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A METHOD FOR QUANTITATIVE INTERPRETATION
OF WIDEBAND, DRILL-HOLE EM SURVEYS
IN MINERAL EXPLORATION

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A Thesis submitted in conformity with the requirements
for the Degree of Doctor of Philosophy in the
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Dedicated to the memory of my Father
TABLE OF CONTENTS

ABSTRACT..................................................................................vi

ACKNOWLEDGEMENTS...............................................................viii

1 INTRODUCTION

1.1 EM and base-metal exploration.................................1
1.2 Borehole geophysics background.............................5
1.3 Statement of thesis problem.....................................7
1.4 Approach to problem
    and organization of thesis.................................10

2 PRELIMINARY INVESTIGATIONS

2.1 Literature review.........................................................13
2.2 The test program.......................................................17
2.3 Results of the test program......................................18

3 EM FIELD PROGRAM

3.1 Description...............................................................25
3.2 Survey equipment....................................................27
    3.2.1 Pulse EM
    3.2.2 Step-response EM
    3.2.3 Frequency-domain EM
3.3 Test sites - geology and EM data..............34
  3.3.1 GERTrude
  3.3.2 Gertrude West
  3.3.3 POWder MAGazine
  3.3.4 Falconbridge Copper 266
3.4 Summary........................................56

4 ELECTROMAGNETIC MODELLING
  4.1 Introduction.................................59
  4.2 Suitability of plate and sphere models.......61
  4.3 Theoretical considerations...................63
    4.3.1 Plate
    4.3.2 Sphere
    4.3.3 Eigencurrent analysis
    4.3.4 Determination of direction
  4.4 Convolution with practical waveforms..........82
  4.5 Computer programs PLATE and SPHERE..........83
    4.5.1 Description of computer programs
    4.5.2 Computational precision: PLATE
    4.5.3 Computational precision: SPHERE
  4.6 Scale modelling..............................89
  4.7 Hybrid computer model
    - interaction with a simple loop..............90
5 INTERPRETATION WITH SIMPLE MODELS
   5.1 Introduction...........................................93
   5.2 Static effects of target geometry..................94
   5.3 Dynamic effects of eddy-current behaviour...104
   5.4 Range of investigation...............................115
   5.5 Rate of decay........................................117
   5.6 Modelling of UTEM and multifrequency EM.......121
   5.7 Interference between target conductors
       and powerlines.....................................125
   5.8 Modelling of intersections..........................128
   5.9 Exploration example................................128

6 SPECIALIZED MODELS
   6.1 Description..........................................132
   6.2 Block conductors....................................133
   6.3 Multiple plates.....................................139

7 TRANSVERSE MAGNETIC COMPONENTS
   7.1 Problems.............................................146
   7.2 Benefits..............................................148

8 CONCLUSIONS
   8.1 Achievement of objectives..........................158
   8.2 Summary of test sites...............................161
       8.2.1 GERTrude
       8.2.2 Gertrude West
       8.2.3 POWder MAGazine
       8.2.4 Falconbridge Copper 266
8.3 Future research and development............163

REFERENCES.........................................................165

APPENDIX A INTEGRAL EQUATION SOLUTION FOR EM INDUCTION IN A THIN PLATE

APPENDIX B EM INDUCTION IN A CONDUCTING, PERMEABLE, TWO-LAYER SPHERE

APPENDIX C CONVOLUTION OF EM RESPONSE WITH PRACTICAL WAVEFORMS; COMPUTER PROGRAMS

APPENDIX D WAVEFORM SPECIFICATIONS OF DRILL-HOLE EM PROSPECTING SYSTEMS

APPENDIX E SCALE-MODEL FACILITY
Drill-hole geophysical surveys are an obvious means of extending the search for massive-sulphide deposits to depths which are inaccessible to conventional surface exploration techniques. The present investigation combines field and model studies of an EM prospecting method which utilizes a large, fixed transmitter loop with a downhole axial-component magnetic field sensor. Such a system is shown to be well suited to the task of detecting deeply buried massive-sulphide conductors located in resistive host rocks at appreciable distances from the drill hole. The thesis proposes a technique whereby drill hole survey data collected with a wideband large-loop EM system can be routinely interpreted on a quantitative basis. Systems using impulse-like, step-function or frequency-domain waveforms are considered.

The interpretation technique is based on forward EM modelling using two simple conductor shapes: a thin, rectangular plate and a two-layer sphere. The analysis is facilitated by "eigencurrent" decomposition of the induced current vortex into a set of non-interacting loops with simple RL-circuit behaviour. The solutions have been implemented in interactive computer programs which are fast, inexpensive and sufficiently versatile to accommodate the configurations and waveforms used in many practical EM systems.

The diffusive nature of the inductive process dictates
that both stationary (spatially dependent) and dynamic (time or frequency dependent) properties are important in the diagnosis of three-dimensional targets. Model fitting using the stationary characteristics of the anomaly profile allows a first estimate of target parameters such as location, shape and attitude. Direction to the conductor may be difficult to determine unambiguously. The dynamic properties of the eddy currents, which may be observed with particular sensitivity near null points in the anomaly profile, are a useful basis for refining the interpretation. As shown by scale-model experiments, the dynamic aspects of the response are affected by departures from the simple models. Mineralization which is significantly thicker away from the drill hole may reveal itself in field observations through such effects.

Field studies carried out at test sites in the Sudbury and Noranda base-metal mining areas near known deposits indicate that many of the important effects predicted by the model studies are, indeed, observed in nature. The results presented in the thesis are intended to serve as guidelines during the model-fitting process and to help exploit the inherent advantages of the large-loop EM method. It is recommended that computer modelling be applied both at the design and at the interpretation stages of a survey. Simulation of a three-component system suggests that such measurements would be a significant improvement, as the two transverse components can help resolve ambiguities in the location of the target.
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CHAPTER 1

INTRODUCTION

1.1 EM and base-metal exploration

Electromagnetic (EM) induction has many applications, but the element of economically significant discovery makes the search for base-metal orebodies one of the most intriguing. Of the EM properties of geological materials, specifically conductivity, permittivity, and permeability, the most variable is conductivity. It ranges over more than 8 decades in value (see Figure 1-1). Crystalline rocks of the Precambrian shield, for example, are extremely resistive \((10^{-5} - 10^{-3} \text{ S/m})\). The mineral grains themselves are insulators, and the conductivity is controlled by electrolytic conduction in minor fluid-filled cracks and pores (< 1% porosity). Base-metal ore deposits, on the other hand, often possess conductivity values near the top of the range by virtue of electronic transport in massive concentrations of metallic sulphide minerals such as pyrrhotite, pyrite, chalcopyrite, galena, and pentlandite \((10 - 10^3 \text{ S/m})\). Sphalerite is a notable exception. For thirty years, EM prospecting techniques have successfully exploited the anomalously high conductivity to locate many massive-sulphide bodies in Precambrian host rocks.
Fig. 1-1 Geoelectric model for massive-sulphide exploration using drill-hole EM.
Eddy currents are induced in target conductors which are favourably situated in a time-varying magnetic field \( \mathbf{H} \). Most prospecting techniques use an artificial inductive source, i.e. time-varying current flowing in a loop of wire, known as the transmitter. A primary electric field \( \mathbf{E} \) exists everywhere according to Maxwell's expression of Faraday's Law:

\[
\text{curl} \mathbf{E} = -\frac{dB}{dt},
\]

where \( B = \mu H \) is the magnetic flux density, \( \mu \) is the magnetic permeability, and all field quantities are implicit vector functions of spatial coordinates and time. Impressed upon a medium of sufficiently high conductivity \( (\sigma) \), \( \mathbf{E} \) will cause significant current to flow (eddy currents) as determined by Ohm's Law:

\[
\mathbf{J} = \sigma \mathbf{E}.
\]

The eddy currents contribute to the magnetic field. Conventionally \( \mathbf{H} \) is divided into a primary component due to the current in the transmitter and a secondary component due to the currents in the ground. The relationship between the secondary fields and the currents is expressed by Ampere's Law:

\[
\text{curl} \mathbf{H} = \mathbf{J} + (d\mathbf{D}/dt)
\]

where the second term, due to displacement currents, has negligible magnetic contribution at the low frequencies usually employed. Secondary magnetic fields, detected by the EM system's receiver as anomalous values, are usually plotted as profiles of anomalous field versus position of
the detection system. It is from these profiles that the conductor's presence is usually inferred.

As Figure 1-1 illustrates, EM prospecting may be greatly complicated in practice by a multiplicity of conductors, both of economic and non-economic interest. Much current research effort is directed towards improving the resolving capabilities of EM methods for the kinds of complex conductivity distributions that occur in exploration. The recent trend in commercial EM instrumentation is to provide wideband systems. These take advantage of the diffusive nature of magnetic and electric fields in the low-frequency or quasistatic approximation to provide more information. The sales of wideband systems demonstrate the exploration industry's acceptance of this improvement.

Quantitative interpretation of field data is normally accomplished through forward modelling, whereby the EM system's response to conductors of simple shape is determined. Model responses are obtained via scaled laboratory experiments or mathematically; the latter involves solution of the partial differential diffusion equation:

\[ \nabla^2 \mathbf{H} = \sigma \mu \frac{d\mathbf{H}}{dt}, \]

subject to boundary conditions which specify the continuity of the tangential components of \( \mathbf{E} \) and \( \mathbf{H} \) and the normal component of \( \mathbf{J} \) at the conductor's surface. While such models may sometimes seem geologically unrealistic, the gross
characteristics of field survey anomalies are often reproducible with sufficient fidelity to satisfy the explorationist's requirements for target diagnosis. Furthermore, simple models can often supply physically satisfactory explanations of the important aspects of the induction process in geological conductors.

1.2 Borehole geophysics background

Borehole geophysical methods have for many years found extensive use in oil-well logging, the main goal being subsurface geological mapping by means of techniques which are sensitive to physical properties of the rocks in the immediate vicinity of the drill hole. However, in the exploration for metalliferous minerals, borehole methods are more often directed to "third-dimension" prospecting where the aim is to detect deposits which are not intersected by the hole.

Routine application of drill-hole geophysical methods seems potentially capable of extending the search for base-metal deposits to greater depths, a necessary process as fewer near-surface bodies remain undiscovered. An effective geophysical procedure would surely improve the return on exploration drilling expenditures. However, drill-hole geophysical techniques have not kept pace in development with their surface counterparts; the latter have been undergoing steady improvement in exploration depth, as documented recently by Seigel (1979), and Ward (1979). The
disparity in development rates can perhaps be attributed to minimal demand, but certainly one must also lay blame on the lack of suitable techniques, poor reliability of equipment, and uncertainty in final results due to lack of interpretational aids. Any examination of the problem should obviously address itself to these factors. Accordingly, a research program was undertaken in 1974 by the Geological Survey of Canada (GSC), having been stimulated by potential users in the Canadian mining industry.

In 1975 Dyck et al. reviewed the state of the art as reported in the literature. They described a number of test cases which were at least technical successes. This indicated that drill-hole electrical techniques were indeed promising methods, although a clear lack of interpretational material made it difficult to assess which target parameters could be reliably determined by the various types of survey.

But while the literature was encouraging, it was apparent that geophysical prospecting in drill holes was anything but routine. Why? An empirical test program involving several Canadian mining companies was organized by the GSC and carried out by the author (Dyck, 1975a). The test program was designed to test commercially available equipment and to answer the following questions: firstly, which technique would be most effective under a given set of circumstances; and secondly, what are the real, practical problems which could be encountered in drill-hole surveys? The emphasis was placed on exploration for massive sulphides
in Precambrian terrain. The results of the test program clearly focussed attention on EM methods using a large transmitter loop and a drill-hole receiver (large-loop EM system). The ability of this method to detect large, distant massive-sulphide deposits in the presence of conductive but uninteresting minor mineralization along the drill hole, coupled with the unsophisticated instrumentation requirements, were paramount factors in reaching this conclusion (see Chapter 2 for supporting evidence).

It was clear from the test program that reliable, improved equipment was a necessity if the large-loop method was to gain acceptance by the exploration industry. The equipment which was subsequently produced inspired a further program of field tests with very promising results. The detection ability of the method was obviously excellent; it was also clear that the method required a comprehensive interpretation scheme.

1.3 Statement of thesis problem

The main goal of the thesis is to provide a means of routine interpretation of drill-hole EM surveys performed for the purpose of massive-sulphide exploration in Precambrian terrain with equipment consisting of a large transmitter loop and a downhole solenoid sensor. The research problem is one of determining how most effective use can be made of the method's inherent advantages and how best to overcome the disadvantages. The "hardnosed"
economics of mineral exploration demand that interpretation be straightforward yet sufficiently quantitative to permit specification of additional drilling with a fair degree of confidence.

It is reasonable to assume that routine application of drill-hole geophysics is more likely to happen first in a mining-camp, an environment which might be characterized as a volume of rock very favourable for exploration and thus punctured by numerous drill holes. Closer examination of the geoelectric section (Figure 1-1) will elucidate the research problem in the context of a typical base-metal mining camp. The target may be buried at a large depth (D) which is beyond the exploration range of a conventional surface survey. But the critical distance for the success of a drill-hole survey is clearance (C), the lateral displacement from the hole. What is required of a surface transmitter is that sufficient primary field be available at the target.

The main unknowns are, of course, the target conductor's geometric, positional and electrical parameters. It the task of the EM system and subsequent data interpretation to furnish estimates of these parameters. It is apparent that simple detection of a target is not sufficient and that more quantitative information is required from the survey. The measurement data set itself may contain unknowns, such as true probe position and orientation. An additional complication arises when an interpretation must be based on one profile alone or, worse
still, a portion thereof, when the drill hole is blocked or has been terminated without passing fully through the zone of interest. Only rarely does sufficient observational data exist as to allow independent estimates of many target parameters, unlike the situation in a surface survey where strike length and strike direction of a target can be determined from a succession of parallel profiles.

It is worthwhile defining a geological signal-to-noise ratio \((S/N)\) specific to the drill-hole problem. Referring to Figure 1-1 geological signal \((S)\) is the secondary-field signature of the deep target orebody. Geological noise \((N)\) combines the responses of all other natural conductors in the vicinity and, as shown by the empirical test program, may be an overwhelming factor. Geological noise may result from graphitic rocks (not shown), minor sulphide stringers, other mineral deposits known from detailed drilling or mining (represented in the diagram as the "shallow target"), and mineralized horizons along which the deep target is likely to occur. In many sulphide mining camps extensive mineralized horizons typically less than 1 m thick but quite conductive may be the most important geological noise source. Deep drilling in a mining camp is usually directed at a specific favourable geological horizon (eg. the norite contact in the Sudbury basin) and if appreciably mineralized these horizons are conductors of geometry which is similar to that of the target. Conductive overburden may distort the primary field a measurable amount but its contribution to
geological noise is less troublesome because of the distance separating it from the target conductor.

1.4 Approach to problem and organization of thesis

One of the main contributions reported here is the development of flexible computer routines for forward modelling of drill-hole EM surveys. The programs were designed to be operated interactively and inexpensively, thus placing the user at liberty to "play" with the models. Basic algorithms for modelling induction in a finite, rectangular, thin plate (Annan, 1974) and a two-layer sphere (Nabighian, 1971), both situated in free space, were chosen for the purpose.

Improved instrumentation was essential in acquiring a high quality set of field data for the research. While not a subject of this thesis, instrumentation developed subsequently to the Geological Survey test program is responsible for most of the field data presented herein. The main emphasis has been placed on the Pulse EM system manufactured by Crone Geophysics Limited. However, to investigate how the results apply in general to wideband systems employing the same geometry, two other waveforms have also been studied, the step response (UTEM, Lamontagne, 1975) and the continuous wave frequency-domain response (Scintrex Limited DHEM system).

An invaluable ingredient in the research program was access to suitable test sites, a number of which have been
established throughout the course of this work. Very few mineral deposits meet the criteria for a good test site. An ideal test drill hole is a "near miss" of a massive-sulphide orebody known in detail from other drilling. Furthermore, to be of use in continuing research, the longevity of the site must be assured, which is more likely if the body is subeconomic. There is always a danger of drill-hole cave-in but this is less of a problem in the relatively competent crystalline rocks of the Precambrian shield. Obviously the usefulness of a site also depends on the generosity of property owners in providing continued access and in releasing a certain amount of geologic information.

Organization of the thesis reflects the various chronological stages through which the research has progressed. Chapter 2 describes the important results from the literature review and empirical test program which led to definition of the research program. Chapter 3 outlines the field-oriented portion of the program. Survey data is introduced at this stage to give the reader some experience with the nature of the field observations. This is an important step in that a general body of published data and experience is, unlike for surface EM, not available for drill-hole surveys.

The computer models, PLATE and SPHERE, are developed in Chapter 4. Chapter 5 is concerned with application of the computer models to drill-hole EM interpretation and development of intuitive feeling for the subtleties of the
interpretation process. Simple models are considered more appropriate for this purpose than completely arbitrary three-dimensional models, at least at the outset. However, some inadequacies of the simple interpretation models have been investigated in Chapter 6 by examination of responses due to specialized models obtained by scale-model experiments.

It is hoped that in the next generation of drill-hole EM systems the single-component axial sensor will be replaced with a three-component device. Chapter 7 has thus been devoted to showing how this improvement will enhance the power of the method.

No attempt has been made to arrive at an exhaustive analysis of any one field survey; however, the results which are presented here will hopefully provide the basis for more routine quantitative interpretation.

For ease of reference, information on the technical details of the problem such as formal theoretical solutions, computer programs, instrumentation, etc., are given in Appendices.
CHAPTER 2

PRELIMINARY INVESTIGATIONS

2.1 Literature review

A thorough review of the literature carried out by Dyck et al. (1975) shows that most of the available publications described unique applications of a particular method; few of the cases were of a sufficiently general nature to form the basis for routine application. The highlights of the review are presented here. Seismic, electrical, gravimetric, nuclear, thermal, and directional surveying (path of borehole) methods were discussed in terms of relevance to prospecting for and evaluation of metalliferous mineral deposits. With the exception of electrical and magnetic methods, the various techniques have seen very limited use.

Drill-hole magnetic measurements have been used mainly in iron-ore prospecting for both remote detection via magnetic field intensity and in situ assay by magnetic susceptibility (Hood and Dyck, 1975). Electrical methods have seen the greatest use in drill-hole geophysical prospecting for base-metal deposits (Dyck, 1975b) which is not surprising considering that electrical surveys (airborne and ground) are a prime surface exploration tool. In fact, success has often been achieved by downhole adaptation of a
surface method, usually with some modification of system geometry and/or procedure imposed by the additional constraints of the drill hole.

The common electrical methods including electromagnetic (EM), resistivity and induced polarization (IP) profiling, and mise-a-la-masse techniques are shown schematically in Figure 2-1. They can be loosely grouped into two categories. In one category, all active elements are confined to the borehole, for example, a dipole-dipole EM with transmitter and receiver profiling at fixed separation (Figure 2-1g; Elliot, 1961, 1966; Smith and Hallof, 1971; Drinkrow, 1975). Another example is the pole-dipole resistivity-IP array (Figure 2-1b), commonly used with multiple spacings (Seigel, 1952; Wagg and Seigel, 1963; Sumner, 1972). An unfortunate aspect of these systems is that they usually possess axial symmetry about the borehole rendering them useless in determining direction to any target they discover.

The second category is surface-to-hole methods. One of the elements, usually the source, is conveniently located on the surface and the receiver alone is passed down the borehole. The directional array (Wagg and Seigel, 1963) and the downhole radial array (Hauck, 1970) shown in Figure 2-1c and 2-1d are two examples used in resistivity-IP work. EM techniques in this category are the systems which employ a large transmitter loop lying on the surface (Figure 2-1f (Noakes, 1951; Salt, 1966) or a surface dipole transmitter of variable orientation employed in a null mode of operation
**RESISTIVITY - IP**

**EM**

- **(a)** Pole-Pole Normal Two
- **(b)** Pole-Dipole Lateral Three
- **(c)** Directional Array
- **(d)** Downhole - Radial Array

**Repeat V measurement for each source**

**MISE-A-LA-MASSE**

**Fig. 2-1** Configurations of various systems used in drill-hole surveys with electrical methods.
(Ward and Harvey, 1954; Salt, 1966) as shown in Figure 2-1e. The receiver of these systems is normally a solenoid sensor coaxial with the drill hole, which again has azimuthal symmetry. However, the asymmetry necessary for directional determination can be furnished by the primary field.

The mise-a-la-masse method, depicted in Figure 2-1h, falls into a hybrid category as current is usually injected directly into a conductor known from a drill intersection. Mapping of equipotential surfaces is carried out at the ground surface and in other boreholes. Warpage of the equipotential surfaces caused by the conductor, is used to diagnose the shape and location of the target away from the intersection point. Successful applications have been described by Parasnis (1967) and Pelton and Hallof (1971). More recently, Mwenifumbo (1980) has placed the method on a firmer quantitative footing.

