to delineate the massive sulfide deposits. Gravity results may be totally misleading in situations where deep weathering has affected the sulfide zone, or in areas where irregular overburden conditions prevail. The deeper weathering of the massive sulfides commonly results in the formation of a leached zone of significantly reduced density compared to the adjacent wall rocks. Under these conditions the effects of the underlying mass will be

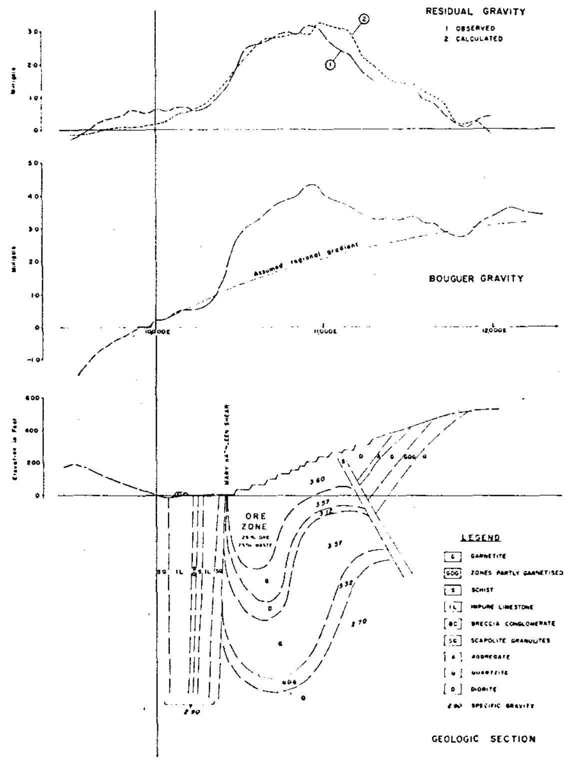


Fig. 6 Mary Kathleen, Queensland, gravity profiles over the ore zone. From Boniwell, 1965.

greatly diminished due to the adverse, near-surface effects. This accounts for the commonly observed presence of negative gravity anomalies over some large orebodies in arid regions. Deposits in the Mt. Isa district in Australia, provide a typical example (Smith, 1980). The use of the gravity method in massive sulfide exploration in many environments is therefore not a recommended practice.

In the glaciated terrains of Canada and Northern Europe, gravity surveys are commonly used to follow up airborne electromagnetic and induced polarization anomalies as they provide the best means of differentiating between graphite and massive sulfides. The results of a gravity survey over the MacDonald Mine in Quebec are outlined in Fig. 7. The orebody has an estimated tonnage of 12 million tons and it is composed predominantly of pyrite with subordinate sphalerite and chalcopyrite. The orebody was completely covered by overburden, but it was clearly defined by the gravity results which produced an anomaly of nearly 3 milligals. The results of a survey of this nature can be utilized to make preliminary estimates of the tonnage of the deposit, provided some basic figures about the density distribution of both ore and host rocks are reasonably well known. (The accuracy of these estimates is largely dependent on how closely

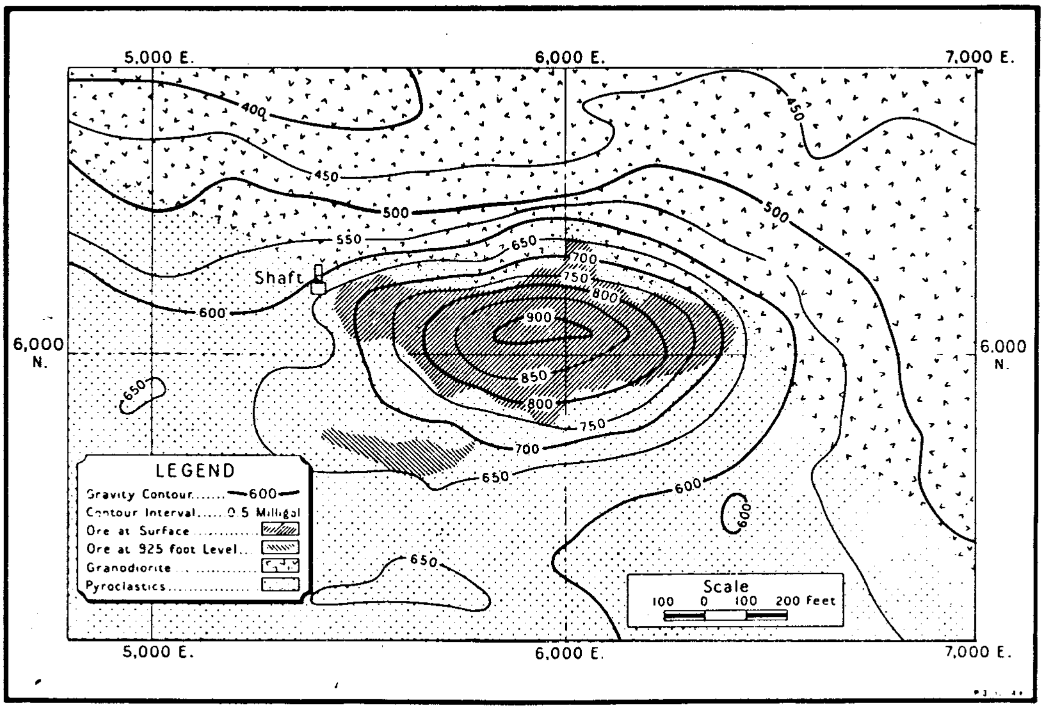


Fig. 7 Positive gravity anomaly over the MacDonald Mines orebody, Dufresnoy Township, Quebec. From Innes, 1967.

the orebody's shape approaches that of the spheroids, cylinders or tabular bodies that are used in the gravity analysis). The tonnage estimates may be exceedingly accurate under ideal conditions and the majority of estimates appear to be accurate to within 30 percent of the actual tonnage figure. This information is exceedingly valuable, particularly if it is available from the beginning of the evaluation stage, and it will be of direct value in subsequent mine planning and development.

Gravity surveys are used on a routine basis in exploration for massive sulfides in the Spanish pyrite belt and an excellent account of exploration techniques applied in this region is given by Strauss et al. (1977). Detailed 50 x 50m, or 100 x 40m grids are used at the initial stage of some exploration programmes and the results have proved to be effective enough to detect even small sub-economic deposits, provided the surface topography is relatively smooth. The results of a broad gravity survey over the Tharsis Mine area is presented in Fig. 8. The effectiveness with which the gravity survey located all the deposits is evident. Gravity profiling is also used as a routine method to following up electromagnetic and induced polarization anomalies because it provides the most effective means of locating massive sulfide mineralization in depth.

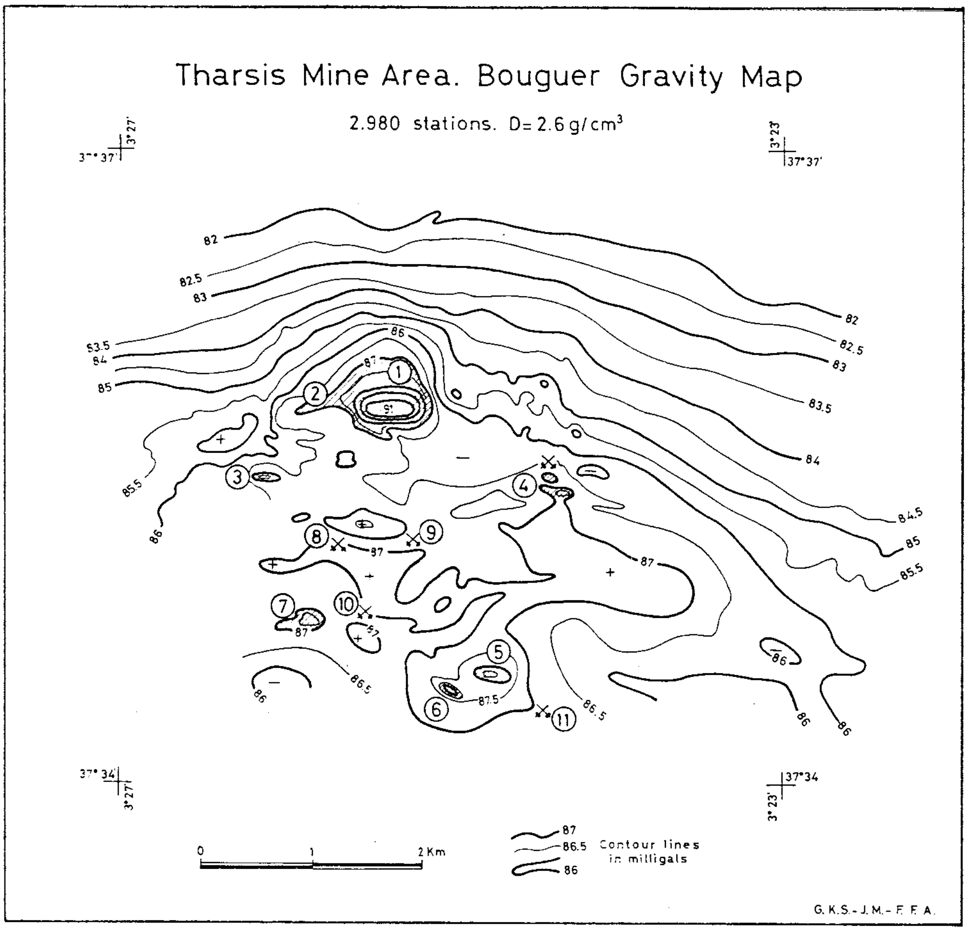


Fig. 8. Bouguer gravity map of the Tharsis mine area. *Numbers in circles* are locations of sulphide orebodies: *1*: Filon Norte and San Guillermo, representing approx. 90 million t; *2*: Sierra Bullones (partly worked out) with approx. 12 million t; *3*: Filon Centro, 3 million t; *4*: Prado Vicioso, massive and disseminated pyritic ore, total approx. 4 million t; *5*: Almagrera, approx. 10 million t; *6*: Nueva Almagrera, 3 million t; *7*: Cantareras, approx. 6 million t; *8*: Filon Sur, worked out; *9*: Esperanza, dissem. copper deposit, worked out; *10*: Vulcano, worked out; *11*: Lapilla, partly worked out, with estimated remaining reserves 0.5 million t (From Strauss et al., 1977).

The Mattagami No. 2 orebody in Canada, is a small spherical shaped volcanogenic sulfide deposit some sixty feet in diameter. The body lies at a depth of ninety metres and was found as a result of magnetic response of its magnetite capping, but gravity methods were employed to screen the magnetic anomaly. A 0.5 milligal. gravity anomaly was detected over the magnetic body which was only questionably indicated by later IP, EM and Afmag surveys. This example suggests that gravity surveys may have considerable merit in prospecting for volcanogenic sulfide deposits, provided the target area is well defined and the conditions over the prospect are suitable for conducting a gravity survey.

Regional gravity surveys have been used extensively in the mapping of sedimentary basins and its ability to detect subtle density contrasts between the sedimentary piles and the underlying basement complex is firmly established. The technique has been widely applied in petroleum exploration and an extremely high degree of precision has been achieved in these surveys. Similar techniques have been widely applied in coal exploration and to a lesser extent in studies of Proterozoic basins which hold considerable potential for sedimentary iron, manganese, gold, uranium and base metals. The recent classic discovery of the Roxby Downs copper-uranium-gold deposit in South Australia, under 300 metres of cover, can be attributed to the successful integration of regional magnetometer and gravimeter surveys, coupled with sound geological modelling. This example is one of the few available in the literature which illustrates the application of gravity techniques to exploration for base metal deposits in sedimentary environments. The tremendous success of this exploration programme illustrates the potential value of the gravity method in sedimentary basin analysis.

So far as the writer is aware, the use of the gravity method has never been applied on a regional basis on the Copperbelt where the effective use of electrical and electro-magnetic techniques is minimised due to the presence of a thick deeply weathered conductive overburden. The general lack of outcrop in this region makes prospecting difficult, and much poorly orientated stratigraphic drilling has been done on the Copperbelt. The highly irregular basement topography evident on the Copperbelt exerts a profound control on the distribution of the copper deposits in the overlying meta-sediments. The gravity method could probably be applied with good effect to the task of delineating the structure of the basement underlying the Roan meta-sedimentary succession. Allowances would have to be made for variations in overburden thickness but the wealth of drilling data already available over many areas could form a sound basis for making these estimates. The accurate delineation of the paleo-topography of the Roan basin by gravimetry would provide the most accurate means of predicting suitable environments where other major copper deposits may occur.

An example of the use of gravity in mapping basement structure is outlined in profile form in Fig. 9. The upper profile was compiled from seismic data and the interpretation was subsequently confirmed by diamond drill information. The corresponding Bouguer gravity profile as depicted in the underlying section (Fig. 9), clearly defines the precise location of the basement high and other irregularities on the underlying surface. The basement highs commonly become a focal point for the growth and development of carbonate reef complexes, which commonly host carbonate lead-zinc deposits of the Mississippi Valley-type. The lead-zinc deposits of Missouri, Pine Point and along the Griquatown fault zone in South Africa, are all contained within carbonate reefs that are developed above basement highs. Stromatolitic reefs are preferentially formed on the flanks of basement highs on the Copperbelt, and in the Wheal Austin-Pinnacles sedimentary copper deposits in South Australia (Rowlands, 1978). The stromatolitic reefs normally occur on the immediate flanks of the copper orebodies. The delineation of basement highs by gravity means can therefore provide extremely valuable data which are of direct value in outlining the potentially mineralized sedimentary environment.

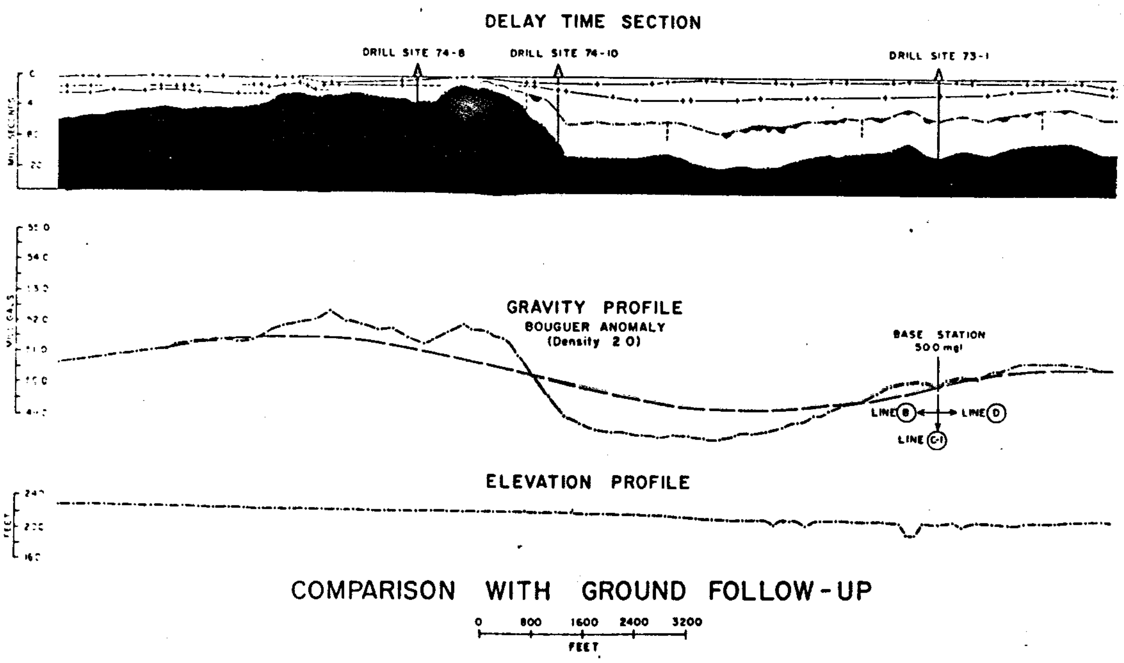


Fig. 9 Gravity profile over a shallow sedimentary basin. From Deguen et al., 1974.

Detailed gravity surveys are currently being utilized in the direct detection of carbonate reefs which may form potential hosts for oil. Nettleton (1972) describes a number of successful applications of gravity surveys in locating carbonate reefs but the high costs associated with these surveys is prohibitive. The use of similar methods in base metal exploration is not yet economically feasible, but more detailed gravity traverses over potentially mineralized ground may be contemplated on a restricted basis. The success of the gravity method in the detection of reefs buried at 1000m or more is due to the density contrast that exists between the reef complex and the adjoining sedimentary formations. The reef complex may be considered as a local horizontal facies change and the reef is commonly bound by thick, low density evaporite sequences in the backreef environment, while the forereef is characterized by carbonaceous siltstones or shales. Numerous types of reefs have been recorded in the geological record and this accounts for the varying responses (both positive and negative) that have been recorded in surveys designed for petroleum exploration. The results of a gravity survey over a reef complex in the Jameson area, U.S.A., is shown in Fig. 10a, together with a contour plan showing the top of reef, Fig. 10b. The reef complex is clearly defined by a subtle positive gravity anomaly.

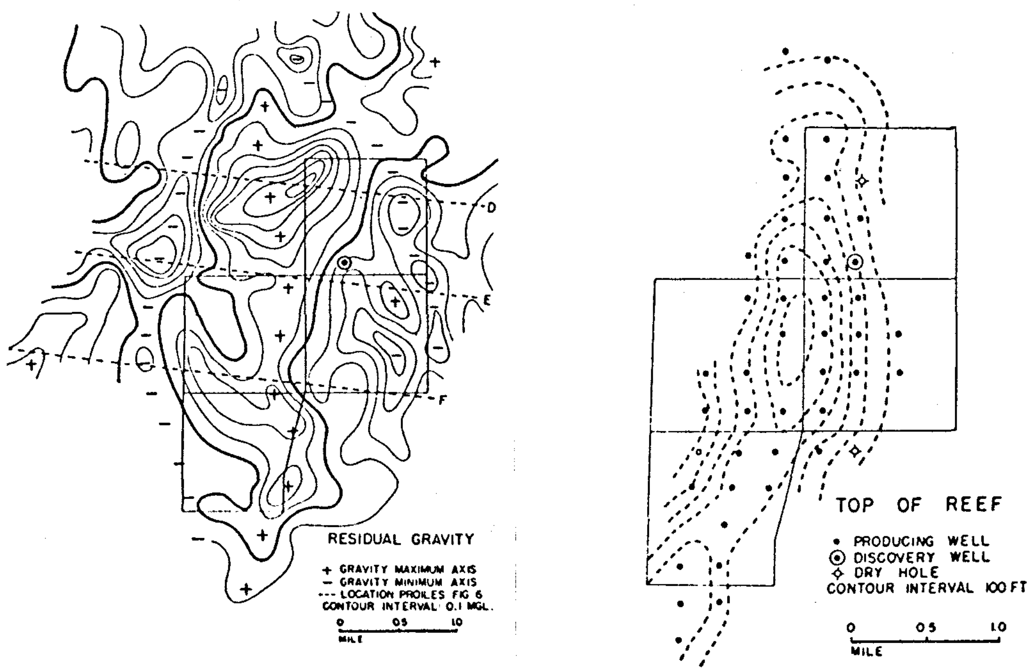


Fig. 10. Residual gravity and top of reef contours over a carbonate reef complex buried at 1,830 metres, Jameson area, U.S.A. (From Nettleton, 1972).

The high porosity of reefs that are commonly encountered in areas containing carbonate-hosted lead-zinc deposits may be detectable by gravity methods. The high permeability of the reefs can be expected to give rise to subtle negative gravity anomalies and these areas could be expected to hold enhanced potential. In the majority of cases other geochemical, geological or geophysical data would be required to more accurately delineate drilling targets.

The use of gravity surveys in the exploration for gold and uranium in the Witwatersrand Basin is outlined in papers by Weiss (1957) and Roux (1967). Pretorius (1979) provides a broad regional outline of the gravity field over the Witwatersrand Basin and the salient features of this field are presented in Fig. 11. Notable

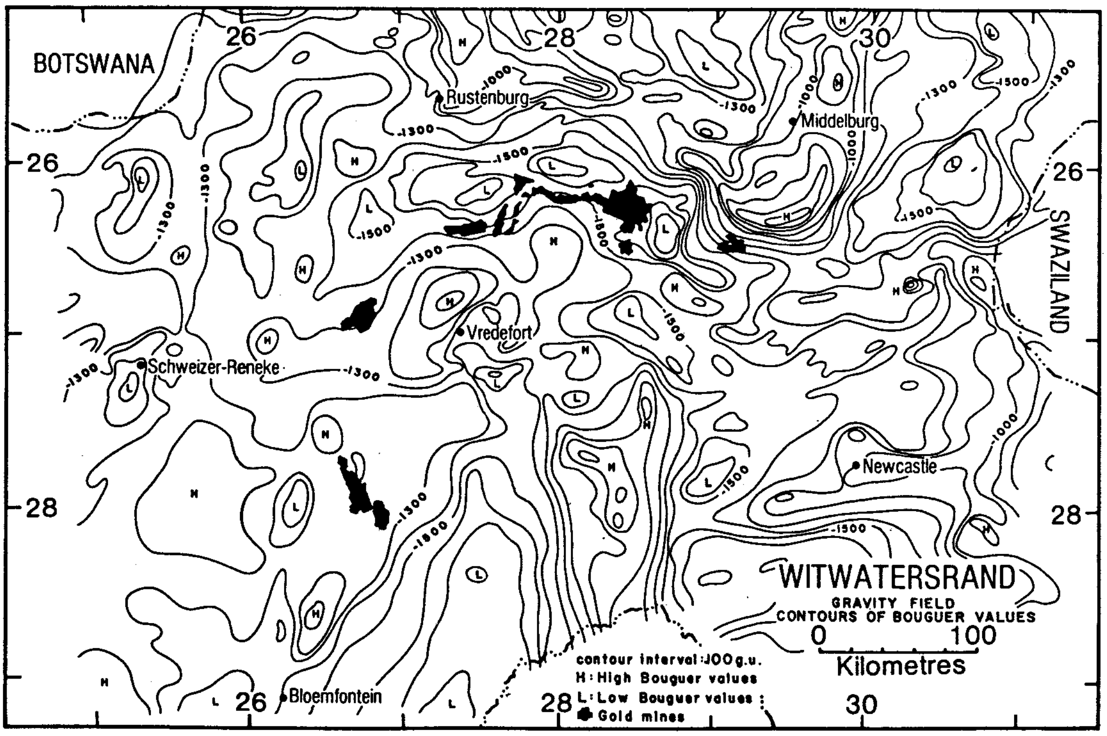


Fig. 11 Bouger gravity field over the Witwatersrand Basin in the Transvaal and Orange Free State Provinces - South Africa. From Pretorius, 1979.

features of this Bouguer gravity map include :

(a) The close spatial relationship of the major goldfields on the Reef to a string of prominent and isolated gravity lows which correspond to prominent domes in the basement. These features are not as pronounced in the Welkom goldfield because the basement domes lie at a considerably greater depth.

(b) The alluvial fans facies which host the Witwatersrand placers are localized on the flanks of the basement domes and these areas lie in the intervening zones between gravity highs and lows. The areas outlined by gravity lows, correspond to original fan head areas while the areas marked by gravity highs correspond to the thickened distal parts of the Witwatersrand Basin. The concentration of economically significant gold and uranium, in the mid and distal fan regions respectively, tends to punctuate the fact that areas outlined by prominent gravity lows and highs hold little, if any, economic potential.

(c) The pronounced arcuate nature of the Witwatersrand Basin is clearly defined on the gravity map. The location of the Evander Goldfield on the north-eastern side of the prominent basement ridge, is clearly indicated by the gravity data. This fact enhances the potential for locating new goldfields in the region broadly coincident with the -1200 g.u. contour to the east and north-east of the Evander field, as well as to the north-west. As these areas all lie under appreciable thicknesses of younger sedimentary core, the value of the gravity data is even more apparent.

Integrated gravity and magnetic surveys are used extensively in the exploration for gold and uranium deposits in the Witwatersrand. The successful geological interpretation of this data has led to the discovery of four important goldfields, under significant thickness of younger cover. The successful use of gravity can be attributed to the density contrast between the thick sequences of Witwatersrand sediments (2.75 - 2.83 gm/cc), and the underlying granitic basement (2.63 gm/cc). The gravity data provides an accurate means of establishing and mapping the existence of Witwatersrand Sequences beneath a cover of younger rocks. It also provides an accurate means of detailing the structure within the basin as can be seen in the geological section across the St. Helena Gold Mine (Fig. 12). The reader is referred to an interesting paper by Weiss (1957) for a more detailed account of the use of gravity in the discovery of the Stilfontein Gold Mine.

One of the most important applications of the gravity method lies in the exploration and subsequent delineation of iron and manganese deposits. Numerous papers are available and reference should be made to papers by Leney (1966), Webb (1966) and Hinze (1966) for further details. The relatively large tonnage and high density of most iron and manganese deposits makes them an ideal target for detection by the gravity method. Gravity surveys are particularly

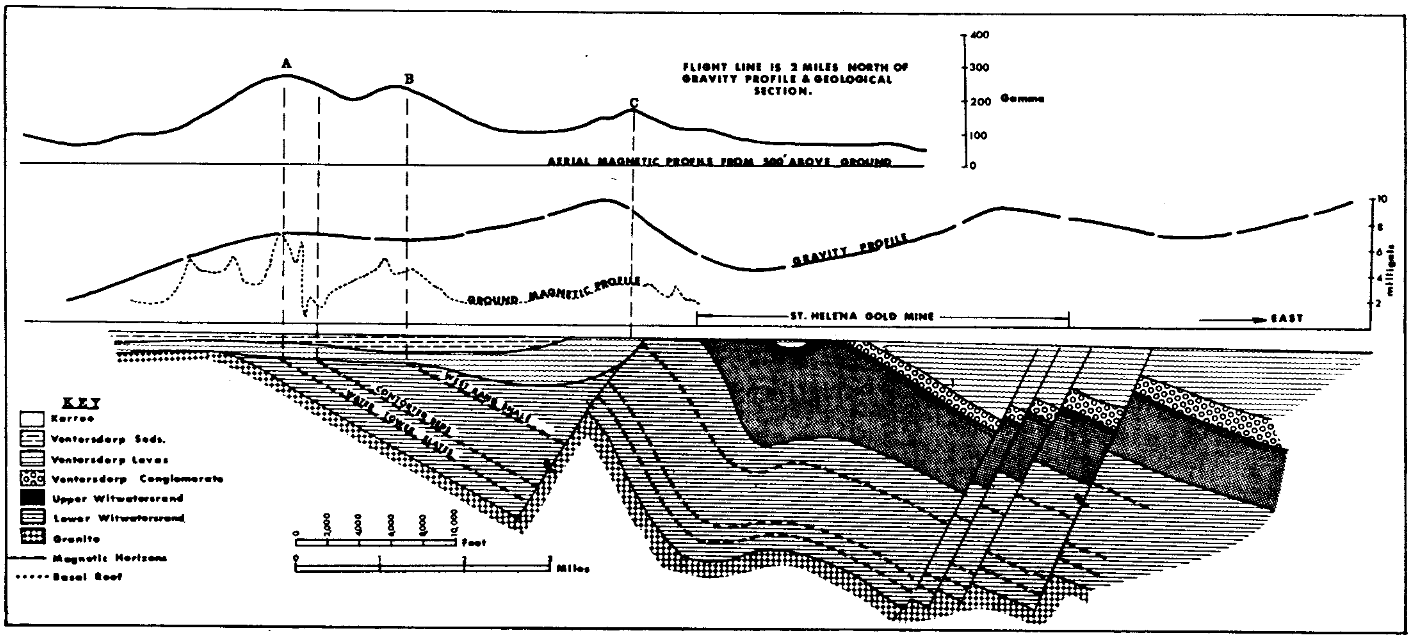


Fig. 12 Gravity, ground magnetic and aerial magnetic profiles and geological section across St. Helena Gold Mine environs. From Roux, 1967.

valuable in outlining the lateral extent and orebody limits of non-magnetic, hematitic iron and manganese ores. Gravity methods have been used effectively in the Sishen, Hammersley and Lake Superior iron ore districts to outline the orebodies, and relatively accurate quantitative estimates of the in situ tonnage have been made from these surveys.

Iron and to a lesser extent, manganese, are generally associated with magnetic formations and airborne magnetometer surveys are normally used in the initial exploration stage in order to locate the iron formations. Bacon and Wyble (1952) provide an interesting example of the use of regional gravity surveys in mapping the non-magnetic Riverton Iron Formation in the Iron River-Crystal Falls district in Michigan, Fig. 13. The iron formation dips inward to form a triangular shaped synclinorium which is defined by a broad positive gravity anomaly. Similar general surveys may be of potential value in situations like those encountered in the Kalahari manganese field where thick, essentially non-magnetic, subhorizontally disposed manganese orebodies occur under a comparatively thick sedimentary cover sequence. The manganese orebodies are hosted by the Hotazel Iron Formation which could be mapped using magnetics, but gravity surveys can be used to screen these areas because contrasting densities exist between the siliceous banded iron formations and

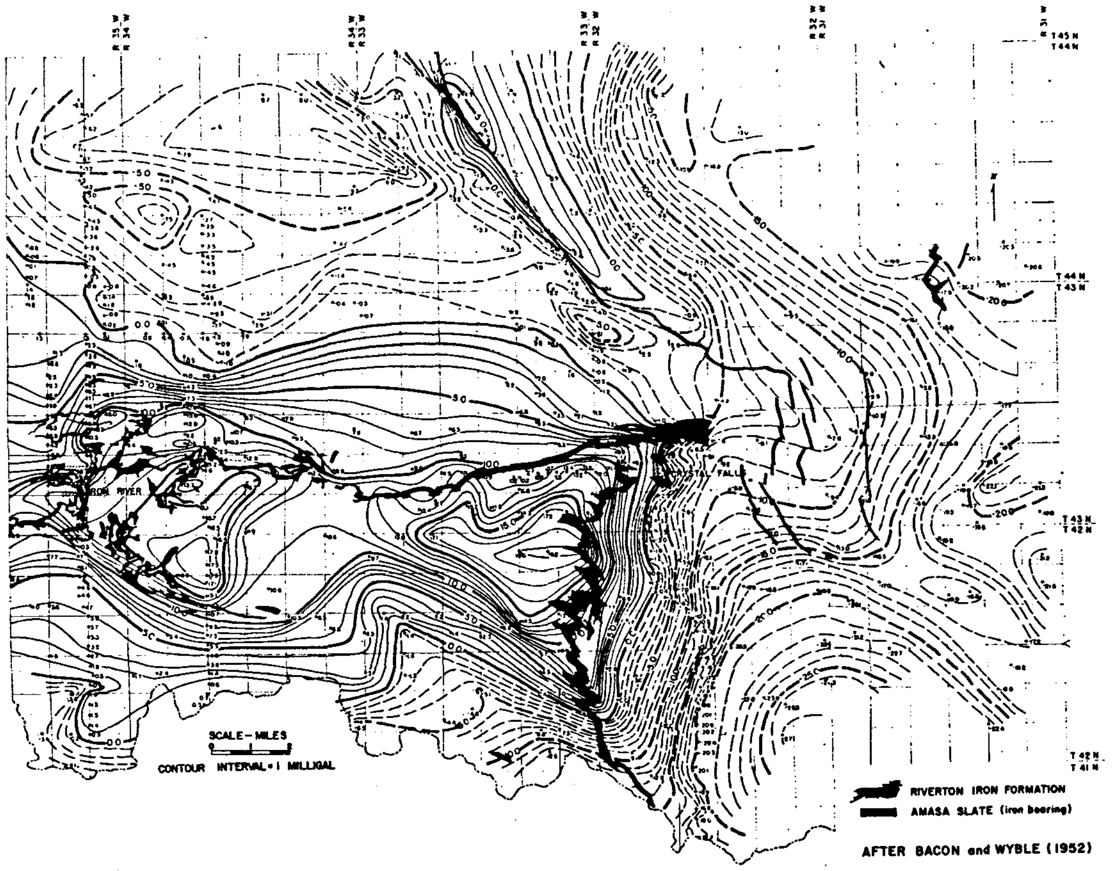


Fig. 13 Bouguer gravity map of the Iron River - Crystal Falls mining district, Michigan. From Leney, 1966.

the massive manganese orebodies. The presence of major faults in the underlying iron formations should be readily discernable on both the gravity and magnetic data. Fault zones would be indicated by a rapid linear change and steepening in the gravity and magnetic contours. The accurate prediction of the faults would be of immediate value in the delineation drilling stage and this information is of tremendous value in the subsequent mine planning and development stage.

An account of the successful use of gravity surveys in the exploration of the Warramboo iron ore deposit in South Australia, is provided by Webb, 1966. The hematitic iron ores of this district and the geologic environment are essentially similar to those at Sishen-Postmasburg area in South Africa. The deposits are associated with Proterozoic banded iron formations which are totally masked by younger sand and calcrete. Magnetic surveys are used to map the distribution of the iron formations. Gravity surveys are conducted over priority areas that are assessed from the results of the aeromagnetic surveys. Integrated magnetic and gravity surveys are widely used in other iron ore districts around the world.

An illustrative example of the use of the gravity method in iron ore exploration is provided by Leney, 1966. This case history relates to exploration of the Iron Mountain deposit in Missouri; a large pipe-like, hydrothermal iron deposit. The ore consists of coarse-grained specularite which occurs as fracture fillings and replacements in brecciated andesite porphyry. Parts of the orebody are virtually non-magnetic but magnetite is erratically distributed in the deposit and this gave rise to a prominent magnetic anomaly on surface. A geological section through the orebody is shown in Fig. 14, together with magnetic and gravity profiles. The steeply dipping central orebody was discovered in 1929 by drilling under the crest of the magnetic high. The delineation drilling programme outlined substantial reserves and the decision was made to proceed with underground mine development. The presence of the large, sub-horizontally inclined limb of the orebody was only discovered a number of years later, following the completion of a gravity survey. The gravity survey revealed a large gravity high to the south of the main orebody and the flat lying, near-surface limb was subsequently mined using open-cast methods. The profitability of the whole mining

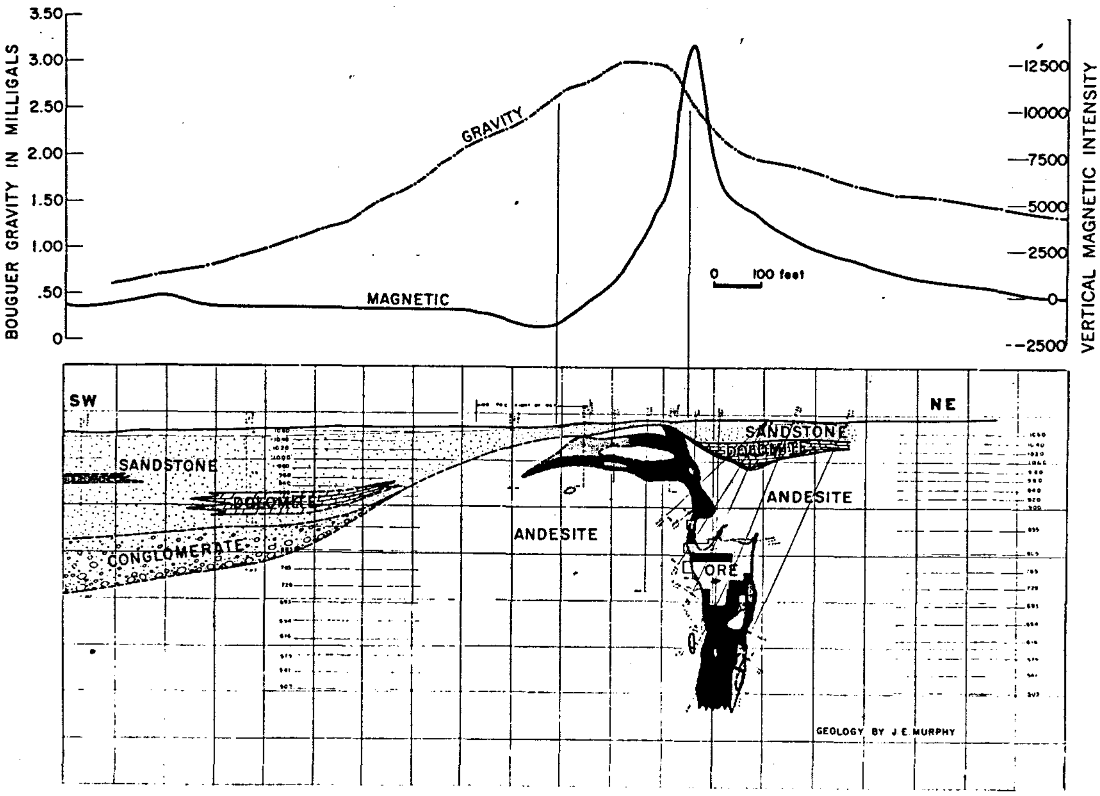


Fig. 14 Gravity and magnetic profiles over the Northwest orebody at Iron Mountain, Missouri. From Leney, 1966.

venture would have been substantially improved if the presence of the near-surface orebody had been established from the outset. The potential value of gravity surveys in iron ore exploration should always be considered by explorationists engaged in prospecting for iron.

The sensitivity with which the gravity method can detect variations in the thickness of overburden can be effectively utilized in mapping the thickness of unconsolidated sands and gravels filling old valleys. The pronounced density contrast between the unconsolidated sediments and the underlying bedrock, is generally readily detectable and gravity is therefore potentially valuable in the exploration of buried placers and uranium deposits associated with valley calcretes. Calculations of the depth to bedrock can be utilized to locate the deepest portions of the palaeo-valleys, and these areas normally contain the maximum potential. Daly (1965) provides an example of the use of gravity in the exploration of tin placers near Ardlethan in central New South Wales. The country in the vicinity of the buried placer is flat, the channel is covered by lateritic and sandy clays and the placer, where present, is lying on weathered bedrock. Gravity surveys and seismic methods were both applied successfully and the results were essentially similar. The gravity method (Fig. 15) was found to be the most suitable method for reconnaissance work; as it was found to be faster and less expensive, it had the particular advantage of being less affected by variations in the weathering of the underlying bedrock.

