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# COMMENTS ON THE FEASIBILITY OF USING THE RAPID RECONNAISSANCE MAGNETIC INDUCED POLARIZATION METHOD IN THE SEARCH FOR PORPHYRY COPPER TYPE MINERALISATION

HARE GROUP OF MINERAL CLAIMS
HIGHLAND VALLEY AREA OF THE
KAMLOOPS MINING DIVISION
BRITISH COLUMBIA, CANADA
MAP SHEET M 921/11E
50°35' NORTH LATITUDE
212°05' WEST LONGITUDE

FOR

CENTURION EXPLORATION INC.
157 ALEXANDER STREET,
VANCOUVER, B. C.
V6A 1B8

MINERAL RESOURCES BRANCH
ASSESSMENT REPORT
No 10,848
PART 1 of 3

A.W. HOWLAND-ROSE,MSc,DIC,AMAusIMM,FGS.
SYDNEY, N.S.W., AUSTRALIA

FEBRUARY 27th, 1981

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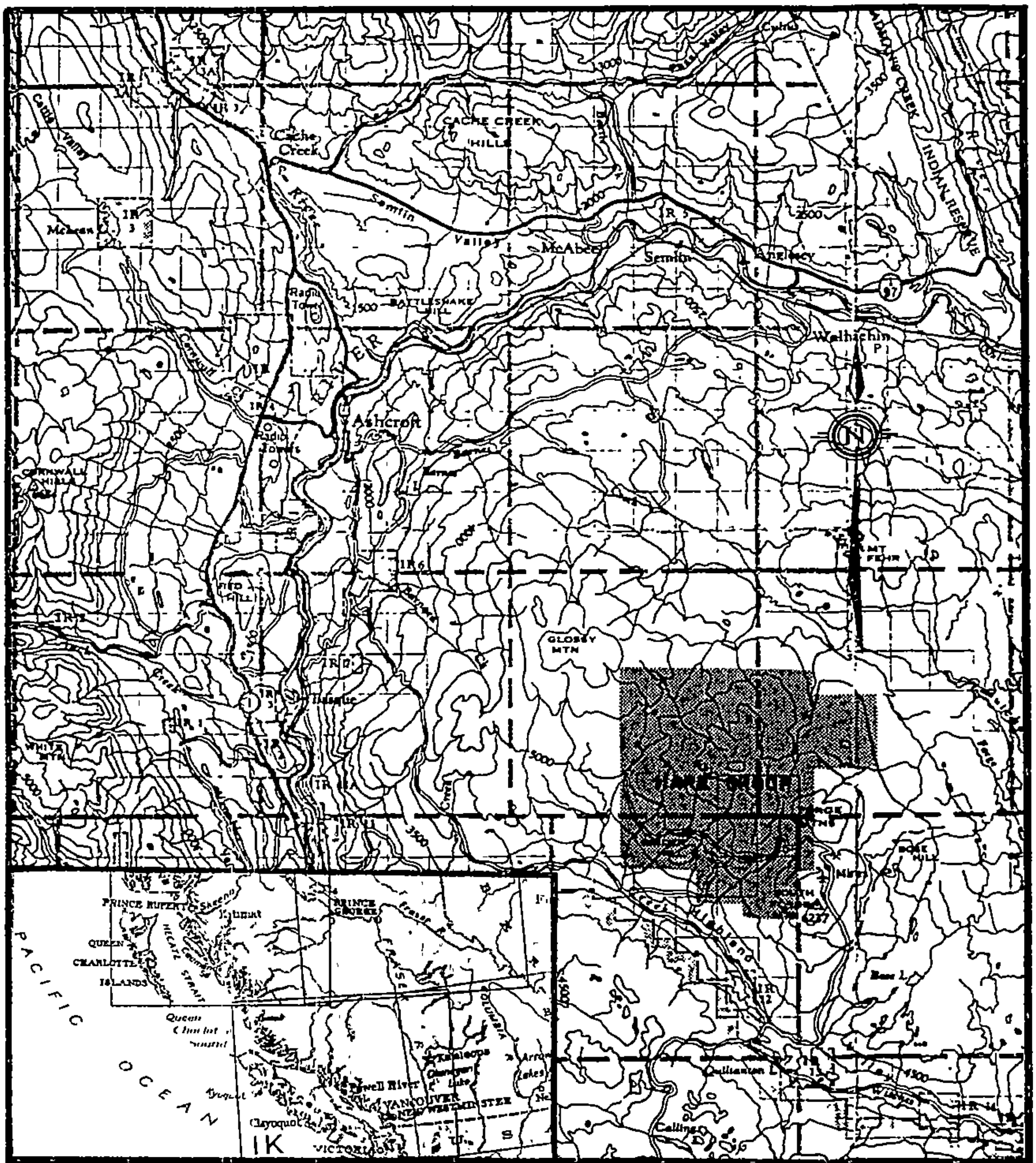
# APPENDIX

"The Present Application of the Magnetic Induced Polarization(MIP) Method in the Time and Frequency Domain."



## FIGURE Nº 1

# CENTURIAN EXPLORATION INC.

## HARE GROUP OF MINERAL CLAIMS
## LOCATION MAP

SCALE 1 : 250,000

0 5 10 15 20 25 30 km.

| | |
|---|---|
| **92 I/NW & NE** | **DATE: MAR. 15, 1983** |

# COMMENTS ON THE FEASIBILITY
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## *INTRODUCTION*

This report discusses the feasibility of employing the rapid reconnaissance magnetic induced polarization (RRMIP) method in the search for porpyhry copper deposits within the basalt and glacial moraine covered areas of the Highland Valley of British Columbia.

The Reports by N.L. Tribe, P.Eng. discussing the geological potential of the Hare Group of Mineral Claims, Kamloops Mining Division of British Columbia has been thoroughly studied by the author together with a number of the references made in that report. Based on extensive Australian experience, and a test survey carried out in the Highland Valley, it will be argued that RRMIP can be used to efficiently explore for large deposits such as the disseminated porphyry copper deposits which lie under cover of at least 300 metres depth and perhaps deeper.

## *DESCRIPTION OF THE SYSTEM*

### *Background*

The magnetic induced polarization method was developed by Scintrex Limited of Toronto, Ontario specifically to overcome the problem of deep and often intense oxidation frequently of high conductivity which is prevalent over a large portion of continental Australia.

While the phenomena observed, namely induced polarization and resistivity, are the same as for electrical induced polarization which is extensively and successfully used in Canada, the mode of measurement of these phenomena gives the method a unique advantage in areas of deep overburden, particularly where these areas have bulk conductivities significantly greater than the bedrock below.

### *Method*

The rapid reconnaissance magnetic induced polarization method (RRMIP) is briefly described in the appendix, however, for those totally unfamiliar with electrical geophysical methods, a very simple explanation follows which hopefully will convey the significant features of the method in the application to the search for porphyry copper mineralisation in the Hare Group of Mineral Claims.

There are two significant electrical properties of rocks and ore bodies which are of great assistance in identifying zones of potential economic interest. The first is *resistivity*. This can be described as the resistance of a rock to the passage of electric current through it. Obviously those sections which are less resistive will allow greater quantities of current to flow than those which are more resistive. Massive sulphide zones, fault zones, zones of deeper and more intense oxidation and graphite horizons, are examples of units which will allow greater quantities of current to pass. In RRMIP, the measurement of resistivity is made with a very sensitive horizontal field magnetometer. This senses the volume of current flowing in the section below by virtue of the fact that current is simply the number of electrons flowing, and each of these electrons carries a magnetic field with it as it moves. Thus the magnetic field observed by the magnetometer is proportional to the current flowing through the volume of overburden and rock below the sensor. This measurement is called Magnetometric Resistivity (MMR). Positive values define areas of relative conductors, and negative values define areas which are relatively resistive. This parameter can be used as a method for tracing rocks having different resistivities beneath conductive overburden, as well as to define specific conductors which may of themselves be of potential economic interest. This is possible because the magnetic sensor which is used on these surveys measures only the *horizontal* component of the current flow, and thus current flow within the essentially horizontal overburden will be de-emphasised, and the influence of steeply dipping resistivity contrasts beneath any conductive layer emphasised.

The second, and in the present case, more significant property is known as *induced polarization.* This phenomenon involves the storage of some of the electrical energy at the grain boundaries of sulphide (or graphite) grains, and the water contained between grain boundaries in rocks and ore bodies. If a pulsed current is used, the sulphide (or graphite) zones will charge during periods of current flow, and discharge during periods when the current ceases to flow. It is this discharge of stored energy which is the induced polarization effect. The magnetic sensor is sufficiently sensitive to define the small magnetic fields associated with this discharge. The magnetic induced polarization effects are measured in terms of Relative Phase Shift (RPS). Positive values denote *internal* polarization from *within* sulphides or graphite, while negative values generally denote the discharge of the polarization effect *external* to the source.

The reason for a magnetic sensor being used rather than simple electrical contact with the surface of the ground is that with the latter, conductive surface layers effectively mask the major changes in resistivity beneath the conductive surface layer, and invariably either completely short out the induced polarization effect, or render it unrecognisable against geological background noise. However, in the magnetic induced polarization method, the magnetic sensor will enable the magnetic field due to the passage of the primary current (MMR) and the discharge of the induced polarization effect (RPS) to be measured at surface from events below the overburden.

### *Field Operations*

A large current dipole of the order of 2 to 3 kilometres will be placed along the preferred strike direction, and lines surveyed at right angles to the current line at 200 to 250 metres intervals, with stations at 25 to 50 metre intervals along lines. Readings of the primary magnetic field (resistivity) and the secondary field (induced polarization) are taken at each station and compiled into profiles and contour maps, generally by computer.

For a more comprehensive understanding of the method, it is recommended that the appendix and the references therein be studied.

## *TEST SURVEY*

### *Introduction*

In order to test the feasibility of employing the RRMIP method in the Highland Valley, a test survey was carried out by Mr. N. Fiset, B.Sc., geophysicist with Scintrex Limited of Toronto, Canada, under the direction of the author. The work was carried out over two days in late June, 1980.

## *Objective*

The primary objective of the survey was to ascertain the logistical and geophysical feasibility of carrying out RRMIP surveys in the Highland Valley, and to develop a cost effective approach to the systematic coverage of the prospective areas. In particular the following conditions needed to be established:- 1) The level of current obtainable in the large 1½ to 2 kilometre current dipoles required in porphyry copper exploration; 2) The primary magnetic field due to the primary current; 3) The noise levels in the measurement of the primary field (Hp) and of the critical parameter, the induced polarization effect (RPS); 4) The time required to level the sensor in the softer humus soils; 5) The time required to lay the energising loop.

## *Discussion*

The equipment employed included a Scintrex TSQ-3 RRMIP transmitter, a Scintrex MFM-3 horizontal fluxgate magnetometer and a Scintrex IPRF-2 frequency domain (harmonic) induced polarization receiver.

The test survey employed a current dipole with electrodes placed 1½ kilometres apart. The current wire was laid so as to avoid the three 800 metre lines surveyed. The three survey lines, 1S, 2S and 3S, were placed 250 metres, 50 metres and 150 metres from the grid centre (see Figure 1) with readings of the primary field (Hp) and two independent measurements of the induced polarization effect, Relative Phase Shift (RPS) and Percent Frequency Effect (PFE) being taken at each station.

For completeness the data acquired is appended as Figures 2-4, but the interpretation therefor is not discussed as the primary objectives of the test are as outlined above.

The test survey demonstrated that with only minimal electrode preparation, a current of 5.5 amps was achieved at a voltage of only 600V. On the three test lines the primary magnetic field,Hp, varied from 1.4 gamma to 0.6 gamma, resulting in a noise level in the all important induced polarization field of 0.1° for RPS and 0.1% for PFE, with higher levels as winds increased. The sensor was able to be levelled in minimal time, while the energising cable had to be laid by hand (as opposed to vehicle in Australia) - no major difficulties were encountered in this exercise.

The test survey implied that a daily production of about 80 stations per operator would be possible assuming minimal time lost to travel and noise.