The references given here are examples only; a more extensive bibliography is available in the publication by Dyck, et al. (1975). The electrical techniques appeared the most promising but there was a definite lack of interpretational material, a situation which has been alleviated somewhat in the interim (for example: Woods, 1975; Drinkrow, 1975; Drinkrow and Duffin, 1976; Woods and Crone, 1980). However, the state-of-the-art up to 1975 is epitomized by the work of Salt (1966) who tested a variety of IP, resistivity, and EM methods at the site of the Lac Dufault orebody, Quebec. He felt that any one of the methods
would have been able to detect the orebody from a drill hole passing within 40 m of the target's margin, but he found a number of questions difficult to answer. Salt mentions, for example, the difficulty in determining direction of the orebody with respect to the drill hole surveyed, the problem of determining the effective range for a particular method, and the difficulty in sorting the anomalies of orebody targets from the anomalies of unwanted conductors. Restricted access to modelling aids obviously contributed strongly to Salt's sense of frustration in handling these problems.

2.2 The test program

The purpose of the test program was to evaluate in a variety of known geological environments those borehole techniques which were commercially available. Only those thought to be capable of detection at a reasonable distance from the hole were included; logging techniques (sensitive only to physical properties in the immediate vicinity of the drill hole) were excluded.

The following systems were tested: 1.) large-spacing resistivity arrays (pole-dipole, pole-pole, electrode separation up to 50 m) were used to measure resistivity and IP effects (Figure 2-1a,b); 2.) the directional resistivity-IP method (Figure 2-1c) was also tried. 3.) vector measurements of the earth's magnetic field were made with a drill-hole version of a three-component fluxgate
magnetometer. In the EM category, two different types of survey mode were tested: 4.) both transmitter and receiver in the drill hole (coaxial dipole-dipole EM, Figure 2-1g) and 5.) a large transmitter loop on the surface and a single-component receiver downhole (Figure 2-1f). The variable tilt method (Figure 2-1e) was not available for testing, so the author's impression is based mostly on the experience of a user.

2.3 Results of the test program

The test program exposed many problems, both practical and inherent, but the results provided a solid base of knowledge about a number of test sites which were later used for more specialized research. The main observations were the following:

1. Downhole resistivity-IP surveys tended to emphasize conductive mineralization intersected by the drill hole even when this was not of significant quantity. Very noisy profiles (see Figure 2-2a) were obtained so that in the crystalline metamorphic environments visited (Sudbury, Ontario, Noranda, Quebec, and Bathurst, New Brunswick mining camps) the method was largely unable to detect off-hole sulphide deposits. Furthermore, the directional method in which potential warpage of a surface-injected current system is used to derive directional information, gave inconclusive results even for a target which was barely missed. It appears that, in
resistive host rocks such as those of the Precambrian shield, extensive but only moderately conductive minor mineralization dominates the results.

2. The downhole magnetometer method was discounted for a similar reason. In both environments tested (Sudbury basin, Bathurst mining camp) very large gradients (greater than 10,000 gamma/m) were observed; Figure 2-2b shows an example profile from Sudbury. A large number of scattered but intense magnetic sources is to blame, presumably small concentrations of pyrrhotite judging by the relationship to known intersections.

3. The main drawback of the dipole-dipole EM system is its restricted radius of exploration. The limiting factor for sensitivity is geometric noise which, in simple instruments such as that tested, is estimated to be 1% of primary field; this limits the search radius to about 0.5 of the coil separation (see, for example, Brant, 1965). For a coil separation of 30 m, which is the maximum size that can be conveniently handled, the search radius is limited to about 15 m under good conditions. Furthermore no directional inferences are possible since the coaxial configuration has perfect axial symmetry. The system has three advantages, however: interpretation of simple isolated conductor situations is easily handled by parametric type curves (Drinkrow, 1975; Drinkrow and Duffin, 1976); the instrument is readily adaptable to continuous profiling; in deep holes the system can escape
Fig. 2-2 Drill-hole geophysical test data from TRILLabelle site, Sudbury, Ontario. (TRILL-34619)
completely from surface effects such as conductive overburden. In spite of these advantages, the deciding factor is the obvious large sensitivity to small pockets of conductive mineralization at or near the drill hole. Figure 2-2c shows a dipole-dipole EM profile in an environment (Sudbury basin) in which its effectiveness for off-hole exploration is completely obliterated.

4. The large-loop EM method appeared most suitable for a number of reasons: a) the radius of exploration seemed to be larger than for any other system, an advantage achieved mostly by its ability to enhance geological S/N. Figure 2-2d illustrates this conclusion by comparing the two clearly defined anomalous zones with the responses of the other methods. The causative conductor at 400 m is believed to be 40 m from the drill hole; it was not detected by the other methods. On the other hand the large-loop response in the depth range 200 to 250 m is clearly due to intersected mineralization. Theoretical verification of the enhanced geological S/N is possible using the computer modelling facility to be developed in Chapter 4; Figure 2-3 compares the response of two EM systems to a large and small plate conductor. The large-loop system discriminates on the basis of both anomaly amplitude and wavelength; the dipole-dipole EM does not, as its response is controlled by that portion of the plate nearest the drill hole. b) implementation of the large-loop system is relatively straightforward
Fig. 2-3 Geological S/N enhancement by large-loop Crone Pulse EM system (TX 100 X 100 m) compared to dipole-dipole EM system. Models were computed using program PLATE (see Chapter 4). Amplitude scale is linear-logarithmic (linear -10 to +10) for all profiles.
because it is a simple adaptation of a surface method: the downhole portion can be less sophisticated and it is relatively easy to attain a large magnetic transmitter moment when the loop area can be large and a motor generator can conveniently supply the power. At the same time, one can introduce the asymmetry necessary for directional determination by appropriate location of the transmitter. c) the technique can be adapted for continuous profiling when a sufficiently high frequency is employed (say > 200 Hz to avoid motion noise). d) since it was apparent from the tests and surface survey experience that a wideband system with a low base frequency is desirable (see, for example, Lamontagne, 1975) the large-loop system again seemed to offer the greatest flexibility.

5. The third type of EM system which employs a variable tilt dipole transmitter could not be properly assessed due to lack of availability. Comments are based on a short trial with a very rough experimental setup and discussions with an experienced user (Betz, pers. comm. 1974). The main advantage of the system is that its transverse transmitter moment permits extraction of directional information; its small physical size, furthermore, makes it convenient to use in underground operations. The compromise is that it is difficult to achieve a strong enough magnetic field at great depth, especially for a low-frequency system. The wideband requirement also
implies a very laborious rate of production since it is a null method. Certainly, continuous profiling is not possible.

Conclusions:

The program clearly focussed attention on the large-loop EM system. This method appeared to provide the best all-round performance in terms of geological signal-to-noise ratio, the ability to detect large conductors at considerable lateral distance and depth, and the possibility of reasonably quantitative interpretation including determination of direction to the target. It was therefore decided to concentrate further immediate research efforts on this method.

The test program also suggested that other avenues could be worth following. For example, a rather crude set of experiments performed by the author showed that it was feasible to measure VLF fields (10 - 30 kHz; generated, for example, by U.S. Navy communications transmitters) at considerable depth in Precambrian rocks. Follow-up work has been carried out by the Mineral Exploration Research Institute (MERI, Montreal, Canada) under contract to the Geological Survey of Canada and by Roy (Ph.D. thesis, in prep., 1981). Other experimentation, in conjunction with MERI, involving downhole measurement of natural telluric fields has led to further studies by Bazinet (1979).
CHAPTER 3

EM FIELD PROGRAM

3.1 Description

Practical problems exposed by the early test program strongly suggested the need for better, more reliable instrumentation. New or improved equipment was subsequently produced and used to obtain the results presented in this chapter. Field surveys were carried out by the author, or under his supervision, concentrating on the Precambrian massive sulphide exploration problem. As the equipment was very new the surveys were often of an experimental nature with procedures being developed and the validity of the data being established as surveying progressed.

Table 3-1 summarizes all EM surveys performed to date with the large transmitter loop configuration. A total of 65 surveys, counting different loop locations, was carried out in drill holes ranging in depth from 200 to 900 m. The large volume of data precludes presentation in its entirety; the data which appears in the thesis is specially marked in the table.

Four of the test sites are in the Sudbury basin, GERTrude, Gertrude West, TRILLabelle, and POWder MAGazine, a reflection on the large number of orebodies and exploration
<table>
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<th>Test site</th>
<th>Crone Pulse EM</th>
<th>Multifrequency EM (Scintrex)</th>
<th>UTEM</th>
<th>Noranda DHEM</th>
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**LEGEND**

Transmitter loops coded N, S, E, W for North, South, East, or West locations OR A, B for others.

- data presented in thesis
drill holes in the area. Data from TRILLabeled was presented in Figure 2-2 to illustrate the effects of geological noise. Detailed information will be given here for the other three Sudbury sites only. A fourth site is included from the Noranda mining camp (Falconbridge Copper 266).

A note on the symbolic nomenclature used for test drill holes: the full site name is written with the symbolic part in upper case type (eg. GERTrude); in referring to a drill hole, the symbol is followed by the company drill-hole designation (eg. GERT-9266).

3.2 Survey equipment

Figure 3-1a is a block diagram of the large-loop drill-hole EM system whose geometric configuration is common to all three types of EM units used here: an impulse-type system, a step-function system, and a multifrequency system where the names refer to the received primary waveform or "system function". The transmitter loop is comparable in size to the depth of the drill hole and in the surveys reported here ranges from 250 to 500 m per side. A priori knowledge of the geology permitted multiple loop locations designed to maximize expected differences in transmitter coupling with the target.

3.2.1 Pulse EM

The impulse-like system was built for the Geological Survey of Canada by Crone Geophysics Limited, Mississauga, Ontario, and will henceforth be referred to as Crone PEM or
Fig. 3-1  (a) Block diagram of large-loop EM system.
(b) Secondary field responses shown schematically for locations A and B.
Fig. 3-2 (a) Pulse EM waveform specifications showing pulse shape, width and delay time of sampling windows, and variable gain factor for each channel. (b) "Typical" anomaly profiles for Pulse EM system in drill hole which intersects (position A) and misses (position B) a sheet conductor (after Woods, 1975).
just Pulse EM. Pulse EM had been successfully developed as a surface horizontal-loop system (Crone, 1976). The transmitted current is a repetitive step and the system function is, therefore, a series of pulses. Timing is supplied by either radio or wire link. Secondary field due to eddy currents induced in nearby conductors is detected by the system as a function of time between pulses by means of 8 sampling windows (see Figure 3-2a for waveform and sampling specifications). The system function is zero during the sampling time so the channel values will be zero in the absence of secondary fields. Thus the influence of the primary field is removed by time separation of the primary and secondary fields. This feature contributes to the sensitivity of the system, but the advantage so gained is offset to some extent by the requirement for large dynamic range in the instrumentation. For the surveys reported here the receiver gain was adjusted at each station to give constant primary pulse height, automatically normalizing the channel data to the measured pulse amplitude. This procedure produces a relatively constant receiver noise level of approximately 1-2 ppk of the primary voltage to a depth equal to the transmitter loop dimensions.

Figure 3-1 also illustrates schematically the waveforms and sign conventions adopted: positions A and B indicate the anomalous waveforms to be expected when the sensor is directly approaching (or passing through) the conductor (A) and when it is stationed to one side of the
conductor (B). "A" gives a decay curve (transient) which is the same sign as the primary pulse while "B" gives a transient of opposite sign.

A "typical" Pulse EM anomaly may then resemble either of the two profiles shown in Figure 3-2b drawn from the work of Woods (1975) and presented in the form used in production surveys and in this thesis. Amplitudes of the sample at various delay times are displayed on a linear-logarithmic scale and plotted as a function of depth. The earliest samples usually have the largest amplitudes and in most cases it is unnecessary to label the individual traces. Both A- and B-type anomalies are shown. For position A the anomaly is entirely positive with a gradual buildup from both sides to a peak at the depth where the conductor is intersected. For a conductor which is bypassed (position B), the anomaly consists of two positive flanks separated by a negative main lobe. Sign changes (or nulls) will henceforth be referred to as "crossovers". In carrying out interpretation we will see that it is important to recognize and use departures from this "typical" anomaly signature.

3.2.2 Step-response EM

The University of Toronto EM (UTEEM) system has been found to be highly useful employed for surface surveys and considerable effort has been concentrated on its interpretation (Lamontagne, 1975; Lodha, 1977; Macnae, 1981). The UTEEM transmitter generates a repetitive triangular current waveform so that the system function is a
series of repetitive steps of alternating sign (Figures 3-1, details in Figure D-1). A timing link is obviated by the use of synchronized, low drift, crystal oscillator clocks. Again the decaying secondary field is measured as a function of time with binary-spaced windows. In this case, however, the decay is sampled in the presence of the primary field which must be removed by calculation using precise geometry and subsequent subtraction, or by direct measurement of a late-time channel which is relatively unaffected by the transient (both of these are used, see Appendix D).

Again we refer to Figure 3-1 for the appropriate sign conventions: position A gives a negative anomaly (opposite to change of state of primary field); position B produces a positive anomaly.

UTEM surveys were performed in two drill holes at the GERTrude test site by interfacing the Crone PEM downhole hardware (probe and winch) to the UTEM II receiver. This was done by insertion of a wideband, X10 preamplifier. Due to the more band-limited nature of the downhole coil compared to the UTEM surface coil, the early UTEM channels were lost and only channels 7 to 1 are usable (0.195 to 12.5 ms delay time at a base frequency of 30 Hz).

3.2.3 Frequency-domain EM

Frequency-domain surveys were carried out using the SE-77 DHEM (Scintrex Limited, Willowdale, Ontario). This also is a system initially developed and used for surface surveys as a five-frequency TURAM (two-coil) comparator
receiver. The transmitter generates a primary field with switch-selectable frequency in the range 35 to 2835 Hz. The signal is detected downhole with a wideband induction coil (in the surveys reported here, the winch and probe assembly from the Crone PEM were used). The surface receiver, a sensitive phase-lock amplifier, is driven by a conveniently located coil which supplies reference amplitude and phase information to the receiver (timing link). The SE-77 system includes an additional amplifier with switch-selectable ranging and phase shift in order to accommodate the wider dynamic range required in drill-hole surveys as opposed to normal TURAM operation. Information obtained with this system is the amplitude of the in-phase component of the total field (primary plus secondary) normalized to the reference field strength, and the phase difference between total field and reference field (see Appendix D for the approximation used). The zero levels of these two quantities are completely arbitrary as no attempt is made to calibrate them. In the absence of conductive material, only the normal primary field attenuation with depth will be observed in profile along with zero phase change. Secondary effects will be superimposed on the primary field variation. For small anomalies the perturbations are approximately in-phase and quadrature components of the secondary field relative to the primary field. Display of field data in the thesis is as depth profiles of amplitude (logarithmic scale) and phase (linear scale; 10° phase shift corresponds to 17.5 %
quadrature anomaly). The logarithmic amplitude display is used to accommodate the effect of primary field attenuation and, in a sense, "normalize" secondary amplitude to primary field strength. Measurement at position A will result in negative anomalous amplitude values and at position B will produce a positive anomaly (as for the step response).

3.3 Test sites - geology and EM data

Figure 3-3 shows the geology of the Sudbury basin area. The Sudbury irruptive is composed of igneous rocks lying in and on older Archean granite-greenstone terrain. The outermost zone of the irruptive is the Sudbury norite and other quartz-dioritic rocks and comprises the so-called "hanging wall" in most of the mines. Its contact with the Archean granite and granite gneisses, greenstone and sedimentary rocks on the footwall side is known as the norite contact. The contact may have a very steep or very shallow inward dip. The ore zones, which are examples of magmatic deposits (Naldrett and Sangster, 1975), generally lie on or near this contact. The ores consist of predominantly pentlandite, pyrrhotite, and chalcopyrite, with accessory cubanite and pyrite and has been described by Naldrett and Kullerud (1967) as "monotonously similar" in mineralogical character. Both massive sulphides and disseminated sulphides occur (the latter usually on the hanging wall side of the contact. As expected, the deposits exhibit a high electrical conductivity. They are also known
Fig. 3-3  Sudbury area geology with locations of drill-hole geophysical test sites (courtesy of INCO).
to be magnetic due to the abundance of pyrrhotite (Schwarz, 1972).

Detailed geological information was not always available to the author. As some of the holes were drilled in the 1930's, core logging performed at the time was limited to those sections of most immediate interest, i.e. the sulphide intersections. For this reason and to respect company confidentiality, only total sulphide concentrations and location of the norite contact are given here. The outline of the deposits is defined somewhat arbitrarily as 10% total sulphides over 0.3 m minimum width.

3.3.1 GERTrude

Geological information is presented in Figure 3-4 in plan and section with locations of all drill holes marked to show the extent to which this deposit is known. The section was chosen to best illustrate the overall character. Parts of the deposit once outcropped and were mined in the area marked "pits". The deposit dips to the north at 45° and reaches its maximum known depth at about 500 m to the north. The 40 m intersection indicated to the south of GERT-9266 is the only significant known deviation from an otherwise uniform thickness of 10-15 m. A halo of lesser sulphides in stringer and disseminated form surrounds the deposit, apparently mostly on the hanging wall. One of the test holes GERT-9273 intersects the deposit, while the other two, GERT-9266 and -9279, miss by 30 and 100 m, respectively.

Figure 3-5 presents examples of Pulse EM data from
Fig. 3-4 GERtrude test site in plan and section, showing four loop locations, and all drill holes which define location of lower part of deposit. Surveyed drill holes are labelled.
Fig. 3-5 Pulse EM field data (continuously normalized to measured pulse amplitude) from GERTRUDE. Channels are marked Early (E) and Late (L).
surveys which used the transmitter loops shown in Figure 3-4. The GERT-9273 profile is south-loop data. The positive response between 300 and 400 m appears typical of an intersected conductor, the peak occurring at a depth of 352 m which coincides with the massive-sulphide intersection. In the immediate vicinity of the peak, and coinciding with poorer grade sulphides, are some sharp, local variations of the EM response; other than this the profile is quite smooth. The wide shoulder, more obvious on the north-loop response, indicates the conductor is detected at least 100 m above the main intersection. The weaker negative anomaly centred at 220 m is indicative of a second weaker conductor away from the hole, and above the main conductor. Minor intersections in adjacent drill holes would appear to corroborate its existence. It should be noted that continuous normalization with respect to measured pulse height results in an exaggerated peak due to severe distortion (and amplitude reduction) of the pulse in the immediate vicinity of a conductor.

Three anomalies are found in GERT-9266 using the north transmitter loop response. Anomaly A at 310 m depth is the response of the main conductor. Anomaly B corresponds to mineralization lying on the norite contact at or very near the hole. This small conductor was detected in one of the earlier surveys using the 30 m dipole-dipole EM unit. Anomaly C at 435 m depth has no corresponding expression in the geologic log. It is probably due to a hitherto unknown
conductor not reached by the drilling.

The lower flank of the A anomaly is obliterated by the B and C anomalies. However some interpretation can be carried out using Woods' (1975) scale-model results for rectangular plate conductors. Estimating the separation of the lower crossovers to be 100-140 m, we can determine that the near edge of the conductor is a maximum 30 m away and the far edge is an additional 120-240 m away, in reasonable agreement with the geological evidence. The observed time constant for anomaly A ranges from 0.4 ms to 6 ms as delay time increases. As the longest time constant encountered in Woods' model set is 3 ms, we can only place a lower bound on the conductivity-thickness estimate of 100 S. Using surface UTEM data, Lodha (1977) estimated the conductivity-thickness of the shallower parts of the body to be at least 1000 S.

Interesting amplitude comparisons for anomaly A can be made between the data from the four loops (only the north loop profile is shown). The east-loop response is largest and the west-loop response the smallest. While the difference (about 100 ppk) is significant as far as the instrumentation is concerned, it is not clear whether anomaly amplitude is most affected by proximity of the loop or a better angle of coupling, or perhaps both. However the foregoing observation would indicate that the response is due to the bulk of the conductor lying updip and not that part to the west.

An additional complexity to be investigated is the behaviour of the peak of anomaly A which migrates downward a
distance of 10-15 m in going from samples at 0.15 ms to 6.4
ms. Such an effect would normally be attributed to diffusion
of the magnetic field through a geometrically thick
conductor, an explanation which does not satisfy the
geological constraints.

The Pulse EM survey in GERT-9279 was completed to a
depth of only 450 m due to severe noise conditions of nearby
power lines. The sharp anomaly at 420 m appears due to a
small pod of intersected mineralization although none is
mentioned in the log. Of greater interest is the broad
anomaly below 350 m depth which, in spite of its low
amplitude (5 ppp), is very clear. The early channels peak at
about 300 m and later channels at 370 m. The anomaly is at
approximately the correct depth to be explained by the known
conductor to the south. An alternate possibility arises
because of gaps in the drilling pattern towards the north
and east. This invites speculation that a different
conductor is involved.

