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TIME DOMAIN AND MULTIFREQUENCY ELECTROMAGNETIC RESPONSES IN MINERAL PROSPECTING

BY

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy in the University of Toronto

C 1977 G. S. Lodha
ABSTRACT

Extensive, wide band EM surveys were made over three previously known bedrock conductors in the Canadian Shield. The conductors varied in size from small to very large, having strike lengths of approximately 100 m., 300 m. and 2 kms. All the conductors are located in crystalline host rocks which appear to be quite resistive. They are mostly covered by overburden whose thickness and conductivity are not well known, but which probably do not exceed 15 m. and $10^{-2}$ mhos/m respectively. The characteristics of the conductors (geometry and conductance) are only partially known from drilling. The surveys were carried out with UTEm Mark II system built at the University of Toronto by Y. Lamontagne and G. F. West.

The observed data were compared with the theoretical data computed by using a free-space rectangular thin plate model. The parameters of the models were adjusted, within the known geological constraints, to achieve a best fit between the model and field responses. It was apparent in each case that some aspects of the observed responses can not be explained on the basis of the simple models. However, in all cases the response at intermediate or later delay times could be matched reasonably well with the responses computed for models whose parameters are consistent with the known geology.

The present research was devoted to investigating the validity of EM interpretation methods based on the use of simple uniform models in free space. It is well known that such simple models are not valid for the geological situations that exist in some parts of the world. However, it is widely believed that such simple models are indeed valid in areas of relatively resistive host rock and overburden such
as the Canadian and Baltic Shields. The three studies reported in this thesis give some qualified support to this belief in simple models. In all three cases the induced current system (at least over most of the time range studied) is believed to be basically a vortex current in the main conductor and does not involve the host rock and overburden.

Considerable deviations of the observed response from that of simple model response are found at early delay times. These deviations are believed to be due to the effects of the finite thickness of the conductive zone and of a halo of poorly conducting material situated around the main core. Whatever its cause, this effect has an important bearing on the interpretation techniques. It appears that natural conductors do not have a clear inductive limit to their response as do simple models, and this makes the interpretation of size and geometry more difficult. It also means that conductivity thickness (conductance) estimates based on simple models can be erroneous (too low) unless the late stage of the time delay (or the low frequency, resistive range of the frequency response) is observed.

Computer programmes were developed by extending Annan's (74) eigen function technique to compute responses for airborne, ground and drill hole EM systems in the time or frequency domain for a free space, rectangular, finite, thin sheet model. This model was then utilised to compare the responses of various recently developed time domain and multifrequency EM systems. UTEM, Crane PEM and INPUT systems were studied in the time domain. Turam loop and horizontal loop EM systems were studied in the frequency domain.
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I am deeply indebted to my thesis supervisor, Professor G. F. West, who patiently advised me during the entire research, and also critically examined and corrected the manuscript. All these years he was always willing and available for discussions. I am grateful to all the faculty members in Geophysics for their keen interest and in particular to Professors G. D. Garland, R. M. Farquhar, N. Edwards, R. C. Bailey and D. W. Strangway for constant encouragement during the progress of this work.

This research would not have been completed without the help of Dr. Annan and Dr. Lamontagne. Dr. Annan provided the basic thin sheet computer programmes. Dr. Lamontagne provided some computer programmes and supplied the UTEM instrument required for this research, and together with Mr. J. Macnae helped me in the field work and subsequent computer processing and plotting of the field data. Discussions with Messrs. J. E. Betz, J. D. Crone, A. V. Dyck, R. J. Caven and Dr. Nahighian, and the availability of some of their unpublished data have been an asset in this research. Help received from the mining companies, i.e. UMEX and INCO Limited during the field work and permission to use some of their data is gratefully acknowledged. Details of some of the instruments were made available by Apex Parametrics Ltd., Crone Geophysics Ltd., Questor Surveys Ltd. and Scintrex Ltd.

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CHAPTER 1

INTRODUCTION

1.1 Problems of Interpretation in EM Prospecting

Standard Electromagnetic (EM) prospecting methods are designed to locate zones of exceptionally high conductivity situated in a relatively insulating host medium. The standard interpretation methods applied to the survey results usually treat any conductive zone as a uniformly conductive body isolated in free space. Thus all anomalous response is attributed to one process i.e. the induction of an eddy current vortex in the conductive body.

It has been long realized by practicing geophysicists that standard EM prospecting systems which use one or two frequencies and small coil separations proved satisfactory for finding and delineating conductive sulphide occurrences at shallow depths in easy geological environments. However, quantitative interpretations of geometrical and conductive properties by fitting simple models to the field data often arrive at rather different results when data from surveys at two different frequencies and/or different coil separation over the same body are analysed. (Parasnis - 71, Lodha et al.-70). In areas where the conductive bodies are deeper, or the overburden is thick and irregular, or the host rock is conductive, standard EM systems have often produced results which have been very difficult to interpret. In many such areas, EM prospecting techniques have had to be abandoned.

1.2 Model Studies and Nature of Complex EM Responses

In last twelve years, the attention of many scientists from different universities, research institutions and exploration agencies all over the world has been drawn to the interpretation problems. Many studies
have been done using various models of the ground. The model responses have been obtained by physical scale model measurements, analytical mathematics and numerical simulation on computers. Results of these model studies can be broadly classified here in two categories i.e. as they apply to (a) moving source receiver systems & (b) fixed source systems.

Lowrie & West (1965), and Fraser & Ward (1967) have investigated the overburden effects through scale model experiments, simulating overburden by metallic sheets. Lowrie & West reported that the overburden causes mainly a rotation of the phase of the anomaly, while others have reported decrease in the response due to screening and assumed the effect to be mainly an attenuation.

Negi et.al. (67, 69, 73), Wait (69), Fuller (71), and Nabighian (71) studied the effect of a conductive overburden and host rocks by using the analytical solution for a layered sphere. Negi concluded that overburden produced a negative screening, i.e. increased the detectability of the target. Roy (70) reviewed the existing evidences at that time and defined the term "detectability of the target" more carefully.

Gupta Sarma et.al. (71), Gaur et.al. (72, 73), Gupta et.al. (73), Verma (75) have done extensive physical model studies of targets of different shapes buried partially or fully in a conducting solution in a model tank. They studied targets in galvanic contact with the host medium and/or overburden, and also target conductors insulated from the surrounding medium. The horizontal coplanar coil configuration was generally used, but other coil configurations were also investigated.

Hohmann (75) has numerically obtained the response of a three dimensional model buried in a conductive host. His conclusions corroborate the above referred scale model results for the horizontal loop EM system response of targets buried in a conductive host.
To study fixed source EM systems, the response of an infinitely long target buried in a conducting host and/or with an overburden has been studied by numerical modeling on a computer by Parry (71), Hohmann (70, 71), Coggon (71), Swift (71), Vozoff (71) and Collins (76). In all cases except one the source was an infinite wire or uniform field. In one example from Swift's study the Turam anomaly due to a buried inhomogeneity was obscured by an overburden of irregular depth. In another example by Hohmann, the anomaly was shifted in phase and decreased in amplitude on account of the conductive host. In general, the authors demonstrated that in the two dimensional model situations, neglect of conductive overburden or conductive host can lead to serious errors in interpretation.

Ward et.al. (1973) & Wong (73) reported physical scale model experimental results of aluminium sheet of finite strike length buried in a conductive half space. The source was a very long wire. Ward et.al.'s comparison of their experimentally obtained responses of finite sheets to that of theoretical results over sheet of similar cross section but infinite strike length in a similar conductive host demonstrated that anomalies from a conductor of finite strike length differ markedly from those of a conductor of infinite length.

Lajoie & West (76) have numerically computed the Turam response (large loop source) of a finite thin sheet buried in a horizontally stratified conductive environment. The cases studied by them were a shallow plate and a deep plate in a conductive half space, and a deep plate in an insulating or a conductive host rock under a conductive layer. In all cases the top of the plate was separated from the overburden and the conductivities of the plate, layer and host rock were varied widely. They found that a conductive overburden layer alone causes a phase rotation and an attenuation of the local anomaly, while a conductive host medium
causes mainly the addition of a component to the anomaly due to the "gathering" of current from the host medium into the conductor. The strength of the current gathering effect may vary from negligible to enormous, as its amplitude and phase depend strongly on the conductive host rock. When a conductive overburden and a moderately conducting host rock are present, both effects may arise.

Parasnis (71, 73), Preston (75), Lamontagne (75), Collins (76) have discussed the possible wide discrepancy between electromagnetic field survey results and those expected from simple model studies.

One may summarize the studies cited above as follows. It is now generally agreed that the EM induction process in nature can be considerably more complicated than it is in the simple isolated, uniform conductor model. Some of the complicating phenomena are:

1. A conductive overburden rotates the phase and decreases the amplitude of anomalies from buried conductors when the conductors are not in close contact with the overburden.

2. Conductive host rock can lead to an increase in amplitude and rotation of the phase of an anomaly.

3. When the conductive overburden and conductive host are both present and are in galvanic contact with a bed rock conductor, the results are not readily predictable.

4. The response of a conductive body may be considerably altered by the presence of a less conductive halo around it, such as may be caused by disseminated mineralisation around a massive core.

5. Even if a halo is not present, the finite thickness of a mineralised body may complicate its EM response, making plate models unsatisfactory.

6. The presence of magnetic materials i.e. magnetite and pyrrhotite may
alter the conductive response to an appreciable degree.

(7) Few sulphide deposits are so massive that one expects all appreciable induced currents to flow entirely within the semi-metallic mineralisation. Wherever the induced current flow crosses, even briefly, into electrolytic conductors, induced polarization effects will arise. The effective conductivity of a mineralised zone may thus be a complex function of frequency. This corresponds, in the time domain, to conductivity changing with delay time. Although this statement is broadly accepted, it is still not accepted that this effect may be very important.

(8) Finally, different EM systems are affected to different degree by the above complexities of nature.

Conclusions drawn by some of the well known workers in EM prospecting are quoted here to elucidate the magnitude of the problem involved.

(a) Ward et.al. (1973)

"In general, present methods of interpretation of electromagnetic data are invalidated by conductive overburden or conductive host rock. Conductivity in this sense extends from 1 mhos/m to $10^3$ mhos/m and hence encompasses host rock and overburden conductivities encountered routinely throughout the world".

(b) Parasnis (1971, 74)

"It seems likely that multi-frequency surveys could be used to detect ore conductors below a highly conductive overburden since phase rotation due to it is directly proportional to the frequency and can be controlled." "However, conventional interpretation techniques are evidently inadequate in such circumstances and new ones need to be devised".
(c) Gaur et.al. (1972, 73)

"The result of the present investigations show a significant contribution of a conducting host rock on the response of ores buried there and underline the necessity of accounting for this effect in the interpretation of electromagnetic data". "Presence of overburden even if slightly conducting plays a role of far reaching significance. To ignore its presence would, therefore, render the interpretation of induction prospecting data liable to serious errors".

(d) West et.al. (1975)

"At the present stage of our knowledge we cannot say when and how important these various factors will be in different types of terrain*. However, it is clear that difficult conditions for EM methods are those situations where these effects rather than simple induction begin to dominate the results. To make EM methods fruitful in difficult terrains* we must be able to separate from one another all the various different induction phenomena which may be occurring. It is clear that this will only be possible if one can determine the EM response of the ground over a wide frequency band. Development of EM interpretation theory is largely a matter of working out the response of EM instruments systems to various models of the ground. Any programme of EM modelling needs to be linked to the interpretation of real field data, preferably from areas where a reasonable amount of ground truth is available".

1.3 Development of Multifrequency & Time Domain EM Instruments

In order to make electromagnetic methods more useful in different geological environments and to locate deeper conductors which will produce

* The word 'terrain' is used here for geological environment.
only weak anomalies, several multi-frequency and time domain EM instruments have been developed in the last twelve years, and the better known of these are listed below.

Barringer (1965) has developed the induced pulse transient airborne EM system (INPUT). Modified versions of INPUT have been developed by Lazenby (1973) and Gupta Sarma et al. (1976). This system utilizes half sinusoidal, repetitive, current pulses of alternating polarity in the transmitter and measures the transient voltage induced in a towed receiver coil by taking a number of samples during the interval between each pulse. Seigel et al. (1976) have developed the TRIDEM system measuring inphase-quadrature component at three frequencies for a fixed wing coplanar coil system. Wagg (77) has discussed test results of the EM-30 airborne EM system employing vertical coaxial coils and measuring inphase-quadrature components at two frequencies.

After a comparative study of various horizontal loop ground EM instruments by Betz (74), Vaarø and Betz have produced a multi-frequency horizontal loop system (MAX-MIN-II), with transmitter-receiver separation of up to 800 ft and five frequency of 222 Hz to 3555 Hz. Crone (76) in cooperation with Newmont has developed a loop-loop time domain pulse system. He energizes the ground by a ramp function switch off current (approximately 1.4 millisecond) in transmitter loop and measures the induced secondary field in a receiver coil during off current time of approximately 9.4 millisecond. His system is geometrically equivalent to horizontal loop system. Paterson et al. (72) have described results of low frequency ground EM surveys with EM-25 in Western Australia. Ward et al. (74) have developed a fourteen frequency loop-loop system measuring tilt angle and ellipticity for continuous sounding profiling in search of mineralized bodies and for investigating earth layering responses.

Scintrex (76) has developed a five frequency Turam type ground
and bore hole EM system (SE-77 receiver in frequency range of 35 Hz to 2835 Hz). Lamontagne & West (73, 75, 76) have developed a time domain ground EM instrument called UTEM. In this system the transmitter delivers accurate calibrated current of precise triangular wave form. The receiver uses a coil as sensor and thus measures the amplitude of the time derivative of primary and secondary magnetic fields in 10 time intervals. This system is geometrically equivalent to the Turam loop system in frequency domain and is described in detail in Chapter 2.

The response of the above wideband EM systems to real conductors in nature is not yet well studied in the literature. Only a few examples are known today and these include the following
(a) The INPUT system was evaluated by Geological survey of Canada by actual surveys over Hawkesbury test site and in Project Pioneer study in south eastern Manitoba. The survey results were interpreted with the aid of extensive model studies (after Dyck, Becker & Collett - 73, 74).
(b) A fourteen frequency EM survey was conducted over Cavendish test site measuring tilt angle and ellipticity in continuous sounding profiling approach (after Ward et.al. 74).
(c) Test surveys were conducted with the UTEM time domain system over Cavendish, Joutel and Prosser (after Lamontagne, 75).
(d) A few case histories of multifrequency horizontal loop EM responses are available (after Betz, 76).

1.4 Scope of Research and Thesis Outline

The controversy regarding the usefulness of simple free space uniform models for routine interpretation of field data collected by conventional narrow band EM systems is well known by now. One wonders if EM prospecting is
ever as simple as the early ideas envisaged. In routine geophysical exploration usually there is not much possibility of verifying an interpretation of conductor parameters beyond a simple confirmation that a conductive feature exists in the expected spot. While the literature of EM prospecting abounds with studies of hypothetical models, it contains rather few detailed studies of the EM response of actual geological conductors. Certainly, when one considers the wide range of geological settings and the great variety of ore mineralization types that arise in nature, there is an obvious need for such studies.

With the developments of accurate, calibrated wideband field instruments it is an appropriate time to re-examine the usefulness of simple uniform free space models in EM interpretation. This can best be done by surveying some of the real conductors in nature with wideband EM systems and then checking for the internal consistency of quantitative interpretation using simple free space uniform models and in addition for consistency of the interpreted model with what is known of the subsurface.

Detailed wideband EM studies were made in three areas, namely Gertrude West, Gertrude and Pickle Lake, where small, medium and large size conductors are known to be present. These are all situated in northern Ontario, in the Precambrian Shield and the host environments are comparatively resistive. The field surveys were conducted using the UTEM Mark II time domain EM instrument developed at the University of Toronto by Y. Lamontagne and G.F. West.

The observed data were first interpreted with the simple model decay curves of Lamontagne (75). Preliminary interpretation indicated that the conductors could be approximated by thin sheet models. The free space, rectangular, thin sheet model of Annan was modified and utilized to com-
pute the detailed theoretical response for plate model conductors. The observed data were then closely compared with the model data. The geometry of the conductors was partially known from drilling. Thus the parameters of the models were adjusted within the known geological constraints, to achieve a best fit between the model and the field responses. Additional multifrequency and narrow band EM data available in these areas were also analysed to check on the consistency of interpretation.

A modified finite thin sheet model was also utilized to study the response of various commercially available time domain and multifrequency electromagnetic systems used in mineral prospecting. The systems studied besides UTEM were Turam loop EM, Horizontal loop EM, Crone pulse EM and INPUT. The computed response of these systems to finite thin sheet models of various depths, dips and conductivities give some comparative idea of their depth of penetration and conductivity-thickness response spectrum.

Since all the field work was done with the UTEM instrument, Chapter 2 is devoted to the review of the UTEM system and known interpretation techniques. Chapter 3 deals with the details of modification to Annan's rectangular thin plate model. Adoption of this model to study response of various multifrequency and time domain EM systems is also demonstrated there. Chapters 4 and 5 deal with the actual field data and their interpretation over three conductors located in two areas, namely the Sudbury basin and Pickle Lake. Additional multifrequency data available from other horizontal loop surveys and Turam bore hole surveys are also examined there. Chapter 6 deals with the comparative study of the response of various wide band EM systems. Chapter 7 gives the summary and conclusions of the present work. The mathematical details of the solution for EM induction in the thin sheet are discussed in Appendix 1.
CHAPTER 2

UTEM SYSTEM & INTERPRETATION MODELS (A REVIEW)

2.1 Introduction

In order to study the applicability of simple free space, uniform conductor models in the interpretation of EM data, wide band field surveys were conducted over three known conductors using the UTEM Mark II time domain ground EM instrument. This instrument has been developed at University of Toronto mainly by the work of Y. Lamontagne & G.F. West. An awkward but essential feature of EM prospecting is that the observed field responses depend not only on the features of the ground but also strongly on the characteristics of the prospecting system. Thus interpretation and modelling data are uniquely tied to particular field systems. Since the majority of the field data presented in this thesis were collected with the UTEM system, it is essential to introduce here the basic characteristics of the instrument, the data reduction procedures and what is known about how the system will respond to the various situations listed in Chapter 1. This chapter is essentially a review of Lamontagne's (75) thesis to a large extent.

2.2 The Measuring System

The UTEM system is shown schematically in Fig. 2.1. A fixed, motor-generator driven transmitter generates a time varying current in a large insulated loop lying on the ground. The EM field of this fixed loop is mapped with the receiver unit. The usual field sensor is a vertically oriented solenoid, but other coil orientations or a pair of grounded electrodes can also be used. The sensor is connected to a receiver unit which amplifies
**Fig. 2.1:** The usual UTEM survey configuration (after Lamontagne, 75)

**Fig. 2.2(a):** UTEM transmitter current waveform

**Fig. 2.2(b):** The sampling scheme in the UTEM receiver. The amplitudes $A_1$, $A_2$ etc. are measure of the total field. The shaded areas represent secondary field due to induction. (after Lamontagne, 75)
the signal from the sensor and performs a variety of measurements on it. The survey lines are usually run outside the loop, perpendicular to its longer edge. The setup is geometrically equivalent to that of the Turam ground EM system (Parasnis, 1973).

The transmitter current shown in Figure 2.2a has a precise triangular waveform with a fundamental frequency in the range 9-35 Hz. Since the receiver is a coil it senses the time derivative of the magnetic field. Thus it produces a square waveform in free space. Any secondary component due to currents induced in the ground will modify the primary shape, and be detected as a distortion of the square waveform. In order to investigate the distortion of this square waveform over a wide range of delay times the receiver takes ten individual samples according to the scheme depicted in Figure 2.2.b. If the base frequency of the system is 30 Hz, the delay time between a discontinuity and the start of the earliest window is about 16 microseconds (μs). Sample windows increase in width in a binary progression. The latest sample, which frequently serves as a reference value, is labelled channel 1. The earliest sample is called channel 10. The sample values are averages over the window intervals and over a large number of transmitter cycles. Data are recorded in the receiver unit on a cassette magnetic tape.

2.3 Data Reduction

The receiver unit measures absolute field intensity. For interpretation purposes the measurements are presented in a variety of formats. Data can be presented as absolute secondary field in percent of primary field i.e.
\[ \text{Ch}(i) = \frac{H_{1}^T - H_{1}^P}{H_{1}^P} \times 100 \ldots \quad (2.1) \]

*where \( H_{1}^T \) = Total measured field in the ith channel

\( H_{1}^P \) = Total calculated free space primary field in direction of the measurement

\( H_{1}^P \) = Total free space primary field

\( \text{Ch}(i) \) = Amplitude of ith channel

Because a fairly accurate knowledge of the relative position of the transmitter loop and receiver unit is required to calculate the primary field amplitude with precision, the sensitivity for small anomalies may be enhanced by comparing the observed amplitudes in channel 2 to 10 with the observed amplitude in channel 1. For vertical fields the reduction formula is shown below.

Data presented in this manner are called reduced secondary fields i.e.

\[ \text{Ch}(i) = \frac{H_{1}^T - H_{1}^P}{H_{1}^P} \times 100 \ldots \quad (2.2) \]

where \( i = 2 \) to 10 and channel 1 is reduced as (1) above.

In practical cases where the amount of secondary field persisting to channel 1 is very small, the reduced secondary fields are identical to the absolute secondary fields.

Reduced secondary field or absolute secondary field data are finally plotted by programmable calculator on a x-y plotter in the form of multitrace sections, where each trace shows the response measured on one time channel as a function of distance along the traverse. The data

* In the above notation symbol \( H \) is used to represent \( H \) measurements, i.e. it is actually \( H' \) which is sensed by the receiver coil.
sections are plotted in a standard format with the scales and station labels indicated. The different channels are distinguished by symbols. In some cases, all channels are plotted on one axis and one scale. In others, the earlier channels (10 to 5 usually) are plotted at a coarser scale in the upper half of the diagram and the later ones are plotted in the lower half with enlarged vertical scale, one channel being repeated for comparison. The points are plotted along the abscissa axis at their nominal position rather than using the exact position used in reduction. One complete example of the plotted data can be seen in Figure 5.4 (Chapter 5).

2.4 Measurement Accuracy

Instrumental inaccuracies and drifts are not the important factors in limiting the accuracy of UTEM measurements. Although some error in the test surveys may come from instrumental sources, the limiting sources of error are background electromagnetic noise of natural and cultural origin, and topographic and planimetric positioning error. In extreme cases, the presence of extremely large EM fields from local sources such as VLF radio stations and major power lines may prevent operation of the UTEM system. However, power line harmonics which are not identical to odd harmonics of the transmitter base frequency are strongly rejected by the measuring system because of the scheme of sampling windows. Also, known interfering signals of narrow bandwidth such as local VLF stations can be attenuated by filters if necessary.