## *Recommended Procedures*

Considerations of target size, terrain and access suggest the most cost effective approach in the area should consist of the following components:-

1) Interline spacing should be 200 to 250 metres
2) Station interval - 25 to 50 metres
3) The energising cables should be laid so as to avoid unnecessary movement of the transmitter
4) The energising cable should be strung above the ground to minimise wire cuts due to animals.
5) While the TSQ-3 (3 kilowatts) transmitter proved satisfactory, an 8 kilowatt transmitter is recommended. This will allow larger current dipoles to be used (2½-3 kilometres), resulting in less wire laying and higher signal to

noise ratios.

6) The survey crew should consist of:-

   a) Senior operator and assistant
   b) Second operator and assistant
   c) Generator man

At the commencement of the survey, a three man team is recommended, the senior operator should direct the survey, and act as geophysical operator full time, the second operator would lay out energising cable, and operate as time permits. Should conditions permit, two additional field hands could be added so as to allow two full-time readers on the grid. The detailed composition of the crew should, however, depend on the most cost effective approach dictated by the circumstances.

## *Conclusion*

The results of the test survey have shown that conditions in the Highland Valley are most favourable for the execution of RRMIP surveys, and furthermore, subject only to terrain and access problems, results should be comparable with those obtained in Australia.

## *Recommendations*

1) It is recommended that an RRMIP survey be carried out over the 74 square kilometres of the Hare Group of Mineral Claims, or over that portion of the area which is considered of greatest interest.

2) Survey lines should be at 200 or 250 metre spacing, with station intervals at 25 to 50 metres along these lines.

3) A five man crew is recommended as detailed above.

4) At 250 metre line intervals, and 50 metre station intervals, each square kilometre should be surveyed in one day.

5) The charges made by Scintrex on a daily basis would be as follows:

| | |
|---|---|
| a) TSQ-4 (8 kilowatt transmitter), IPRF-2, MFM-3 | C$200 |
| OR | |
| b) TSQ-3 (3 kilowatt transmitter), IPRF-2, MFM-3 | C$150 |
| c) Second IPRF-2/MFM-3 | C$ 80 |
| d) Senior geophysical operator (geophysicist)<br>(Standby C$175) | C$250 |
| e) Second geophysical operator<br>(Standby C$150) | C$180 |

Daily charges are estimated at:

| | |
|---|---|
| Single operator crew a) and d) | C$450 |
| Double operator crew a), c), d) and e) | C$710 |

Services to be provided by Centurion would include:

For single operator crew:

| | | |
|---|---|---|
| Two field hands, estimated | C$200 | |
| Vehicle, say | C$100 | |
| Accommodation C$30/man/day | C$ 90 | C$390 |

For double operator crew:

| | | |
|---|---|---|
| Three field hands, estimated | C$300 | |
| Two vehicles, say | C$200 | |
| Accommodation C$30/man/day | C$150 | C$650 |

Therefore daily costs for data acquisition are $1360 for a double operator crew which should cover an average of 1½ square kilometres per diem. Thus the approximate per kilometre estimate for data acquisition is

C$900.

Data compilation and reporting is not expected to exceed C$50/kilometre.

Mobilisation will be at cost plus 12% and standby rates ex Sydney, Australia or Toronto, Canada as applicable, and are estimated at C$12,500

Total cost estimated for the 74 square kilometres of the Hare Group is thus estimated as follows:

| | |
|---|---|
| Data acquisition | $66,600 |
| Data processing and reporting | $14,800 |
| Mobilisation/demobilisation | $12,500 |
| | $93,900 |
| Contingency: | $23,475 |
| | $117,375 |

The above estimates are based on the test survey averaged out, but it should be noted that actual costs will depend on the actual conditions found to exist on the Hare Group of Mineral Claims as a whole.

A.W. HOWLAND-ROSE, MSc,DIC,AMAusIMM,FGS.

# CERTIFICATE OF QUALIFICATION

I, Anthony William Howland-Rose, of Killarney Heights, Sydney, New South Wales, Australia, hereby certify that:-

1. I am a Consulting Geophysicist living at 1 O'Connell Avenue, Killarney Heights, Sydney, Australia.
2. I have practised my profession for eighteen years.
3. I have graduated with the degrees of:

   Bachelor of Science Upper Second Class Honours in Geology, Queens University, Belfast.

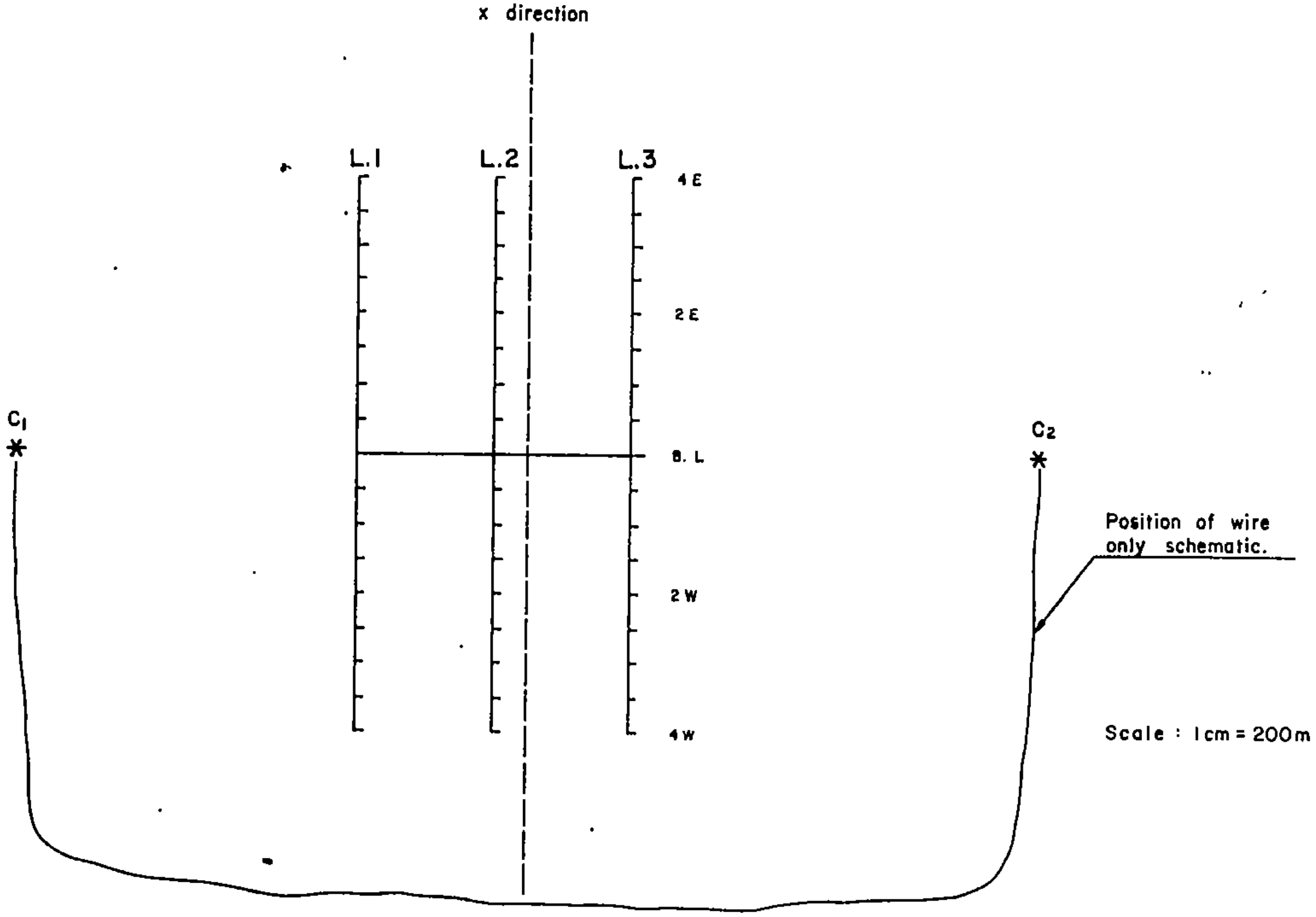
   Diploma of Imperial College in Applied Geophysics, Royal School of Mines, Imperial College, London.

   Master of Science in Applied Geophysics, London University.
4. I am a Fellow of the Geological Society of London, an Associate Member of the Australasian Institute of Mining and Metallurgy, an Active Member of the Society of Exploration Geophysicists, the Australia Society of Exploration Geophysicists and the European Society of Exploration Geophysicists.
5. I have no direct, indirect or contingent interest in the shares of Centurion Exploration Inc., or the mineral claims subject of this report nor do I expect to receive any such interest.
6. This report dated 27th February, 1981 is based on the report dated 15th November, 1980 by N.L. Tribe, the references listed therein, and the results of a test survey carried out by Scintrex Limited within the proposed survey area.

7. Consent is hereby granted to use this Report, in its complete form only, in a Filing Statement, Statement of Material Fact, or Prospectus by Centurion Exploration Inc.

Dated at Sydney, Australia this 27th day of February, 1981.

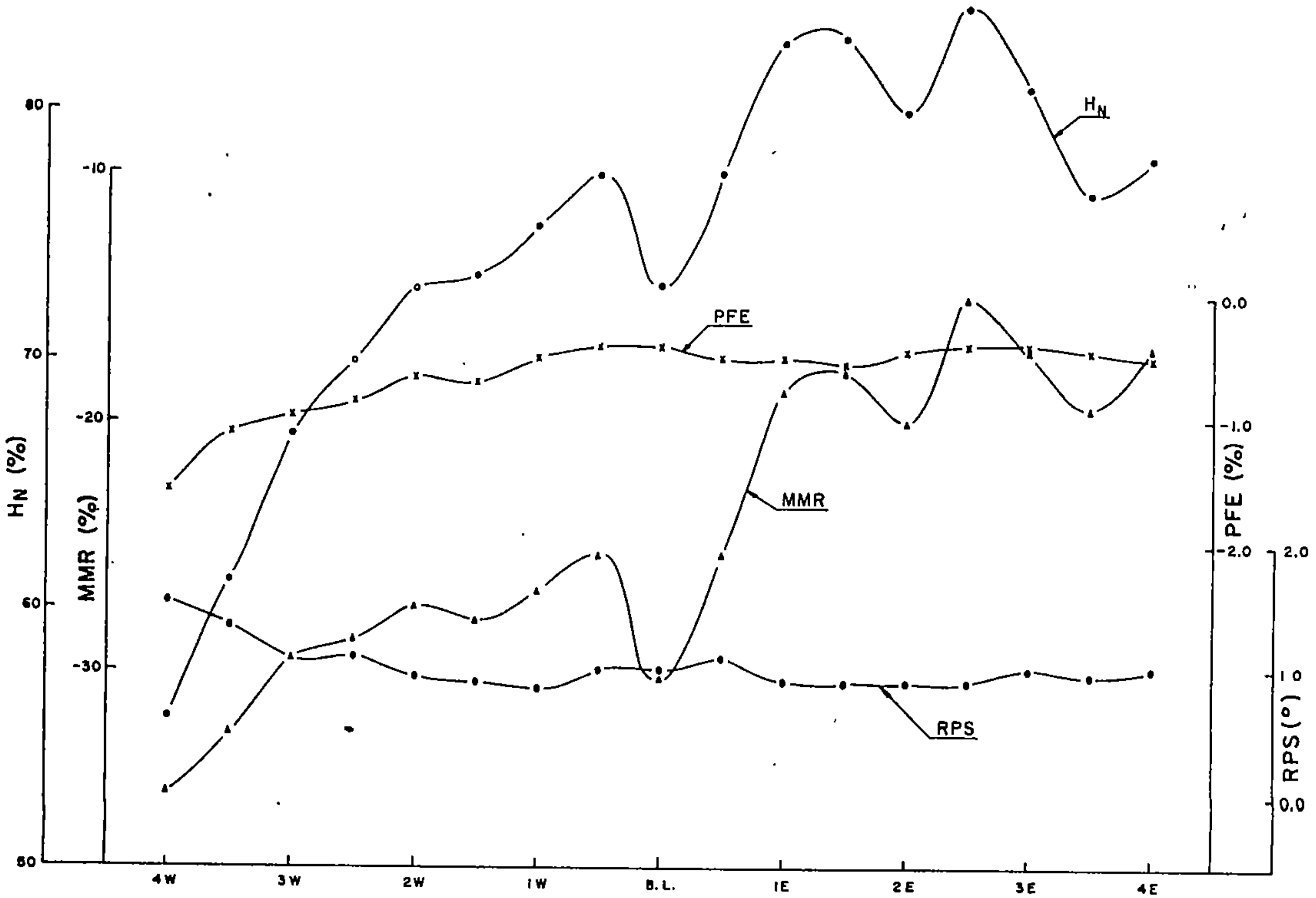
A.W. Howland-Rose, MSc,DIC,AMAusIMM,FGS.
Geophysicist