GERT-9266 is the only drill hole where all three
methods have been tested. Figure 3-6 shows UTEM and
multifrequency profiles for the north loop. Two different
procedures for data reduction and display have been used to
show the effect on interpretation. The UTEM data has been
reduced to Channel 1; the multifrequency data is presented
as raw amplitude and phase values but the calculated primary
field has been included so that secondary fields can be
determined graphically.
Fig. 3-6 UTEM and multifrequency surveys of GERT-9266 using north loop. Multifrequency data is in arbitrary units (relative to surface reference).
We see that both UTEM and multifrequency surveys successfully detected the same three conductors as the Pulse EM. As expected, on referral to Figure 3-1, anomalies for both systems are of opposite sign to the Pulse EM anomalies. Anomaly A is comparable in size for UTEM and multifrequency systems (about 50% and 60% respectively) but about 3 to 4 times larger, in terms of primary field signal, than the Pulse EM response. The PEM response has the largest signal to instrumental noise ratio, however. The method of plotting the frequency data makes it difficult to observe the exact locations of the crossovers (sign changes) and the migration of the peak of the anomaly A. One expects the peak position to be frequency dependent as it is time dependent in the time domain. Use of an expanded plotting scale as a remedy is not recommended without careful consideration of how the primary field is removed. The 35 Hz response is not generally useful as a measure of the primary field since it may not be significantly anomaly-free (in this case 10%), and secondly, judging by observation of the instrument in operation, it is the least well determined frequency. Furthermore its use would encounter the same problem as with a calculated primary field: that of fitting the base level. The same absolute data reduction procedure used in UTEM surveys could be applied here but only with an absolute amplitude calibration on the part of the multifrequency equipment. However, it is the object of the thesis to study the behaviour of the fields, not methods of data
enhancement, so the matter will be pursued no further.

3.3.2 Gertrude West

The Gertrude West deposit lies some 800 m to the west of GERTrude along strike of the norite contact. Distribution of sulphides is shown in Figure 3-7. There are apparently two distinct zones. The larger zone outcrops, where it strikes east-west, dips at 45° to the north to a depth of about 200 m. The smaller zone is blind, lying about 30 m below the lower part of the main zone. The north-south section through GW-23090, also shown, indicates a considerable thickness of sulphides, as much as 50 m of massive mineralization. It is atypical, in that neighbouring sections indicate much thinner intersections. The main zone appears to have a bulb-like termination in the vicinity of GW-23090. GW-29303 is reasonably close to a down-dip extension of the thinner section to the northeast.

The Gertrude West site resembles a version of GERTrude scaled down by a factor of two. However, there are some striking differences. The north-loop response for both drill holes is shown in Figure 3-8. The negative lobe at 180 m is indicative of an off-hole conductor. In all Gertrude West surveys a similar single anomaly was obtained. Based on the sharpness and amplitude of the anomaly, GW-23090 appears quite close to the target. In GERT-9266 the strongest response came from the south and east loops while at Gertrude West they give the smallest. The effect is difficult to explain by differences in transmitter coupling.
Fig. 3-7 Gertrude West test site in plan and section. Outline of sulphide in plan zones is estimated from the drill holes shown.
Fig. 3-8 Pulse EM field data from Gertrude West site. Data is continuously normalized to measured pulse height.
A frequency-domain model study was performed, in cooperation with the GSC, by Kay (1977) to interpret the Gertrude West multifrequency data. The results indicated that a sheet-like conductor must extend to within 10 m of GW-23090 to explain the peak anomaly amplitude. The multifrequency surveys and also Kay's modelling experiments both show upward peak migration (with decrease in frequency) similar to what we observe in the Gertrude West Pulse EM data. Thus we are presented with a conundrum: at Gertrude West we have a conductor which is apparently much thicker than at GERTrude, yet we observe peak migration opposite to that expected for a thick conductor.

Time constants observed at Gertrude West are in the neighbourhood of 4 to 5 ms, i.e. decays are comparable to those observed at GERTrude. As the Gertrude West body is the smaller of the two its conductance must be larger, a result which is in qualitative agreement with Lodha's (1977) conclusions. In this instance a greater delay time on the pulse EM system would probably have added beneficial information.

3.3.3 POWder MAGazine

The site is a claim-size block of ground on the north range of the Sudbury basin. Whereas the GERTrude and Gertrude West deposits have a relatively well established configuration, drilling on the POWder MAGazine has produced a rather disjointed picture of irregularly distributed massive sulphide occurrences lying approximately along the
norite contact. Generally speaking, the intersections are more significant in the section shown in Figure 3-9 and to the east, whereas to the west they are much poorer. It is believed that no orebody exists on the property (Penstone, 1978, pers. comm.). From an exploration point of view, the purpose of a downhole survey here is to corroborate this notion. A second problem to investigate is whether or not the top part of the large Fraser orebody can be detected at long range, say from POWMAG-L348 which is estimated to pass by within about 100 m.

Six of the drill holes, as labelled, were surveyed by Pulse EM from loop location (A). Profiles from two holes, shown in Figure 3-10, were selected to illustrate the variability of the EM response. POWMAG-L348 has a strong intersection-type anomaly at about 650 m indicating that the intersected sulphides are conductive and reasonably extensive. The late-time anomaly at 550 m depth is evidence that more conductive mineralization lies updip. POWMAG-L295 intersects only 3% disseminated sulphides at 510 m and shows a correspondingly weaker intersection-type anomaly at that depth. The late channels are very different in character from the early ones. The large width of the late-channel response suggests the existence of a rather large conductor to the side of the hole. Any attempt at interpretation, however, is severely hampered by the presence of a continuous large amplitude "background" response which extends from top to bottom of the drill hole. The background
Fig. 3-9 Powder Magazine test site in plan and section. Single transmitter location and all drill holes in vicinity are shown.
Fig. 3-10 Pulse EM field data from POWder MAGazine. Data is continuously normalized to measured pulse height.
secondary response is attributed to induction in man-made conductors on the surface. This conclusion is based on mapping of induced currents in power lines, railroad tracks, etc., at the site. Similar problems were found at Falconbridge Copper 266. The geometric behaviour (which looks like a growth with depth because of continuous normalization of data by the measured primary field of the loop) is consistent with a fixed current pattern 2 to 3 times more extensive than the transmitter loop and with a time constant of about 0.5 ms. There are three important consequences: firstly, the anomaly is displaced from zero background and undergoes considerable visual distortion on a logarithmic plot; secondly, the response is driven up into the least sensitive operating range of the instrument; finally, the field which the conductor "sees" may be severely distorted at depth where the primary field is weak. The reduced sensitivity is responsible for the apparent failure to detect the Fraser orebody in POWMAG-L348. Data from this site will be used later in the thesis to determine quantitatively the interfering effects of large amplitude secondary backgrounds.

3.3.4 Falconbridge Copper 266

The FC266 is a small copper-zinc orebody situated in the Noranda mining camp, and is a good example of a volcanogenic massive sulphide deposit. Such deposits are of great economic importance (Naldrett and Sangster, 1975; Franklin et al., 1975). The general consensus (Franklin et
al., 1975) is that these deposits are of syngentic, volcanic-exhalative origin. The ore appears to have been formed by rising, metal-bearing hot springs which deposit metallic sulphides as a sediment on a volcanic sea floor. Felsic volcanic rocks are usually closely associated with the deposits. The deposits typically have two distinct zones, an upper stratabound massive lens consisting of pyrite, sphalerite, and chalcopyrite, and a lower alteration pipe feeder zone consisting of disseminated chalcopyrite and pyrite. The observation that "termination of oregrade material is abrupt" (Mattinen and Watkins, 1977, pers. comm.) is in agreement with the description by Spence (1975) that ore deposits must have formed as hard sulphide sinters in restricted lenses. The strong likelihood of "near misses" of such small, deeply buried but rich deposits creates an ideal opportunity for the use of drill-hole EM techniques in conjunction with a deep exploration drilling program. In the Noranda camp most of the known deposits occur in the middle of a thick volcanic pile of Archean andesite-rhyolite flows which are characterized by shallow dips and rather extensive dimensions (up to 400 m thick and 10 km lateral extent; Spence and de-Rosen Spence, 1975).

Figure 3-11 shows the main geological features in the immediate vicinity of FC266. The Amulet rhyolite-andesite contact is complicated by interspersion of several volcanic flows associated with as many as three distinct exhalative horizons, T (top), M (middle), and B (bottom),
Fig. 3-11 Falconbridge Copper 266 lens shown schematically in plan and section.
3.12 Pulse EM field data from FC 266 test site. Data is continuously normalized to measured pulse height.
each of which has associated pyrite-pyrrhotite mineralization which is known to extend over large areas (Mattinen and Watkins, 1977, pers. comm.). The ore lens itself, lying at the base of the Amulet andesite at 550 m depth, is situated about midway between the Amulet lower-A orebody and the Millenbach orebody, about 1 km updip and downdip, respectively.

Nine drill holes were surveyed with Pulse and multifrequency EM. Only one loop location was used due to logistic difficulties in moving the loop far enough to achieve significantly different coupling. Three of the chronologically numbered holes intersect ore, FC266-D226, -D266, and -D271, although -D266 is considered the discovery hole. All drill holes show anomalies associated with both T and B contacts, but superimposed on the secondary background response. Both intersection and non-intersection characteristics are exhibited but these do not always correlate with the core-log description although they always occur at the correct depth. For example, -D237 (Figure 3-12) has an intersection anomaly at the B contact, whereas the log lists only minor mineralization. This suggests that more concentrated sulphides ring the drill hole in doughnut-like fashion. In another example, -D226 shows an off-hole response at the T contact where the drill intersected almost 1 m of semi-massive sulphides at 609 m, indicating that the best mineralization was missed. Also, the negative anomaly midway between the two contacts appears to be due to the
feeder pipe mineralization below the main zone. The discovery drill hole, -D266, predictably has a strong intersection anomaly where it passes through the orebody. Inspection of all nine profiles leads to the conclusion that five of these, FC266-D219, -D226, -D229, -D240, and -D246, have responses directly attributable to parts of the orebody lying away from the drill hole.

3.4 Summary

We have examined a number of drill-hole EM responses, none of which are simple. They all, perhaps, raise more questions than answers, although the EM data obviously can extend the search radius of the drill hole by several 10's of metres. Table 3-2 summarizes the problems, solutions to which the remaining chapters are dedicated. The interpretation problem can now be stated explicitly as follows:

1. Under what circumstances can the direction to the target be determined?

2. What are the observable parameters which can help to distinguish between thin, tabular bodies and thick, compact bodies?

3. How well can parameters such as target attitude and conductivity be estimated?

4. How can significant thickening of mineralization away from the drill hole be predicted?
### Table 3-2

**Summary of Observations and Interpretation Problems at Test Sites**

<table>
<thead>
<tr>
<th>Location</th>
<th>Apparent Shape</th>
<th>Geological Noise</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERtrude</td>
<td>Dipping sheet (45° towards drillhole)</td>
<td>Moderate (intersected sulphides in ore horizon)</td>
<td>What is the explanation for the downward migration of the peak of anomaly A? Is the known conductor the sole source of the EM response? Is there significant interaction between multiple conductors?</td>
</tr>
<tr>
<td>Gertrude West</td>
<td>Irregularly shaped sheet dipping towards drillhole (45°) with embedded cylindrical or spherical blob.</td>
<td>Low</td>
<td>Why does a conductor which is thick exhibit thin-sheet behaviour.</td>
</tr>
<tr>
<td>POWder Magazine</td>
<td>Dipping plane with scattered occurrences of massive sulphides, continuity unknown.</td>
<td>High - sulphides intersected in horizon.</td>
<td>What is the continuity of the known sulphides, i.e., are the intersections part of an extensive conductor which accounts for the observed response? What are the effects of a background secondary field caused by powerlines?</td>
</tr>
<tr>
<td>FC266</td>
<td>Compact conductor (lens) with underlying conductive zone.</td>
<td>High - fairly extensive conductive mineralization lying on same horizon, underlying horizon also conductive.</td>
<td>Can the response of the orebody be recognized in high geological noise? How can one deal with a large secondary background?</td>
</tr>
</tbody>
</table>
An important observation with implications for EM modelling concerns the conductivity of the host rock. In-hole resistivity surveys (see Chapter 2) have shown that the host resistivities are in excess of 10 k ohm-m in Precambrian environments. As far as concerns the magnetic field of an inductive source, the host medium is adequately represented by free space in any modelling procedure. The good fit between measured background (primary field) and calculated free-space primary field for the multifrequency method (Figure 3-6) is evidence that this true in practice. Background secondary fields due to man-made conductors (for example, Figure 3-10), or conductive overburden, pose a much more serious problem when the host rock is highly resistive. Current channelling effects are inconsequential and only the current vortex induced directly within the conductive zone need be considered (Lajoie and West, 1976).
CHAPTER 4

ELECTROMAGNETIC MODELLING

4.1 Introduction

Inspection of representative field data from four test sites has shown that a qualitative explanation of drill-hole EM responses is possible in terms of the known geology. Close examination of these responses, however, suggests that their details may be the key to solution of the interpretation problem stated in Section 3.4. The basic requirement for interpretation is EM modelling facilities which are suited to the drill-hole exploration problem. The facilities should be capable of handling, in a convenient fashion, the large number of parameters needed to describe fully a three-dimensional problem of considerable geometric and electrical complexity. Use of the simplest three-dimensional models will minimize the complexity but, hopefully, retain sufficient flexibility to provide meaningful simulation of the important details of the field observations. The success of previous workers in simulating wideband EM responses with models of fairly simple shape (see, for example, comprehensive studies by Bosschart, 1964; Ghosh, 1972; Dyck et al., 1975; Lodha, 1977; Woods and Crone, 1980; Spies, 1980) lends credence to the approach.
Furthermore, simple models implemented in fast and inexpensive computer programs could provide EM responses for a variety of prospecting systems and make trial-and-error fitting of field data by forward modelling preferable to reliance on a vast or incomplete suite of prepared model responses.

This chapter describes the EM modelling facilities developed in this research. They were created by synthesizing and elaborating various previously available basic components. The primary facility is in the form of a pair of interactive programs residing on the Digital Equipment Corporation VAX 11/780 computer in the Physics Department, University of Toronto. The programs have been designed for maximum versatility in forward modelling of either a finite, rectangular, thin plate (solution and core programs: Annan, 1974), or a two-layer sphere (theory due to Nabighian, 1971), both situated in free space. Examination of the physical consequences of the theoretical response functions is undertaken in this chapter to provide insight which in later chapters will prove useful in appreciating the model responses. Supplemental modelling to investigate more complex conductors was performed, on the Geophysics Laboratory's scale-model apparatus, to explore a number of inadequacies in the simple computer models.

4.2 Suitability of plate and sphere models

The criteria used in selecting models included
availability of basic algorithms, suitable physical attributes, and geological applicability. A number of finite-sized models are known to be amenable to analytical solution; for example, conducting spheres, cylinders, and spheroids have been analyzed in the quasi-stationary approximation (eg. Wait, 1960), as well as two-layer spheres (eg. Wait, 1969; Fuller, 1971; Hjelt, 1971; Nabighian, 1971). If a coordinate system suitable for easy application of the EM boundary conditions and separation of the diffusion equation cannot be found, as is the case, for example, with tabular bodies, one must resort to numerical techniques (eg. Lamontagne and West, 1971; Coggon, 1971; Annan, 1974; Hohmann, 1975; Pridmore, 1978). The method of Annan was adopted as it was designed and proven to give answers with reasonable accuracy and economy and, furthermore, core computer programs written by Annan were already available.

The plate and sphere models have quite different characteristics as far as EM induction is concerned (Figure 4-1). The plate confines the eddy-currents to one plane regardless of the orientation of the inducing field, thus producing a secondary-field "moment" which is always perpendicular to the plate. The sphere, a conductor which is isotropic both geometrically and electrically, produces a secondary response whose moment is always parallel to the primary field.

The plate model is thus useful for studying geometric
Fig. 4-1 Plate and sphere models showing principle secondary moment dependence.
conditions in which shape combined with attitude are important. It will be useful here to study sheet-like conductors such as GERTrude and conductive mineralized horizons which constitute geological noise. The sphere seems suited to representing compact conductors such as the lens and feeder-pipe sections of the FC-266 deposit. It may also prove useful in predicting a significant thickening of a conductor away from the drillhole or in representing the nearest edge of a thick tabular body. The layering feature of the sphere is expected to be applicable to simulation of halo effects such as when a disseminated sulphide zone surrounds a more conductive inner core of massive sulphides; the sphere may also have magnetic permeability so that effects of associated magnetic minerals (e.g. pyrrhotite) may be included. As previously discussed (Section 3.4), the high resistivity of Precambrian host rocks is well suited to modelling with conductors surrounded by free space.

4.3 Theoretical considerations

The unifying feature of induction in confined conductors located within an insulating region is that the secondary fields can be represented as the sum of simple fractions in the frequency domain, and, in the corresponding transient process, as the sum of exponentials (Kaufman, 1978a). Kaufman places this generalization on a simple physical basis by visualizing the induced currents as a vortex consisting of N elementary current filaments. The
strictly solenoidal nature of the currents is ensured by the condition \( \text{div} \mathbf{J} = 0 \) (no galvanic current sources). The currents must close on themselves within the body since \( \mathbf{J} \cdot \mathbf{n} = 0 \) (no current flow across the boundary). Each ring is driven by an emf, \( V = \oint \mathbf{E} \cdot d\mathbf{s} = -i \mu \omega \oint \mathbf{H} \cdot d\mathbf{a} \). When \( N \) is large the system produces a good approximation to the external magnetic field. If the problem is assumed to possess axial symmetry the form of the current filaments will be frequency independent. Each ring has resistance, \( R \), and mutual inductance, \( M \), with every other ring including itself (i.e. self inductance). Kirchhoff's law, applied in the frequency domain, leads to a set of \( N \) linear equations to be solved for the unknown currents, \( I \), in each ring. In matrix form

\[
( [R] + i\omega [M] ) I(\omega) = V(\omega) \quad (4-1)
\]

where \([R]\) is a diagonal matrix of resistances, \( R \), and \([M]\) is a symmetric matrix with self inductances as diagonal elements and mutual inductances as off-diagonal elements which, combined as above, form an impedance matrix \([Z]\). The algebraic eigenvalue problem is

\[
( [R] + i\omega [M] ) x = \lambda x
\]

which may be rewritten as

\[
[R'] [M] x = (1/i\omega) (\lambda R^{-1} - I) x.
\]

Thus the eigenvalues of \([R'] [M]\), are

\[
\lambda_n = (1/i\omega) (\lambda_n/R_n - I)
\]

They are values of inductance/resistance ratio for systems of current filaments which are non-interacting, i.e. eigencurrents specified by the eigenvectors, \( x \). The
eigenvalues of the impedance matrix [Z] are then
\[ \lambda_n = (i\omega T_n + l) R_n \]

Currents within the body may then be expressed in terms of the eigencurrents as:
\[ I = [S] [D] [S^T] V \quad (4-2) \]
where [D] is a diagonal matrix with elements
\[ \frac{1}{(i\omega T_n + l) R_n} \]
and [S] is the transformation matrix whose columns are the eigenvectors, x.

The current at a point within the body may be written as a sum of simple fractions

\[ I(\omega) = \mu H \sum_n s_n h_n \left\{ \frac{i\omega}{(i\omega T_n + l) R_n} \right\} \]

where the \( s_n \) are coefficients resulting from the transformation matrix [S] and \( h_n \) is an areal coefficient for the nth current filament \( (V = -i\omega \mu h_n H) \). The corresponding sum of exponentials may be derived by application of the Fourier transform as

\[ I(t) = -\mu H \sum \{ s_n h_n (1/T_n) \exp(-t/T_n) \} \]

4.3.1 Plate

The foregoing formalism is closely analogous to Annan's (1974) development of a practical numerical method for determining the EM response of a thin, rectangular conducting plate for a magnetic source of any geometry. The plate is constrained to be inductively thin, i.e. current
density across the plate is constant such that it may be represented by a surface current density, $K_s$. The reader is asked to refer to Appendix A for the details of the method. A review of the technique may also be found in Lodha (1977) and Macnae (1981). A brief description follows.

Using the equivalent source concept (description of the background medium by a Green's function) Annan arrives at the integral-equation analogue of Equation 4-1 (see Equation A-1) for the induced plate currents. The induced currents are then expressed in terms of a scalar potential. Discretization of the integral equation and reduction to an eigenvalue problem is accomplished using the Galerkin method which involves expanding the scalar potential as a linear combination of a finite set of trial functions (in this case, Chebychev polynomials). The eigenpotentials (and hence eigencurrents) which result from solution of the eigenvalue problem behave electrically as a set of non-interacting simple loops (examples are shown in Appendix A). The induced current density, and the secondary magnetic field components, are calculated from a matrix equation similar to Equation 4-2 where the elements of the matrices are determined numerically (expressions are given in Appendix A). The EM response of the plate to excitation by a step change in magnetic field may then be constructed approximately as a finite sum of eigencurrents:

$$S(t) = \sum_{n=1}^{N} a_n(x,y,z) \ b_n(x,y,z) \ \exp(-t/\tau_n) \quad (4-3)$$
\[ \tau_n = \mu \sigma s S \beta_n / 2 \] is the time constant of the \( n \)th eigencurrent, the intrinsic eigenvalue, \( \beta_n \), depends only on the width/length ratio \((W/S)\), \( \sigma s \) is the plate conductance (conductivity-thickness product), and \( S \) is a plate dimension (see Figure 4-2a).

\( a_n(x,y,z) \) is the excitation coefficient, i.e. the coupling between the primary field and the \( n \)th eigencurrent,

\( b_n(x,y,z) \) is the secondary field coefficient which determines the contribution of the \( n \)th eigencurrent to the field measured at the receiver, and

\( N \) is the total number of trial functions in the approximation.