According to the experience of the test surveys, it is routinely possible to measure $H_z$ out to a distance of 3000 ft. from a 2400 x 2000 ft. loop using a peak transmitter current of 3.5 amps with precisions in the reduced measurements of about 0.5, 0.7, 1.0, 1.5, 2, 3, 4, 5, 6 and 8%
in channels 2 to 10 respectively. The channel 1 anomaly can be determined to about $\pm 2\%$, if the station position is sufficiently well known.

2.5 Simple Models

In order to get a feeling for the types of response UTEM would produce over different geological environments, Lamontagne (75) carried out a series of scale model experiments over simple free space models of different shapes. These are shown in Figure 2.3. For each model, the main features of the vertical magnetic field ($H_z$) anomaly are shown. The spatial shapes of the anomalies obtained by the system are similar to the normalized secondary field anomalies calculated from Turam data. The reduced UTEM data can be regarded simply as the ratio of the secondary field to the primary field in percent at any given point. The anomaly shapes for the various simple models are discussed below.

2.5.1 Thin Dyke

A conductive steeply dipping body in the shape of a thin dyke gives an $H_z$ anomaly of cross-over shape (Fig. 2.3A) with the positive lobe on the side of the conductor nearest to the transmitter. The zero crossing indicates the approximate location of the conductor. Anomalies have similar shapes on the different channels, but at later times they tend to be broader and slightly shifted in the down-dip direction. A deep conductor exhibiting a broad anomaly will show a broader and higher amplitude response on the far side of the cross over. The conductivity-thickness product of the conductor is calculated from the rate of the time decay and the strike length.
2.5.2 Finite Horizontal Conductor

A thin horizontal conductor of limited dimensions which does not extend under the transmitter loop produces an anomaly consisting of a low over its central area with positive shoulders of comparable amplitude near its edges (Fig. 2.3B). The positions of the shoulders are systematically shifted to the centre at later channels. The variations also become much more gradual and of much smaller amplitudes at later times. Again, the rate and type of decay and size permits one to assess the conductivity-thickness of the layer.

2.5.3 Block Conductor

This type of conductor produces a simple negative anomaly over the top of the conductor (Fig. 2.3C). Almost no positive shoulders are present, although the near-transmitter edge variation may be sharper. At short times, the anomaly is fairly flat bottomed (if the conductor is shallow) and can have amplitudes of up to 200%. On later channels the anomalies are more rounded and the inflection points at the edges are systematically drawn in. The degree of sharpness of the short time anomaly indicates the depth of the burial. The time decay of the anomaly over the centre of the body shows a characteristic inverse power law variation at the later times, from which the conductivity of the block can be interpreted.

2.5.4 Thick Dyke

If the thickness of a dipping conductor is comparable to its depth of burial, its response is intermediate between the response of a thin dyke and that of a blocky conductor (Fig. 2.3D). Such thick dyke conductors produce a negative anomaly roughly over their top, with a relatively weaker positive shoulder on the transmitter side. At later times,
Fig. 2.3: Illustrating the form of UTEM anomalies over some simple shapes. Examples A-D are drawn for conductors far from the loop. If the conductor is near the loop where the primary field intensity varies rapidly, the form of the profiles may be somewhat altered. (after Lamontagne, 75)
the anomaly becomes more similar to a simple cross-over anomaly and the position of the zero crossing moves toward the centre of the conductor. The time decay of the shoulder anomaly at later times indicates the conductivity-thickness of the conductor. If the 'top anomaly' can be roughly separated from the cross-over part, it can be used to interpret the conductivity and width of the conductor. A dipping conductor will show the thick dyke response only when the thickness is comparable to the depth (thickness ≥ 0.25 depth). The blocky conductor response (no positive shoulder) appears only when the body has a width comparable to its other dimensions.

2.5.5 Large Horizontal Conductor

The anomaly shape due to such a conductor extending under the transmitter loop shows a positive shoulder near the transmitter and an increasing negative deflection away from the loop (Fig. 2.3E). Unlike the cross-over type of anomaly, the zero crossing migrates away from the transmitter very drastically at later times. The later time response is positive, very broad and of rapidly vanishing amplitude. This type of response is very useful for interpreting the conductivity-thickness of extensive overburden. The interpretation is based on the location of the zero-crossing and maxima on the early channels. The amplitudes depend mostly on the sizes of the conductor and of the transmitter loop.

2.6 Time Decays for Simple Uniform Models

The type of time decay is strongly dependent on the nature of the body causing the anomaly. Fig. 2.4 shows the time variation of the responses due to the various types of conductors discussed above. In this display, both the amplitude and time are plotted on logarithmic scales. For time,
this corresponds to a scale with equispaced channels because of the binary spaced sampling windows. An exponential decay is also plotted for comparison. It is apparent that the cross-over type of anomaly measured over a thin dyke has a decay which becomes similar to an exponential at late times. For a thicker dyke with the same conductivity-thickness, the amplitudes are higher and the decay faster at first, but at later times \((t \gg \omega d^2)\), the time response is similar to that of a thin dyke. By shifting the anomaly for coincidence at later times, one reads the characteristic time \(t_1\) from which the conductivity-thickness can be calculated.

\[
\sigma d = 10 \frac{t_1}{\mu_0 S}
\]

The shoulder anomaly at the edge of a horizontal conductor can be interpreted the same way. In the formula, 'S' is the strike length of the dipping conductor or the width of the horizontal conductor. The deviation from the thin dyke response sometimes permits us to estimate the conductor thickness and its conductivity separately.

The time decay of the centre anomaly of a horizontal conductor of limited extent has a variation similar to an inverse power law \(1/t^3\) (which shows as a constant slope on the log-log plot) over most of the normally measured time range. Again the conductivity-thickness can be interpreted from the decay rate.

A block-like conductor also produces a time decay which resembles an inverse power law, but of order about \(1/t^2\). Thus the decay is relatively slower than both the nearly exponential decay of a thin dyke and the roughly inverse cube decay measured over an horizontal conductor. A knowledge of the size of the block-like body permits us to interpret its conductivity. For a thick dyke, the shoulder anomaly has a time decay similar to that of a thin dyke, except for possibly higher amplitudes at early times, whereas
Fig. 2.4: Time decays of UTEM model anomalies plotted as log (amplitude) vs log (time). These curves can be used for interpretation as described in Table 2.1. (after Lamontagne, 75)
the time decay at the top anomaly is more similar to that measured over a block-like conductor.

The time decays obtained with the UTEM system are particularly simple because the system as a whole has a fairly fundamental type of time response. The system response resulting from the triangular wave excitation and the wide band coil (which takes the time derivative) is a square wave response. Thus the measurements are the same as if we transmitted a square wave and measured the magnetic field with a very wideband magnetometer. This makes the measured responses very similar to step responses. The only appreciable difference occurs on the last channel and can normally be corrected for. Because of this feature and the sampling used, time is scaled the same way as conductivity. For example, if the conductivity of a body was doubled, the channel 8 anomaly would become the channel 7 anomaly, the channel 7 anomaly would become the channel 6 anomaly, etc. It is this feature which permits the fairly simple interpretation methods outlined above. In general, this sliding scale method of interpretation is not applicable for time domain systems with more complicated waveforms.

2.7 Interpretation of Simple $H_z$ Anomalies

The interpretation of the simple types of anomalies discussed above is summarized in Table 2.1 and is based on characteristic times extracted from the anomalies. For this purpose, the time decays of the observed anomalies are plotted in the same format as in Fig. 2.4 and by sliding vertically and horizontally on Fig. 2.4 are superposed with the appropriate curve such that the end portions of the decays coincide. The marks labelled $t_1, t_2, \ldots$, on the model curves then point to the charac-
teristic times of the measured anomaly which can be interpolated from 
the mean channel time. On Fig. 2.4, \( t_2 \) points to the time 
where a small difference from thin dyke response is detectable. De-
pending on thickness, it may be at a different position on the thin dyke 
response curve. If \( t_2 \) is much longer than \( t_1 \), we are dealing with a 
block conductor. The early time on the model decay curve points to the free 
air inductive limit which is numerically twice the frequency domain (Turam) 
inductive limit. For shallow block or horizontal conductors, this value 
should be nearly 200%, so that there is very little latitude for shifting 
along the vertical axis. For dyke-like conductors, the free-air inductive 
limit can be roughly estimated from the interpreted conductor geometry by 
making use of Turam interpretation charts (estimated strike length, depth 
and approximate dip are required). This estimate can similarly be used 
to restrict the vertical range of shifting, thus enabling a more precise 
estimate of the characteristic time to be made.

2.8 Complex Inductive Responses

As will be illustrated later, the early part of the anomaly decays 
often deviate substantially from the free-air-model decays because of the 
finite thickness of the conductor, the presence of a conducting halo around the 
main conductor and interactions with conductive overburden or host rock. 
Some other deviations may occur at late times and are believed to be mostly 
due to IP effects. Deviations at early times are due to a variety of causes. 
Conductive overburden which is insulated from the main conductor causes 
blanking (attenuation) of the anomalous response. Enhancement (amplification) 
of the response may be due to the gathering of current from the host rock 
or overburden, or to a halo of poorly conducting material which temporarily
enlarges the conductor. Some examples of these phenomena are discussed in subsequent sections.

2.8.1 Conducting Halo/Finite Thickness Effect

The decay plots of Fig. 2.4(b) show that for early time channels the amplitude of the response is larger for a finite thick dyke than a finite thin dyke. This is due to the inductive thickness effect which has been studied, in the frequency domain, by Bosschart (64) and by Lamontagne & West (70). The higher inductive limit of curve B is consistent with frequency domain scale model studies. In qualitative terms, the halo effect due to a poorly conducting zone surrounding the massive conductor is of a similar nature. Essentially the halo effect and finite thickness effect can both be attributed to skin effects and their contribution to UTEM response is in increasing the amplitude and rate of the decay at early times. The effect of a conductive halo alone has not yet been studied in detail for UTEM system, but the maximum effect of finite thickness has been studied by considering the extreme model of a sphere in a uniform or dipolar field. The resulting decays are shown in Figure 2.5. By comparison of the sphere decay response against simple exponential decay, it is evident that the effect of finite thickness is to gradually increase the amplitude of the response towards early time channels. This is true even if higher order multipoles are considered for a dipole excitation source at a reasonable distance from the sphere. When one compares this gradual increase of response with the sharper increase in amplitudes seen in some of the field examples shown in Figure 2.10, one may visualize the nature of the response due to halo effect. It appears that the increase in response due to halo in early time channels is larger and thus the decay due to halo is much more rapid than that due to the finite thickness effect.
Fig. 2.5: Response of a sphere in uniform field or dipolar field (uniform field data after Lamontagne, dipolar field data after Lodha) along with exponential decay due to simple loop for UTEM. $T_c$ is the time constant of the exponential.

Fig. 2.6: UTEM sampled decays for a finite thin sheet embedded in a conductive half space. The sampled decays are transformed from frequency domain response computed by Lajoie (73). (after Lamontagne, 75)
2.8.2 **Host Rock Effect**

It is known from the work of Lajoie (1973) in the frequency domain that a surrounding host rock of moderate conductivity will usually increase the magnitude and shift the phase of the anomaly due to the buried conductor. Lamontagne obtained time domain UTEM responses from his frequency domain data. The computed UTEM sampled step response for four host rock conductivities, compared with the free air response, is shown in Figure 2.6. Curve 1 represents the free-air response whereas curves 2 - 5 are responses computed for progressively higher host rock conductivities. These results underestimate the true responses by about 20% because of approximations in the original frequency domain solution and uncertainties in the transformation process. In spite of their limitations the decays illustrate well the main effect of the host rock conductivity. The effects are an initial attenuation of the response (similar to the overburden blanking) followed by an important enhancement of the anomaly amplitude. For moderate host rock conductivities, (curves 2 and 3, $\rho = 500 \& 200$ ohm-m) the later part of the decay closely resembles the free air decay within the resolution of the data, except for a slight time shift similar to that seen for the blanking effect. In cases where the host rock has a higher conductivity, the current gathering effect lasts longer than the inductive response of the plate alone. Such responses exhibit a very abrupt decay after a peak, which can help to identify them. In cases 4 and 5 where the host rock resistivity is less than 50 ohm-m, interpretation is expected to be more complicated, since the response is mostly dependent on the host rock conductivity.

However in cases such as 2 & 3 where host rock resistivity is of the order of 200 to 500 ohm-m and above, it may be possible to obtain a good interpretation of the finite thin sheet model by fitting the late part of
the decay to free air model curves.

2.8.3 Overburden Effect

Conductive overburden can modify the response of underlying conductors in a variety of manners. Two simple cases of uniform overburden insulated from the target and one in contact with the underlying target, have been studied for the UTEM system.

2.8.3(a) Overburden not in contact with the underlying target (blanking effects)

Conductive overburden which is not in contact with the main conductor is known to attenuate and shift the phase of the response of underlying conductors. (Lowrie & West, 1965). To investigate these effects in UTEM system response, scale model experiments were conducted by Lamontagne. His results are shown in Figure 2.7. The dotted line in Figure 2.7a represents the response of a sheet model in the absence of overburden and the solid line the response when the intervening overburden is present. In the decay plot of Figure 2.7b the peak-to-peak amplitude of the local anomalies relative to the smooth background, which is the response of the overburden alone (dashed line), is plotted. The initial absence of a local anomaly for model B gives the effect its name 'blanking'. The effect can be thought of as a gradual suppression of the early part of the local anomaly or as a shift of the whole anomaly (with some distortion) to later time. A pure shift would correspond to a phase rotation in frequency domain.

The interpretation of partially blanked responses is based on the fact that the late response is nearly unaffected by the overburden effect for sufficiently conductive bed rock bodies. The good fit of the late channel response to that of the free air model in Fig. 2.7 shows that the characteristic time of the dyke model can be determined with only a small
Fig. 2.7(a): Response of a finite dyke under a conductive overburden as determined by UTEM scaled model measurements. The central profile across a dyke of 300 m (scaled) strike length is shown. The transmitter has scaled dimensions of 600x600 m. (after Lamontagne, 75)

Fig. 2.7(b): Decay of the peak-to-peak response of the dyke relative to the overburden response (i.e. difference between solid and dashed lines of Fig. 2.7(a)). (after Lamontagne, 75)
relative error if the response is clearly visible in the last few channels. When the inductive limit is not known, the latitude for vertical shift makes the fitting process more subjective, but even if the inductive limit can only be estimated within a factor of two, the determination of the characteristic time (and therefore of the properties of the model) is known better than 30%, because of the abrupt cut off of the late portion of the decays. In practice it appears possible that if the response can be recognized clearly in spite of overburden blanking, its interpretation can be made with good enough precision.

2.8.3(b) Overburden in contact with the underlying target (current gathering effects)

When the electrical contact between a conductive overburden and a bedrock conductor is good, currents from the overburden can be gathered in the underlying conductor, producing an effect similar to that of a conductive host rock discussed in the next section. The situation was modelled by Lamontagne for UTEM by soldering two metal plates to simulate a dyke in contact with the overburden. This is reproduced in Figure 2.8(a). The anomaly amplitudes are strongly increased compared to Figure 2.7(a). The decay in Figure 2.8(b) shows a very large anomaly enhancement, caused by the contact, at early times. The anomaly reversal of Fig. 2.7(b) on early channels is eliminated by the contact. The change in the general background response compared to that of the overburden alone (dashed line) indicates that the effect of the contact with the dyke is mostly to short-circuit the overburden currents which would normally be flowing in its neighbourhood. This is referred to as channeling effect.

When the overburden has appreciable thickness, such that the width of the contact is comparatively small, it is expected that the channeling effect will be more limited, being restricted by the conductivity of the
Fig. 2.8(a): $H_2$ response of a dyke in contact with a conductive overburden obtained by scale modelling. (after Lamontagne, 75)

Fig. 2.8(b): Comparison of the decay of a dyke in contact with overburden with that of free air model. (after Lamontagne, 75)
overburden near the area of contact. For a given overburden conductivity and thickness, the effects of current gathering are expected to be maximum only if the width of the contact is much greater than the overburden thickness. Other model experiments (not shown here) have shown that an overburden sheet of finite extent produces more subdued effect. It can increase or decrease the anomaly depending mostly on the general polarity of the overburden currents which the dyke is short circuiting.

In any case it appears that most of the current gathering effects may die out reasonably fast, and the later time response may approach reasonably close to the free air dyke response which could be used for determining the characteristic time for simple model interpretation.

2.9 Non-Inductive Responses

In several examples of UTEM field data, some responses have been observed on late channels which cannot be explained in terms of simple induction processes. The non-inductive magnetic responses usually appear as a component of the anomalous fields which does not decay within the time range covered. This effect is discussed below under the heading Magnetic Effects.

The other effects observed at late times are the reversal of the sign of the decaying magnetic field or non-inductive electric field responses identified by much larger magnitude usually growing with decay time. This effect is considered most likely to be due to induced polarization phenomena and is discussed under the title of IP Effect.

2.9.1 Magnetic Effects

If a highly susceptible formation is present, such as would produce a strong anomaly on a magnetic survey (say >> 500\(\gamma\)), it may significantly
alter the magnitude of the H field at all times. The effect will be most clearly seen after the inductive transient has died out, and it is equivalent to a change in the primary field intensity, i.e. a constant proportion of secondary field is introduced. The effect will only be visible in the channel 1 measurement, if the other channel values are reduced to channel 1. The form of the $H_z$ anomaly should be similar to the ordinary induced magnetic anomaly for a vertical magnetometer and a vertical inducing field, as long as the body is reasonably small in comparison to the distance to the transmitter. A feature sufficient to produce a 6000γ anomaly in a 60,000γ earth's field should produce about a 10% channel 1 anomaly with UTEM.

2.9.2 IP Effects

It is somewhat surprising, but the UTEM system has the capability of observing certain types of IP responses because of the triangular transmitter current waveform. Consider a moderately conductive, non-polarizable environment where the inductive transients die out after the first few sampling windows. A steady, time-invariant induced current flow pattern will then exist in the ground for the remainder of the halfcycle. This current flow will generate a secondary magnetic field, but because the H sensor detects only $\partial H/\partial t$, it will not be detected.

Now consider what will happen if a polarizable element exists somewhere in the path of the induced current. The polarization phenomenon can be thought of as a growth in resistivity with time during the halfcycle. Thus one should expect a systematically rising $E$ field in the element and a steadily decreasing $J$ and $H^5$. Because UTEM operates at a high frequency, from an IP point of view, the IP effect will usually be small and steady, viz., $E$ should grow linearly with time and $\partial H^5/\partial t$ should be constant and negative. On the channel number time scale, (i.e. logarithmic
time scale) \( E \) should appear to grow exponentially with decreasing channel number as long as the growth is not comparable to 100%. In the \( H \) channels, the IP effect will appear as a constant with respect to channel number. The normal \( H_z \) reduction scheme will therefore remove the effect from all except the channel one data. Fig. 2.9(a) shows schematically what is to be expected.

2.10 UTEM Anomaly Amplitudes & Separation of Various Effects in Time Decays

The UTEM anomaly amplitudes are simply related to frequency domain amplitudes. The limiting anomaly amplitude at short time is exactly equal to twice the inductive limit anomaly measured in the frequency domain. This behaviour is valid for any model. As with other EM systems, the observed total UTEM response is expected to be complicated by the presence of various complicating factors such as finite thickness, conducting halo around a massive conductor, conductive overburden, conductive host rock, presence of magnetic minerals and induced polarization effects. A decay curve showing these complications in data from one field test area is shown in Figure 2.10. From the foregoing discussion (section 2.8 and 2.9) and the example from the Prosser area in this figure it may be evident that most of these complications in a moderately complex environment (like that of the Canadian Shield) are restricted to either the early channel response or the late channel response.
Fig. 2.9: Induced polarization effects. Figure shows general nature of IP response. Polarization leads to a rise in \( E \) and a fall in \( H^p \). It is seen in the UTEM measurements as an exponential rise in \( E \) in the latest channels and a constant negative pedestal in \( \delta H^p / \delta t \). (after Lamontagne and West, 75)

Fig. 2.10: Time decays [log (amplitude) vs log (time)] of observed anomaly from a test site near PROSSER. A large bedrock conductor is buried here under a uniform conductive overburden. The various complicating effects are shown in the figure. (after Lamontagne, 75)
TABLE 2.1

Interpretation of Time Decays Using Simple Models

Use in conjunction with Fig. 2.4
Mks units used throughout

A. **Finite Thin Dyke:** Plot peak-to-peak anomaly and use curve A with horizontal and limited vertical shifting to find \( t_1 \)

\[
\sigma d = \frac{10t_1}{\mu_0 S}
\]

\( S = \) strike length, \( \mu_0 = 4\pi \times 10^{-7} \), H/m,
\( d = \) dyke thickness, \( \sigma = \) dyke conductivity

B. **Finite Thick Dyke:** First interpret as a thin dyke by fitting later part of decay to curve A to find \( t_1 \). Then estimate \( t_2 \) as shown on Curve B. \( t_2 \) is the time at which there is a 3% relative amplitude enhancement from the thin dyke response. Alternatively, \( \frac{1}{2}t_2 \) corresponds to a 10% enhancement. A rough thickness estimate is then obtained from

\[
d = \frac{t_2 S}{10t_1}
\]

C. **Infinite Thin Dyke:** When a dyke is much more extensive than the transmitter loop, the decay differs from the finite strike length case. Use curve C to find \( t_3 \) and calculate \( d \) from

\[
\sigma d = \frac{10t_3}{\mu_0 B}
\]

\( B = \) effective length of the conductor; in practice use

\[
B = (LL^2 + CX^2)^{1/2}
\]

where:
\( LL = \) is the length of the transmitter loop
\( CX = \) is the distance between the conductor and loop.

The formula is valid only for strictly continuous dykes; in such cases the anomaly amplitudes should be consistent with the effective length.
D. **Finite Thin Horizontal Layer:** Plot negative centre of anomaly and fit to curve D (time shift only) to find $t_5$.

$$\sigma d = \frac{4t_5}{\mu_0 W}$$

$W =$ width of conductor (smallest horizontal extent).

E. **Finite Thick Horizontal Layer:** First interpret as a thin layer using later part of decay curve. Then find time $t_4$ when observed decay curve deviates a factor of 1.35 earlier than the thin layer curve. This gives a rough thickness estimate from

$$d = \frac{Wt_4}{4t_5}$$

F. **Block Conductor:** Plot centre anomaly and fit to curve F (time shift only) to find $t_6$

$$\sigma = \frac{Wt_4}{\mu_0 W^2}$$

$W =$ width of block.
CHAPTER 3

INTERPRETATION MODEL

3.1 Introduction

As stated in Chapter 1, the main objectives of this research is to test the ability of simple, free space conductor models to explain the EM response of real conductors in the ground. An obvious prerequisite to such a test is a facility for obtaining model responses appropriate to any field measuring system, and capable of representing conductors of various shapes, sizes and attitudes. Such modelling has often been done in the past, generally for a simple individual EM system, by analogue scale model measurements and also by computing results for analytically soluble geometries.