## MIP TEST
## CENTURION RESOURCES
## GRID PLAN
HIGHLAND VALLEY, B. C.

80 – T 2063

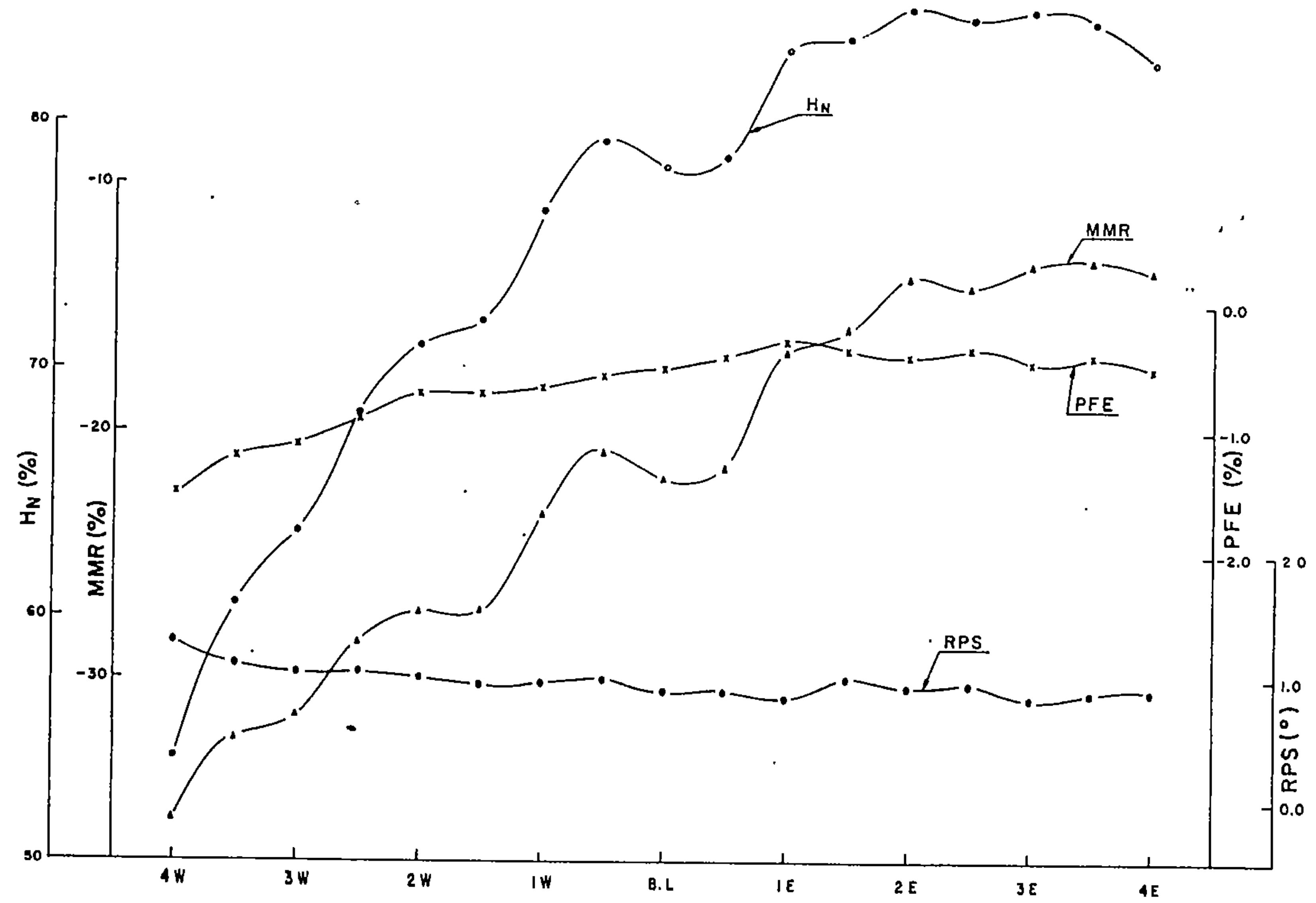
FIGURE 1



MIP TEST
CENTURION RESOURCES
LINE 1S
HIGHLAND VALLEY, B.C.

80 - T 2063

FIGURE 2



## MIP TEST

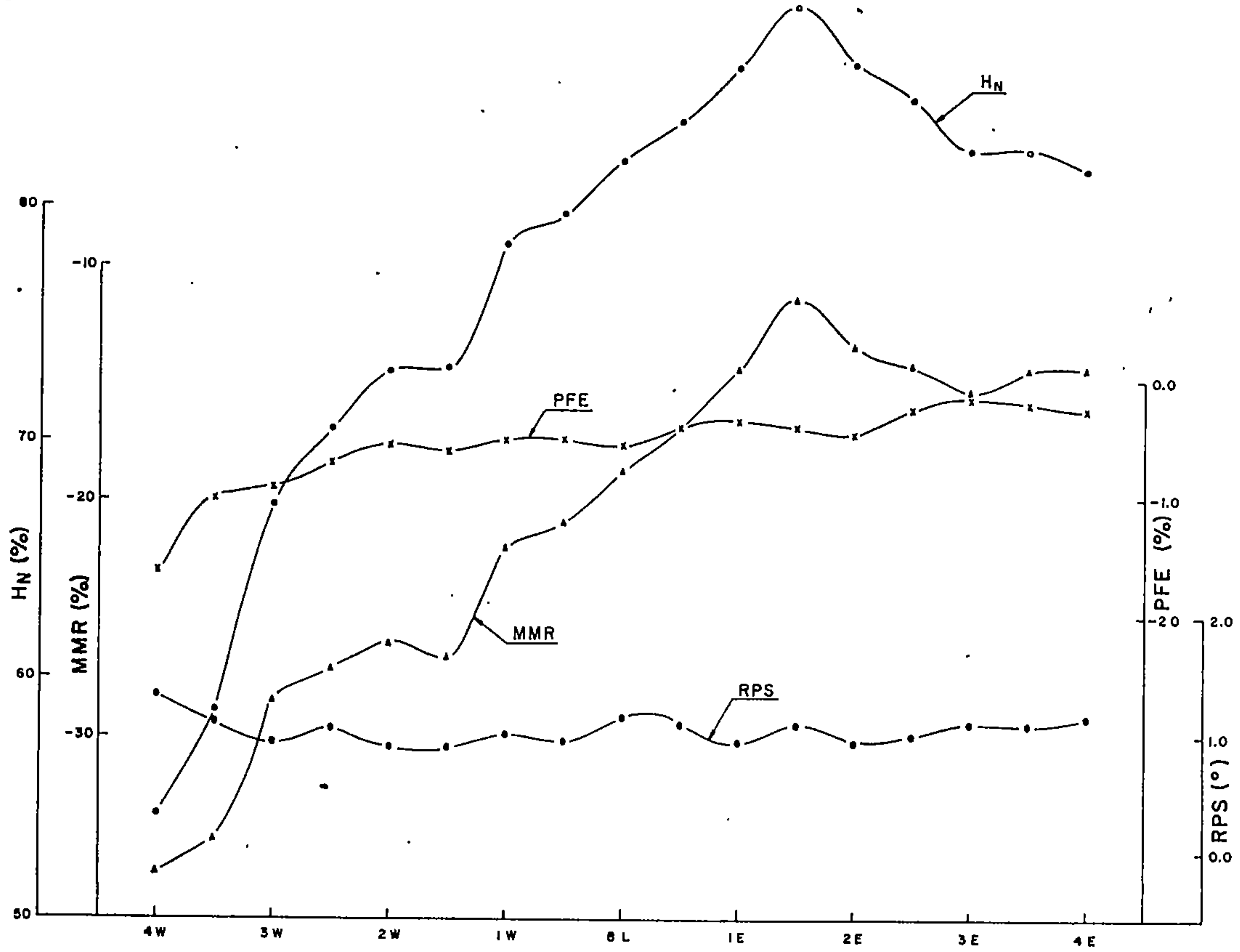
CENTURION RESOURCES

LINE 2S

HIGHLAND VALLEY, B.C.

80-T 2063

FIGURE 3



# MIP TEST
## CENTURION RESOURCES
## LINE 3S
HIGHLAND VALLEY, B. C.

80 – T 2063

FIGURE 4

# THE PRESENT APPLICATION
# OF THE MAGNETIC INDUCED POLARIZATION (MIP) METHOD
# IN THE TIME AND FREQUENCY DOMAIN

## *INTRODUCTION*

Since the Magnetic Induced Polarization (MIP) method was introduced into Australia some six years ago, very considerable field experience has been gained. The purpose of these comments is to discuss the application of the method, the form of the responses observed, and how the standard anomaly forms are generated. This is a simple non-mathematical description designed to enable the geologists to visualise just how the energising and induced polarization currents flow in the ground, and how to interpret these in a qualitative sense, for it is the geologist who is far better qualified to interpret this data in a structural context. It is the author's opinon that MIP data is more often than not, simpler and more diagnostic to interpret than EIP or EM data in the conductive conditions which exist over much of Australia's land mass.

## *The Uniqueness of the MIP Method .....*

It is essential to grasp the very basic differences between the magnetic mode of acquiring induced polarization data (MIP) and the more conventional electrical mode (EIP). As even geophysicists of some experience have had difficulty in appreciating the full significance of this method, it is necessary to state in simple terms some of the unique attributes of the method.

1 - Conventional EIP data monitors *ONLY* the current flow *AT THE SURFACE* generated by the storage of charge (IP effect) *WITHIN* the body. With MIP both the current flow *OUTSIDE*, but more importantly *INSIDE* the chargeable

source, are *DIRECTLY MONITORED*. Thus the external (EIP) polarization from mineralisation *NEED NOT NECESSARILY COME TO THE SURFACE* for it to be monitored.

2 - In conventional EIP, the transfer of the induced polarization signal from the source mineralisation to the *surface* involves a considerable loss of energy by "friction" and "chemical reactions" en route, whereas for MIP, as the movements in current *at depth* are monitored *from depth* via their associated magnetic fields, very much less loss of energy is involved. Thus, the fall off in response with distance from a chargeable source is very much less as seen with MIP than that seen with EIP.

3 - With conventional EIP methods, the external induced polarization effect is monitored via two potential electrodes placed some distance apart (commonly 25 to 100 metres), effectively *averaging* the response over this distance. However, as the MIP sensor is about 60 centimetres in length only, in the MIP method it is essentially a *point source* measurement which improves resolution very considerably.

4 - Where conventional EIP techniques are applied to highly conductive overburden/ oxidation regions, the multi-layering within this zone very considerably reduces or even eliminates the EIP signal en route to the surface. With MIP, both primary and secondary (IP) current flow within this zone has *NO MATERIAL INFLUENCE* on the data. Thus the problems of "masking" are eliminated with MIP.

5 - As the EIP induced polarization signal flows from source to surface, the medium through which it passes not only reduces its amplitude (see 2 above), but also modifies the *form* of the signal. Thus the decay form observed at the surface will tend to be that of the *medium* rather than the *source*. However, as the MIP monitors the magnetic field from the decay *within* the source itself, no such distortion in the *internal* polarization decay form can be expected.

6 - The EIP method is essentially a measurement of *absolute* levels of apparent resistivity and chargeability as observed at the surface. However, the MIP

method measures the *relative* properties of chargeability and resistivity, and is thus more sensitive to these differences.