As the amplitude coefficients are pure functions of geometry, the geometric and time-dependent parts of the solution are completely decoupled. All that is required is that the primary field (normal component) be calculable on the surface of the plate. It is thus straightforward to obtain the response to a dipolar field, a uniform field, or the field of a polygonal loop.

4.3.2 Sphere

Similar results can be obtained analytically for the two-layer sphere. It was decided to follow explicitly the solution by Nabighian (1971) which for convenient reference has been described in skeletal form in Appendix B. The differential equation for the stream function, \( \psi \), may be viewed as an analytical eigenvalue problem

\[ D\psi - k^2 \psi = 0 \]
Fig. 4-2
(a) Sphere and plate parameters
(b) Geometric parameters of prospecting system.
The eigenfunctions for the differential operator in a spherical coordinate system (see Equation B-1) are combinations of Legendre polynomials \((P_n(\cos \theta))\) and modified spherical Bessel functions \((I_n(kr), K_n(kr))\) and exponentials \((\exp(i\omega t))\). Application of the boundary conditions (continuity of tangential \(E\) and \(H\) across the surfaces of the core and shell of the sphere) leads to the characteristic equation for the problem. The roots of this equation form an infinite set of discrete eigenvalues, \(p_{nm}\). The step response of a sphere can be written as

\[
S(t) = \sum_{m}^{M} \sum_{n}^{N} d_{nm}(x, y, z) q_{nm}(B/A, \sigma_2/\sigma_3, \mu_2, \mu_3) \exp(-t/\tau_{nm})
\]

(4-4)

where we now have a sum over \(M\) multipoles of order \(m\) (Legendre polynomials). The external magnetic field for each multipole may be thought of as being constructed from \(N\) eigencurrents of order \(n\). The time constants

\[
\tau_{nm} = \frac{\sigma_2 \mu_3 A^2}{p_{nm}}
\]

where both \(p_{nm}\) and \(q_{nm}\) are functions of sphere parameters, \(B/A, \sigma_2/\sigma_3, \mu_2\) and \(\mu_3\) only (see Figure 4-2a for definition of parameters).

The possible primary field configurations are somewhat more limited than with Annan's numerical method as it is convenient analytically to expand the primary field in spherical harmonics. The coefficients of the harmonics are easily derived analytically for a magnetic dipole source. The uniform field response is obtained by using just the
lowest order multipole (m = 1, dipole). To obtain the response to a large loop, the response to a dipole must be integrated numerically over the loop.

4.3.3 Eigencurrent analysis

Following the convention of Nabighian (1971),

\[ S(x,y,z,t) = H \sum \bar{c}_n(x,y,z) \exp(-t/\tau_n), \quad t \geq 0 \]
\[ = 0, \quad t < 0 \]

is defined, in general, to be the response generated by the sudden turn-off (step) of a primary magnetic source, where \( \bar{c}_n \) is referred to as the \( n \)-th coupling coefficient. As mentioned previously, Equation 4-3 is applicable to any geometry of confined conductor located in free space, including a plate or a sphere. Analysis of the type carried out by Kaufman (1978a and b) is helpful to appreciate features of the modelling results to be presented in subsequent chapters.

If the eigencurrents are ordered so that \( \tau_n \geq \tau_{n+1} \), then, in general, the magnitudes of \( \bar{c}_n \) decrease systematically with increasing \( n \). Figure 4-3 shows the variation of \( \bar{\beta}_n \) for the plate and \( p_{nm} \) for the sphere. Each plate eigencurrent has a different geometry as shown in Figure A-1; the more complex the pattern, the more rapid is the decay and usually also the geometric attenuation. Provided that the source is displaced from the conductor, the coefficients become vanishingly small as \( n \) increases. A similar situation exists for the sphere. All the eigencurrents for one multipole have
Fig. 4-3  Behaviour of eigenvalues for (a) plate (b) sphere
Variables are defined in Sections 4.3.1 and 4.3.2.
the same external magnetic field geometry and thus have fixed relative values of \( c_n \). The relative values of the coupling coefficients for different multipoles obviously determine the rate of convergence of the series in equation 4-5 and must be carefully considered when truncating the series in a practical calculation.

The impulse response (to a negative impulse) may be obtained by differentiating Equation 4-5:

\[
\text{Im}(t) = H \sum_n c_n \{ \delta(t) - (1/\tau_n) \exp(-t/\tau_n) \}, \quad t \geq 0 \quad (4-6)
\]

\[
\text{Im}(t) = 0, \quad t < 0
\]

Likewise the frequency spectrum is obtained via Fourier Transform

\[
F(\omega) = H \sum_n c_n \left\{ \frac{i\omega\tau_n}{1 + i\omega\tau_n} \right\}
\]

\[
= H \sum_n c_n \left\{ \frac{\omega^2\tau_n^2 + i\omega\tau_n}{1 + \omega^2\tau_n^2} \right\} \quad (4-7)
\]

Figure 3-1 shows schematically the response for each of the three fundamental system functions and Table 4-1 summarizes their inductive and resistive limits. We see that the system function dictates the form of the weighting function for each term in the series.

Convergence of 4-5, 4-6 or 4-7 may be hastened by the time or frequency factor in each term. It is slowest at the inductive limit. The in-phase response converges at the same rate and to the same value as the step response. The \( 1/\tau_n \) factor counteracts the natural convergence of the \( c_n \) so
**TABLE 4-1**

LIMITING EXPRESSIONS FOR FUNDAMENTAL RESPONSES

<table>
<thead>
<tr>
<th></th>
<th><strong>Inductive limit</strong></th>
<th><strong>Resistive limit</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(early time)</td>
<td>(late time)</td>
</tr>
<tr>
<td>(high frequency)</td>
<td>(low frequency)</td>
<td></td>
</tr>
<tr>
<td><strong>Step response</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S(t)$</td>
<td>$\sum_n c_n$</td>
<td>$c_i \exp\left(-t/\tau_i\right)$ where $\tau_i &gt; \tau_n$</td>
</tr>
<tr>
<td>Equation (4-5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Impulse response</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I(t)$</td>
<td>$\sum_n c_n / \tau_n$ *</td>
<td>$c_i / \tau_i \exp\left(-t/\tau_i\right)$ where $\tau_i &gt; \tau_n$</td>
</tr>
<tr>
<td>Equation (4-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frequency spectrum</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-phase</td>
<td>$\sum_n c_n$</td>
<td>$\omega^2 \sum_n c_n \tau_n^2$</td>
</tr>
<tr>
<td>Equation (4-7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frequency spectrum</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadrature</td>
<td>$1/\omega \sum_n c_n / \tau_n$ *</td>
<td>$\omega \sum_n c_n \tau_n$</td>
</tr>
<tr>
<td>Equation (4-7)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* See text
that the inductive limits of the impulse and quadrature responses are slowest to converge. It has been pointed out by Kaufman (1981, pers. comm.) that the series for the impulse and quadrature responses may not converge (at the inductive limit) for real bodies with an infinity of poles (eigenvalues). They therefore do not necessarily predict the correct functional behaviour for all real bodies in the inductive limit. They do, however, predict the behaviour of models for which the response is, in practice, calculable from a truncated series. In the resistive limit, the time-domain responses reduce, by definition, to one term. The in-phase and quadrature responses converge more slowly but with coefficients \( \tau_n^2 \) and \( \tau_n \), respectively, each of which improves the convergence relative to its inductive limit counterpart by a factor \( \tau_n^2 \). As the higher order modes are also geometrically more complex (Figures A-2, 4-5) convergence is also affected by proximity of either source or detector to the conductor; for example, the sphere multipole of order \( m \) is attenuated by a factor \( 1/r^{m+2} \) when the receiver is a distance \( r \) away. The worst convergence can be expected to occur when receiver and transmitter are both close to the conductor and either the impulse or the quadrature frequency response is desired.

The same factors which control the convergence are responsible for the relative contributions of the individual eigencurrents to the total eddy-current distribution. Slow convergence means that the higher orders contribute more to
the response and since they are responsible for forcing the induced currents to the outside of the conductor (Annan, 1974) the quadrature and impulse currents at the inductive limits should be closer to the edge of the plate than the in-phase or step currents. Frequency-domain current patterns computed by Annan (1974) and Lamontagne and West (1971) clearly show this. The effect is illustrated schematically in Figure 4-4 for both plate and sphere models. For the sphere model the closer the response is to the inductive limit, the larger the contribution of the high order multipoles is to the total response. As the even orders are spatially antisymmetric (about the equatorial plane of the sphere, see Figure 4-5) the net result is an asymmetric current pattern displaced towards the transmitter in the inductive limit (as demonstrated by Best and Shammas, 1979). The asymmetry is greatest in the quadrature and impulse responses.

The eddy currents migrate as the response moves from the inductive to the resistive limit. This means a collapse of the current vortex towards the centre of the plate. For a sphere in a uniform field the vortex collapses radially inwards from the surface, as illustrated by McNeill (1980), but the only externally visible effect on the response is a uniform decrease in amplitude everywhere along the profile. The relatively quicker decay of the higher order, asymmetric contributions induced by a non-uniform field means that the current vortex also migrates laterally through the sphere,
Fig. 4-4  Schematic representation of eddy currents in sphere and plate as function of time or frequency. Sphere is cross-sectional view showing diffusion through the conductor away from the source. Plate shows plan view of collapse of induced current vortex.
Fig. 4-5 Profiles of first four multipole contributions to vertical component of sphere response. Sphere is same model as in Figure 5-8.
reaching a stable configuration as a diffused current ring around the equator.

The final current distribution depends, however, on the type of excitation. Both step and impulse responses result from identical induced-current patterns in the resistive limit, that of the principal order eigencurrent, although their amplitudes differ by a factor of $1/\tau_n$. Another difference is that the resistive limit of the impulse response is reached at a later time since the higher modes are more dominant. In contrast, the current pattern of the frequency response always contains a contribution from the higher order eigencurrents. Lowering the frequency further does nothing to change the relative contributions once the frequency dependence can be moved outside the sum in Equation 4-7. Of the two frequency-domain components the quadrature response exhibits the greater departure from the principle mode.

The observations of the previous paragraph can be related to the resolving power of the inductive methods as analyzed by Kaufman (1978b). Resolving power in Kaufman's discussion is defined as the ability to discriminate between targets of different induction number (selectivity) solely on the basis of their low-frequency or late-time response. In the time domain, the selectivity can, in principle, be increased without limit, since there is always a sufficiently large $t$ at which the eddy currents in the highest $\tau$ target will predominate according to
\[ S/N = \frac{c_s}{c_n} \cdot \frac{\exp(-t/\tau_s)}{\exp(-t/\tau_n)} , \]

where \( \tau_s \) and \( \tau_n \) are time constants of the target and extraneous conductor, respectively (\( \tau_s > \tau_n \)). In other words, the influence of purely geometric factors, \( c_s \) and \( c_n \) becomes insignificant at sufficiently late times. This would allow determination of \( \tau_s \) from the final rate of decay. The limiting \( S/N \) for the in-phase and quadrature responses are

\[
S/N = \frac{\sum_n c_{ns} \tau_{ns}^2}{\sum_n c_{nn} \tau_{nn}^2} \quad \text{and} \quad \frac{\sum_n c_{ns} \tau_{ns}}{\sum_n c_{nn} \tau_{nn}} ,
\]

respectively, independent of frequency. Evidently further decrease of frequency does not increase the resolving power because it does not further reduce the contribution of the higher order terms. The selectivity may thus be controlled entirely by geometric factors (through the \( c_n \)) such as the conductors' shapes, sizes and proximity to the prospecting system.

An important situation arises when the contribution of the principle order is small, such as in the vicinity of a profile crossover. The shift of the crossover with time or frequency should thus be a sensitive indicator of migration of eddy currents. One would expect the crossover migration of the impulse response to be strongest, again by virtue of greater initial contributions from the higher orders.

4.3.4 Determination of direction

The secondary field is examined to demonstrate the conditions under which direction to the target may be
Fig. 4-6 Principle of determination of direction to target using axial magnetic field only (SOLID) and transverse component only (DASH): (a) profile sampling one lobe of secondary field; (b) profile sampling both lobes.
unambiguously determined using profiles of the axial component. In both models a vortex current circulates so that a "dipolar-like" secondary field approximation is adequate for explanation. Figure 4-6 shows two extremes: in case (a) the sign of the profile is independent of the side of the drill hole on which the conductor is located; in case (b) the corresponding pair of profiles gives antisymmetric results. It is clearly necessary to sample both lobes of the "dipole" to make a determination of direction. A profile of the axial component will consist of two contributions, one symmetric and the other antisymmetric, for situations between the two extremes. How well the antisymmetric contribution can be recognized in practice will depend on other factors such as geological noise, etc.

The possibility of success is also model dependent. Secondary moment in the sphere depends on the primary field direction so that it may be possible to arrange the proper conditions through judicious choice of transmitter location. The induced moment is perpendicular to a plate conductor so that proper conditions depend upon the attitude of the plate with respect to the drillhole. Since exploration drill holes are usually oriented normal to the expected plane of the target, directional information is potentially more difficult to extract for a plate-like conductor. Magnetic field components transverse to the drill hole would obviously help to alleviate any ambiguity, a topic to be pursued further in Chapter 7.
4.4 Convolution with practical waveforms

EM systems utilizing three ideal waveforms have been discussed previously. Real time-domain systems provide, at best, an approximation to an ideal discontinuity response. The UTEM response is a very good approximation for the delay times used, once the finite gate width and repetitive nature of the waveform are taken into account. In pulse EM systems it is necessary to control the turn-on and turn-off of transmitter current, $i_{TX}$, in a manner so that the system function (di$_{TX}$/dt in coil receiver systems) is known and consistent. Partial sine and cosine waveforms, exponentials, and linear ramps are commonly achieved in commercial prospecting systems. Simple functions like this can be convolved analytically with the EM response of finite conductors expressed as an exponential sum. If the waveform $f(t)$ used in practice can be piecewise decomposed into these functions, the total response for that system can be obtained in a straightforward manner by piecewise analytical integration of the convolution integral.

$$g(t) = \int_{-\infty}^{\infty} I(t-t') f(t') \, dt$$

where $I(t) = -Im(t)$ is the true (positive) impulse response. This procedure has been used in the past by Verma (1972) and subsequently to the present program development by Holladay (1980). Appendix C contains the expressions for the
waveforms currently incorporated into the computer programs.

Practical EM systems sample the transient with windows of finite width over which the decay is averaged. Finite window width, $\Delta$, is accommodated by integration

$$g_{\text{Window}}(t) = \int_{t-\Delta/2}^{t+\Delta/2} g(t) \, dt$$

where $t$ is the mean delay time of the gate. This operation is again simple since $g(t)$ consists entirely of exponentials for $t > 0$. Repetition of waveform, on a period $T$, is obtained through summation of all previous events. For a waveform of alternating polarity:

$$g_{\text{Repeat}}(t) = f(t) - f(t+T/2) + f(t+T) - f(t+3T/2) + \ldots$$

$$= \sum_n 1 / \{1 + \exp(T/2\tau_n)\}$$

4.5 Computer programs PLATE and SPHERE

4.5.1 Description of computer programs

A wide range of options has been built into the computer programs to improve their versatility. All electrical and geometric parameters shown in Figure 4-2 are variable inputs to the programs. Detailed instructions for operation of the program may be found in the USER MANUAL (Dyck et al., 1981). Appendix C of the thesis shows some of the options available. The waveform options are tabulated in Table C-1. Subroutines for this part of the computation are
common to both PLATE and SPHERE. Table C-2 shows the normalization options for fixed-transmitter surveys. As the programs will handle uniform, dipolar, and large-loop sources, it can be appreciated that a wide variety of drill-hole, surface, and airborne EM systems are accommodated.

Structure of the programs reflects the computational effort involved in the various stages (see Figures C-1, C-2). In each program, two driver subroutines handle the main streams for fixed and moving transmitters. The geometrical portion precedes the time-dependent computation. The core programs for PLATE as written by Annan (1974) and subsequently used by Lodha (1977) were implemented without modification except for conversion of the original IBM FORTRAN routines to VAX-11 FORTRAN IV-PLUS. Programming of the core programs for SPHERE follows, as closely as possible, the layout of equations in Nabighian (1971). The programs can be run in either interactive or batch mode. Cycling through while varying parameter values makes optimal reuse of the most laborious calculations to economize on computer time. Eigenvalues, once computed for either model, are automatically stored on disk for recall on subsequent runs. Output files are structured for plotting via an interactive routine for graphical output on the VAX system electrostatic plotter. Sample outputs are shown in Figures C-3 and C-4 as they are received with all parameters summarized in the caption. A fifty-point profile can be
obtained in 1-2 minutes CPU time, including plotting.

4.5.2 Computational precision: PLATE

Truncation of the exponential series imposes the most critical limitation to accuracy. Annan (1974) and Lodha (1977) routinely used 15 eigencurrents as does the PLATE program described here. As can been seen in Figure 4-3a, the time constants barely span one decade, whereas two decades would more adequately describe wideband EM induction.

Improving the accuracy by using up to 36 eigencurrents was attempted; the results are shown in Figure 4-7 for a horizontal loop system in which both coils are very near the plate in relation to the plate dimensions. When the response is displayed in argand format, inaccuracies in the in-phase are particularly evident. Considerable improvement results from using 21 or 28 exponentials, as the saturated in-phase appears to be converging to a value around -25%. This is an obvious means of testing for convergence, if somewhat laborious on a routine basis. The erratic behaviour of the curve for 36 eigencurrents is believed to be due to breakdown in numerical quadrature routines used for computing interaction between test functions and the magnetic fields and is one reason for abandoning the attempt. Computational economy is another: a point of diminishing returns has been reached as doubling the number of eigencurrents increases the computation time by X8, thus obviating the advantage of the method in producing fast and
Fig. 4-7 Response of horizontal loop system to large vertical plate. Using more eigencurrents improves solution towards inductive limit until breakdown occurs with 36 eigencurrents.
inexpensive turnaround of EM responses. Furthermore, the inductively thin constraint on the model prevents it from reproducing the correct high-frequency limit for any real conductor such as an orebody or laboratory model. Real bodies are inductively thick when the response reaches saturation (by definition, the magnetic field is entirely excluded from the interior of the conductor). For example, the perfectly conducting half-plane produces an anomalous response of approximately -35% (Grant and West, 1965) for the horizontal-loop system set-up of Figure 4-7.

Consistency checks were used to demonstrate the proper performance of the various options and where possible independent tests used (for example, Annan's original test model was duplicated; Jones and Wong (1975) results were also reproduced satisfactorily). However the user of the program is left with the ultimate responsibility in deciding if the precision suits his needs (Dyck et al., 1981). Provision of automatic flagging of unsatisfactory precision based on relative values of the coupling coefficients was considered. The idea was dropped because of the non-monotonic behaviour (see Figure 4-3a) of the coupling coefficients.

4.5.3 Computational precision: SPHERE

For the sphere model, truncation of the double series is chiefly a matter of computational economy. The program routinely uses 150 eigenvalues for each multipole. In order to force convergence of each multipole to precisely the
inductive limit, a special algorithm was implemented. Figure 4-3b shows that the roots of the characteristic equation \( p_{nm} \) reach a constant linear spacing. Since quasistatic EM responses are diffusive rather than resonant in nature, they are usually sampled on a logarithmic basis. It is then sufficient to use eigencurrents whose time constants are spaced as broadly as four per decade (Lamontagne, 1975; Holladay, 1980). The amplitude coefficients for these "predicted" time constants are determined by preserving the relative amplitude density of the analytical expressions and adjusting the level to give the analytically determined inductive limit.

The computational effort in SPHERE is directly proportional to the number of multipoles included. The program uses ten multipoles, and gives an accuracy of better than 1% if both transmitter and receiver dipoles are at least one sphere diameter from the centre. Output from the program allows for examination of individual multipole contributions.

Response to a non-dipolar rectangular loop is computed by Gaussian quadrature. This is physically equivalent to representing the loop with rows of dipoles, appropriately located and weighted. Since the number of dipoles affects the computational effort directly, the order of the Gaussian quadrature is chosen during execution, again leaving the user the responsibility for accuracy of the solution.

Performance of the sphere program was tested with
satisfactory results in a similar manner to the plate program through checks against independent results such as those computed by Lodha (1974) and by Lamontagne (1975).

The results reported here are considered to adequately represent the proper behaviour since, for example, the dynamic time-dependent nature of eddy currents in both models tends to be underestimated due to neglecting higher order terms.

4.6 Scale modelling

Experiments to simulate the response of the Crone PEM to complex conductor configurations were performed on the Geophysics Laboratory scale-model facility (Villegas-Garcia, 1979) which is described briefly in Appendix E. Scaling factors used were

\[ \frac{L_i}{L_m} = 1000; \quad \frac{t_i}{t_m} = 10; \quad \frac{\sigma_i}{\sigma_m} = 10 \]

in order to observe the usual EM scaling condition

\[ \frac{t_m}{\sigma_m \mu_0 L_m} = \frac{t_i}{\sigma_i \mu_0 L_i} \]

where m and f subscripts refer to model and field parameters, respectively, and L is a typical dimension. Positioning errors of 1 mm in the laboratory and 1 m in the field are thus equivalent. The waveform was simulated digitally with 876 points per 1/2 period which translates to
a time resolution of 25 μs, comparable to the field equipment. Graphite (σ_m = 10^6 S/m) was used to simulate thick conductors and targets of varying thickness (σ_i = 1 S/m). Aluminum sheets (σ_m = 2X10^7 S/m) were used to simulate multiple-plate configurations with sheet conductance values ranging from 10 to 1000 S. A comparison of scale-model and computed results is shown in Appendix E.