Some well-known scale model studies of half plane conductors in free space have been done by West (60), Strangway (66), Ketola and Puranen (67) and Nair et.al. (68) for horizontal loop-loop EM system. Ghosh (72) studied the response of various airborne EM systems to semi-infinite and finite thin sheet conductors in free space by scale model studies in the frequency domain. Palacky (72, 74) obtained the time-domain INPUT response by transforming the frequency domain data of Ghosh and also by direct scale model experiments using an actual field receiver. The scale model response of a finite thin sheet model excited by a uniform, dipolar or line source field has also been studied by Svetov (60), Bhattacharya & Patra (65), Poddar & Bhattacharya (66) in terms of amplitude-phase or amplitude-frequency relationships. Bosschart (64) and Lamontagne (70) have studied the same model for the fixed loop source Turam method. Bulgakov (71), Kamenetsky (62), Velikin (67), etc. have studied the same model for
the Russian MPPO transient EM system. Becker et al. (72) have studied the same model for INPUT system.

While physical scale modelling is the most flexible technique for obtaining model responses of free space conductors because there are few restrictions on conductor geometry, it can be a very laborious process when a large number of cases must be worked out. It can be especially trouble-some when modelling time domain EM systems, since the equipment does not adapt easily to time scaling. Computed models on the other hand lack much flexibility in conductor shape. Until recently cylinders, uniform and layered spheres, homogeneous or stratified half spaces, and half plane sheets were the only practical shapes.

The advent of numerical modelling has relieved the situation somewhat. Adequate and economical methods for handling arbitrarily shaped three dimensional conductors are not yet available. However, Annan's (74) 'two and a half' dimensional model of a rectangular finite thin sheet conductor in free space showed a promising possibility. This model appeared to meet the requirements of handling any type of EM system (in time or frequency domain) and of providing a conductor with at least two arbitrarily adjustable dimensions, along with the possibility of a reasonable economy, although Annan only tested it in a limited way for frequency domain systems. It was thus decided to develop the Annan's method into a practical modelling facility to handle a variety of time domain and multifrequency airborne, ground, or bore hole EM systems employing moving source-receiver geometry and fixed source geometry. Before going into the details of this numerical modelling facility we will first outline Annan's procedure.

3.2 Outline of Annan's Model

Annan's solution for the rectangular finite thin sheet is discussed
in detail in Appendix 1. In principle he solves the integral equation for
the induced currents 'Ks' in the thin sheet in terms of an infinite set
of eigen currents \((K_i, i = 1 \text{ to } \infty)\). He further demonstrates that the total
induced currents can be reasonably well approximated by summing up a limited
number of eigen currents (fifteen in the present case for a reasonably
deep sheet) multiplied by appropriate coefficients \(\lambda_i\). The values of these
coefficients depend upon the source-sheet geometry, frequency of excitation,
conductivity and size of the sheet. The form of the eigen currents depends
only on the width-to-length ratio (R) of the sheet. Each individual eigen
current system in turn is represented by a set of eigen potentials. One
such eigen potential map for a sheet with 'R' equal to 0.5
is shown in Figure 3.1. The eigen current flow associated with the indi-
vidual eigen potentials can be visualized from the contour map of eigen
potentials \((U_n)\). The eigen current flow is parallel to the equipotential
lines of \(U_n\) (\(n = 1\) in the given figure) and is proportional to the gradient
of \(U_n\). Examination of this potential map shows that the corresponding eigen
current flow is in the form of rings or eddies and that the surface eigen
current density is greatest near the edges of the sheet.

Each coefficient \(\lambda_i\) is further divided into two parts \(H_i\) and \(D_i\)
\((\lambda_i = H_i \cdot D_i)\), the first depending upon the source-sheet geometry and called
an excitation coefficient (matrix [H] in equation A1-11) and the second,
\(D_i(\omega)\) or \(D_i(t)\), depending upon the frequency or decay time of the field.
(\(\omega\) and \(t\) are non-dimensional in frequency or time). In the appendix \(D_i^{(\omega)}\)
is used to indicate a diagonal matrix, but \(D_i\) is used here to indicate
the \(i^{th}\) value along the diagonal.

The crux of Annan's method is finding the eigen currents. Each
is a real function of position multiplied by a complex function of
Fig. 3.1: Equipotential map for 1st eigen potential of rectangular sheet for $R = 0.5$ in Annan's solution. Eigen current flow is along the equipotential contours.
frequency. Because of their orthogonality, the eigen currents do not
interact with each other. Thus each individual eigen current responds in
the same manner as current induced in a simple isolated wire loop.
The total solution can thus be viewed as the sum over a set of non-
interacting loop responses, with the loops having differing inductance
to resistance ratios. The eigenvalues \( x_n \) associated with the eigen
currents are just the self inductance to self resistance ratios of the
individual eigen potentials. The solution, in terms of eigen potentials
for a given geometry, therefore yields the total frequency or time re-
response. Once the whole induced current field in the sheet is known, the
secondary field at a desired point can be calculated by numerical inte-
gration, using the Biot-Savart law.

For computational purposes, the whole process can be divided
into four parts.

(a) Computation of the finite set of eigen potentials and corresponding
eigen values for a sheet of length-to-width ratio

(b) Computation of excitation coefficients \( (H_i) \) for each eigen potential,
having specified the source-sheet geometry.

(c) Computation of 'secondary field coefficients' (for the field produced
at the receiver position by each eigen current), having specified the
sheet receiver geometry.

(d) Computation of the system response (frequency or transient) by specifying
the sheet conductance and the waveform or frequency of the source field and
combining these with the eigen functions (eigen potential + eigen
values), excitation coefficients, and secondary coefficients, using

Annan tested this scheme in the frequency domain for a vertical
sheet excited by a vertical dipole source or large loop source.
3.3 Modification of the Model

In order to apply Annan's model to the real earth situation where a sheet-like body might be represented by a dipping and/or plunging rectangular plate and where the exciting dipole source is moving and can have arbitrary orientations, modifications were made to his programmes. Annan's basic program is very expensive to run if only a single result is required. It has, however, the potential of reasonable economy in mass calculations if intermediate steps can be saved and reused and much of the modification and enlargement of the programs was for this purpose. The programmes required to perform step 3.2(a) above were used without change. The eigen functions were calculated once for sheets of 'R' equal to 0.1, 0.2, 0.333, 0.5, 0.625, 1.0, 2.0 and 4.0 and stored on disk as a partitioned data set. This set cover a sufficient range with sufficient density to meet most requirements.

The computer programmes required for steps 3.2(b) and 3.2(c) had to be altered a great deal to simulate real field situations. Details of this are discussed in section 3.4. For step 3.2(d) completely new programmes were developed to compute responses for a variety of different EM systems. Finally, the computed data had to be edited and plotted in a suitable format. One example of plotted data at its original scale is shown in Figure 3.9(b) and many more examples are shown in Chapter 6 in reduced form.

A major task in the modification of Annan's programmes was to develop a procedure wherein the eigen functions for different sheets, the excitation coefficients for different source-sheet geometry, the secondary coefficients for each observational station, and the computed data for different systems for each individual profile are stored, catalogued and
filed on the computer for repetitive use to economize on the computing cost. Some of the salient features of this are shown by block diagrams in Figures 3.2, 3.3 and 3.4.

Figure 3.2 shows how previously computed and stored eigen functions are used to compute desired excitation coefficients and secondary coefficients which are then stored for further use.

Fig. 3.3 shows how the desired system response is computed and stored as well as plotted on a printer for visual examination and manual editing. One must manually choose the appropriate main programme for the desired system and specify an index number to identify the profile points for which excitation and secondary coefficients have previously been stored as a partitioned data set. When dealing with large data sets, one must insure that correct eigen functions, excitation coefficients and secondary coefficients are read back from files. The main programme S1 to S7 performs this part of the job by calling various subroutines specifically designed for this purpose. The computed response is then again stored with appropriate identification.

Figure 3.4 shows a block diagram of the plotting programme. For each EM system there is an appropriate main plotting programme which has a built-in facility for editing the number of profile points, the number of interpolated points required for producing a smooth profile, and labelling, etc.

The modelling facility ultimately evolved into twenty main programmes and about ninety subroutines. In the facility, three main programmes and about fifty subroutines came from the Annan's work, one main programme and four subroutines came from Lamontagne's work, and the structure of eight plotting subroutines came from work of Howell. Quite a few of Annan's subroutines were modified. Many subroutines are interconnected up to an order of four or five in the sense that they keep calling other subroutines.
Specify $N$, $R$,
$\xi$, $\eta$, $\xi'$, $\eta'$
(4) (4) (23) (23)
uses stored values of
Chebyshev polynomials
from standard tables
and calculates eigen
functions $(\chi_n', c_n')$
stores data on Disc.
Needs main programmes
1, 2, 3 & subroutines
of Annan

*Compute excitation
coefficient one set
by $x_3$ axis, perpendi-
cular to plane of
the sheet

Specify Geometry
of the sheet

Transform field
coordinate system
to sheet coordinate
system

Read appropriate
eigen functions
from stored data

Specify location
of receiver station
and number of
stations

* Compute secondary
coefficients, three
sets one correspond-
ing to $H_1'$, $H_2'$ &
$H_3'$ component of
the field each

Store Excitation
Coefficients

Store Secondary
Coefficients

* uses subroutines used in 1,2,3 and modified subroutines of Annan

Fig. 3.2 Flow Diagram for Computing Excitation & Secondary Coefficients
Fig. 3.3  Flow Diagram for Computing Response of Different EM Systems.
Choose appropriate main plotting programme corresponding to EM system S1, S2, S3, S4, S5, S6

Read stored data from 'b' and choose appropriate scale, interpolation factor and edit the profiles

* Produce Calcom/Gould profile plot for various frequencies or time channels and plot legend

* uses Lamontagne spline interpolation routine, modified Howell's plotting subroutines & U.T.C.C. plotting subroutines.

Fig. 3.4 Flow Diagram for Plotting Profiles on Calcom/Gould Plotter.
To list all the programmes in unpressed deck form would required about
10,000 cards.

3.4 Sheet Geometry and Orientation

To specify the relative positions of models and actual airborne,
ground or bore hole EM systems conveniently, a 'field' coordinate system is
used. It is a cartesian system with one axis vertical and its origin
taken at a point vertically above the centre of the top edge of the sheet.
The strike of the sheet is parallel to the 'y' axis. To specify a dipping
and plunging conductive body, the sheet is first tilted along its top edge
to the given angle of dip ($\delta = 90^\circ$ for a vertical sheet) and is then ro-
tated along a axis passing through the centre of the sheet for appropriate
plunge. The scheme is diagramatically shown in Figures 3.5(a), (b) & (c).

Transformations from the field coordinate system to the sheet
coordinate system required by the computer programmes are carried out in
two steps: first translation and then rotation. The relations used for
translation are

\[
\begin{align*}
    x_1' &= Y/A \\
    x_2' &= R \times \sin \delta + \frac{D}{A} + \frac{Z}{A} \\
    x_3' &= X/A - R \times \cos \delta
\end{align*}
\]

(3.1)

where

- $D$ = Depth to the top of the sheet
- $Z$ = Height of the system above ground level
- $R$ = Width to length ratio ($W/S$)

For rotation of the coordinate system, including plunge, rotation
is first made for dip ($\delta$) and next for plunge ($\eta$). The translated field
coordinates $x_1'$, $x_2'$, $x_3'$ are converted to the sheet coordinate system $x_1''$, $x_2''$, $x_3''$ by the transformation matrix $[0]$ as follows:
Fig. 3.5(a) Plan view in x-z plane for a vertical thin sheet. $(x, y, z)$ is field coordinate system and $x_1, x_2, x_3$ is the sheet coordinate system (b) Plan view in x-z plane for a dipping sheet $\delta$ is the dip and D i.e. depth to the top of the sheet. (c) Plan view for a dipping and plunging sheet in y-z plane ($\eta$ = plunge).
\[ [x''] = [0][x'] \]  

(3.2)

where the element of matrix \([0]\) are given by:

\[
[0] = \begin{bmatrix}
\cos \eta & \sin \delta \sin \eta & -\cos \delta \sin \eta \\
-\sin \eta & \sin \delta \cos \eta & -\cos \delta \cos \eta \\
0 & \cos \delta & \sin \delta 
\end{bmatrix}
\]  

(3.2a)*

The geometry and distance of the source and receiver are first normalized to the half strike length of the sheet and then transformed to the sheet coordinate system. Secondary fields \(H'_1, H'_2, H'_3\) are calculated at desired observation points in sheet coordinates, and are finally transformed back to the field coordinate system \((H_x, H_y, H_z)\) by use of the transformation matrix \([Q]\) as follows:

\[
[H] = [Q][H'']
\]  

(3.3)

where the elements of transformation matrix \([Q]\) are give as follows:

\[
[Q] = \begin{bmatrix}
-\cos \delta \sin \eta & -\cos \delta \cos \eta & \sin \delta \\
\cos \eta & -\sin \eta & 0 \\
\sin \delta \sin \eta & \sin \delta \cos \eta & \cos \delta 
\end{bmatrix}
\]  

(3.3a)

The matrix \([Q]\) is obtained by taking into consideration the reverse rotation and change of axis direction involved during translation by equation 3.1 above.

The absolute values of the computed primary and secondary fields remain in units normalized to half strike length of the sheet, but their

* \(\delta\) is positive and varies from 0 to 180° from +x axis to -x axis. \(\delta = 90°\) for vertical sheet.

\(\eta\) is positive if rotation of sheet is counter-clockwise as viewed from positive x axis. It varies from 0 to 90°.
ratio is valid for the actual field system.

3.5 Frequency Domain Response

The two multifrequency EM systems studied systematically are the Turam system and the horizontal loop EM system. Their system-sheet geometry, with nomenclature used and quantities measured, are shown in Figures 3.6(a) and 3.7(a) respectively. In the Turam system, the quantities directly measured from the instrument are the field strength ratios and phase difference between two receiver coils. The usual field practice has been to keep a distance of 100 ft. between receiver coils 1 and 2. The data are normally plotted as reduced ratios (i.e., the observed field strength ratio normalized by the free space field-strength ratio) and phase differences. Alternatively, data are plotted as real and imaginary parts of the secondary field, given in percent of free space primary field at some fixed point, usually a point vertically above the top of the conductor. Plots in both forms are shown in Figures 6.1(c) & 6.1(b) respectively, and they are discussed in detail in Chapter 6. For the horizontal loop EM system, the quantities measured are the real and imaginary part of the secondary field in percent of primary (free space) field. A representative plot is shown in Figure 6.1(d).

Responses for both of these systems (and also for a bore hole EM system discussed in section 4.3.3) are computed directly by use of relations Al-23 where [C] comes from relation Al-11(a). Once the system sheet geometry is fixed, the response depends upon the values of the diagonal matrix components $D_n(\omega)$ ($n = 1, 15$) such that

$$D_n(\omega) = \left( -\frac{i\alpha}{1+i\alpha R_n} \right)^n$$

(3.2)
and \[ \alpha = \sigma d \mu \omega A \]
\[ A = \text{half strike length of the sheet in metres} \]
\[ \sigma d = \text{conductance of the sheet (d very small for thin sheet)} \]
\[ \mu = 4\pi \times 10^{-7} \text{H/m} \]
\[ R = \text{width to length ratio of the rectangular sheet} \]
\[ x_n = n^{th} \text{ eigen value for the sheet} \]
\[ \omega = \text{frequency of excitation} \]

In the present system, the main programmes S2 & S3 of Figure 3.3 compute the response of the Turam system in secondary field format and reduced ratio phase format respectively. Main programme S7 computes the response of the Turam bore hole EM system. Main programme S4 computes the response for the horizontal loop EM system. The present programmes are designed to compute responses for a maximum of five frequencies in a single run. Computed data for the Turam system and the horizontal loop system have been compared with the data obtained for the same sheet conductors from other independent scale model and computed studies.

Scale model and computed responses for the Turam system for a sheet of 2000'x1000' at a depth of 200' are available from Lamontagne & West (71). The sheet conductance used was 7.98 & 121.62 mhos for an excitation frequency of 500 Hz. The transmitter used was 4000'x2000' loop at a distance of 1000' from the sheet. The response of the same sheet was computed with the present technique for a sheet conductance of 40 mhos and excitation frequencies of 100 Hz and 1520 Hz. The response parameter for the sheet in both cases is exactly the same. The responses are plotted as real and imaginary parts of the secondary field and are shown in Figure 3.6(b). It can be seen that the agreement between the various techniques is very good.
Fig. 3.6(a): Geometry and fields measured for Turam loop system.

Fig. 3.6(b): Turam loop secondary field response for a sheet of 2000' x 1000' size at a depth of 200'. Loop size is 4000' x 2000', cd is 40 mhos.
Fig. 3.7(a): Geometry and field measured for Horizontal loop-loop EM system.

Fig. 3.7(b): Horizontal loop EM response for a sheet of 256' x 128' size at a depth of 33'. 
\( \sigma d = 53 \text{ mhos} \), \( L = 200' \) and frequency = 1000 Hz.
For the horizontal loop-loop EM system the scale model response of a sheet of 256' × 128' at a depth of 33 ft. is available for a coil separation of 200' from Jones and Wong (75). The frequency of excitation and sheet conductance are 1000 Hz and 53 mhos respectively. The response is available for both $H_z$ and $H_x$ components. The computed response from the present technique using main programme S4 is shown, along with Jones and Wong's result, in Figure 3.7(b). Small discrepancies are observed at the anomaly peaks which could be due to errors in either the numerical or the scale model results (or both).

3.6 Time Domain Response

Three time domain systems namely UTEM, Crone pulse EM and INPUT have been studied systematically. Their system-sheet geometry, the nature of the transmitted waveform and the nomenclature used are shown in Figures 3.8(a), 3.9(a) and 3.10(a). Each system gives a multichannel profile in which each channel response is essentially the amplitude of the transient responses at a certain sampling time in the waveform. The observed amplitude is averaged over a time window and over several waveforms, and normalized to percent, per thousand or PPM of the primary field, as shown in the above referred Figures.

For a given source and sheet geometry the time domain impulse response of each eigen current of the sheet is obtained by replacing equation 3.2 above by 3.3 below as in Al-11(b)

$$D_n(t) = \left( -\frac{1}{R_n} \frac{e^{-t/\tau_n}}{\tau_n} \right)$$  \hspace{1cm} (3.3)

where

$$\tau_n = \sigma d \mu_0 A R_n$$
All the time domain systems studied have a system function \( P(t) \)
(the signal in the receiver due to the transmitter, if the system were in free
space) different than an impulse. In the UTEM system \( P(t) \) is a repeated step,
i.e. a square wave, while in the Crone PEM system \( P(t) \) is the derivative
of a modified ramp. For INPUT, the system function is a truncated cosine
waveform. The time domain received signal \( S(t) \) from the sheet at any
sampling time \( 't' \) is given by convolution of the primary system response
\( P(t) \) with the impulse response of the sheet \( G_i(t) \), i.e.

\[
S(t) = P(t) * G_i(t) \tag{3.4}
\]

Thus the impulse response obtainable from equation 3.3
above needs to be convolved with the appropriate system function to ob-
tain the response at the various desired sampling times. The sampling
times and time windows for the UTEM, Crone PEM and INPUT systems are
shown in Tables 3.2, 3.3 & 3.4 respectively. To compute the time domain
channel response from \( S(t) \), it is necessary to account for the width
of the time windows and averaging. Lamontagne (76) provided a programme
which computes the channel response of each system for a range of ex-
ponential \( S(t)'s \), i.e. for responses of the form given by 3.3. A
table of channel response for each of 66 values of \( \tau_n \) is provided. These
values increase from the smallest value to the largest in binary progression,
and cover the entire range of \( \tau_n \) values which are normally encountered.
The main modelling programme computes the \( \tau_n \) value for each eigen current,
then instead of applying it in \( e^{-t/\tau_n} \) as is done for a step response,
the programme picks up the four \( \tau_n \) values from the table which are nearest
to the computed \( \tau_n \) value and interpolates an accurate value of channel
response.

In the present main programme, S1 computes the response of the
UTEM system, S5 computes the response for the Crone PEM system and S6 computes the response for the INPUT system. Data computed from these programmes have been compared with data obtained for the same model from other independent scale model studies.

For the UTEM system, a scale model response for a horizontal thin sheet of 240 m x 150 m at a depth of 11 m is available from Lamontagne (75), the sheet conductance being 30 mhos. This is a difficult test case for the numerical technique because the whole induced current system is so close to the observation points. The comparison is shown in Figure 3.8(b). It is not clear whether the small discrepancies observed are due to limitations of the numerical technique or limitations of the scale model data, however the former is more probable.

No scale model results are available for the Crone PEM system. However, the $H_z$ component of the response for the sheet used for the horizontal loop-loop system in the frequency domain (Fig. 3.7(b)) is computed for this system, for a coil spacing of 200'. This is shown in Figure 3.9(b), which also shows the normal data presentation format used for this system. Points on the survey profile where data have been computed are shown by vertical lines on the bottom scale. The smooth curve profiles were obtained by interpolating two to five data points between the model values by means of a fifth order spline interpolator.

For the INPUT system, scale model results for a sheet of 770'x 385' at a depth of 50 ft. below ground are available from Palacky (74). His original data for a 44 mhos sheet conductance are exactly reproduced in upper part of Figure 3.10(b). Computed data reduced to the same scale are shown on the lower part of that Figure. There is some discrepancy, but because full details of the system used in the scale modelling are not
UTEM

DISTANCE FROM TRANSMITTER (m)

 SCALE MODEL RESULT BY LAMONTAGNE (75)  
 x COMPUTED DATA BY LODHA

TRANSMITTER  
(600m x 600m)

FINITE HORIZONTAL SHEET  
240m x 150m  σd = 30 Mhos

Fig. 3.8(a): Geometry, nature of transmitted waveform and system function for UTEM system.

Fig. 3.8(b): UTEM response for horizontal sheet 240 m. x 150 m. at a depth of 11 m. cd = 30 mhos.
Fig. 3.9(a): Geometry, nature of transmitted waveform, system function and gain of various channels for Crone PEM system.

Fig. 3.9(b): Crone PEM computed response for a sheet of 256' x 128' at a depth of 33', $\omega d = 53$ mhos and $L = 200$ feet.
Fig. 3.10(a): Geometry, nature of transmitted waveform and system function for INPUT system.

Fig. 3.10(b): INPUT response for 770° x 385° sheet at p = 50°, dd = 44 mhos. Flying elevation is 400 feet.