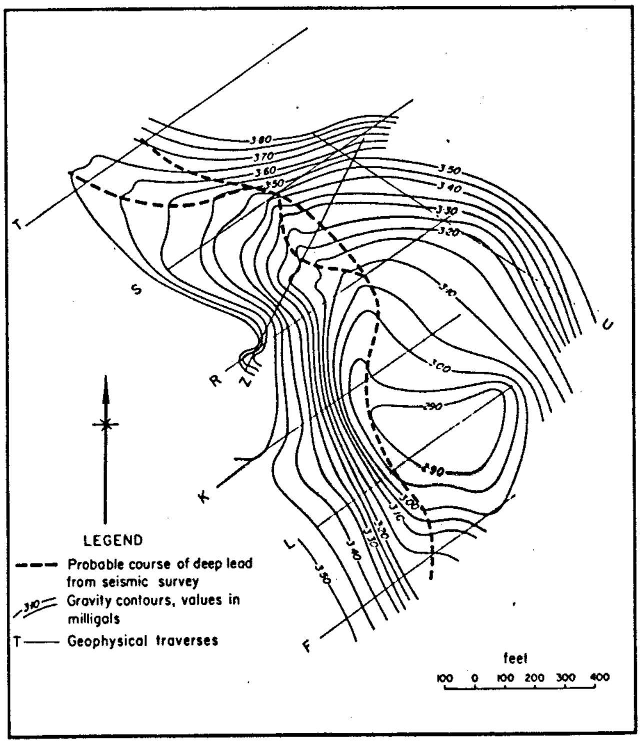


Figure 15 Gravity contours of unweathered bedrock, Upper Yithan deep lead, Ardlethan, N.S.W.

THE MAGNETIC METHOD

Of all the geophysical methods currently available, magnetics remains the cheapest and most widely used technique. Magnetics has found such wide application in mineral exploration that it is generally included in every comprehensive geophysical campaign, and the method is used extensively as an aid to geological mapping.

The uses of magnetics in mineral exploration can be subdivided according to the potential value of the method in locating ore, into direct and indirect surveys. Direct surveys are designed to locate mineralization that is consistently associated with magnetically susceptible host rocks or in which the ores themselves are magnetic. Examples are to be found in many iron ore deposits, skarns, chrysolite asbestos, kimberlites, and carbonatites, together with most copper-nickel (platinum) deposits and polymetallic sulfide deposits. In these instances magnetic surveys may be effectively employed during the initial exploration programme; in the subsequent delineation drilling phase; and in some circumstances it may be utilized to help classify different blocks of ore. In the majority of cases where a direct association is anticipated between the mineralization and magnetite, magnetics will provide the most cost-effective means of outlining the potentially mineralized ground. Exceptions lie in areas of good exposure where geological mapping will inevitably prove to be the most effective means of locating the potential ore environments. In these instances, ground magnetics and geochemical surveys may be directly applied to areas which are considered, on the basis of detailed geological surveys, to be of possible potential.

Magnetic methods have many indirect applications in mineral exploration and the majority of these methods relate to the use of magnetics as a mapping tool. The primary aims of these surveys are to recognise the depth, position, shape, and attitude of the magnetic bodies in an area, and then to interpret these values in terms of geological models and environments. The magnetic method can be utilized effectively to map the distribution of various rock units, at or near the surface, or in the basement, underlying significant thicknesses of younger cover sequences. Magnetic surveys may also be used to locate secondary magnetic horizons such as volcanics and intrusives, even at considerable depths. If a consistent spatial or stratigraphic relationship is known to exist between these magnetically susceptible horizons and ore, the magnetic data may be potentially valuable in locating the associated ores. Accurate calculations of shapes, dips, depths and magnetizations of the magnetic sources may be made from magnetic profiles. This information can be utilized to determine the depth to basement or to a potentially mineralized host rock and this will assist in the subsequent evaluation of these target areas by diamond drilling. Magnetic maps also provide a great deal of structural information. Magnetic discontinuities and linear boundaries often reflect faults, or dikes which may be of genetic significance in locating epigenetic mineralization. Folding will also modify the characteristics of the magnetics over an area by altering the position of magnetically susceptible horizons with respect to the earth's surface. In these situations the axes of magnetic highs and lows will generally be broadly coincident with anticlinal and synclinal zones respectively. Regional magnetometer surveys are potentially valuable in defining the extent of different structural provinces and they outline areas in which more detailed surveys may be helpful. Regional surveys also provide a wealth of background information which is required in interpreting the results of more detailed, local surveys.

Unlike the majority of geophysical surveys, the value of a magnetometer survey does not end with the first interpretation, but it is enhanced as more is discovered about the geology of an area. Magnetic surveys should therefore be planned as an integral part of a geological mapping programme. Armed with a good geological map, an experienced magnetic interpreter will be in a far better position to appreciate the significance of individual anomalies and this will greatly enhance the quality and accuracy of the interpretation. Close liaison between the geologist and geophysicist is required in the interpretation of all magnetic data in order to optimise the survey results. An accurate interpretation can only be made by combining the geological and magnetic information in such a manner that they illuminate each other.

The magnetic method is not subject to as many limitations as the gravity method because of the high sensitivity of modern magnetometers coupled with strong susceptibility contrasts that are commonly encountered between different rock types. Nevertheless, the magnetic method can only be used effectively where rocks have a contrasting magnetic susceptibility and as such, the method is not widely used for mapping purposes in young sedimentary basins. An important limitation of the airborne magnetic survey lies in its resolution which is a function of the flight line spacing, flying height and the strike of the major axis of the body relative to the flight path. These limitations are utilized advantageously in routine mineral surveys which are flown at a constant ground clearance in order to map near surface responses. Basement mapping surveys on the other hand are flown at a higher altitude and at a constant barometric level in order to minimise surface noise so as to enhance basement responses. The noise level and sensitivity of the magnetometer are other factors which impose important limits on the resolution of magnetometer surveys. Geological noise levels are particularly important in ground magnetic surveys and the influences of surficial magnetic scree can impose serious constraints on the effectiveness of ground magnetic surveys in some areas. Fairly significant magnetic distortions may also be encountered in hilly country and spurious anomalies may be observed over these areas.

The earth's total magnetic field is appreciably weaker in equatorial latitudes than it is at higher magnetic latitudes with the result that the magnetic anomalies over a body at low latitudes will be significantly weaker than for the equivalent body at higher latitudes. This is largely due to the low magnetic inclination of the total magnetic field in equatorial regions. The character of the magnetic field at low latitudes imposes important limitations on the effective use of magnetic surveys in these regions, particularly where the dominant geological strike trends in a north-south direction. Magnetic bodies aligned north-south tend to produce strong anomalies at their northern and southern ends. Weaker bead-like strings of anomalies are developed over the intervening areas and this makes interpretation extremely difficult. Magnetic bodies orientated in an east-west direction, tend to produce more elongate anomalies, parallel to the faces of the magnetic body. Magnetic surveys flown at low latitudes are normally conducted on lines orientated north-south and the resulting pattern of the anomalies on the map is predominantly east-west. These factors should be borne in mind by geoscientists working in equatorial latitudes.

The development of the airborne magnetometer during World War II had a profound impact on exploration due to its comparatively low cost, high speed and potential value in directly or indirectly locating ore. Airborne magnetic surveys have been utilized widely over the past forty years and in many areas the use of magnetics led to the direct detection of orebodies. Even in situations where magnetics is not likely to be of direct value in locating ore, the information provided by an airborne magnetometer survey is generally of sufficient value to offset the cost of the survey. Consequently regional magnetometer surveys have found widespread applications both in the mineral and petroleum industries, and surveys of this nature are normally flown by the geological survey departments of most countries.

The result of all magnetometer surveys are definitive insofar as they record the response of magnetically susceptible masses on the ground. Different rock types are characterized by different magnetic susceptibilities as reflected in their magnetite content, and subtle variations in the concentration of magnetite are normally readily detectable by modern magnetometers. This fact has led to the extensive use of magnetics as a routine mapping tool and in this context the method is of immense value. The marked variations that may exist between the magnetic susceptibilities of similar rock types in different geological environments imposes some limitations on the interpretation of magnetic data. Consequently, an airborne magnetometer survey can only be used to outline different rock units, and naming of these units depends on local correlations with geology. Rock units are commonly distinguished according to the shape, linearity, polarity, coherency, and amplitudes of the magnetic anomaly, or to a combination of these factors. Airborne radiometric surveys are normally flown concurrently with airborne magnetometer surveys in most modern surveys and this provides auxiliary information which is of potential value in geophysical mapping.

Airborne magnetic surveys are particularly valuable in poorly exposed areas, especially where the geology is complex as typified by most strongly deformed metamorphic and volcanic terrains. The pronounced lithological variations that are usually developed in these areas provide ideal conditions for the use of magnetics and in these situations geophysical mapping may be more cost effective than routine geological mapping. It should be emphasised however, that this is not the case in many instances as properly exercised photogeological mapping, where applicable, is considerably quicker and the results are more definitive. When properly exercised, magnetic surveys should be utilized to augment geological mapping as typified by the regional mapping conducted by the Bureau of Mineral Resources (B.M.R.) in Australia. Geologists of the B.M.R. utilize the results of airborne magnetometer surveys extensively in mapping and compiling 1:250 000 scale geological sheets. The general lack of outcrop over many areas in Australia necessitates the extensive use of magnetics and it enables the geologist to extend his geological interpretation beyond outcropping areas, with a fair degree of confidence. Ideally, all regional photogeological mapping surveys should be integrated with airborne magnetometer surveys as the latter will provide a great deal of valuable lithological and structural data that should help in the compilation of an accurate geological plan. The integration of photo-geological and geophysical data in the compilation of geological maps, will undoubtedly become increasingly popular in future regional mapping exercises as more geophysical data becomes available. In this regard the magnetic information is particularly valuable as it provides the best means of assessing the behaviour and distribution of potentially mineralized bodies in depth. To conclude it can be stated that the use of magnetics as a mapping tool is unsurpassed in covered areas, and in regions of difficult accessibility, including heavily vegetated and swampy-water covered terrains. Outside these areas the application of airborne magnetics should be carefully assessed according to the relative merits of photo-geological mapping.

The recent development of an aeromagnetic gradiometer (Hood et al., 1979), offers further potential for improving the accuracy of aeromagnetic maps. The gradiometer was designed in Canada and it records only the vertical magnetic gradient of the earth's total magnetic field. The resolution of the magnetic gradiometer is considerably better than the total field magnetometers that have been traditionally used in airborne magnetic surveys. The complex, composite anomalies that were commonly encountered in conventional total field magnetic surveys can now be resolved into their individual components and the effects of the regional magnetic gradient can be automatically removed to better define shallower features. The practical application of the gradiometer allows for a sharper delineation of surficial geological units with contrasting susceptibilities and the method is thus a better geological mapping tool than the total field magnetometer. Vertical gradient surveys also define fault zones more accurately and the technique may therefore be of particular value in the exploration of porphyry copper, and other epigenetic, fault-controlled deposits. Vertical gradient surveys suffer from one major disadvantage which is a product of the methods higher resolution. The enhanced resolution produces coherency problems in the subsequent compilation of the data and this necessitates flying at a closer line spacing than would normally be the case in total field surveys. Magnetic gradiometer surveys should nevertheless find increasing application in mineral exploration and their main potential will undoubtedly lie in areas where more detailed surveys are required.

A typical example of an aeromagnetic map together with an aeromagnetic interpretation map of the same region, is provided by Campbell and Mason, 1979, Fig. 16. The survey area is underlain by a high grade gneissic basement which is overlain in turn by a relatively thin succession of isoclinally folded meta-sediments and meta-volcanics. The quartzo-feldspathic gneisses of the basement (unit $B+B_1$) core major easterly plunging anticlinal structures. In the north-western sector of the map the basal gneiss are overlain by a variable sequence of pink gneiss which are moderately magnetic (D1 - D4) and this unit is not well developed in the south-eastern portion of the region. Two linear magnetic anomalies, AM1 and AM3 are locally developed within the pink gneiss and base metal mineralization was found to be spatially related to the remanently magnetized AM1 horizon. The mineralization was hosted by a mixed volcano-sedimentary succession which is correlated with non-magnetic rocks belonging to unit A. The linear anomaly defined as the AM2 horizon, is intimately associated with the weakly magnetic, C unit which is in part, due to discrete concentrations of magnetite in a differentiated sill complex. The basic sill had been emplaced into an extensive calc-silicate sequence which lies within the upper part of the local succession. The weakly magnetic calc-silicate unit is preserved within easterly plunging synformal structures and isolated erosional remnants, located in the central portion of the area. The east-west trending D3 magnetic trend is coincident with a broad shear zone that is developed immediately north of a prominent ridge of meta-quartzites and associated pelitic schist.

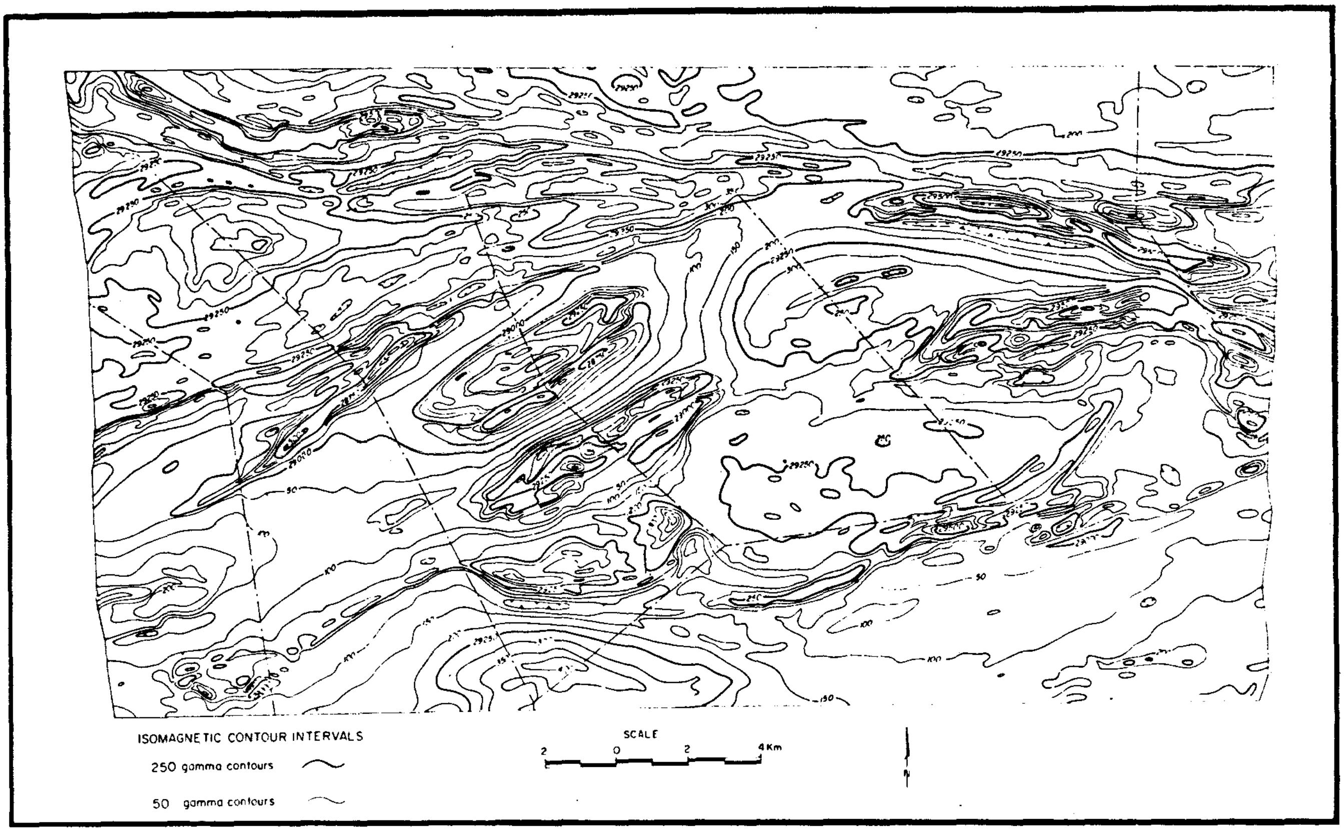


Fig. 16A Aeromagnetic contour map, Pofadder East Block.

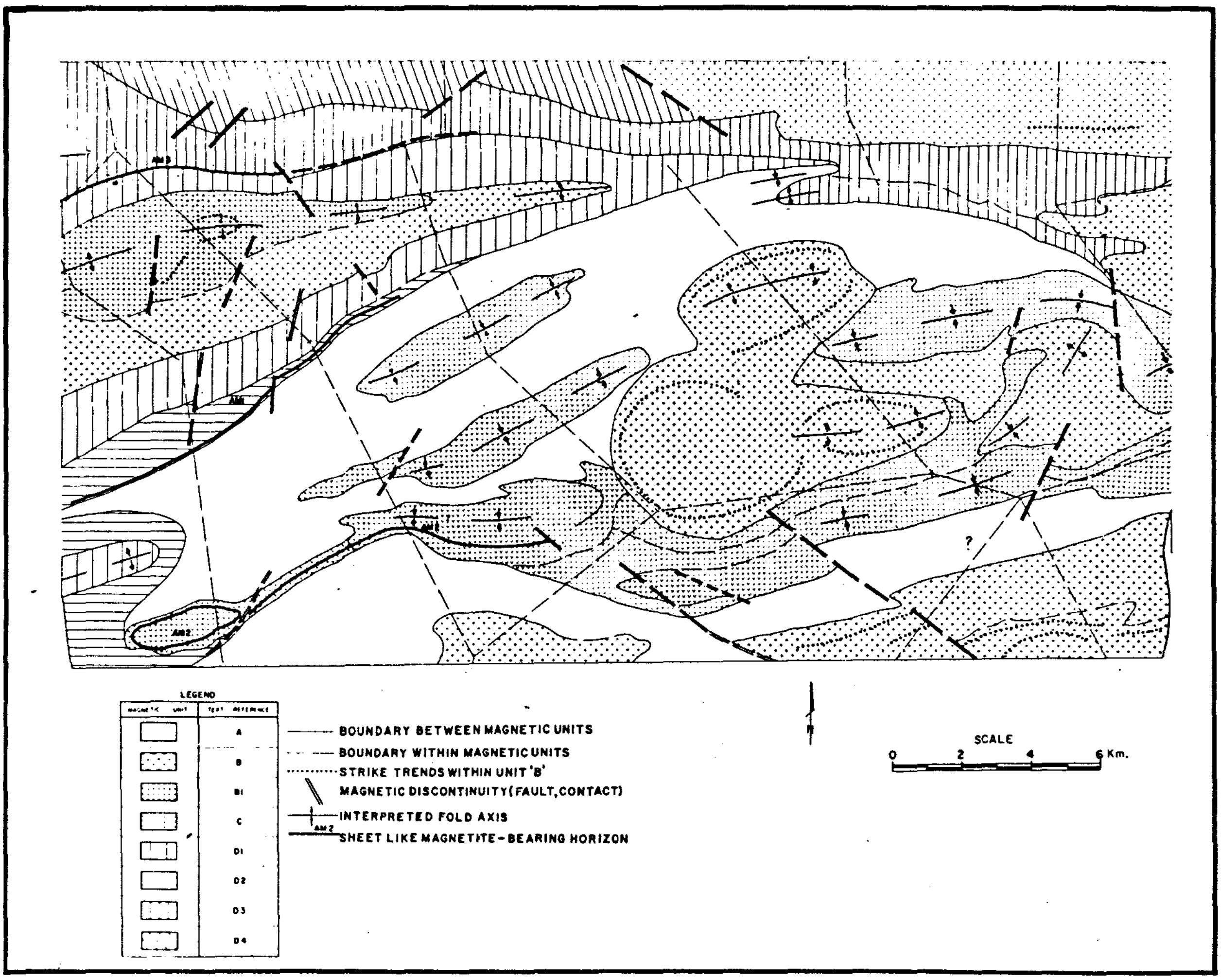


Fig. 16B Aeromagnetic interpretation map, Pofadder East Block

From Campbell and Mason, 1979.

The use of magnetics over the Pofadder East Block was primarily designed to locate magnetite quartzites which were thought to be genetically associated with base metal mineralization. Approximately 20 anomalous magnetic zones were located by the survey and these areas were followed up using ground magnetics, soil geochemistry and geological mapping. Photogeological mapping over the same region on 1:36 000 scale government black and white photos provided significantly more detailed information at a substantially reduced cost. This fact tended to reduce the value of the aeromagnetic interpretation map over the Pofadder East Block, but this example illustrates the potential value of airborne magnetometer surveys in areas which cannot be accurately mapped by photogeological means.

The results of magnetometer surveys flown by the government, can be collated into large-scale aeromagnetic maps and these regional plans can provide structural information which may be of direct value in mineral exploration. Regional magnetic compilations have often enhanced large-scale structural features which are not always apparent to the geologist working on the ground. A typical example is provided by the aeromagnetic map over the southern portion of Great Britain which is presented in Fig. 17. The two prominent east-west trending fault zones (D and E) in the southern section of the map bound a broad zone of relatively low magnetic intensity which coincide with the thickened meta-sedimentary sequence of the Hercynian fold belt. The orogenic tin granites in Cornwall are clearly outlined by a broad magnetic halo which is developed in the metamorphic aureole surrounding the granites. The southern contact of the Hercynian fold belt is bound by basement rocks which are characterized by more intensive magnetic signatures. On the northern side of the Hercynian front some major north-northeasterly and north-northwesterly trending fault zones are evident. The presence of some of these major structures was not recognised before the aeromagnetic survey data became available, because of the presence of younger Mesozoic and Tertiary cover successions. An appreciation of these major tectonic features is important as they have commonly provided loci for magmatism which is often closely associated with the generation of metalliferous deposits. In many instances, the search for certain classes of ore deposits may be effectively confined to specific tectonic regimes which can be delineated using the results of regional magnetic surveys. An appreciation of the metallogenic significance of broad scale magnetic features

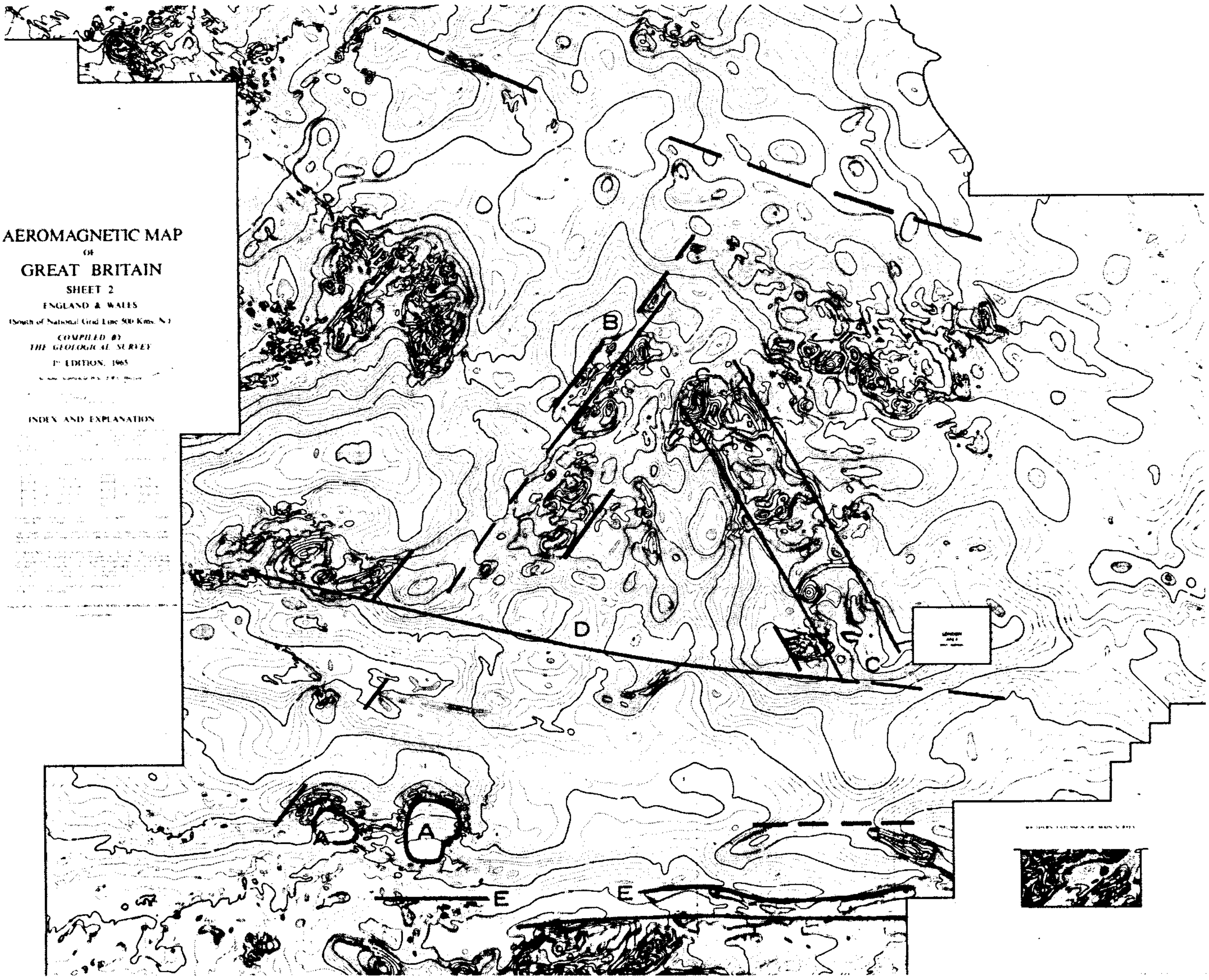


Fig. 17. Aeromagnetic survey flown at 1 000 feet above southern Britain. line spacing 2 km 1=67°. (A) Magnetic halo around Hercynian granites (Cornwall), (B) Major fault (Church Stretton Fault), (C) Major magnetic feature lying below Palaeozoic and Mesozoic rocks, (D) Hercynian front, (E) Basement boundaries in rocks lying below the English Channel (Crown Copyright, Geological Survey Map. Magnetic Map. Reproduced by permission of the Controller, H.M. Stationery Office). Scale 1:3 400 000 approx.)

(From Boyd, 1976).

can, and should, be utilized in delineating areas of enhanced mineral potential.

The majority of basic and ultrabasic intrusives contain significant concentrations of magnetite and ilmenite and these masses are readily detectable by the magnetic method. Magnetometer surveys have therefore been widely used in the exploration for ores that are genetically related to basic intrusive and extrusive bodies. Deposits associated with basic bodies include sulfide nickel, copper and platinum ores, magnetite and titaniferous ores, chromite and chrysotile asbestos ores, and lateritic nickel deposits.

Nickel deposits are genetically related to basic or ultrabasic igneous rocks, and these masses can be effectively delineated by magnetic means due to their high magnetic susceptibilities. Papers dealing with the use of magnetics in exploration for nickel sulfide deposits are provided by Dowsett (1967), Roth (1975) and Fraser (1978), to which the reader is referred for more comprehensive accounts. Pyrrhotite characteristically forms the dominant sulfide phase in most nickel deposits and the ores typically occur as magmatic segregations along the base of the igneous host. Magnetite is normally associated with nickel-copper sulfide deposits and the combined effects of pyrrhotite and magnetite are often sufficient to produce a detectable magnetic response over the mineralization. Airborne magnetics are generally regarded as the most effective means of outlining the potential host rocks to nickel sulfide deposits and ground magnetics are utilized extensively to map out the ultrabasic and basic bodies on the ground. Footwall irregularities are particularly important in localising nickel sulfide deposits and detailed ground magnetics could be used to outline the footwall depressions which form the most likely sites for mineralization.

On a regional scale the broad association between many major nickel camps and major fault zones is apparent. The Sudbury Intrusive and Thompson Nickel Belt in Canada are spatially related to the boundaries between the Grenville-Superior and the Churchill-Superior structural provinces respectively. The deposits in Western Australia are related to a prominent north to north-northwesterly trending braided fault zone while the important deposits in the Noril'sk region in the U.S.S.R. are genetically related to the Noril'sk fault zone that has developed along the northwestern margin of the Siberian craton. These major crustal sutures are not always readily apparent on the ground but they are fairly obvious linear features on regional aeromagnetic and gravity compilations. Regional geophysical compilations are therefore potentially valuable in the initial selection of prospective areas in which sulfide nickel deposits can be expected.

Magnetic surveys have been used extensively in the Sudbury district in Canada where they have proved to be the most cost-effective means of mapping out the units of the Sudbury Nickel Irruptive. The marked susceptibility contrasts that are developed between the gneissic footwall rocks and the basic sublayer of the nickel irruptive, can be readily outlined by magnetic methods. The dike-like offshoots and fault zones in the basal gneisses should also be recognisable. The ores at Sudbury may contain up to 20 percent magnetite and most of the near-surface sulfide deposits were detectable using magnetics as is evident in Fig. 18.

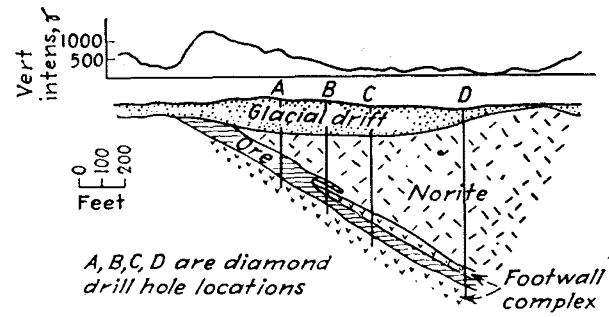


Fig. 18 Magnetic field over the nickel sulfide ore body at Sudbury, Ontario. From Dobrin, 1960.

Since the discovery of the Kambalda nickel sulfide deposits in Western Australia in 1966, a major world-wide exploration effort has been directed towards the discovery of sulfide nickel deposits in Archean greenstone belts throughout the world. Magnetic surveys were used extensively in most of these exploration programmes, many of which successfully located economically viable nickel sulfide deposits. The nickel sulfide deposits of the Kambalda type are hosted by spinifex textured flow peridotites or their subvolcanic equivalents and these ultrabasic bodies can be readily distinguished using magnetics.

The results of an airborne magnetic survey over the Pioneer Dome in Western Australia is illustrated in Fig. 19. The geology in this region is essentially similar to that encountered in most greenstone

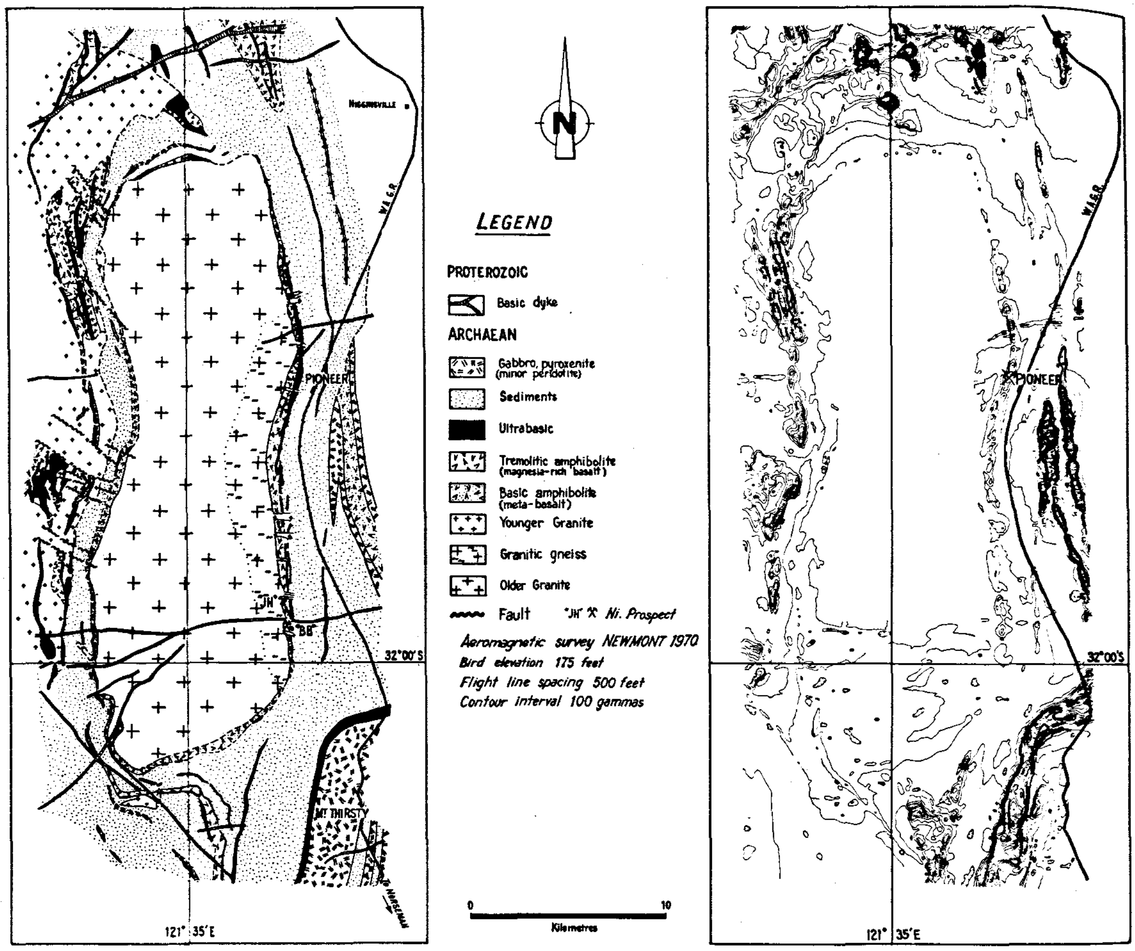


FIG. 19-Pioneer Dome, Norseman—A, geology, B. aeromagnetic map

(From Cox and Tyrwhitt, 1975)

belts and the magnetic survey was flown at a preliminary stage as part of a nickel sulfide exploration programme. The results of this survey (Fig. 19) were used to map out the distribution of the ultra-basic bodies over the region and the magnetic signatures can be regarded as being characteristic of this type of environment. The potential value of airborne magnetics as a mapping tool is self-evident and characteristic magnetic patterns can be related to all the different rock units in the region. The strongest magnetic anomalies are developed over the differentiated basic sills that occur in the eastern and south-eastern portion of the area. These strong magnetic responses are probably due to the iron enrichment in the partially fractionated basic melts and to late-stage enrichment in the gabbroic layers. The differentiated sills do not host significant concentrations of nickel sulfides but the basal peridotites that host the nickel sulfide deposits in the Archean are inevitably hosted by 100 - 500m thick sequence of komaiitic basalts (designated tremolitic and basic amphibolite in Fig. 19), and these units appear as anomalous linear zones on the aeromagnetic map. The ultrabasic portions of these belts can be delineated by detailed magnetic surveys because of their high magnetite content, and these areas are normally located by ground magnetometer surveys. Subsequent exploration would normally involve detailed mapping, soil geochemistry and trenching prior to more detailed geophysical investigations and drilling.

An account of the use of magnetics in the exploration for nickel sulfide deposits in the southern extension of the Manitoba nickel belt is provided by Roth (1975). Fig. 20A shows the results

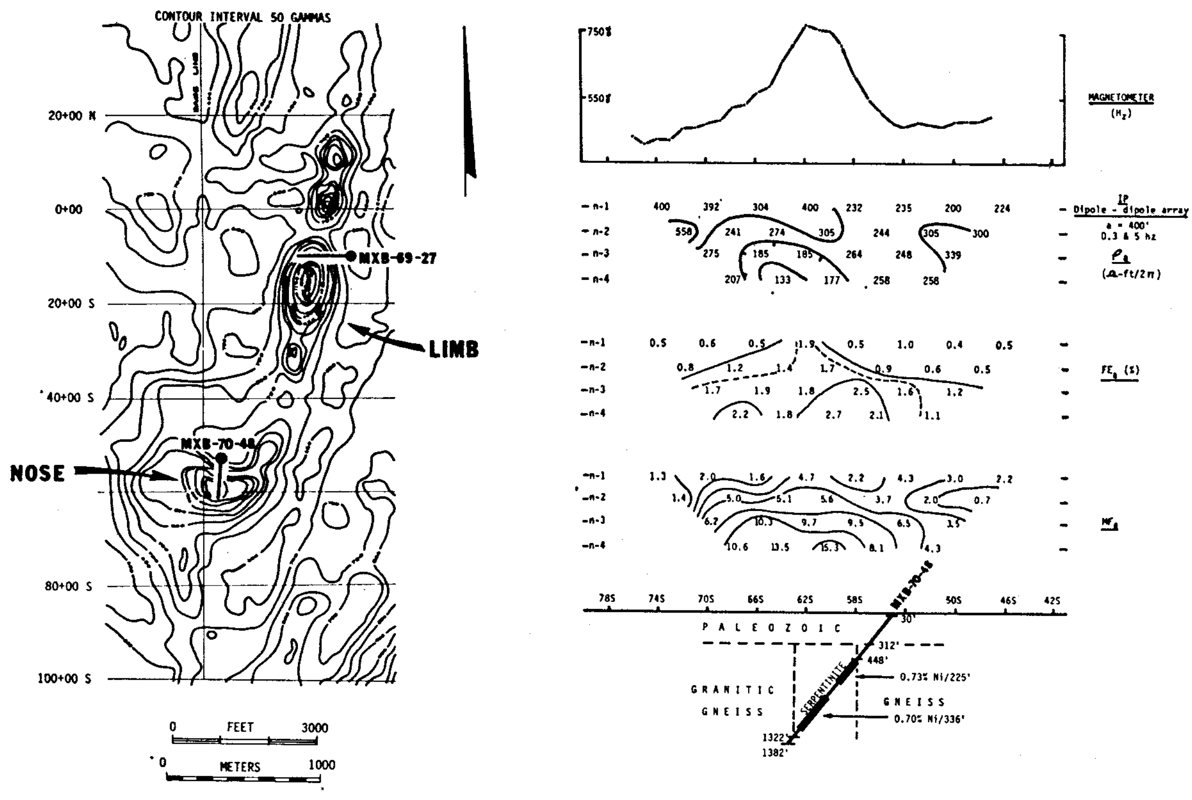


Fig. 20A and B. Detailed magnetics and induced polarization over a disseminated nickel sulfide deposit in the Manitoba nickel belt, Canada.