4.7 Hybrid computer model - interaction with a simple loop

Multiple conductors occur sufficiently often in nature that a powerful enhancement of the computer modelling facility could be realized by incorporating multiple conductor capability. The mutual coupling between conductors can be included in an analytical or numerical solution through an interaction matrix such as in Equation 4-1 where now the current-filament rings exist in more than one body. Implementation of (4-1) in a practical technique such as Annan’s integral-equation method would be cumbersome at best because the eigenvalue problem would require numerical solution for every new geometrical arrangement of the plates. To overcome this objection, we could begin with a set of non-interacting induced current loops in each body specified by an impedance matrix

\[ [R] + iω[L], \]

where both \([R]\) and \([L]\) have diagonal elements only. To include the effects of interaction between current loops in different bodies, we must write, for two interacting bodies
(denoted by subscripts 1 and 2),

\[
\left( [R_1] + i\omega [L_1] \right) I_1 + i\omega [M_{12}] I_2 = V_1
\]

and

\[
(i\omega [M_{21}] I_1 + ( [R_2] + i\omega [L_2] ) I_2 = V_2
\]

where \([M_{12}]\) and \([M_{21}]\) are matrices of mutual inductances between a current loop in one body and all the loops in the other body. A special case of this situation can be easily handled without major alteration to the program structure of PLATE and SPHERE. Let us suppose that body 2 is a single-turn loop in close coupling with the primary transmitter loop such that the currents induced in body 2 are much larger than those in body 1 (a distant conductor). We may then neglect the term containing \([M_{21}] I_1\) and take into account the remaining interaction term by considering the influence of currents in body 2 on the target response as a perturbation or "tertiary effect". It is straightforward to calculate the tertiary effect of a simple loop excited by the primary source. This model is particularly useful in simulating man-made conductors such as powerlines, because the induced currents do not migrate geometrically as they do in a geologic conductor. The secondary field of the simple loop excited by the transmitter via \(f(t)\) is

\[
H^t(t) = A_L f(t) * \{ -\delta(t) + 1/\tau \exp(-t/\tau) \}
\]

where \(\tau\) is the time constant of the loop and \(A_L\) is the mutual coupling between the primary and secondary loops.
The tertiary response is thus

\[ H_{3L}^{3L}(t) = \sum_n c_n \left\{ -\delta(t) + \frac{1}{\tau_n} \exp(-t/\tau_n) \right\} \ast H_l(t) \]

Waveform options 7 and 8 implement this feature for the turn-off portion of the PEM waveform (see Table C-1). To use the tertiary option, judicious selection of values for \( A_L \) and \( \tau \) and secondary-loop location is made by trial-and-error fitting of secondary-loop response to background field observations in non-anomalous regions. These parameters are then used to compute the tertiary effect of the target bodies.
CHAPTER 5

INTERPRETATION WITH SIMPLE MODELS

5.1 Introduction

We are now in a position to apply plate and sphere models in free space to quantitative interpretation. The first step is to determine how the various parameters of the models control the anomaly profile. It will become evident that both time dependence (dynamic properties) and spatial dependence (static properties) of the induced eddy currents are important in the analysis of three-dimensional targets. Geometric variables of the prospecting system are included so that it becomes evident how they can be adjusted to best advantage. Secondly, for the method to be of use in practical interpretation, it must be demonstrated that simple models are, indeed, adequate to explain certain aspects of the field data. While extreme cases are chosen for illustrative purposes, the effects shown are observable in nature; where possible, the useful range of physical parameters is determined.

With few exceptions, the standard Crone PEM profile display is of linear-logarithmic amplitude with the data multiplied by a delay-dependent gain factor (see Figure 3.2). The latter directly affects the apparent decay rate so
that channel 1 is not necessarily the largest amplitude for slowly decaying transients. The channel traces are labelled E (early) and L (late) so that the progression from early to late time is easily ascertained. Two different normalization schemes are used, continuous normalization or point normalization, as indicated in the caption of each diagram. "Continuous normalization" (to measured pulse height) has been applied to the field data. Theoretical responses intended for comparison with field surveys are continuously normalized to the axial component of the primary pulse (secondary field is not included in the pulse but is usually small). All other cases are "point normalized" i.e. ratioed to the total primary field at the centre of the sphere or at the mid-point of the plate edge nearest to the drill hole, as the case may be. Point normalization avoids introducing distortion of the response due to variation of primary field along the profile.

Interpretation of the axial component of the secondary magnetic field is the prime concern of this chapter so that component is presented as a solid trace on all profiles. Transverse components have been included in the model profiles as a broken line since they are available without extra effort from the modelling program and reference will be made to them in Chapter 7.

5.2 Static effects of target geometry

Figures 5-1 and 5-3 show the effect of variable
Fig. 5-1a  Effect of transmitter-target coupling to a flat-lying square plate equal in size to the transmitter loop. The plotted response is for a plate conductance of 100 S when the plate dimension is 100 m. The amplitudes are point normalized to the total primary field at the mid-point of the plate edge nearest the drill hole.
Fig. 5-1b  Effect of transmitter-target coupling for a steeply dipping plate (same parameters as in Figure 5-1a). The amplitudes are point normalized to the total primary field at the mid-point of the plate edge nearest the drill hole.
coupling between the transmitter and the target for plate and sphere models, respectively. The responses have been point-normalized to be independent of primary field strength at the target.

As shown in Figure 5-1a the anomaly shape is relatively independent of transmitter position due to the fixed plane of eddy-current flow. Slight departures from this rule can be appreciated by reference to Figure 5-2. For example, anomaly width is decreased when the primary field on the plate is close to grazing incidence, as occurs with transmitter locations 1 and 3. Coupling of the transmitter to the principal symmetric eigencurrents (orders 1 and 3) is reduced in this case, lessening their contribution to the main current vortex. The total current distribution probably looks more like a figure-eight vortex (order 2 eigencurrent) since the coupling changes sign across the plate. The partial sign reversal (channels 1-5, Tx 1, Figure 5-1a) is caused by primary field reversal on the part of the plate nearest the drill hole. The sign reversal would have been complete for an even more distant transmitter. A similar situation would arise if the transmitter were situated to the right of Tx 3. Determination of direction to target would be very unreliable under such circumstances.

Anomaly shape is affected drastically by change in plate attitude (Figure 5-1b); this is principally due to change in coupling between plate and receiver, and it should be noted that the crossover positions remain relatively
Fig. 5-2 Transmitter-target coupling for models of Figures 5-1a and 5-3. Primary field diagram is taken from Atlas of primary fields (Macnae, 1980).
independent of transmitter location. However, a complete sign reversal may occur with changing transmitter position. A very large transmitter offset is required to observe a reversal for a horizontal plate, especially if the plate is deeply buried, but much less is required when the plate is steeply dipping. Several points in the example confirm the concept of determination of direction as was presented in Figure 4-6. The sign of the anomaly depends on whether or not the plate is between the transmitter and the drill hole. For that information we cannot rely completely on the principal lobe (that part of the anomaly which is opposite the near edge of the plate and which reflects the symmetric contribution to the profile; see Figure 4-6). For example, a direction ambiguity would result between transmitter 1, dip -60°, and transmitter 3, dip +60°. Instead, the profile asymmetry resulting from the antisymmetric contribution makes it possible to resolve the ambiguity, if enough of the profile can be observed.

Figure 5-3 illustrates a similar study for a spherical target. Because the eddy-current distribution is not confined to a simple plane, the anomaly shape strongly depends on primary field direction. The crossover depth shifts noticeably as the transmitter location is varied. Determination of direction is straightforward for a spherical target as the necessary profile asymmetry can be produced by judicious choice of transmitter offset, unlike the case of a tabular body.
Fig. 5-3  Effect of transmitter-target coupling for a sphere whose diameter is equal to one side of square transmitter loop. The responses are for a sphere of conductivity 1 S/m when the diameter is set at 100 m. The amplitudes are point normalized to the total primary field at the centre of the sphere.
Fig. 5-4 Plate and sphere models compared to field data from GERT-9266. (a) Crone Pulse EM field data. (b) Updip plate. (c) Downdip plate. (d) Sphere. (e) Section. (f) Plan and component legend (note compressed scale). Amplitudes are continuously normalized to axial primary field. Models are placed symmetrically with respect to N-S section through GERT-9266.
Figure 5-4 shows a comparison between Pulse EM field data from GERT-9266 and several theoretical models chosen to explain the upper anomaly (anomaly A, depth 310 m). The updip plate model (b) provides the best simulation of the gross anomaly characteristics and the best correspondence with the known geology. The downdip plate (c), which in the absence of grid-drilling information would have been equally acceptable geologically, must be rejected on the basis of the sharply diminished south-loop response due to poorer coupling; the mirror image of plate (c) must be rejected on similar grounds as it would have produced a small north-loop response. The sphere (d) was located to reproduce the observed anomaly peak location for the north transmitter loop and its size adjusted to obtain a reasonable peak amplitude. A large spherical conductor is unacceptable on the basis of the known geology. However, the model shows that such a shape would have resulted in a very large shift of the upper crossover (about 90 m) when the south transmitter was used. While detailed discussion of the sphere-like character of the anomaly is reserved for later, it should be pointed out that the crossover of the observed late-time channels (4-8) does appear to be both time and transmitter dependent; this suggests that at late time, the conductor does behave somewhat like a sphere.

Figure 5-5 explores the influence of conductor size and location on anomaly width which, in this diagram, is defined as the distance between null-points (crossover separation),
Fig. 5-5 Crossover separation as a function of plate dimensions, $S$ and $W$, and clearance, $C$ (borehole to near edge distance). $D$ is the depth of a flat-lying plate. All units are normalized to $S$. 
a parameter previously used by Woods (1975). For a sphere, the principle moment is dipolar and so the crossover separation is approximately equal to \( \sqrt{2} \) times lateral displacement of its centre. Small plates far from the hole would have similar dependence. For nearby plates, the crossover separation is a more complicated function of plate dimensions and clearance. When \( W > 2 \), the dependence on \( W \) lessens, indicating that the smaller plate dimension controls the anomaly width. This diagram should serve only as a preliminary guide in fitting plate size and clearance to an observed response. Without full model fitting the charts are only useful in placing upper or lower limits on interpreted values of \( W \) and \( C \). Furthermore, other parameters can affect the crossover separation. The depth of burial (Figure 5-5a) is one of these. Figure 5-1 shows also that for the plate model, crossover separation is dependent on coupling aspects, at least in the extreme cases shown.

5.3 Dynamic effects of eddy-current behaviour

Time or frequency migration of eddy currents in a plate can be predicted on the basis of varying contribution of the eigencurrents to the total current vortex, as we have seen in Chapter 4. The current migration manifests itself as crossover migration in the anomaly profiles as shown schematically in Figure 5-6a. At the inductive limit, the induced current vortex is forced closer to the edge of the conductor producing a relatively narrow anomaly in a nearby
Fig. 5-6  Effects of eddy-current migration on crossover position, (a) schematically, and b) for pulse, step, and frequency systems. The amplitudes are point normalized to the total primary field at the mid-point of the plate edge nearest the drill hole.

N.B. Linear-logarithmic scale for UTEM data.
drill hole. As the response progresses to the resistive limit, the current ring collapses away from the drill hole and towards the centre of the plate, thus spreading the anomaly. The current ring also becomes less concentrated in the process. Figure 5-6b shows how eddy current migration is displayed by three different EM systems. Note that PEM and UTEM responses are plotted on identical log-linear amplitude scales. As predicted in Chapter 4, PEM indeed shows stronger crossover migration, in this case about 5% of the plate dimensions. The frequency-domain profile shows the same phenomenon but it is somewhat obscured by the linear amplitude scale. Close examination, however, reveals that the crossovers migrate outward with decreasing frequency and that the in-phase separation is larger than the quadrature for the same frequency.

As crossover separation for a plate model is dependent on the size of the plate and the clearance, we also expect the migration distance to be dependent on both parameters. When the geometric conditions are favourable, crossover migration should be detectable if the anomalous response is strong enough to be observed throughout at least one decade of time or frequency. A field example from the FC266 orebody in Figure 5-7 shows the migration to be observable in nature. Anomaly B is caused by a conductor sufficiently large and closeby to produce a significant migration, while the conductor producing anomaly A is too small and/or too distant.
Fig. 5-7  Field example of crossover migration. Anomaly B shows migration; anomaly A does not. Amplitudes are continuously normalized to axial primary field.
Figure 5-8a depicts schematically how we expect diffusion of the eddy currents to take place through a sphere in a direction away from the transmitter. Both crossovers and the anomaly peak should migrate downwards, as the contribution of the higher order asymmetric multipole modes diminishes. Figure 5-8b shows the model response as a function of conductivity. A conductivity of 100 S/m places the whole response near the inductive limit so no migration occurs but all traces are highly asymmetric. Lowering the conductivity to 10 S/m changes the decay rate only slightly but significant migration occurs, about 50-70% of the sphere radius. Significant migration is still evident with the conductivity lower still (1 S/m), so it appears that diffusion effects are again readily visible throughout one decade of time (or frequency). The magnitude of migration depends, of course, on the sphere diameter and the degree of non-uniformity of primary field across it. The results of Figure 5-3 predict that migration effects should be detectable even when the sphere is two diameters away from the transmitter.

While diffusion effects can be strong in theory, to observe clear cut examples in nature is much more difficult. The GERT-9266 response shown in Figure 5-4 is certainly the most striking example, exhibiting marked downward migration of the peak (10-15 m channels 1-8) and corresponding downward movement of the early-time crossovers, as predicted by the sphere model shown in the same diagram. As mentioned
Fig. 5-8  Effect of eddy-current diffusion through a sphere for the layout of Tx 2 in Figure 5-3. The amplitudes are point normalized to the total primary field at the centre of the sphere.
previously, the sphere model is geologically unrealistic but the apparent diffusion effect is difficult to ignore. The effect will be investigated with scale-model experiments in Chapter 6.

Figure 5-9 shows three possible diffusion examples, from FC266. The first of these, hole -D246, shows downward migration of approximately 5 m at the T contact (anomaly A). The migration is presumably an indication of the thickness of the ore conductor at its north end. The ore cap has a known thickness of only 9 m, but it is conceivable that the underlying feeder pipe zone of disseminated mineralization is also contributing. Anomaly B in hole -D226 shows us that the feeder zone is quite conductive as its decay is not noticeably faster than the T-contact anomaly in the same hole. Due to the noisy traces in this area considerable imagination is required, but some peak migration can perhaps be identified on the B anomaly as well. Anomaly C in hole -D240 is different again. It exhibits a low amplitude but slowly decaying feature centred just above a sharp four-channel anomaly at the T-contact. Geological data for the area indicates that a dyke severs near-hole sulphides from the sulphides in the main lens cap, accounting for the two distinct responses. The hint of peak migration in the C anomaly is believed due to a rather steep slope of the top face of the lens, which increases its effective thickness. Although these three examples may, admittedly, not be totally convincing, they serve to show how even subtle
Fig. 5-9  Field examples of eddy-current diffusion. The profiles have been positioned to level the T contact on the diagram. Amplitudes are continuously normalized to axial primary field.
changes in anomaly character may be useful indicators of a lens- or sphere-like target. It should be emphasized that the small size of the target in this example relative to its depth of burial is a condition far from ideal for producing noticeable diffusion.

Returning to migration of eddy currents in plates, we examine the case where the plate is not perpendicular to the drill hole. A shift in the effective eddy-current axis is seen as a lateral displacement of the anomaly along the profile, as shown schematically in Figure 5-10a. Peak migration occurs in the direction of dip and the dip-side crossover migration is enhanced at the expense of the other. For a plate updip from the drill hole, the migration will be opposite to that of a sphere; migration due to a downdip plate will be distinguishable from that of a sphere only by the absence of migration of the upper crossover.

The examples in Figure 5-10b show that a ± 30° dip influences the crossover migrations only slightly and produces a minimal peak migration which may not be visible in field data. A dip of ± 60° produces a more readily visible effect. The plate has been placed with its near edge at a depth of 200 m to minimize the effects of coupling between transmitter and plate. However the -60° example is nearly null coupled to the lower portion of the plate. The early-time eddy currents are not concentrated as closely as usual to the lower edge and so the early-time upper crossover does not obey the general predictions. It is
Fig. 5-10  Effect of non-perpendicular attitude on observation of eddy-current migration in plate conductor. (a) schematic; (b) computed; plate is equal in size to square loop (Tx 5 of Figure 5-1a). If plate dimension is 100 m., then responses correspond to conductivity-thickness of 100 S. The amplitudes are point normalized to the total primary field at the mid-point of the plate edge nearest the drill hole.
controlled mostly by the currents in the upper portion of the plate. Thus we observe an upper crossover migration which is opposite in direction to that normal for a plate. The effect is even more pronounced when the plate is shallower as shown in Figure 5-1b.

Examples of migration due to plate dip are relatively easy to find in field data. Profiles containing examples have been previously shown so they will only be listed here.

Example 1: GW-23090, Figure 3-8, peak migration 180+170 m and exaggerated migration of upper crossover. Interpretation:- Dip in the vicinity of drill hole must approach vertical to produce such a strong effect; alternatively, migration could be enhanced by inhomogeneity of the plate (conductance increasing away from edge).

Example 2: GW-29303, Figure 3-8, peak migration 200+180 m, same comments as Example 1.

Example 3: FC266-D223, Figure 5-7, B anomaly at B contact, migration 580+570 m, enhanced upper crossover migration, probably due to updip plate conductor (away from orebody).

Example 4: FC266-D240, Figure 5-9, B contact, migration 700+695 m, updip plate conductor (beneath orebody).

Example 5: FC266-D226, Figure 5-9, T contact, migration 610+600 m, updip plate, (edge of orebody).

Example 6: FC266-D229, not shown, T contact, migration 625+628 m, not distinguishable from sphere effect.

It will be noticed that all examples, except number 6,
are indicators of updip conductors.

5.4 Range of investigation

The range of investigation involves not only the ultimate clearance at which a target can be detected but also the maximum distance at which diagnostic features can be recognized. Since there are many variables which affect the range of investigation, such as instrument sensitivity, geological noise, cultural artifacts, etc., it is instructive to examine how the character of the response could change as a function of clearance using the modelling programs.

The plate response as a function of increasing clearance has been previously discussed in Section 5.2, the main effect being that of increased crossover separation and diminished anomaly amplitude. Of additional interest is the sphere fall-off behaviour shown in Figure 5-11 which is due to the diminishing contribution of higher order multipoles. Since the principle mode is dipolar, amplitude and crossover separation obey the dipolar law, especially for late time when the dipole term predominates. Of course the dipole term can contribute to asymmetry when the profile is not parallel to the primary field at the centre of the sphere. However, the asymmetric contributions from higher order multipoles reduce as the fourth or greater power of the distance (the second order, with $r^{-4}$ dependence, is the strongest asymmetric multipole, see Figure 4-5). The migration effect
Fig. 5-11  Effect of increasing clearance on sphere anomaly and magnitude of the diffusion effect. Model corresponds to layout of Tx 2 in Figure 5-3. The amplitudes are point normalized to the total primary field at the centre of the sphere. The diffusion effect is visible even at a clearance of one radius.
is visible even at 2 radii from the sphere's centre because it has been attenuated by only twice as much as the anomaly amplitude.

The GERTrude case affords an opportunity to test the distance dependence predicted by plate and sphere models using GER-9279 which is 125 m north and 125 m west of GER-9266, data for which was shown with fitted models in Figure 5-4. Figure 5-12 compares model data for the updip plate and sphere of Figure 5-4 with GER-9279 field observations. If we concentrate on the late-time response, we see that the predictions of both models are reasonable, the plate predicting the amplitude more correctly. Both models predict the peak location to be at least 50 m below the conductor at this distance, in agreement with the observations. Position of the anomaly crossover is less agreeable but it may be displaced by the early-time anomaly at 300 m. One must conclude that the upper anomaly has a separate source, perhaps the same conductor as the one detected in GER-9273 at 220 m although this interpretation has not been modelled. By identifying the common source of anomalous responses in two widely separated drill holes as the main GERTrude orebody, we have determined the operating range of the Pulse EM system to be 150 m, or a distance approximately equal to the dimensions of the target.

5.5 Rate of decay

In this section we examine PEM decay behaviour. To
Fig. 5-12: Modelling of GERT-9279 response for models also shown in Figure 5-4: (a) Pulse EM field data, (b) Updip plate, (d) sphere. (Note: plan has compressed scale). Amplitudes are continuously normalized to axial primary field. The plate model predicts better than the sphere model the anomaly fall-off with distance.
facilitate comparison with profile data, amplitudes including the standard Crone time-dependent gain factor are plotted on the usual linear-logarithmic scale. Response is plotted in Figure 5-13 as a logarithmic function of mean window delay.