SCALE MODEL RESULTS AFTER PAILLACRY (74)
### TABLE 3.1

**Sampling Windows for UTEM (Base frequency = 30 Hz)**

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>WINDOW from</th>
<th>WINDOW to</th>
<th>MEAN SAMPLE TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.33 ms</td>
<td>16.66 ms</td>
<td>12.5 ms</td>
</tr>
<tr>
<td>2</td>
<td>4.17</td>
<td>8.33</td>
<td>6.25</td>
</tr>
<tr>
<td>3</td>
<td>2.08</td>
<td>4.17</td>
<td>3.125</td>
</tr>
<tr>
<td>4</td>
<td>1.042</td>
<td>2.08</td>
<td>1.562</td>
</tr>
<tr>
<td>5</td>
<td>0.521</td>
<td>1.042</td>
<td>0.781</td>
</tr>
<tr>
<td>6</td>
<td>260.4 µs</td>
<td>521 µs</td>
<td>391 µs</td>
</tr>
<tr>
<td>7</td>
<td>130.2</td>
<td>260.4</td>
<td>195.3</td>
</tr>
<tr>
<td>8</td>
<td>65.1</td>
<td>130.2</td>
<td>97.7</td>
</tr>
<tr>
<td>9</td>
<td>32.6</td>
<td>65.1</td>
<td>48.8</td>
</tr>
<tr>
<td>10</td>
<td>16.3</td>
<td>32.6</td>
<td>24.4</td>
</tr>
</tbody>
</table>

### TABLE 3.2

**Sampling Windows for Crono Pulse EM (Base frequency = 21.65 Hz)**

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>WINDOW from</th>
<th>WINDOW to</th>
<th>MEAN SAMPLE TIME</th>
<th>RELATIVE GAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 µs</td>
<td>200 µs</td>
<td>150 µs</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>400</td>
<td>300</td>
<td>1.38</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>700</td>
<td>550</td>
<td>1.93</td>
</tr>
<tr>
<td>4</td>
<td>700</td>
<td>1100</td>
<td>900</td>
<td>2.68</td>
</tr>
<tr>
<td>5</td>
<td>1.1 ms</td>
<td>1.8 ms</td>
<td>1.45 ms</td>
<td>3.73</td>
</tr>
<tr>
<td>6</td>
<td>1.8</td>
<td>3.0</td>
<td>2.4</td>
<td>5.18</td>
</tr>
<tr>
<td>7</td>
<td>3.0</td>
<td>5.0</td>
<td>4.0</td>
<td>7.19</td>
</tr>
<tr>
<td>8</td>
<td>5.0</td>
<td>8.6</td>
<td>6.8</td>
<td>10.0</td>
</tr>
</tbody>
</table>
**TABLE 3.3**

SAMPLING WINDOWS FOR MARK VI INPUT (Base frequency = 144 Hz)

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>WINDOW from</th>
<th>WINDOW to</th>
<th>MEAN SAMPLING TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>150 μs</td>
<td>375 μs</td>
<td>262.5 μs</td>
</tr>
<tr>
<td>2</td>
<td>375</td>
<td>600</td>
<td>487.5</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>920</td>
<td>760</td>
</tr>
<tr>
<td>4</td>
<td>920</td>
<td>1330</td>
<td>1125</td>
</tr>
<tr>
<td>5</td>
<td>133 ms</td>
<td>183 ms</td>
<td>1.58 ms</td>
</tr>
<tr>
<td>6</td>
<td>183</td>
<td>2.37</td>
<td>2.1</td>
</tr>
</tbody>
</table>
available, it is quite possible that the two cases are not exactly equivalent and the match appears quite reasonable under the circumstances.

3.7 Computation Time

As numerical modelling routines go, the present method requires only a small computation time and a modest amount of core storage. The most expensive part of the analysis is the numerical quadrature used to find the integral coefficients used in finding the eigen potentials. The time required to generate the integral coefficients for a polynomial degree of 4 and high accuracy integration (values within 0.5% of the true values) was of the order of 1.2 minutes using 120 K bytes of core on an IBM 370-165. But this was needed only once for each sheet of different 'R'. The time required to generate the eigen functions using the integral coefficients is only about 2-3 seconds. Excitation and secondary coefficients are computed using 100 K bytes memory in about 1 second of computation time per station. Other programmes to combine eigen functions, excitation and secondary coefficients and compute system response normally take less than two/three seconds of computing time. The Calcom/Gould plotting programmes need about 150 K bytes of memory, but again the computing time is very short. One benefit of the storage system comes from the fact that the same set of secondary coefficients can be used to compute the responses of a fixed sheet-receiver geometry for all types of EM systems. Furthermore, the UTEM and Turam systems have the same geometry, as do the Crone pulse transient EM system and the horizontal loop system. Model cases for these systems can be converted from one to the other for small cost. Despite the relative efficiency of the method when large numbers of cases must be computed as in the present research, the costs mount up. The University of
Toronto Computer Centre class 'C' job facility (no computer time charge for jobs run at night) has been a great asset in this regard. Total computing bills for all the work done during this thesis research have been about $4,000.

3.8 Limitations of the Method

Annan's technique, like all other numerical methods, is an approximate procedure. In situations where the source field at the sheet is locally very intense, or the receiver is very close to one part of (or all of) the sheet, accurate results can only be obtained by using a large number of eigen functions. In the present programmes only fifteen eigen functions have been used and the source field can be digitized for a maximum of 1000 points over the sheet. Because of these limitations the results of the present study, where the sheet-source or sheet-receiver distance is about one tenth (or less) of the strike length of the sheet, are not highly accurate. Very often the quadrature component behaves irregularly. Examples of this limitation are evident in the computed responses shown in Figures 6.1(b), (c) & (d). In other cases the amplitudes of the peaks in the computed responses will be less than the actual response considering the total induced currents. This is mainly because the total induced currents are represented by a set of infinite eigen functions and our technique uses only fifteen eigen functions. However, the good agreement between the computed responses for various systems and the responses known from other independent studies, even in the difficult cases in Sections 3.5 and 3.6, shows that the use of fifteen eigen functions is quite satisfactory for present purposes where the response of deeper sheet-like bodies is to be studied.
Only the applicability of the technique has been demonstrated in this Chapter. Some of the comparative responses of the different frequency and time domain systems studied are discussed in Chapter 6.
CHAPTER 4

SUDBURY AREA
(INCO'S GERTRUDE DEPOSITS)

4.1 Introduction and Geology

The Gertrude deposits of INCO Limited are located about 2.5 miles west of Inco's Creighton mine. These can be approached by highway 17 & 536 up to Creighton and then private Inco road. The nickel-copper sulphide ore bodies around this area, generally, occur at or near the outer margins of a body of igneous rocks known as the Sudbury irruptive. In plan the irruptive forms an elliptical basin - 37 miles long and 17 miles wide (Fig. 5.1). The outer part is composed of coarse grained felsic norite and the inner part is a micropegmatite or granophyre. The rocks inside the irruptive, the White water group, consist of tuff, slate and sandstone. Older rocks north of the irruptive are principally Archean granites. The southern contact of the irruptive, in most places, is with the Sudbury group, a sequence of metamorphosed and locally brecciated sediments and volcanics of Aphebian age intruded by granites and gabbros of various ages. The irruptive itself is metamorphosed, faulted, brecciated and transected by diabase dykes.

The Sudbury ores consist of massive sulphides, breccia sulphides, and disseminated or stringer sulphides in silicates. The most abundant sulphide minerals are pyrrhotite, pentlandite, chalcopyrite and cubanite. The overall nickel to copper ratio is close to 1:1 but in some ore bodies there are significant departures, generally in the direction of increasing nickel. The origin of the Sudbury irruptive and its associated ore is still
a matter of conjecture. Cases are made for the irruptive being a spoon-shaped sill, a lava lake remnant, a ring dyke, a funnel shaped intrusion, or an intrusion associated with a meteorite impact crater. Regardless of the irruptive's origin, the most commonly accepted theory on the origin of the sulphide minerals is that they were present in the main felsic norite magma and segregated as fluid droplets from the silicate fraction, settling towards the lower contact to form pools of ore in depressions in the basement. In places, subsequent tectonic activity caused the sulphides to migrate into the adjacent country rocks, forming ore bodies offset from the main irruptive. Some recent theories (Naldrett and Kullerud, 1967) suggest that this theory needs revision. According to them a complex group of intrusions and intrusive breccias occurs as a semi-continuous layer along the base of the main felsic norite and, in places, projects as dykes into the footwall. These 'sublayer' rocks, which vary in composition from quartz diorite to mafic norite, contain or lie adjacent to all known ore bodies in the Sudbury district. They contain abundant inclusions and are intrusive into the felsic norite. These sublayer rocks contain about fifty times as much nickel and copper as the felsic norite. The complication, according to them, is that the ores were deposited during a later intrusion of sulphide rich silicate magma along the basal contact of the irruptive.

The Gertrude deposits were discovered early in Sudbury's history, and small old workings exist near the surface showings. The deposits consist of zones of unspecified mineralogy. Gertrude, and Gertrude west are separated by about 3000 ft. Gertrude is the larger deposit and it apparently consists of a zone of mineralization dipping at about 45°N with a near surface strike length of about 800 ft. and an apparent depth extent of 1800 ft. A vertical diabase dyke (trap) cuts through this deposit at a depth extent (along dip)
Fig. 4.1: Geological plan map of Sudbury basin. Gertrude deposits are located at 'G'.
of 1000 ft and possibly separates the upper part of the deposit from the lower part. 'Gertrude West' has a similar dip, but it has a much smaller strike length of about 300 ft, and extends up to a depth of 800 ft. The mineralized zones have variable thickness which reaches many tens of feet in places and the sulphides tend to be massive.

4.2 UTEM Survey

The Gertrude deposits were selected for the test surveys with the UTEM system mainly because the geometry of the mineralized zone is well defined by means of closely spaced drill hole intersections made available by Inco Limited. The sites have also been object of numerous tests of drill hole exploration methods in the past few years. The objective of the UTEM survey on these two deposits was to test the applicability of simple models in EM interpretation, and to see if the deeper portion of the Gertrude body surveyed with bore hole methods could be detected by a deeply penetrating fixed source, large scale, wide-band system.

The survey was carried out with the help of Y. Lamontagne & J. Macnae from September 16 to 29, 1976. For each zone, a transmitter loop somewhat larger than the estimated strike length of the mineralized bodies was laid to the south (up dip) of the zones. The vertical magnetic field \( H_z \) was measured along traverses running across the strike direction of the zones. A few stations on all the traverses in each area were repeated by a 'drift loop' to check the accuracy of measurements and correct for the day to day variations in the receiver coil sensitivity. The maximum sensitivity change was found to be ±2%.

Inco's original grid had many missing pickets, and so all the lines were rechained. Line and station nos. correspond with Inco's nomenclature. The loop layout and location of survey lines in the two
Fig. 4.2: UTEM lay out map of Gertrude area showing geological boundaries, location and depth of the deeper part of the mineralised zone, and interpreted shape of the upper mineralised zone. Drill hole 9266 is on line 12 W.
areas namely Gertrude & Gertrude West are shown in Figures 4.2 & 4.10 respectively. The survey data and interpretation of results from the two areas are discussed separately.

4.3 Gertrude Area

4.3.1 Survey results and preliminary interpretation

The UTEM survey (measuring the $H_z$ component at 30 Hz base frequency) was carried out over five lines from loop 103 as shown in Figure 4.2. The original loop 103 was laid south of the Gertrude deposit at a distance sufficient to have good coupling with the deeper part of the body. Unfortunately, there is a great deal more near-surface mineralization than was originally expected and the transmitter wire turned out to be closer to the outcrop trace of the zone (near line 16W) than was desirable. The north side of the loop was therefore moved 200 feet southwards (Loop 104) and parts of lines 16W ($H_z$ component) and 12W ($H_x$ component) were resurveyed. At the same time, a lower frequency of 15 Hz was employed to better sample the long time decays.

The response is plotted at a vertical scale of 1 div. = 20% and horizontal scale of 1 div. = 100 ft. The systematic displacement of true zero by +4% from the plotting axis is due to an error in the coil sensitivity constant used during data reduction. This was not corrected since it has no ill effect on the data presentation.

Clear crossover anomalies are observed on (Fig.4.3) the lines 8W, 12W & 16W at stations 3.5S, 4.5S and 5.8S respectively indicating the location of the top edge of the conductive body. The anomaly dies out on either side on the lines 4W & 20W. The approximate strike length of the body is therefore around 1000 ft. The sharpness of the crossover gradually
Fig. 4.3: Observed absolute secondary field UTEM anomalies on lines 4W, 8W, 12W, 16W and 20W in Gertrude area. ($H_z$ component)
decreases from 16W towards 8W indicating the top of the body to be shallowest near L16W and top plunging at a low angle towards east. The negative anomaly on line 8W is divided into two parts (or has two peaks). An old shaft is located on the line at about 5S. It appears from UTEM data, that the near surface massive sulphides were mined out by old miners leaving less conductive sulphides in shallow near surface zone, while the massive sulphides still exist at the depth. The width of the negative response on line 16W is appreciably smaller, probably because of the smaller depth extent of the conductor near that line. On all three anomalous lines, dip to the north is indicated by the migration of the crossover to the north at the later time channels.

The observed anomalous profiles on lines 8W, 12W & 16W are shown on an expanded scale in Figures 4.5, 4.6 and 4.7. Decay plots of peak-to-peak amplitudes for line 12W & 16W and of negative amplitudes at station 1N on line 8W are shown in Figure 4.4. The observed decay plots do not conform to any of the simple scale model decays. Firstly the response, particularly on line 12W and to some extent on 16W is extremely persistent even up to channel 1 (12.5 or 25 msec). The decays are nearly linear with respect to channel number (logarithmic with time) within the range of the time sampled i.e. they approximate inverse power laws. Decays of lines 8W and 16W do show a tendency to become more rapid at the latest time channel, but this is not seen on line 12W. This behavior is probably due to a very slow diffusion of the electromagnetic field into a core of extremely conductive massive sulphides. For this body it appears that the base frequency would have to be lowered at least an order of magnitude to obtain complete penetration of the field through the entire body.

Fitting of the finite thin sheet model to the observed
data was tried, presuming that a much greater rate of decay would have been seen if the 30 Hz base frequency were lowered by a factor of 4 to 8. The theoretical decay curves shown by regular dashed lines in Fig. 4.4 are all drawn for the minimum decay rate that could fit the data on the assumption that the diffusive effect is present. In a situation of this type thin sheet model decay could be fitted to any part of the two three points of the observed decay with different characteristic times. This is shown by two model decays for line 12W with alternate dash and dot lines with characteristic decay time $t'_1$ & $t''_1$. Each faster decay or smaller characteristic time $t_1$ to $t'_1$ to $t''_1$ may correspondingly reflect the response of outer less conductive and slightly larger size of the sheet like mineralized body. The maximum characteristic time $t_1 = 80$ msec is used to calculate the conductance of the inner part of the mineralized zone. On line 16W surveyed with 15 Hz frequency there are some indications of the beginning of the faster part of the decay in late time channel response. The theoretical decay of the infinite sheet model gives a characteristic time of 70 msec. Again this is not the absolute minimum decay part of the observed curve and true conductance of the innermost core will be larger than that determined by this model fitting.

The bimodal nature of the decay plot for line 8W is obvious as shown in Figure 4.4. On this line the early time channel 8, 7, 6 can be fitted to a finite thin sheet model with characteristic time $t_1 = 1.55$ msec. This gives conductance of about 40\(\Omega\) mhos for shallow part of the conductor left over after removing massive sulphides. The late time channels 4,3,2 & 1 can also be fitted to thin sheet model decay with characteristic time of 50 msec. This gives conductance of about 1300 mhos for the remaining deeper sulphides around line 8W. All the calculated conductances, presuming a strike
Fig. 4.4: Time decays of observed anomalies and scale model decay of thin sheet model on lines 8W, 12W and 16W.
length of 1000 ft for the mineralized body, are shown in Table 4.1. The conductance estimates are obviously minimum values since the earliest possible onset of a rapid decay has been assumed.

**TABLE 4.1**
PRELIMINARY INTERPRETATION OF GERTRUDE ANOMALY

<table>
<thead>
<tr>
<th>Line</th>
<th>Base freq. (Hz)</th>
<th>Approximate depth (ft)</th>
<th>Characteristic time used msec.</th>
<th>Conductance (od) mhos</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>8W</td>
<td>30</td>
<td>-</td>
<td>1.55</td>
<td>40</td>
<td>Upper part of mineralized zone</td>
</tr>
<tr>
<td>8W</td>
<td>30</td>
<td>-</td>
<td>50</td>
<td>1300</td>
<td>Lower part of mineralized zone</td>
</tr>
<tr>
<td>12W</td>
<td>30</td>
<td>165</td>
<td>8.9</td>
<td>230</td>
<td>Outermost part of mineralized zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44</td>
<td>Next inner</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td>Further inner</td>
</tr>
<tr>
<td>16W</td>
<td>15</td>
<td>75</td>
<td>70</td>
<td>1800</td>
<td>Inner part of mineralized zone</td>
</tr>
</tbody>
</table>

* Strike length of 1000 ft. was taken for calculating od of the sheet like body.

4.3.2 Detailed interpretation

Profile fitting started with a model of 900 ft strike length and 1800 ft depth extent dipping 45°N. These dimension corresponded with what was initially thought to be the shape of the mineralized body. It was immediately evident that computed amplitudes were too large. Models with rotation of the sheet by ±15° from reported dip of the vein were computed, but these did not produce a negative
part of the computed anomaly close enough to the observed one. It was, however, felt that the vertical trap dyke around 3N may have divided the mineralized vein in two parts. Accordingly, modelling continued with 1000'×1000' sheet at a depth of 50 to 100' with dip of 45°±5°. The computed response on line 12W began to approach the observed data. Twenty-seven different models had to be tried with minor adjustments in depth to the top, depth extent, strike length, dip and conductance of the sheet before computed data on all the five profiles could be matched with the observed data.

Conductive bodies in nature cannot be expected to be of perfect rectangular shape, uniform conductivity and thickness. Local variation of the shape and conductivity of a large conductor will mostly affect the response on the line nearest to the local inhomogeneity. To be a good fit to the Gertrude conductor, the model should ideally be a plate of irregular outline in which a local variation in conductivity thickness could be introduced. Since such a model is not easy enough to simulate on a computer, the effort here was to arrive at the closest possible approximation of the real body by varying shape, depth and conductivity thickness of the rectangular plate somewhat from line to line, while keeping the attitude of the plate constant. Variations in conductivity-thickness are then necessary, in some part to compensate for the changes in overall size of the model plate conductor.

The computed profiles which are closest to the observed data for lines 8W, 12W and 16W are shown in Figures 4.5, 4.6 and 4.7 respectively. Parameters of the computed models are shown in the respective figures as well as in Table 4.2. It appears from the fitting of the computed data to the observed data, that on line 16W the conducting body has a
depth extent of more than 333' and less than 500' (Fig. 4.7). On line 12W
the depth extent appears to be between 675' and 1000' (Fig. 4.6). The ob-
served and computed data for the $H_x$ component surveyed from loop 104,
using the same model as that of L21W, are shown in Figure 4.8. Again the
match is reasonably good. On line 8W the observed anomaly is distorted, and
Figure 4.5 shows the observed anomaly at normal and expanded scales for
the late channels, with two attempts at model fitting. The upper most
profile is computed for a sheet of 1200' x 810' size at a depth of 45 ft.
This shows the response expected if there was a uniformly conductive plate
going from the surface trace to the trap dyke. However, the observed decay is
much faster for stations between 2 and 6S, and slower for the late channels
between 2S and 8N. Therefore a computed anomaly is shown in the bottom
of the figure which matches well with the slowly decaying part of the field
anomaly. It indicates a highly conductive body at a depth of 300 ft and
with a depth extent of 600 ft, i.e. the bottom edge of the model is at
the same point as for line 12W. The surface plan of the computed models
which best explain the observed anomalies on all the five lines is shown
in Figure 4.2 along with the survey lines and the geology.

A generalized version of the computed model with a somewhat
irregular outline, dipping 45° to the north fits very well with the known
geology and shape of the upper part of the mineralized vein known from
drilling results. The drilling data for the upper part of this body are
not available for use in this thesis, but have been shown to us in INCO's
office at Sudbury.

All the computed profiles which match the observed profiles
are for sheet conductances in the range of 1000 to 3000 mhos. Actual
conductance used from line to line along with depth to the top, depth
extent, strike length and plunge of the top are shown in Table 4.2.
Fig. 4.5: Observed and computed H component profile for line 8W. Surveyed from loop 103 at 30 Hz base frequency.
Fig. 4.6: Observed and computed H component profile for line 12W. Surveyed from loop 103 at 30 Hz base frequency.
Fig. 4.7: Observed and computed $H_z$ component profile for line 16W. Surveyed from loop 104 at 15 Hz base frequency.
Fig. 4.8: Observed and computed H\textsubscript{x} component profile for line 12W. Surveyed from loop 104 at 15 Hz base frequency.
It is quite noticeable from model fitting to the observed data of the $H_x$ component on line 12N, where a base frequency of 15 Hz was employed, that conductance values of 2000 mhos are obtained as opposed to the 1000 mhos from model fitting to the $H_z$ data from the same line surveyed at 30 Hz. In both cases best fitting was attempted at late time channels, mainly Ch. 1 to Ch. 3. Similarly, interpretation of line 16W surveyed with 15 Hz base frequency shows conductance of 3000 mhos which is a factor of one and half to three times the conductance obtained on line 8W and 12W with 30 Hz base frequency data. This conforms with the preliminary interpretation where it is observed that the field has not yet penetrated through the entire thickness of the body. Any lower frequency used would enhance the response of the more conductive inner portion of the mineralized body.

There is, of course, some latitude in the fitting process. For a medium size sheet of 1000'×1000' size, changing size and depth to the top by 10% would not introduce any noticeable change in the computed response. Similarly changing dip by ±5° would not modify the shape appreciably. Changing conductance essentially shifts the response along the channel axis in a decay plot which would become noticeable on doubling the conductivity. Accordingly, the size of the best fitting sheet is defined within a accuracy of ±10% and conductance defined in this particular case is a minimum value. Actual conductance is expected to be higher. The large uncertainty in conductance is mainly because it is improbable that the EM field has penetrated through the entire thickness of the conductive body at decay times in the range of channels 1-3 where the fitting was most concentrated.

This model fitting is consistent with a body extending down dip up to 800' or 1000' only, whereas the drilling information indicates that
mineralization is found up to 1800'. This situation would appear appropriate if the conductor is discontinuous at the trap dyke present near 3N and the deeper body is much less conductive. There are no clear indications in the observed UTEM data of any conductor north of 3N. However, the known deep body north of the trap dyke would have to have a conductance comparable to the shallowest part, to be picked up with the UTEM system. As will be discussed in the following section, there is evidence from bore hole EM survey results of Dyck (76) that the deep part of the conductor north of the trap dyke has a much lower conductance than the shallow part. In my opinion, it is impossible to see a deep conductor of such low conductance by surface EM methods with the present loop setup, especially in the presence of a shallow conductor of comparable size, with a conductance about 50 times that of the deep one.