7 - In the EIP method, the electric field is often severely distorted by local and often insignificant inhomogeneities in resistivity. However, as the primary (resistivity) and secondary (IP) magnetic field measurements are summed over a large volume of rock, they are not *distorted or masked* by local inhomogeneities.

*A Definition of Terms .....*

Before going into the detailed qualitative discussion of the principles of operation, it is best to define the terms used in the description.

*Energisation:-* The process by which current is introduced into the volume of rock which is the subject of the survey. *Primary Current Flow:-* The flow of current through this medium as a result of this energisation. *Primary Magnetic Field* ($H_P$)*:-* The magnetic field generated by virtue of the primary current flow in the subsurface.

*Induced Polarization Effect:-* The "condenser like" storage of energy on an electronic/electrolytic boundary, for instance on sulphide/electrolyte boundaries. *Internal Polarization:-* The induced polarization effect *within* the body, which is the *source* of all induced polarization phenomenon, whose discharge is always in the *OPPOSITE DIRECTION* to the primary current flow which caused it.

*External Polarization:-* The induced polarization effect which flows *outside* or *external* to the causative source which is always of the same sign as it is in the same direction as the energising primary current. *Secondary Magnetic Field* ($H_S$)*:-* This is the magnetic field caused by the flow of secondary currents within (internal) and outside (external) of the causative source.

*Decay Form* ($\Delta M$)*:-* This term describes the decay of the energy stored within the body. It may be more rapid than "normal" or slower than "normal". (A detailed description follows on Page 9).

*Comparison of the Electrical and Magnetic Modes of Acquiring Induced Polarization Data .....*

By far the most meaningful way in which to visualise the nature of MIP (and indeed EIP) data, is to consider the *energy storage concept* and to look at the primary current flow pattern and the resultant equipotential field caused by this energising current, and then the consequent secondary current flow pattern and its associated secondary potential field caused by the decay of the energy stored on electronic/ electrolytic contact boundaries, which is known as induced polarization. As this is most easily visualised in the time domain, this description is confined to that domain.

*Energisation Process .....* Normally current is applied to the volume to be sampled by means of two electrodes placed semi-parallel to the expected strike of the target mineralisation. In the diagram shown in Figure 1, the fine solid lines represent the current flow pattern so generated. The dashed faint lines represent the equipotential surfaces (lines in the section).

In the *electrical mode*, the two potential electrodes (see Figure 1) will measure the *resistivity* of a volume of material defined by the equipotential surfaces which are always at right angles to the current flow.

*Energy Storage Process .....* The material through which the current passes will store some portion of the energy in a way determined by the properties of the storage material. The amount of energy stored will depend on the total area of the sulphides (or graphite etc.) presented to the current, and thus, the greater this surface area with respect to the volume of material, the greater will be the energy stored. Finely disseminated material will store substantially more energy than coarse grained material.

*The Discharge of Stored Energy .....* On cessation of the energising current flow, the energy stored by the *chargeable source* will discharge *internally* within the source as shown by the solid arrows in Figure 2, and *externally* around the body in the medium surrounding the source as shown by the solid heavy lines in Figure 2. These currents are respectively known as *internal* and *external* current flow. The former is of *negative sign* as it is in the *opposite direction* to the original energising current, and the latter is of *positive sign* as it is in the *same*

# EIP & MIP ENERGIZATION

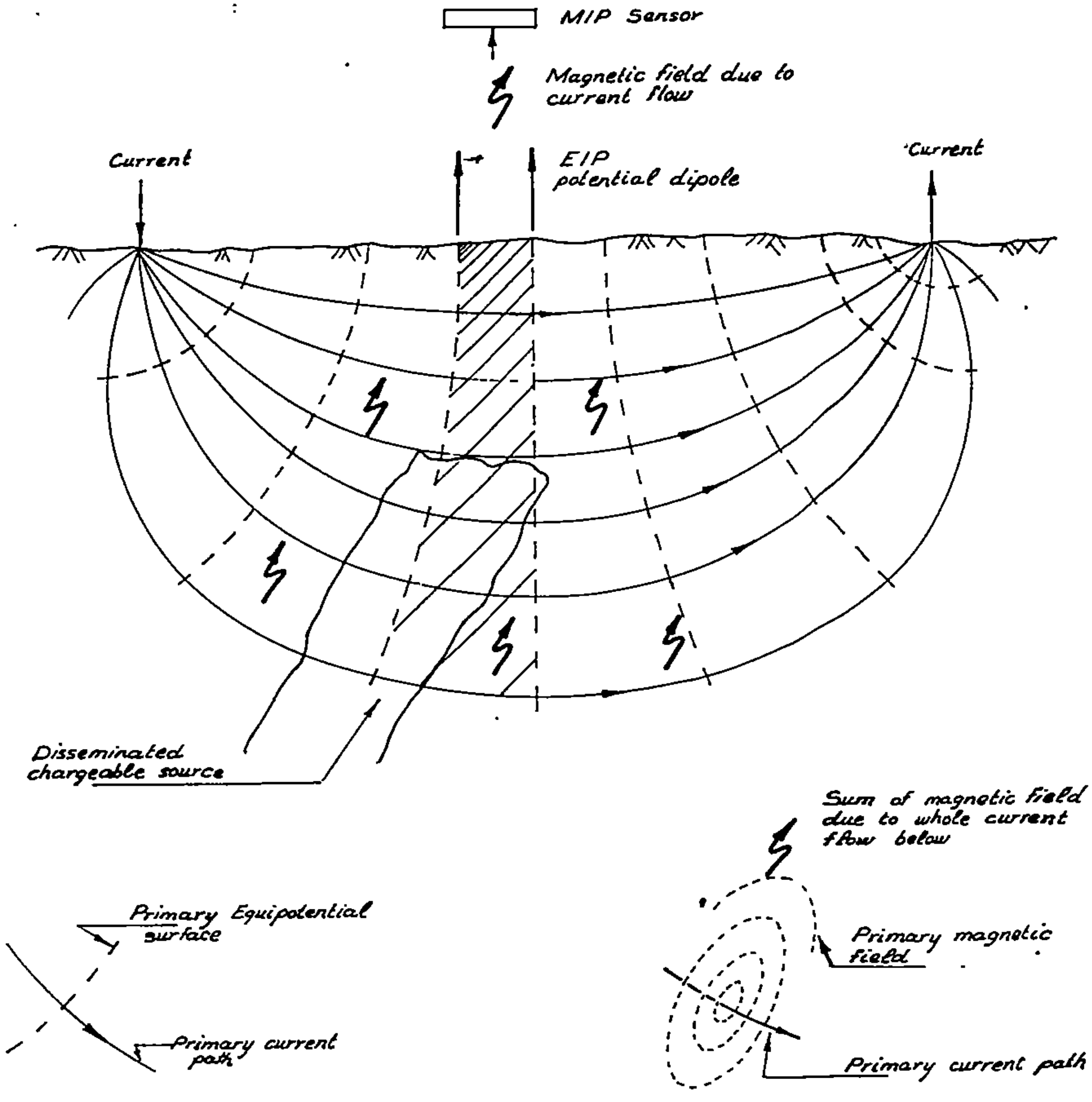


Fig. 1

# EIP & MIP
## DISCHARGE OF INDUCED POLARIZATION

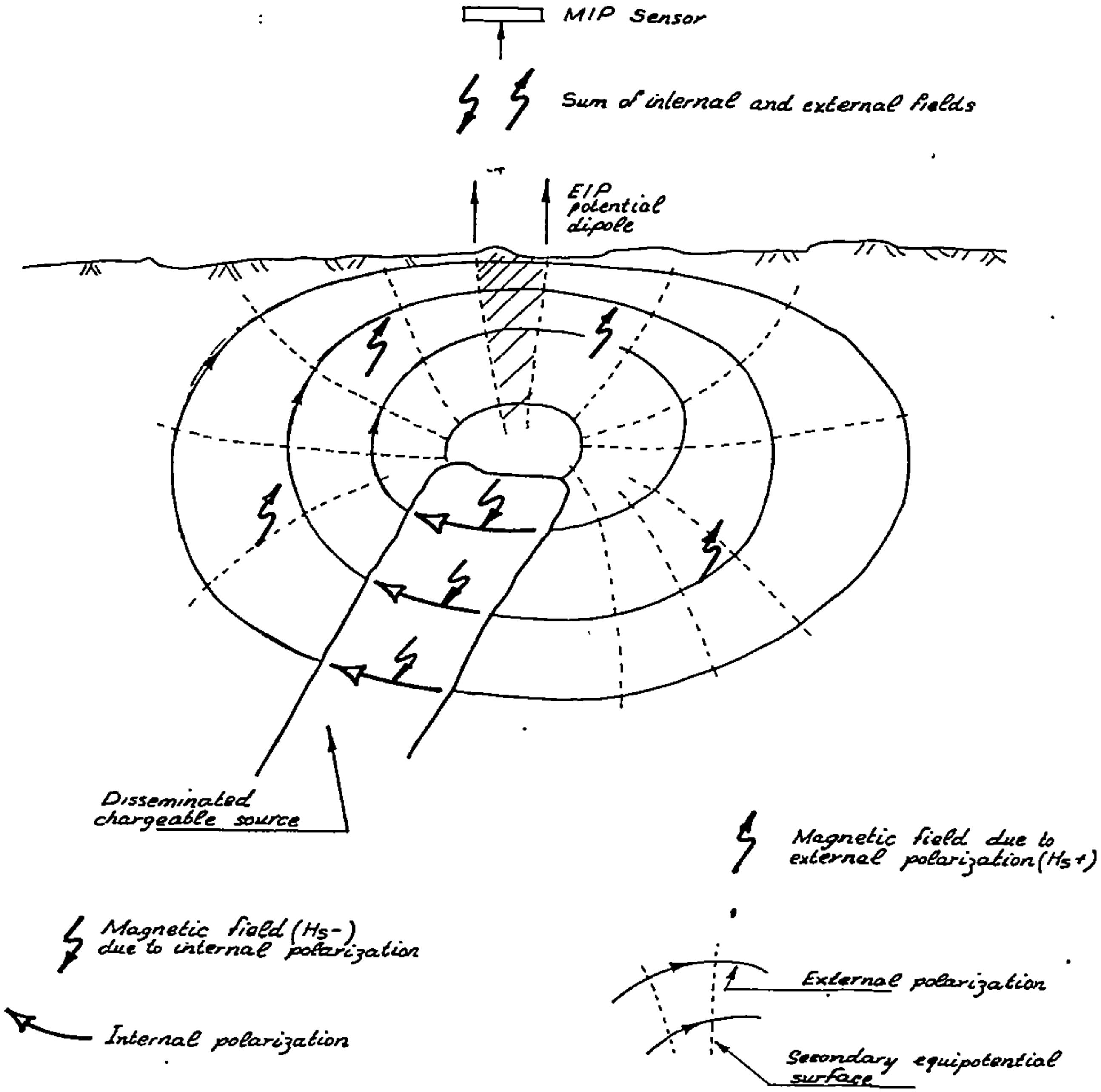


Fig 2.

*direction* as the energising current.

In the electrical mode,. only the discharge *external* to the body is investigated. In Figure 2 the thick solid lines show this discharge together with the *equipotential surfaces* (thick broken lines) which this current imposes. As with the charging process these surfaces must be at right angles to the current lines which impose them. The potential electrodes will therefore measure the stored energy (chargeability) as seen via the secondary equipotential field. It is important to note that *(i)* this is *NOT* the same volume as the resistivity measurements and *(ii)* it is *NOT* the original IP signal as stored by the body, but a measurement distorted and processed by the environment through which it has passed.

In the *magnetic mode* a very sensitive magnetometer (Scintrex MFM-3) is used to "sense" the horizontal component of the magnetic field due to the current flow both *inside* and *outside* of the *source material.* This is possible because each electron which flows in the ground carries with it an associated magnetic field. This magnetic field will pass *unhindered* through the environment and thus both the discharge *internally* and *externally* to the source can be monitored on the surface.