Plate and sphere models are intended to illustrate typical behaviour but have been chosen to approximate the GERTrude conditions. The models for Figure 5-4 were selected to give a decay which persists to the late channels, thus causing a bunching of the early-time amplitudes, and even an apparent growth with time, due to the Crone variable-gain factor. Figure 5-13a,b illustrates and shows for comparison the GERT-9266 decay at 310 m, obviously quite different. The conductance window for strong anomalous response for this particular model is from 10 S to 300 S. For larger conductances the response diminishes due to the $1/T$ factor in the amplitude coefficient for the pulse response. A homogeneous sphere model with the size shown has a corresponding response window from 0.1 to 10 S/m. Neither model can simulate the distinctly double-staged decay which was observed at GERTrude.

Figure 5-13c shows the decay for a layered sphere with the core 100 times more conductive than the shell. As the core is allowed to shrink (B/A: 1-$\infty$) the decay changes from that of a homogeneous sphere with conductivity of the core to that of a homogeneous sphere with conductivity of the shell. When the core radius is 0.5 of the total radius a
Fig. 5-13 Pulse EM transient behaviour for several GERTrude models of Figure 5-4, (north loop response). (a) Updip plate and field data; (b,c,d) sphere. Decays are shown for the peak response at 310 m depth.
plateau develops which is similar to the GERTrude decay, another indication of its sphere properties.

Figure 5-13d shows the effect of magnetic permeability on the Pulse EM response, which is to boost the initial amplitude and slow the decay. Permeability effects can be observed independently of conductivity effects only when the system function is "on". For the Crone PEM system this is limited to the duration of the primary pulse. The effect of permeability is, however, directly observable in the late-time response of the UTEM system as a non-decaying anomaly (Lamontagne, 1975).

5.6 Modelling of UTEM and multifrequency EM

The updip-plate model (b) of Figure 5-4 produces the UTEM and multifrequency profiles for GERT-9266 shown in Figure 5-14a. Both responses clearly approach the inductive limit at the shortest delay times and highest frequencies. The UTEM response is larger than the frequency response by a factor of two due to the normalization scheme employed by the UTEM system:- step amplitude = 200%. Comparison with the GERTrude field data (Figure 3-6) shows that the gross anomaly shapes and locations are reasonably well simulated. The UTEM model agrees well in amplitude for the earliest channel (No. 7) measured, but as with the Pulse EM response, the theoretical model decay is too slow for early channels and too quick for late channels to match the field amplitudes correctly. Not shown here are the UTEM
Fig. 5-14a  GERT-9266 multifrequency and UTEM response calculated for model of Figure 5-4 ( updip plate) for comparison to field data of Figure 3-6. Amplitudes are continuously normalized to axial primary field.
Fig. 5-14b  GERT-9266: step response transients and frequency spectra for plate and sphere models and field data. The layered sphere predicts the two-stage behaviour observed in the field data.
response and model for GERT-9279, which are in good agreement with one another and exhibit the same features as the Pulse EM response.

Similar comparison of the multifrequency data also shows a discrepancy. The same plate model (b) predicts approximately the correct phase behaviour, i.e. maximum quadrature at a frequency of 315 Hz, but the predicted amplitudes are too low (by a factor of two at 2835 Hz). The explanation lies in the degree of definition of the inductive limit as is evident upon examination of Figure 5-14b. For detailed comparison between frequency spectrum and UTEM decay, the frequencies are plotted in decreasing order on the same logarithmic scale as the UTEM channel delay times. UTEM channel 9 (0.049 ms delay) is plotted as equivalent to a frequency of 2835 Hz on the basis of the model responses shown. Both the plate (b) and homogeneous sphere (d) responses exhibit a clear inductive limit. These models are a poor basis for amplitude comparison to the field data, as neither the UTEM or multifrequency observations define such a clear inductive limit. UTEM in particular, fails to do this, being band limited by the downhole sensor to channel 7 as the earliest time delay measurable. By extrapolating the UTEM and multifrequency data to the inductive limit, we see that the UTEM response is larger roughly by a factor of two, as expected.

A layered sphere model was demonstrated in Figure 5-13c to predict the two-stage Pulse EM decay. Figure 5-14b
shows that UTEM and multifrequency responses for the same model also predict the two-stage behaviour in the respective field observations. An increase in size of the sphere and/or reduction in its clearance would be required to give a better amplitude match. Lodha (1977) has shown that it is possible to achieve a reasonable interpretation of a two-stage UTEM decay by fitting each portion of the decay separately using different plate models. The difficulty in applying the same procedure to the present problem would appear to lie in matching both the decay pattern and the geometric shape of the anomaly simultaneously.

5.7 Interference between target conductors and powerlines

Profiles from the POWder MAGazine test site exhibit a very smooth systematic anomalous response everywhere at early times. Figure 5-15 shows that this "background" can be modelled with fair accuracy by assuming the cause to be a single-turn loop on the surface (secondary loop) in close coupling with the primary transmitter loop. Excitation of the "secondary" loop is not determined directly; rather the size of the loop, the mutual coupling factor between the two loops, and the time constant of the exponential decay are determined by trial and error so that the computed background simulates the observed background. The computed background shown in Figure 5-15c and -15e is the PEM response of a secondary loop 2500 X 2500 m, approximately concentric with the primary loop, with a time constant of
Fig. 5-15  Tertiary effects of background secondary response; models chosen appropriate to POWder MAGazine site (plate 300 x 300 m, conductance 100 S, located at D = 530 m and 65 m from drillhole). Amplitudes are continuously normalized to axial primary field. The tertiary response has noticeable effect on the anomaly shape.
0.5 ms. The model response (secondary effect only) shown in Figure 5-15b was chosen for illustrative purpose only, and is not intended as an interpretation of the geology. Figure 5-15c shows the computed background added to the model response, with interaction between the model and the secondary loop not included. Notice that distortion due to the logarithmic display alone casts the superimposed anomaly into a form which resembles the field data.

Figure 5-15d shows the response of the model when excited by the secondary loop (tertiary response). The tertiary response provides a means of evaluating the significance of the distortion of the primary field by the background response of the secondary loop. As the secondary loop is larger than the primary loop the distortion grows with depth, thereby having substantial influence on quantitative modelling procedures. As can be seen from the combined secondary and tertiary effect in Figure 5-15f, the interpreted conductor quality is affected by an increase in the apparent decay rate. The final model consisting of background plus secondary and tertiary responses is shown in Figure 5-14e. Ideally, interpretation would take place with the background subtracted, i.e. the field equivalent of Figure 5-14f. This is possible only with higher precision data, not data with logarithmic sensitivity such as is acquired with the present Pulse EM equipment.
5.8 Modelling of intersections

Because the PLATE modelling program represents induced current systems as the sum of only 15 test functions (eigencurrents), it is incapable of accurately modelling situations where nearby fine details and far away broad features of the current systems both have significant influence on the anomaly profile. The limitation is not considered a serious shortcoming by itself since an ideal uniform plate model would itself be inadequate in simulating sharp local anomalies which usually reflect irregularly distributed sulphides. Modelling of the flanks of the anomaly does, however, seem possible, and can give an estimate of the lateral extent of the conductor. GERT-9273 shown in Figure 5-16 is an example. If we concentrate on the late-time channels, the 150 X 150 m plate obviously gives a better fit than a 50 X 50 m plate, in agreement with the known geology.

5.9 Exploration example

Figure 5-17 shows the interpretation of a survey carried out in a Precambrian environment. Very limited information was available to the author, a situation which is common in exploration. Figure 5-17a shows in plan and section the four transmitter loops employed in four quadrants around the collar of a 45° drill hole. Two possible models are shown also. Figure 5-17b shows a tabulation of the field data compared to the model
Fig. 5-16  Modelling of anomaly due to intersected conductor using plate of two different sizes and a conductance of 50 S. Poorly computed response near and through plate has been removed. Amplitudes are continuously normalized to axial primary field.
Fig. 5-17  Example of interpreted sphere and plate models for exploration survey in Precambrian environment using four transmitter loops around inclined drillhole. The amplitudes are point normalized to the primary field. Pulse EM channels 1, 3, and 5 only, are plotted.
The field profiles form mirror images if taken in east-west and north-south pairs. Also the depth of the crossover is independent of transmitter position. Furthermore the slow decay with time indicates that the feature is of high conductivity. Both plate and sphere models simulate the observed sign reversals. The plate model is more successful in predicting the absence of crossover shift with transmitter loop location. However, the plate is incompatible with the preferred geological strike direction which has been inferred to be perpendicular to the azimuth of the drill hole. The sphere model lies roughly along strike from the observed minor mineralization in the drill core. We can speculate that the gross features are best explained by a blob or sphere-like conductor with possible plate-like extension towards the drill hole to explain the fixed crossover. Some reassurance can be had in the fact that a single additional drill hole can be specified which would reach either target. Without the aid of the computer programs, however, it would have been difficult indeed to unscramble the observations.
CHAPTER 6

SPECIALIZED MODELS

6.1 Description

Although the sphere and plate models can explain many features of field EM profiles in drill holes, they are inadequate to explain others (for example, there are unresolved conflicts in details of the GERTrude observations). To study some of the additional complexities, analogue scale-model experiments were undertaken. The principal situations investigated were: 1. Conductive blocks of uniform and variable thickness; 2. Multiple thin plate conductors. Although the experiments are not intended to precisely simulate any one set of data, they have been chosen appropriate to GERTrude, using north- and south-loop transmitters, size and locations of conductors which approximate the conditions at that site. Scale-model results are generally noisier than computed responses, so to prevent trace crossing only the odd-numbered channels of the axial component are presented (with identification); late channels have been dropped if variations therein were deemed insignificant with respect to the noise level.
6.2 Block conductors

Figure 6-1 shows the response of a tabular body with a scaled thickness of 25 m and conductivity of 1 S/m. No diffusion effects are evident, although the thickness of the conductor has some observable influence, depending on transmitter-plate coupling, which is believed due to the effect of geometric thickness on crossover positions and their migration patterns. Absence of diffusion effects is consistent with the requirement for both inductive and geometric thickness; both conditions are necessary for the eddy-current vortex to travel through the conductor a significant distance. The importance of skin effect in the conductor increases as the ratio R (thickness / skin depth) increases. Lamontagne and West (1971) suggest that thickness must be considered if R > 0.5. From their results we can determine that R \leq 1.2 will allow < 10% depletion of current density within the interior of the conductor, an acceptable tolerance in working with logarithmic secondary-field amplitudes. We conclude that the conductor of Figure 6-1, for which Pulse EM channel 1 has an equivalent skin depth of approximately 20 m, is inductively thin (R = 1.25). This conclusion is confirmed by the decay pattern (not shown) which is not significantly different from the interpolated decay pattern of a thin plate of the same conductance.

Observed departures from the equivalent thin-plate anomaly (whose crossovers are represented in Figure 6-1 by
Fig. 6-1 Pulse EM response of a thick conductor (300 x 150 m strike length, 25 m thick, conductivity 1 S/m) for channels 1, 3 and 5. The position and direction of crossover migration of coincident thin plate of same lateral dimensions are indicated by arrows. The thick plate increases the crossover separation slightly. Amplitudes are continuously normalized to axial primary field.
arrows) are thus due to geometric thickness effects, i.e. due to eddy currents which are not strictly confined to one plane. The most striking example is the response of the downdip thick plate excited by the south loop. The corresponding thin plate has a normal but small-amplitude signature as it is in nearly null coupling with the primary field. However, the primary field couples well with the edge face of the thick body, producing an asymmetric signature characteristic of a secondary moment nearly perpendicular to the drill hole. The decay of this "edge-face" response is rapid by virtue of the relatively small area of conductor exposed to the inducing field. The other profiles in Figure 6-1 are dominated by the normal mode of induction in the principle plane of the conductor. Crossover separation is, in general, greater than for the thin-plate counterpart by a distance comparable to the finite thickness of the induced current vortex. Modification of the crossover migration pattern is due to contribution of the edge-face response. For example, the response of the updip thick body in the field of the south loop shows the effect of an asymmetric component similar, but of opposite sign, to that of the downdip thick plate excited by the same loop. The effect is observable as downward enhancement of lower crossover migration and a slight reversal (downward) of upper crossover migration. Recognition of such effects in field data would obviously be of practical use in determining direction to the target.
Figure 6-2 shows the response of a block which is thicker (50 m) than its clearance (30 m). The difference in anomaly produced by the two loops is due to contributions by the edge-face response which are of opposite polarity (due to reversal of primary field direction across the edge face). In the south-loop response this causes reduction and enhancement of upper and lower crossover migrations, respectively, as well as some downward shift of peak response. The same effects, but of opposite sense, are even more readily observable in the north-loop response. The mechanism may be thought of as an induced moment which rotates with time. The early-time response of the north loop exhibits asymmetry characteristic of a sphere excited by a near-horizontal field. The late-time anomaly shows that the current vortex has stabilized in a horizontal plane. Accordingly, the early- and late-time limits could be computer modelled using SPHERE and PLATE, respectively. It will be noticed also that the north-loop anomaly decays more rapidly due to transmitter-plate coupling which varies appreciably over the conductor due to its great length. The placement of the south loop, however, produces a more consistently good coupling over the area of the plate, thus increasing the decay time of the response.

Additional complexity is introduced by variable thickness as is shown in Figure 6-3. A conducting wedge with its thin edge nearby the drill hole and excited by the south loop produces a very broad anomaly. This is characteristic
Fig. 6-2  Pulse EM response for tabular body (750 x 300 m strike length, 50 m thick, conductivity 1 S/m). The north loop induces a "rotating moment effect". Amplitudes are continuously normalized to axial primary field.
Fig. 6-3 Pulse EM response for wedge (375 X 400 m strike length, 0 -> 75 m thick, and conductivity 1 S). Amplitudes are continuously normalized to axial primary field. Accelerated eddy-current migration is visible when the thin edge is nearer the drill hole.
of a distant plate vortex and indicates that the thick part is contributing most to the induction. Movement of eddy current away from the edge is accelerated by increasing conductance, thus contributing to the enhancement of crossover migration. Such an effect in a body dipping towards the drill hole is likely the cause of the very prominent peak and crossover migration observed at Gertrude West (Figure 3-8). The north-loop response for the same conductor shows considerably reduced crossover separation, reduced peak amplitude, and faster decay, all symptomatic of primary field coupling which is much better with the thinner portion of the wedge. The apparent quality of the conductor is thus strongly coupling dependent.

When the thick portion of the wedge is nearest the drill hole, its response resembles that of a uniformly thick body. The main features are the "rotating moment" effect, which appears even more strongly than previously due to increased edge-face response, and a relatively weaker late-time response caused by reduced conductance of the bulk of the conductor.

6.3 Multiple plates

Possible double-plate conductors have been encountered at GERTrude and FC266 sites. Figure 6-4 shows that significant interaction can occur even for relatively poorly conducting plates (conductance 10 S) provided the plates are close enough together, in this case 40 m, for plates 300 X
Fig. 6-4  Pulse EM response of double-plate conductor. Transients are plotted for peak responses at U (Upper) and L (Lower) plate. L & U signifies the combined response including interaction; L & U - U means that the U plate response has been subtracted. Amplitudes are continuously normalized to axial primary field. The two plates behave together like a laminated thick body.
150 m. As the plotted transients show, interaction slows the
decay compared to the single-plate values. We see also that
spatial resolution is better at higher induction number
(early time or larger conductance); this would be expected
on the basis of greater concentration of eddy-currents near
the edges of the plates. Although the plates are of equal
conductance, the upper plate has the stronger peak at early
time while the lower plate has the larger peak at somewhat
later time, akin to diffusion through a "thick" conductor.
The two plates behave rather like a single thick body but
lamination of the conductor precludes induction in the edge
face.

Figure 6-5 shows the combined response of two plates of
differing conductivities. When the poorer conductor is on
top (Figure 6-5a), the upper crossover shows a reversal from
the usual direction of migration. The lower crossover
undergoes reverse migration when the poorer conductor is
underneath (Figure 6-5b). The reversal occurs on the side of
the poorer conductor due to the differential offset caused
by a more rapid decay. Otherwise general anomaly shape is
similar to the thick conductor of Figure 6-1. Resolution of
the two conductors at early time is dependent on the primary
field coupling. At late time the anomaly stabilizes on the
plate with the higher conductance, a practical demonstration
of Kaufman's (1978b) resolving power. An interesting case
occurs when the plates are minimum coupled with the primary
field: only the higher conductance plate generates an
Fig. 6-5a  Pulse EM response of double-plate conductors (300 x 150 m. strike length) showing the effect of dip for top plate less conductive (10 and 40 S conductance). Amplitudes are continuously normalized to axial primary field. The upper crossover migrates in the reverse direction from that of a single thin plate.
Fig. 6-5b  Pulse EM response of double-plate conductors (300 X 150 m. strike length) showing the effect of dip for top plate more conductive (40 and 10 S conductance). Amplitudes are continuously normalized to axial primary field. The lower crossover migrates in the reverse direction from that of a single thin plate.
anomaly and its anomaly has been enhanced, compared to its isolated response, by its association with the second plate.

A double plate conductor can produce sphere-like diffusion effects when the upper plate is less conductive. When the lower plate is less conductive the apparent diffusion effect (i.e. crossover migration) is upward. The effect may be indistinguishable from the rotating moment effect due to edge-face response in a thick conductor.

The final example (Figure 6-6) compares a double-plate response (both plates updip) to that of combined updip and downdip plates. High conductance values (1000 and 120 S) have been deliberately chosen to produce an exaggerated effect. We see that at Channel 7 the peak response is in the process of shifting to the higher quality conductor. The model was prompted by the GERTrude problem. Whereas Figure 5-4 shows that the updip-downdip ambiguity for isolated plates is easily resolved on the basis of primary field coupling, the presence of another conductor can alter that through interaction effects. Direction to a target might be difficult to determine under such circumstances.
Fig. 6-6  Pulse EM response for combined updip and downdip double plates (300 X 150 m. strike length) with conductances of 1000 and 120 S., respectively. Amplitudes are continuously normalized to axial primary field. Determination of direction to the lower body is complicated by the presence of the upper body.
CHAPTER 7

TRANSVERSE MAGNETIC COMPONENTS

7.1 Problems

We have limited the discussion, thus far, to the interpretation of drill hole EM observations made with a single-component, axial magnetic field sensor. The question arises: can the measurement of three orthogonal components assist in resolving ambiguities of interpretation? There are three problem areas associated with the use of the two additional components oriented at right angles to the drill hole (transverse components): design and fabrication of transverse sensors, orientation of sensors during measurement, and interpretation of a three-component data set.

The instrumentation problem is one of packaging sufficiently sensitive sensors transversely into small diameter housings (preferably with an outside diameter less than 37 mm). Worthington et al. (1981), using a novel mu-metal construction have shown this to be feasible at an operating frequency of 2 kHz. Construction of a wideband sensor to operate at frequencies down to 20 Hz presents an even greater challenge. The wideband specification, as we have demonstrated here for the axial component, is necessary
for geological selectivity.

The second problem concerns knowledge of the orientation of the device during the measurement process. All standard solutions appear to have shortcomings: use of the earth's magnetic field may be adversely affected by nearby magnetic minerals; gravity devices do not function in vertical or near vertical holes; miniature gyroscopic stabilizers are limited in accuracy by drift problems and have very high cost. The primary EM field can furnish the orientation reference provided, of course, that the primary field can be separated from any secondary field that may exist. The proviso may be difficult to achieve in a very magnetic and/or conductive environment but the approach would obviate the need for additional devices in the downhole probe.

A third problem is the interpretation of a full three-component data set. Measurement of transverse components in a drill hole is, with respect to the direction of the profile, equivalent to the usual vertical component measurement in surface surveys while the axial component corresponds to the surface horizontal component. Limited use is normally made of three components on the surface, but where tried, the extra data has been found helpful in refining the interpreted position, attitude, and depth of the target (for example, Barnett, 1977; Barnett et al., 1978). As the technological problems are severe, we will concentrate here on demonstrating a means of interpreting
the data.

7.2 Benefits

Figure 4-6 illustrates schematically the principal advantage to be gained by performing three-component drill-hole surveys. In case (a) where the profile samples only one lobe of the secondary field, the appropriate transverse component gives unambiguous direction to the source, whereas in case (b) it does not. This is the complement of the information supplied by the axial component as shown in the same diagram.

As we will see, it is desirable, even with three-component observations available, to use the behavioural variations of transmitter-target coupling to avoid misinterpretation of conductor location. However, for conductors buried deeply in comparison to size, this problem is minimized. Figure 7-1 shows simulated responses for plate and sphere models which demonstrate, in unequivocal fashion, the hypothetical determination of location of the FC266 lens. Both models were chosen to approximate the axial (Z) component response of the northern end of the lens closest to the three drill holes FC266-D219, -D246, and -D240. As the primary field is essentially vertical at the location of the models, the Z-component data is useful for direction determination only in conjunction with other information such as advance knowledge of the dip. However, sign of the X and Y component responses depends uniquely on which quadrant
Fig. 7-1  Pulse EM three-component responses computed for FC-266 using a plate model (left-hand side) and a sphere model (right-hand side). Amplitudes are continuously normalized to axial primary field. Direction to the conductor is easily determined from the ratio of peaks of the X and Y components.
the target occupies with respect to the drill hole. By simple vector summation of the X and Y components, azimuth of the conductor’s centre can be determined to within about 5°, so that each profile could independently have provided the necessary information.