### Table 4.2

**Detailed UTEM Data Interpretation Using Finite Thin Sheet Model for Gertrude Anomaly**

<table>
<thead>
<tr>
<th>LINE NO.</th>
<th>LOCATION OF TOP</th>
<th>DEPTH TO THE TOP (ft)</th>
<th>SIZE OF THE SHEET S (ft)</th>
<th>W (ft)</th>
<th>CONDUCTANCE od (mhos)</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>8W</td>
<td>3.5S</td>
<td>45'</td>
<td>1200'</td>
<td>810'</td>
<td>1000</td>
<td>upper portion $\eta = -5^\circ$ (for possibly mined out ore)</td>
</tr>
<tr>
<td>8W</td>
<td>1.3S</td>
<td>300'</td>
<td>1200'</td>
<td>600'</td>
<td>2000</td>
<td>Deeper part of the body $\eta = 0$</td>
</tr>
<tr>
<td>12W</td>
<td>4.5S</td>
<td>75'</td>
<td>1000'</td>
<td>675', $\lambda = 900'$, $\lambda = 1000$</td>
<td>1000</td>
<td>Plunge = +10° (at 30 Hz)</td>
</tr>
<tr>
<td>12W</td>
<td>4.5S</td>
<td>75'</td>
<td>1000'</td>
<td>1000'</td>
<td>2000</td>
<td>Hx component at (15 Hz)</td>
</tr>
<tr>
<td>16W</td>
<td>5.8S</td>
<td>15'</td>
<td>1000'</td>
<td>333', $\lambda = 400'$, $\lambda = 500$</td>
<td>3000</td>
<td>Plunge = +10° (at 15 Hz)</td>
</tr>
</tbody>
</table>
4.3.3 Multifrequency EM survey of drill hole 9266

A. Dyck (76) of Geological Survey of Canada has surveyed this drill hole located on line 12W at station 10N with multifrequency Scintrex bore hole SE-77/DHEM-5 EM unit. The frequencies employed were 35, 105, 315, 945 and 2835 Hz. His source field was a large rectangular loop, 1600' x 1400', with the short sides running north-south and the long sides running east-west. The drill hole was located inside the loop such that one long side was 150' south and one short side was 600' east of the drill hole. For measuring induced fields one receiver coil (the reference) was kept fixed on the top of the drill hole and the other receiver coil was suspended inside the hole up to a depth of 1400'. The normal Turam field strength ratios and phase difference between the down hole receiver coil and the reference coil were measured every 10 or 20 ft. This data is shown in Fig. 4.9(a). The observed field strength ratios were converted to reduced field strength ratios before plotting. For the frequencies from 105 to 2835 Hz field strength ratio data are normalized to 35 Hz data. The plotting position is at the down hole receiver coil location.

A systematic positive anomaly is observed around 1000' depth in the field strength ratios as well as in the phase data. The amplitude of the field strength ratios is constantly increasing with frequency while phase angle amplitudes show a peak around 315 Hz frequency and start decreasing with further increase of frequency. An attempt was made to compute this anomaly using a thin sheet model. The model chosen was 700' x 700' sheet at a depth of 650', dipping at an angle of 30° towards the drill hole. Two models were chosen with their location so adjusted that the nearest edge of the sheet was 50' or 100' away from the drill hole. The computed data for the former sheet are shown in Figure 4.9(b) next to the observed data. Location of the model sheet along with the Turam source loop is
(a) Observed data (by courtesy of A. Dyck(76) and INCO Limited).

(b) Computed data for the theoretical thin sheet model ($\sigma_d = 25$ mhos).

Fig. 4.9: Observed and computed EM data from drill hole 9266. Observed data are collected by Dyck with Scintrex SE-77/DHEM-5 Unit. Field strength ratios for 105 Hz to 2835 Hz are normalized with 35 Hz data.
also shown there. The computed profiles for the phase shift are quite similar to the observed profiles at all frequencies. The shape of the computed field strength ratios is similar to the observed ones, although the amplitudes of the computed response at higher frequencies are slightly larger. A second model with the sheet 100' away from drill hole (not shown) has a computed response of lower amplitude than the observed one. It is thus possible that the conductive sheet is about 75' from the drill hole. The lower part of the observed response around 1300-1400' depth appears to be due to some other mineralized stringers. The assumed model sheet here very well represents the dimensions of the lower part of the mineralized zone north of the trap dyke. The computed data give a conductance of 25 mhos for the sheet. This gives us an impression that lower part of the mineralized body has a very poor conductance compared to the upper part of the mineralized zone which is in the range of 1000 to 3000 mhos.

4.3.4 Summary & Conclusions

Geometrically the main anomalous UTEM response seems quite adequately explained by a free space finite thin sheet model. However, the pattern of observed decay is certainly not explained. The anomalous gradual decay pattern in time domain is equivalent in frequency domain to a slow change in phase angle (in phase to quadrature ratio) and amplitude with frequency. This anomalous slow decay is interpreted to be due to diffusion through a halo. Quantitative modelling of this phenomenon is not available except for a sphere model, but it is thought that it may be modelled roughly by increasing the conductivity and decreasing the size of an appropriate uniform conductor model as a function of increasing decay time or decreasing frequency. This assumption has not been adequately
tested, but it is certainly not inconsistent with the results shown here.

There seems a good possibility that the induced currents producing the anomaly are vortex currents, which are largely confined within the mineralized zones. The survey shows some evidence of regional induced currents in the overburden or bed-rock, but the secondary fields of these current systems are observed to have a much faster time decay than the main anomaly. Possibly current gathering makes some contribution to the main anomaly at early times, but it is hard to see how it could contribute significantly to the medium and late time anomaly. Furthermore, a gathered current component would flow more or less unidirectionally across the conductor and it is hard to see how the good geometrical fit could have been achieved if this was the case.

It appears in this area, that in spite of the severe halo effects, finite thickness effects and minor overburden and host rock effects present in the UTEM data, it is possible to judiciously use simple uniform models and arrive at reasonable interpretation of the causative body.

The interpretation of UTEM data and multifrequency bore hole EM data indicate that the entire mineralized zone in this area is divided into two parts by the presence of vertical dyke. The near surface mineralization extends up to a depth of about 900' along dip and ends just south of the vertical trap dyke. The core of this part of the mineralized zone has a very high conductance. The minimum estimated conductance of the massive core is 1000 to 3000 mhos. Since the data using 15 Hz base frequency has systematically given a higher conductance than the 30 Hz base frequency data it is certain that the EM field has not penetrated the innermost core which may have a conductance much higher than 1000 to 3000 mhos. The interpreted shape of the upper part of the mineralized
zone is shown in Figure 4.2 in horizontal plan view. The solid thick line indicates the interpreted shape of the body as based on three different, best fitting, models shown by dotted lines. From the multifrequency bore hole data of Dyck (76) it appears that deeper part of the mineralized zone north of the trap dyke has an approximate size of 700'x700' and its conductance is about 25 mhos.

4.4 Gertrude West Area

4.4.1 Survey results and preliminary interpretation

The UTEM survey, measuring the $H_z$ component at 15 Hz base frequency, was carried out on the five lines from loop 105 shown in Figure 4.10. The lines are 200 ft apart and observations were made at 50 ft intervals. The reduced data were originally plotted as absolute secondary fields and are shown for all five lines in Figure 4.11. The gradual shifting of profiles from the horizontal axis, which is particularly visible on the lines 36W and 44W, is probably due to poor geometrical control on the relative positions of the transmitter and the survey lines. Distances were remeasured in the course of the survey, but line orientation was not checked rigorously. The observed variations are probably due to bending of the survey lines due to compassing errors caused by strong local magnetic anomalies which are known to exist in this area. For example, the departures on the end lines (36W & 44W) are consistent with a misorientation of both of these lines of about 10° clockwise relative to the transmitter. For this reason some of the data was replotted, as channel 1 reduced data and is shown in Figures 4.13, 4.14 & 4.16 for lines 38W, 40W & 44W respectively. The replotted data include only channels 1 to 5 at the expanded scale of 1 div. = 5%. Clearly the channel 1 subtraction in reduced data format takes away all the effect of survey errors and the data from
Fig. 4.10: UTEM survey lay out map of Gertrude West area showing geological boundaries, location and depth of mineralised zone.
channel 2 to 5 are good representations of the response of the conductor in the ground. Some of the noise towards end of the lines around 4 to 6N may be due to nearby power line running at an oblique angle of 30° to the base line and at a distance of 500 to 800 ft from the end of the lines.

The survey shows clear crossover anomalies on lines 40W and 42W. On line 40W, the crossover anomaly is quite broad and very well developed. The apparent displacement of the crossover on channel 9 and 8 on this line appears to be due to a broad slightly positive response superposed on the cross over anomaly. This positive response is probably due, at least in part, to induction in poorly conductive overburden or host rock and is seen on all lines except, perhaps, L42W. On this line there appears to be a superposition of two cross over anomalies, of much the same nature as the response on line 8W of Gertrude. The larger response (at 235°) is more abrupt and has a moderate decay rate. The smaller one, which is displaced to the north has a much slower decay. On line 44W, the cross over is very weak but the broad negative north of station 0 gives a definite indication of the presence of some anomaly. On the east side on line 38W a very weak response can be recognized. This can be seen on the expanded scale shown in Figure 4.13. There is no anomaly on line 36W except for the slight host rock or overburden response on channels 9 and 8.

A study of Figure 4.11 shows that the conductive zone appears to have a near surface strike length of only about 300 or 400 ft. The conductive body is shallowest on line 42W and slightly deeper on line 40W. The nature of the weak anomalies on line 38W and line 44W suggests that the conductor may not extend under these lines or it may be quite deep. The two part anomaly on line 42W may be due to mining of the upper portion of the sulphide body. Mining activity is indicated by the pit at 43W, 2S.
The sharp cross over anomaly around 2.4S possibly points to the less conductive, near surface mineralization remaining here, while the slowly decaying negative anomaly north of station 1S may show the presence of deeper, more conductive sulphides. The anomalies on the other lines show, approximately, this same slow decay.

The peak-to-peak decay plots (after correcting for the base) for profiles from three lines 38W, 40W and 44W are shown in Figure 4.12. For line 42W decay is plotted for slowly decaying negative part of the anomaly at station 0.5S. As opposed to Gertrude the observed decays here show rapid decay from channels 4 to 1 (towards later time). An effort to fit a finite thin sheet theoretical decay curve to the observed decay is shown in Figure 4.12. Dotted lines show theoretical decay curves while solid lines show the observed decays. It appears that the fit is reasonable on channels 1 to 4 for all the lines, and channels 1 to 6 on line 38W. The small deviation on channel 7, 8 and 9 on line 38W mostly show the effects of finite thickness and some halo effect. On line 40W and 42W enhancement of the observed anomaly on channels 5 to 9 may be due to a combination of finite thickness, conducting halo and some overburden effect. On line 44W the small enhancement of the observed anomaly on Ch. 5, 6, 7 may be due to thickness and halo effects, while strong enhancement on channel 7, 8 & 9 may be due to a combination of halo and strong overburden effects. This corroborates well with the surface observation that bed-rock is exposed on surface on line 38W and part of 40W and 42W. Thickness of the overburden gradually appears to be increasing towards line 44W as per surface evidences.

In spite of a complicated response on early time channels, the observed late time channel decay that fits well with the thin sheet model was utilized to calculate the characteristic time $t_1$. Lamontagne's formula
Fig. 4.11: Observed absolute secondary field UTEM anomalies on Lines 36W, 38W, 40W, 42W and 44W.
Fig. 4.12: Time decays of observed anomalies and scale model decays of the sheet model for lines 38W, 40W, 42W and 44W.
shown in Table 2.1 was used to calculate the conductance \( \sigma_d \) of this sheet type body. The results are shown in Table 4.3

### TABLE 4.3

**PRELIMINARY INTERPRETATION OF GERTRUDE WEST ANOMALY**

<table>
<thead>
<tr>
<th>LINE NO.</th>
<th>APPROXIMATE DEPTH/DISTANCE FROM LINE (ft)</th>
<th>CHARACTERISTIC TIME (msec)</th>
<th>CONDUCTANCE ( \sigma_d ) (mhos)</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>38W</td>
<td></td>
<td>44</td>
<td>3830</td>
<td>Strike length of 300 ft</td>
</tr>
<tr>
<td>40W</td>
<td>100-150</td>
<td>44</td>
<td>3830</td>
<td>was taken for calculating ( \sigma_d )</td>
</tr>
<tr>
<td>42W</td>
<td>25</td>
<td>25</td>
<td>2180</td>
<td></td>
</tr>
<tr>
<td>44W</td>
<td>200-300</td>
<td>29</td>
<td>2530</td>
<td></td>
</tr>
</tbody>
</table>

#### 4.4.2 Detailed Interpretation

The preliminary interpretation, known geology, and the geometry of the anomalies suggest that it should be possible to approximate the conductive body by a finite thin sheet model. If the early part of the anomalous decay is due to diffusion in a halo, the apparent size of the model will depend on which part of the decay curve is approximated. It was decided to concentrate on fitting channels 2-4, since this part of the data appeared to fit well with the finite thin sheet model decay in preliminary interpretation.

An initial model of size 250' \( \times \) 1000' with a depth to top of 100',
dipping at 48° north was chosen to compute the response of this mineralized zone. The dimensions of 250'×1000' were initially chosen to use the sheet eigen values for R = 2.0 or 4.0 to get an approximate idea of the nature of response. With the initial computation it became evident that to accommodate varying depths to the top of mineralized zone under different lines, one would need a displacement of the top of the sheet not only in the vertical direction but also laterally towards south, particularly for fitting the data from line 42W. This is clearly seen in the horizontal plan view of the different sheet models (shown in Figure 4.20) required for the final fitting of data on all the lines.

In all, fifteen different models with slight variations in depth to the top, size, plunge of the top and conductivity were tried in order to obtain a good fit of computed data to the observed field data. As explained earlier in section 4.3.2, the minor variations in the model from line to line are needed to account for the irregular shape and conductivity of the actual mineralized body.

The computed model profiles for lines 38W, 40W, 42W & 44W along with the observed profiles are shown in Figures 4.13 to 4.16. Details of each best fitting model are also given. The effect of misorientation of the survey lines and the loop on the data is visible on channel 1 of Figures 4.13, 4.14 & 4.16 but the reduced secondary field format of the data compensates for the other channels. For ease of comparison the computed profiles are plotted in the same format as the observed profiles.

The similarity of the computed profiles to the observed profiles on channels 2 to 5 is reasonably good for lines 38W, 40W and 44W. This is evident on Figures 4.13, 4.14 and 4.16. On line 42W shown in Figure 4.15, the observed profile shows absolute secondary fields. The negative
MODEL 14 370' x 740'
DIP = 48°
PLUNGE = -20°
DEPTH = 200'
\( \sigma_d = 2000 \) mhos

Fig. 4.13: Observed and computed reduced secondary field profile for line 38W.
Fig. 4.14: Observed and computed reduced secondary field profile for line 40W.
Fig. 4.15: Observed and computed absolute secondary field profile for line 42W.
Fig. 4.16: Observed and computed reduced field profile for line 44W.
part of the profile as discussed earlier is complicated by the presence of a positive bump at station 1.5S. However, an attempt to fit this profile with a 250'×500' sheet at 30 ft depth is also shown. The negative lobe does not match exactly in terms of amplitude, but the general shape of the profile and the decay rate north of station 1.5N is similar. South of station 1.5N the anomaly decays more rapidly than the modelled decay. The calculated conductance of the model on this line is only 1000 mhos as compared to the 2000 mhos required for the model on other lines. This is mainly because of difficulty of proper fit and due to the presence of less conductive part of the left over near surface mineralization.

<table>
<thead>
<tr>
<th>LINE NO.</th>
<th>LOCATION OF TOP (ft)</th>
<th>DEPTH TO THE TOP/DISTANCE OF NEAREST EDGE</th>
<th>SIZE OF THE SHEET S(ft)</th>
<th>W(ft)</th>
<th>CONDUCTANCE (σd) mhos</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>38W</td>
<td>0.5S</td>
<td>200</td>
<td>370</td>
<td>760</td>
<td>2000</td>
<td>dip = 48° Plunge = -20°</td>
</tr>
<tr>
<td>40W</td>
<td>2S</td>
<td>100</td>
<td>350</td>
<td>700</td>
<td>2000</td>
<td>dip = 48° Plunge = 0</td>
</tr>
<tr>
<td>42W</td>
<td>2.4S</td>
<td>30</td>
<td>250</td>
<td>500</td>
<td>1000</td>
<td>dip = 48° Plunge = 0</td>
</tr>
<tr>
<td>44W</td>
<td>0</td>
<td>190</td>
<td>400</td>
<td>800</td>
<td>2000</td>
<td>dip = 48° Plunge = -20°</td>
</tr>
</tbody>
</table>

4.4.3 Multifrequency horizontal loop EM data interpretation

Multifrequency horizontal loop EM data collected by Betz (77) over line 41W with Max-Min II unit at a coil separation of 200 ft and 400 ft are shown in Figures 4.17 and 4.18 respectively. The plotted profiles
at all five frequencies and both coil separations indicate that the body dips north. Quantitative estimates of depth to top and conductance from each profile using the dipping half plane model phasor diagram of Grant & West (65) is shown in Table 4.5. Conductance (od) estimates at both coil separations increase rapidly with decreasing frequency, i.e. the inphase to quadrature ratio of the anomaly changes much more slowly with frequency than a plate model predicts. This is the analogue in the frequency domain of the very gradual decay observed in the time domain. A plot of the variation of interpreted conductance with frequency is shown in Figure 4.19. Variations of this type have been observed on several mineralized zones by Betz (76) and his interpretation is also that the low conductance estimate arises because the EM field has not penetrated through the entire thickness of the mineralized zone at the frequencies used. The conductance calculated from the multifrequency HLEM data indicate a gradual increase in effective depth of penetration in the body of the mineralized zone with decrease in frequency. Extrapolation of the interpreted conductance in Figure 4.19 to very low frequencies (less than 1 Hz) gives a conductance value in the range of 3000 to 5000 mhos for both coil separations. This extrapolated conductance should be true conductance of the massive mineralized zone.

From Table 4.5 it is clear that the multifrequency data for a coil separation of 200 ft gives a depth of about 50 ft for the top of the body. Interpreted depths of the top from the 400 ft coil separation using half plane model are about 110'. The discrepancy arises mainly due to the use of a half plane interpretation diagram for the larger coil-separation data. For a body 350' in strike length surveyed with a 400 ft coil separation, the choice of finite thin sheet model would be more appropriate. Thus the depth estimate
using a 200 ft coil spacing, (affected to a smaller degree by the finite length of the zone) is likely to be closer to the true depth in this case.

### TABLE 4.5
INTERPRETATION OF MULTIFREQUENCY HLEM DATA FROM LINE 41W

<table>
<thead>
<tr>
<th>FREQUENCY (Hz)</th>
<th>PEAK TO PEAK RESPONSE</th>
<th>( \alpha )</th>
<th>D/( \ell )</th>
<th>DEPTH (ft)</th>
<th>( \sigma_d )</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>222</td>
<td>Ip(%) 25 OP(%) 6</td>
<td>37</td>
<td>.29</td>
<td>58</td>
<td>346</td>
<td>Coil Sep. (( \ell )) = 200 ft</td>
</tr>
<tr>
<td>444</td>
<td>Ip(%) 28 OP(%) 7</td>
<td>36</td>
<td>.27</td>
<td>54</td>
<td>168</td>
<td>&quot;</td>
</tr>
<tr>
<td>888</td>
<td>Ip(%) 31 OP(%) 7</td>
<td>36</td>
<td>.25</td>
<td>50</td>
<td>84</td>
<td>&quot;</td>
</tr>
<tr>
<td>1717</td>
<td>Ip(%) 34 OP(%) 7</td>
<td>36</td>
<td>.23</td>
<td>46</td>
<td>43</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FREQUENCY (Hz)</th>
<th>PEAK TO PEAK RESPONSE</th>
<th>( \alpha )</th>
<th>D/( \ell )</th>
<th>DEPTH (ft)</th>
<th>( \sigma_d )</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>222</td>
<td>Ip(%) 27 OP(%) 5</td>
<td>47</td>
<td>.3</td>
<td>120</td>
<td>220</td>
<td>Coil Sep. (( \ell )) = 400 ft</td>
</tr>
<tr>
<td>444</td>
<td>Ip(%) 28 OP(%) 6</td>
<td>45</td>
<td>.28</td>
<td>112</td>
<td>105</td>
<td>&quot;</td>
</tr>
<tr>
<td>888</td>
<td>Ip(%) 31 OP(%) 5</td>
<td>45</td>
<td>.26</td>
<td>104</td>
<td>53</td>
<td>&quot;</td>
</tr>
<tr>
<td>1717</td>
<td>Ip(%) 31 OP(%) 7</td>
<td>43</td>
<td>.25</td>
<td>100</td>
<td>26</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

It is known from studies made by Ghosh (72) and Jones & Wong (75) that in general when the response of a finite sheet conductor is interpreted using half plane interpretation diagrams, the depths obtained are greater than the true depth, while the conductance estimate is not much changed. The two different depths obtained by two coil separation in present case are in conformity with their observations.
Fig. 4.17: Multifrequency Horizontal loop EM data for \( L = 200' \) over line 41W.
Fig. 4.18: Multifrequency horizontal loop EM data for $L = 400'$ over line 41W.
Fig. 4.19: Variation of conductance with frequency of Horizontal loop EM data.
4.4.4 Summary & Conclusions

The line to line estimates of the depth to the top of the mineralized zone obtained from preliminary and detailed UTEM interpretation are reasonably close. The interpreted depth to the top of about 50' on line 41W using a 200' coil separation, multifrequency HLEM survey is within the reasonable depth limits of 30' on L42W, and 100' on L40W, obtained by the detailed UTEM survey.

The conductance obtained on line 41W from multifrequency HLEM data interpretation increases from 25 mhos to 350 mhos as the frequency decreases from 1717 Hz to 222 Hz. This gradual increase in conductance value (\(\sigma_d\)) indicates that the electromagnetic field is gradually penetrating deeper into the conducting body. The extrapolated value of conductance (Fig. 4.19) to a low frequency of 1 Hz gives an estimate of 3000-5000 mhos which is quite close to the UTEM interpreted values.