From Roth, 1975.

of a ground magnetometer survey which mapped the distribution of the ultrabasic host rocks under Paleozoic cover. The survey defined a linear magnetic anomaly of moderate amplitude that terminated in the south. Vertical loop electromagnetic surveys were used to screen these anomalies and they indicated a weak anomaly associated with the magnetic feature. Induced polarization surveys were used to pinpoint the source of the response and the results confirmed that the magnetic source was moderately conductive and weakly polarizable (Fig. 20B). The first drill hole (MXB 69-27) intersected a wide serpentinized ultramafic that carried subeconomic nickel sulfide mineralization. Holes drilled in the nose of magnetic anomaly (MXB 70-48) intersected economically interesting concentrations of nickel sulfides. Subsequent delineation drilling proved 7.3 million tons of ore at an average grade of 1.33% Ni (at a 1% Ni cutoff), to a depth of 356m. The mineralization consisted of finely disseminated pentlandite and millerite, pyrrhotite being essentially absent. The style of mineralization contrasted significantly with that encountered in other mines in the Manitoba nickel belt and this factor, in large part, explained the deposit's relatively poor response to electro-magnetic surveys. The results of magnetic and electro-magnetic surveys over the massive pyrrhotite-rich Thompson orebody provide an interesting comparison, to which the reader is referred.

Regional magnetic surveys have been flown over the Bushveld Igneous Complex in South Africa and most of the rock types in this region can be accurately mapped using the magnetic data. Detailed ground and airborne magnetic surveys have been widely used in the exploration and subsequent exploitation of the chromite and platinum resources of the Bushveld. The detailed magnetic surveys are used primarily to provide structural information which is utilized in mine planning and development. The positions and trends of dikes and faults can be accurately predicted from the results of detailed magnetic surveys and this information is particularly valuable in the development of the chromite resources of the Bushveld. High quality, hard lumpy chromite ores are normally encountered in areas adjoining major fault zones in the basic phase of the complex, and the development of mining blocks should be laid out parallel to the fault trends. Basic dikes adversely effect mine development and their prediction by magnetic methods, during the exploration phase, has direct economic advantages. Detailed magnetic surveys have also been employed successfully to outline the aerial extent of potholes in the Merensky Reef and this is of immense value in mine planning and development.

The magnetic method is particularly valuable in the exploration of chrystotile asbestos deposits because of their association with ultrabasic intrusive rocks. The asbestos is inevitably contained within masses of serpentinized peridotites which occur in the basal sections of major differentiated sills, the majority of which are of Archean age. Magnetite and asbestos are both formed as a result of the serpentinization of olivine and the serpentinite bodies are normally characterized by a relatively high magnetic susceptibility. Airborne magnetometer surveys provide the quickest and most economical means of delineating the differentiated bodies and adjacent granitic intrusives that are thought to be of genetic significance in the formation of chrysotile.

In many deposits, magnetite is commonly found in seams along the margins of the asbestos veins or as discrete seams and disseminations within the limits of the fibre mineralization. In these situations magnetic surveys may be of direct value in outlining the asbestos fibre zones. A magnetic profile over an area of chrysotile mineralization in the Garrison Township, Ontario is presented in Fig. 21. The area is covered by 15m of overburden but magnetic highs clearly defined the position of the asbestos and massive serpentine zones. Magnetic lows were recorded over the volcanics in the footwall, and moderately weak responses were recorded over the carbonatized serpentine. Low (1957) provides another case history which describes the successful application of magnetics in locating asbestos deposits in the Pennington Dike in Quebec. The peridotite dike was largely covered by glacial moraine and extended for 22 kms along strike. The magnetic data indicated that the dike pinched and swelled substantially and the asbestos deposits were found to be localised in the widest portions of the dike.

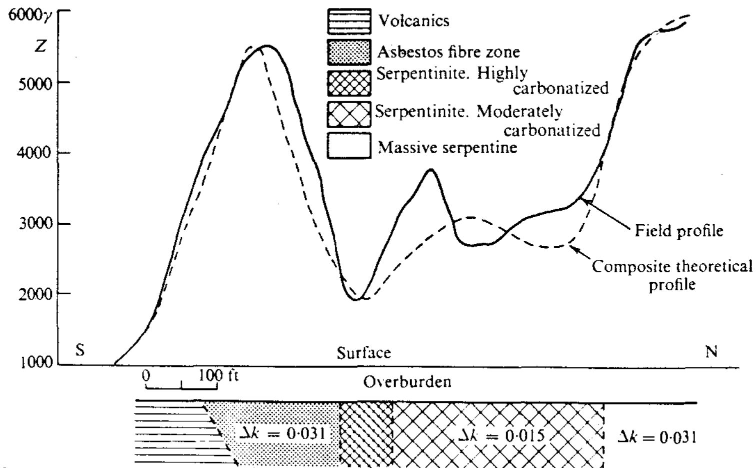


Fig. 21 Vertical-component ground magnetic profile in area of asbestos mineralization, Garrison Township, Ontario. From Telford et al., 1976.

The main limitations in the use of magnetics in asbestos exploration are that the magnetic results give no indication of the grade of the asbestos, and not all anomalous areas are mineralized. Spurious anomalies are prevalent in areas containing strongly sheared and brecciated serpentinites. Abnormally high magnetic readings are often recorded over barren pyroxene-rich parts of the peridotites and this complicates the magnetic interpretation. The shear zones are found close to the contacts of the peridotite and their linear magnetic character may help distinguish these zones from the asbestos deposits. Most chrysotile deposits are preferentially developed in the more strongly deformed sections of the host serpentinites and many deposits are located below major shear zones. The presence of spurious structural magnetic anomalies may, in itself therefore, provide an indirect guide to asbestos. Magnetic prospecting can be regarded as a useful exploration method in the delineation of chrysotile asbestos deposits. The technique is particularly valuable in prospecting for asbestos deposits in depth and under surficial overburden.

The geochemistry of magnetite in acid intrusive environments is intimately linked with the behaviour of iron in the magmatic melts. Under conditions that favour the formation of biotite, a water saturated melt will yield a magnesium-rich biotite with significant quantities of magnetite and associated oxides. Anhydrous melts tend to produce iron rich biotites together with iron-magnesium silicates and iron-titanium oxides, but very little magnetite. In closed granitic systems, the ferrous oxide will generally be totally used up in forming iron-rich biotites and hornblende, leaving very little magnetite. In shallow intrusive environments the magmatic system is open with respect to water and this promotes the formation of magnesium-rich biotites and magnetite. These factors explain many of the magnetic characteristics of the acid intrusive environment. The majority of deep level, granitic rocks are characterised by uniformly low magnetic susceptibilities. The contrasting magnetic properties of the wallrocks adjoining these bodies enables the magnetic method to accurately outline the granitic bodies, as is evident in Fig. 22. This figure also illustrates the effects of contact metamorphism, which has enhanced the magnetic characteristics of the lavas adjoining the intrusive. A prominent fault contact is evident along the northern boundary of the granodiorite.

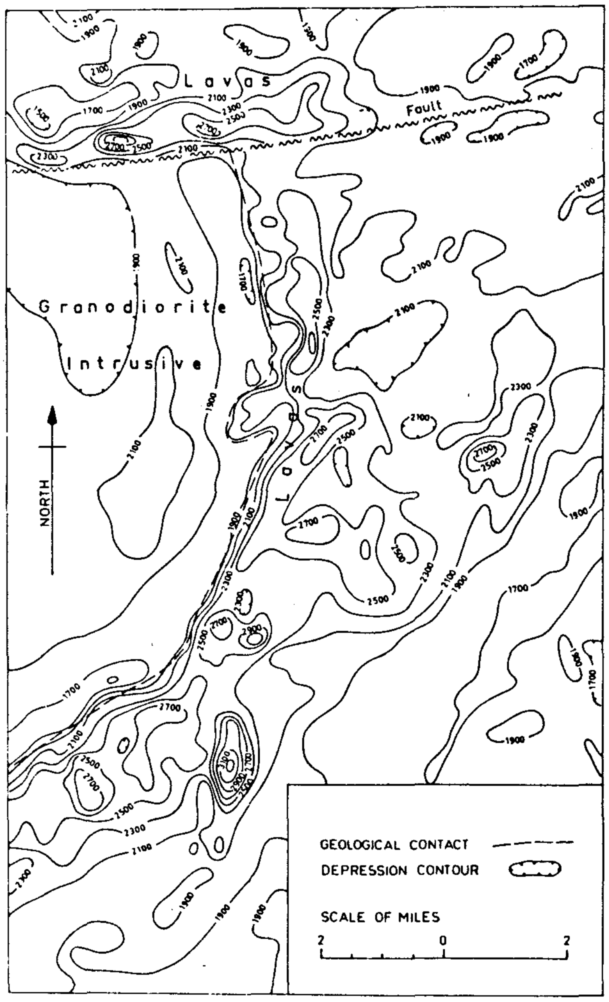


Fig. 22 Aeromagnetic map over a plutonic intrusive environment in Canada. From Parasnis, 1966.

Many tin deposits around the world display a close genetic relationship with intrusive granites and the majority of these deposits are concentrated in the hood phase of granite cusps or in the overlying predominantly sedimentary, sequences. The ability of the magnetic method to outline these intrusive masses both on surface and under shallow cover is of potential value in tin exploration. The use of magnetics is further enhanced as the majority of tin granites are characterized by anomalous concentrations of incompatible radiogenic elements which can normally be outlined by airborne radiometric surveys. Radiometric surveys are recorded routinely in most aeromagnetic surveys and when utilized in conjunction with magnetics, the distribution of potential tin granites will be readily discernable.

Irregular magnetic patterns are likely to develop in the hood phase of granite plutons and in the overlying rocks, due to the increased hydrothermal activity that is developed in these areas. These zones may be broadly coincident with linear fault and fracture zones which can be successfully outlined using the airborne magnetometer as evident in Fig. 22.* The hydrothermal tin-tungsten deposits in the Van Rooi's Vlei region in the Northern Cape Province of South Africa provide a typical example. The tourmaline-rich tin-tungsten deposits in this region are localized in an east-west trending braided fault system that is clearly defined by the enhanced magnetics in the region. Although magnetite normally accompanies the ores of this district, the direct use of magnetics in locating the tin deposits on the ground was not successful due to the presence of similar magnetic responses in the country rocks. The mapping of major fault lineaments and areas containing anomalous concentrations of magnetite in this region, should however provide an effective means of locating priority areas for further exploration.

Magnetic surveys have been applied successfully on the west coast of Tasmania to locate large tin-sulfide orebodies in the Renison Bell and Cleveland tin mining areas. The cassiterite in these deposits is contained within massive pyrrhotite and these broad sulfide zones can be delineated by magnetic methods. The deposits at Renison are, in large part, controlled by their proximity to a major fault, which has a reported throw of over 800m, and a fault of this magnitude would probably be readily identified by the use of airborne magnetics.

Most of the world's major tungsten mines, including the King Island, Sangdong and Bishop mining districts occur in magnetite rich skarns that are locally developed in impure calcareous horizons adjoining plutonic intrusives. The location of the scheelite rich replacement deposits can normally be assessed using detailed magnetic surveys. An example of one such survey is provided by Horvath (1957), in his review of the exploration of the Rye Park scheelite deposits in New South Wales, Australia. The geology of the area consists of a volcanic suite of Silurian porphyries together with dacitic and calcareous tuffs which have been intruded by two small granite stocks. The ore consitst of a fine grained aggregate of garnet, mica, scheelite,

* Reference should be made to the regional aeromagnetic map covering the southern portion of Great Britain on page 39 . The tin bearing granites of Cornwall are clearly outlined on this map due to the enhanced magnetic responses around the margins of the granites.

wolframite, magnetite, apatite and fluorite. The results of a ground magnetic survey over the prospect outlined a number of strong anomalies (Fig. 23) of limited extent, and delineation drilling proved the presence of a number of small, subhorizontally disposed bodies. Very good correlations were found between the magnetic data and the drilling results, with values of greater than 0.5% WO_3 in all holes located within the areas of high magnetic intensity.

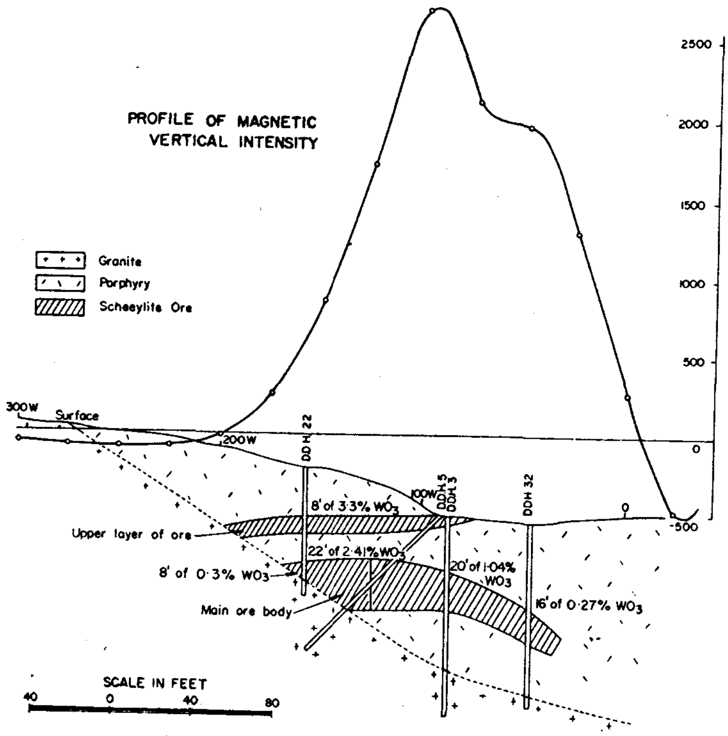


Fig. 23 Magnetic profile over the Rye Park scheelite deposit, N.S.W., Australia. From Horvath, 1957.

A somewhat more unusual application of the magnetic method is provided by Corner and Henthorn (1978), who noted a marked correlation between all the known occurrences of uraniferous alaskites and negative geomagnetic anomalies in the Damara Orogenic belt in South West Africa. The remanent magnetization was interpreted as resulting from the effects of the Damara orogenic event. The negative magnetic anomalies, Fig. 24, were stratigraphically confined to the Nosib Group sediments which host most of the uraniferous alaskites in the region. The main conclusion drawn from this research was that "the negative geomagnetic anomalies form an important prospecting criterion as they may be used to delineate target areas for further exploration in areas covered by sand, scree and duricrust."

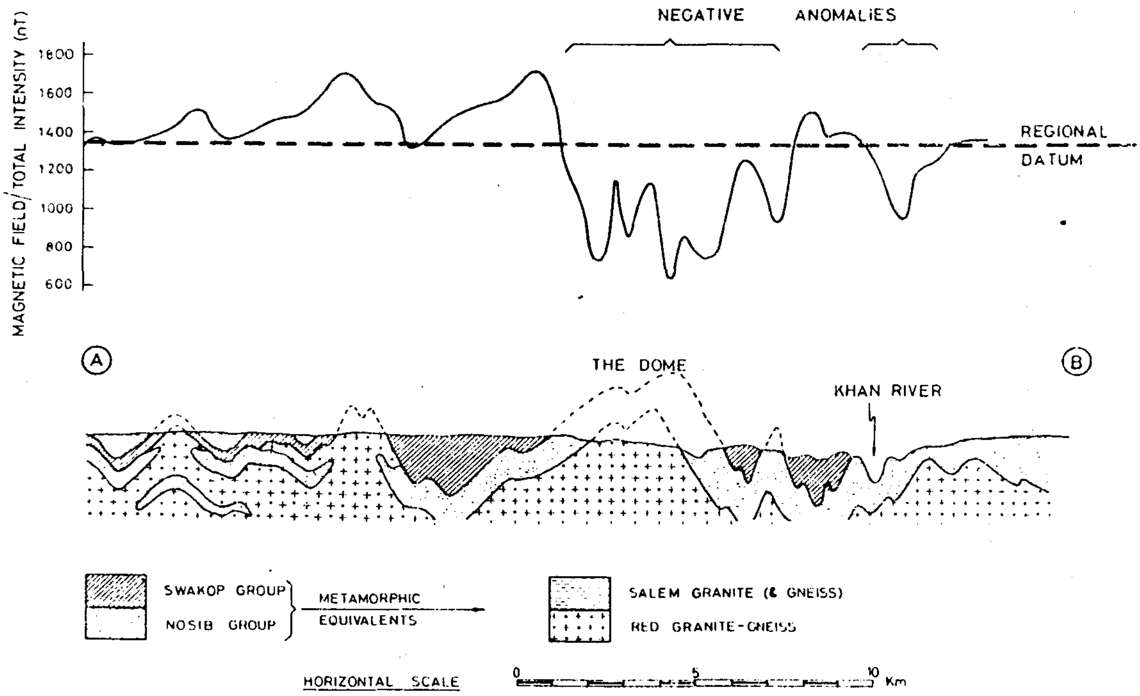


Fig. 24 Geological section across the Rössing Dome showing aeromagnetic responses of the alaskitic granites. From Corner and Henthorn, 1978.

The results of magnetic surveys over porphyry copper deposits have shown widely varied results but in the majority of cases magnetics is not sufficiently definitive to be used in the exploration for porphyry deposits. Drummond and Godwin (1976) indicate that magnetite (hematite) has only been recorded in notable quantities in 24 out of 36 major porphyry deposits in the Canadian Cordillera. Significant magnetic anomalies were only associated with a few of these deposits; in all cases the magnetite was preferentially developed beyond the main porphyry zone. Consequently in the majority of cases magnetite is only of limited value in porphyry exploration. Magnetite is more likely to be found in porphyries that are emplaced into reactive host rocks including basic volcanics, andesites, shales, siltstones, calcareous sediments and dolomitic rocks. In these situations, magnetic surveys may play an indirect role in locating porphyry deposits but the use of magnetics is not practically feasible and geochemical and/or geological methods would generally be applied. The discovery of the Island Copper deposit of Vancouver Island, B.C., forms an exception insofar as the deposit was discovered as a result of prospecting in an area that was outlined by a 4 mile long by 1 mile wide aeromagnetic anomaly, as shown in Fig. 25.

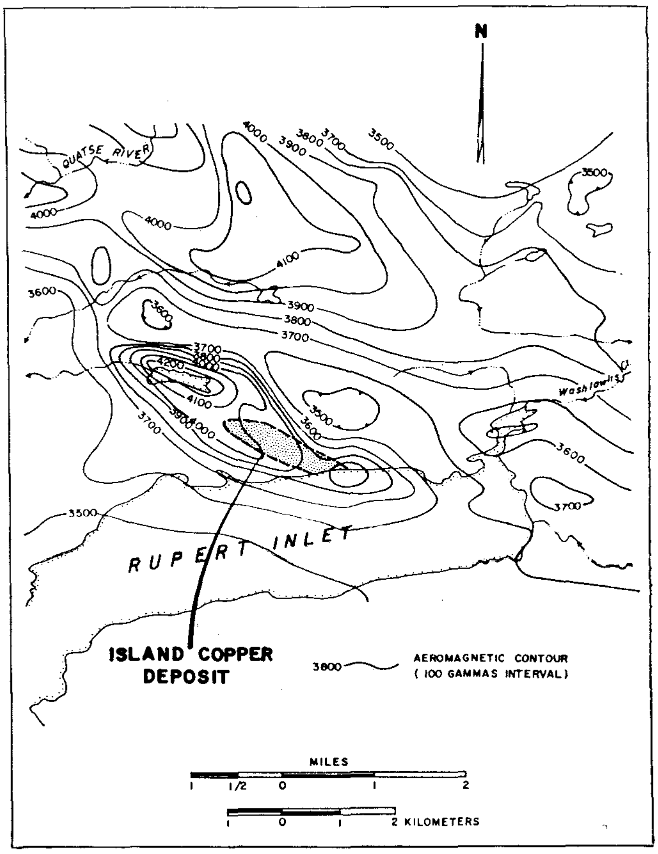


Fig. 25 Aeromagnetics survey results over the Island Copper Mine, British Columbia. From Cargill et al., 1976.

Studies of volcanogenic and volcanic-exhalative sulfide deposits around the world have indicated a close genetic relationship between the sulfide deposits and magnetite-bearing exhalite beds. The small iron and manganiferous beds are generally an ubiquitous feature of the stratiform ore environment. The iron-manganese horizons are inevitably localized in the hangingwall of the orebodies but their relationship to ore is more variable. In some situations the sulfides are closely linked with magnetite and in these situations magnetics provides a direct means of locating these orebodies. In other cases the relationship between the ore and the exhalative iron-manganese formations is more tenuous and these horizons may be laterally displaced from the massive sulfide deposits. In these situations magnetic surveys are of indirect value in defining the positions of the potentially mineralized horizons and detailed geological mapping coupled with geochemical surveys may provide the best means of homing in on the priority area. It should be mentioned that in many geological environments, a number of magnetite bearing exhalite beds may exist and these need not bear any genetic relationship to ore. Nevertheless the magnetic survey, by detecting strong linear anomalies over the potentially mineralized exhalite zones, can quickly and effectively locate areas which require more detailed follow-up.

In a number of deposits a predictable relationship exists between sulfide mineralization and magnetite, and this characteristic may be of direct value in exploration. The majority of the cupreous pyrite deposits of the Cyprus and Besshi type are capped by magnetic-bearing exhalite zones which are commonly best developed in the stratigraphic hangingwall of the sulfide deposit and they lens out laterally. This is the situation observed in the deposits along the Matchless amphibolite belt in South West Africa and an account of exploration in this region is given by Campbell and Mason (1979). The results of a ground magnetometer survey are presented in Fig. 26, over an area which was covered by surficial calcrete and sands. An elongate linear magnetic anomaly was defined on the ground which was correctly interpreted as an exhalative magnetic quartzite horizon. Subsequent ground electromagnetic follow-up and diamond drilling indicated three zones containing economic concentrations of copper sulfides. All three zones were found to be coincident with the main magnetic anomalies and the intervening zones were essentially barren. Analagous situations are developed at Matchless and Otjihase that are located along the eastern section of the Amphibolite belt.

The major stratiform base metal sulfide deposits of the Broken Hill type in both Australia and Southern Africa, also show a close genetic relationship to laterally extensive magnetite quartzites (Stanton, 1976). This feature was used extensively in the exploration for deposits of this type in the North Western Cape in South Africa. The fairly marked magnetic anomalies that were developed over two strongly deformed Pb-Cu-Ag deposits in the Aggenys area is evident in Fig. 27. The anomalies are caused by the combined effects of the magnetite quartzites and pelitic schists. The latter contain disseminated magnetite which forms a broad envelope around the ore-bearing assemblage. This contributes to the above-average magnetic susceptibility of the pelitic schists in the ore environment. The magnetite content of the pelitic schists and the thickness of this unit is noticeably diminished outside the Black Mountain-Broken Hill-Gamsberg ore environments, where magnetite quartzites are only weakly developed. In this region airborne magnetometer surveys could have been used effectively to delineate the potential ore environment quickly and efficiently.

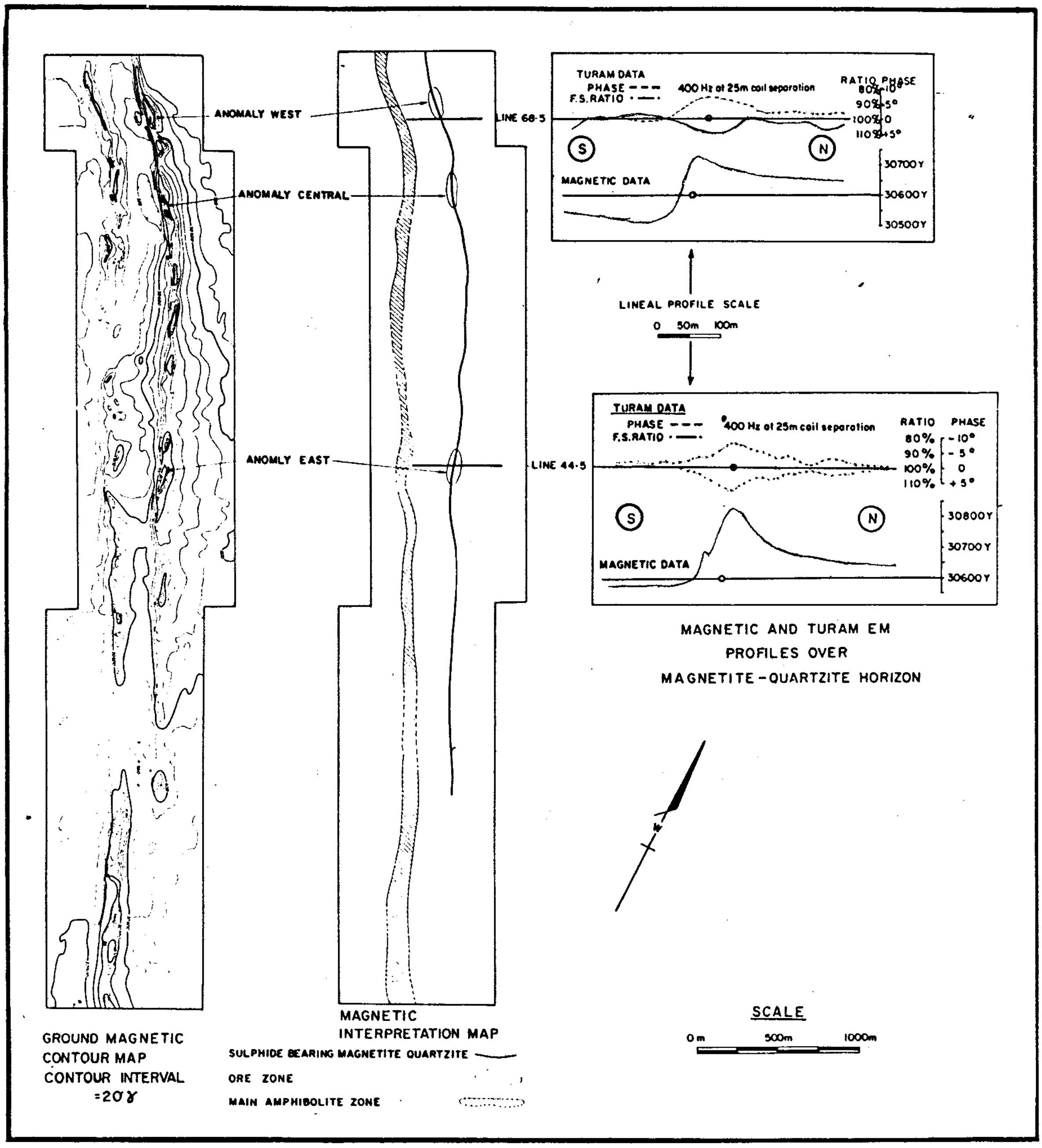


Fig. 26 Ground magnetic and electromagnetic results over the cupreous pyrite deposits, Anomaly Zone area, South West Africa. From Campbell and Mason, 1979.

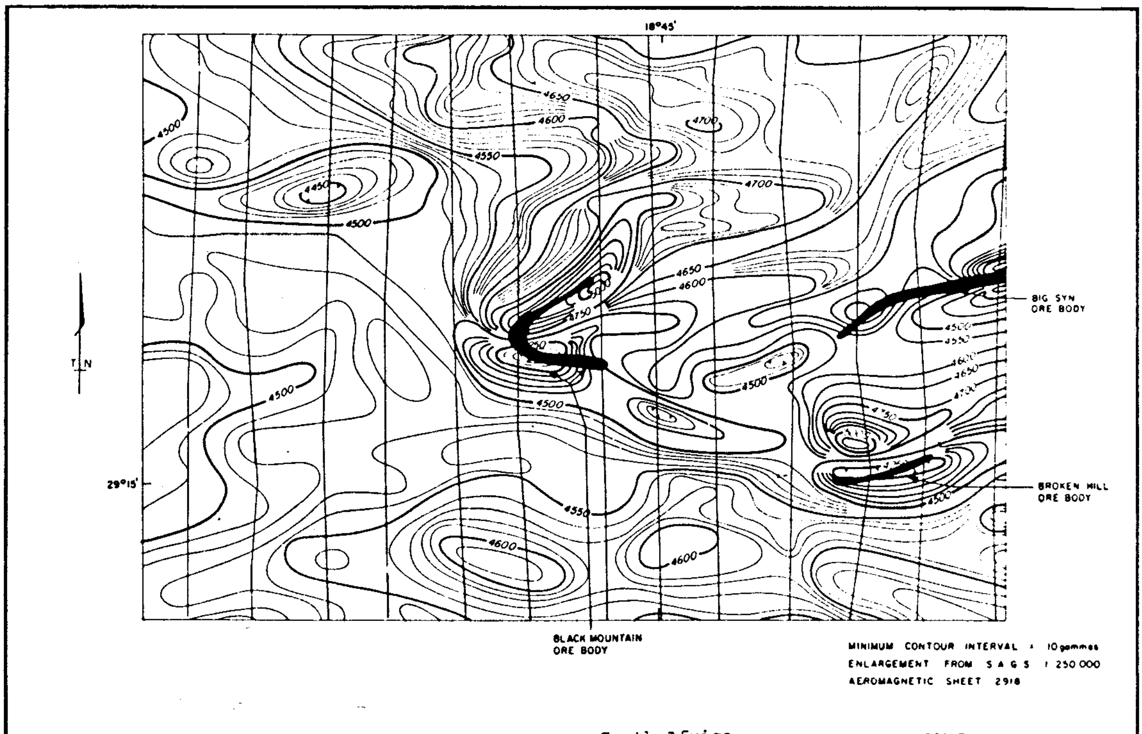


Fig. 27 Aeromagnetic contour map, Aggenys area, South Africa. From Campbell and Mason, 1979.

A more variable and less predictable relationship exists between the magnetite (pyrrhotite) content of volcanogenic ores of the Kuroko type, massive sulfide deposits. These deposits are characterized by a wide range of magnetic susceptibilities, many deposits being outlined by significant magnetic anomalies, while other deposits respond only weakly or not at all. Research into the underlying causes of this variation in the magnetic characteristics is considered beyond the scope of this dissertation, but is provides an interesting avenue for future study. Sangster and Scott (1976), have noted the association of magnetite with the chloritic feeder pipe zone which normally underlie these deposits. Perhaps a relationship exists between the composition of the wallrocks adjoining the alteration pipe and the magnetite content. The nature and grade of metamorphism is undoubtedly another important factor in the formation or destruction of magnetite that warrants consideration insofar as it has a direct bearing on the potential value of magnetic surveys. If the formation of magnetite is favoured by conditions of static-thermal metamorphism (which appears to be the case), and it is destroyed by dynamo-thermal metamorphic conditions, a consideration of the nature of metamorphism over the prospective area may be potentially valuable in assessing the applicability of a proposed magnetic survey. In this connection, the inversion of pyrite to pyrrhotite under high grade metamorphic conditions should be considered as a factor that is likely to enhance the magnetic susceptibility of a massive sulfide deposit.

The Izok Lake massive sulfide provides an example of the magnetic style that is characteristic of those volcanogenic deposits that are detectable using the magnetic method (Fig. 28). The deposit contains in excess of 12 million tons of massive zinc rich sulfides. The rocks of the mine area comprise highly metamorphosed and recrystallized metavolcanics and meta-sediments that have been intruded by numerous granitic bodies. No magnetic anomalies were recorded over the North Zone (Podolsky and Slakis, 1979), but a strong anomaly was evident over the main Central Zone due to the presence of widely disseminated magnetite and/or pyrrhotite. This anomaly could be traced in depth towards the north-west and this data was utilized in laying out the diamond drill grid. Although a number of electrical and electromagnetic surveys were conducted over the prospect, it was ultimately concluded that magnetic surveys were the best and most

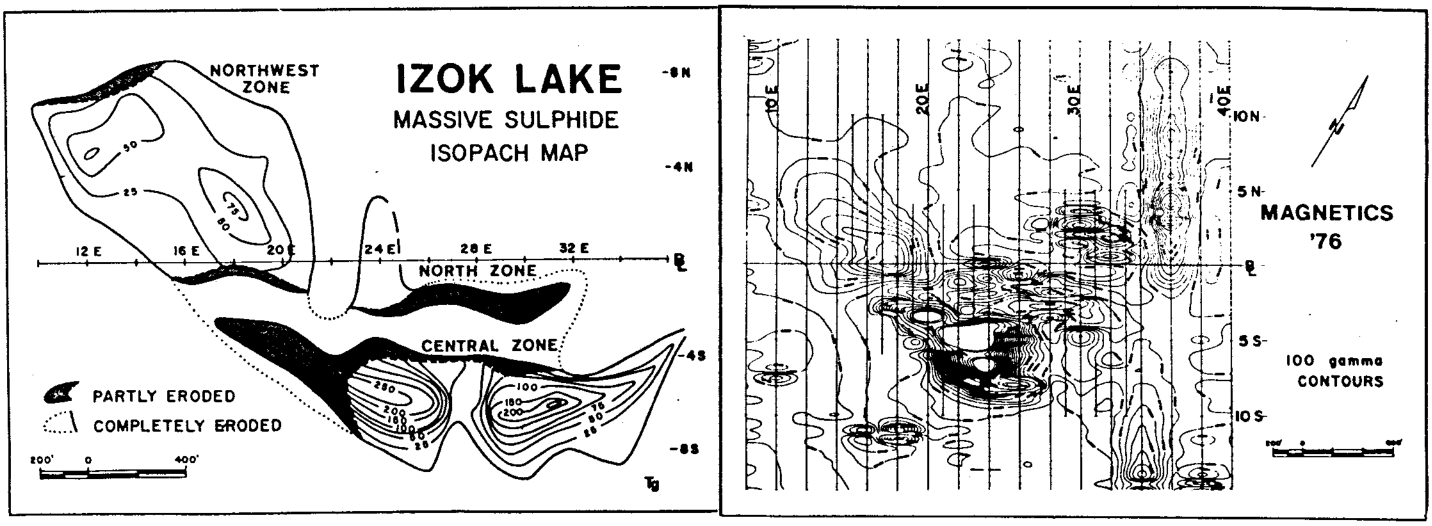


Fig. 28 Massive sulfide isopach map and ground magnetics over the Izok Lake deposits. From Podolsky and Slakis, 1979.

sensitive tool to use to delineate the extent of the known sulfides, and detect new ones at depth.

In the Mt. Lyell, Cobar and Tennant Creek mining districts of Australia (and elsewhere), numerous hydrothermal replacement Cu-Au (Ag-Bi) deposits are localized along major fault and shear zones. The gold-rich deposits at Tennant Creek and Cobar are both associated with appreciable concentrations of magnetite and both ground and airborne magnetometer surveys have been used extensively in the exploration for new orebodies (Rayner, 1967; Brooke, 1975). The recent discovery of the Elura massive lead-zinc-silver-pyrrhotite deposit in the Cobar district, under 100m of overburden, resulted from the follow up of a 30 gamma aeromagnetic anomaly. The exploration programme was apparently designed to locate hydrothermal replacement deposits akin to the Cobar deposits but the success of the programme serves to illustrate the wide potential value of the magnetic method in massive sulfide exploration.

The Real de Angeles silver deposit in Mexico, provides another interesting example which serves to demonstrate the value of magnetics in prospecting for hydrothermal deposits. Stoiser and Nieto (1979), describe the deposit as an asymmetrical funnel-shaped body that measures 400 x 500m near surface and extends to a depth of 300m. The deposit is hosted by flysch sediments and consists of galena, sphalerite and silver ore minerals. Magnetite has not been recorded, but pyrrhotite, pyrite and arsenopyrite were widespread in narrow fault veins and fractures, as disseminated grains, and along bedding planes. The total sulfide content lies in the 5-15 percent range of which less than 3 percent corresponds to the ore minerals, galena and sphalerite. The magnetic response (Fig. 29), is thought to be entirely due to the presence of disseminated pyrrhotite which averages 5% by volume, but locally it may exceed 15%. The trend of the magnetic anomaly parallels the orientation of the dominant fault trend and the orebody is centred directly under the positive magnetic high. In this example the value of the magnetic data was not fully appreciated until after the delineation drilling programme, but ordinarily it would be advisable to ascertain the cause of magnetic anomaly from the outset.

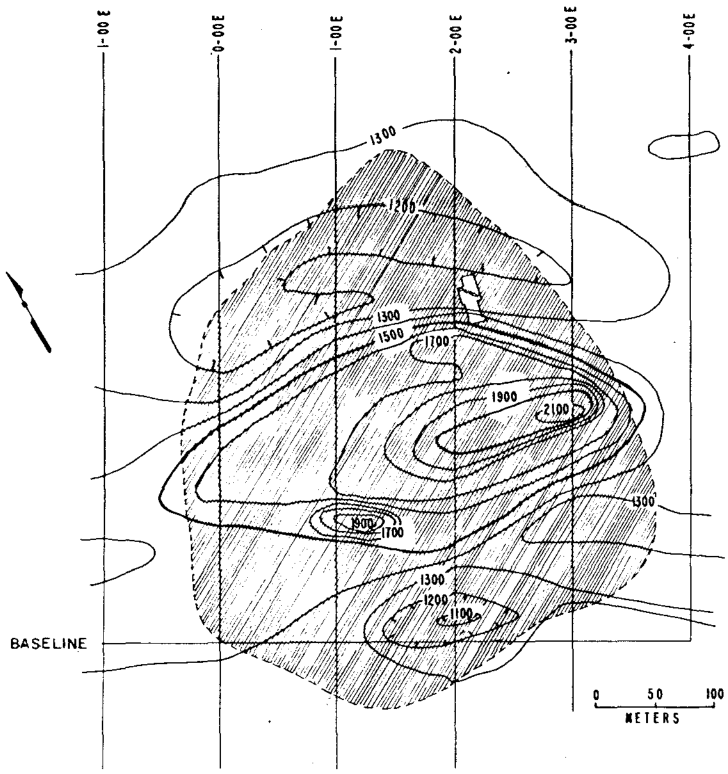


Fig. 29 Vertical field magnetic anomaly map over the Real de Angeles silver deposit. From Stoiser and Nieto, 1979.