### *The Form of MIP Anomalies .....*

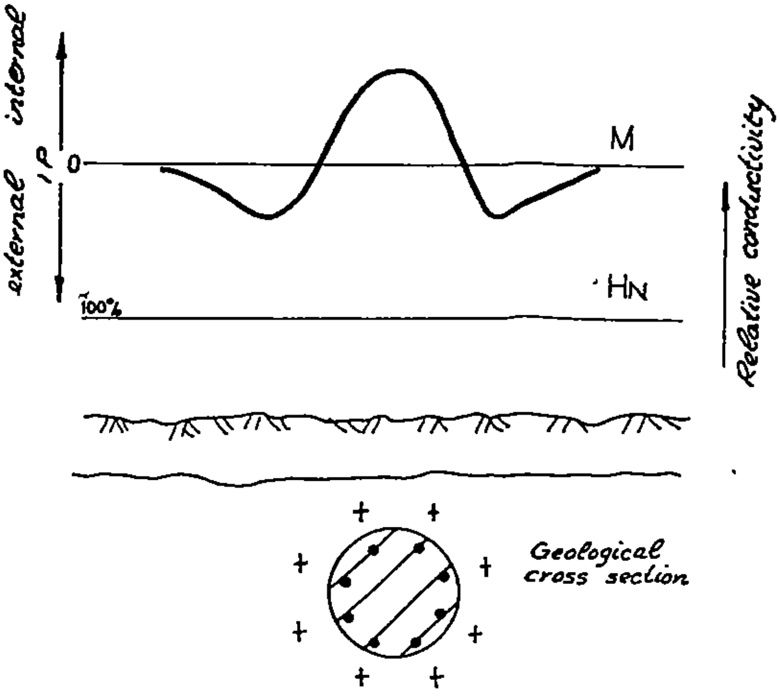
In the MIP method, the energising field is normalised with respect to the energising current electrodes. Details of this procedure are given later in this paper. In the description Figures 3 to 6, the magnetic field due to the primary passage of the energising field $H_N$, can be regarded as "relative bulk conductivity" plotted upwards. In these figures, *internal* polarization (which is negative in sign becuase it flows in the opposite direction to the energising current), is plotted upwards, while *external* polarization (which flows in the same direction as the energising current and is therefore positive in sign) is plotted downwards.

The enclosed Figure 3 demonstrates the theoretical form of an MIP anomaly from a source which has no electrical contrast with the enclosing material, but has the property of retaining charge. (In nature such anomalies are in fact observed from the ilmenite fraction within heavy mineral deposits in beach sands.)

# TYPICAL M.I.P ANOMALY FORMS

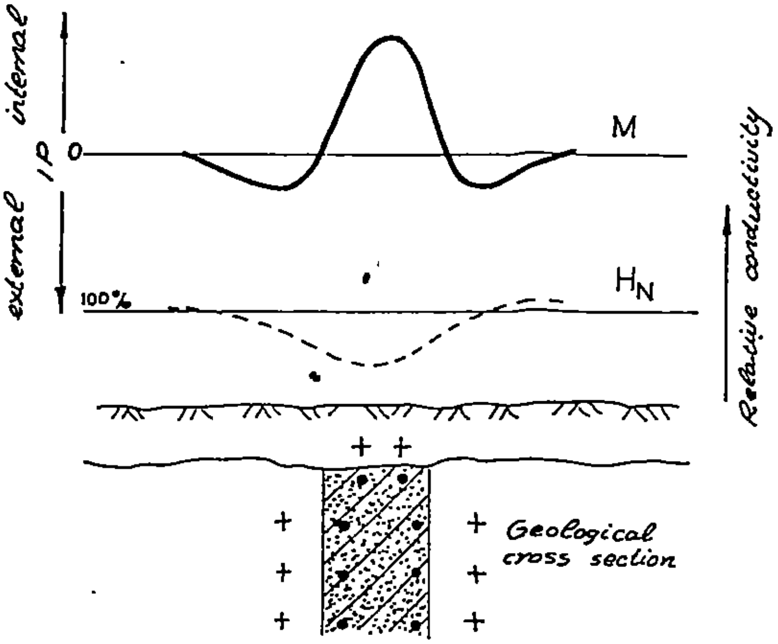
## THEORETICAL MODEL

CHARGEABLE SOURCE
NO RESISTIVITY CONTRAST



## TYPE A

CHARGEABLE SOURCE
RESISTIVE SOURCE



NOTE:

- \+ *External current flow into plane of paper*
- • *Internal current flow out of plane of paper*

Fig. 3

Energisation is along strike, into the plane of the paper. In all figures the current flow direction is represented by arrows, with dots representing current flow *out of* the plane of the paper, and crosses represent the current flow into the plane of the paper.

In Figure 3, over the source, the magnetometer will "see" a surplus of internal (negative) current flow, while on the flanks of the body, the external (positive) current flow will become predominant. The *"head and shoulders"* MIP anomaly shown is *always* seen over all sources. It is the distortions in shape, form and zero level that yield vital information as to conductivity of the source, conductivity of the environment above and about the source, the depth to the source and the nature of the mineralisation in and around the source.

*TYPE 'A' (Figure 3)* ..... shows the typical anomaly form over a chargeable source which is more resistive than the surrounding medium. In such cases the normal *"head and shoulders"* anomalies coincident with a depression in the $H_N$ are observed. An example of such an anomaly form is chalcopyrite/pyrite in quartz veins itself within a more resistive conductive rock unit.

*TYPE 'B' (Figure 4)* ..... In this case the chargeable source has no resistive contact with the enclosing material. This example is very similar to the theoretical model. An example of such an anomaly form would be over disseminated sulphides within a homogeneous rock unit.

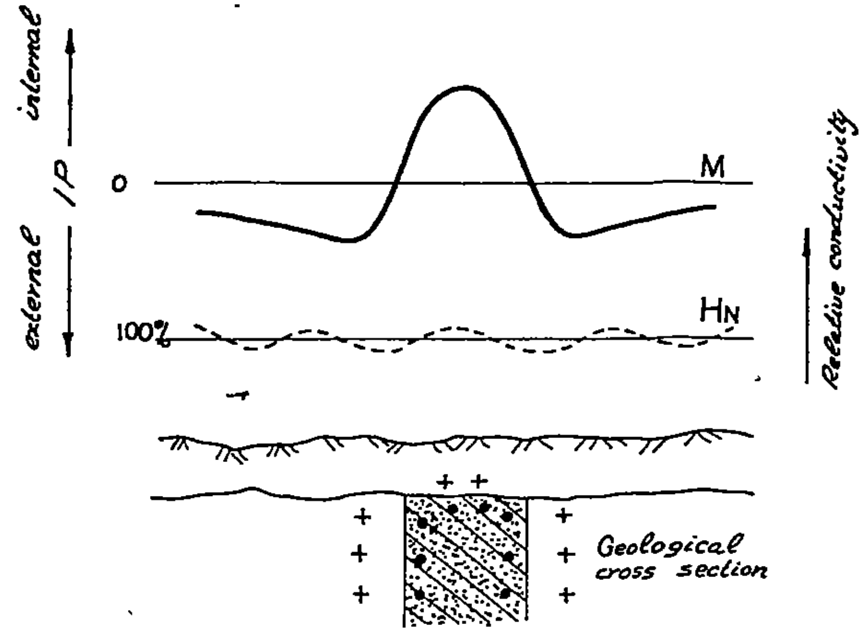
*TYPE 'C' (Figure 4)* ..... In this case the source of the chargeable material is itself more conductive than the enclosing rock type. When the observed $H_N$ values are *less than* 180% - 200%, a normal *"head and shoulders"* anomaly is observed over the source. In practice, observed $H_N$ values rarely exceed 150% of normal.

*TYPE 'D' (Figure 5)* ..... In this most important anomaly form which invariably is associated with massive sulphides which are both conductive and electrically continuous, a massive sulphide *must* be surrounded by a disseminated halo within more resistive host rocks. In this case the disseminated sulphides will naturally store the induced polarization charge *far more efficiently* than the massive electrically continuous core. Thus, on completion of the energisation process,

# TYPICAL M.I.P. ANOMALY FORMS

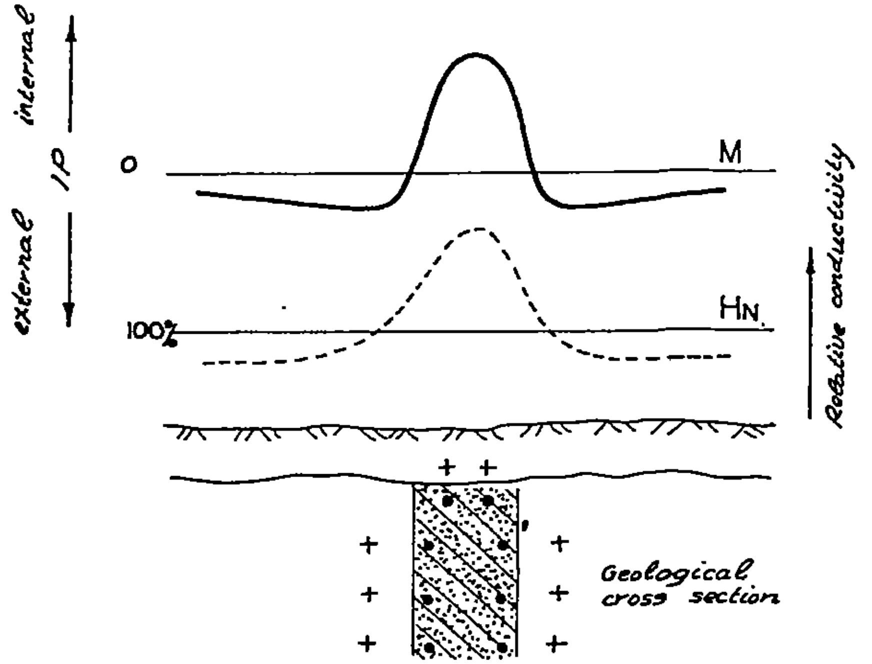
**TYPE B**

CHARGEABLE SOURCE
HOMOGENOUS



**TYPE C**

CHARGEABLE SOURCE
CONDUCTIVE



NOTE:

- \+ *External current flow into plane of paper*
- • *Internal current flow out of plane of paper*

Fig. 4.

the charge stored within the disseminated halo will preferentially discharge through the conductive massive sulphide core. This effect has *NEVER* been observed where $H_N$ values have been less than 180% of normal. This anomaly form due to its high $H_N$ and coincident predominantly external (positive) current flow, is diagnostic when observed. An example of such a response is the Mt. Windarra pyrrhotite/nickel / copper deposits in Western Australia.

*TYPE 'E' (Figure 5)* ..... A distorted MIP response curve is generated when a polarizable body is located on a contact between rocks of quite different resistivities. This is rather common in Western Australian nickel deposits. In such a case the return polarization current flow will be concentrated in the more highly conductive rock type instead of being symmetrically distributed on both sides of the body. The resultant MIP response is an asymmetric curve, with its *internal* (negative) maximum lying on the more resistive side of the body and the *external* (positive) current peak lying on the more conductive side. Sometimes the asymmetry is so large that the "crossover" is almost directly over the polarizable body. The $H_N$ peak is shifted over the conductive rock side of the polarizable body.

### *Composite Anomalies .....*

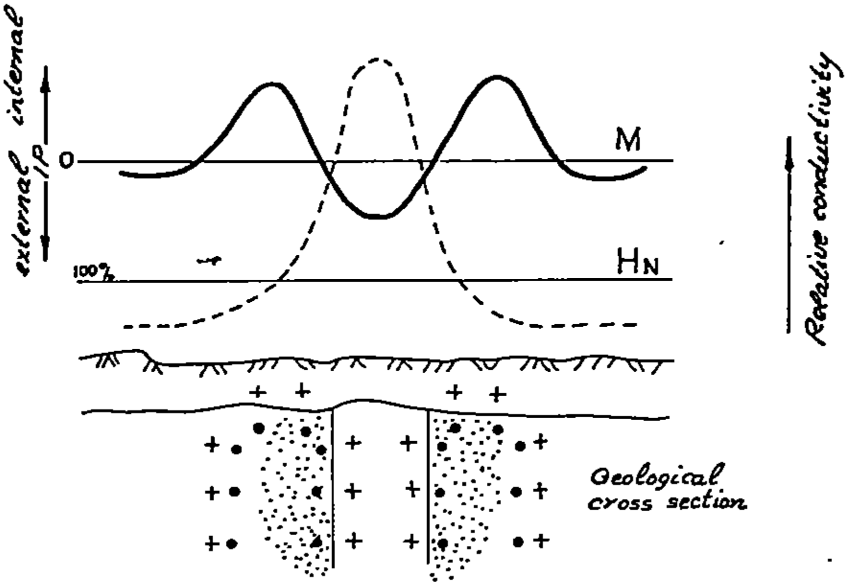
As can readily be appreciated, the above examples 'A' to 'E', represent single simple bodies. In the field, more often than not, the sources vary in composition and therefore in chargeability and resistivity *across strike, along strike* and *down dip*. For example, while the *form* of Type 'C' and Type 'D' anomalies are very different in appearance, the geological situation which gives rise to them requires relatively little change in conductivity to materially change their form from 'C' to 'D'.