The conductance of the sheet conductor obtained by detailed interpretation of UTEM data varied from 1000 to 2000 mhos. This was determined by an optimum geometrical and amplitude fitting of the computed sheet model profiles to the observed profiles for channels 2 to 4. The conductance values determined by preliminary interpretation varied from 2000 to 4000 mhos. These are roughly a factor of two higher than those obtained by detailed interpretation. The discrepancy can be explained by the fact that in preliminary interpretation the decay curves took into account the rapid decay at late time channel 1, and beyond that where electromagnetic field has penetrated more deeper into the conductive core as against channel 2 to 4 data of detailed interpretation. Thus, while the conductance of preliminary interpretation reflected the interior core of the mineralized zone, detailed interpretation showed a slightly bigger, less conductive core.
Although the absolute value of the conductance of 1000 to 4500 mhos determined from UTEM and extrapolation of HLEM data is high for most of the narrow band standard EM systems operating between 200 to 2000 Hz, it appears that massive part of the mineralized bodies can have such high cd values. In the past, Strangway (66) has reported conductance values as high as 300 mhos and in recent years Betz (76, 77) and Lamontagne (75) have reported high conductance values in the order of thousands of mhos. The presently determined conductance value is still lower by about a factor of 10 than the estimated values of conductivities of sulphides in specimens measured in the laboratory.

The location and shape of the four different rectangular sheet models required for detailed line to line interpretation and the interpolated shape of the model (shown by thick lines) which can best explain the true conductor is shown in Figure 4.20. The interpreted shape of the sheet in this figure very closely resembles the shape, size and location of the actual mineralized zone known from drilling (in Figure 4.10).

In this area the mineralized body is of small size and the deviation from the rectangular plate model shape are significant. Further the UTEM response on early channels is complicated by finite thickness effect, conductive halo effect and effect of overburden. In spite of these complications a good fit of the observed profiles has been obtained over some of the later channels by computed profiles for finite thin sheet model. The geometrical shape of the computed model is close to the shape of the mineralized zone known from drilling. The conductance values estimated from the UTEM data are in agreement with the extrapolated values of conductance obtained from multifrequency horizontal loop data of much smaller scale. This all leads to the belief that in spite of the variety of moderate complications, details
of which are difficult to model specifically, the induced currents are largely vortex currents confined within the mineralized zone. It appears possible here to separate out the various complicating phenomena and apply simple uniform model interpretation to the late time channel UTEM response. The interpretation yields a reasonable estimate of the geometry and good insight into the conductance (σd) of this mineralized body.
Fig. 4.20: Horizontal plan view of the computed models giving best fitting Ch. 2-5 response on all the observed profiles.
CHAPTER 5

PICKLE LAKE AREA

(UMEX KAPKICHI CONDUCTOR K1-1)

5.1 Introduction

Kapkichi Conductor K1-1 is located about 6 miles WNW of Central Patricia (Fig.5.1), about 500 ft. north of the gravel road connecting UMEX Thierry mine to highway 599 in the north western part of Ontario. It was discovered by UMEX in 1970-1971 in the course of a systematic exploration program covering an area of 83 sq. kms. around Kapkichi Lake. The area was covered by lines at 400 ft. interval with stations 100 ft. apart. A fixed transmitter, vertical loop, dip angle survey (Fig.5.2) with a Scintrex SE-300 EM unit (1600 Hz frequency) had located this conductor extending over a strike length of a little over 1200 ft. A vertical field magnetic survey with a Mcphar M-700 flux gate magnetometer indicated an associated magnetic anomaly of up to 7000 gammas (Fig.5.3). The main Thierry mine which has proven reserves of about 15 million metric tons of average 1.63% copper and 0.2% nickel (extending in a shear zone of 3200 ft strike length and 1600 ft. depth extent) lies 2 miles west of this conductor. Conductor K1-1 was selected for test surveys with UTEM system to see if the system could locate the deep part of the doubly plunging top of the body and also to test the applicability of EM interpretation techniques based on simple uniform models in free space to field data collected from a wide band EM system.

5.2 Geology

The area is part of the Superior Province of the Canadian shield (K-Ar ages mostly about 2500 my. old) which is dominantly composed of
Fig. 5.1(a): Geology of Pickle Lake Area after Sage et al. (1973).

Fig. 5.1(b): Lay out of UTEM survey in Kapkichi conductor K1-1.
Fig. 5.3: Magnetic anomaly contour map in Kapkichi Kl-1 zone.
granitic, gneissic and volcanic rocks. Most of the economic mineral deposits are restricted to 'greenstone belts' which in this region usually occur as linear narrow bands of basic volcanic rocks of variable metamorphic grade. The volcanic bands contain variable amounts of intermediate to acid tuffs and numerous minor intrusions. The Pickle Lake volcanic belt (part of this is shown in Fig. 5.1) is about 80 kms. long and 15 kms. wide. In the belt around Thierry mine area the dominant rock types is amphibolite, consisting of hornblende and plagioclase, which is a metamorphosed mafic volcanic rock. The Thierry ore body lies along a contact between greenstone and granite is marked by a hornblende-biotite-chlorite schist. Verbeek et al. (1972) suggested that the copper and nickel were metamorphically mobilized from associated ultrabasic rocks and concentrated in the shear zone. Ultrabasics adjacent to the hornblende biotite-chlorite schist are also mineralized. In the K1-1 anomaly zone all the mineralization encountered by drill holes is in ultrabasic only.

Glacial deposits have formed a thin but persistent blanket over much of the area. The area was completely covered with about 2 ft of snow in December 1976, when the UTEM survey was carried out. The rocks have a roughly E-W strike and dip of about 50°-60° in the area surveyed.

The mineralization in the K1-1 zone consists of pyrite with chalcopyrite, nickeliferous pyrrhotite and rare pentlandite. The average disseminated mineralization in ultrabasics in this zone as per drilling information from few deep bore holes is less than 0.6% of combined copper-nickel metal. There are a few massive sulphide stringers within ultrabasics with overall mineralization of less than 2% in the massive part. A drill section along line 156E is shown in Fig. 5.16.
5.3 UTEM Survey

The UTEM survey was carried out in the area with the help of Y. Lamontagne between 24th November to 22nd December, 1976. Roger Caven, Chief Geophysicist of UMEX introduced us to the area and helped with the initial survey. EM Survey was done from two loops, one near Conductor K1-1 and other near Thierry mine referred as loop 111 and 201 respectively. A system frequency of 15 Hz was employed. Results from the data on lines surveyed from loop 111 only are discussed in this thesis. The layout of loop 111 and corresponding survey lines are shown in Figure 5.1(b).

Throughout the survey, the $H_z$ component of the total field was measured along lines cut and picketed at 100 ft. intervals by UMEX for their earlier magnetic and dip angle EM survey. However, all the pickets were rechained during the UTEM survey and the distance of each observed station from the front edge of the transmitter loop was accurately determined. Data from this area are presented as reduced secondary field plots. One representative plot from line 156E is shown in Figure 5.4. Channels 10 to 4 (or 5) are plotted on the upper half with the coarser vertical scale of 1 division = 20%. Channels 4 or 5 to 1 are plotted on the lower half with the vertical scale of 1 division = 5%. (Channel 4 or 5 is repeated for comparison). The horizontal scale is 1 div. = 100 ft. The points are plotted along the abscissa at their normal positions at 100 ft intervals. However, the exact position was used in the data reduction calculations.

Line 156E of Figure 5.4 is a typical example of this area. The narrow and sharp anomaly at station 117N is due to a buried telephone
cable which runs along the gravel road and lies approximately parallel to
the front edge of the loop. The anomaly was observed on all the profiles
with varying amplitude depending upon the distance of the buried cable
from the nearest picket. In geophysical literature this type of feature
is referred to as a cultural anomaly. It has not been studied in detail here.
The main interest of the present study is in the response of the mineralized
zone which is observed on this line from station 121N to 150N. The cross
over from positive to negative secondary field at station 125N represents
the location of the top of the conductive body, which dips at an angle of
50-60° towards north.

Figure 5.5 shows a compilation of data for Channels 5 to 9 for seven
lines from 152E to 176E over a strike length of 2400 ft. Data from lines
144E and 148E are unfortunately missing. The portion of the magnetic tape
carrying this data was accidentally overwritten and the data is lost. How-
ever, visual check of the analogue meter during the survey had indicated a very
weak anomaly on line 148E and no anomaly on line 144E. The sharpness of
the cross over on various lines indicate that the causative body is shallowest
on line 160E and it becomes deeper or either side. The plunge of the top
appears to be steeper towards the west (L 152E) than towards the east (L 176E).
The conductor can be definitely traced beyond 164E up to line 176E and it
does seem to continue beyond. A study of the anomaly decay indicates the
slowest decay to occur on line 152E. Decay rate increases gradually towards
the east, up to L 176E. This seems to indicate that the conductance of the
body (cd) is highest on line 152E and becomes less as one moves towards the
east.
Fig. 5.4: Typical UTEM profile on Line 156E. Amplitudes of various channels for decay curves are selected from locations 'B' and 'C'.
Fig. 5.5: Reduced secondary field observed UTEM field ($H_z$) profiles (Ch. 5 to Ch. 9) for lines 152E to 176E.
Fig. 5.6: Computed UTEM profiles ($H_2$) for thin sheet model (Ch. 5 to Ch. 8) for lines 152E to 176E. Details of different models are shown in table 5.3 and Fig. 5.14.
5.4 **Interpretation**

5.4.1 **Vertical loop data**

Quantitative interpretation of the UMEX fixed transmitter, vertical loop, dip angle survey data shown in Figure 5.2 was attempted using the type curves of West (60) for a half plane sheet dipping at 60°. The observed dip angle profiles were matched with the scale model type curves available for D/\ell ratio of 0.02, 0.05, 0.12 and 0.3 and \( \alpha \) values varying to 5, 10, 15 and \( \infty \). The observed shape and amplitude of dip angle profile on line 160E match with type curves for D/\ell value of 0.12 and \( \alpha \) value of 15. On the same type curve set, line 156E amplitudes are slightly greater than the type curve for \( \alpha \) value of 15 and much less than type curve for \( \alpha \) value of \( \infty \). An approximate estimate of 30 has been made for value of \( \alpha \) on this line. The observed profiles on line 152E and 164E match reasonably with type curves for D/\ell = 0.3 and \( \alpha = 15 \). This gives estimates of conductance varying from 10 to 20 mhos and depths to top varying from 60 ft to greater than 120 ft on the four lines (152E, 156E, 160E & 164E) on which anomalies were present with this survey. Detailed line to line interpretation is shown in Table 5.1.

5.4.2 **Preliminary interpretation of UTEM data**

Preliminary quantitative interpretation of the UTEM data was attempted on all the lines by first plotting decay curves of channel response along two sections 'B' and 'C' on each profile and then applying the interpretation procedure of Lamontagne (75) reviewed in Chapter 2. Complete profiles and their decay plots along two sections for two representative lines, 160E & 168E are shown in Figures 5.7 to 5.10. In general, the observed decay plots on all profiles are bimodal. The representative plots
of Fig. 5.8 & Fig. 5.10 show that the observed decay of the early time channels 10, 9, 8 is quite rapid and cannot be fitted to any of the simple model decays of Fig. 2.4 (Chapter 2). The observed decays from channels 7 to 3 are reasonably gradual and can be fitted to uniform simple model decay. On some of the profiles the observed decay is quite slow from channels 3 to 1. The example of this is shown in Fig. 5.10. This slow anomalous decay from channels 3 to 1 is analogous to the induced polarization effects discussed in section 2.9.2. This can be recognized as a complex non-inductive response, but at present no attempt has been made to interpret it.

The early time rapid decays correspond to the response at high frequency in the frequency domain where the contribution to the anomaly of a variety of causes like finite thickness effect, conducting halo effect, conductive overburden effect and conductive host rock effect are important. Theoretically, the decay plot of the response of sphere shown in Fig. 2.5 gives some idea of effect of finite thickness. The deviation of early channel responses in our present data is more abrupt than the gradual diffusive effect caused by the finite thickness of the sphere model. This rules out the thickness effect to some extent. The possibility of current gathering effect due to conductive overburden (in contact with bedrock conductor) or conductive host rock or strong halo effect enhancing this early channel response cannot be ruled out. As at present no quantitative models are available to interpret this early part of the complex decay, it is reasonable with the present scope of the research to separate out this early time complex decay from the intermediate time (Ch. 7 to Ch. 3) gradual decay. The interpretation discussed here is mostly devoted to this intermediate part of the decay which best fits the simple model decay.

The fitting of the intermediate response of the observed decay curves to simple model decay curves shows that most of the data fits a finite thin
dyke model decay. Only in a few cases were the decay plots close to the infinite thin dyke model (decay at B of line 168E, Figure 5.10). This leads one to believe that this conductive body is close to the finite thin sheet theoretical model but approaches the half plane model. Calculation of conductance (σd) or thickness of the body (d) using formulae of Table 2.1 requires an estimate of the strike length (s) of the sheet. Normally the anomaly pattern across series of parallel lines gives a good estimate of the strike length of the conductive body. In this case, a study of the field survey results of Figure 5.5 shows the anomaly is open at one end and possibly at both ends, indicating a strike length which is certainly not less than 2400 ft. Lamontagne's formulae of Table 2.1 gives effective strike length of an infinite sheet as 2700 ft. This comes from the relation \( S = (LL^2 + CX^2)^{1/2} \). Using this \( S \) of 2700 ft. and characteristic time \( t_1 \) from decay plots, the conductance (σd) of the dyke model was determined on all seven lines from 152E to 176E. Line to line interpretation is shown in Table 5.2. Results of refined interpretation discussed in section 5.5 later are also shown in this table along with the preliminary interpretation.

A magnetic anomaly map provided by UME, (Fig. 5.9) along with vertical loop EM anomaly shows that the conductive body has an associated magnetic response as well. To examine the effect of the associated magnetic minerals on the EM response, we have plotted channel 1 responses on all the lines along with magnetic profiles. This is shown in Figure 5.13. Here the magnetic anomaly is plotted at a scale of 1 div. = 3000 \( \gamma \)'s and channel 1 response is plotted at a scale of 1 div. = 6%. There is reasonably good correlation between channel 1 response and magnetic response on various lines. It appears that about 6000 \( \gamma \)'s of magnetic anomaly (10% of total
TABLE 5.1

FIXED TRANSMITTER DIP ANGLE DATA INTERPRETATION

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Location</th>
<th>Depth to Top (ft)</th>
<th>$\alpha$ (degree)</th>
<th>$\sigma$ (mhos)</th>
</tr>
</thead>
<tbody>
<tr>
<td>152E</td>
<td>126N</td>
<td>&gt; 120</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>156E</td>
<td>124N</td>
<td>= 60</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>160E</td>
<td>124N</td>
<td>= 60</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>164E</td>
<td>123N</td>
<td>= 120</td>
<td>15</td>
<td>10</td>
</tr>
</tbody>
</table>
Fig. 5.7: Reduced secondary field ($H_s$) observed UTEM profile (Ch. 1 to Ch. 10) for L 160E.

Fig. 5.11: Computed UTEM profile ($H_s$) using finite thin sheet model for L 160E.
Fig. 5.8: Decay curves at station B and C for line 160E.

Fig. 5.10: Decay curve at station B and C for line 168E.
Fig. 5.9: Reduced secondary field ($H_2$) observed UTEM profile (Ch. 1 to Ch. 10) for L 168E.

Fig. 5.12: Computed UTEM profile using finite thin sheet model for line 168E.
Fig. 5.13: Correlation of magnetic anomaly with UTEM Ch. 1 anomaly.
<table>
<thead>
<tr>
<th>Line No.</th>
<th>Location of conductor</th>
<th>Characteristic time (m.sec.)</th>
<th>Preliminary estimate with S=2700 ft. conductance ½(d mhos)</th>
<th>Refined estimate with S=6400 ft. conductance ½(d mhos)</th>
<th>Nature of model fitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>152E</td>
<td>126N</td>
<td>17.6</td>
<td>171(B)</td>
<td>72(B)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.5</td>
<td>121(C)</td>
<td>51(C)</td>
<td></td>
</tr>
<tr>
<td>156E</td>
<td>125N</td>
<td>10</td>
<td>107(B)</td>
<td>45(B)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.25</td>
<td>50(C)</td>
<td>21(C)</td>
<td></td>
</tr>
<tr>
<td>160E</td>
<td>124N</td>
<td>8.9</td>
<td>85(B)</td>
<td>36(B)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.5</td>
<td>83(C)</td>
<td>35(C)</td>
<td></td>
</tr>
<tr>
<td>164E</td>
<td>124N</td>
<td>5.2</td>
<td>50(B)</td>
<td>21(B)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>47(C)</td>
<td>20(C)</td>
<td></td>
</tr>
<tr>
<td>168E</td>
<td>124N</td>
<td>2.5</td>
<td>24(B)</td>
<td>10(B)</td>
<td>Infinite dyke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2</td>
<td>31(C)</td>
<td>13(C)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td>172E</td>
<td>123+50N</td>
<td>3.6</td>
<td></td>
<td>15(B)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td>176E</td>
<td>123N</td>
<td>2.5</td>
<td>24(B)</td>
<td>10(B)</td>
<td>Finite thin dyke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0</td>
<td>28(C)</td>
<td>12(C)</td>
<td></td>
</tr>
</tbody>
</table>
earth's field) will give rise to about 10 to 15% of EM anomaly in channel 1 and subsequent absolute secondary field values of later channels. As discussed in section 2.9.1, when data are plotted in reduced secondary format as in the present area, it is expected that the channels 2 to 10 response will be free of the complication caused by the effect of magnetic materials on the EM response. Smaller magnetic anomalies of the order of 100 to 1000 $\gamma$'s would in general not cause channel 1 anomaly greater than 1 to 3% and thus complications in EM interpretation arising out of the presence of magnetic materials in conductive body may not be serious on channel 2 to 10 in reduced secondary field data of UTEM system.

5.4.3 **Detailed interpretation**

On the basis of the preliminary interpretation it seemed likely that the finite sheet model discussed in Chapter 3 could explain the anomalies on most of the lines. It is applicable even for such a large conductor because the fixed loop transmitter source is also large and relatively far away from the body. The cut and try method of forward interpretation was used by computing the response of a provisional model, comparing the theoretical model response to observed response and adjusting the geometry and conductance of the model again and again. Fitting started with a model sheet of $3200' \times 1600'$ dipping 60°N. Depth of the top (with no plunge) was varied between 100 to 500 ft. below ground level. It soon became obvious by comparison of the shapes of the computed and observed responses that one needs a bigger sheet to match the amplitude and shape of the field data. By gradually increasing the size of the sheet it was found that a sheet of 6400 ft strike length and 3200 ft depth extent was required to obtain a close fit to the shape and amplitude of the observed response for most of the central profiles. Increasing the
strike length of the sheet beyond 6400 ft increased the amplitudes marginally, while decreasing the size reduced amplitudes and changed the shape of the profile drastically.

To obtain a good line-to-line fit of observed responses with the computed response of rectangular finite thin sheet model, local adjustment of the size, depth to the top, plunge of the top edge and conductivity of the sheet is required. None of the conductive bodies in nature can be expected to be of perfect rectangular shape and uniform conductivity. Local variation of the shape and conductivity of the large conductor would effect the response on line nearest to the local inhomogeneity. The best model to fit this particular conductor would be possibly a plate of irregular shape and within which local variation in conductivity could be introduced. However, since such a model was not available, the approach used here was to arrive at a closest possible approximation of the real body by varying shape, depth and conductivity of the rectangular plate marginally from line to line. A total of 31 slightly different models had to be tried before satisfactory fit could be achieved on all the lines. Computed responses for channels 8 to 5 for all the profiles are shown in Figure 5.6 with exactly same vertical and horizontal scale as in the plots of observed response in Figure 5.5. Detailed computed responses on all the channels for line 160E and line 168E are shown in Figures 5.11 and 5.12. The similarity of the observed and computed responses as evident from comparison of Figure 5.5 with 5.6, 5.7 with 5.11 and 5.9 with 5.12 is quite encouraging. The detailed geometry and conductivity of the model sheet required to obtain each fit is shown in Table 5.3. Figure 5.14 shows the geometry of various plates required to obtain the fit. Figure 5.15(a) shows the top of the interpreted conductor from line to line in vertical section. Figure 5.15(b) shows the
### TABLE 5.3
DETAILED UTEM DATA INTERPRETATION USING FINITE THIN SHEET MODEL FOR PICKLE LAKE AREA

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Location</th>
<th>Depth to Top (ft)</th>
<th>Size of the Sheet S (ft)</th>
<th>Size of the Sheet W (ft)</th>
<th>Conductance σd (mhos)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>152E</td>
<td>126N</td>
<td>600</td>
<td>6400</td>
<td>1280</td>
<td>100</td>
<td>Dip 60°N Plunge 30°W</td>
</tr>
<tr>
<td>156E</td>
<td>124.5N</td>
<td>350</td>
<td>6400</td>
<td>2133</td>
<td>25</td>
<td>Dip 60°N Plunge 30°W</td>
</tr>
<tr>
<td>160E</td>
<td>124N</td>
<td>100</td>
<td>6400</td>
<td>3200</td>
<td>17.5</td>
<td>Dip 60°N Plunge 30°W</td>
</tr>
<tr>
<td>164E</td>
<td>124N</td>
<td>400</td>
<td>6400</td>
<td>3200</td>
<td>20</td>
<td>Dip 60°N Plunge 14°E</td>
</tr>
<tr>
<td>168E</td>
<td>123N</td>
<td>500</td>
<td>6400</td>
<td>3200</td>
<td>15</td>
<td>Dip 60°N Plunge 14°E</td>
</tr>
<tr>
<td>172E</td>
<td>122N</td>
<td>600</td>
<td>6400</td>
<td>6400</td>
<td>12.5</td>
<td>Dip 60°N Plunge 14°E</td>
</tr>
<tr>
<td>176E</td>
<td>121N</td>
<td>700</td>
<td>6400</td>
<td>6400</td>
<td>12.5</td>
<td>Dip 60°N Plunge 14°E</td>
</tr>
</tbody>
</table>
plan view of the interpreted conductor in the horizontal plane, with shallow and deep edges and variation of the model conductance from line to line.

For such a large sheet, changing the depth of the top by about 10% will not introduce any noticeable change in the amplitude or shape of the profile. Similarly, changing the size by about 5 to 10% will not produce a noticeable difference in the profiles at the plotted scale. Also a change in dip of ±5° will not introduce a noticeable difference. Changing conductance (cd) essentially shifts the response along the channel axis in a decay plot, and thus doubling the conductivity would cause a shift of one channel spacing and thus would be quite noticeable. The conductance of the model sheet is defined to ±25% in most cases.