The magnetic method was used in the exploration of subvolcanic gold-silver deposits in Nicaragua (Middleton and Campbell, 1979). The host rocks to the mineralization in the Loco Mine area of Nicaragua, comprise a sequence of Tertiary volcanics. The gold deposits occur as fracture controlled epithermal quartz veins that formed in a volcanic centre. Extensive hydrothermal alteration of the basalts in the mine area has destroyed most of the primary magnetite and a conspicuous ovoid shaped magnetic low is developed over the mineralized zone. A ring-shaped area of high (41 000 gamma) susceptibility surrounds the mineralized zone and it corresponds to areas of unaltered basalt. This example indicates the importance of carefully assessing the likely effect of hydrothermal fluids on the magnetic characteristics of an area. Broad circular zones of both positive or negative magnetic relief, may be associated with subvolcanic precious metal deposits.

Airborne magnetic surveys have been widely used in mapping the depth and configuration of the basement below major sedimentary basins. These surveys form an integral part of most petroleum exploration surveys, but recent adaptions to the method have been made in order to map shallow sedimentary basins. As with other magnetic methods, basement mapping surveys are cheap, quick and they can provide accurate depth estimates to the underlying basement. Surveys of this nature have not been used extensively in mineral exploration to date, but the method may be potentially valuable in exploration for sedimentary copper, carbonate lead-zinc, unconformity uranium, coal and other sedimentary ores, including Proterozoic gold-uranium placers.

Magnetic basement mapping techniques were originally dependent on the presence of a relatively uniform magnetic basement. The reliability of the method was adversely effected by magnetic inhomogeneities in the underlying basement. When these conditions were encountered, it was often difficult if not impossible, to distinguish between responses due to variations in the thickness of sedimentary sequences and those due to susceptibility contrasts in the basement. The effects of lithological variations in the basement are not as severe in mapping deep sedimentary basins because of the smoothing effects that are introduced by increasing the depth to the source. This is clearly illustrated in Fig. 30, which is a magnetic profile over the Canadian Arctic Islands (Reford, 1975). The profile shows the change in sharpness of the anomalies in going from shallow basement over Devon Island, to depths in excess of 300m in the Jones Sound Graben. The amplitude of the magnetic anomalies becomes weaker as the basement depth increases. The relatively smooth responses in the eastern

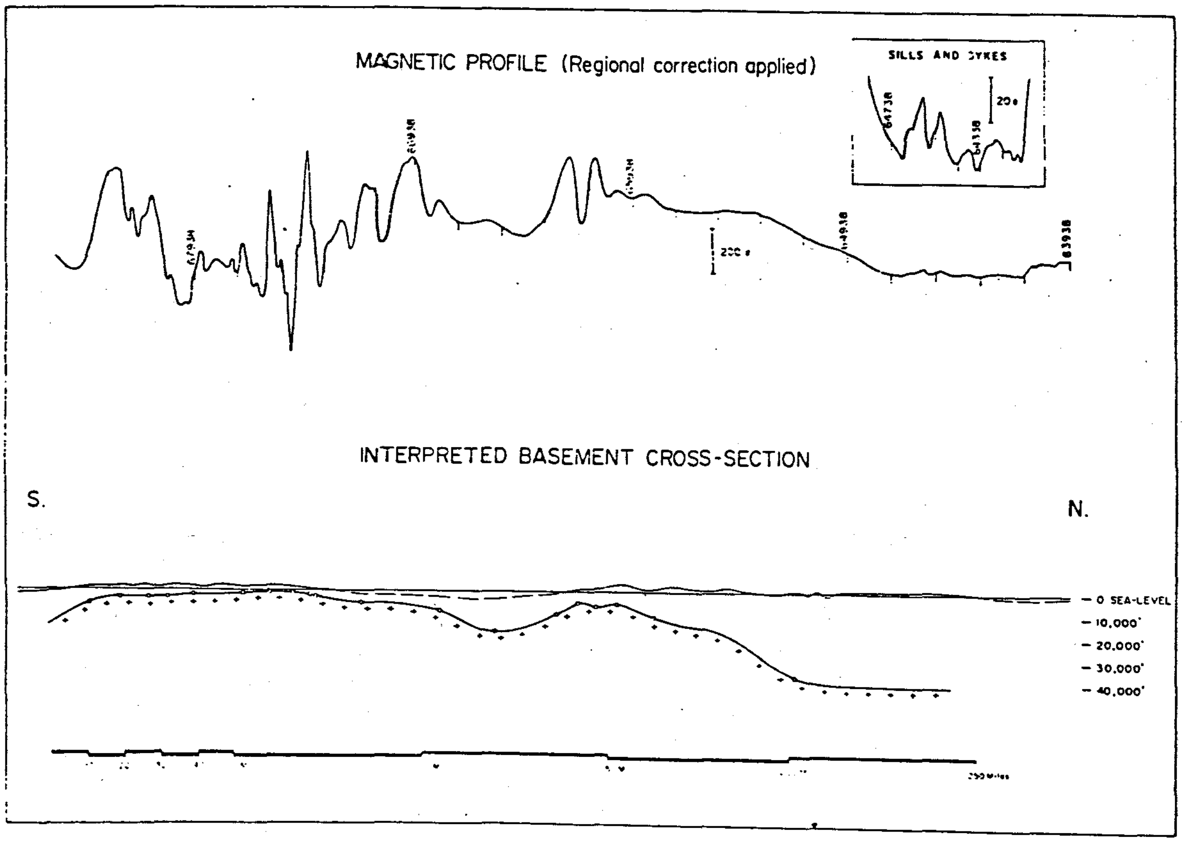


Fig. 30 Magnetic profile in the Canadian Arctic Islands.
From Reford, 1975.

section of the profile, are thought to be due to basement effects from a depth of more than 9000m. This example clearly shows the more complex nature of the magnetic pattern over the shallower portions of the basin.

Recent developments in mapping shallow sedimentary basins utilize the highly irregular anomaly pattern from the basement. The numerous magnetic responses derived from the underlying basement are now utilized to make depth estimates, through the analysis of the individual magnetic profiles. Computer programmes are available to perform the anomaly depth calculations automatically and the accuracy of the final survey results are largely a function of the number of basement anomalies that are available for analysis. The accuracy of the computer results are dependent on its ability to make a multitude of depth estimates from basement anomalies and to average these results to achieve a more reliable estimate. The accuracy of the final depth estimates can ordinarily be expected to be within $\pm$ 10 percent of the depth to the source below the aircraft. The magnetic data can also be used to locate fault zones which would appear as disruptions of the magnetic anomalies, or as linear magnetic boundary zones, possibly supported by changes in the depth estimates across the fault trace. If mineral deposits are associated with certain basement rocks, favourable zones may also be delineated by the magnetic data.

An interesting outline of the use of magnetics in shallow basin mapping is provided by Allingham (1966). The study relates to the exploration of Mississippi Valley-type lead-zinc deposits in the Bonne Terre area of the southeast Missouri mining district. The survey was initiated to aid in exploration for new lead-zinc deposits which are preferentially developed in reef complexes around palaeohighs in the basement or in the topographically higher ground between the basement highs. The reefs are flanked by shallow basins which are partly filled by argillaceous sediments. The results of the magnetic survey and the location of the known deposits is depicted in Fig. 31. The magnetic map was obtained by downward continuation of the total intensity aeromagnetic data to the level of the Precambrian surface. A broad association of the lead deposits with magnetic highs is apparent in most areas, and more elongate zones of mineralization occur in the areas between the magnetic highs. The shallow basins between the reef complexes are characterized by anomalies of low amplitude or by magnetic lows. Prominent magnetic lows are also developed over some of the major faults in the district, presumably due to alteration of the magnetite along the fault zone.

The magnetic method has been used extensively in exploring for gold and uranium deposits in the Witwatersrand Basin in South Africa. Magnetics are used to map out the highly magnetic shale horizons in the Lower Witwatersrand which maintain a fairly constant and predictable stratigraphic relation to the overlying gold-uranium placers. The magnetic data is used essentially to provide structural information about the lower Witwatersrand shales and this information, considered in conjunction with gravity data, provides the main guide for deep exploratory drilling. The ability of the magnetic surveys to locate the magnetic units in the lower Witwatersrand succession and major fault zones is shown in Fig. 32.

Airborne and ground magnetic surveys have been used extensively in the exploration of iron ores. Iron deposits containing magnetite

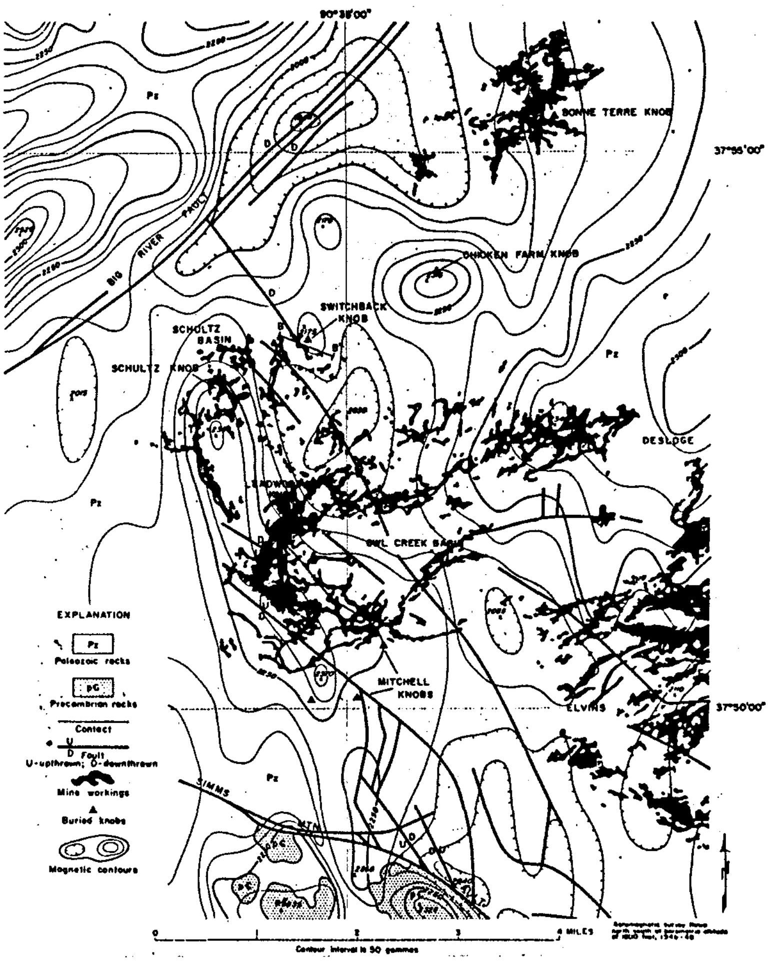


Fig. 31 Total intensity aeromagnetic map of the Bonne Terre area, southeastern Missouri. From Allingham, 1966.

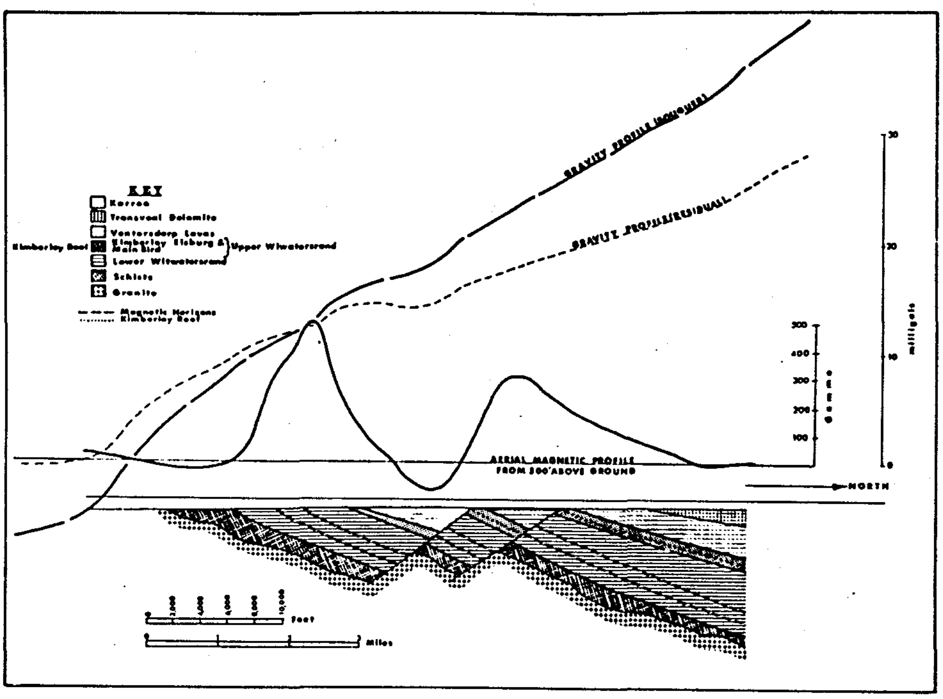


Fig. 32 Magnetic profile over faulted Witwatersrand sediments in the Evander Goldfield. From Roux, 1967.

are normally readily detectable by magnetics and similar surveys are used in the exploration for hematite deposits that are normally hosted by Proterozoic banded iron formations. The results of a typical survey over a Proterozoic iron ore district in South Australia are depicted in Fig. 33. The known economic iron ore deposits in the Middleback Range are hematitic ores which are not directly responsible for magnetic anomalies. The ranges contain large quantities of jaspilites which give rise to strong magnetic anomalies. The hematite bodies are not directly related to the main magnetic anomalies, but are developed in the adjacent areas, as illustrated in Fig. 33. Aeromagnetics and ground magnetic surveys are used to establish the general area of search, and gravity surveys are used subsequently to delineate the drill targets.

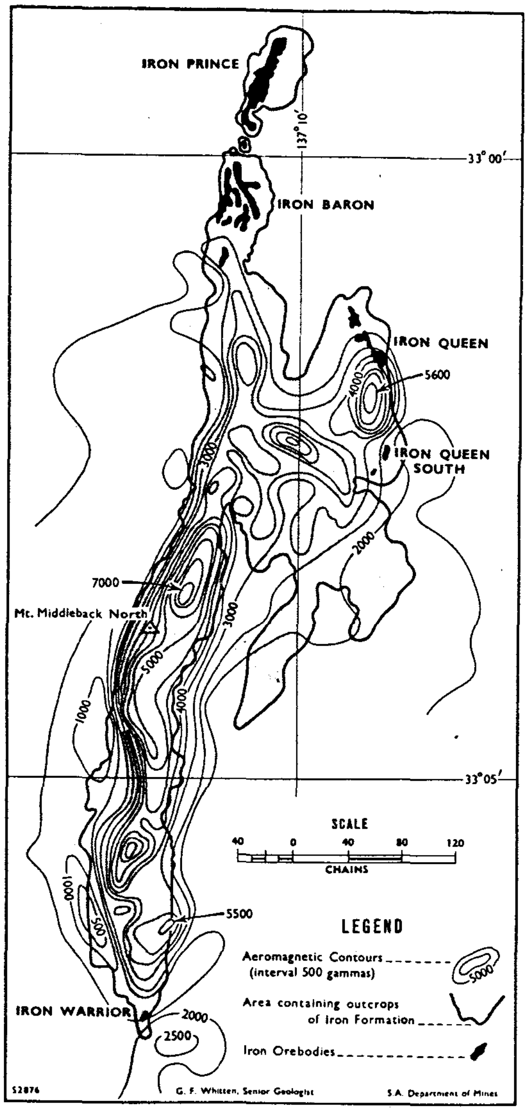


Fig. 33 Northern Middleback Range, showing results of low level (300 ft) aeromagnetic survey and location of economic iron deposits. From Webb, 1966.

Many iron ores with a high magnetite to hematite ratio, such as those related to igneous rocks, may be detected directly by magnetic methods. At Savage River, Tasmania, airborne magnetics defined the extent of a major magnetic anomaly and ground magnetic surveys were used to guide the delineation drilling programme (Rayner, 1967).

In many open pit mining operations, magnetic surveys may be used to outline different ore grade blocks. Fluctuations in the magnetite-to-hematite ratio, and areas containing increased silica, may be delineated by magnetic surveys. To maintain a uniform mill feed in many iron ore mines, it is common practice to classify the different ore types according to their magnetite content. A typical example is provided by the magnetic profile over an iron ore deposit in the Mesabi Range, presented in Fig. 34. The shallowly dipping Bewabik Iron Formation contains magnetite as a primary constituent and variations in the magnetite content of the ores are directly related to the degree of oxidation. Direct shipping ores are found in the intensely oxidized portions of the iron formations and these zones can be distinguished because they are broadly coincident with prominent magnetic lows. The less oxidized, magnetite rich ores can be more efficiently beneficiated and they coincide with magnetic highs. The magnetic surveys also provide information concerning the location,

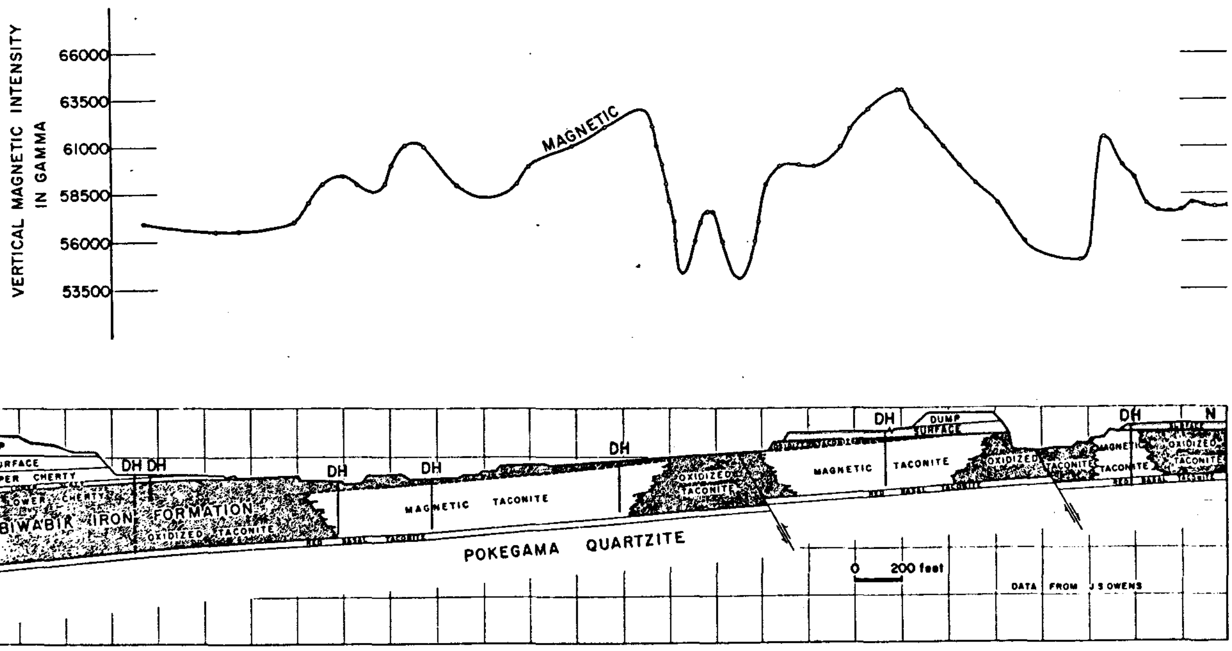


FIG 34 A typical cross section showing the relationship of magnetic lows to oxidation in the Biwabik iron formation on the western Mesabi Range.

depth, attitude and structure of the orebody through an analysis of the magnetic profiles. The depth estimates are particularly valuable in locating drill holes and in preliminary engineering studies of stripping ratios, and mining feasibility studies.

In certain situations magnetic surveys can be directly applied to the exploration of placer deposits. Many of the buried tin placers in the New England district in New South Wales, occur in old valleys that have been covered by flood basalts. The basalts are normally best preserved in the old river valleys and magnetic surveys may be used to map the distribution of the basalts. The strongest anomalies are usually found over the thickest parts of the basaltic sequence which is broadly coincident with the placer deposits, preserved in the deepest parts of the old river valleys.

Detrital magnetite may be concentrated along with gold, tin and other valuable constituents, in modern placers. Detailed magnetic surveys have been successfully applied in mapping the distribution of magnetite in order to locate placer gold in Alaska. The close correlation between the magnetic response and the distribution of gold values is evident in Fig. 35, which shows the results of a magnetic survey over a buried pay streak placer at Portage Creek in Alaska. The success of magnetics in the area was enhanced by the weak magnetic responses from the underlying basement.

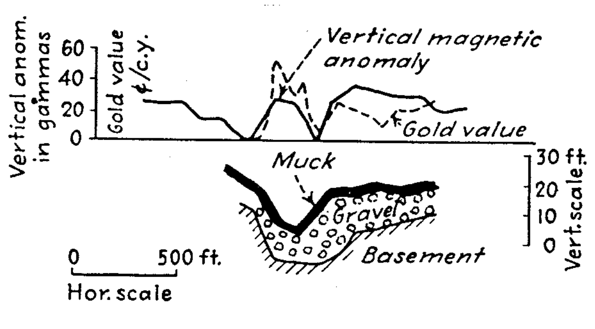


Fig. 35 Magnetic field, gold values, and geologic structure over the Portage Creek gold placers, Alaska. From Dobrin, 1960.

THE SELF POTENTIAL METHOD

The self potential (S.P.) method involves the direct measurement of naturally occurring potential differences on the earth's surface. Strong negative potentials are commonly encountered in areas overlying oxidizing sulfide deposits, graphitic shales, fault zones and other conductors. The generation of self potential anomalies above orebodies has been traditionally explained as being due to the migration of ions caused by sulfide weathering. This interpretation has been questioned by Sato and Mooney (1960) who suggest that the "electrical current is produced by the separate but simultaneous reduction of oxidizing agents near the surface and oxidation of the reducing agents at depth". The electrons are apparently transferred directly through the orebody from the reducing agents to the oxidizing agents. This theory enabled Sato and Mooney (1960) to predict the formation of strong self-potentials when the orebody is : 1) composed of minerals that are difficult to oxidize, 2) of a low electrical resistance, 3) extends vertically across the water table, and 4) exists close to the surface. These factors apparently impose important constraints in the applicability of the self potential technique in many geological environments.

The self potential method is cheap, simple and direct, but it is not totally reliable. The best results can be expected in relatively flat terrain with shallow oxidation and relatively high, stable water table conditions. In deeply weathered environments, the presence of the watertable above the level of past oxidation is not ideal and self potential anomalies are not developed over these orebodies. The method should be avoided if the overburden is greater than 30m, but it is an ideal method for locating small bodies at shallow depths because it is definitive and inexpensive. Graphitic horizons and strong fault linears both produce clear anomalies. While this adds seriously to the ambiguity of the method, in the majority of surveys it may provide a good cheap means of mapping fault zones. Problems are generally encountered in attempting self potential surveys in flat lying arid districts, due to the deep water table conditions, coupled with adverse effects produced by dry surface conditions and high resistivity layers. Spurious anomalies tend to develop over the crests of hills, presumably due to the irregular water table, and these 'ridge' anomalies can easily obscure and distort anomalies derived from oxidizing sulfides. Self potential responses tend to change dramatically after heavy rains, due to the increased electrochemical reactions. These effects are more noticeable after long, relatively dry periods.

On the west coast of Tasmania, the effects of recent glaciation, high rainfall and rapid erosion, have resulted in many fresh sulfide bodies being exposed close to the surface. Under these conditions the self potential method (and practically all other electrical methods) have given excellent results (Smith, 1980). In the Renison Bell tin field, cassiterite occurs as dolomitic replacement deposits in association with massive pyrrhotite. Strong and well defined self potential, magnetic, electromagnetic, resistivity and equipotential line anomalies are associated with the tin orebodies. Self potential surveys also worked well on the Cuni copper-nickel prospect that is situated in poorly drained, low lying country to the south-west of the Renison tin deposits. The Cuni deposits comprise of small 20 000 ton segregations of massive millerite that are locally developed along the base of a gabbro sill. Ground magnetic surveys were also used effectively on this prospect to outline the non-outcropping basic bodies.

A comprehensive case history relating to the discovery of the Que River massive sulfide deposit in Tasmania (Webster and Skey, 1979), serves to illustrate some of the limitations of the self potential method. The results of an S.P. survey over the prospect are illustrated in Fig. 36. A strong -200 to -300 millivolt anomaly was produced over the eastern shoot which consists of bands and stringers of coarsely crystalline pyrite, with subordinate galena, sphalerite and chalcopyrite. Heavily pyritized and altered pyroclastics are developed to the east of this lens which outcrops on the top of a low rise. Topographically it lies approximately 10m above the sub-outcropping western lens which is characterized by more massive high grade mineralization. The ore is rich in sphalerite (22-23% Zn) and galena with the Zn:Pb ratio approaching 2:1 in most intersections. The ore in the western lens commonly exhibits bands, in the 1 mm to 1 cm range, of pyrite, sphalerite and galena with minor chalcopyrite. The western orebody outcrops intermittently on the surface, and it attained a maximum width of 13m at a depth of approximately 100m. The very poor S.P. response of the western shoot is evident in Fig. 36, and the same body failed to respond to electromagnetic methods.

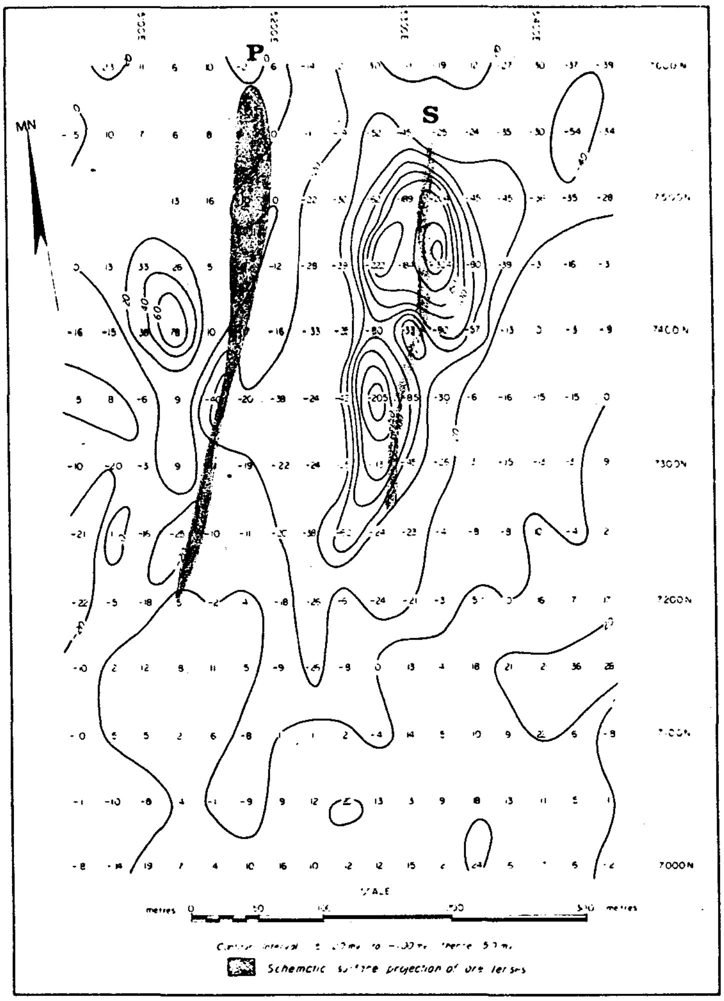


Fig. 36 Self-potential contour map. Que River Prospect, Tasmania. From Webster and Skey, 1979.

Self potential surveys can be effectively applied in exploring for massive copper-nickel sulfide deposits, an account of which is provided by Bergey et al. (1957). The copper-nickel orebodies at the Temagami Mine, Ontario, are localized along the footwall of a large intrusive gabbro. The orebodies contain approximately 2.25 million tons of ore assaying 1.6 percent combined copper and nickel and over 50 000 tons of nearly massive chalcopyrite. Self potential anomalies of over 300 millivolts were obtained over the massive chalcopyrite orebodies (Fig. 37) and anomalies of over 500 millivolts were recorded over the more massive copper-nickel sulfide ore.

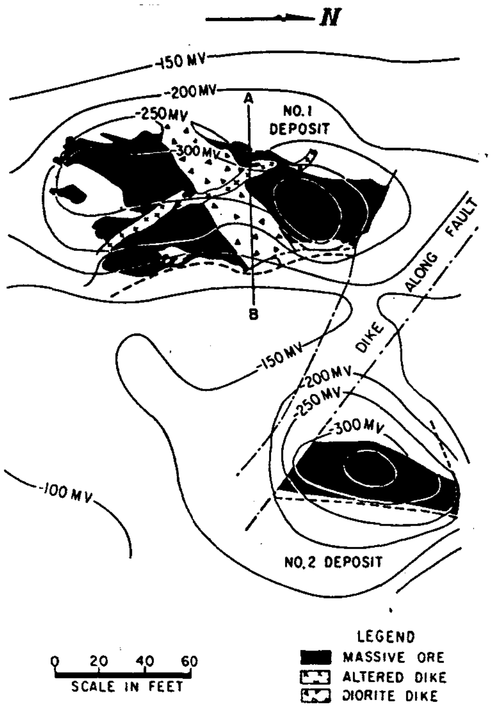


Fig. 37 Self-potential anomalies over the massive chalcopyrite orebodies. Temagami Mine, Ontario. From Ward, 1966.

A brief outline of the use of the self potential method on the Zambian Copperbelt is provided by Garlick and Gane (1961). The extremely deep oxidation of sulfides and effects of tropical weathering adversely effect most electrical techniques on the Copperbelt, but the self potential method has apparently worked well in many instances. Substantial self potential anomalies are developed over most of the known deposits and this technique has been widely applied in conjunction with soil geochemical surveys. The results of a self potential survey over the Chibuluma orebody is outlined in Fig. 38. A notable feature of this anomaly is that the 100 millivolt peak is laterally displaced from the suboutcrop of the orebody for a distance up to 100m and this feature is commonly observed on the Copperbelt.

Numerous spurious self potential anomalies were inevitably encountered in the Copperbelt and screening of these anomalies was done using soil geochemical surveys. The results of the self potential surveys were found to be useful in mapping various formations, faults,and fractures. Carbonaceous shales and pyritic tillite beds consistently produced conspicuous negative anomalies which were traceable over most of the Copperbelt. The self potential effects were found to be considerably smoothed during, and immediately after, the rainy season,and surveys conducted during this period were easier to interpret.

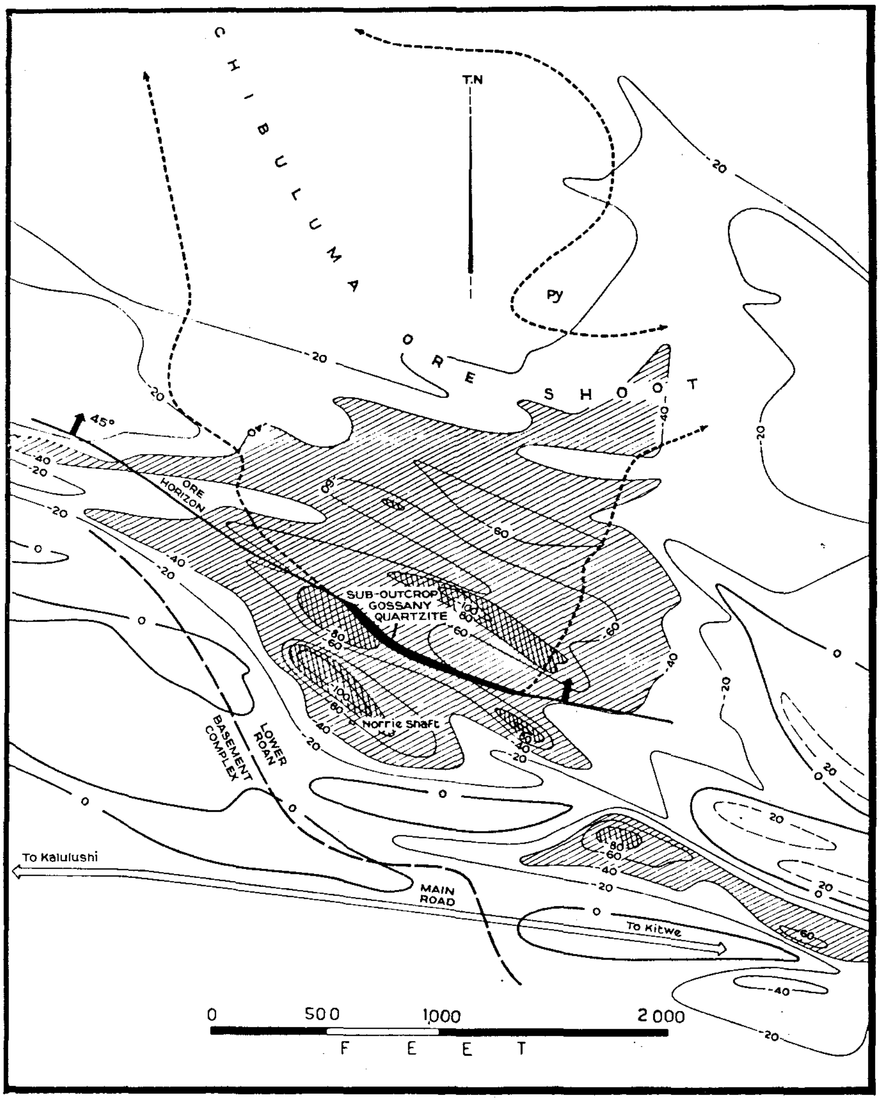


FIG. 38 Chibuluma. Self potential contours (millivolts) above Chibuluma orebody. The minus 60 millivolt contour coincides with the plan projection of the shallower part of the ore shoot; "parasitic" anomalies occur in the footwall of the orebody. From Garlick and Gane, 1961.

The Kimheden sulfide deposits in Northern Sweden are essentially similar to the deposits along the Matchless Amphibolite Belt in South West. The mineralization consists of cupreous pyrite that is hosted by sericitic quartzites and the deposits produce a relatively strong self potential effect as is evident in Fig. 39. The sulfide lenses are weathered in the west but relatively fresh host rocks are developed over the rest of the area. Relatively fresh sulfides are commonly encountered at depths of 10m or less, and this fact enhances the potential value of self potential surveys in the region. A number of distinct S.P. anomalies were encountered over the area covered by the survey and the centres of maximum potential (300 - 450 mV) were broadly coincident with the underlying sulfide mineralization. No correlation appeared to exist between the peak of the

S.P. response and the maximum widths of mineralization as subsequently determined by diamond drilling.

The self potential method could be used in prospecting for many different types of sulfide deposits, provided the sulfides are relatively massive. As the method is primarily dependent on the generation of natural potentials due to sulfide weathering, the presence of pyrite or pyrrhotite, as a primary constituent, is desirable as this will promote sulfide weathering. Conduction will be enhanced by the presence of massive interconnecting sulfides, a condition that is more likely to be developed in deposits that have been remobilized by metamorphism. Where applicable the self potential method can provide a relatively cheap and effective means of locating sulfide deposits. Self potential surveys can be conducted by relatively unskilled labour and this factor could enhance the use of self potential surveys in some areas, given a reasonably favourable depth of weathering and other environmental factors.

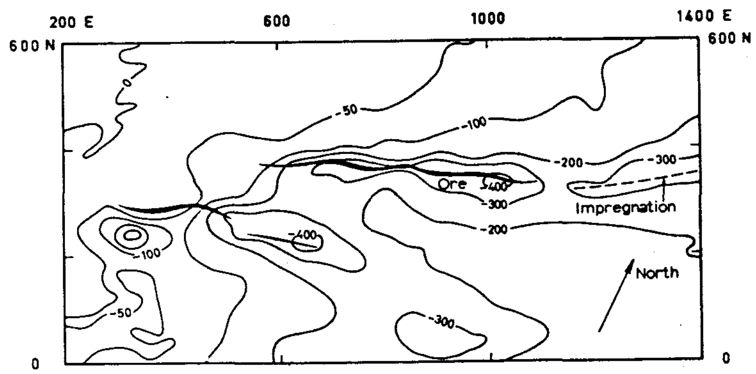


Fig 39 Self-potential map of the Kimheden pyrite orebody, northern Sweden. Coordinates in m, contours in mV. (Courtesy of BGAB.) From Parasnis, 1966

THE INDUCED POLARIZATION - RESISTIVITY METHOD

The induced polarization (IP) resistivity method was primarily designed to detect disseminated sulfide mineralization, and its effectiveness in this regard has been firmly established. The method is very useful in the search for large zones of disseminated sulfides that can be detected at depths of 500m or more. Induced polarization surveys have also been successfully used in the search for zones of higher grade mineralization associated with volcanogenic sulfide deposits and carbonate hosted lead-zinc deposits. The I.P. method is one of the few geophysical techniques that can be effectively applied in the search for sedimentary copper, tin, tungsten and epigenetic precious metal deposits, due to the common association of disseminated sulfides with these ores.

Another important use of the induced polarization method stems from the techniques ability to distinguish between ionic and metallic conductors. Water filled faults and shears, conductive overburden, and other features commonly produce spurious electro-magnetic anomalies and they can easily be interpreted as being due to metallic conductors. The I.P.-resistivity method can be used to resolve spurious E.M. anomalies because the anomalies associated with fault zones are normally defined by a resistivity low. Furthermore, since these anomalies are due to ionic conduction, appreciable I.P. effects are not developed over shear zones. Metallic mineralization must be present to cause a significant I.P. effect under most geological conditions. Another important factor of relevance in this regard, is that the I.P. method is a better indicator of the volume of metallic mineralization present, while the E.M. method is more sensitive to the area of a conductor. The last mentioned factor accounts for the ability of the E.M. method to detect water-filled fault and fracture zones.

The depth penetration characteristics of the I.P. method are extremely favourable and this is another important factor that enhances the potential of induced polarization surveys. In regions of conductive overburden, most electro-magnetic surveys are adversely effected and the depth penetration of E.M. methods may be severely limited in these situations. In environments where conductive overburden conditions prevail, the I.P. method has decided advantages over the E.M. methods and under geologically favourable conditions the methods ability to detect orebodies buried at considerable depths, is a distinct advantage.