In the interpretation of MIP therefore, the electrical characteristics of known 'Type Deposits' similar to those being sought, together with local information as to the possible range of structure in the area, is of primary importance. In other words, geological input is often of greater importance than quantitative geophysical data.

# TYPICAL M.I.P ANOMALY FORMS

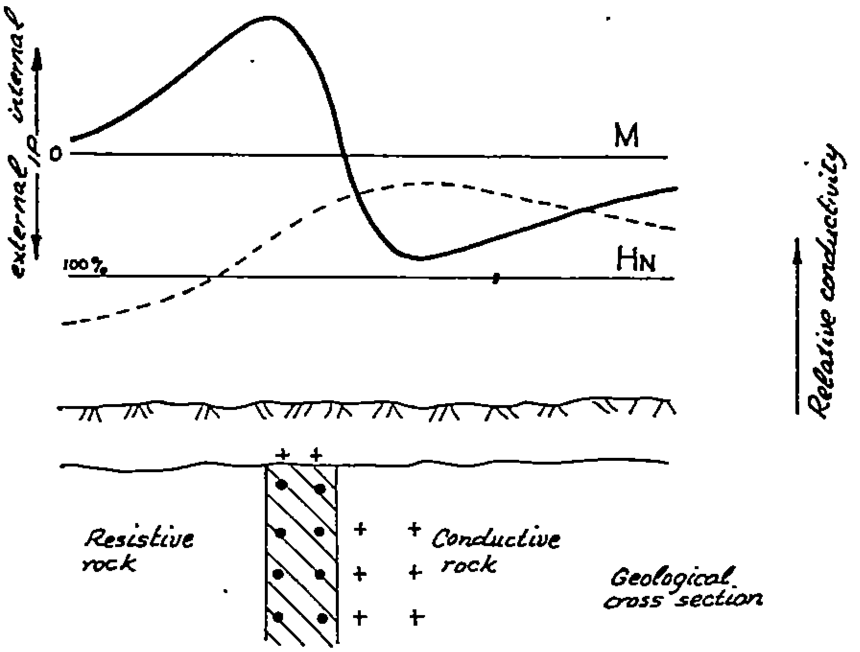
## TYPE D

CHARGEABLE SOURCE VERY CONDUCTIVE WITH DISSEMINATED HALO



## TYPE E

CHARGEABLE SOURCE ON CONTACT BETWEEN TWO ROCK TYPES OF DIFFERING RESISTANCE



NOTE:

- + *External current flow into plane of paper*
- ● *Internal current flow out of plane of paper*

Fig. 5.

### *The Alternative Way of Acquiring MIP Data .....*

The initial work in Australia was carried out in the Time Domain, and the chargeability was measured in terms of *milligamma/gamma.* In the Frequency Domain, a single operating frequency of either, 3, 1, 0.3 or 0.1 Hz with a frequency stability of better than 0.01% is transmitted. The induced polarization effect is then measured in terms of the first and third harmonic of the fundamental frequency in Relative Phase Shift (RPS) which to the first approximation is free of electromagnetic coupling effects, or as Percent Frequency Effect (PFE).

The relationship between these modes of measurement of the induced polarization phenomenon in the magnetic induced polarization method is as follows:-

| Domain | Time | Frequency | |
|---|---|---|---|
| Equipment | IPR-8 (or 10) | IPRF-2 | |
| Units | milligamma/gamma | degrees(°) | Percent Frequency Effect (%) |
| equivalence | 15 milligamma/gamma ≡ | 1.6° ≡ | 1% |

It is important to note that in common with the electrical mode of measurement, the induced polarization effect will be identical regardless of the way in which the measurement is made, providing always that (i) the frequencies of energisation and (ii) the geometry of the energising current electrodes and sensor remain the same with respect to the body.

### *The Polarity of EIP and MIP Anomalies .....*

The polarity of the three ways in which the induced polarization effect can be measured varies, depending on which mode (magnetic or electric) or which domain (Time or Frequency) we are operating in. The table below sets out the differences in detail.

| Domain | Parameter | Mode of Measurement<br>EIP<br>External Polarization Dominating over Body | <br>MIP<br>Internal Polarization Dominating over Body* |
|---|---|---|---|
| Time | Chargeability | positive | negative |
| Frequency | Relative Phase Shift (RPS) | negative | positive |
| Frequency | Percent Frequency Effect (PFE) | positive | negative |

* *For Type 'A', 'B' and 'C' anomalies only*

*"Noise" and its influence on MIP Data .....*

The "noise" in magnetic induced polarization data is essentially relatively minor variations in the earth's magnetic field which decreases in amplitude as the equator is approached. In the Time Domain where the IP Phenomenon is summed over a relatively long period, the influence of a "noisy" magnetic field is maximum. In the Frequency Domain, the time required to acquire a single reading is very considerably less, hence the noise component is also less. The following table derived from field experience shows the primary magnetic field (Hp) required in order to take a meaningful measurement of the induced polarization effect for the time and frequency domain.

For time domain these are:

| Hp | Accuracy of M Reading |
|---|---|
| 6 gamma (plus) | ±0.2 milligamma/gamma |
| 4 gamma | ±0.4 milligamma/gamma |
| 2 gamma (minus) | an educated guess! |

For frequency domain (at 3Hz)

| Hp | Accuracy of PFE and RPS |
|---|---|
| 1 gamma (plus) | ±0.05% or ±0.05° |
| 0.6 gamma | ±0.10% or ±0.10° |
| 0.4 gamma (minus) | an educated guess! |

Note: for lower frequencies, higher Hp is required.

*The Importance of Decay Curve Information .....*

Considering the time domain first, fine grained mineralisation absorbs the charge *rapidly*, and once the passage of the energising current is stopped, the stored charge is *rapidly* discharged. If the mineralisation is *effectively* coarse grained (i.e. either coarse grained as such, or agglomerates of finer grain), the charging and consequent discharging will be much *slower*. Only with MIP is the actual decay within the source monitored, therefore major differences in decay characteristics can be observed. Figure 6 shows how this is accomplished using the IPR-8 time domain receiver. In sketch (A), EP represents the energising pulse, while the rapid decay form is due to fine grained material discharge, and the slow decay form is due to coarse grained mineralisation. You will note from the figure that the rapid decay form has a greater amplitude to start with. This is due to the fact that as the IP effect depends on the total surface area of the sulphides present, the disseminated material per sulphide volume present will give a greater IP effect.

Normally three "slices" are measured which are shown in Figure 6 as $M_1$, $M_3$ and $M_5$. The red decay form included in Figure 6A is the 'normal' or 'average' decay form usually observed over normal rocks. The IPR-8 processes the data by dividing this normal decay into each of the slices $M_1$, $M_3$ and $M_5$. This is done so that any deviation from 'normal' is readily apparent. Figure 6B displays the result of this processing of data. The rapid decay form (e.g. fine grained disseminated) will result in $M_1 > M_3 > M_5$, while the slow decay form (e.g. coarse grained massive, but not necessarily electrically continuous) will result in $M_1 < M_3 < M_5$.

The ΔM parameter is a shorthand display of the decay form: $\Delta M = |M_5| - |M_1|$. Thus, when this quantity is *positive* it implies *coarse* grain size, and when *negative* implies *fine* grain size for a given mineral.

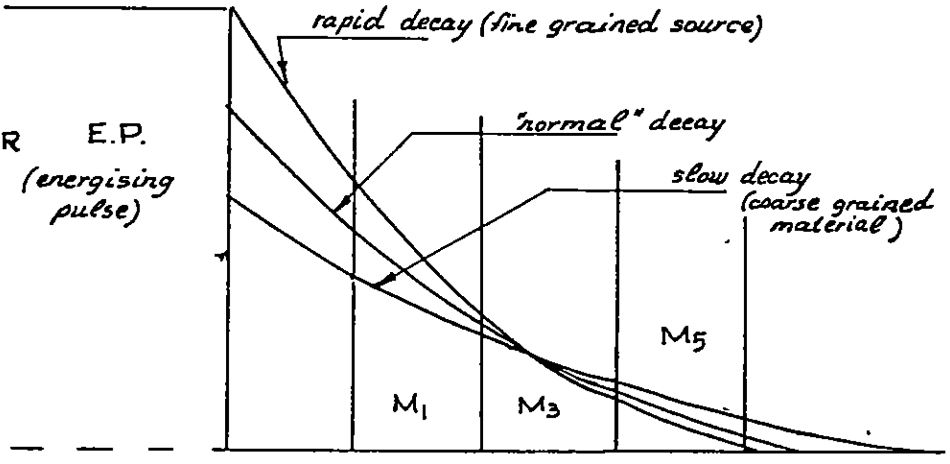
Where a substantial range in chargeability is recorded in an area, it is necessary to normalise the decay factor ΔM by the amplitude of the chargeability. This is done by dividing ΔM by $M_3$ and multiplying the factor by 100%.

The normalised decay form $\Delta Mn\% = \dfrac{|M_5| - |M_1|}{M_3} \times 100\%$

and displays the variation in decay form from 'normal' in percent.

(A)

DECAY AS OBSERVED
BY IPR-8 M.I.P. RECEIVER
PRIOR TO PROCESSING



(B)

DECAY AS OBSERVED
BY IPR-8 MIP RECEIVER
AFTER NORMALISATION FOR
A "NORMAL" DECAY FORM

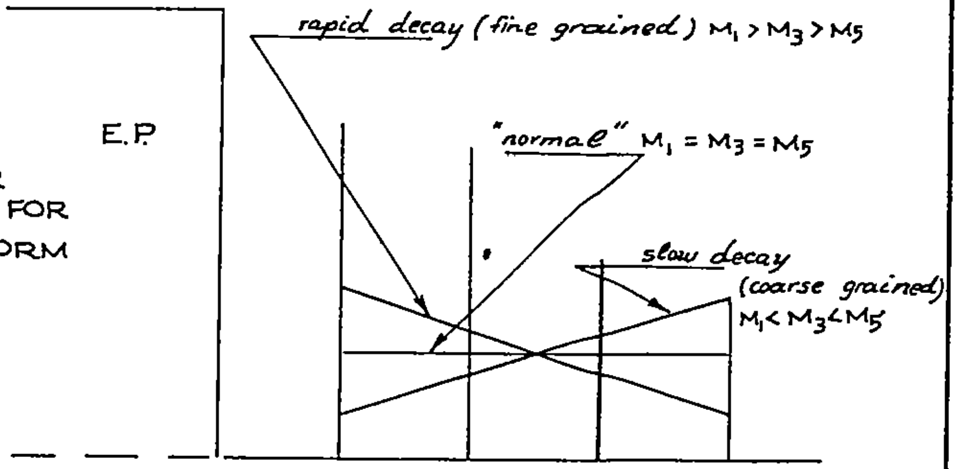


Fig 6.

This decay form can be seen by varying frequency domain measurements over a wide frequency. For a slow decay form, MIP data acquired at a lower frequency will be relatively larger in amplitude than that acquired at higher frequencies, while conversely for fast decay forms the MIP will be emphasised by higher energising frequencies.