5.5 Summary & Conclusions

The UTEM preliminary interpretation of conductance (cd) in Table 5.2 is higher approximately by a factor of two compared to the detailed interpretation of Table 5.3 obtained by forward method of matching observed field profiles to theoretical finite thin sheet model. This discrepancy arises mainly because of the use of a shorter effective strike length of 2700 ft (for a longer sheet) in the preliminary interpretation. The detailed computed profile fitting of the observed data clearly demonstrates that a strike length shorter than 6000 ft is not reasonable. Further increase of the strike length beyond 6000 ft has a marginal effect in this case. This indicates that the finite thin sheet model response is approaching an infinite sheet. However, this leads us to believe that original empirical formula of Lamontagne, (Table 2.1) which assumes that the effective size of the infinite sheet to be equivalent to \((L^2 + CX^2)^{1/2}\) needs revision. This was tested by direct comparison of computed profiles of finite sheets of different
sizes and also by comparing the decay plot of large sheet computed from present technique with that of Lamontagne's scale model decay and using his characteristic time $t_3$ on curve C of Figure 2.5. It appears that effective strike length for infinite sheet will be roughly three times the length of the longer side of the transmitter loop. The revised estimates of the conductance (od) and thickness of the sheet using a modified strike length of 6400 ft gives interpretation of conductance close to the detailed interpretation.

Comparison of the UTEM plate model interpretation with the dip angle interpretation of Table 5.1 shows that the UTEM interpretation gives a slightly higher conductance and considerably larger depth-to-the-top. This is not so very surprising, however, as one has to visualize that dip angle data with traverses at 400 ft from the fixed transmitter has limited depth of penetration and the eddy currents will be induced only in the uppermost part of the conductive body near the survey system. UTEM, being a large scale fixed transmitter system induces a broad eddy current vortex in the whole conductor. Small protruberances on the conductor will not have much effect. Also, if the conductor has a gradual feather edge, the small scale system will likely emphasize the outer part of it. Furthermore, the UTEM interpretation emphasized data in the intermediate channel range which corresponds to frequency range of 60 Hz to 1000 Hz. This is much less than the 1600 Hz used in the dip angle survey. If we had concentrated the UTEM interpretation on early channel response near the positive peak and crossover of the UTEM data profile, it might well have given a depth and conductance estimate closer to the dip angle EM interpretation.

From the nature of the response and interpreted strike length of the thin sheet in preliminary interpretation it appears that the present interpretation of the prominent intermediate channels has, in
general, indicated the large scale moderate conductor. The effect of the more massive mineralized zone on line 152E, 156E & 160E can be recognized from the shape of the late channel response (Ch. 1 to 4) but no quantitative interpretation can be attempted for it at present. It appears that in large Loop UTEM system as with any other large scale system, the moderately conducting but large shear zone or ultrabasic zone has given a prominent large amplitude response. The response of small massive conductor located by vertical loop appears to be lost to a large extent in this large response. However, it is possible that we would have picked up the massive small vertical loop conductor in preference to the large moderate conductor if survey was repeated with a much smaller transmitter loop.

Looking to the conductance estimate in Table 5.3 and Figure 15(b) it appears that the most massive part of the conductive body lies close to line 152E. The Conductance gradually decreases further east indicating general disseminated sulphides in the main ultrabasics unit or presence of less conducting material in the shear zone.

In this area the interpreted conductor is so large and its true extent is not known geologically, hence one cannot use the model fitting to completely disprove the existence of unidirectional current flow. The best one can say is that the computed anomaly is definitely consistent with the induced current being a vortex restricted to the conductor. However, the following three alternate possibilities are worth mentioning.

(a) No general response attributable to overburden or host rock is seen even in the earliest channel in other parts of the profile. All anomalies exist in the specific anomaly zone only and hence general current gathering from host rock or overburden in a large area is unlikely. The early channel response in the anomalous area may arise mainly from localized overburden over generally depressed topography along the
ultrabasic rock unit and the main anomalous response may be due to vortex current in (Ch. 3 - Ch. 7) a mineralized ultrabasic or shear zone along the contact of ultrabasics with amphibolites.

(b) The early time anomaly may be caused by eddy current induction in large moderately conducting mineralized ultrabasics. This is followed by intermediate time channel anomaly which may be caused by eddy current induction in more conductive core (i.e. in shear zone).

(c) The observed early time anomalies are due to unidirectional currents flowing from conducting host to conducting overburden or disseminated mineralized zone (ultrabasics) and intermediate time channel anomalies are due to unidirectional current flow from conducting host to massive mineralized core.

For interpretation 'c' to be valid host rock must have resistivity of less than 200 ohm-m which does not appear to be very reasonable in this area. Interpretation (a) & (b) both presume the existence of a vortex current and are in agreement with our model fitting.
Fig. 5.14: Geometry of different sheet models (section along dip of the sheet) to fit all the observed profiles.
Fig. 5.15(a): Vertical section showing top of the interpreted conductor.

Fig. 5.15(b): Surface plan view of the interpreted conductor.
Fig. 5.16: Geological section as delineated from drill hole results along line 156E.
CHAPTER 6

COMPARATIVE STUDY OF DIFFERENT MULTIFREQUENCY
AND TIME DOMAIN EM SYSTEMS

6.1 Introduction

In the last few years several different, moderately wideband, time domain and multifrequency EM prospecting instruments have been developed in an effort to locate deeper conductors, to differentiate the response of mineralized bodies from that of unwanted conductors like overburden etc., and to better estimate the true conductance of the conductive zones. Although the general response characteristics for the HLEM and Turam systems (frequency domain) and the INPUT system (time domain) are well studied, relatively little quantitative data are available for surface time domain systems such as Crone PEM or UTEM. Quantitative studies of the response of different time domain and multifrequency systems to the same conductor are definitely not known. To make a comparative study of these systems, particularly to examine their depth sensitivity and their response to bodies of widely varying conductance, at various depths and with differing dip, five wideband EM systems have been studied. These are, in the frequency domain, the horizontal loop-loop EM (HLEM), the Turam system, and in the time domain, the UTEM system, the Crone Pulse EM (CPEM) and the INPUT system. These systems were described in section 3.5 and 3.6, where examples of thin sheet modelling were given.

The responses of all these systems were computed for a thin sheet of 600 m strike length and 300 m depth extent. Dip of the sheet was varied from 0 to 135° (0° horizontal sheet and 90° for a vertical sheet). Likewise, depth was varied from 60 m to 300 m in steps of 60 m. A few cases
were also studied for a sheet at 30 m depth. In the case of INPUT which is an airborne system, the response was computed for a sheet depth of 5 m, 65 m etc. with the increment in steps of 60 m up to a depth of 245 m. This was done for reasons of economy so as to use the same secondary coefficients in numerical computation as for other systems. The conductance of the sheet was varied from 5 mhos to 1000 mhos. This covers the range from resistive to the inductive limit for all the systems studied. In this study a total of 150 profiles were computed. It is impossible to reproduce all the profiles studied, in this thesis. They are reported separately in the University of Toronto EM research report no. 1. (Lodha and West - 76). Only a brief summary of the pertinent results from that study is discussed here.

Such a large sheet conductor (600 m × 300 m) acts approximately as a half plane model for moving source-receiver type systems like HLEM and CPEM, when small coil separations of 60 m to 90 m are employed. The effect of finite sheet size is visible in these systems when a large inter-coil separation is used, say 180 m as computed here. In the INPUT system, when this sheet is at a depth greater than about 60 m below normal ground level (i.e. 180 m below flying height) the effect of finite size would be visible. For large scale fixed source systems such as UTEM and Turam, all the data are computed for a transmitter loop with 600 m × 300 m sides. The top edge of the sheet conductor is located 300 m from the front edge of the loop. This conductor can certainly be considered large, but is still of finite size for such a large loop. All the responses were computed for a survey line which is symmetrically placed with respect to the sheet.
6.2 Anomaly shapes

Response of all the five systems for a vertical sheet at a depth of 60 m is shown in Figure 6.1. The UTEM anomaly profile shapes are very similar to the secondary field Turam loop response. The cross over indicates location of the sheet conductor in both cases. In the reduced ratio, phase difference format a peak is observed over the top of the body. The Crone PEM response for transmitter-receiver \((T_x-R_x)\) separation of 60 m is shown in Figure 6.1(e). Response for all channels (with proper amplification) is plotted at a linear scale for amplitude values up to ±10 ppm and in logarithmic scale for all higher amplitudes. The amplitude of all the anomalies varies with increase or decrease in depth of the vertical sheet, but the general shape of the profiles remain the same.

Shapes of the anomaly profiles change from this mostly symmetrical or antisymmetrical pattern for a vertical sheet to an asymmetrical shape for dipping sheets. The change in the shape depends upon the dip and depth of the sheet. However when the dip is 0° or 180°, corresponding to a horizontal sheet, some symmetry returns (except for INPUT anomalies). The anomaly shapes for the horizontal sheet are shown in Figure 6.2. The small undulations in quadrature or in-phase component in 6.2(b), (c) and (d) are probably due to limitations of the computational technique. For both UTEM and Turam (secondary field) the cross over of vertical sheet is replaced by a negative peak over the central part of the sheet. The edges of the sheet are represented by a change over to positive side lobes (Figure 6.2(a) and (b)). In the UTEM anomalies, the amplitude of the positive peak farther from the loop is larger due to the nature of the normalization technique used in this case. In the HLEM system the response is complicated and it varies from small central positive peak with two main negative side lobes.
Fig. 6.1: Response of UTEM, Turam (secondary field and amplitude phase format), Horizontal loop, Crone PEM and INPUT (65 m.) system to a vertical sheet at 60 m. depth, $\sigma_d = 50$ mhos.
Fig. 6.2: Response of UTEM, Turam (secondary field and amplitude phase format), Horizontal loop, Crone PEM and INPUT (65 m.) system to horizontal sheet at 60 m. depth, σd = 50 mhos.
for a 180 m coil separation to a single positive peak with small negative shoulders, for a 90 m coil separation (not shown here). In general the anomaly is positive if both coils are over the sheet and negative if one of the coils is not directly above the sheet. The Crone PEM response for a 60 m coil separation is mostly negative as opposed to the positive response for the vertical sheet. In the case of INPUT, the response has two peaks (Figure 6.2(f)); with the main peak over the approaching edge of the sheet, and followed by small second peak. Such anomalies are sometimes confusing in the field data, where they may give the impression of two vertical sheet conductors.

In general, the amplitude of responses of all the systems over a horizontal sheet are much greater than the corresponding anomaly amplitudes for a vertical sheet at the same depth. It is also evident with the examples of Figure 6.1 and 6.2 that all these systems respond very well to this sheet conductor at a depth of 60 m irrespective of its dip and can be considered among the group of deep penetrating EM systems.

6.3 Depth penetration

The response of all these systems for increasing depth of the vertical sheet conductor is discussed in this section. To compare detectability of various systems for this vertical sheet the following instrument sensitivity is taken into consideration. Depending upon the accuracy of survey grid and geological noise, the anomaly amplitudes of two or three times the instrument sensitivity may be recognizable in the actual field surveys.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crone PEM</td>
<td>±1 parts per thousand</td>
</tr>
<tr>
<td>2. Horizontal loop EM</td>
<td>±0.5% in inphase and quadrature components</td>
</tr>
<tr>
<td>3. INPUT system</td>
<td>±25 ppm</td>
</tr>
<tr>
<td>4. Turam system</td>
<td>±0.5% in computed inphase and quadrature components or 0.01 in reduced field strength ratios and 0.1° in phase difference</td>
</tr>
<tr>
<td>5. UTEM</td>
<td>±1%</td>
</tr>
</tbody>
</table>

The Crone pulse EM is a time domain equivalent of the HLEM system where the measurement sensitivity is much increased. Smaller coil separations may therefore be employed. Most Crone PEM surveys known to date have been done with coil spacing of less than 60 m, but higher power transmitters are being made and a larger separation will undoubtedly be used in future. The response of the 60 m system for a sheet at 120 m depth as shown in Figure 6.3(a) is hardly recognizable. However the anomaly would be recognized if surveys could be made with 90 m coil spacing (Figure 6.3(b)).

HLEM systems are now available (e.g. Apex, MAX MIN - II) where the transmitter-receiver separation can be conveniently increased up to 180 m or more. Response of the sheet at 120 m depth would hardly be recognized in survey conducted with 90 m coil separation (Figure 6.3(c)), but the response would definitely be recognized in survey with 180 m coil separation. Response for this sheet at 180 m depth when surveyed with a 180 m coil separation is shown in Figure 6.3(d). It appears the response is just recognizable even at this depth.

The response of INPUT system to a vertical sheet for two depths of 185 m and 245 m below ground level is shown in Figure 6.4(a) and (b). The response may be recognized in the first case of 185 m depth, however it may be difficult to predict a conductor on the basis of the response of
Fig. 6.3: Response of CPEM and HLEM system to a deep vertical plate (120 m. and 180 m.) at varying coil separation.
Fig. 6.4: Response of INPUT to a vertical sheet at 185 m. and 245 m. depth.
Fig. 6.5: Response of Turam and UTEM system to a deep vertical sheet.
Figure 6.4(b) for a depth of 245 m.

The Turam loop response for a sheet at 120 m depth in reduced ratio and phase difference format is shown in Figure 6.5(a). The distance between the two receiver coils in this case is 30 m. The response of the sheet at this depth is well recognized. The computed response for the same sheet at 180 m depth with same receiver coil separation of 30 m is hardly recognizable. However if the separation between two receiver coils can be increased to 60 m or 90 m in field surveys, the response would become measurable. The effect of increasing the distance between two receiver coils from 30 m to 60 m on response of the sheet of Figure 6.5(a) is shown in Figure 6.5(b). Clearly the amplitudes of the observed anomalies increases directly in proportion to the increase in coil spacing. It is therefore assumed that if the distance between receiver coils in the fixed loop Turam surveys is increased to 60 or 90 m, it may then be possible to detect the present vertical sheet up to a depth of 240 m. The computed data in the secondary field format for such a sheet at a depth of 240 m are shown in Figure 6.5(c). The anomalies are quite visible in this data presentation format even if they may be quite weak in reduced ratio format.

The UTEM profile for a vertical sheet at a depth of 300 m is shown in Figure 6.5(a). The inductive limit of the anomaly is about 9% and can definitely be recognized in a field survey.

6.4 Effect of conductivity

The response of all the systems was computed for a vertical sheet at 60 m depth (30 m in case of HLEM), the conductance of the sheet being varied from 5 mhos to 1000 mhos. The peak-to-peak anomaly amplitudes for each channel or frequency of each system are plotted in Figures 6.6 to 6.10 as a function of sheet conductance. Such a plot is here referred to as a
conductivity aperture diagram. It shows, for a given system, the range of conductivity in the model which gives an appreciable response.

6.4.1 UTEM

The conductivity aperture diagram for this system for absolute secondary field data is shown in Figure 6.6. All the aperture curves have a knee shape. Essentially, a very good conductor gives nearly the same response on all channels, but a poor conductor gives a response only on the higher number channels. The form is basically the same as for the in-phase response of Turam loop system shown in Figure 6.7. Because of the pattern of the channel sampling in UTEM, the aperture curves of the measuring channels are nearly the same, except for a lateral shift along the conductivity by a factor of two for each channel number. If the system function were a non-repetitive step rather than a periodic square wave, this would be exactly true. For poor conductor, the difference is entirely negligible, but for conductivity-thickness higher than about 100 mhos, the anomaly response on channel 1 is appreciable and the periodic nature of the transmitted signal must be taken into account.

Although the periodicity of the system function reduces the response for highly conductive bodies vis-a-vis that of a non-repetitive step, it does not cause it to vanish. In the limit of a perfect conductor, all the channels respond similarly, with the response amplitude one half that of the step response.

6.4.2 TURAM EM

The conductivity aperture diagram for the inphase and quadrature component of this system is shown in Figure 6.7. As in all frequency domain cases, the quadrature component curves have a hump form and inphase curves
have a gradually increasing response, reaching the inductive limit above 50 to 100 mhos. Curves for different frequencies are identical except for a horizontal translation. The similarity of the inphase curves to the UTEM aperture curves is marked, but there are quantitative differences. The knee is sharper but the ultimate slope is less steep in the frequency domain case. Nevertheless, a rough equivalence can be made between the two sets. Channel 6 of UTEM response for a base frequency of 30 Hz is roughly equivalent to the Turam inphase data at 300 Hz. The equivalent frequencies for channel 10 and 1 are thus approximately 4800 Hz and 10 Hz. However the notion of equivalence is not very reliable for channels 1 and 2.

6.4.3 Horizontal loop-loop EM

The conductivity aperture diagram for this system is shown in Figure 6.8. The diagram is prepared from the computed response for a vertical sheet at 30 m depth surveyed with a coil spacing of 180 m. The aperture diagram has the expected humped form for the quadrature anomaly and the knee form for the in phase. For comparison, the aperture curves for a half plane conductor are also plotted using data taken from Nair et al. (1968). One can see that this plate of 600 m x 300 m size behaves essentially as a half plane, except when it has a very low conductance.

The aperture diagram shows that at 222 Hz, a large plate of this size gives a response near the inductive limit when the conductance is over 100 mhos. It is also interesting to find that Turam at 200 Hz and 180 m HLEM at 222 Hz have nearly the same response aperture for this particular plate and present system dimensions.
6.4.4 Crone PEM

The aperture diagram derived for this system for a sheet at 60 m depth surveyed with 180 m coil separation is shown in Figure 6.9. However this can be scaled down for a sheet of 300 m x 150 m at 30 m depth surveyed with coil spacing of 90 m, or a sheet of 150 x 75 m at a depth of 15 m surveyed with a coil spacing of 45 m as shown by scales B and C in the figure. A study of this figure shows that the gain factors applied to the channel output (discussed in Chapter 3, Figure 3.9(a)) are designed to approximately equalize the maximum anomaly produced on any channel by a conductor of given geometry. The aperture curves have a humped form, somewhat similar to the quadrature response of frequency domain system, but with a broader top and steeper cut off slope. Direct comparison with the HLEM quadrature aperture curves for the same sized system shows that channel 1 of CPEM is very roughly comparable to a HLEM frequency of 500 Hz and channel 8 is comparable to about 15-20 Hz.

6.4.5 INPUT

There are many slight variants of the INPUT system. The version used here is a mark VI INPUT as flown by Questor Ltd. The aperture diagram for this system for a sheet at 65 m depth is shown in Figure 6.10. The diagram for sheet depth of 5 m is not shown here, but is nearly identical except that it is shifted up in amplitude by a factor of 60 and to higher conductivity thickness by a factor of 1.25. The peak of channel 1 anomaly is at 10,000 ppm and 15 mhos rather than 1700 ppm and at 12 mhos of the present diagram. The aperture diagram for a depth of 5 m corresponds well with the given by Palacky and West (73) for a half plane. The diagram shown here for sheet depth of 65 m has a slightly lower amplitude than Palacky and West's half plane model indicating that the finite extent of the plate has
**Fig. 6.6:** Conductivity Aperature diagram for UTEM system.

**Fig. 6.7:** Conductivity Aperature diagram for Turam system.
Fig. 6.8: Conductivity Aperature diagram for Horizontal loop EM system.

Fig. 6.9: Conductivity Aperature diagram for Crone PEM system.
Fig. 6.10: Conductivity Aperature diagram for INPUT system.
some influence in this case. This conductivity aperture diagram shows that the INPUT anomaly
of a very massive sulphide body whose conductance is over 400 mhos might be seriously attenuated. In real field situation this has not proved to be a great problem apparently because a halo zone of lower conductance is often present surrounding a massive ore body and the system will pick up the less conductive halo zone even if highly conducting core of the main conductor may not produce measurable response. However this limitation must be understood.

6.5 Conclusions

Comparative study of the response of various wideband EM systems to a 600 m x 300 m sheet model in free space can briefly be summarized as follows.

(1) The amplitude of the responses of all the systems to a horizontal sheet is much larger than that of a vertical sheet of the same size, conductivity and depth to the top. Put another way, a horizontal sheet like conductor can be detected up to a greater depth than a vertical conductor. Furthermore, the shape of the profile for most of the systems is simple and nearly symmetrical or antisymmetrical for a vertical or a horizontal sheet conductor. The response of a dipping sheet is usually a compromise between the vertical and horizontal cases. Thus, the nature of profile in most cases should give some indication of the direction of the dip and in some cases may help in determining amount of dip.

(2) The Crone Pulse EM system can detect this vertical sheet up to a maximum depth of about 100 m when using the presently available transmitter-receiver coil separation of 60 m. Facility to increase the coil separation up to 90 m or 120 m for this system may be quite useful in
increasing its present depth of penetration. It has not been mentioned before but it has to be realized that absolute amplitude of normalizing primary pulse reference in this system (defined as 1000 ppk) changes from station to station depending upon the response of the ground. As such any rigorous quantitative interpretation of the field data collected with this system needs some caution.

(3) As is well known, the horizontal loop-loop EM systems with the facility of increasing transmitter-receiver separation up to 180 m may be able to see a vertical sheet like body up to a depth of 150 m.

(4) The moving source-receiver INPUT system may, depending on the system noise level during the survey be able to detect the sheet like body up to a depth of about 200 m.

(5) In a fixed source Turam loop system where the field strength ratios and phase differences are presently measured with the receiver coils usually 30 m apart, the vertical sheet like conductor may be detected up to a depth of 150 m. However the facility to increase distance of the two receiver coils in field measurements to 60 m or 90 m could help in increasing the depth of detectability of such a vertical sheet conductor to 250 m or more.

(6) With the UTEM system the discussed vertical sheet may be located up to a depth of 300 m.

(7) All the wideband EM systems studied here have reasonably large conductivity width aperture (with the exception of INPUT system). They may be able to detect a sheet like conductive bodies of conductance varying from 2 mhos to 1000 mhos or above. However INPUT appears to have its upper range limited to about 400 mhos. This is mainly because of the higher base frequency of 144 Hz for this system.
7.1 Summary

In order to examine the validity or otherwise of simple free space uniform models in the interpretation of wide band EM data, an extensive study was made of three geological (mineralised) conductors embedded in resistive host rock of the Canadian Shield. The observed data were compared in detail with simple model data to see if a consistent match can be obtained. After making allowances for the geometrical complexities of even the simplest natural conductor, compared to any feasible interpretational model, it was found that most of the EM response at late delay times (corresponding to low frequency in frequency domain) can be explained in terms of vortex currents induced in the target conductor. Some of the early time delay response (corresponding to high frequency response in frequency domain), which cannot be explained by simple uniform models, was attributed to the effect of finite thickness and the presence of conducting halos around natural conductors. The results from the three test areas, namely Gertrude West, Gertrude and Pickle Lake, are summarized below.

7.1.1 Gertrude West

In this area the mineralised body is of small size (350' x 700') and the geometrical deviations of the conductor from the rectangular plate model shape are significant. The UTEM response on early channels does not follow the simple models. However, the late channel response conforms reasonably well to the model decay. The early channel
deviation is apparently due to conductive halo effects, and also some overburden effects. In spite of these complications a good match was obtained between the observed profiles and profiles computed using a finite thin sheet model. The geometrical shape of the computed model is close to the shape of the mineralised zone known from drilling. The conductance values of 1000 to 4000 mhos estimated from the UTEM data are reasonably consistent, and are in conformity with the extrapolated values of conductance obtained from multifrequency horizontal loop EM data. This leads one to believe that in spite of the irregular features of the real geological conductor (details of which are difficult to model individually), the induced currents are largely vortex currents confined within the mineralised zone. It appears possible in this case to separate out the various complicating phenomenon and apply a simple free space uniform model interpretation to the late time channel UTEM response.