Most metal sulfides respond to the I.P. effect including chalcopyrite, pyrite, bornite, chalcocite, pyrrhotite, arsenopyrite, and molybdenite, but sphalerite will not produce a significant response. Graphite inevitably produces a strong I.P. effect and its presence in many geological environments constitutes a major problem in the interpretation of I.P. results. Iron and manganese oxides in the MnO_2 and FeO_2 form (magnetite and pyrolusite) can also respond to the I.P. method and this effect may further complicate interpretation in some regions. Ground magnetic surveys are therefore normally run over zones of high chargeability prior to drilling, to test for the possible presence of magnetite. Platy silicate minerals can also produce fairly marked I.P. effects, particularly montmorillonites and vermiculites, but koalins, chlorites, muscovites, biotite and talc are not normally anomalous.

The magnitude of the I.P. response is primarily dependent on the grain size of the responsive minerals and the smaller particles tend to produce the most pronounced I.P. effect. In order to respond to the I.P. method the mineral grain boundaries should be fresh as thin oxide coatings are sufficient to render a sulfide inactive. Thin coatings of limonite around sulfides or magnetite grains will totally surpress the induced polarization effects around the mineral grain boundaries. It is therefore important to assess the effective depth of weathering prior to the initiation of a survey and adjust the electrode spacing accordingly.

The induced polarization-resistivity technique has been used extensively in mineral exploration for a wide variety of ore types, despite its comparatively high cost, which exceeds that of electromagnetic methods. The popularity of the method stems from its effectiveness and it is also possible to obtain resistivity, self potential and electromagnetic information which can help in the resolution of anomalies. The induced polarization effects are measured with both frequency and time domain equipment. It is generally accepted that both methods are equivalent and neither method has important advantages over the other. A number of different electrode arrays are available and the choice of a suitable array is largely dependent on the nature of the survey. Computer modelling studies were made by Coggon (1973) to assess the relative merits of the different I.P. arrays and the results of this work are summarized in Table 3.

The effectiveness of an I.P. survey is largely dependent on the electrode spacing as it influences the magnitude and width of the anomaly. The electrode spacing is particularly important when the source of the anomaly is of a limited volume. A short electrode separation should be used to locate a relatively small body at shallow depths, but a similar target, located at greater depths, will be difficult to detect. The electrode spacing should always be at least twice as great as the depth to the top of the responsive body in order to produce a maximum I.P. effect. The cost of induced polarization surveys escalates significantly with smaller electrode spacings and it is therefore best to use as broad a separation as possible. The overall volume, shape and depth of the anticipated discovery are the most important factors that should be considered in choosing an optimal electrode spacing.

TABLE 3 From Sumner, 1979

Summary of features of IP arrays

	Dipole-Dipole	Pole-Dipole	Gradient	Schlumberger and Wenner
Response amplitude	Good	Fair	Poor	Poor
Dip of structure	Poor	Poor	Good	Fair
Depth of exploration	Good	Good	Fair	Poor
Resolution of mineralization	Good	Good	Fair	Poor
Freedom from EM coupling	Fair	Fair	Poor	Poor
Interpretability of layering	Poor	Poor	Fair	Good
Depth estimates	Fair	Fair	Fair	Fair
Signal-to-noise ratio	Poor	Fair	Good	Good
Labor needed	Poor	Fair	Good	Good
Susceptibility to noise	Fair	Fair	Good	Good

Resistivity measurements are routinely made in conjunction with the induced polarization method and it provides additional information that can be used to assist in the interpretation of the chargeability data. The resistivity (I.P.) method can be used in two ways :

1. Resistivity sounding measurements can be made by measuring the apparent resistivity for increased electrode spacing. This resistivity data is useful for outlining horizontal disposed beds and it can be applied to most sedimentary environments.

2. The electrode separation can be kept constant and resistivity - I.P. is recorded as the array is moved along a traverse. In this manner apparent resistivity and chargeability data can be obtained at various positions along a line. Arrays of this nature are normally used in most mineral exploration surveys.

In many regions, the major rock units can be classified according to resistivity contrasts and it is possible to map these units broadly with resistivity measurements made during the compilation of a routine I.P. survey. The accuracy with which these units can be mapped may be greatly enhanced if ground magnetic data is also available as this improves the accuracy of the geophysical interpretation. This approach has direct application in areas of extensive overburden because it enables the geologist to trace the extent of various lithologies which have been identified in outcropping areas.

The high sensitivity of the resistivity method may be used for mapping the details of ore bearing formations and other geological features that are associated with variations in electrical resistivity, including faults and shear zones. The resistivity data is potentially more valuable than the chargeability information because different rock types can normally be distinguished by their apparent resistivities. If the resistivity data is compiled as contour plans the resulting map will reflect fairly accurately the nature and distribution of different lithologies. The information provided by the chargeability data is also valuable but conductive zones are normally relatively narrow. Consequently this information may more effectively delineate the trend of the conductors but the broad distribution of the main lithological units is better defined by resistivity data. Resistivity mapping works particularly well in high grade metamorphic terrains due to the sharp contacts between rocks of markedly different resistivities.

Induced polarization-resistivity methods have been widely applied in the search for nickel sulfide mineralization in the

Archean granite-greenstone terrain in Western Australia. Most of the rocks in this environment are deeply weathered and this favoured the use of the I.P. method. The results of dipole-dipole, pole-dipole and gradient array surveys over two narrow zones of nickel sulfide mineralization is presented in Fig. 40. The resistivity data clearly

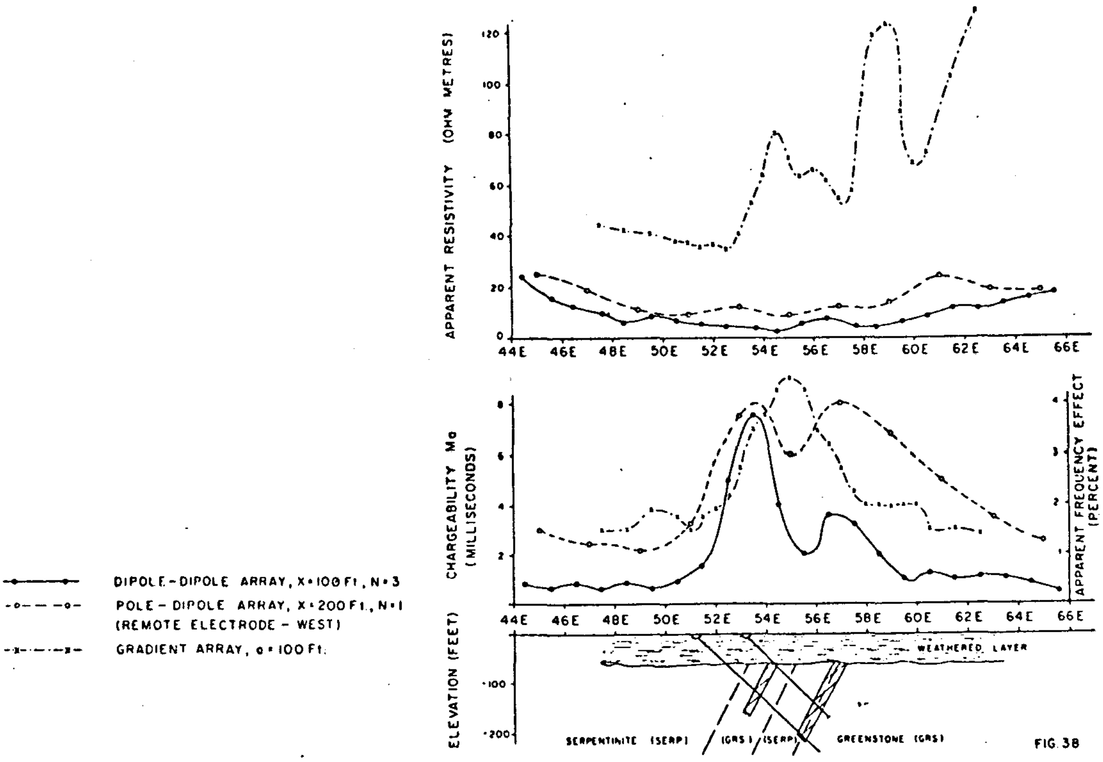


Fig. 40 Results of an induced polarization survey, over narrow zones of nickel sulfide mineralization in Western Australia. From Smith, 1980.

indicates the enhanced response of the gradient array in situations where a conductive surface layer is present. The contrasting resistivities of the serpentinites and greenstones is apparent on the gradient profile, the latter being characterised by resistivities of greater than 60 ohm metres. The gradient array I.P. profile fails to differentiate between the two mineralized zones but it shows a single anomalous peak centred over the two zones. The dipole-dipole and pole-dipole data both show two distinct I.P. peaks that are centred directly over the two mineralized zones. These arrays would therefore be preferable in locating diamond drill sites in situations where more than one mineralized zone is likely be be encountered.

The results of an I.P.-resistivity survey over the Posiedon orebody at Windarra, Western Australia are presented in Fig. 41,

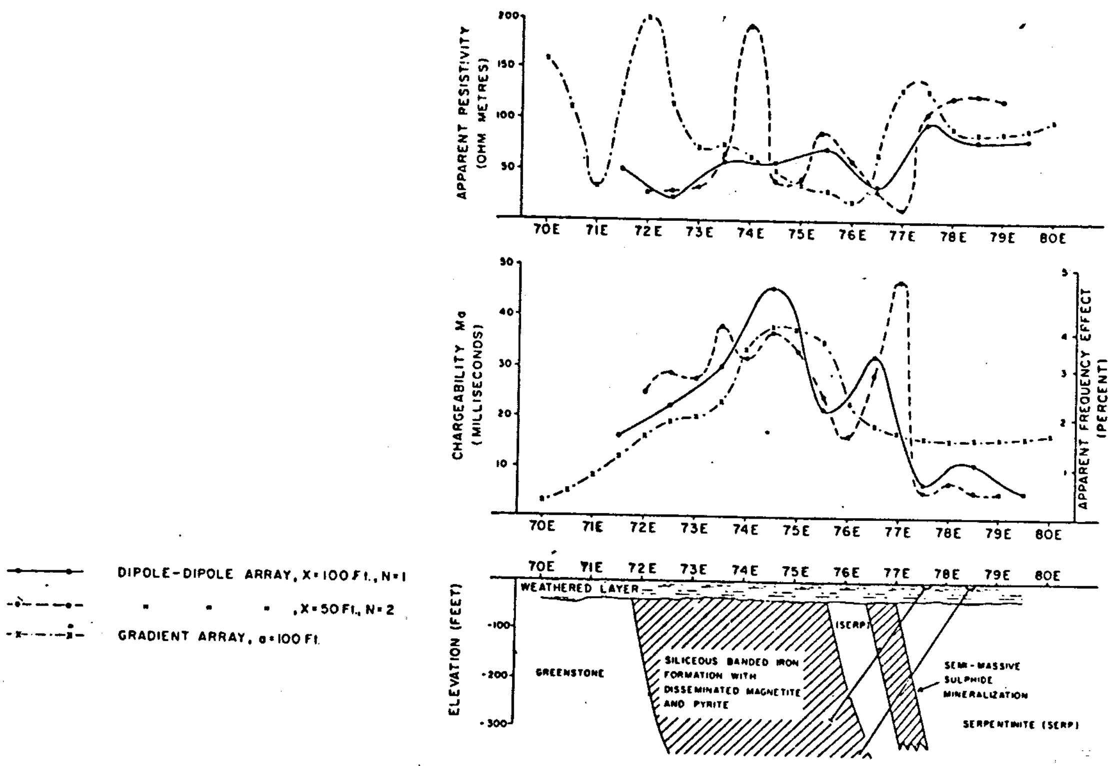


Fig. 41 Results of an induced polarization survey over the Posiedon nickel sulfide orebody, Windarra, Western Australia. From Smith, 1980.

together with the corresponding geological cross-section. The ore zone at Windarra is associated with a serpentinised peridotite and the ore comprises a normal pyrrhotite-pentlandite assemblage. Sulfides, on average, represent 15-25 percent by volume of the ultramafic host. The sill-like ultramafic body lies with apparent conformity between banded iron formations to the west and meta-basalts to the east. The iron formation contains pyrite and magnetite and it produces a strong I.P. response. The gradient array data over the mineralized zone (Fig. 41) shows an irregular resistivity effect with a local high over the copper-nickel sulfide zone. The single broad peak was obtained on the chargeability data using the gradient array. A better I.P. response was obtained over the mineralized zone using a dipole-dipole array and a significantly stronger anomaly was located over the banded iron formation.

An interesting example of the use of induced polarization surveys in exploration for nickel copper sulfides in the Temagame area and an electromagnetic survey was commissioned to explore the strike extensions of the host peridotite. The Turam electromagnetic results located several conducting zones and three of the E.M. anomalies were drilled with negative results, before the decision was made to conduct an induced polarization survey. The results of both surveys are illustrated in Fig. 42. The strong E.M. anomalies that were tested by holes 1, 2 and 3 in the southern portion of the area, were not associated with any significant I.P. responses. The

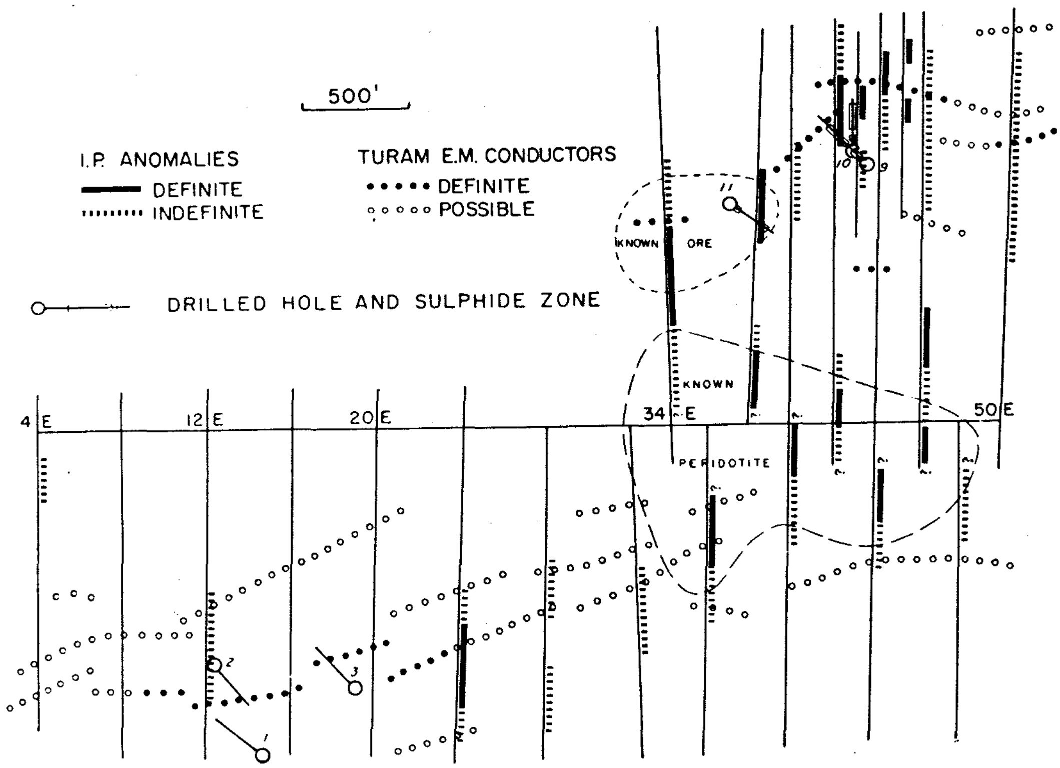


Fig. 42 Results of induced polarization and Turam E.M. survey over nickel sulfide mineralization in the Temagami area, Ontario. From Hallof, 1967.

source of the anomalies was due to narrow shears and fractures. The I.P. anomalies located over the peridotite formed broad zones of moderate chargeability and they were thought to be due to the presence of magnetite. Strong I.P. and E.M. anomalies were located over the known mineralization and in an area to the northeast. This anomaly was tested by diamond drill holes 9, 10 and 11, all of which intersected substantial amounts of disseminated and massive sulfides. The results of this case history clearly illustrate some important characteristics of the I.P. method, namely its enhanced ability to distinguish between narrow zones of ionic conduction and broad zones of disseminated mineralization. The limitations of the Turam E.M. system and potential value of detailed magnetic surveys in this environment, are also apparent.

In cases where small copper-nickel sulfides are expected near surface, the I.P. or S.P. methods should always be used in preference to electromagnetic surveys. A section through the MacLennan orebody in the Sudbury district is illustrated in Fig. 43, together with the corresponding magnetic E.M., S.P. and I.P. profiles. Extremely weak electromagnetic results were obtained over the orebody but distinct anomalies were obtained with the other methods. In most geological environments orebodies of this type can be most effectively delineated using a combination of magnetics and induced polarization which would ordinarily be used to augment geochemical and geological information.

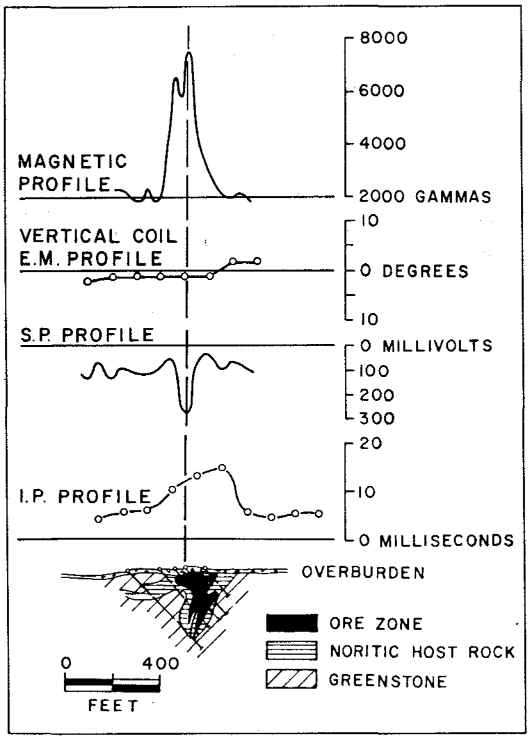


Fig. 43. Geophysical results over the MacLennan orebody, Sudbury, Ontario, showing the enhanced I.P. response and poor E.M. results over the suboutcropping nickel sulfide deposit. From Dowsett, 1967.

The induced polarization method may even produce meaningful results over deposits which are of a predominantly massive sulfide character as illustrated by the discovery of a large copper-nickel orebody in the Montcalm Township in Canada. The deposit contains 60 percent pyrrhotite with lesser pyrite, pentlandite and chalcopyrite, and the results of an I.P. survey over the orebody are shown in Fig. 44. The survey used a dipole-dipole array with an electrode spacing of 50m. The frequency effect reached a maximum of only 3.2 percent and a resistivity low of 53 ohm metres. Although the location of the deposit was not obvious on the resistivity data, it was more clearly defined on the metal factor and frequency effect.

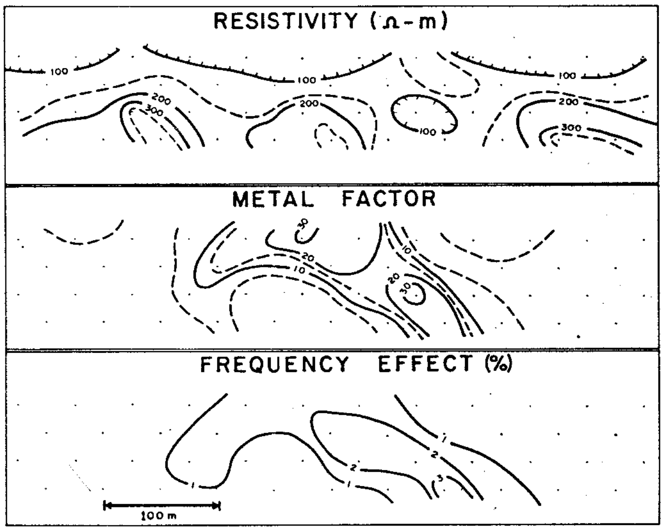


Fig. 44 Induced Polarization survey results over a Copper-Nickel deposit, Montcalm Township, Ontario.
From Fraser, 1978.

The most important factor to be considered when using induced polarization methods in prospecting for nickel-copper sulfide deposits lies in the fact that magnetite can produce a significant I.P. response. The interpretation of the results of an I.P. survey over nickel prospects should therefore be guided by the results of geological and magnetic surveys. Pyritic tuffs and shale horizons are commonly encountered in the country rocks adjacent to the ultrabasic bodies that form the preferred host rocks for nickel sulfide mineralization. These horizons also produce strong I.P. effects which can further complicate the interpretation of the geophysical data. Spurious I.P. anomalies derived from pyritic, volcanoclastic sediments, shales and graphitic horizons can generally be recognized by their more persistent character. The low magnetite content of these horizons also provides an effective means of screening out these spurious anomalies. The vast majority of nickel sulfide deposits respond geophysically to I.P. and magnetics and a combination of these methods provides an effective means of defining target areas. The I.P. effects produced by magnetite provide the main problem in distinguishing sulfide responses from anomalies due to magnetite. Geological and/or geochemical considerations therefore usually provide the most effective means of assigning a priority to I.P. anomalies located during the exploration for nickel sulfide deposits.

The use of induced polarization surveys in tin-tungsten exploration is not well documented but the widespread association of sulfide mineralization with many exogranitic deposits suggests that I.P. methods may be effectively applied in some instances. Sulfides of pyrite, pyrrhotite, arsenopyrite, galena, chalcopyrite and molybdenite are common associates of hydrothermal tin deposits. The successful application of I.P. surveying to tin-tungsten exploration will largely depend on the amount of sulfides present and their relation to the cassiterite mineralization. The extent to which the sulfides are disseminated in the country rocks adjacent to the tin-tungsten mineralization is also a critical factor which will be controlled by the composition of the wall rocks, degree of fracturing of the host rocks, together with the depth and extent of hydrothermal activity. Large replacement deposits and stockwork lode systems form potentially good targets for detection with I.P. methods, but narrow lode generally present poor targets.

The relatively small size of most tin deposits would necessarily dictate the use of small potential and current electrode spacings in the majority of situations and this will impose limitations on the depth of penetration. In some areas, as for example, on the Rooiberg A Mine, extensions to the known tin mineralization is actively being sought and the constraints imposed on the depth penetration of the I.P. method by the small electrode spacing presents a major problem. In situations like these, consideration may be given to conducting I.P. surveys underground, along all the existing development headings. This would be particularly valuable in locating depth extensions of the replacement bodies below the lower levels of the mine. Small electrode spacings should be maintained in order to obtain a maximum I.P. response from the replacement pockets which contain significant local concentrations of sulfides. Underground surveys may also be contemplated in prospecting for other lode occurrences including precious metal deposits.

The large volume and disseminated nature of most porphyry copper (molybdenite) deposits makes them ideal targets for detection by induced polarization methods. The dipole-dipole electrode array is normally employed in porphyry exploration because it uses shorter wires than the other arrays for the same search depth. This minimises the adverse effects of inductive coupling which is a problem when long wires are laid out over a conductive overburden. It is also desireable to use lower frequencies as this minimises the effects of inductive coupling and this enhances the sensitivity and depth penetration characteristics of the I.P. survey.

Porphyries form very large targets which extend in depth and they are commonly surrounded by a zone of barren pyrite. Frequently the maximum I.P. response occurs over the barren pyrite zone but careful interpretation can often separate zones of different intrinsic I.P.-resistivity effects, thereby defining the different zones of mineralization. An example is provided by an extensive I.P. survey over the Poison Mountain deposit, the results of which are illustrated in Fig. 45. The I.P. survey shows a well defined zone of high chargeability peripheral to the best copper mineralization. The main anomalous zones (>15 millisec) are coincident with a pyritic halo while anomalies in the 5-10 millisec. range reflect the better grade mineralization, in contrast to the background levels of less than milliseconds. This association of I.P. anomalies with the porphyry mineralization is apparently typical of most deposits. The most valuable sulfide zone is associated with neither the central low nor the peak chargeability response, but rather with the zones of intermediate intensity between the highest and the lowest I.P. effects. This is an important fact to note, especially if diamond drilling intersects a pyrite rich zone that coincide with a moderately strong frequency effect,as it may well indicate that the economic mineralization lies in the adjacent area.

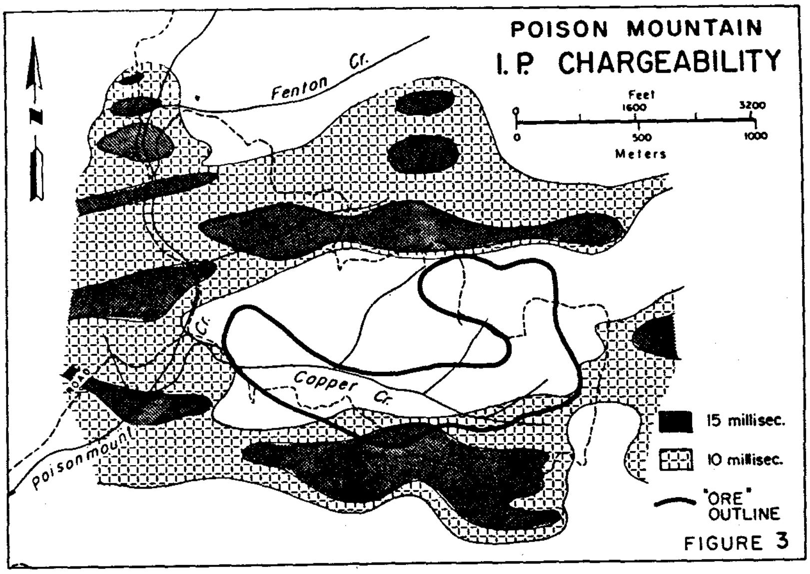


Fig. 45 Induced polarization-chargeability results over the Poison Mountain porphyry deposit, British Columbia. From Seraphim and Rainboth, 1976.

Linder (1975) provides an interesting description of the results of an induced polarization survey over the Shaft Creek porphyry copper-molybdenum deposit in British Columbia.

"Induced polarization surveys by McPhar Geophysics Ltd., using a 200 foot electrode spacing, show a large anomalous area closely related to the Schaft Creek deposit .... The strongest anomalies trend north along the breccia and connects the South and North breccia deposits. The main deposit is marked by intermittent, less intense, probable and possible anomalies. The anomalous area also extends several thousand feet south of the main deposit, probably because sulfide distribution is related to strong north-south fracturing. The induced polarization results can be interpreted to outline a partial pyrite halo which is strongly developed in the west and moderately well developed in the south.

The induced polarization anomalies result primarily from the distribution of pyrite. The volume percent of chalcopyrite, bornite and molybdenite required to be of economic interest, is so small that only relatively weak anomalies occur over the main deposit".

The importance of using relatively widely spaced potential electrode spacings in porphyry exploration is emphasised by Seigel (1971). If the depth to the top of a broad zone of disseminated mineralization is variable, measurements with a small electrode interval may detect only the mineralization that is closest to the surface. If a distinct zonation of copper values is evident within the broad zone of mineralization, holes drilled to test the shallow zone may not intersect the best ore. This situation was encountered in conducting induced polarization surveys over the Lornex porphyry deposit in British Columbia. The results of I.P. surveys over this deposit are presented in Fig. 46. The resistivity expression is featureless, but 3 array measurements at electrode spacings of 200 and 400 feet, indicate the uneconomic pyritic mineralization in the eastern side of the porphyry. The strongest I.P. effects were produced over the economic mineralization at depth on a 800 foot spacing. The stronger response over the mineralization in this example was due to the higher grade nature of the disseminated sulfide zone.

The main problems involved in the interpretation of I.P. resistivity data in porphyry environments, lie in the extent of the disseminated sulfide zone. The anomalies are generally extremely broad and it may be difficult to interpret the anomalies in terms of the underlying geology. Whether or not the anomalies are due to barren pyrite or economic sulfides may also be difficult to ascertain.

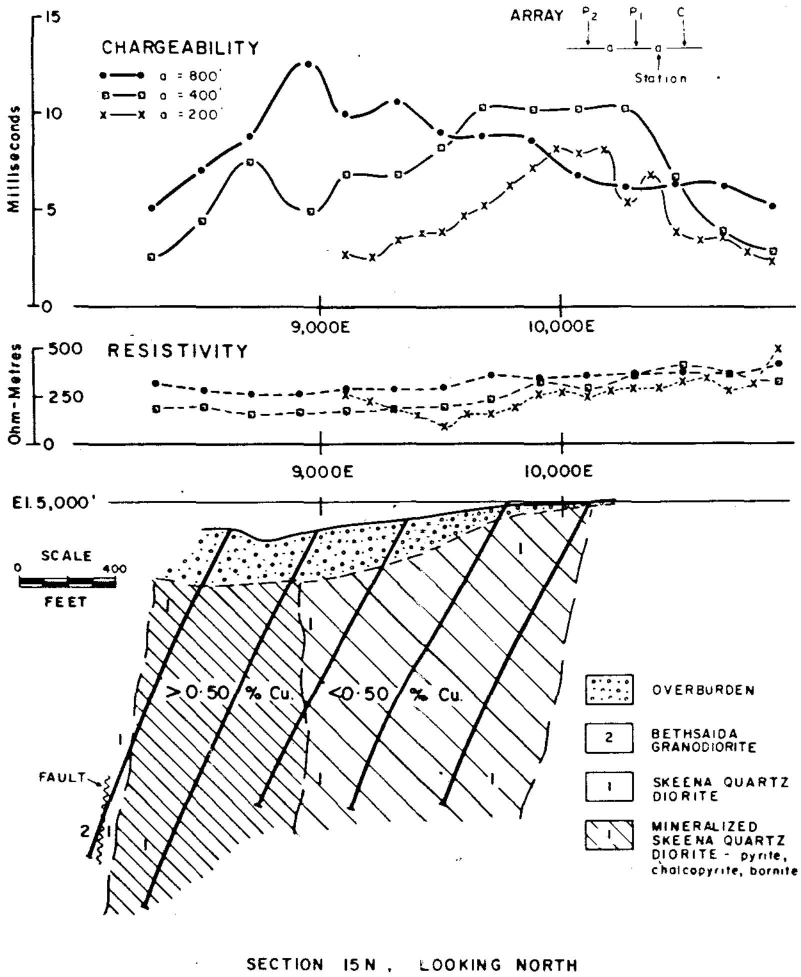


Fig. 46 Geophysical and geological section, Lornex porphyry copper deposit, British Columbia, Canada. From Seigel, 1971.

It is therefore imperative that the geology over a porphyry deposit is relatively well known before initiating a large I.P. survey. A thorough understanding of the generation and geological characteristics of porphyry systems is potentially the most valuable means of interpreting the results of induced polarization surveys over porphyry deposits.

Induced polarization surveys have been used widely in the search for massive sulfides which normally give both an I.P. and resistivity effect. Although massive sulfide zones might normally be detectable by more economical electromagnetic methods, there are situations in which the I.P. method must be used. Where the presence of thick overburden and deep weathering have created a highly conductive surface layer, the induced polarization method is commonly used in preference over the electromagnetic method.

The use of the induced polarization method in the search for massive sulfides over recent years has resulted in the discovery of a number of massive sulfide deposits that have failed to respond to E.M. techniques. The large Kidd Creek orebody near Timmons, Ontario, is widely quoted as being an airborne E.M. discovery, but the actual orebody is only a weak E.M. conductor and the main geophysical response apparently resulted from the graphitic shales that are well developed in the footwall of the deposit (Fig. 47). Induced

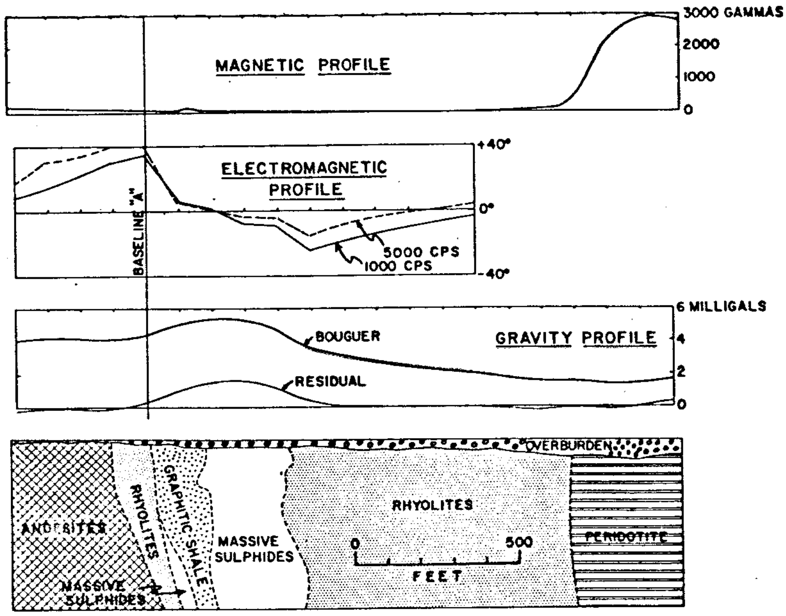


Fig. 47 Geophysical profiles over the Kidd Creek massive sulfide deposit. From Donohoo et al., 1970.

polarization surveys have been used more widely in the Kidd Creek area over recent years, and some new deposits have been located. The I.P. data shown in Fig. 48 detected a broad zone of massive sulfides under 55m of glacial overburden. The same zone failed to respond to the vertical loop electromagnetic method as evident in the top profile in Fig. 48.

Hallof (1967) provides a number of examples which demonstrate the use of induced polarization methods in exploring for massive sulfides. In the New Brunswick region of eastern Canada and in many other areas, massive sulfide zones have been located using induced polarization surveys in areas where previous electromagnetic surveys failed to detect mineralization. This is demonstrated in Fig. 49 which shows two, near surface, massive sulfide zones that failed to respond to a vertical loop E.M. survey. The two sulfide zones lie

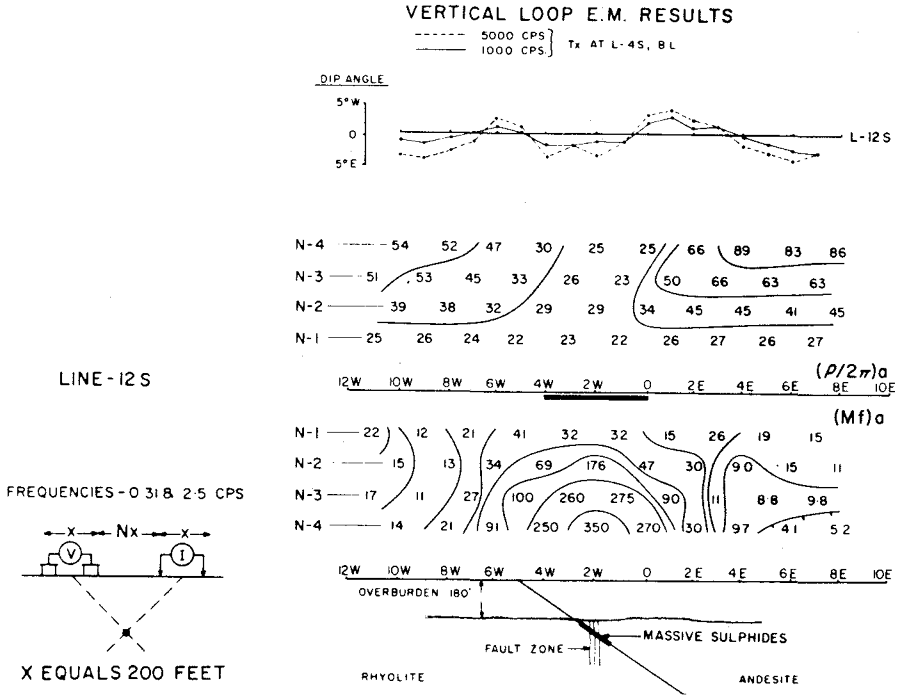


Fig. 48 Comparison of E.M. and I.P. results from the Timmins area, Canada. From Hallof, 1967.

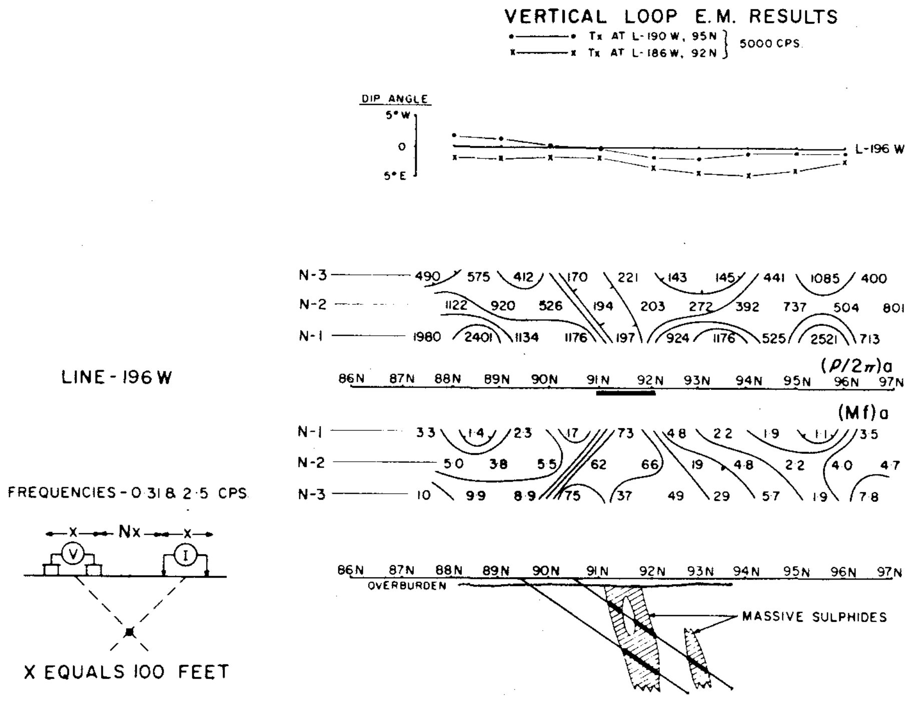


Fig. 49 Induced polarization and E.M. results over mineralization in the Newcastle area, New Brunswick, Canada. From Hallof, 1967.

along the contact between underlying volcaniclastic rocks of high resistivity and lower resistivity argillites. The orebody was clearly indicated by the result of the induced polarization survey (Fig. 49).