*Electromagnetic Coupling .....*

In common with electrical induced polarization magnetic induced polarization can be subject to electromagnetic coupling. In the *time domain* this can readily be identified by abnormal distortions in the decay curve, a typical example would be where:-

$$M_1 << M_3 \cong M_5$$

In the *frequency domain* the magnetic induced polarization effect is read in both RPS and PFE. The former is *free of electromagnetic coupling to a first approximation,* while the latter is not. Therefore an observation of the variation of the RPS and PFE from their theoretical relationship of 1%PFE + 1.6°RPS can warn of the presence of EM coupling.

*The Influence of the Size of the Current Dipole .....*

The current dipole is normally placed parallel to the expected strike of the mineralisation. This array will couple best to lenticular bodies with depth extent and with a strike extent of about one-third the size of the current dipole or larger. *Therefore, to maximise the "focus" of the current dipole for "small" bodies, small current dipoles should be employed.* From an operational point of view the current dipole is normally about three to five times the expected length of the target ore body.

A more important influence on the determination of the current dipole size is the depth and intensity of oxidation. The deeper and/or the more intense the oxidation, the larger the current dipole must be to get a significant proportion of the current to penetrate the freshrock target volume.

*Current Penetration into Freshrock Through Conductive Overburden .....*

The MIP method was developed for conductive overburden situations we encountered in the Kalgoorlie nickel belt in the late 1960's. As we saw the problem then, there were two quite separate problems. The first was to energise the volume of rock that the geologist wished to search and the second was to obtain at the surface a meaningful signal which did indeed represent the electrical characteristics of the underlying freshrocks and ore zones.

Basically the first part of the problem was capable of solution even in the late 1960's. Electrodes down holes and/or large generators with large current dipoles were (and are) capable of deep energisation. Nigel Edwards in his paper with Howell in Geophysics Vol. 41-6A page 1172 demonstrates this point well in Figure 3 reproduced below.

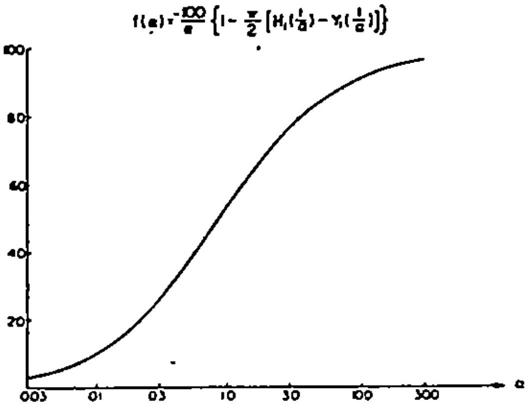


FIG. 3. The function $f(\alpha)$ which determines the percentage of current remaining in a conductive, thin surface layer above a resistive half-space.

The vertical axis represents the percentage of the current remaining in the overburden, while the horizontal axis represents the f(α).

$\alpha = 2S\rho_2/L$

Where S is the conductivity thickness product of the overburden and $\rho_2$ the resistivity of the freshrock and L the current dipole. This can be rewritten as $\alpha = 2\rho_2/\rho_1 \times d/L$ where $\rho_1$ and $\rho_2$ are the resistivities of the overburden/oxidation and freshrock respectively, and d and L are the depth of oxidation and the current dipole respectively. For ease of field use it can be recast as a series of curves for different ratios of $\rho_1/\rho_2$ to show percentage current penetration of the freshrocks for the various ratios of d/L. (Figure 7)

In practice electrical soundings will yield diagnostic information as to the bulk resistivity ($\rho_1$) and thickness (d) of the weathered zone. As the resistivities of rock types are known and can be reasonably estimated for any area if drill hole information is not available, $\rho_2$ can be reasonably estimated. As an example, take an area where the overburden/oxidation has a bulk resistivity ($\rho_1$) of 50 ohm-metres, and a depth (d) of 25 metres over bedrock ($\rho_2$) known to average 2000 ohm-metres. Thus $\rho_2$ will equal about 40 $\rho_1$, therefore for 40% of the current generated to penetrate the bedrock the current dipole is required to be 50 times

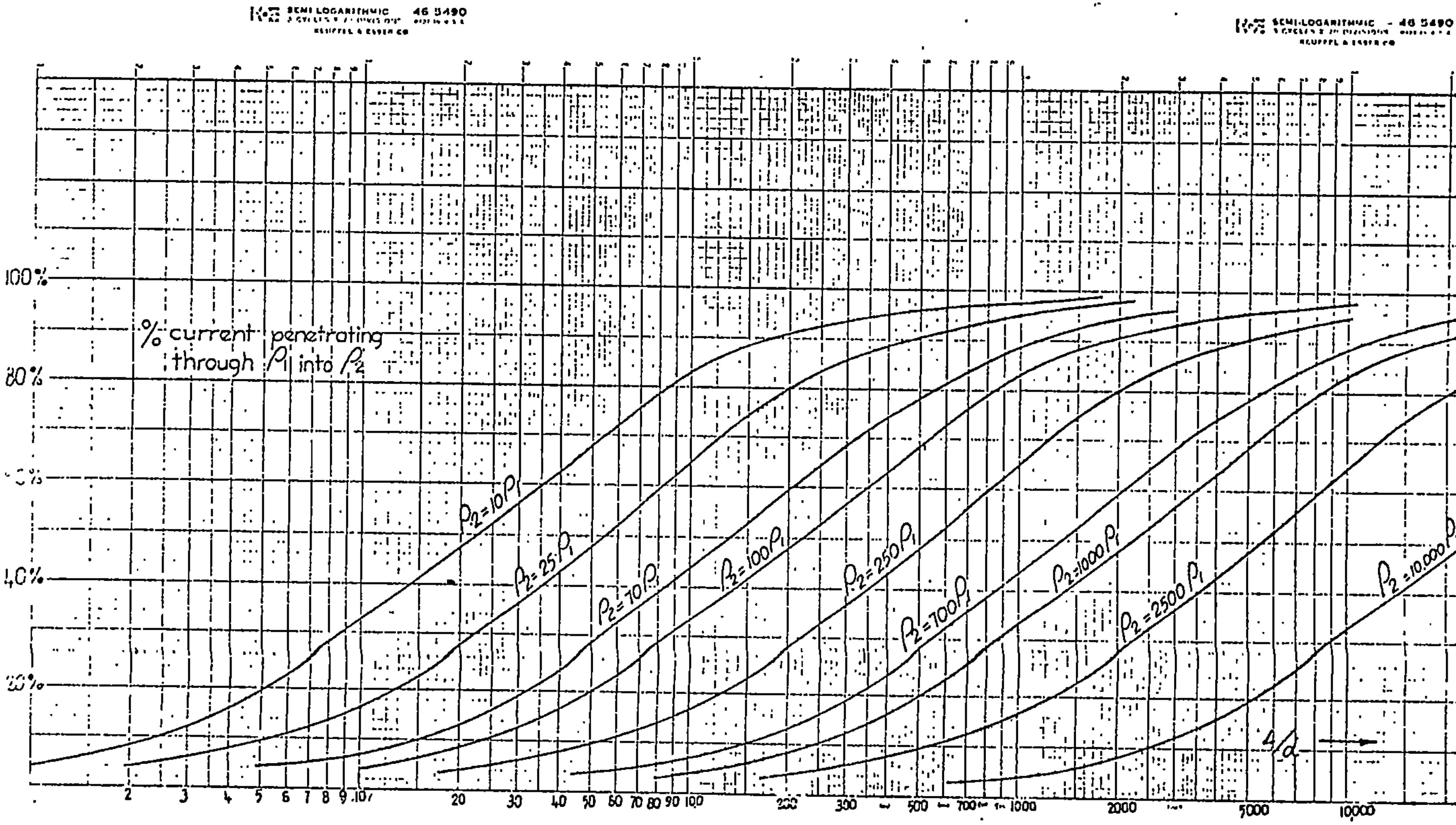

K&E SEMI-LOGARITHMIC 46 5490
K&E SEMI-LOGARITHMIC 46 5490
100%
80%
60%
40%
20%
% current penetrating through $\rho_1$ into $\rho_2$
$\rho_2 = 10\rho_1$
$\rho_2 = 25\rho_1$
$\rho_2 = 70\rho_1$
$\rho_2 = 100\rho_1$
$\rho_2 = 250\rho_1$
$\rho_2 = 700\rho_1$
$\rho_2 = 1000\rho_1$
$\rho_2 = 2500\rho_1$
$\rho_2 = 10{,}000\rho_1$
4/a →
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
200
300
500
700
1000
2000
5000
10,000

FIG. 7

the depth of oxidation of 25 metres, i.e. 25 × 50 = 1250 metres. (Figure 7)

### *Data Processing and Presentation .....*

For large scale reconnaissance surveys carried out in the frequency domain (known as rapid reconnaissance magnetic induced polarization - RRMIP), the data is processed by computer and presented in terms of RPS, PFE, MMR, $H_N$, HSQ/I and HSP/I, some of which are presented as line printergraphs (usually RPS, MMR and HSQ/I). For ease of interpretation and for structural information, RPS and MMR are normally also contoured, generally at the scale of 1:2500.

In the time domain, the chargeability, M, together with $H_S$ and $H_N$ are usually hand plotted. The generally smaller size of the current dipoles (500 ±100 metres) precludes a meaningful contour presentation in most cases. Again, a scale of 1:2500 is favoured.

### *Field Procedures .....*

Most (but not all) fieldwork to date has been carried out using *gradient arrays* as shown in Figure 8. In practice the current dipole (L) is laid parallel to strike and varies up to 600 metres for time domain surveys and 3000 metres in the case of frequency domain (RRMIP) surveys. From each gradient set-up a block some 0.6 kilometres in strike length by about 0.4 kilometres in width can be surveyed. The line interval depends on the minimum strike length of the target zone, while the reading intervals along lines are normally about 25 to 50 metres.

In the time domain some 40 to 60 stations can be read per operator in good conditions while the figure in the frequency domain is about 100 to 120 per operator per day. Normally two operators are used.

From a practical point of view, as MMR/MIP is a magnetic field method, it necessarily depends on strong current flow. Thus the method works best in areas which are conductive rather than those which are highly resistive. Areas where MIP/MMR appears to have been particularly useful are Kalgoorlie, Western Australia, western New South Wales, north-west Queensland and northern Australia, always in areas of conductive overburden.

### *Edwards Array .....*

Edwards has developed a multi-source MMR/MIP sounding array designated the Edwards array (Edwards & Howland-Rose, 1979). The array is designed to ascertain the depth to source and depth to the centre of current flow for infinite slabs, and are used to follow-up in detail significant features located on reconnaissance surveys.

The configuration of the array is shown in Figure 9. The main features are (i) an infinite current electrode $C_2$ placed along strike (ii) close electrodes $C_1{}^1$ to $C_1{}^n$ placed at distances $y$ along strike, (iii) the MFM-3 sensor is placed at various stations along $\chi$. For each location the Hp and RPS readings are taken for each current electrode separation $C_1{}^n$ to $C_2$. The data is then computed and plotted either as profiles or as pseudosections as shown in Figure 9. In this figure each data point is plotted in the pseudosection with the horizontal distance $x$ along the survey line against $y$ the distance of the close current electrode $C_1{}^n$ from the survey line $\chi$. It must be emphasised that the Edwards multi-source array is a very recent development, the first field data having been acquired in late 1979 over Elura (Howland-Rose, 1980).

As yet there are few computer models and those available (Edwards & Howland-Rose, 1979) are for tabular infinite bodies. Therefore the comments must necessarily be descriptive. The significant factors are considered to be the *relative* values of interior and exterior polarization, for should induced polarization be uniform, no anomalism will be observed. Similarly should the resistivity be uniform, the expected MMR will be zero. Variations in resistivity alone will not produce an MIP response (Howland-Rose et al, 1980, p.41). The MIP method will be sensitive only to lateral inhomogeneities (Howland-Rose et al, 1980, p.40) which, in most circumstances where steep dipping rocks occur is the significant factor.