Reference to model responses from Chapter 5 illustrates the general behaviour of the transverse components. The X-component in Figure 5-1a, for example, has polarity which depends on whether the target is in the positive or negative direction from the drill hole. No Y-component exists in Figures 5-1 and 5-3 because the drill hole, conductor, and transmitter are all symmetric about the X-Z plane. In Figure 5-1, the response due to transmitter 1 indicates that distinction must be made between sign dependence based on location of the plate and sign dependence based on coupling between plate and transmitter. We see that dip of a plate conductor could be determined from the ratio of peak amplitudes of the X component. Figure 5-1b also shows that when the dip reaches ± 60°, the Z component contains the most diagnostic direction information.

Just as the axial-component response for a sphere is strongly dependent on transmitter location, so is the transverse-component response. Primary field orientation for transmitters 1 and 3 is such that the Z component contains all directional information. The anomaly for the X components is observed to be proportionately wider than the corresponding Z-component anomaly for transmitter 2 due to
the flattened shape of the dipole lobes.

Dynamic behaviour observable in transverse-component profiles is largely predictable from the Z-component response. A possible by-product of the additional components is that crossover migration of transverse components may be more readily detectable than the peak migration of the axial component, provided that all components are measured with equal sensitivity. Tx's 1 and 3 (Figure 5-3) generate a feature of interest in the X component of the sphere response which is not observable in the axial component, viz, diffusion through the sphere toward and away from the drill hole is observed through outward and inward crossover migrations of the X component, respectively.

Additional complexity arises when the transmitter is offset from the plane of symmetry, thus introducing a Y-component anomaly. Figure 7-2 demonstrates the effect for a square plate: the X- and Y-component anomalies have similar shapes. The symmetric eigencurrents do not contribute to this effect, only those eigencurrents which are antisymmetric and are excited by the (in this case) asymmetric primary field. Determination of the conductor's location from the ratio of X- and Y-peak amplitudes gives an apparent azimuth rotated from the plate's centre towards the transmitter. Error in azimuth determined by the same procedure is amplified when a plate conductor dips towards the drill hole. For example, a plate excited by transmitter 2 and dipping -60° gives a departure of 30° from the true
Fig 7-2  Pulse EM three-component responses computed for plate model of Figure 5-1 but with transmitter offset from vertical plane of symmetry (X-Z plane). Plate is 100 X 100 m, conductance = 100 S. The amplitudes are point normalized to the total primary field at the mid-point of the plate edge nearest the drill hole. The Y-component response is due to the offset of the transmitter.
azimuth of the plate centre, based on $Y/X = 0.5$ observed at a depth of 50 m.

Different behaviour characterizes the response of a sphere model excited by a transmitter offset from the vertical plane of symmetry ($X-Z$ plane) as is shown in Figure 7-3. In this case rotation of the secondary moment towards the transmitter produces a unipolar $Y$-component anomaly whose sign depends on whether the transmitter is offset in the positive or negative $Y$ direction. The reversal in time dependence behaviour (growth with time) for the $Y$-component anomaly produced by transmitter 1 (depth of sphere = 100 m) is caused by a large relative contribution from higher order multipoles (in particular the quadrupole moment, $m = 2$) at short delay times. This is essentially a shielding effect, due to the thickness of the conductor which is located between the transmitter and receiver. Shielding effects can also be observed in the other components as a reduction of early-time amplitude compared to the corresponding components of the Tx-3 anomaly.

Observations of transverse components can be used to advantage for direction determination even when there is more than one conductor present. Figure 7-4 shows an example with dipping plate conductors of two different conductances (10 and 40 S) lying on opposite sides of the drill hole. The north loop generates more straightforward responses as both plates are well coupled to the primary field. At late time the $X$-component response due to the north loop is an
Fig. 7-3  Pulse EM three-component responses computed for sphere model of Figure 5-3 but with transmitter offset from vertical plane of symmetry (X-Z plane). Sphere has conductivity = 10 S/m, radius = 50 m. The amplitudes are point normalized to the total primary field at the centre of the sphere. Offset of the transmitter rotates the induced moment, thus producing a Y-component response.
Fig. 7-4  Pulse EM response (X-component) for two plates (conductance 40 and 10 S, 300 x 150 m strike length) lying on opposite sides of the drill hole. Amplitudes are continuously normalized to measured primary field (X-component). The transmitter loop and drill hole layout are the same as in Figure 5-4. The X-component wideband response resolves the ambiguity in location for both updip and downdip plates.
asymmetric anomaly whose sign depends on whether the plate of higher conductance is updip or downdip with respect to the drill hole. The corresponding early-time response does not resolve which of the two conductors is updip but the anomaly clearly indicates that there is a conductor on each side of the hole. The south-loop response is different as the downdip plate is only weakly coupled to the south loop. When the poorer conductor lies downdip it goes virtually undetected. When the better conductor is downdip, however, it does have some effect on the late-time response. Whereas the location of the lower conductor was extremely difficult to determine from Z-component profiles (see Figure 6-6), observation of the X component resolves the ambiguity completely.

The foregoing discussion shows that there exist a number of complicating factors in applying transverse components to interpretation of direction of a conductor and that these are, to some extent, model dependent. Access to transverse-component information, therefore, does not obviate the need for multiple transmitter layouts. It is still desirable to use transmitter-model coupling behaviour to help distinguish between models to ensure proper determination of direction.

Modelling results from the GERTrude site serve to illustrate the hypothetical application of transverse component observations. Both X- and Y-component model profiles are included in Figures 5-4 and 5-12 for GERT-9266
and GERT-9279, respectively. For example, Figure 5-4b and c show that the up- or downdip location of the conductor could have been uniquely determined using a plate model from the sign change in the X-component anomaly. Similar information can be extracted from the other profiles although these are complicated to some extent by factors such as transmitter offset.

Worthington et al. (1981) have suggested that the measurement of transverse components of the secondary magnetic field avoids domination of the results by a vertical or near vertical primary field and that the sensitivity for detecting conductors at a distance is thereby greater. Examination of the modelling results presented in this chapter and in Figure 5-12 shows that this is not necessarily the case. Indeed, the results demonstrate that the principle advantage to be gained by using the transverse components lies in determining the location of the conductor with respect to the drill hole. Success of the technique in practice will, of course, depend on the availability of precise knowledge of the sensors’ orientation.
CHAPTER 8

CONCLUSIONS

8.1 Achievement of objectives

This investigation has demonstrated that wideband drill-hole EM surveys can be interpreted via interactive computer modelling of simple three-dimensional conductor shapes. We have found that two simple models, a thin, rectangular plate and a two-layer sphere, adequately simulate many aspects of anomalous field responses which are important in a quantitative interpretation scheme. The approach has avoided the potential danger of obscuring the underlying physical phenomena in a morass of detail by using completely arbitrary three-dimensional models. At the same time, fast and inexpensive computation of responses makes interpretation by trial-and-error fitting a viable alternative to matching with a suite of curves.

Eigenvalue decomposition of EM responses has proven to be a powerful tool throughout the investigation. The convenience of the approach has been felt both in the computation phase and in the analysis of responses in terms of the underlying physics. In the case of the thin-plate model, a numerical procedure allows us to visualize the induction process directly in terms of eigencurrents flowing
in the plate. The analytical solution of the sphere model leads to a comparable eigencurrent concept but one where eigenfunctions are grouped into multipoles for expansion of the secondary magnetic field.

The diffusive nature of the inductive process, and how diffusion is manifested in profiles of the secondary magnetic field, are readily appreciated in terms of the stationary and migratory properties of the induced current vortex. Eddy-current migration can be observed with particular sensitivity at points along the profile where the measured component is null (crossover locations) and, with lesser sensitivity, at peaks of the response. Much of the discussion has centred around categorizing model responses by the dynamic behaviour of their crossovers and peaks, details of which may be found in Chapters 5 and 6. An important conclusion is that, under many conditions, spheres, thick plates, and double plates all produce effects which render the models distinguishable from thin plates. Furthermore, the responses of the more specialized conductors (double plates and block conductors) can often be separated into parts for which plausible explanations can be based on either of the simple models (plate or sphere).

The study has also shown that the large-loop EM system is well suited to the problem of massive-sulphide exploration in resistive host rocks such as those of the Precambrian. The method combines the advantage of an extended search radius with the geometric flexibility
necessary to investigate three-dimensional targets. Although the effort has been concentrated on a commercial version of a pulse system (Crone Pulse EM), it should also be possible to apply the results to other wideband systems such as UTEM (step function) and Scintrex DHEM (multifrequency).

On the basis of experience with model and field studies gained throughout this project, we conceive the following ideals for maximizing the value of a drill-hole EM survey.

1. Computer modelling combined with some a priori knowledge of the geological and surface conditions should be used to design the survey. This is an important step, as it is not possible to specify a general optimum procedure. The range of investigation is one parameter which should be tested at this stage.

2. The surveys should be carried out paying strict attention to details of the responses. A very dense station spacing (1 m or less) may be required to accurately map the dynamic behaviour of anomalies and ensure high quality data.

3. The gross characteristics of any anomalies can be interpreted by computer modelling, to yield a first estimate of conductor geometry:— location, attitude, etc.

4. The dynamic characteristics of the anomaly should be exploited to refine the interpretation. Mineralization which is significantly thicker away from the drill hole may reveal itself by subtle but systematic departures
from the simple plate model. In steps 3 and 4 it is important, even though an apparently satisfactory model fit has been found, to test the other model (plate or sphere).

5. The interpretation may be complete at this stage. If not, reiteration of previous steps may be necessary. An additional field experiment under a modified procedure could easily be designed by computer to help the interpreter to choose between two vastly different interpretations both of which satisfy the observations.

8.2 Summary of test sites

Drillhole geophysical test sites in the Sudbury and Noranda massive-sulphide mining areas have provided an information base for interpretation research. EM survey data from these sites has acted as a guide to the selection and development of models suitable for interpretation. Although no attempt has been made to furnish a detailed interpretation of any one test site, certain conclusions can be reached or reaffirmed on the basis of the modelling results.

8.2.1 GERTrude

When the GERTrude site was designated for test purposes it was thought to be a massive-sulphide body of fairly simple shape, having been defined by numerous drill holes. However, details of the EM responses and reexamination of the drill logs show that the GERTrude target is anything but
simple. It has become evident by comparison with modelling results that the field observations are not entirely consistent with the accepted geology. The existence of additional highly conducting sulphides must be invoked to account for the diffusive character of the responses observed in GERT-9266: one possibility is that a deep trough-like feature, perhaps attached to the main zone, lies between drill holes GERT-9266 and -9273. The complexity of the observed response would presumably have encouraged further drilling if a normal exploration atmosphere prevailed at the site; recognition of this complexity through the EM observations is itself a worthwhile achievement. It is, nevertheless, somewhat disappointing that a more definitive interpretation could not be made. A measure of satisfaction has been gained by identifying the source of the broad, late-channel anomaly in GERT-9279 at 370 m depth as the main GERTrude target.

8.2.2 Gertrude West

The Gertrude West field observations appear to be reconcilable with the known geology on the basis of model responses which have been presented here. A plate-like structure dipping to a point very near the drill hole accounts for the narrow, large-amplitude peak of the observed anomaly but underestimates the magnitude of migration of the peak and crossover. The migration could be accelerated by a variable plate conductance which is rapidly increasing in a direction away from the drill hole or it
could be enhanced by the rotating moment effect due to induction in the edge face of a geometrically thick conductor. Either explanation is consistent with the 50 m thick section of massive sulphides known to exist to the south of GW-23090.

8.2.3 Powder Magazine

The exploration objective was to determine the continuity and extent of the massive sulphides at the Powder Magazine site. However, the main effort here was directed to showing that the observed large amplitude background response could be modelled by induction in powerlines on the surface. Furthermore, it was demonstrated that the effect of the background response on the secondary field of a deeply buried target could be handled by considering it as an additive tertiary effect.

8.2.4 Falconbridge Copper 266

The multitude and variety of EM anomalies portrays the high level of geological noise in the vicinity of the ore lens. However, correlations between the orebody and EM indications of its presence are possible on the basis of oftimes subtle changes in anomaly character. A resurvey of the site upon completion of the mining operation will hopefully corroborate this remark.

8.3 Future research and development

Several avenues of future effort in drill-hole EM methods are evident. 1) The modelling work carried out in
the present study should be ample encouragement for the development of three-component, wideband, magnetic field sensors and the accompanying orientation hardware. 2) To expand the applicability of drill-hole EM, the use of large-loop EM systems in non-resistive environments should be investigated through a program of model and field studies similar to the present one. 3) The work of Macnae (1981) shows that electric-field responses from an inductive source can often provide complementary information in geophysical prospecting. The application of electric-field measurements in drill-hole surveys thus bears investigation. 4) The large volume of data warrants the use of an on-site minicomputer for data acquisition and processing, particularly if additional magnetic- and electric-field components are measured. Implementation of modelling software on the same computer, or one which is readily accessible from field locations, would make the whole interpretation scheme more practicable. Although the prototype versions of PLATE and SPHERE have performed remarkably well, a major improvement could be made in streamlining the input/output procedures. Another welcome improvement is the addition of routines for handling multiple conductors.
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APPENDIX A

INTEGRAL EQUATION SOLUTION FOR
EM INDUCTION IN A THIN PLATE

The following is a recapitulation of Annan's (1974) numerical technique:

The basic integral equation for the currents induced in the conducting plate is:

\[ \frac{K_s}{\sigma_s} - i\omega \mu_0 \int \int K_s(r') g(r,r') \, d^2r' = E_0 \]  \hspace{1cm} (A-1)

As the sheet is inductively thin (current density does not vary across the thickness of the plate), the current has been represented as a surface current density, \( K_s \); \( \sigma_s \) is the conductance of the sheet (conductivity-thickness, os).

i.e. \( \mathbf{E} = \mathbf{J} / \sigma = \mathbf{Js} / \sigma s = K_s / \sigma_s \)

In \( (A-1) \), \( \omega \) = frequency of alternating field (time dependence \( \exp(-i\omega t) \)),
\( \mu_0 \) = magnetic permeability of plate = permeability of free space,
\( g(r,r') \) is the Green's function for the free-space induction problem = \( 1 / (4\pi |r-r'|) \)
\( E_0 \) = primary electric field in plane of sheet

The geometric parameters are given in Figure A-1.

The conditions \( \nabla \cdot K_s = 0 \) and \( K_s \cdot e_3 = 0 \) ensure that \( K_s \) is
solenoidal (no galvanic sources in the plate) and does not cross the boundaries of the plate (conductor-insulator interface), respectively. Since $K_s$ lies in the plane of the sheet and $\nabla \cdot K_s = 0$, $K_s$ may be expressed in terms of a scalar potential, $U$, as

$$K_s = \text{curl} \ (U \ e_3) = -e_3 \times \text{grad} \ U .$$

$U$ is zero on the edge of the plate since $K_s \cdot e_3 = 0$.

The eigenfunction response for the solenoidal-current potential is formulated following the Galerkin approach. The potential, $U$, is expanded in terms of a set of trial functions $\Phi_{nm} = (1-\xi^2) (1-\eta^2) T_n(\xi) T_m(\eta)$

$$U = \sum_{nm} c_{nm} \Phi_{nm} , \ n+m \leq N$$

(A-2)

where $N$ is the maximum polynomial degree of the test functions, $T_n$ is a Chebyshev polynomial of the first kind and order, $n$, $\xi = x_1/a_1$, and $\eta = x_2/a_2$. 

Fig. A-1 Thin sheet geometry
In matrix notation $U = [\Phi][C]$ where $[\Phi]$ is a row vector with entries $\Phi_{nm}$ and $[C]$ is a column vector of unknowns to be determined. The Galerkin formulation of (A-1) is:

$\{(1/\sigma_s) \{ [F] - i \omega \mu_0 (a_2/a_1) a_1 [L] \} [C] = -i \omega \mu_0 a_1 [H] \} (A-3)$

where

$[F] = \int \int \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_1} \right\}^T \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_1} \right\} + \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_2} \right\}^T \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_2} \right\} \; dx_1 \; dx_2 (A-4)$

$[L] = \frac{1}{2a_1} \int \int \int \int g(x_1, x_1', x_2, x_2') \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_1} \right\}^T \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_1} \right\} + \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_2} \right\}^T \left\{ \frac{\partial \Phi(x_1, x_2)}{\partial x_2} \right\} \; dx_1 \; dx_2 \; dx_1' \; dx_2' (A-5)$

$[H] = \frac{1}{2a_1} \int \int \left[ \Phi(x_1, x_2) \right]^T H_{03} (x_1, x_2) \; dx_1 \; dx_2 (A-6)$

As an operator equation, (A-3) becomes

$[Z] [C] = [V] (A-7)$

where $[Z] = [R] + i [X]$

$[R] = 1/\sigma_s [F]$

$[X] = -\omega \mu_0 (a_2/a_1) a_1 [L]$

$[V] = -i \omega \mu_0 a_1 [H]$.

Diagonalization of $[Z]$ is a two-stage process. Treated as a weighted eigenvalue problem:

$[Z] [C] = \lambda [R] [C] (A-8)$
[F] is diagonalized first so that
\[ D^{-\frac{1}{2}}(f_i) [v]^{T} [F] [v] D^{-\frac{1}{2}}(f_i) = l \]  \hspace{1cm} (A-9)
where \( D \) is a diagonal matrix of eigenvalues \( (f_i) \) of \([F]\) and \([v]\) is a unitary matrix whose columns are the corresponding eigenvectors. Applying the transformation (A-9) to (A-8) we get
\[ \{ 1/\sigma_s + [L'] \} [C'] = \lambda(1/\sigma_s) [C'] \]
where \([L'] = D^{-\frac{1}{2}}(f_i) [v]^{T} [L] [v] D^{-\frac{1}{2}}(f_i) \)
and \([C'] = D^{\frac{1}{2}}(f_i) [v]^{T} [C] \).

We now have a standard eigenvalue problem
\[-i\omega \mu_o (a_2/a_1) a_i [L'] [C'] = (\lambda - l) 1/\sigma_s [C'] \]  \hspace{1cm} (A-10)
The eigenvalues, \( \beta_n \), of \([L'] \) are defined by
\[-i\omega \mu_o (a_2/a_1) a_i \beta_n = 1/\sigma_s (\lambda - l) \]
or \( \lambda_n = 1 - i\omega \mu_o \sigma_s a_i (a_2/a_1) \beta_n \)
The transformation is defined by \([S]\), the matrix of eigenvectors of \([C]\), as
\[ [S]^{T} [Z] [S] = D(\lambda_n) \]
where \( D \) is the diagonal matrix of eigenvalues of the weighted eigenvalue problem (A-8)
and \[ [S] = [v] D^{-\frac{1}{2}}(f_i) [S'] \]
where \([S'] \) is matrix of eigenvectors of \([C'] \).

The solution of (A-3) is
\[ [C] = [S] D\{ -i\alpha \sqrt{(1-i\alpha \beta_n a_2/a_1)} \} [S]^{T} [H] \]  \hspace{1cm} (A-11)
for a frequency-domain source,
and \[ [C] = [S] D\{ -\exp(-t/(\tau_n a_2/a)) \sqrt{\beta_n} \tau_n (a_2/a_1)} [S]^{T} [H] \]  \hspace{1cm} (A-12)
for a time-domain impulse source,
where \( \alpha = \omega \mu_o \sigma_s a_i \), and \( \tau_n = \mu_o \sigma_s a_i \beta_n \).
The individual eigenpotentials may be computed from 

\[ [U] = [\Phi] [S] \] 

where the nth element of the row vector \([U]\) corresponds to the eigenpotential whose eigenvalue is \(\beta_n\). A complete set of eigenpotentials need be computed only once for each width/length value of the plate; the number of eigenpotentials depends on the value of \(N\). Eigenpotentials for \(a_2/a = 0.5\) and \(N = 4\) (a total of 15) are mapped in Figure A-2. The eigencurrent streamlines are parallel to the potential contours in this diagram.