Another important characteristic of the I.P. method lies in its greater depth penetration capabilities compared to the E.M. method. The I.P. method has a greater depth of detection than the E.M. method for all but vertical, thin, sheetlike conductors. This property enhances the potential value of the I.P. surveys in sulfide exploration when the target is thought to lie at a considerable depth. Exploration for massive sulfides in the Flin Flon area, Manitoba, utilized I.P. surveys to locate mineralization buried at a depth of 70m below Paleozoic limestone. The results of both Horizontal loop and turam E.M. surveys were negative, as evident in Fig. 50. The I.P. survey generated a strong anomaly which was found to be due to massive sulfides and graphite.

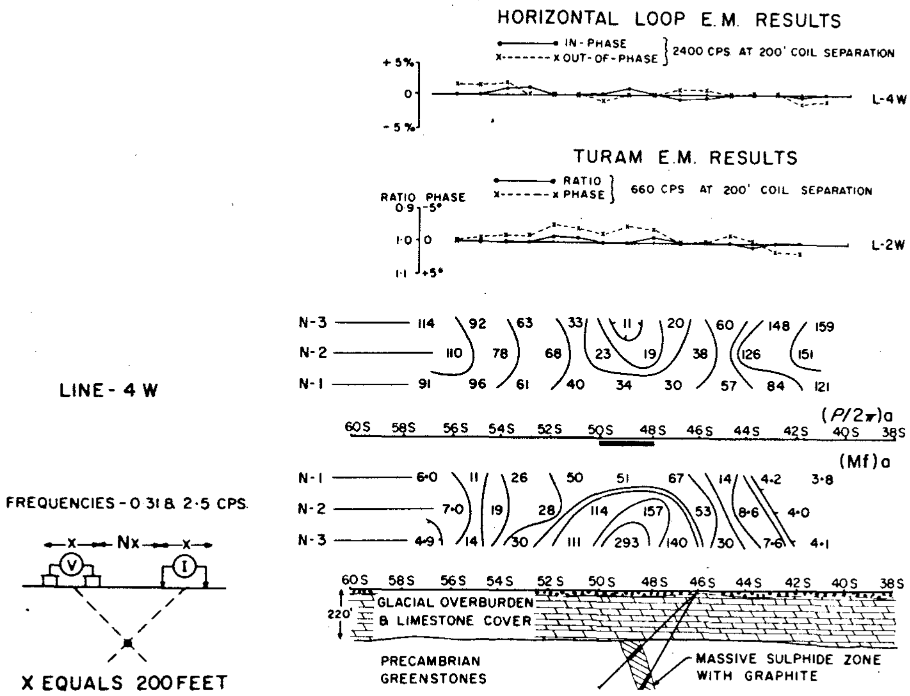


Fig. 50 Comparison of E.M. methods and I.P. results from the Flin Flon area, Manitoba, Canada. From Hallof, 1967.

The third main application of the I.P. method in the exploration of massive sulfide deposits lies in arid and tropical areas. The use of electromagnetic methods in these environments is limited due to the presence of ionic conductors which generate many extraneous E.M. anomalies. The results of induced polarization-resistivity surveys in conductive overburden situations is more definitive because the I.P. technique responds to metallic conductors. The ionic conductors in arid regions do not respond well to I.P. survey methods and this fact may be employed to eliminate many extraneous anomalies. Fig. 51 demonstrates the strong electromagnetic anomaly over a major fault zone in the arid, Mutooroo area of South Australia. The adjacent banded massive sulfide zone did not respond very well to a vertical loop E.M. survey, but a distinct I.P. anomaly was obtained over the mineralized zone.

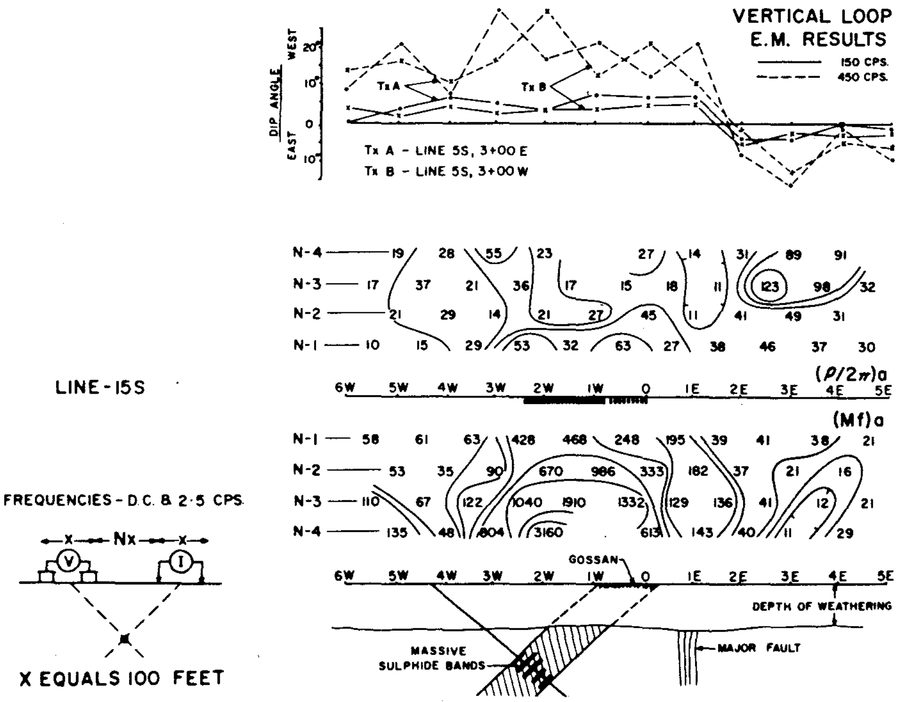


Fig. 51 I.P. and E.M. results from the Mutooroo area in South Australia. From Hallof, 1967.

The use of induced polarization in the exploration for sulfide mineralization has many distinct advantages over the electromagnetic method, provided the source is sufficiently wide to generate an anomalous response. The main limitation of the I.P. method lies in its comparatively high cost when considered in relation to electromagnetic survey methods. Consequently the E.M. method is normally the preferred geophysical means of prospecting for massive volcanogenic sulfide deposits but it is important to note that there are situations in which I.P. may be more effectively employed.

The exploration for carbonate hosted lead-zinc deposits has benefited in a number of instances from the application of induced polarization methods. Papers dealing with this subject can be found in Callahan and McMurry (1967), Seigel (1971), Lajore and Klein (1979), to which the reader is referred for more details.

The successful application of I.P.-resistivity surveys in the exploration for carbonate hosted lead-zinc deposits is essentially dependent on the presence of pyrite or marcasite in the lead-zinc ores. In regions where iron sulfides are not intimately associated with the lead-zinc mineralization, the induced polarization method should not be used. In these situations further exploration would have to be geochemically or geologically oriented because other geophysical methods cannot be used effectively in delineating Mississippi Valley type ores.

Carbonate reef complexes form the potential host rocks for the majority of carbonate lead-zinc deposits. Pyrite and graphite are commonly encountered in many reef environments and they are particularly abundant in the back reef environment where strongly reducing conditions prevailed. The indiscriminate use of the I.P.-resistivity method in the carbonate reef environment may therefore lead to the delineation of a multitude of anomalies and this factor should be borne in mind by those involved in lead-zinc exploration in the carbonate environment. This method should ideally be applied to areas that are considered to hold potential on the basis of geochemical and/or geological evidence given an established association of iron sulfides with the lead-zinc mineralization.

The Mogul Mines lead-zinc-silver deposit in the Silvermines District of Ireland, is located in lower Carboniferous limestones near the fault contact with Devonian sandstones. The location of the deposit was indicated by a broad geochemical anomaly and induced polarization surveys were utilized in conjunction with electromagnetic and graviometric surveys to establish the presence of mineralization in depth. The results of an I.P. survey over the Mogul Mines deposit is presented in Fig. 52. The chargeability peaked at 20 msec. over the near surface portion of the orebody, and the anomaly tailed off in a direction paralleling the dip of the orebody. A pronounced resistivity low, of the order of 80 ohm-m was coincident with the I.P. response. Subsequent drilling outlined 11 000 000 tons of ore, averaging 2.8% Pb, 8.2% Zn and 0.8 oz Ag.

A recent review of the use of geophysics in the Pine Point area of Canada, is given by Lajoil and Klein (1979). The ores are hosted by a Devonian barrier reef complex and consist of sphalerite, marcasite, galena, pyrite and occasional pyrrhotite, in decreasing order of relative abundance. Comparative geophysical tests conducted in 1963 clearly demonstrated that I.P. was potentially the most valuable exploration tool in the district, due to an extensive cover of glacial till which averages 15m in thickness over most of the area.

Exploration at Pine Point uses stratigraphic drilling to define areas of good geological potential and induced polarization surveys are employed to locate targets for drilling. The I.P. method originally employed a gradient array with a potential electrode

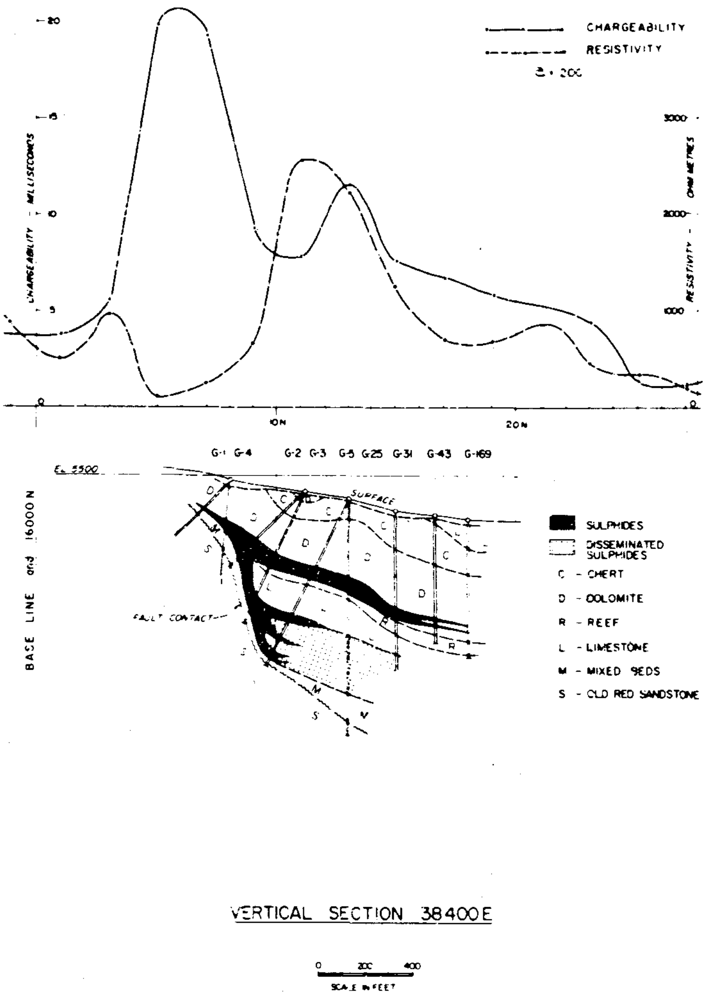


Fig. 52 Geophysical I.P. and geological section, Mogul Mines lead-zinc deposit, Ireland. From Seigel, 1971.

spacing of 60m and this configuration located a number of high grade (>15% combined sulfides) deposits. The four chargeability anomalies evident in Fig. 53, all reflect the presence of lead-zinc orebodies lying at a relatively shallow depth below glacial cover. The very low variation in the background level of the chargeability in the Pine Point district (Fig. 53) is a characteristic feature and it simplifies geophysical interpretation considerably. NB (This pattern is probably not characteristic of all reef complexes and considerable difficulty may be encountered in interpreting I.P. results over similar environments elsewhere.)

In order to detect the lower grade orebodies (± 4% Pb, 1,5% Zn, 1% Fe) at Pine Point, it was necessary to halve the current, and potential electrode spacing to 610m and 30m respectfully in order to detect a definite I.P. anomaly. The high cost of these surveys prompted the use of two separation pole-dipole arrays which were subsequently found to be better focused for the detection of weakly disseminated mineralization. The pole-dipole arrays also made it

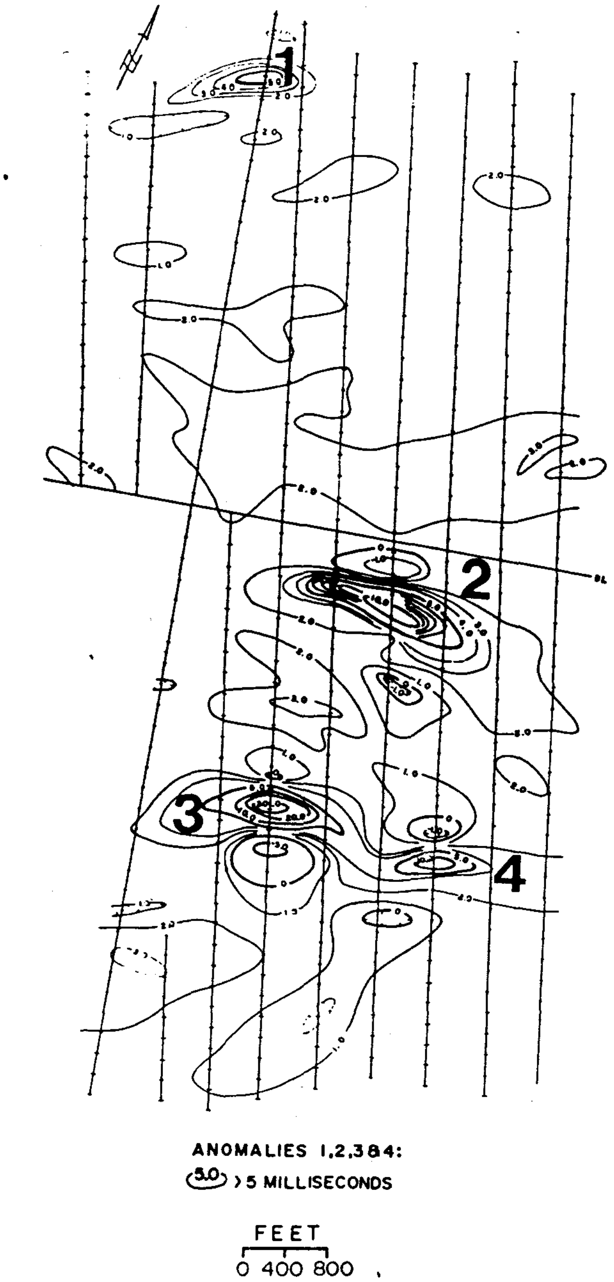


Fig. 53 Chargeability contour map of gradient array I.P. survey over four carbonate hosted lead-zinc deposits, Pine Point, Canada. From Lajoie and Klein, 1979.

easier to interpret the depth and lateral limits of the polarizable sources. The pole-dipole surveys located a number of low grade deposits but they were unable to detect sphalerite-rich lead-poor orebodies that occur in association with minor (± 1%) conductive sulfides even at shallow, 30-40m depths. In the absence of a geochemical response the low grade sphalerite rich bodies continue to represent extremely difficult exploration targets.

Callahan and McMurry (1967) summarise the results of extensive geophysical surveys that were conducted over the Mississippi Valley lead-zinc deposits in southwest Wisconsin, U.S.A. The results of induced polarization and electromagnetic surveys in this district were generally disappointing, despite the presence of galena and pyrite in the ore. Smith (1980) provides one example from the Wisconsin district in which a dipole-dipole survey located a small, pyrite-rich, ore zone at a depth of approximately 100m, as shown in Fig. 54. The same orebody failed to respond to vertical loop electromagnetic measurements using frequencies of 1000 Hz and 5000 Hz. The majority of deposits in the Wisconsin district fail to respond to applied geophysical methods and consequently geophysics has played a subordinate role to geological and geochemical methods in the majority of carbonate lead-zinc districts in the United States.

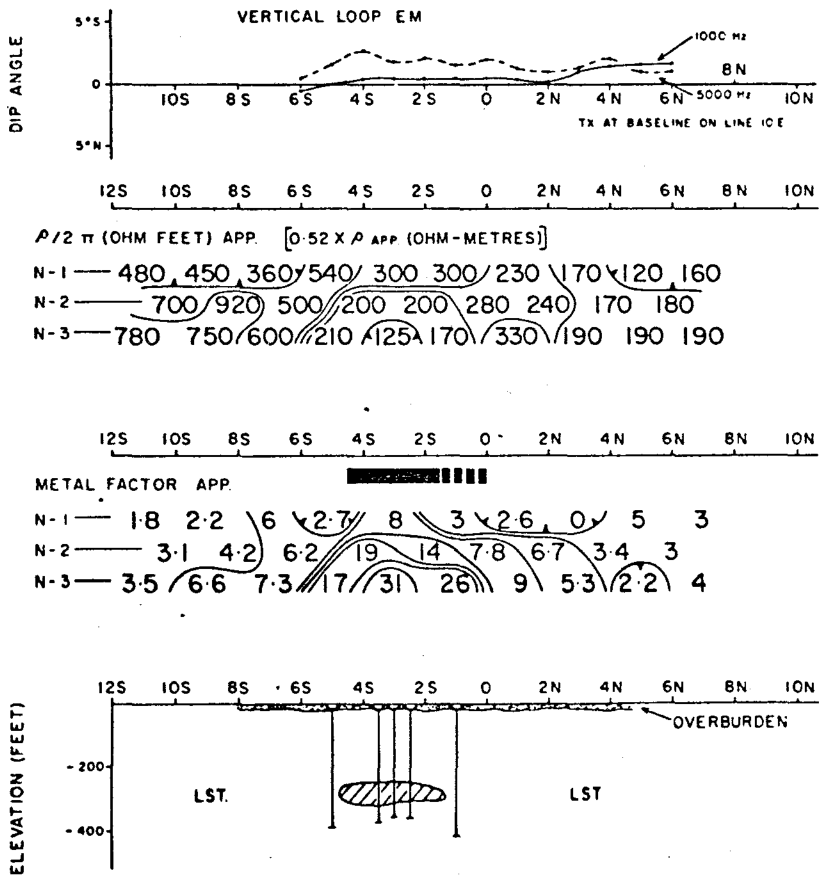


Fig. 54 Induced polarization results over a pyritic orebody in the Wisconsin lead-zinc district, U.S.A. From Smith, 1980.

The highly variable results that have been obtained by I.P. surveys directed at locating carbonate lead-zinc deposits, suggest that the method should be applied with caution in carbonate environments. The successful application of I.P. surveys in exploration for Mississippi Valley type deposits is dependent on the presence of iron sulfides which need not be associated with the ores of a particular district. Indeed, in many situations relatively widespread concentrations of biogenetically derived pyrite and graphitic schists may generate numerous spurious anomalies and this may limit the effectiveness of I.P. surveys in many, if not most, carbonate reef environments. The relatively high grade nature of the deposits at Pine Point and their mineralogy, are important factors which enhance the value of I.P. in the Pine Point district but the method is less effective in locating lower grade deposits, particularly when zinc rich ores are anticipated. Carbonate hosted deposits that display a close genetic relationship with volcanic or volcaniclastic units, as is the case in Northern Ireland, and deposits of a replacement origin, are normally associated with iron sulfides and I.P. resistivity surveys may find more direct application in these areas. In the majority of cases however, induced polarization surveys should be used to locate drilling targets that have already been delineated by geochemical and/or geological surveys. The limitations of the I.P. method should be kept in mind at all times, and the absence of an I.P. response over a potential area need not reflect the absence of ore grade mineralization, either near surface or in depth.

The mineralization in the majority of sedimentary copper, and lead-zinc deposits occurs as discrete grains of sulfide and pyrite is commonly closely associated with these ores. The sedimentary sulfide ores should therefore respond to the induced polarization method. Hancock (undated) indicated that both surface and down hole I.P. surveys over the Kalulushi East deposit on the Zambian Copperbelt, met with moderate success; with high frequency effects and low resistivities corresponding to the mineralized zone. Reference to the use of I.P.-resistivity methods in the exploration of sandstone hosted galena deposits in Sweden, is made by Parasnis (1967). The mineralization consists of finely divided disseminated galena in Eocambrian sandstones that are subhorizontally disposed. A geological section and geophysical profile over the deposit are outlined in Fig. 55. The ore horizons produced a recognizable I.P. response that is coincident with a resistivity low.

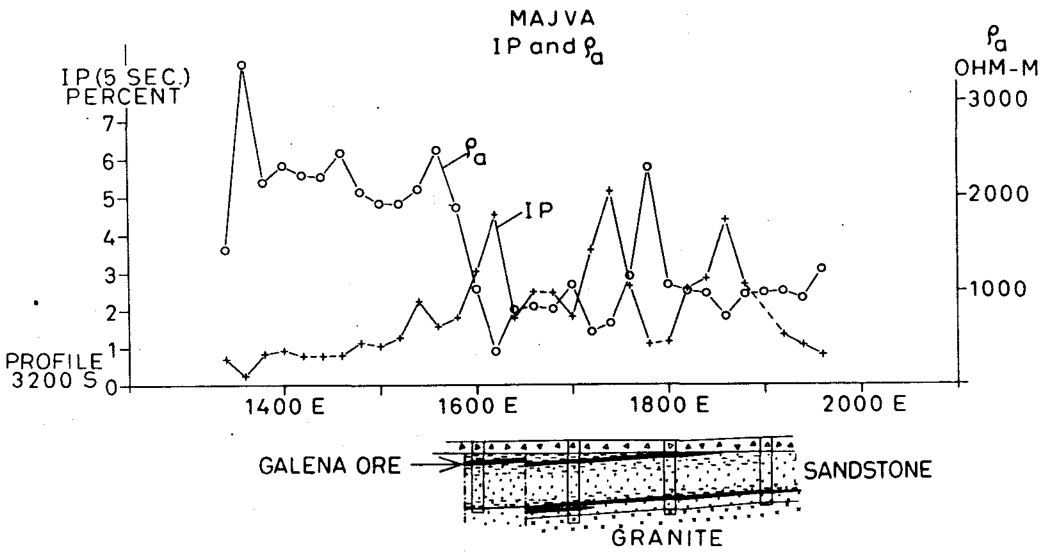


Fig. 55 Apparent resistivity and time domain I.P. results over the sandstone hosted galena deposits, Majia area, northern Sweden. From Parasnis, 1967

A major shortcoming of the I.P. method in exploring for base metal deposits of sedimentary origin, lies in the widespread occurrence of pyrite and graphitic horizons in the same environment. The I.P. effects observed over these extraneous sources cannot be readily distinguished from anomalies generated over economic mineralization. The geologist contemplating using I.P. methods in prospecting for sedimentary copper and lead-zinc deposits, should appreciate this fact. Induced polarization surveys should only be conducted in areas where the geological environment is relatively well known and where the presence of a deposit is suspected. Ideally, a fair degree of geological and/or geochemical orientation work should have been completed over the prospective area prior to commissioning an I.P. survey. In areas where outcrop is scarce, consideration should be given to using magnetics at an early stage in order to restrict the search area as discussed previously in earlier chapters. In the majority of cases the accurate interpretation of the geophysical information should be geologically orientated and based on a thorough appreciation of the restricted marginal marine or fluvial environments which host most sedimentary base metal deposits.

The use of the induced polarization method is not confined to the detection of relatively large porphyry and massive sulfide mineralization. The technique can also be applied effectively in the search for relatively small and narrow ore bodies provided a smaller, potential and current electrode spacing is used. Induced polarization-resistivity surveys have been applied successfully in the exploration of a wide variety of epigenetic lode deposits, including precious metal and tin-tungsten lodes, as well as sulfide veins and narrow replacement deposits. As the majority of these hydrothermal deposits are narrow and steeply inclined, the use of gradient arrays should be avoided as bodies of this nature are difficult to detect using the gradient configuration.

The Putsberg prospect in the Northwest Cape, South Africa, provides an example of the use of I.P.-resistivity surveys in locating a narrow, steeply dipping disseminated copper pyrite zone. Geophysical orientation surveys using gradient I.P., self potential and horizontal loop E.M. failed to produce a recognizable response over the mineralized zone (Campbell and Mason, 1979). Frequency domain dipole-dipole, and Time domain 3 array I.P. surveys, both produced significant anomalies above the zone of mineralization and over an adjacent graphitic schist horizon, Fig. 56. Time domain I.P.

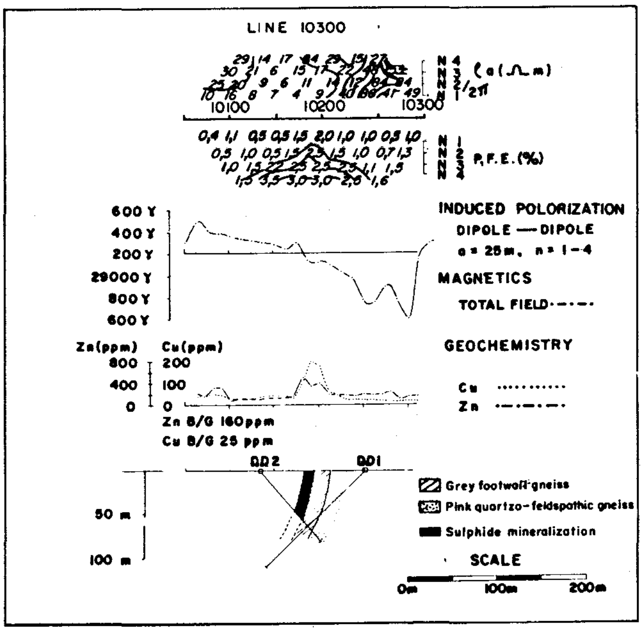


Fig. 56 Results of I.P.-resistivity surveys over the cupreous pyrite deposit, Putsberg, N.W. Cape Province, South Africa. From Campbell and Mason, 1979.

surveys using a 25m potential electrode spacing were used extensively during the exploration programme in order to trace the stratiform ore zone under calcrete covered areas. The close spatial association of the ore zone with the adjacent, highly resistive footwall gneiss

(Fig. 56) proved to be of immense value in recognising the significant anomalies. The anomalies due to the graphitic schist horizons were consistently related to areas of low resistivity; a characteristic feature of the schistose host rocks. Recognition of these two horizons under calcrete and tillite covered areas helped in the design of the percussion drilling programme which tested the potential of the I.P. anomalies.

Seigel (1971) provides an interesting example which illustrates the importance of using a short electrode (a) separations in order to produce an anomalous I.P. response over a narrow, steeply dipping, ore zone. The small (± 1 million ton) Alwin copper deposit in British Columbia, Canada, occurs in a steeply dipping fracture zone in the Buichon batholith. The ore zone is less than 15m wide and contains approximately equal amounts of chalcopyrite and pyrite which together account for 6-7 percent of the rock volume. The results of the survey are presented in Fig. 57. The I.P. survey failed to produce a recognizable response using an electrode spacing of 200 and 400 feet, but

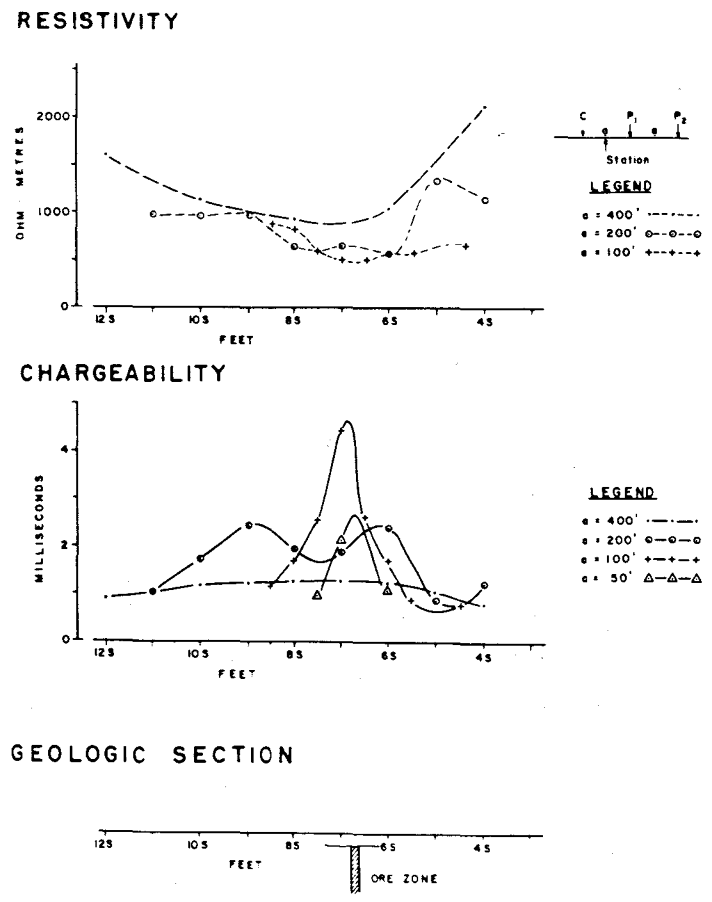


Fig. 57 Geophysical and geological section, Alwyn copper deposit, British Columbia, Canada. From Seigel, 1971.

a definite anomaly was encountered using an 'a' spacing of 100 feet. When a relatively narrow orebody is anticipated it is therefore necessary to utilize a narrow electrode spacing and the orebody must lie near surface.

The Gortdrum copper deposit in Ireland was discovered as a result of a regional soil geochemical survey which indicated a moderately strong copper anomaly. An induced polarization survey was conducted over the anomalous region in order to access the area's potential and an anomalous I.P. response was obtained at a distance of approximately 100m from the centre of the geochemical anomaly. Fig. 58 illustrates the nature of the geophysical response obtained over the area. The chargeability profiles suggest the presence of a broad steeply dipping mineralized zone. There was no resistivity expression over the body but a prominent resistivity high was obtained from the adjacent Old Red Sandstones. Drilling revealed the presence of disseminated chalcocite and bornite with tetrahedrite and minor chalcopyrite-pyrite mineralization. The total sulfide content did not exceed 3% and the mineralization was found to extend from surface to depths of 75-150m. The mineralization was localized by the Gontdrum fault and formed replacement bodies in Carboniferous limestones. The drilling completed in 1966 indicated reserves of 3.8 million tons at an average grade of 1.19% Cu and 23 g/ton Ag in an orebody suitable for open pit mining. The success of geophysical exploration in this region was largely due to the high sensitivity of the pulse-type I.P. survey which gave a good indication of the attitude of the orebody.

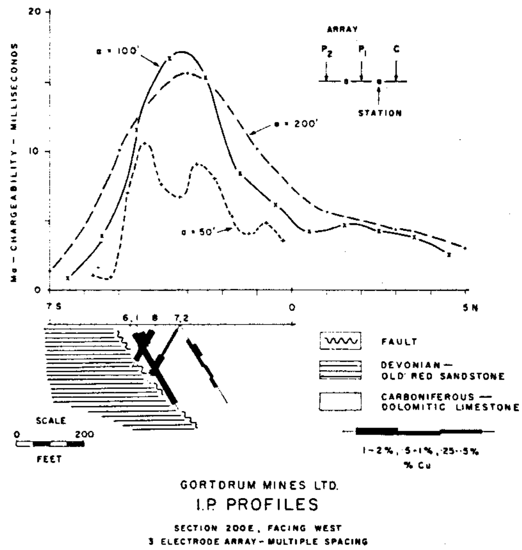


Fig. 58 Results of an induced polarization survey over the Gortdrum deposit, showing the effects of varying the potential electrode spacing. From Seigel, 1966.

Disseminated pyrite and arsenopyrite is often concentrated in a broad halo around epigenetic precious metal deposits. The mineralization is commonly localized by prominent shears or associated fracture zones and these deposits can often be located by using induced polarization-resistivity methods. The resistivity data is valuable because extensive silicification of the shear zones normally accompanies the precious metal mineralization. Consequently these zones can often be defined by the presence of moderately strong resistivities. Coincident resistivity and chargeability highs should delineate potentially auriferous ground along or adjoining the major shear zones, but the precious metal distribution within these sulfide rich envelopes can only be assessed by drilling or underground development.

Case studies dealing with the application of the induced polarization to gold exploration are not widely publicised. Kelly (1957) provides details relating to the successful application of resistivity surveying in exploring covered areas on the Broulan-Porcupine Gold prospect, in the Timmins mining district, Ontario. Rocks in the mine area comprise an altered and carbonatized Archean volcanic sequence, together with greywackes and slates. The ore shoots consist of quartz veins and sulfide mineralization that are best developed in the fractured competent horizons rather than in sheared incompetent beds. The resistivity data showed the location of silicified zones underlying high resistivity bands. Testing of the more resistive zones located the orebodies of the Broulan-Porcupine mine which produced 244 000 oz of gold from 1.15 million tons of ore between 1939 and 1953. This survey was conducted in 1936 prior to the development of the induced polarization method, which, if it was available, would have delineated the orebody due to the presence of well disseminated pyrite. This example effectively demonstrates the potential value of the resistivity information in precious metal exploration.

The strike extent of auriferous reefs in Southern Tanzania, was determined using an integrated electrical resistivity and magnetic surveys (King, 1957). The gold bearing quartz reefs occupy shears that traverse Archean granite gneiss and sulfides of galena, pyrite and chalcopyrite accompany the gold mineralization. Geophysically the shear zones were expected to yield high resistivity and low magnetic values and these characteristics were used to trace the extensions of the reef beyond a faulted dike contact. The interpretation of the data was complicated by the varied depth of soil, weathered bedrock, and water table conditions. Once allowances had been made for these factors, the results showed that the reefs were probably located a little to the east of their previously expected position. This supposition was not confirmed prior to the writing of the paper, so the accuracy of the geophysical interpretation remains uncertain.

The Real de Angels, precious metal deposit in Mexico, was clearly defined by chargeability and resistivity anomalies. The I.P. effects recorded over the deposit registered a peak of 25 millivolts against a background of 3 millivolts and the orebody limits were roughly coincident with the 10 millivolt contour interval, as portrayed in Fig. 59. The resistivity data was equally definitive with a low of 20 ohm-metres being less than a tenth of the background resistivity in the area. The pronounced I.P. and resistivity effects recorded over the Real de Angels deposit, was due to a predominance of narrow interconnecting sulfide stringers.

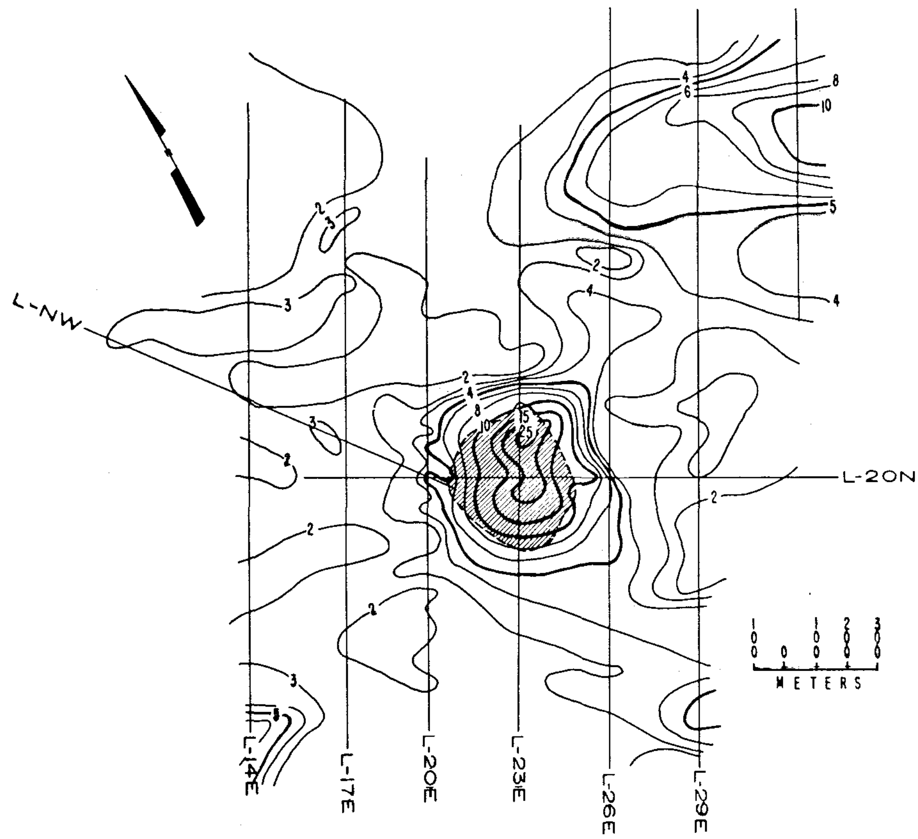


Fig. 59 Chargeability contour map over the Real de Angels precious metal prospect, Mexico, electrode spacing 100m. From Stoiser and Nieto, 1979.

The induced polarization method was also applied with good effect in exploration of the Coco Mina gold deposits in Nicaragua. The deposits occur within a small caldera like structure and it is associated with a broad zone of disseminated sulfides (Middleton and Campbell, 1979). The results of the I.P.-resistivity survey, presented in Fig. 60, clearly define the extent of the pyritized volcanic

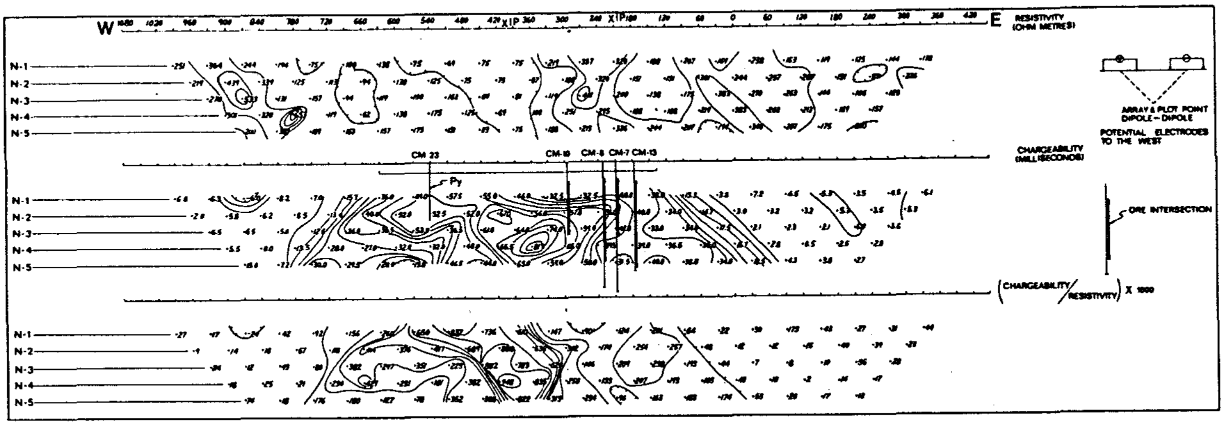


Fig. 60 I.P. resistivity profile through the Coco Mina disseminated precious metal sulfide deposit, Nicaragua. From Middleton and Campbell, 1979.

breccia which envelops the auriferous lodes and it delineated the lateral extent of the mineralized horizons under younger andesites. Chargeabilities of over 80 milliseconds were recorded over the pyritic breccia and this was in marked contrast to the low background values of 2-4 milliseconds, encountered over the adjacent volcanics. Low resistivities values are characteristic of the altered breccia zone while high resistivities (>200 ohm-metres) are associated with the adjacent unaltered basalts. Diamond drilling within the zone delineated by the high chargeabilities indicated a probable tonnage of 11.3 million tons of 0.05 ozs Au, 0.77 ozs Ag and 3.4% Zn. These results further demonstrate the potential value of induced polarization surveying in the exploration and evaluation of precious metal deposits.