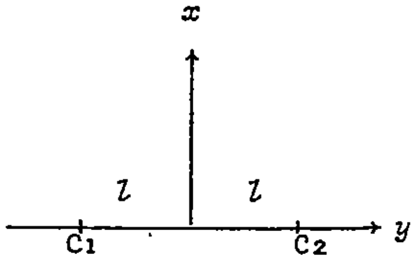
### *Units and Parameters .....*

#### *A - Measurements of relative resistivity of the earth for gradient array:*

The MIP sensor senses the horizontal magnetic field due to the passage of the primary current in the ground. Unlike EIP resistivity data, it sums *all* current to depth by virtue of its magnetic field. The field at any point in the survey area (Hp), must be adjusted for the position of the current dipole. The formula for the calculation of the normal ($H_{Norm}$) field at any point is:-

$$H_{Norm} = 100I\left[\frac{y + l}{x^2 + (y + l)^2} - \frac{y - l}{x^2 + (y - l)^2}\right]$$

Where I is current in amps, $y$ is distance from the centre line and, $x$ is the distance from centre line joining the electrodes, and $2l$ is the distance between electrodes.



$H_N$, the *normalised horizontal field* is given by the expression:-

$$H_N = \frac{Hp \times 100\%}{H_{Norm}}$$

$H_N$ is expressed in percent variation from normal, normally being either a homogeneous underlying resistivity *or* any complex horizontal layering. Normal will be 100%.

MMR, the *Magnetometric Resistivity* is given by the expression:-

$$MMR = \frac{Hp - (Hu \times I)}{\frac{400I}{l}} \times 100\%$$

MMR is expressed in percent variation from normal, 0 being normal. This parameter will tend to emphasise conductivities in regions of high current density.

*B - Measurements of Relative resistivity of the earth for a multi-source (Edwards) array:-*

$$MMR\ (\%) = \frac{B^a \times 100}{\frac{100I}{y_1} - \frac{100I}{y_2}}$$

Where $B^a = B^m - B^p$

and $B^p = \frac{100y_1}{(x^2 + y_1{}^2)} - \frac{100y_2}{(x^2 + y_2{}^2)}$

$y_1$ = distance of station from $C_1$ parallel to Y axis, $y_2$ = distance to $C_2$ parallel to Y axis, $x$ = distance from centre line, $B^a$ = anomalous field, $B^m$ = measured field and $B^p$ = normal field ( see Figure 9)

### *C - Measurements of the Induced Polarization Effect*

In the time domain *chargeability* (M) is measured in terms of milligamma/gamma.

In the frequency domain two independent measurements of chargeability are taken.

(i) RPS, *Relative Phase Shift*, is given by the expression:-

$$RPS = 3\theta_f - \theta_{3f}$$

where $\theta_f$ and $\theta_{3f}$ are the phase shifts of the fundamental and third harmomic of the transmitted square wave.

(ii) PFE, *Percent Frequency Effect*, is given by the expression:-

$$PFE = \frac{A_1 - 3A_3}{3A_3} \times 100\%$$

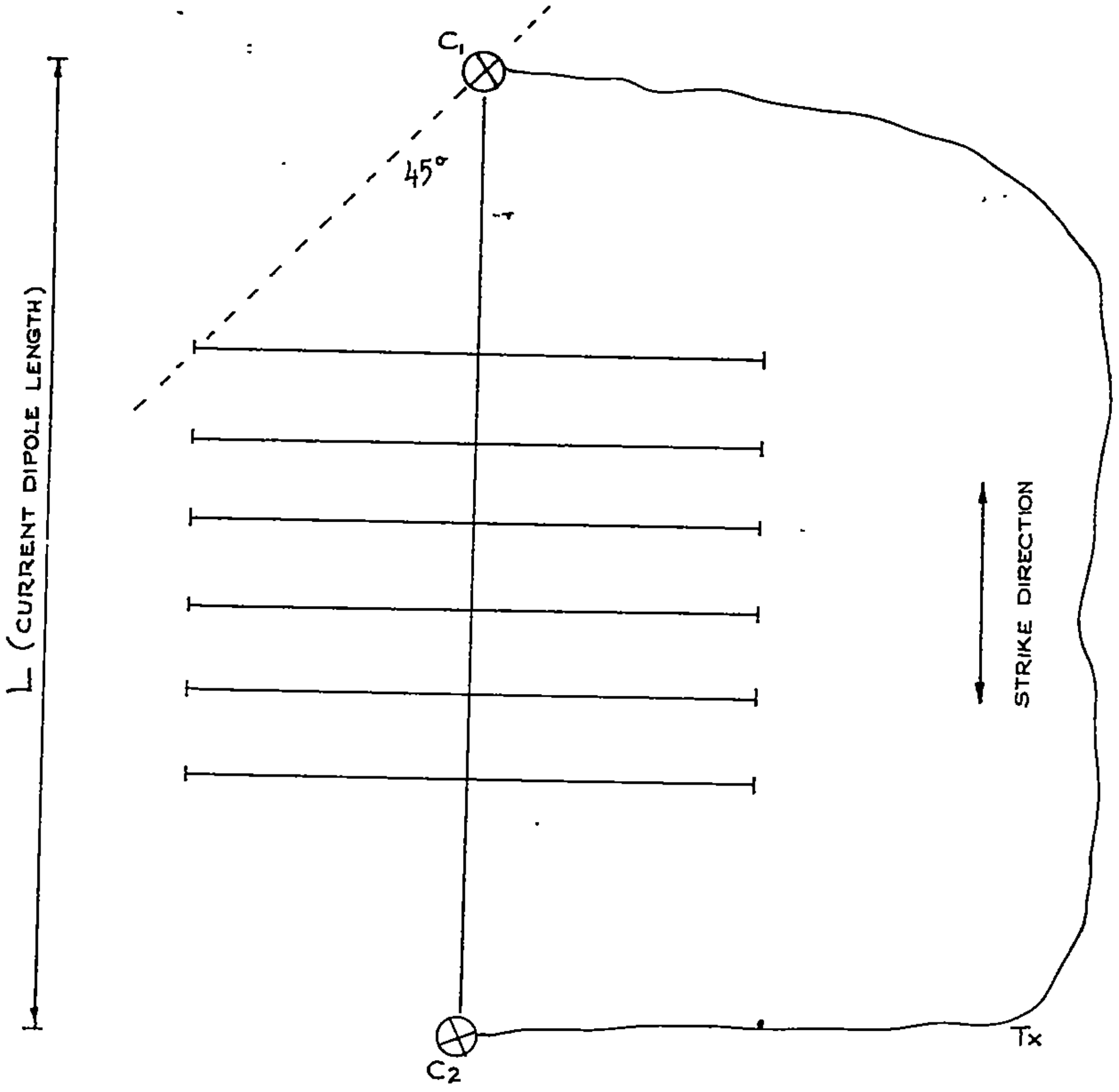
where $A_1$ and $A_3$ are amplitudes of the fundamental and third harmonic of the transmitted square wave.

### *D - Derived Parameters*

In areas of large variations in current density due to conductivity inhomogeneities, or close to electrodes it is more meaningful to present the secondary current magnetic fields due to polarization effects. These derived parameters will *emphasise* induced polarization effects *in areas of high current density* whereas the original induced polarization data in terms of M, PFE or RPS will *emphasise* induced polarization effects in areas of *low current density*.

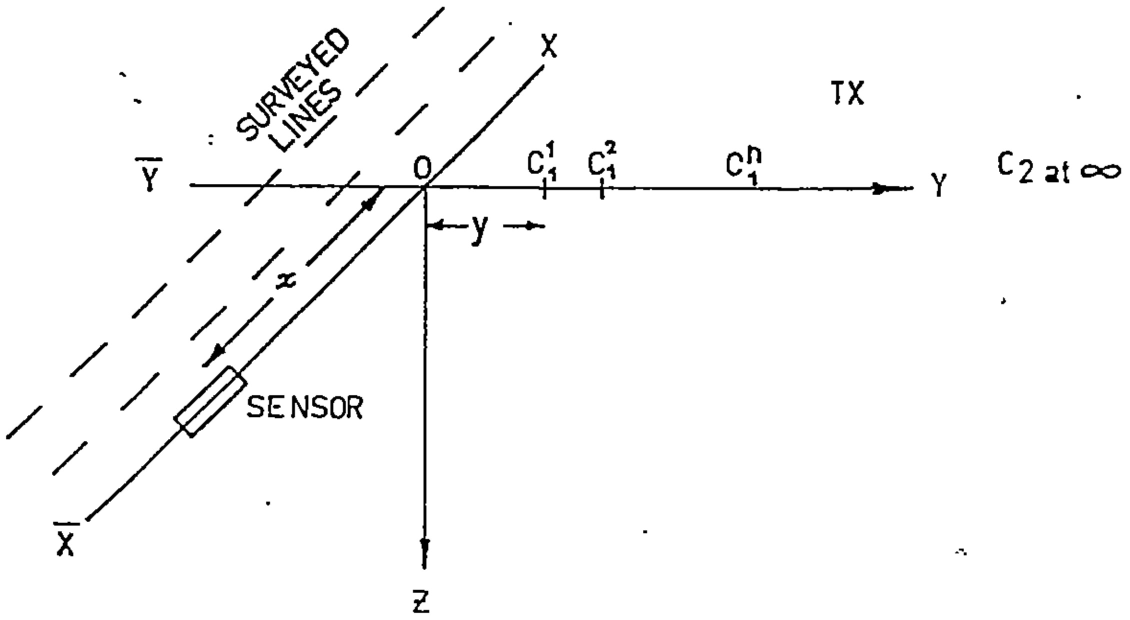
It should be noted that by examining the induced polarization phenomenon in terms of chargeability (M, RPS or PFE) AND by means of the secondary magnetic field, we can observe induced polarization effects from both high *and* low current density areas.

In the time domain the secondary field is calculated as follows:

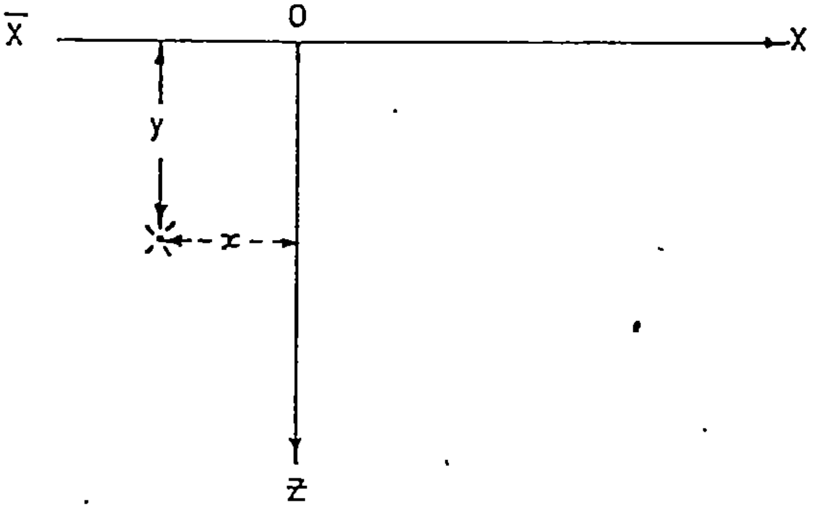


GRADIENT ARRAY

Fig 8



Field setup



Pseudosection plotting format

✳ plotting point

Fig. 9

MULTI-SOURCE (EDWARDS) ARRAY

$$H_{Si} = \frac{Hp}{I} \times Mi \times 100 \quad \text{(milligamma/amp)}$$

where I is the current in amps, and M is the chargeability of the $i$-th slice of the decay curve.

In the frequency domain these secondary fields are termed:-

(i) Quadrature change HSQ/I

$$HSQ/I = \frac{Hp}{I} \sin\theta \times 1000, \quad (\theta = \frac{RPS}{2})$$

(ii) In-phase change ΔHSP/I

$$HSP/I = \frac{Hp}{I} \times \frac{PFE}{100} \times 1000$$

Both HSQ/I and ΔHSP/I are expressed in milligamma/amp of primary current strength.

*Final Comment .....*

The above remarks briefly outline the present procedures in the execution, computation and interpretation of Magnetic Induced Polarization data in the time and frequency domain. It is recommended that the reader should now study the papers listed in the "References" to obtain a more comprehensive understanding of the method.

A.W. HOWLAND-ROSE,MSc,DIC,AMAusIMM,FGS.

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