7.1.2 Gertrude

Geometrically, the main anomalous UTEM response seems quite adequately explained by the free space finite thin sheet model. However, the pattern of observed decays is not. The anomalously gradual decay in the time range is interpreted to be due to diffusion of induced currents through a halo. Quantitative modelling of this phenomenon is not available except for a sphere model. It is, however, thought that this might be modeled, very roughly, by increasing the conductivity and decreasing the size of an appropriate uniform conductor model. This assumption has not been adequately tested, but is certainly not inconsistent with the experience here.
It appears that, in spite of the severe halo or finite thickness effects, and minor overburden and host rock effects present in the UTEM data, it is possible to judiciously use a simple uniform model and arrive at a reasonable interpretation of the causative body. It seems very likely that the induced currents producing the anomaly are mainly vortex currents which are largely confined to the core of the mineralized zone. The minimum estimated conductance of the massive core is 1000 to 3000 mhos. Since the data at the 15 Hz base frequency systematically gave a higher conductance than at the 30 Hz base frequency, it is certain that the 30 Hz, and possibly the 15 Hz, EM fields did not penetrate the innermost core which may therefore have a conductance higher than the estimated 1000 to 3000 mhos.

In this area the originally expected mineralised zone of size 1000' x 1800' is interpreted to be divided into two parts. The upper mineralised zone, of size 1000' x 900', extends from surface to a vertical depth of 600' reaching up to the southern contact of a vertical trap dyke. The lower mineralised zone, north of the dyke, is approximated by a 700' x 700' sheet. This lower zone is interpreted as having a conductance of 25 mhos.

7.1.3 Pickle Lake Area

It appears that the response of the UTEM system (like any other large scale system) is dominated by the large, moderately conducting conductor in this area. The response due to a small massive conductor located by vertical loop is visible on some profiles in late time channels, but it generally cannot be seen alone in the response due to the large moderate conductor. It would have been possible to
pick up a small massive conductor located by vertical loop, in preference to the large moderate conductor, if part of the survey had been repeated with a smaller loop.

In this area the interpreted conductor is so large that its true geological extent is not known. However, a reasonably good geometrical fit of the computed profiles to the observed profiles is possible under the assumption that the induced current is a vortex, restricted to the conductor. In view of the uncertainty of the geological model, fitting the theoretical profiles to the observed profiles can not be used to disprove the existence of undirectional current flow; however, the following observations are pertinent.

(a) All anomalies exist in the specific anomaly zone only. The response generally observed outside the anomaly zone is fairly smooth, even in the earliest channels, and hence current gathering from large areas of host rock or overburden is unlikely to occur in the anomaly zone.

(b) All the decay curves are bimodal, with the early channels 10 to 7 decaying faster than the intermediate channels 7 to 3. On some decay curves even slower decay is noticeable in Channels 3 to 1. This slower decay could be attributable to polarization effects.

(c) The faster decay of early time channels 10 to 7 may be attributed to current gathering in conductive overburden. Overburden may be present along the slightly depressed topography following the ultrabasics. The intermediate decay can then be explained as being due to the vortex current induced in the shear zone (partially mineralised) or in the ultrabasics with their disseminated mineralisation.
(d) The early part of the decay could alternatively be explained by short time constant currents in the disseminated sulphides within the ultrabasics. This is then followed by a long time constant intermediate decay produced by vortex currents induced in the massive part of the conductor (or the shear zone).

(e) The existence of unidirectional current gathering in disseminated poor conductors and the massive sulphide conductor would need country rocks with a resistivity of 200 ohm-m or less, and these are ruled out by the observations made in (a) above.

It thus appears possible, even in complex situations like this, to use simple uniform models to explain the observed anomalies.

7.2 Conclusions and Recommendations

(1) It is apparent from the results of the three field examples discussed above that the observed responses at intermediate or late times could be matched reasonably well with simple free space model responses, and the model parameters are consistent with the known geology. In all three cases the induced current system which corresponds to most of the time range studied is believed to be mainly a vortex current in the main conductor.

(2) The deviations of the observed response from the simple model response at early times are believed to be mainly due to the effect of the finite thickness of the conductive zones and to the presence of a halo of poorly conducting material around the main mineralised core.

The effect of finite thickness was not included in the computer model. The effect of varying conductivity was, however, examined in an approximate fashion by fitting different simple model decay
curves to different parts of the observed decay curve. Each larger characteristic time is believed to indicate the conductivity-thickness parameter of a smaller inner core. This observation has important implications for the use of simple uniform models in the interpretation of EM anomalies. It appears that natural conductors do not have a clear inductive limit to their response as do the simple models, and this makes the interpretation of size and geometry more difficult. It also means that conductivity or conductance estimates based on simple models can be erroneous (too low) unless the late stage of the time decay (or the low frequency, resistive range of the frequency response) is observed.

In practical terms this means that the interpretation of EM data collected with small scale moving source-receiver systems is not likely to be unique. Most of these systems "see" only part of the conductive body. The portion of the body responsive to the system gradually increases with lower frequency and/or larger coil separation, yielding interpretations based on data from a larger portion of the body. Interpretation of multifrequency horizontal loop EM data from Gertrude West area gives parameters which conform with this observation. On the other hand, for small or medium size conductors surveyed with large scale systems (as in the Sudbury area), the entire target body may be under the influence of a nearly uniform field. Under such circumstances, when the frequency is low enough for EM field to penetrate the entire body, reliable interpretation of conductance may be possible. Any further lowering of frequency would not change the conductance of the
body. Betz (76) has observed similar diffusion effects over other natural conductors in horizontal loop EM survey data. It was not possible to make extensive model studies for the halo effect during this research. Detailed quantitative studies of this effect by varying conductivity within the model for models of various shapes are still needed to enable better interpretation of wide band EM prospecting data.

(3) Some regional overburden or host rock effects are visible in the UTEM data from the Sudbury area, but a close examination of the profiles indicate that this is restricted to the early time channels 10 and 9 only. The data at later time channels are definitely free of this effect.

(4) In the Pickle Lake area the nature of profiles does not indicate any regional overburden or host rock effects. The early time decay of the anomalous zone (Ch. 10 to Ch. 7) could be interpreted as an enhancement of the anomaly due to current gathering in the localised overburden over low level topography along the ultrabasics. However, the presence of overburden could not be confirmed in survey during winter when the area was covered with 2-3 feet of snow. An alternative explanation of the enhancement of early time response due to diffusion effects caused by disseminated mineralisation within the ultrabasics is preferred.

(5) Strong vertical field magnetic anomalies up to 10000 γ are present in the Pickle Lake area. The magnetic anomalies are associated with the conductive zone. In the UTEM reduced data format the effect of high magnetic susceptibility on EM response is expected to be restricted to channel 1 response. Plot of channel 1 UTEM
anomaly corroborates well with the magnetic profile on most of the lines surveyed. In some places amplitude of channel 1 is not in proportion to the observed magnetic anomaly, but this could be due to remanence. However, the UTEM data on remaining channels appears to be free of this magnetic effect.

(6) Small scale moving source-receiver systems are economical for locating conductors up to a depth of 100 to 150 m. The top of the conductor determined by the shape of the profile is normally a good indication of its location. Increasing the size of the body at greater depths is no advantage for such systems. On the other hand, large conductors give a premium to large scale systems. When the difficulties of separating multiple responses are not very severe, conductors with lateral dimensions of several hundred meters can be detected at 200 to 300 m. depth. A rough rule of thumb for these systems is to characterize a target by three dimensions, (i.e. length, width, thickness). The body is generally quite detectable at a depth-to-top of from one-half to one times its mid-sized dimension.

(7) Large scale systems tend to magnify the response of moderately conductive large bodies compared to highly conductive small bodies (as in the Pickle Lake area). Sometimes, when the total response parameter or time constant of an extensive moderately conductive zone is larger than that of smaller massive conductors of particular interest, it may be difficult to detect the smaller conductors. Thus, while planning the survey and selecting the loop size, one has to keep in mind the approximate size of the massive conductor of interest as well as any other large scale regional conductors in the area.
A rectangular finite thin sheet model has been implemented to compute the response for any airborne, ground or bore hole EM system in the time or frequency domain. The present modeling procedure employs only fifteen eigen functions. The computed response for airborne and ground EM systems is reasonably close to the true response as long as the depth to the top of the finite sheet is greater than 0.1 times the strike length of the sheet. For bore hole EM systems the amplitude of the response will, in general, be underestimated if the sheet is too close to the drill hole, but the shape of the profile is expected to be reasonable.
APPENDIX I

EM Induction in a Thin Sheet; Annan’s Method

The salient features of Annan’s solution for the inductive response of the thin sheet which have been used in actual computations are given here. The geometry of the sheet conductor is shown in Fig. A1.1. Any primary EM field \((\mathbf{E}_0, \mathbf{H}_0)\) may cause a surface current to flow in the sheet. Assuming an insulating host medium and negligible displacement currents, the basic integral equation for the sheet current \(\mathbf{K}_s\) is

\[
\frac{\mathbf{K}_s}{\sigma_s} - i\omega \mu_0 \int_\mathcal{A} \mathbf{K}_s(r') g(r, r') d^2 r' = \mathbf{E}_{0,2}
\]

with the constraints that

\[\mathbf{K}_s \cdot \mathbf{n} = 0 \quad \text{and} \quad \nabla \cdot \mathbf{K}_s = 0\]

i.e. \(\mathbf{K}_s\) is solenoidal and does not cross the boundaries of the sheet.

In the above equation:

- \(\sigma_s\) = surface sheet conductivity
- \(\omega\) = frequency of excitation (time variation \(\exp(-i\omega t)\))
- \(\mu_0\) = magnetic permeability of the sheet
- \(g(r, r')\) = green’s function = \(\frac{1}{4\pi |r-r'|}\)
- \(\mathbf{E}_{0,2}\) = primary electric field in the \(x_1, x_2\) plane

Since \(\mathbf{K}_s\) is a vector which lies in the plane of the sheet and \(\nabla \cdot \mathbf{K}_s = 0\), \(\mathbf{K}_s\) may be more conveniently expressed in terms of a scalar potential \(\mathbf{u}\) where

\[
\mathbf{K}_s = \nabla \times \mathbf{u} \hat{\mathbf{e}}_3 = -\hat{\mathbf{e}}_3 \times \nabla \mathbf{u}
\]
Fig. A1-1: Schematic diagram of the sheet parameters and coordinate system as used by Annan (74)
The condition \( \overline{K_s} \cdot \hat{n} = 0 \) constrains 'u' to be identically zero on the edge of the sheet.

Annan uses the Galerkin approach to reduce equation A1-1 to a matrix equation suitable for numerical solution. To do this he expands the current potential 'u' as a series of "trial" functions in the form

\[
u = \sum_{nm} C_{nm} \phi_{nm}\]

where \( n+m \leq N \) (N being the maximum polynomial degree of the approximate solution).

In matrix notation this can be written as

\[
u = [\phi][C]\]  \hspace{1cm} \text{A1-2}

where

\[\phi = [\phi_{00}, \phi_{10}, \phi_{01}, \phi_{20}, \phi_{11}, \ldots, \phi_{ON}]\]

The "trial" function chosen is such that \( \phi_{nm} \) is a Chebyshev polynomial \( T_n(\xi) \) and \( T_m(\eta) \) of the first kind and of order \( n \) and \( m \) respectively.

i.e.

\[
\phi_{nm} = (1-\xi^2)(1-\eta^2)T_n(\xi)T_m(\eta)
\]

where

\[
\xi = \frac{x_1}{a_1} = \frac{x_1}{A}
\]

and

\[
\eta = \frac{x_2}{a_2} = \frac{x_2}{AR}
\]

In the equation A1-2 above, \([C]\) is a column vector of the same order as \([\phi]\) and is yet to be determined. By use of the Galerkin method equation A1-1 above reduces to a matrix equation of the form

\[
\left\{ \frac{1}{\sigma_s} [F] - i\omega \mu A^2 [\gamma] \right\} [C] = -i\omega \mu A[H]
\]  \hspace{1cm} \text{A1-3}

In the equation A1-3 above, \([F]\), \([\gamma]\) and \([H]\) are given by:
\[
[F] = \int_{a_1}^{a_2} \int_{a_1}^{a_2} \{ \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_1} \right]^T \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_1} \right] + \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_2} \right]^T \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_2} \right] \} \, dx_1 \, dx_2 \quad \text{A1-4}
\]

\[
[y] = \frac{1}{4a_1a_2} \int_{a_1}^{a_2} \int_{a_1}^{a_2} \int_{a_1}^{a_2} \int_{a_1}^{a_2} g(x, x_1', x_2', x_2') \left\{ \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_1} \right]^T \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_1} \right] \right. + \left. \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_2} \right]^T \left[ \frac{\partial \phi(x_1, x_2)}{\partial x_2} \right] \right\} \, dx_1 \, dx_2 \, dx_1' \, dx_2' \quad \text{A1-5}
\]

\[
[H] = \frac{1}{2a_1} \int_{a_1}^{a_2} \left[ \phi(x_1, x_2) \right]^T H_{03}(x_1, x_2) \, dx_1 \, dx_2 \quad \text{A1-6}
\]

[y] and [F] are both real and symmetric matrices.

Since the trial functions $\phi_{nm}$ are all known, and only the coefficients $C_{nm}$ are unknown, the left hand side of A1-3 may be written as an operator acting on $C$. We thus have

\[
[Z][C] = -i\omega \mu A[H] \quad \text{A1-7}
\]

where

\[
[Z] = [R] + i[X] \quad \text{A1-8}
\]

and

\[
[R] = \frac{1}{\alpha} [F] \quad \text{A1-9}
\]

and

\[
[X] = -i\omega \mu \alpha A^2 [\gamma] \quad \text{A1-10}
\]

A solution to A1-7 is sought in the form of an eigen function expansion for [C]. However, the matrix [Z] cannot be diagonalized directly.

By a rather complicated manipulation, the solution of equation A1-3 or A1-7 above for the so far unknown column vector [C] is found to be the following sequence of equations. The various terms introduced in solution A1-11(a), A1-11(b) are defined in A1-14 to A1-16.
(a) For a frequency domain exciting source
\[
[C] = [C_n][D\left(-\frac{i\alpha}{1+i\alpha RX_n}\right)][C_n]^T[H]
\]
A1-11(a)

(b) For time domain impulse source
\[
[C] = [C_n][D\left(-\frac{1}{RX_n}\frac{e^{-t/\tau_n}}{\tau_n}\right)][C_n]^T[H]
\]
A1-11(b)

where \( \alpha = \omega \beta = \omega \mu \sigma_A \)
A1-12(a)

\( \tau_n = B RX_n = \mu \sigma_A RX_n \)
A1-12(b)

For brevity in discussion the matrices connected with the response parameter in A1-11(a) and (b) are sometimes referred as \([D(\omega)]\) or \([D(t)]\)
such that
\[
[D(\omega)] = [D\left(-\frac{i\alpha}{1+i\alpha RX_n}\right)]
\]
A1-13(a)

\[
[D(t)] = [D\left(-\frac{1}{RX_n}\frac{e^{-t/\tau_n}}{\tau_n}\right)]
\]
A1-13(b)

The matrix \([C_n]\) is defined as
\[
[C_n] = [v][D^{-\frac{1}{2}}(f_i)][C_n']
\]
A1-14(a)

and \([C_n']\) is defined as
\[
[X'][C_n'] = x_n[C_n']
\]
A1-14(b)

in which \( x_n \) are eigen value of \([X']\) and \([C_n']\) are eigen vectors corresponding to each value of \( x_n \). \( x_n \) and \([C_n']\) are both real because \([X']\) is a real symmetric matrix defined as
\[
[X'] = [D^{-\frac{1}{2}}(f_i)][v]^T[X][v][D^{-\frac{1}{2}}(f_i)]
\]
A1-15

In A1-14 and A1-15 above, \([D(f_i)]\) & \([v]\) have the property
\[
[v]^T[F][v] = [D(f_i)]
\]
A1-16
\([v]\) being the unitary matrix composed of the normalized eigen vectors of \([F]\), and \([D(f_i)]\) being a diagonal matrix containing the eigen values of \([F]\). Since \([F]\) is real, \(f_i\) are real and positive and \([v]\) is real.

To compute \([C_n']\) (referred to as the eigen potentials by Annan), it is necessary to find first \([v]\) and \([D(f_i)]\) from \([F]\), then apply these results to \([X]\) to find \([X']\) and then \([C_n']\) and \(x_n'\). Finally, the matrix \([C_n]\) may be formed from which the required solutions may be calculated.

Annan has written programmes to do the integrations involved in forming the matrices \([F]\) and \([\gamma]\). In order to use them, one has to first define \(R\) (width to length ratio of the sheet i.e. \(a_2/a_1\)) and \(N\) (maximum polynomial degree in expansion, which was taken as 4). The numerical integrations are of the form

\[
\left\{\int_{-1}^{1} \int_{-1}^{1} \int_{-1}^{1} \phi_{nm}(\xi, \eta), g(\xi, \xi', \eta, \eta') \phi_{pq}(\xi', \eta') d\xi d\eta d\xi' d\eta' \right\}
\tag{A1-17}
\]

and

\[
\left\{\int_{-1}^{1} \phi_{nm}(\xi, \eta) \phi_{pq}(\xi, \eta) d\xi d\eta \right\}
\tag{A1-18}
\]

which require definition of the \(x\) & \(y\) (\(\xi, \eta\)) and \(x', y'(\xi', \eta')\) points. Four values were taken for each of the former and 23 values for each of the latter. Integrals of the type A1-17 are evaluated numerically using a Gaussian quadrature scheme. Numerical integration for polynomials up to a degree of four (4) gives values of the integral correct to \(\pm 1.5\%\) of the true value. Integrals of the form A1-18 are evaluated analytically. The integral coefficients are calculated by Annan's main programme 1, and are stored on disc as data for future use. Main programme 2 calculates the matrix \([F]\) utilizing the following property of Chebychev polynomial.
\[ \frac{d}{dx} (1-x^2) T_n(x) = -nx T_n(x) + n T_{n-1}(x) \]  \hspace{1cm} \text{Al-19} \\

Eigen values and corresponding eigen vectors of the matrix \([F]\) from which the diagonal matrix \([D(f_i)]\) and unitary matrix \([v]\) are generated are also stored as data on disc.

Main programme 3 reads back the stored integral coefficients and eigen vectors of \([F]\) and generates the matrix \([\gamma]\) from which the matrices \([X]\) & \([X']\) are generated. After formation of \([X']\), its eigen values \(x_n\) and corresponding eigen vectors \(C'_n\) are calculated. Once \(C'_n\), \([D(f_i)]\) and \([v]\) are known the eigen potential matrix \([C_n]\) is computed using Al-14(a). The term \(X_n\) and \(C_n\) of Al-14 are referred to as \textit{eigen values} and \textit{eigen potentials} for the sheet respectively and are stored as data on disc for use by the main modelling programme. The values of \(X_n\) & \(C_n\) depend only on the sheet width-to-length ratio 'R' and on 'N' (maximum polynomial degree of expansion used in numerical integration). For values of \(N = 4\) used here \(X_n\) has 15 values and \(C_n\) correspondingly has 225 (15x15) values. The eigen values & eigen potentials are independent of size of the sheet.

Each individual eigen potential responds in the same manner as a simple loop conductor. The total solution can be viewed as the sum over a set of loop responses (with no interaction between loops) with the loops having differing inductance to resistance ratios. The current flowing in a loop in uniform \(H\) field normal to the loop has the form

\[ I(\omega) = \frac{-i\omega H\times \text{(Area)}}{R_L - i\omega L_L} \]  \hspace{1cm} \text{Al-20} \\

where \(R_L\) and \(L_L\) are the self resistance and self inductance of the loop. The analogy between Al-20 and the terms of the diagonal matrix \([D(\omega)]\) or \([D(t)]\) in Al-11 is apparent. The eigen values \(X_n\) are just the \(L/R\) ratios of the individual
eigen potentials. The solution for the eigen potential for a given geometry, therefore yields the total frequency and/or time (transient) response in one operation.

The formal solution of the EM induction in a thin sheet is complete at this stage within the limitation that \((N+1)(N+2)/2\) eigen functions (eigen values & eigen potentials) of maximum polynomial degree \(N (= 4\) in present study) can characterize a system having infinite sequence of eigen functions.

These eigen functions can be used to express the response of the sheet to any arbitrary excitation source. For a Turam loop source the primary magnetic field at any point on the sheet due to a one ampere current in the loop is given by the Biot-Savart law

\[
\mathbf{H}(r) = \sum_{i=1}^{3} \int \frac{(x_{i}-x_{i}')\hat{e}_{i} \times d\ell}{4\pi R}
\]

The same for a point magnetic dipole is calculated by the relation:

\[
\mathbf{H}(r) = \nabla \cdot \int \frac{\mathbf{m}}{4\pi R} \, dv = \nabla (\mathbf{m} \cdot \nabla) \left( \frac{1}{4\pi R} \right),
\]

where \(\mathbf{m} = \sigma(r)\mathbf{m}\) amp-\(m^2/\text{m}^3\)

This magnetic field generated by the source over the sheet in combination with eigen functions is expressed as excitation coefficients \([H]\) for the source. The integral coefficients for the source field are calculated using the same gaussian quadrature algorithm as those used to evaluate Al-17.

The final step in the analysis is the computation of the anomalous magnetic field \(H_s(r)\) at the desired observation point due to the induced currents \(\mathbf{K}_1\) in the sheet which are given by
\[ \bar{H}_s(r) = \{ -[\phi]\delta(x^i_3)\hat{e}_3 - \sum_{i=1}^{3} [H^i_s]\hat{e}_i \} \{ C \} \]  

where 

\[ [H^i_s] = [H^i_{00}(r), H^i_{10}(r), H^i_{01}(r), H^i_{20}(r), \ldots, H^i_{0N}(r)] \]  

and 

\[ H^i_{nm}(r) = \frac{2}{a_1 a_3} \int_{-a_1}^{a_1} \int_{-a_2}^{a_2} \frac{\phi_{nm}(x'_1, x'_2)}{4\pi R} \, dx'_1, dx'_2 \]  

To calculate \([H^i_s]\) (called the secondary coefficients) the integrals in A1-25 are evaluated in the same manner as the excitation coefficients. Equation A1-11 yields the solution for the equivalent surface current \( \bar{K}_i \) (eigen currents) in the sheet as a function of \( \alpha \) in frequency or \( \beta \) in time domain. Thus combining A1-24 with A1-11 as at A1-23 gives the secondary magnetic field at a desired point due to currents induced in the thin sheet by a known source in either the time or frequency domain.
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