The final step in the analysis is the computation of secondary magnetic fields associated with the induced currents according to \(H_n(r) = [H^S][C]\)

where

\[
[H]^S = \{-[\Phi] \delta(x_3) e_3 - \sum_{i=1}^{3} [H^i_x] e_i \}
\]

\([H^i_x] = [H^i_\infty(r), H^i_0(r), H^i_1(r), \ldots \ldots \ldots \ldots H^i_{on}(r)]\)

\[
H^i_{nm}(r) = \frac{a_1 a_2}{\pi} \int \int \frac{\Phi_{nm}(x_1', x_2', y_3')}{4\pi |r-r'|} \, dx_1' \, dx_2'
\]

The coefficients appearing in Equation 4-3 are determined as follows:

\[ a_n(x, y, z) = \text{elements of } [H] [S] \]

\[ b_n(x, y, z) = \text{elements of } [S] [H]. \]

To complete the correspondence with parameters in Chapter 4, we set \(a_2 = W/2\), and \(a_1 = S/2\).
Fig. A-2  Eigenpotential maps (for plate whose width/length = 0.5) corresponding to 15 test functions (maximum polynomial order, N = 4).
Fig. A-2 continued
APPENDIX B

EM INDUCTION IN A CONDUCTING, PERMEABLE, TWO-LAYER SPHERE

We present a review of Nabighian's (1971) solution by separation of variables for the EM response of a conducting, permeable, two-layer sphere (core and shell) in a dipolar magnetic field. However, only the main steps of the solution are reviewed here and the reader who is interested in the details of the expressions should refer to the original publication. The sphere centre is placed at the origin of a spherical coordinate system \((r, \theta, \phi)\) and a pole of strength \((m)\) at \((r=1, 0, 0)\) as in Figure B-1; the diagram also defines the sphere parameters. At time \(t=0\) the pole is abruptly removed (i.e. primary field is reduced to zero by step turn off). The response to a dipole will be obtained by

\[
\mu_1 = \mu_0 \\
\sigma = 0
\]

Fig. B-1 Geometry for sphere solution
differentiation as the last step of the solution. The polar
symmetry results in an electric field with only a $\phi$
component. Using the scalar stream potential defined by
Schelkunoff (1948, p.403) ($\psi$)

$$E_\phi = (1/r) \partial \psi / \partial \theta.$$  

The stream potential is related to the magnetic potential,
$U$, ($\mathbf{H} = -\operatorname{grad} U$) through

$$\partial U / \partial t = -(1/\mu) \partial \psi / \partial r.$$  

The other field components are thus (Nabighian, 1970)

$$\partial H_r / \partial t = 1/(\mu r^2 \sin \theta) \partial / \partial \theta \cdot (\sin \theta \partial \psi / \partial \theta)$$

$$\partial H_\theta / \partial t = 1/(\mu r) \partial^2 \psi / \partial \theta \partial r$$

$$\mathbf{F}_r = E_\theta = H_\phi = 0.$$  

The potential, $\psi$, satisfies the equation

$$r^2 \frac{\partial^2 \psi}{\partial r^2} + \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial \psi}{\partial \theta} \right) = r^2 \left( \sigma U \frac{\partial \psi}{\partial t} + \varepsilon \mu \frac{\partial^2 \psi}{\partial t^2} \right) \quad (B-1)$$

In the quasistatic (low frequency) approximation the second
term on the right side may be neglected. By separation of
variables, the elementary solutions of (B-1) are determined
as follows:

$$\hat{I}_n (kr)$$

$$\psi = P_n (\cos \theta) \exp (i \omega t) \quad (B-2)$$

$$\hat{K}_n (kr)$$

where

$$\hat{I}_n (kr) = \sqrt{\pi} k r / 2 \quad I_{n+\frac{1}{2}} (kr),$$

and

$$\hat{K}_n (kr) = \sqrt{2 k r / \pi} \quad K_{n+\frac{1}{2}} (kr),$$

are the modified Bessel functions as defined by Schelkunoff
(1948, p.52) and $P_n (\cos \theta)$ are the Legendre polynomials and

$$k^2 = i \sigma \mu \omega.$$
The stream function for each of the three regions can be expressed (for $t>0$) as

$$
\psi_1 = \sum_{n=0}^{\infty} A_n \frac{\hat{K}_n(k_1 r)}{\hat{K}_n(k_1 b)} P_n(\cos \theta) \exp(i\omega t) \quad (r>b)
$$

$$
\psi_2 = \sum_{n=0}^{\infty} \left[ B_n \frac{\hat{I}_n(k_2 r)}{\hat{I}_n(k_2 b)} + C_n \frac{\hat{K}_n(k_2 r)}{\hat{K}_n(k_2 b)} \right] P_n(\cos \theta) \exp(i\omega t) \quad (a<r<b)
$$

$$
\psi_3 = \sum_{n=0}^{\infty} D_n \frac{\hat{I}_n(k_3 r)}{\hat{I}_n(k_3 a)} P_n(\cos \theta) \exp(i\omega t) \quad (r<a)
$$

where $k_i^2 = i_1 \sigma_1 \mu_1 \omega$.

(B-3)

In region 1, $\sigma = 0$ gives

$$
\lim_{k \to 0} \frac{\hat{K}_n(k r)}{\hat{K}_n(k b)} = (b/r)^n
$$

and

$$
\psi_1 = \sum_{n=0}^{\infty} A_n (b/r)^n P_n(\cos \theta) \exp(i\omega t).
$$

Continuity of tangential $E$ and $H$ at $r = a$ and $r = b$ give, for the stream potential,

$$
\frac{1}{\mu_i} \frac{\partial \psi}{\partial r} = \frac{1}{\mu_i^{++}} \frac{\partial \psi^{++}}{\partial r}, \quad i = 1, 2
$$

which are applied to (B-3) to find the coefficients $A_n$, $B_n$, $C_n$, $D_n$. The system of 4 homogeneous equations in 4 unknowns has a non-trivial solution only when the system determinant is zero, i.e. in order to satisfy the boundary conditions, we must choose values of $k_1$ (or $\omega$) that satisfy the characteristic equation (Nabighian equation 10). The roots of this equation form a discrete set of eigenvalues of the problem: $i \omega_s = -X_{3s}^2 / \sigma_3 \mu_3 a^2$, $s = 1, 2, \ldots$

After considerable algebraic effort the solution for the magnetic potential, $U$, in the exterior region is written

$$
U_1 = m \sum_{n=0}^{\infty} \frac{n}{n+1} \frac{b^{2n+1}}{l^{n+1}} \left[ \frac{b^{2n+1}}{l^{n+1}} \right] P_n(\cos \theta) F_n(t)
$$
where $F_n (t) = -2(2n+1) \frac{\mu_3}{\mu_o} \sum_{s=1}^{\infty} V_n^2 / E_n \exp(i \omega_s t)$. 

Negative, real values for $i \omega_s$ lead to a response with a simple decay without oscillation. The variables $V_n$, $E_n$, and $X_3$, are functions of the sphere parameters $b/a$, $\sigma_2/\sigma_3$, $\mu_2$ and $\mu_3$, only. The order of the multipole expansion is $(n)$; each multipole has an infinite set of eigenvalues counted by $(s)$. 

Response to a dipolar field may be obtained by differentiation according to derivative expressions given by Grant and West (1965). The form of these expressions, represented here by the derivative operator, $D_i$, depends on the dipole orientation where $i = 1, 2, 3$ signifies three orthogonal components of the source dipole. The corresponding external magnetic field components of the sphere response are, thus,

$$H_i = -D_i \text{grad} \ U_i$$

from which the the response to an arbitrarily oriented dipole may be obtained. Correspondence with variables occurring in Equation (4-4) is made through

$$d_{ni}(x, y, z) = H_i(r, \theta, \phi) \text{ (after coordinate transformation)}$$

$$= -D_i \text{grad} \left\{ \frac{m}{n+1} \frac{b^{2n+1}}{r^{n+1}} \frac{1}{n+1} \cdot P_n (\cos \theta) \right\}$$

$q_{nm} = -2(2n+1) \frac{\mu_3}{\mu_0} \frac{V_n^2}{E_n}$

$p_{nm} = X_3 \text{, } A = a, B = b$. 

APPENDIX C

CONVOLUTION OF EM RESPONSE WITH PRACTICAL
WAVEFORMS; COMPUTER PROGRAMS

Certain aspects of the computational processes in PLATE and SPHERE programs are given in this Appendix. Table C-1 shows the system waveform options available in the program. Table C-2 lists the corresponding analytical expressions (derived as per Section 4.4) from which the responses due to the various waveforms are computed. Table C-3 lists the options available for normalization of the response by the primary field of a fixed source. Figures C-1 and C-2 are flow charts for PLATE and SPHERE, respectively. Figures C-3 and C-4 are sample graphical outputs from the two programs.
### TABLE C-1

**SYSTEM FUNCTIONS:** \( \frac{dI_{LX}}{dt} \) FOR SYSTEMS USING A COIL RX

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. FREQUENCY DOMAIN</strong></td>
<td></td>
</tr>
<tr>
<td><strong>2. STEP (OFF)</strong></td>
<td>![Diagram of a step function with ( t = 0 ) and ( T \rightarrow 0 )]</td>
</tr>
<tr>
<td><strong>3. IMPULSE (NEGATIVE)</strong></td>
<td>![Diagram of an impulse function with ( t = 0 ) and ( T \rightarrow 0 )]</td>
</tr>
<tr>
<td><strong>4. SQUARE PULSE</strong></td>
<td>![Diagram of a square pulse function with ( t = 0 ) and ( \Delta t )]</td>
</tr>
<tr>
<td><strong>5. 1/2 - SINE PULSE</strong></td>
<td>![Diagram of a 1/2 sine pulse function with ( t = 0 ) and ( \Delta t )]</td>
</tr>
<tr>
<td><strong>6. PEM (CRONE)</strong></td>
<td>![Diagram of a PEM function with ( T_{cycle} ) and ( T_{cycle} /4 )]</td>
</tr>
<tr>
<td><strong>7.</strong></td>
<td><strong>RESPONSE 8 ADDED TO RESPONSE 6</strong></td>
</tr>
<tr>
<td><strong>8.</strong></td>
<td><strong>TERTIARY RESPONSE DUE TO SIMPLE LOOP CONDUCTOR (WAVEFORM 5)</strong></td>
</tr>
<tr>
<td><strong>9. INPUT (BARRINGER)</strong></td>
<td>![Diagram of an input function with ( t = 0 ) and ( \Delta t )]</td>
</tr>
</tbody>
</table>

**USE T_{CYCLE} TO OBTAIN REPEETITIVE WAVE FORMS**
TABLE C-2
CONVOLUTION EXPRESSIONS CORRESPONDING TO WAVEFORMS OF TABLE C-1

1. Frequency domain
   \[ H^S(\omega) = \sum_n c_n (i\omega \tau_n) / (1 + i\omega \tau_n) \]

2. Step (off), \( t > 0 \)
   \[ H^S(t) = \sum_n c_n \exp(-t/\tau_n) \]

3. Impulse (negative), \( t > 0 \)
   \[ H^S(t) = \sum_n -(c_n / \tau_n) \exp(-t/\tau_n) \]

4. Square pulse, \( t > 0 \)
   \[ H^S(t) = \sum_n c_n \exp(-t/\tau_n) \{ \exp(-\Delta t/\tau_n) - 1 \} \]

5. Half-sine pulse, \( t > 0 \)
   \[ H^S(t) = \sum_n -c_n \exp(-t/\tau_n) \{ 1 + (2\pi \tau_n / T) \exp(-T/4\tau_n) \} \]
   \[ / \{ 1 + (2\pi \tau_n / T)^2 \} \]
   where \( T = 4 \Delta t \)

6. Crone Pulse EM, \( t > 0 \)
   \[ H^S(t) = \sum_n -c_n \{ \exp(-t'/\tau_n) - \exp(-t'/\tau_{ON}) \} / \{ \tau_{ON} - \tau_n \} \]
   + Expression (5.)
   where \( t' = t + T_{cycle} / 4 \)

7. Tertiary response (8.) added to secondary response (6.)
TABLE C-2 (continued)

8. Tertiary response due to secondary loop source (see Section 4.7) which is excited inductively by primary source (Expression 5, i.e. turn-off portion only of Crone PEM waveform), t>0

\[ H^{3L}(t) = A_L A \sum_n c_n \left\{ \sum_{i=1}^{5} B_i F_i \right\} \]

where

\[ A = -\tau / \left\{ 1 + (2\pi \tau / T) \right\} \]

\[ F_1 = \exp(-t/\tau_n) \left\{ 1 + (2\pi \tau_n / T) \exp(-T/4\tau_n) \right\} \]

\[ B_1 = (1/\tau + 1/A) / \left\{ 1 + (2\pi \tau_n / T)^2 \right\} \]

\[ F_2 = \exp(-t/\tau_n) \left\{ -2\pi \tau_n / T + \exp(-T/4\tau_n) \right\} \]

\[ B_2 = (2\pi / T) / \left\{ 1 + (2\pi \tau_n / T)^2 \right\} \]

\[ F_3 = \exp(-t/\tau) - \exp(-t/\tau_n) \cdot \exp\left\{-T(1/\tau_n - 1/\tau)/4\right\} \]

\[ B_3 = (2\pi / T) \exp(-T/4\tau) / \left\{ 1 - \tau_n / \tau \right\} \]

\[ F_4 = \exp(-t/\tau) - \exp(-t/\tau_n) \]

\[ B_4 = 1/(\tau - \tau_n) \]

\[ F_5 = \exp(-t/\tau) \left\{ 1/\tau + (2\pi/T)\exp(-T/4\tau) \right\} \]

\[ B_5 = -1 \]

\[ T = 4 \Delta t \]

\[ \tau = \text{time constant of secondary loop} \]

\[ A = \text{mutual coupling between secondary loop and transmitter loop}, A, \tau, \text{and configuration of secondary loop are determined empirically by fitting response of secondary loop to observed background anomaly (see Section 5.7)} \]

9. Airborne INPUT (Barringer), t>0

\[ H^S(t) = \sum_n -c_n \exp(-t/\tau_n) \left\{ 1 + \exp(-T/2\tau_n) \right\} / \left\{ 1 + (2\pi \tau_n / T)^2 \right\} \]

where \( T = 2 \Delta t \)
# TABLE C-3

Secondary Field Normalization Options
(Fixed transmitter option)

<table>
<thead>
<tr>
<th>Number</th>
<th>Component of primary field, to which secondary field is normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$H_x'$ at receiver position</td>
</tr>
<tr>
<td>2</td>
<td>$H_y'$ at receiver position</td>
</tr>
<tr>
<td>3</td>
<td>$H_z'$ at receiver position</td>
</tr>
<tr>
<td>4</td>
<td>$H_{total}'$ at receiver position</td>
</tr>
<tr>
<td>5</td>
<td>$H_{axial}'$ at receiver position</td>
</tr>
<tr>
<td></td>
<td>applicable to drillhole profiles only</td>
</tr>
<tr>
<td>6</td>
<td>None - output in amp/m</td>
</tr>
<tr>
<td>7</td>
<td>$H_{total}'$ at model reference point</td>
</tr>
<tr>
<td>8</td>
<td>$H_z'$ at surface ($Z=0$) above reference point</td>
</tr>
</tbody>
</table>

N.B. Reference point is
a) a user-specified location on the plate.
or b) the centre of the sphere.
Figure C-1
FLOWCHART FOR PROGRAM PLATE

PLATE

MOVING TRANSmitter OPTION

GENERATE OR RETRIEVE EIGENPOtENTIALS

ANNAN CORE PROGRAMS
GENERATE AND DIAGONALIZE \([F]\) AND \([L]\), FORM \([S]\)

EIGENPOtENTIAL STORAGE

FIXED TRANSmitter OPTION

INPUT PLATE AND SYSTEM GEOMETRY

COORDINATE TRANSFORMATION, FIELD TO PLATE SYSTEM

COMPUTE EXCITATION COEFFICIENTS, \(b_n\)
SECONDARY FIELD COEFFICIENTS, \(a_n\)

INVERSE COORDINATE TRANSFORMATION

ANNAN CORE PROGRAMS
GENERATE \([H]\) AND \([H^4]\)

INPUT PLATE GEOMETRY AND RECEIVER LOCATIONS (PROFILES)

COORDINATE TRANSFORMATION
FIELD TO PLATE SYSTEM

COMPUTE SECONDARY FIELD COEFFICIENTS, \(a_n\)

INVERSE COORDINATE TRANSFORMATION

INPUT TRANSMITTER LOCATION

COMPUTE EXCITATION COEFFICIENTS, \(b_n\)
FOR LOOP, DIPOLE, OR UNIFORM FIELD

CHOOSE WAVEFORM AND PARAMETERS

CONVOLUTION WITH SYSTEM WAVEFORM AND NORMALIZATION, ETC.

SPECTRAL MODE OUTPUT

PROFILE MODE OUTPUT

LOOP BACK TO VARIOUS POINTS FOR INPUT OF NEW PARAMETER VALUES

PLOT
Figure C-2
FLOWCHART FOR PROGRAM SPHERE

SPHERE

MOVING TRANSMITTER OPTION

INPUT GEOMETRIC PARAMETERS (SYSTEM AND SPHERE CENTRE)

COMPUTE GEOMETRIC PORTION OF RESPONSE, g_{mn}

COORDINATE TRANSFORMATIONS

INPUT SPHERE PARAMETERS

CHOOSE WAVEFORM AND PARAMETERS

GENERATE OR RETRIEVE EIGENVALUES FOR EACH MULTIPOLE

SOLVE CHARACTERISTIC EQUATION

STORE EIGENVALUES AND COEFFICIENTS

CONVOLUTION WITH SYSTEM WAVEFORM AND PREPARATION FOR OUTPUT

SPECTRAL MODE OUTPUT

PROFILE MODE OUTPUT

LOOP BACK TO VARIOUS POINTS FOR INPUT OF NEW PARAMETER VALUES

PLOT
Fig. C-3 Sample graphical output from program PLATE showing values of all system and model parameters.
Fig. C-4 Sample graphical output from program SPHERE showing values of all system and model parameters.
APPENDIX D

WAVEFORM SPECIFICATIONS OF DRILL-HOLE EM PROSPECTING SYSTEMS

Specifications for the Crone Pulse EM system waveform and the sampling and display of the transient response have been given in Section 3.2.1. In this Appendix we supply comparable information for the other two prospecting systems whose responses have been investigated in the thesis.

UTEM II

A comprehensive resume of the UTEM II system is available from Macnae (1981). Two of his diagrams are reproduced here. Figure D-1 shows the UTEM waveform and binary-spaced sampling scheme. Figure D-2 shows the usual display employed for UTEM surface data. The downhole sensor (Crone PEM sensor) used in conjunction with the UTEM system to collect the observations presented in the thesis differs in electrical characteristics from the UTEM surface coil. Figure D-3 shows the measured step response of the drill-hole coil. Only channels 1-7 are directly usable as a step response without deconvolution of the probe response.
Fig. D-1 UTEM standard waveform and decay-sampling scheme
Fig. D-2 UTEM standard data display.
UTEM CHANNEL NO.

Fig. D-3 Step response of drill-hole sensor used for all field measurements in the thesis.

Multifrequency EM (Scintrex Ltd. DHEM-5 frequency system)

The specifications presented herein are taken from the Scintrex Ltd. brochure (1975). The block diagram for the system is shown in Figure D-4.

Fig. D-4 Scintrex DHEM-5 system
The components of the system function as follows:

**Transmitter**  **TSQ-2M/500 W**

Output power: 500 va maximum (motor-generator driven)

Output voltages: 50, 100, 150, 200, 250 v.

Output waveform: continuous square wave.

Frequencies: 35, 105, 315, 945, 2835 Hz.

Frequency stability: Crystal controlled to better than 0.01%

**Receiver**  **SE-77**

Phase-lock detector

Bandwidth: 0.16 Hz with 1 s time constant.

Frequency selection: 35, 105, 315, 945, 2835 Hz.

Field strength ratio measurement, Range: 0.5 to 2.0

Accuracy: 1%

Phase shift measurement, Range: -20° to +20°

Accuracy: 1°

**Interface unit**

Active filter design.

Voltage range: 60 µv to 20 v in 12 ranges (gain: 2 steps /decade)

Phase range: 0 to 160° in 9 steps of 20°, plus 180° switch.
Fig. D-5  Phasor diagram for Scintrex DHEM-5 system

The system produces the following information:

In-phase component = \( g \left[ \frac{\text{Re} H^S + H^P}{H^R} \right] \)

Phase = \( \Delta \phi + \arctan \left[ g \frac{\text{Im} H^S}{H^R} \right] \)

\[ \approx \Delta \phi + g \frac{\text{Im} H^S}{H^R} \quad \text{for small phase anomalies,} \]

where \( g \) and \( \Delta \phi \) are gain and phase shift, respectively, introduced by the interface unit.

\[ g = \frac{H^R}{H^P} \quad \text{(within a factor of 2 in non-anomalous zones, as } g \text{ varies in steps.)} \]
Villegas (1979) has described the scale-model facility in the Geophysics Laboratory, Department of Physics, University of Toronto. The physical layout is shown here in Figure E-1. The drill-hole EM modelling was performed in the free-air area. Profiles in simulated vertical drill-hole were carried out with traverses parallel to the X-axis. Positioning errors are estimated at less than 1 mm, more than adequate when using 1000:1 scaling of physical dimensions. The electronic measuring system was designed by G.F. West and A. Wieckowski of the Geophysics Laboratory; it is shown schematically in Figure E-2. The model experiments run under control of the microcomputer. The system routines and specific routines for drill-hole experiments were programmed by M. Bloore.

Repeatability of Crone PEM model measurements were comparable to the field measurements, i.e. 1-2 ppk of primary field. Comparison of scale-model data to computed data from PLATE is shown in Figure E-3. Notice that amplitudes, decay patterns and crossover behaviour are all in good agreement.
Fig. E-1  Schematic of physical layout of University of Toronto scale model apparatus (after Villegas, 1979).
Fig. E-2 Schematic of computer-controlled electronic measuring system of scale-model apparatus (after Macnae, 1981)
Fig. E-3 Comparison of scale-model data to response computed by PLAP showing good agreement in amplitude, decay pattern, and crossover behaviour.