To conclude, the induced polarization method can be applied, effectively, in a wide range of different geological environments due to its ability to respond to relatively low concentrations of disseminated sulfide mineralization. The widespread association of disseminated pyrite, pyrrhotite and arsenopyrite with many orebodies enhances the value of the method over the somewhat cheaper, electromagnetic method. In the search for massive sulfides, the I.P. method may be considered as an important technique, particularly when deposits are being sought in depth below the effective limits of the E.M. method and in situations where conductive overburden prevail.

The electrode configuration and separation used in a particular survey, are critical factors that should be carefully assessed before conducting an I.P.- resistivity survey. The choice of a suitable electrode configuration is particularly important in prospecting for narrow orebodies and deposits located at depth. The high and ever-increasing cost of conducting I.P. surveys on the ground, is likely to become an important factor in limiting the use of I.P. surveys to high priority target areas in future.

THE ELECTROMAGNETIC METHOD

Electromagnetic (E.M.) surveys are currently the most popular means of exploring for massive sulfides and the method employs a wide variety of techniques, details of which are provided by Telford et al. (1976). Electromagnetic surveying is based on the propagation of alternating electromagnetic currents in the subsurface of the earth. The artificially induced electro-magnetic field generates a secondary field in the region of a conductor and this distorts the primary field. The amplitude of the induced secondary field will depend on the primary frequency, resistivity of the conductor, its shape, attitude and location, relative to other conductors. These factors are particularly important in exploring areas of conductive overburden where it is usually necessary to survey at lower frequencies in order to obtain a recognisable response from an underlying conductor.

The electromagnetic method differs from the induced potential methods in that measurements of the electromagnetic field can be recorded directly in contrast to applied potential measurements which have to be obtained on the ground using potential electrodes. The ability of the E.M. systems to record the effects of the electromagnetic field directly has enabled the system to be adapted for use in an aircraft. A number of airborne E.M. systems have been developed and magnetic data is usually recorded concurrently with these surveys. The potential value of airborne electromagnetic surveys are thereby, considerably enhanced. The field procedures used in ground E.M. surveys,are relatively straight forward and surveys of this nature enjoy a significant cost advantage over induced polarization surveys.

The electromagnetic survey methods have been used extensively in mineral exploration to locate bodies of high electrical conductivity. Massive sulfide mineralization represents the most common target sought,although the method has been employed in locating unconformity associated uranium deposits, in mapping faults, shears and narrow vein deposits, and in tracing highly conductive clay horizons which are commonly developed above kimberlites and coal measures. Graphitic and pyritic schist horizons may also produce significant E.M. responses and this complicates interpretation, but it may also be used effectively to map out the distribution of these conductive lithologies.

The strength of an electromagnetic response from a conductor is, in large part, dependent on the area of the conductor, consequently E.M. systems usually respond well to fault and shear zones as well as conductive overburden. While these responses may be desirable in some surveys they are a major source of concern in many regions. The number of anomalies generated by electromagnetic surveys in most regions are exceedingly high and this constitutes the main disadvantage of the electromagnetic survey method. The relatively costly procedure of screening all E.M. conductors greatly reduces the cost effectiveness of the method in exploration. Wherever possible electromagnetic survey methods should be used in areas where geological control is available or where the target is sufficiently well understood to readily distinguish between potential and spurious anomalies.

Massive sulfide deposits are normally characterized by electrical conductivities of 1000 to 10 000 millimhos/m and they therefore represent a two to four fold increase over the responses from the adjacent host rocks. The electromagnetic system was primarily designed for Canadian conditions where the massive sulfide bodies are usually overlain by a shallow cover of glacial till, bedrock is fresh and highly resistive, and the groundwater is generally salt free and moderately resistive. The orebodies occur as a massive, relatively fresh sulfide conductor in a resistive environment and these conditions are ideal for the use of electromagnetic methods. A particular shortcoming of the E.M. technique however, lies in areas where deep weathering and soil cover produce conductive overburden conditions. The presence of near surface conductors normally reduces the effective depth penetration of the E.M. methods and the increased noise levels may largely shield the sulfide targets from detection. Spurious anomalies may also develop as a result of variations in overburden thickness, and flying height, or due to the circulation of saline waters in steeply dipping shear zones, contacts etc., and this may further distort the electromagnetic response from a true metallic conductor. Consequently the use of electromagnetic methods under most Australian and South African conditions is inherently more difficult. Recent developments in electromagnetic instrumentation, have improved the efficiency of E.M. surveying in environments of conductive overburden. Many of the latest E.M. systems employ much lower frequencies and a number of channels in order to optimise the results of E.M. surveys over deeply weathered terrains.

Improvements in instrumentation should greatly improve the use of E.M. methods in areas overlain by conductive overburden and the method may find increasingly wide application in future.

Nickel bearing sulfide deposits commonly occur as massive sulfide segregations in the base of ultrabasic igneous rocks. Massive pyrrhotite, and pentlandite form the dominant primary sulfides and the majority of deposits are characterized by high conductivities and magnetic susceptibilities. Integrated airborne electromagnetic and magnetic surveys have therefore been widely used in exploring for nickel sulfide deposits (Dowsett, 1967; Roth, 1975; Fraser, 1978). Airborne E.M. and magnetic surveys proved particularly effective in Canada and Scandinavia where a number of nickel sulfide deposits were discovered using E.M. methods. Similar surveys in the greenstone terrains in Western Australia however, produced poor results due to the presence of deep conductive overburden conditions and induced polarization surveys were generally found to be preferable in this environment.

The majority of the nickel orebodies in the Thompson area of Northern Manitoba, in the Sudbury area of Ontario, and in northwestern Quebec, respond geophysically to the electromagnetic method. The metallic sulfide content of these orebodies is rarely less than 10 percent and pyrrhotite forms the dominant sulfide. Deposits in which only limited sulfide segregation has occurred are normally of a more disseminate nature and they constitute poor E.M. targets. The use of electromagnetic methods in exploration for nickel sulfide deposits is therefore limited to the detection of high grade mineralization. Seigel, 1966 has indicated that extremely high conductivities are normally observed over many nickeliferous sulfide deposits and conductivities may be as much as a thousand times better than their environment.

The results of a detailed ground electromagnetic and magnetic survey over the Thompson area are indicated on Fig. 61. Most of the area is covered with overburden and outcrops are widely scattered but the magnetic data broadly defines zones of strongly deformed banded iron formation and peridotites. Numerous electromagnetic responses were obtained over the same area and the majority of these conductors were associated with magnetic anomalies. Screening of the electro-magnetic anomalies on the basis of their association with magnetic

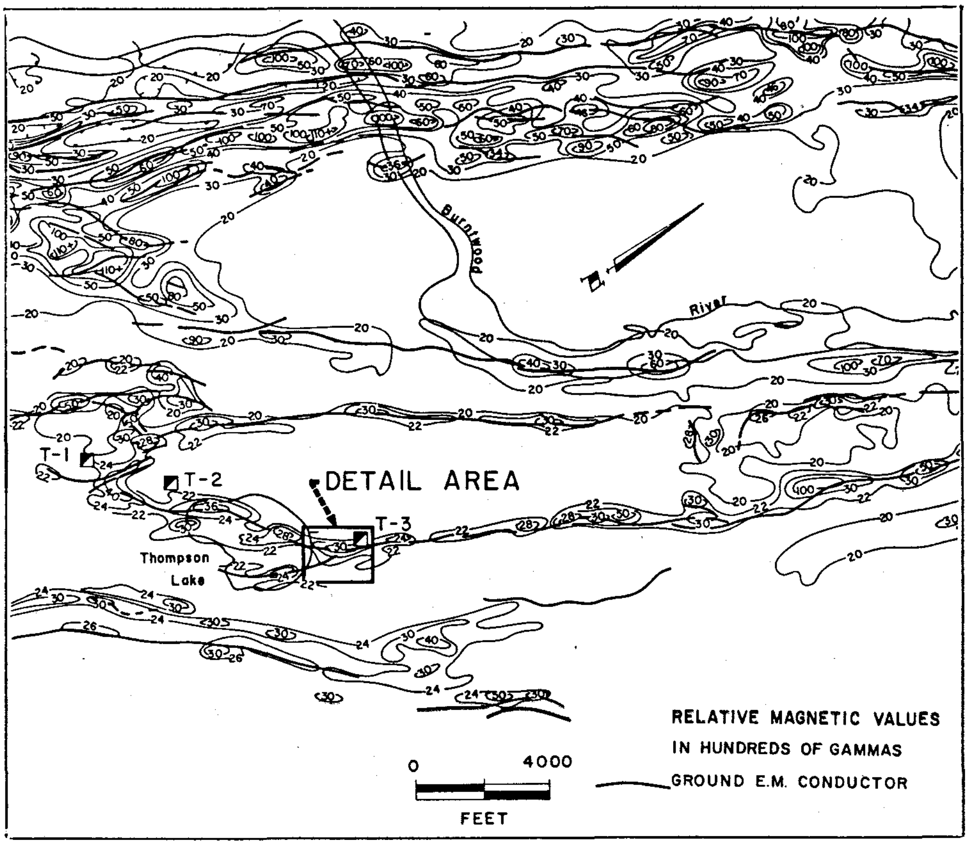


Fig. 61 Ground electromagnetic and magnetic surveys over the Thompson mine area, Manatoba Nickel Belt, Canada. From Dowsett, 1967.

anomalies, was therefore, not feasible and a lot of conductors were drilled in the region prior to the discovery of the Thompson deposit. The majority of the spurious E.M. conductors were found to be due to the presence of graphite and/or barren sulfides associated with magnetic iron formations. The ground electromagnetic conductor over the Thompson orebody corresponds to the T.3 conductor (Fig. 61), which is long and strong. The E.M. conductor is coincident with a string of isolated magnetic anomalies which are produced by the combined effects of magnetite and pyrrhotite in the orebody and adjacent banded iron formation, as illustrated in Fig. 62.

The exploration which resulted in the discovery of the Pipe orebody in the Thompson Belt involved airborne electromagnetic and magnetic surveys which defined priority areas for detailed ground follow up. The peridotite host at the Pipe mine gave rise to a prominent 13 000 gamma magnetic anomaly. The coincident E.M. anomaly obtained over this body, was clearly distinguished as being a high priority target and the orebody was subsequently delineated by diamond drilling.

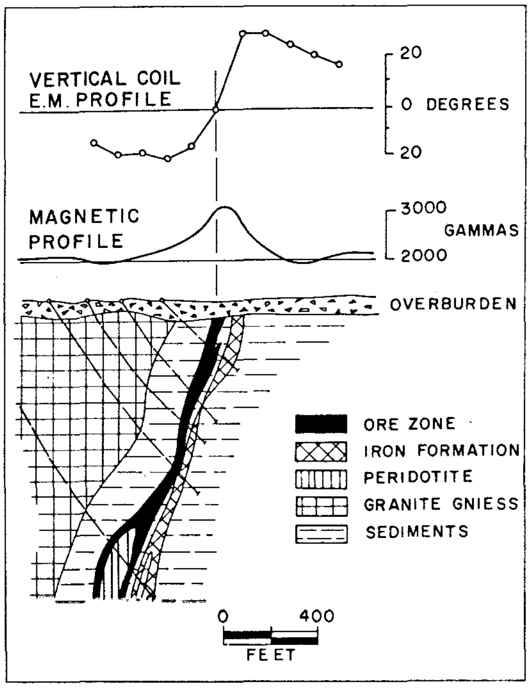


Figure 10 shows a section through the Thompson orebody with corresponding ground geophysical profiles. The electromagnetic conductor coincides with the position of the ore zone and is caused by the conductive sulphides of the ore. Pyrrhotite, which is the major constituent of the ore, is both conductive and magnetic, and is also the major cause of the magnetic anomaly.

(From Dowsett, 1967).

An airborne electromagnetic survey was employed in the exploration for massive sulfides in the Belford-Montcalm Township area of Ontario (Fraser, 1978). The 600 line mile Dighem survey detected 134 E.M. anomalies, the largest of which had an extremely high conductance of 154 mhos. The anomaly was of restricted strike length and it correlated with a 175 gamma magnetic anomaly. The position of the anomaly on the ground was defined by a vertical loop electromagnetic and magnetic survey, the results of which were used to locate the first diamond drill hole, Fig. 63. This hole intersected 244 feet of massive copper-nickel sulfides comprising 60% pyrrhotite, with lesser pyrite, pentlandite and chalcopyrite. The mineralization occurs in gabbro and assayed 0,38% Cu and 0,81% Ni.

The results of the horizontal-loop E.M. survey over the Montcalm Township copper-nickel deposit are presented in Fig. 64. The profiles show the effect of increasing the coil separation, with the best response from the orebody being obtained on the 200 and 400 foot

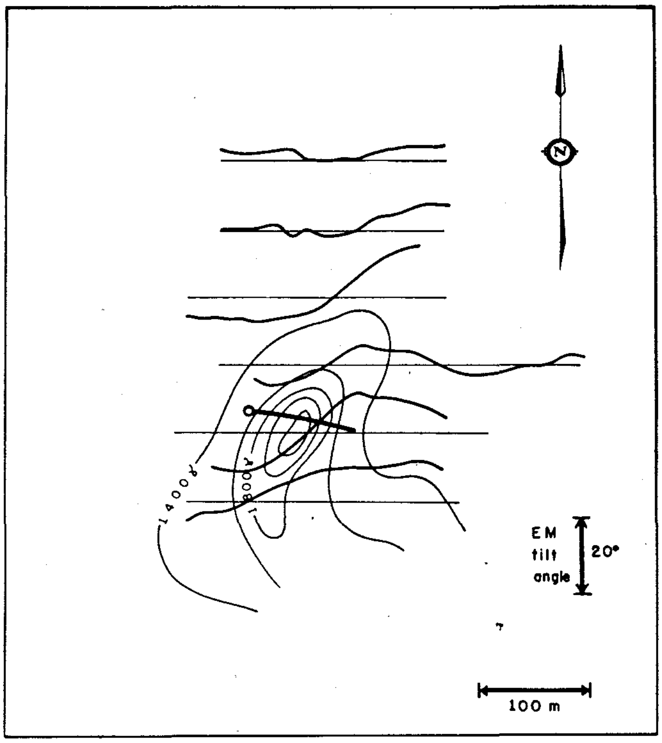


Fig. 63 Vertical Loop E.M. results over a sulfide nickel-copper deposit in the Montcalm Township area, Ontario, Canada From Fraser, 1978.

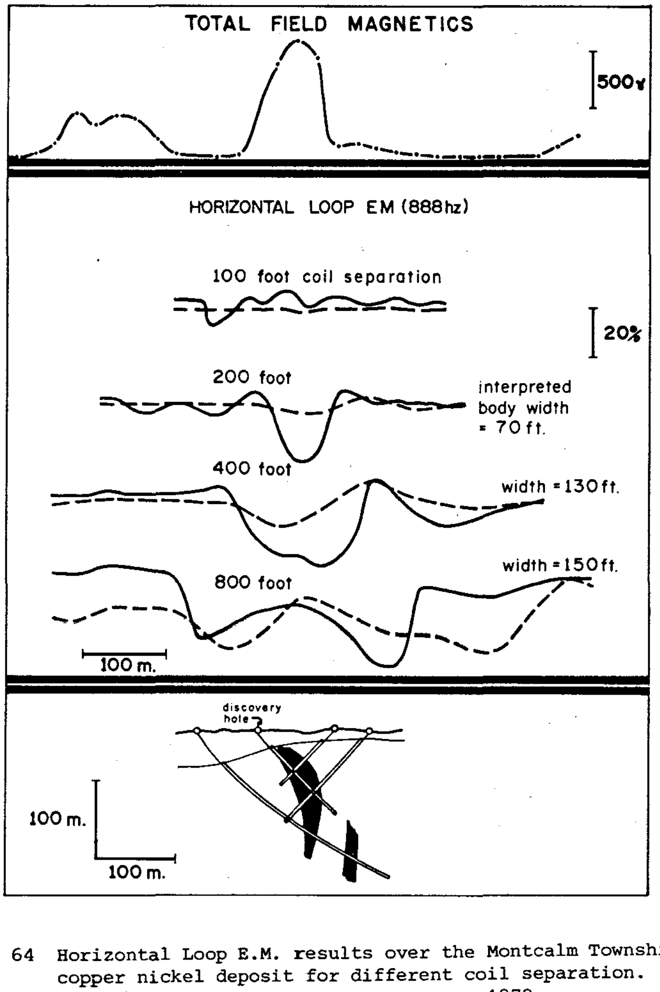


Fig. 64 Horizontal Loop E.M. results over the Montcalm Township copper nickel deposit for different coil separation. From Fraser, 1978.

coil separations. The finite depth extent of the deposit is clearly indicated by the unusual shape of the inphase response for the 800 foot coil separation. The broadening of the anomaly from the 200 foot to the 400 foot coil separations, indicates that the thickness of the deposit increases with depth. This fact was subsequently confirmed by drilling and two mineralized zones were encountered in depth, a feature that was indicated on the E.M. results using an 800 feet coil separation.

One of the main uses of the electromagnetic method lies in the exploration for massive volcanogenic sulfide deposits. Airborne E.M. systems have been widely used in reconnaissance surveys and many examples are available which illustrate the effectiveness of airborne surveys in locating volcanogenic deposits. A major problem that is inherent in all E.M. surveys lies in the number of anomalies that are normally generated by the surveys, particularly in shield areas. This fact is clearly demonstrated by the exploration statistics presented in Table 4, which related to the use of the E.M. method in Canada during the period from 1955 to 1959.

TABLE 4 Exploration statistics relating to electromagnetic surveys in Canada, 1955-1959. From Paterson, 1967.

Square miles surveyed*	125,000 square miles
Line miles of EM	500,000 line miles
EM anomalies located	100,000
EM anomalies selected**	10,000
EM anomalies followed up on the ground	3,000
EM anomalies drilled	1,000
Sulphide bodies found	800
Potential orebodies found	16

* Includes some areas flown more than once. ** Anomalies selected as probably significant by a process of interpretation or 'skimming.'

Although the widespread use of the airborne E.M. method in Canada resulted in the discovery of numerous sulfide deposits during the 1955-1960 period the success rate of finding ore bodies remained relatively low. Only about 2 percent of all the sulfide deposits drilled were found to contain significant quantities of commercial minerals, and this fact resulted in reducing the use of airborne E.M. methods during subsequent years.

The Mattagami Lake No. 1 orebody in Canada, was discovered as a result of the use of airborne electromagnetic and magnetic surveys

(Hallof, 1966). The mineralization is massive to disseminated pyrite, pyrrhotite; sphalerite and chalcopyrite with local concentrations of magnetite. The ore grade averages 12 percent zinc, 0,7 percent copper, 1.25 oz silver and .02 oz gold. The initial discovery in the Mattagami Lake area was due to the presence of a coincident E.M. and magnetic anomaly but a number of other E.M. conductors were encountered in the region, many of which reflected pyritic tuff horizons. The results of a ground E.M. survey over the Mattagami No. 1 orebody, using the shootback E.M. method is shown in Fig. 65. The total dominance of negative dip angles indicates that the conductor has a large horizontal component (Crone, 1966). Vertical hoop E.M. methods were also used effectively in the Mattagami area employing frequencies of 1 000 cps and 5 000 cps, but overburden effects were noted in these surveys so 300 cps E.M. units were employed subsequently to discriminate between the massive sulfide mineralization and poorly conducting overburden. Two other orebodies were discovered in the Mattagami Lake area which failed totally to respond to ground E.M. methods, but their location was indicated by the results of magnetic and I.P. responses. These discoveries lay at a depth of 90 and 180 metres respectively and their vertical pipelike form presented difficult E.M. targets.

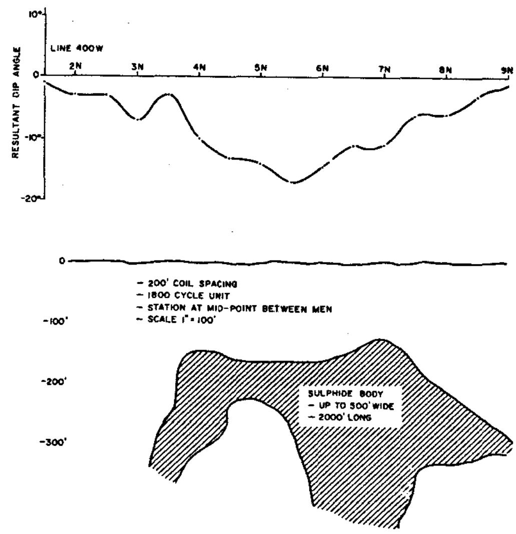


Fig. 65 Results of a ground E.M. survey over the Mattagami No. 1 orebody. From Crone, 1966.

In 1972, an Input E.M. survey discovered a strong, isolated magnetic conductor in the Magusi River area of the Noranda district, Canada. This region had been actively prospected for over 60 years and the discovery was directly attributable to the improved resolution of the then, newly developed Input E.M. system (Telford and Becker, 1979). The response of the Iso massive sulfide deposit, as observed on the original A.E.M. Input survey profile, are shown in Fig. 66. Follow up surveys in the same region, using a detailed Dighem A.E.M. survey located an adjacent deposit, the New Insco orebody (Boldy, 1979). Geologically the deposits are contained within a volcanic pile comprising rhyolite, dacite and andesitic flows on the flanks of a large intrusive granodiorite. The Iso orebody, the largest of the two sulfide deposits, contained 5.8 million tons of ore averaging 1.13% Cu, 2.72% Zn, 0.82 oz/ton Ag and 0.022 oz/ton Au. The smaller New Insco deposit contained a predominance of copper mineralization and it was associated with a strong magnetic response due to pyrrhotite.

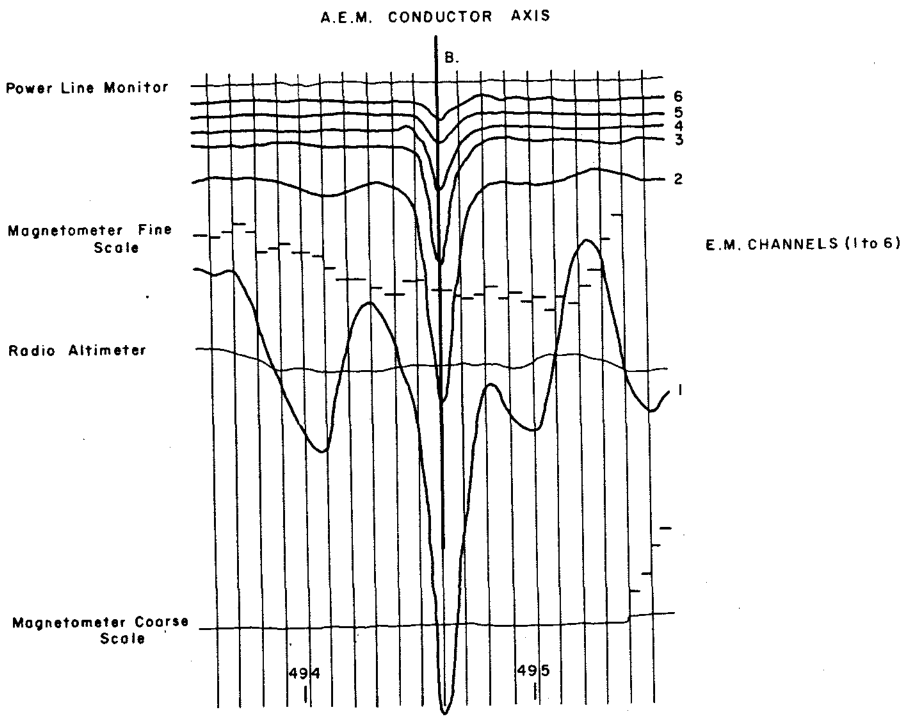


Fig. 66 Survey results of an airborne input E.M. survey over the Iso Orebody, Noranda district, Canada. From Boldy, 1979.

The follow up of airborne E.M. anomalies invariably is done using ground electromagnetic method in order to locate the anomaly on the ground. Horizontal or vertical loop E.M. surveys are normally employed to follow up airborne E.M. surveys and the results of surveys of this nature over the Iso orebody are illustrated in Fig. 67 together with a geological section. The results of an I.P. survey, and assay data relating to the various diamond drill hole intersections shown in the section, are also illustrated. All the geophysical methods had no difficulty in detecting the massive sulfide, buried under 12m of glacial moraine.

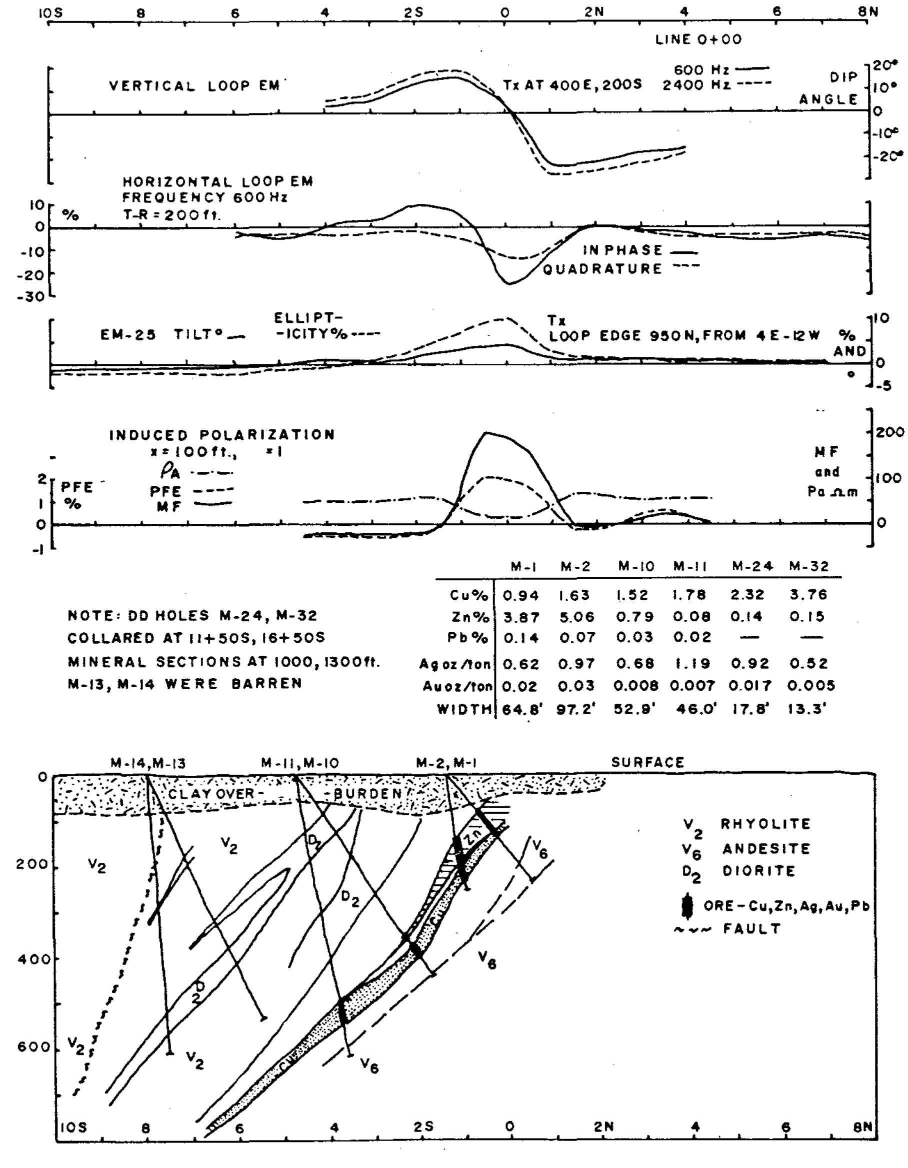


Fig. 67 Geophysical ground E.M. and I.P. profiles over the Iso Orebody, Noranda district, Canada.
From Telford and Becker, 1979.

Airborne electromagnetic surveys have some important limitations in exploring for massive sulfides in some environments. Strauss et al. (1977) in discussing the use of airborne E.M. surveys concluded that the method had proved to be of no practical use in exploring for meassive sulfide deposits in the Spanish Pyrite Belt. The majority of E.M. anomalies produced in the pyrite district were found to be due to carbonaceous black shales and/or wet ground. The results of input surveys over a number of outcropping massive sulfide orebodies were also disappointing as the method failed to produce a significant anomaly over the mineralization. On the other hand, it did produce even six-channel anomalies over areas underlain by abundant carbonaceous shales. The general poor response of the sulfide ores in the Pyrite Belt was attributed to the low depth penetration (less than 30 metres) under the local geological conditions and rough topography of the region.

Campbell and Mason (1979) provide details relating to the use of Turam E.M. methods in exploring for cupreous pyrite deposits associated with magnetite quartzites, in the Gorob region of South West Africa. Although a 4 km long conductive horizon was identified by the Turam survey, no unique responses were obtained in the vicinity of the mineralized sections which were subsequently found to contain up to 40 percent by volume sulfides. The long conductor was attributed to conducting minerals other than sulfides in a zone flanking the magnetite-quartzite unit. This example further demonstrates some important limitations of the Turam method as well as the need to exert care in the interpretation of E.M. data.

The airborne E.M. method may be used effectively in mapping the distribution of graphitic schist horizons which are often intimately associated with some base metal sulfide deposits. Graphite-bearing schist horizons are particularly common in many high grade metamorphic environments as is the case, for example, in the Outokumpie and Kittila areas of Finland (Ketola, 1979). The Vuonos and Saramaki deposits in the Outokumpie district comprise low to medium grade copper-cobalt ores that are associated with highly conductive black schist areas. The associated host rocks include highly metamorphosed micaceous gneiss, serpentinites, dolomites, skarns and more quartzitic assemblages. Airborne E.M. and magnetic surveys have been used extensively in mapping the potentially mineralized graphitic schists. Magnetic anomalies that are coincident with the graphitic schists are considered potentially interesting because they reflect areas containing pyrrhotite and/or skarns, both of which may be intimately associated with the copper-cobalt mineralization. Surveys of this nature may also be contemplated in exploring for Proterozoic, Broken Hill type, stratiform base metal sulfide deposits due to the common association of graphitic and magnetic lithologies in close proximity to the orebodies.

The electromagnetic method responds to the surface area of a conductor and as such it normally responds to major water filled fracture and shear zones. While this property of the E.M. method may be a major problem in prospecting for massive sulfide deposits, it may be used to advantage in structural mapping. Most hydrothermal deposits are structurally controlled and they commonly occur as fracture or fissure fillings. Consequently the E.M. method may be indirectly applied in exploring for structually controlled hydrothermal mineralization, including tin-tungsten deposits, base and precious metal sulfide deposits, together with deposits of antimony, mercury, molybdenum and uranium.

AFMAG and VLF-EM methods have been used fairly extensively in structural mapping and more recently specially tuned input systems have been used in structural surveys. Details relating to the use of the AFMAG system have been provided by Sutherland, 1967, who indicates that the major advantage of the AFMAG system lies in its ease and speed of operation. AFMAG is essentially a dip angle technique which utilises the naturally occurring fluctuations in the earth's field due to distant thunderstorm activity, (located at infinity) as a power source. AFMAG surveys can detect sizable tilt angles at distances up to 250m from conductive fault and shear zones. The large strike length and depth extent of fault zones produce appreciable AFMAG anomalies. These anomalies can usually be readily distinguished on profile plots because they are typified by long and gradual buildups, a kilometer or more on either side of the inflection point which defines the location of the conductor axis. The anomalies generated by smaller, highly conductive bodies are typically sharper, concave responses of limited extent. The results of an AFMAG survey flown over the Duprat township, in the Noranda district of Canada (Fig. 68), illustrate many of the characteristic features of a structurally orientated E.M. survey.

Many hydrothermal precious metal deposits occur in prominent fissures that are developed along or adjacent to major shears or fault zones which may be mapped by E.M. methods. A typical example is provided by the gold deposits in northeastern Nicaragua, which occur as epithermal quartz veins, or disseminated sulfide zones within deeply weathered basaltic lavas, Middleton and Campbell (1979). The deep weathering and obvious structural control of these deposits

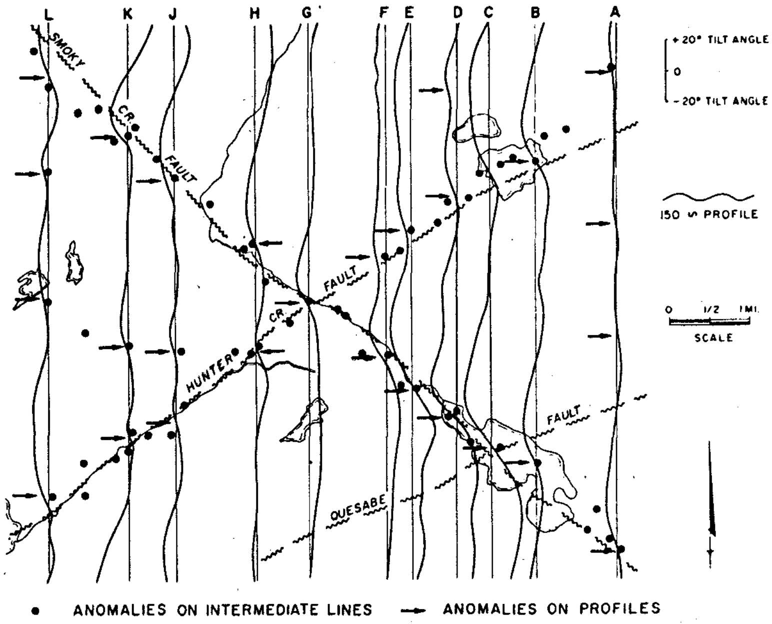


Fig. 68 Results of an airborne SFMAG survey over the Duprat Township, Noranda district, Canada, showing the response of the method to major fault zones.
From Sutherland, 1967.

make them ideal targets for VLF-EM methods which have been used effectively in exploring for other deposits in the region. The results of a ground VLF-EM survey over the Guapinol Gold prospect, portrayed in Fig. 69, shows the clear response of the auriferous quartz veins. The VLF-EM method was used to map out the distribution of the quartz reefs under extensive cover and this helped locate areas for subsequent geochemical and geological study. The success of the E.M. survey in this region is due largely to deep weathering of the clay rich, alteration zone along the contacts of the quartz veins. Similar zones are developed adjacent to many hydrothermal deposits, particularly when reactive wall rocks are evident and the E.M. method could be applied in exploring for many types of small, and commonly high grade, vein deposits.

Electromagnetic surveys have proved most effective in exploring for Proterozoic unconformity associated uranium deposits. Many of these deposits are associated with fractures and shears that are developed in the basement immediately underlying Proterozoic basins or within basal organic rich sediments. The uranium is thought to have been concentrated and precipitated in a reducing environment and deposition has invariably occurred in carbonaceous

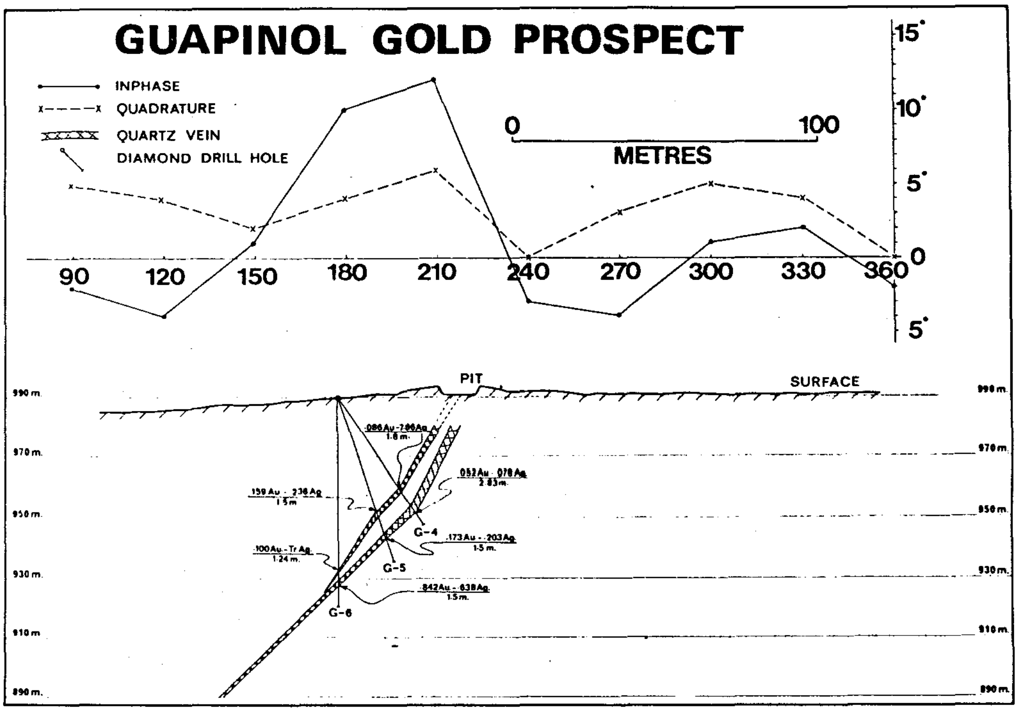


Fig. 69 Drill intersections over the Guapinol gold prospect, Nicaragua, showing the response of the auriferous quartz veins to VLF-EM methods.
From Middleton and Campbell, 1979.

or carbonate rich sediments. The relatively persistent association of uranium mineralization with fault zones and graphitic-carbonaceous sediments, renders many deposits detectable by E.M. methods. Both airborne and ground electromagnetic surveys have been widely used in the exploration of uranium deposits in the Athabascan basin in Canada and in the Pine Creek Geosyncline in northern Australia. The ease with which the E.M. method can map out the distribution of conductive black graphitic shales is readily apparent in Fig. 70 which shows the results of a time domain E.M. (TEM) survey in the uranium rich Rum Jungle province of northern Australia. As the intersection of major faults with the graphitic shale zones provide an ideal location for the precipitation of uranium. The potential value of E.M. surveys in uranium exploration is readily apparent.

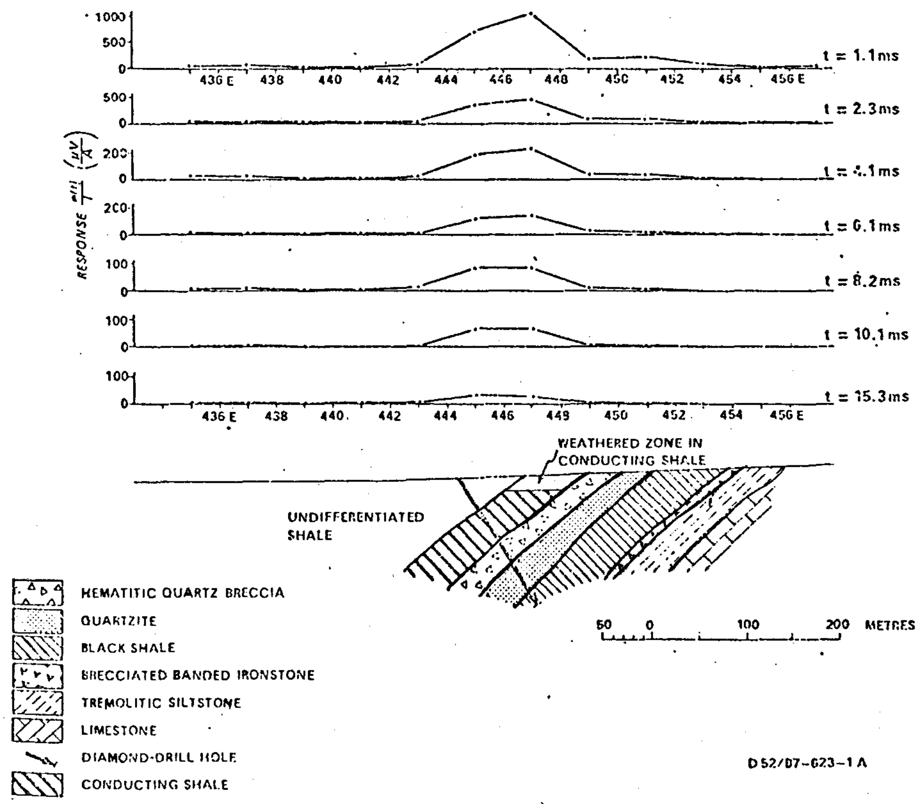


Fig. 70 Geological section through a uranium prospect, Rum Jungle, Northern Australia, showing T.E.M. profiles over the potentially mineralized black shale horizon. From Smith, 1980.

THE USE OF GEOPHYSICS IN INTEGRATED EXPLORATION PROGRAMMES

The purpose of this chapter is to emphasise the role of geophysics in past and future exploration programmes. Preceding chapters have outlined the scope, limitations and applications of various geophysical techniques in a broad range of geological environments. However, in order to gain a full appreciation of the role of geophysics in mineral exploration, it is important to consider its use in integrated exploration programmes.

Mineral exploration is a highly complex and demanding science and to be successful, it generally involves the full integration of the geological, geophysical and geochemical sciences. In the past, mineral exploration has been relatively easy and many discoveries have been made by routine prospecting. The marked increase in demand for metals over the past thirty years provided the necessary stimulus for the development of improved geophysical and geochemical techniques. These methods have contributed significantly in locating a number of new ore occurrences. Many of the orebodies discovered in the past were recognised because they represented amongst the most prominent physical and/or chemical features located in the survey area. As the majority of the obvious near surface deposits have already been located, it can be concluded that an increasingly large proportion of the future discoveries will be reflected as more subtle geophysical and/or geochemical anomalies. Sound geological perception is necessary in order to recognise the significance of the subdued responses and a wide range of methods is available to assist in the environmental reconstruction.

Geophysics forms but a part of an exploration sequence which may involve field geological studies, photogeological interpretation, trace element geochemistry, trenching, drilling or underground development. An example of a typical exploration sequence that may be considered in exploring for massive sulfides, is tabulated below and it illustrates the important role geophysics can play in integrated exploration programmes.

1. Preliminary office study	—geologic digest —photogeologic interpretation —statistical, logistics, & cost study for airborne surveys —study of geophysical parameters
2. Field geologic reconnaissance	—check rock types & properties —cover unmapped areas —correct photogeologic interpretation —possibly conduct a geological reconnaissance —geochemical reconnaissance & orientation surveys
3. Airborne electromagnetic & magnetic survey	—conduct survey —initial interpretation of data —adjust survey in progress if necessary
4. Classification & correlation of anomalies	—quantitative electrical interpretation —quantitative magnetic anomalies interpretation —rate combined anomalies —correlate with geology anomalies where known or assumed —select best anomalies for ground examination
5. Ground electromagnetic & magnetic delineation of best anomalies	—locate & delineate —evaluate conductivity & susceptibility —note obvious causes —reject obviously extraneous anomalies
6. Geologic & geochemical examination of vicinity of remaining anomalies	—map outcrop & float —take soil & stream samples for analysis —reject obviously extraneous anomalies
7. Gravity profiles over remaining anomalies	—two or three profiles over center of electromagnetic-magnetic anomaly —reject obviously extraneous anomalies —quantitative interpretation & geologic correlation of remainder
8. Diamond drilling	
9. Geological & geophysical study of drill core	—economic evaluation —explain all anomalies
10. Reevaluation of all anomalies	
11. Recycle best remaining anomalies	

In designing an effective exploration programme, geologists must utilize the most appropriate aids available in ore search in an efficient and balanced sequence. Economics will normally dictate the preferredexploration strategy but the final choice will be modified by considerations of the local environment, availability of personnel, accessibility, timing aspects and numerous other factors. The relatively low cost of geological investigations compared with geochemical and geophysical methods normally ensures that geology will (or should) form the primary exploration tool in most environments, particularly in areas of abundant outcrop. Geological investigations form an important interpretative base for geochemical and geophysical surveys, consequently geological surveys inevitably form an integral part of most exploration programmes. If the basic geological model applied in the exploration of a region is badly conceived, excessive expenditures are inevitable during the subsequent exploration phases and the probability of locating an orebody will be significantly diminished. Conversely, if the geological characteristics of a deposit and its environment are thoroughly understood before exploration is initiated, greater economy will be effected in the execution of a programme, and the likelihood of success will be considerably enhanced. This is a basic and undisputable fact of mineral exploration which has direct implications on the design of geophysical surveys.

Geochemical methods are cheaper than the majority of geophysical techniques and they are of direct value in locating positive indications of mineralization. Geochemical surveys can also be conducted concurrently with geological investigations and consequently geochemical surveys are commonly employed prior to the commencement of ground geophysical surveys. Trace-element geochemical studies may be used to screen areas that have been defined as priority areas on the basis of airborne geophysical investigations. A typical example would be in following up magnetic anomalies which could reflect magnetite quartzites, skarns or ultrabasic bodies, all of which may hold base metal potential given the right geological setting. Geochemistry is particularly effective in regions largely covered by shallow residual soils and ground magnetic surveys may be employed to augment geological mapping in these areas.

Geological mapping and geochemical surveying is severely limited in areas overlain by thick transported overburden or deep tropical soils and exploration in these regions may be geophysically orientated. The widespread use of geophysics in the glaciated regions of Canada and Scandinavia is largely due to the development of thick glacial moraine which can effectively mask the underlying mineralization. Most geophysical methods work well in glaciated regions due to the resistive nature of the glacial moraine. Geophysical techniques may be preferable to other exploration methods in glaciated regions and airborne techniques may be employed in prospecting the relatively harsh and inaccessible terrain evident in many glaciated areas.

One of the main disadvantages of employing geophysical methods lies in the fact that it is difficult to obtain a unique solution when interpreting geophysical survey results. This is due to the relatively broad overlap in physical properties observed between an orebody, its host rocks and adjacent environment. This characteristic is clearly illustrated in Table 5 , which provides a summary of the physical properties of a number of geological bodies.

In order to screen geophysical anomalies it is commonly necessary to use a number of geophysical methods and this can lead to the successive elimination of extraneous anomalies. Ward (1966) indicates how the successive use of electromagnetic, magnetic and gravity surveys may be employed to eliminate a number of anomalies detected during the search for massive nickeliferous sulfides. Barren pyrrhotite, magnetic carbonaceous sediments and magnetite-bearing massive pyrite bodies will, however, remain a problem, which could only be resolved through the application of geochemical and/or geological methods. Although the successive elimination of extraneous anomalies may be achieved through the use of other geophysical methods, this can be excessively expensive and other exploration techniques should be applied wherever possible. The fact that the majority of ground geophysical investigations are becoming increasingly costly, especially in relation to airborne geophysical methods, will undoubtedly lead to moderation in the use of integrated ground based surveys.

Table 5. Classification of all probable anomaly sources arising in regional electromagnetic surveys. (From Ward, 1966).

Group*	Possible Anomaly Sources	Conductivity	Magnetic Susceptibility	Density
1	Massive sulfides—mostly pyrrhotite	High	Moderate	High
	Graphitic shear zones	High	—	—
	Pyrrhotite stockworks	High	Fair	Fair
	Thin parallel bands of pyrrhotite on bedding planes	High	Fair	Low
2	Massive sulfides—mostly pyrite	Moderate	Low	High
	Graphitic shear zones	Moderate	—	—
	Coarsely disseminated pyrrhotite	Moderate	Fair	Fair
	Massive magnetite	Moderate	High	High
	Massive galena	Moderate	—	High
	Massive pyrite, minor magnetite	Moderate	Moderate	High
3	Massive magnetite	Fair	High	High
	Massive galena	Fair	—	High
	Pyrite stockworks	Fair	—	Fair
	Coarsely disseminated pyrite	Fair	—	Low
	Highly carbonaceous sediments	Fair	—	—
	Graphitic partings on shear faces	Fair	—	—
4	Massive sulfides—most sphalerite	Low	Low (?)	High
	Carbonaceous sediments	Low	—	—
	Disseminated pyrite or pyrrhotite	Low	Low	Low
	Solution-filled faults and shears	Low	—	—
	Swamps	Low	—	—
	Clay layers	Low	—	—
	Lakes	Low	—	—
	Overburden	Low	—	—

* Grouped according to conductivity.

An enlightening example of the role of geophysics in base metal exploration in the Noranda district during the period 1923 to 1974, is provided by Boldy (1979). Geophysical methods have been widely applied in exploring for volcanogenic sulfide deposits in the Noranda region and a balanced account of the relative merits of geophysical,geological and geochemical methods is summarised in Table 6 The table indicates that geophysics formed the primary discovery method in locating 4 out of 21 (or 25 percent) of the volcanogenic sulfide deposits in the district. Routine prospecting located 4 deposits during the early years and geological techniques proved to be the most effective method. Geological investigations located ten volcanogenic deposits in the district. This amounts to 47 percent of all discoveries and the important contribution made by geological techniques is obvious. The relatively poor performance of the geochemical methods in locating only one deposit, reflects the subordinate use of geochemical methods in the region, due to the presence of glacial moraine over much of the district.

Another important feature that is reflected in Table 6 , is that the early geophysical discoveries were made by ground magnetics

TABLE 6 Compilation of discovery technology, volcanogenic sulphide deposits, Noranda district, Quebec. From Boldy, 1979.

		Year of discovery	Prospecting	Geology: Mineralization	Geology: Alteration	Geology: Lithology-stratigraphy	Geology: Structure	Geology: Other	Geophysics: Aerial EM	Geophysics: Ground EM	Geophysics: Ground mag.	Geophysics: I.P.	Geophysics: Gravity	Geochemistry: Soil	Geochemistry: Litho-geochem	Geochemistry: Mercury pathfinder	Depth of deposit from surface
Early years (1920-1935)	HORNE - UPPER 'H'	1923	P	X			X										SURFACE
	AMULET - UPPER 'A'	1925	P	X	X												SURFACE
	AMULET 'C'	1925	P	X		X											SURFACE
	OLD WAITE	1925	P	X	X												SURFACE
	ALDERMAC	1925	X	X	X						P						- 30'
	AMULET 'F'	1929		X	X	X		P									-125'
	HORNE - LOWER 'H' *	1931		P		X	X	X									-1300'
Middle years (1935-1955)	AMULET - LOWER 'A' *	1938		X	P	X											- 700'
	JOLIET	1940	X	P		X											- 25'
	MACDONALD	1944	X	X		X				P							- 25'
	QUEMONT	1945				X	X				P						-200'
	D'ELDONA	1947	X	P		X	X										-500'
	EAST WAITE	1949				X		P									-1300'
Later years (1955-1977)	MOBRUN	1956				X				P			X				- 30'
	VAUZE	1957				P	X										- 25'
	DUFAULT - NORBEC	1961				P	X										-1100'
	DELBRIDGE	1965		X		X						X				P	- 300'
	DUFAULT - MILLENBACH	1966				P	X	X								X	-2300'
	MAGUSI RIVER	1972				X			P								- 50'
	NEW INSCO	1973				X			P								- 50'
	DUFAULT - CORBETT	1974				P	X									X	-2300'

P = PRIMARY DISCOVERY METHOD * = SUBSEQUENT DISCOVERY and E.M. surveys, and airborne E.M. discoveries have proved to be more effective in recent years. The importance of geological studies in making the major contribution to successful exploration in the Noranda district is an important feature that should be noted. This trend is likely to continue in the future and the contribution of geochemistry in other more favourable settings should not be overlooked. Indeed, the relative contribution of integrated geological-geochemical surveys in future exploration, is likely to become increasingly important, because most geophysical methods have distinct detection limits. This effectively limits the depth of penetration of most geophysical methods.

Geophysics has nevertheless an important role to play in future mineral surveys. Geologists are becoming increasingly aware of the need to refine the indirect applications of geophysical techniques in order to extend the geologists' search capabilities in different geological environments. The greater economy and efficiency of airborne geophysical methods are particularly significant in this regard. Future advances in airborne magnetics, radiometrics, electromagnetics and possibly airborne gravimetric surveys, should find increasing use in future mineral surveys. As exploration progressively searches for deposits at ever increasing depths, knowledge and understanding of the geology of mineral environments will form the basis for applying more sophisticated exploration techniques. Geophysics will undoubtedly be used far more in the future to carefully examine and geologically characterise the large-scale environmental features of different metallogenic regions.

The integration of the different exploration techniques will become increasingly important in future surveys. This will place increased demands on the explorationist whose geological perceptions of the ore environment will provide the necessary basis for interpreting geophysical and geochemical data. The geologist's ability to perceive, in three dimensions, the geological environment in which he is working, is potentially the most effective 'remote sensing' technique available in mineral exploration. An awareness of the character of geophysical and geochemical responses that can be anticipated over a blind orebody, is another necessary requirement of a true explorationist. This review was written with an appreciation of the above-mentioned facts in mind, and it is hoped that the reader has benefitted by gaining a better insight into the potential value of geophysics in mineral exploration.

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BIBLIOGRAPHY

Angoran, Y and Madden, T.R. (1977). Induced polarization, a preliminary study of its chemical basis. Geophysics, 42, 788-803.

Bacon, L.O. (1966). Refraction seismic case histories in mining geophysics, In Mining Geophysics, 1, Society of Exploration Geophysicists, 105-113.

Bacon, L.O. and Wyble, D.O., (1952). Gravity investigations in the Iron River-Crystal Falls mining district of Michigan. Mining Engineering, 4, 973-979.

Barringer, A.R. (1967). Regional reconnaissance techniques applied to exploration, In Mining and Groundwater Geophysics. Morley, L.W. (ed), Geological Survey of Canada, Economic Geology Report 26, 202-210.

Becker, A. (1979). Airborne electromagnetic methods, In Geophysics and Geochemistry in the search for Metallic Ores. Hood, P.J. (ed), Geological Survey of Canada, Economic Report 31, 33-43.

Bergey, W.R., Clark, A.R., Frantz, J.C., Keevil, N.B., Gordon Smith, F. (1957). Discovery of copper-nickel orebodies at the Temagami Mine, Ontario. In Methods and Case Histories in Mining Geophysics. 6th Comm. Min. & Metall. Cong, 168-175.

Boldy, J. (1979). Exploration discoveries, Noranda District, Quebec (case history of a mining camp), In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 593-603.

Boniwell, J.B. (1965). The environmental factor in geophysical exploration, In Eighth Commonwealth Mining and Metallurgical Congress, 2, Exploration and Mining Geology. Melbourne, Aust. Inst. Min. Metall., 100-106.

Bosschart, R.A. and Seigel, H.O. (1974). The Tridem three-frequency airborne electromagnetic system. Canad. Min. J., 95, April, 68-69.

Boyd, D.,(1967). The contribution of airborne magnetic surveys to geological mapping, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 213-227.

Boyd, D.M. and Smith R.J. (1980). Geophysics for Geologists. Australian Mineral Foundation, Adelaide, 340p.

Brant, A.A. (1966). Geophysics in the exploration for Arizona porphyry coppers, In Geology of the Porphyry Copper Deposits, southwestern North America. Titley and Hicks (eds). The University of Arizona Press, 287p.

Brock, J.S. (1973). Geophysical exploration leading to the discovery of the Faro deposit. Can. Min. Metall. Bull, 66, No. 738, 97-116.

Brooke, W.J.L. (1975). The Cobar mining field, In Economic Geology of Australia and Papua New Guinea. Knight, C.L. (ed). Monograph Series No. 5, Aust. Inst. Min. Metall., 683-694.

Bryant, D.G. and Metz, H.E. (1966). Geology and ore deposits of the Warren Mining District, In Geology of the Porphyry Copper Deposits, southwestern North America. Titley and Hicks (eds). The University of Arizona Press, 189-203.

Callahan, W.H. and McMurray, H.V. (1967). Geophysical exploration of Mississippi Valley - Appalachian type stratabound zinc-lead deposits, In Mining and Groundwater Geophysics. Morley, L.W. (ed), Geological Survey of Canada, Economic Geology Report 26, 350-360.

Campbell, G. and Mason, R. (1979). The application of airborne and ground geophysical techniques to the search for magnetite-quartzite associated base-metal deposits, In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed), Geological Survey of Canada, Economic Report 31, 757-777.

Cargill, D.G., Lamb, J., Young, M.J. and Rugg, E.S. (1976). Island Copper, In CIM Special Volume 15, Porphyry Deposits of the Canadian Cordillera, 206-218.

Carson, D.J.T. and Jombor, J.L. (1976). Morrison : Geology and Evolution of a Bisected Annular Porphyry Copper Deposit, In CIM Special Volume 15, Porphyry Deposits of the Canadian Cordillera.

Chamberlain, N.G. and Quilty, J.H. (1965). Aeromagnetic surveys in mineral exploration, In Exploration and Mining Geology, 2, Eighth Comm. Min. & Metall Congress, Aust. & New Zealand, 107-111.

Coggon, J. (1973). A comparison of I.P. Electrode Arrays. Geophysics, 38, p737.

Conn, H.K. (1957). Magnetic prospecting for Asbestos Deposits, In Methods and case histories in Mining Geophysics. 6th Comm. Min. & Metall. Cong., Mercury Press, Canada, 135-140.

Coope, J.A. and Davidson, M.J. (1979). Some aspects of integrated exploration, In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed), Geological Survey of Canada, Economic Geology Report 31, 575-592.

Corner, B. and Henthorn, D.I. (1978). Results of a Palaeomagnetic survey undertaken in the Damara Mobile Belt, South West Africa, with special reference to the magnetisation of the uraniferous pegmatitic granites. Atomic Energy Board, Pelindaba, Spec. Pub. 260, 28p.

Crone, D. (1979). Exploration for massive sulphides in desert areas using the ground pulse electromagnetic method, In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed), Geological Survey of Canada, Economic Geology Report 31, 745-755.

Daly, J. (1965). Geophysical prospecting for deep leads, In Eighth Commonwealth Mining and Metallurgical Congress, 2, Exploration and Mining Geology. Melbourne, Aust. Inst. Min. Metall., 144-148.

Dash, B.R. (1978). Induced polarization methods in base metal prospecting in Central India. In Geology and Mineral Resources of southeast Asia. Bankok, Thailand, 14-18 Nov, 1978, Prinya Nutalaya (ed), John Wiley & Sons, 301-308.

Davis, W.E., Jackson, W.H., Richter, D.H. (1960). Application of gravity surveys to chromite exploration in Camagüey Province, Cuba. In U.S.G.S. Prof Pap 400, B133-B138.

Derry, D.R. (1970). Exploration expenditure, discovery rate and methods. CIM transactions, 73, 54-58.

Dobrin, M.B. (1960). Introduction to Geophysical Prospecting. McGraw Hill, 446p.

Dolan, W.M. (1967). Geophysical detection of deeply buried sulphide bodies in weathered regions, In Mining and Groundwater Geophysics. Morley L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 336-344.

Donohoo, H.V., Podolsky, G. and Clayton, R.H. (1970). Early geophysical exploration at Kidd Creek Mine. Mining Congress Journal, 56 (5), 44-53.

Dowsett, J.S. (1967). Geophysical exploration methods for nickel, In Mining and Groundwater Geophysics. Morley, L.W. (ed), Geological Survey of Canada, Economic Geology Report 26, 310-321.

Drummond, A.D. and Godwin, C.I. (1976). Hypogene Mineralization : An impirical evaluation of alteration zoning, In Porphyry Deposits of the Canadian Cordillera. Sutherland Brown, A. (ed). CIM Spec. Vol. 15, 52-63.

Dych, A.V., Becker, A. and Collett, L.S. (1974). Surficial conductivity mapping with the airborne Input system. Can. Min. Metall. Bull, 67 (744), 104-109.

Dych, A.V.,Becker, A. and Collett, L.S. (1975). Input AEM results from Project Pioneer, Manitoba. Can. J. Earth Sci, 12, (6), 971-981.

Fedynsky, V.V. et al. (1967). Geophysics in prospecting and exploration for mineral deposits in the U.S.S.R., In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 667-687.

Fountain, D.K. (1972). Geophysical case history of disseminated sulfide deposits in British Columbia. Geophysics, 32 (1), 142-159.

Fraser, D.C. (1972). Magnetite ore tonnage estimates from an aerial electromagnetic survey. Geoexploration 11, 97-105.

Fraser, D.C. (1974). Survey experience with the Dighem AEM system. Canad. Min. Metall. bull, 67, 97-103.

Fraser, D.C. (1978). Resistivity mapping with an airborne multi-coil electromagnetic system. Geophysics, 43, (1), 144-172.

Garlick, W.G. and Gane, P.G. (1961). Geophysics, In The geology of the Northern Rhodesian Copperbelt. Mendelsohn MacDonald (ed), London, 183-187.

Gay, S.P. (1972). 'The new basement tectonics'. Aeromagnetic Lineaments, their geological significance and their significance to geology. American Stero Map Company, Salt Lake City, Utah, 94p.

Ghosh, S.K. (1978). Scope of aeromagnetic data in resolving problems on geological interpretation, In Geology and Mineral Resources of southeast Asia. Bankok, Thailand, 14-18 Nov, 1978. Prinya Nutalaya (ed). John Wiley & Sons, 223-228.

Goetz, R.F. (1958). A gravity investigation of a sulfide deposit. Geophysics, 23 (3), 606-623.

Griffiths, D.H. and King, R.F. Applied Geophysics for Engineers and Geologists. Pergamon Press, London, 223p.

Hallof, P.G. (1960). Uses of induced polarization in mining exploration. Am. Inst. Min. Eng. Trans., 217, 319-327.

Hallof, P.G. (1967). The use of induced polarization measurements to locate massive sulphide mineralization in environments in which E.M. methods fail, In Mining and Groundwater Geophysics Morley, L.W. (ed), Geological Survey of Canada, Economic Geology Report 26, 302-309.

Hancock, M.C. (undated). The Kalulushi East Copper Deposit. Report R.C.M. Geological Services, Prospecting Department. Kalulushi, Zambia.

Heiland, C.A. (1946). Geophysical Exploration. Prentice Hall, New York, 1013p.

Hendrick, D.M. and Fountain, D.K. (1971). Induced Polarization as an exploration tool, Noranda area. Can. Min. Metall. Bull, 64 (708), 48-57.

Hobson, G.D. (1967). Seismic methods in mining and groundwater exploration, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 148-176.

Hood, P. (1974). Mineral exploration trends and developments in 1973. Canad. Min. J., 95 (2), 163-214.

Hood, P. (1978). Mineral exploration trends and developments in 1977. Canad. Min. J., 99, 163-214.

Hood, P.J., Holroyd, M.T. and McCrath, P.H. (1979). Magnetic methods applied to base metal exploration, In Geophysics and Geochemistry in the search for metallic ores. Geol. Survey of Canada, Economic Geology Report 31, 77-104.

Horvath, J. (1957). Magnetic survey of Rye Park scheelite deposit, New South Wales, Australia, In Methods and case histories in mining geophysics, 6th Commonwealth Mining and Metallurgical Congress. Mercury Press, Canada, 109-111.

Horvath, J. (1970). Electromagnetic prospecting for ore deposits, In Exploration and Mining Geology, 2, Eighth Commonwealth Mining and Metallurgical Congress, Aust. I.M.M., 112-122.

Hugo, D., Maher, M.J. and Maske, S. (1975). A review of the application of the magnetic and gravity methods of prospecting in the Okiep Copper District, In Mineralization in Metamorphic terraines. Verwoerd, W.J. (ed). J.L. Schaik, Pretoria, 355-383.

Innes, M.J.S. (1967). A new gravity anomaly map of Canada : an aid to mineral exploration, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 228-248.

Jacobson, P. (1961). An evaluation of basement depth determination from airborne magnetometric data. Geophysics, 26, (3), 309-317.

Keto, A.M. (1979). On the application of geophysics in the indirect exploration for copper sulfide ores in Finland, In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 665-684.

Klichnikov, V.A. and Segalovich, V.I., 1967. The application of geophysics to exploration for chromite and tungsten, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 476-484.

Komarov, V.A. (1967). The importance of induced polarization method for the exploration of ore deposits, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report, 26, 138-147.

Krishna Murty, J.G. (1978). Role of aerial photo-interpretation and airborne geophysical data in regional geological evaluation and planning exploration activities, In Geology and Mineral Resources of southeast Asia, Bankok, Thailand, 14-18 Nov, 1978 Prinya Nutalaya (ed). John Wiley & Sons, 229-232.

Kruger, F.C. and Lacy, W.C. (1949). Geological exploration of geophysical anomalies near Cerro de Pasco, Peru. Econ. Geol., 44, 485-491.

Krutilchovskaya, Z.A., Pashkevich, I.K. and Simonenko, T.N. (1973). Magnetic anomalies of Precambrian Shields and some problems of their geological interpretation. Can. J. Earth Sci., 10, (5), 629-636.

Kuzvart, M. and Böhmer, M. (1978). Prospecting and exploration of mineral deposits. Developments in economic geology, 8. Elsevier, 431p.

Lajore, J.J. and Klein, J. (1979). Geophysical exploration at the Pine Point Mines Ltd. zinc-lead property, northwest Territories, Canada, In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 653-664.

Lazenby, P.G. (1973). New developments in the input airborne E.M. system. Can. Min. Metall. Bull., 66, No. 732, April, 96-104.

Leney, G.W. (1966). Field studies in iron ore geophysics, In Mining Geophysics, 1. Society of Exploration Geophysicists, 391-417.

Linder, H. (1975). Geology of the Shaft Creek Porphyry Copper and Molybdenum Deposit, Northwestern B.C. CIM Bull, 68, 758, 49-63.

Low, J.H. (1957). Magnetic prospecting methods in asbestos exploration, In Methods and Case Histories in Mining Geophysics. 6th Comm. Min. Metall. Cong., 122-134.

Madden, T.R. and Cantwell, T. (1966). Induced polarization, a review, In Mining Geophysics, II. Society of Exploration Geophysicists, 373-400.

McGrath, P.H. and Hall, D.H., 1969. Crustal structure in northwestern Ontario : regional magnetic anomalies. Can. J. Earth Sci., 6, (1), 101-107.

Middleton, R.S., Campbell, E.E. (1979). Geophysical and geochemical methods for mapping gold-bearing structures in Nicaragua, In Geophysics and Geochemistry in the search for metallic ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report, 31, 779-798.

Nargolwalla, S. and Seigel, H.O. (1977). In-situ mineral deposit evaluation with the sintrex metalog system. Can. Min. J., 98, (4), April.

Nettleton, L.L. (1972). The use of Gravity, magnetic and electrical methods in stratigraphic trap exploration, In Stratigraphic oil and gas fields. Classification, exploration methods and case histories. King, R.E. (ed). SEG Special Publication No. 10, 244-251.

Ogilvy, A.A. (1967). Geophysical prospecting for groundwater in the Soviet Union, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 536-543.

Oostdam, B.L. (1967). Exploration for marine placer deposits of diamonds, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 447-461.

Palacky, G.J. (1975). Interpretation of input AEM measurements in areas of conductive overburden. Geophysics, 40, (3), 490-502.

Parasnis, D.S. (1966). Mining Geophysics. Elsevier Publishing Co., Amsterdam, 356p.

Parasnis, D.S. (1967). Some recent geoelectrical measurements in the Swedish sulphide ore fields illustrating scope and limitations of the methods concerned, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 291-301.

Paterson, N.R. (1971). Airborne electromagnetic methods as applied to the search for sulfide deposits. CIM Bull., 64 (705), 29-38.

Paterson, N.R. (1967). Exploration for massive sulphides in the Canadian Shield, In Mining and Groundwater Geophysics, Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 275-289.

Paterson, N.R. (1971). Airborne electromagnetic methods as applied to the search for sulfide deposits. Can. Min. Metall. Bull. 64, 29-38.

Pelton, W.H. (1977). New I.P. method may discriminate between graphite and massive sulfides. Nth. Miner, 63 (27).

Pretorius, D.A. (1979). The crustal architecture of Southern Africa. The Geol. Society of South Africa, annexure to Vol. LXXVI (1973). Alex L. due Toit Memorial Lectures, No. 13, 60p.

Rayner, J.M. (1967). The role of geophysics in the development of mineral resources, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 259-266.

Redford, M.S. (1975). Magnetics. Unpublished report. Terra-Geoterrex Ltd., Ottawa, Canada.

Roth, J. (1975). Exploration of the southern extension of the Manatoba Nickel Belt. Can. Min. Metall. Bull., 68, No. 761, 73-80.

Roux, A.T. (1967). The application of geophysics to gold exploration in South Africa. In Mining and Groundwater Geophysics. Morley, E.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 425-438.

Sangster, D.F. and Scott (1976). Precambrian stratabound massive Cu-Zn-Pb sulfide ores in North America. Elsevier. Handbook on stratabound ore deposits, 6, 129-222.

Sato, M. and Mooney, H.M. (1960). The electrochemical mechanism of sulfide self-potentials. Geophysics, 25, 226-249.

Scott, H.S. (1957). The airborne magnetometer. In Methods and Case Histories in Mining Geophysics. 6th Comm. Min. & Metall Cong., 26-34.

Seigel, H.O. (1966). Geophysical surveys in base metal exploration. Western Miner, Feb. 1966.

Seigel, H.O. (1967). The induced polarization method. In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report, 26, 123-137.

Seigel, H.O., Hill, H.L. and Baird J.G. (1968). Discovery case history of the Pyramid ore bodies, Pine Point, Northwest Territories, Canada. Geophysics, 33, 645-656.

Seigel, H.O. (1971). Some comparative case histories of base metal discoveries. Geoexploration, 9, 81-97.

Seigel, H.O. (1972). Ground investigation of airborne electromagnetic indications. Proc. 24th Int. Geol. Cong. Montreal, Sec 9, 98-109.

Seigel, H.O. (1974). The magnetic induced polarization MIP method. Geophysics, 39, 321-339.

Seigel, H.O. and Pitcher, D.H. (1978). Mapping earth conductivities using a multi-frequency airborne electromagnetic system. Geophysics, 43, No. 3, 563-575.

Seigel, H.O. (1979). An overview of mining geophysics. In Geophysics and Geochemistry in the Search for Metallic ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 7-23.

Seraphin, R.H. and Rainboth, W. (1976). Poison Mountain. In CIM Special Volume 15, Porphyry Deposits of the Canadian Cordillera, 323-328.

Slichter, L.B. (1955). Geophysics applied to prospecting for ores. Econ. Geol. 50th Anniversary Volume. Lancaster Press Inc. 885-969.

Slichter, L.B. (1960). The need of a new philosophy of prospecting. Mining Engineering, 572-575.

Smith, R.J. (1980). Geophysics as applied to sulfide exploration. In Geophysics for Geologists. Aust. Min. Foundation Workshop course, 131/80, 173p.

Spector, A. and Parker, W. (1979). Computer compilation and interpretation of geophysical data. In Geophysics and Geochemistry in the Search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 527-544.

Stanton, R.L. (1976). Petrochemical studies of the ore environment at Broken Hill, New South Wales, I. Constitution of banded iron formation. Trans. Inst. Min. Metall., Sec. B 85, 33-46.

Steenland, N.C. (1970). Recent developments in aeromagnetic methods. Geoexploration, 8, (3/4), 185-204.

Strauss, G.K., Madel, T.J., Alonso, F.F. (1977). Exploration Practise for Strata-bound Volcanogenic Sulfide Deposits in the Spanish-Portuguese Pyrite Belt; Geology, Geophysics and Geochemistry. In Time and stratabound ore deposits. Klemm and Schneider (eds). Springer-Verlag.

Stoiser, L.R. & Nieto, J.B. (1979). Exploration of the Real de Angeles silver lead-zinc sulphide deposit, Zacatecas, Mexico. In Geophysics and Geochemistry in the Search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 727-734.

Sumner, J.S. and Schnepfe, R.N. (1966). Underground gravity surveying at Bisbee, Arizona. In Mining Geophysics, Vol.1. Society of Exploration Geophysicists, 243-251.

Sumner, J.S. (1976). Principles of induced polarization for geophysical exploration. Elsevier Publ. Co. New York, 277p.

Sumner, J.S. (1979). The induced polarization exploration method. In Geophysics and Geochemistry in the Search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Report 31, 123-133.

Sutherland, D.B. (1967). AFMAG for electromagnetic mapping. In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 228-237.

Tanner, J.G. and Gibb, R.A. (1979). Gravity method applied to base metal exploration. In Geophysics and Geochemistry in the Search of Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 105-122.

Telford, W.M., Geldart, L.P., Sheriff, R.E., Keys, D.A. (1976). Applied Geophysics. Cambridge Univ. Press, London, 860p.

Telford, W.M. and Becker, A. (1979). Exploration case histories of the Iso and New Insco Orebodies. In Geophysics and Geochemistry in the Search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 605-629.

Telford, W.M., King, W.F. and Becker, A. (1977). VLF mapping of geological structure. Geol. Survey Canada Paper 76-25, 13p.

Van Nostrand, R.G. and Cook, K.L. (1966). Interpretation of resistivity data. U.S.G.S. Prof. Paper 499, 310p.

Vozoff, K. (1971). The effect of overburden on vertical component anomalies in AFMAG and VLF exploration. Geophysics 36, (1), 53-57.

Wahl, W.G. and Lake, S. (1957). Airborne Magnetometer survey discovers Manmora Magnetite deposit.In Methods and Case Histories in Mining Geophysics. 6th Comm. Min. Metall. Cong., 155-162.

Ward, S.H. and Rogers, G.R. (1967). Introduction In Mining Geophysics Vol.2, Theory. Soc. of Expl. Geophysicists, 3-8.

Ward, S.H. (1967). Airborne electromagnetic methods, In Mining and Groundwater Geophysics. Morley, L.W. (ed). Geological Survey of Canada, Economic Geology Report 26, 81-108.

Ward, S.H. (1979). Ground electromagnetic methods and base metals. In Geophysics and Geochemistry in the Search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 45-62.

Webb, J.E. (1966). The search for iron ore, Eyre Peninsula, South Australia. In Mining Geophysics Vol. I. Society of Exploration Geophysicists, 379-390.

Webster, S.S. and Skey, E.H. (1979). Geophysical and geochemical case history of the Que River deposit, Tasmania, Australia. In Geophysics and Geochemistry in the search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 697-720.

Weiss, O. (1957). Geophysical surveys discover Stilfontein Gold Mine in South Africa. In Methods and Case histories in mining Geophysics. 6th Comm. Min. Metall. Cong., 341-345.

Westrick, E.W. and Parsons, G.E. (1957). Integrated exploration finds Columbia deposits in Chewett and Collins Townships, Ontario. In Methods and Case Histories in Mining Geophysics. 6th Comm. Min. & Metall. Congress, 184-195.

Witherly, K.E. (1979). Geophysical and geochemical methods used in the discovery of the Island Copper Deposit, Vancouver Island, British Columbia. In Geophysics and Geochemistry in the Search for Metallic Ores. Hood, P.J. (ed). Geological Survey of Canada, Economic Geology Report 31, 685-696.

Yungul, S. (1956). Prospecting for chromite with gravimeter and magnetometer over rugged topography in eastern Turkey. Geophysics, 21 (2), 433-454.

Zablocki, C.T. (1962). Electrical and magnetic properties of a replacement type magnetite deposit in San Bernardino County, California. U.S.G.S. Prof Paper 450D, 103-104.

Zietz, I., Hearn, B.C., Higgins, M.W., Robinson, G.D. & Swanson, D.A. (1971). Interpretation of an aeromagnetic strip across the Northwestern United States. Geol. Soc. Am. Bull., 82 (12), 3347-3372.

Zonge, K.L. and Wynn, J.C. (1975). Recent advances and applications in complex resistivity measurements. Geophysics, 40, 851-864.