ชื่อเรื่องวิทยานิพนธ์ แผนภูมิหลายพารามิเตอร์ สำหรับการแปลความหมายผลตอบสนองทางแม่เหล็กไฟฟ้าในตัวกลางล้อมรอบที่เป็นตัวนำไฟฟ้าสม่ำเสมอ

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บทคัดย่อ

การสำรวจด้านแม่เหล็กไฟฟ้าทางอากาศ ใช้สำหรับหาศักยภาพทางธรณีวิทยาของแร่ที่เป็นตัวนำไฟฟ้า เช่น แร่ซัลไฟด์ หรือ แร่โลหะพื้นฐาน ปัญหาหลักของการแปลความหมายทางด้านการบินสำรวจแม่เหล็กไฟฟ้าทางอากาศในประเทศไทย เกี่ยวเนื่องมาจากความเป็นตัวนำไฟฟ้าของตัวกลางล้อมรอบ และดินชั้นบน ซึ่งส่งผลทำให้ค่า อินเฟส(In-phase) และ ควอเดเจอร์(Quadrature) สูงขึ้น อันเป็นผลมาจาก กระแสไฟฟ้าที่ถูกเหนี่ยวนำในตัวกลางล้อมรอบ และ ดินชั้นบน ไหลเข้าสู่แร่ตัวนำไฟฟ้านั้น

การแปลความหมายด้านการสำรวจแม่เหล็กไฟฟ้าทางอากาศ โดยทั่วไปจะใช้ แผนภูมิอาร์แกน(Argand diagram) เพื่อที่จะหาค่าความนำไฟฟ้า(conductance) และ ความลึก ของวัตถุที่เป็นตัวนำไฟฟ้า แผนภูมิที่ทำมาก่อนแล้ว ส่วนมากสร้างมาจากสภาพของตัวกลางล้อมรอบที่เป็นตัวต้านทานกระแสไฟฟ้า(resistive host) สำหรับงานวิจัยนี้ได้สร้างแผนภูมิสำหรับตัวนำไฟฟ้าที่มีตัวกลางล้อบรอบ และดินชั้นบน เป็นตัวนำไฟฟ้า โดยสร้างจาก โปรแกรม VHPLATE (F.D1.0/A) ในรูปแบบการวางขดลวดแบบโคพานาร์(coplanar) ที่ความถี่ 912 เฮิตซ์ ทั้งนี้เพราะว่า ในรูปแบบนี้ค่าผิดปกติที่ได้จะแสดง 2 พีก(peak) ซึ่งจะสามารถนำไปประมาณค่า มุมเท (dip) โดยใช้ อัตราส่วนระหว่าง พีกใหญ่(major peak) ต่อ พีกเล็ก(minor peak) และ หาความลึกของตัวนำไฟฟ้าโดยใช้ระยะระหว่างพีก(peak separation)แผนภูมิที่สร้างขึ้นใหม่จะแปรค่าพารามิเตอร์(parameters) ของ ตัวนำไฟฟ้า และ ตัวกลางล้อมรอบ ที่ควบคุมลักษณะ(characteristics) และ แอมปิจูด(amplitude) ของภาพตัดขวางของค่าผิดปกติ(anomaly profile)

ผลการเปรียบเทียบ แผนภูมิตัวกลางต้านทานไฟฟ้า(resistive host diagram)ที่ทำมาแล้ว กับ แผนภูมิตัวกลางนำไฟฟ้า(conductive host diagram)ที่ทำใหม่ แสดงความแตกต่างของ ค่าความนำไฟฟ้า และ ความลึก อย่างชัดเจน ลักษณะเด่นของ แผนภูมิตัวกลางนำไฟฟ้า จะแสดงค่าควอเดเจอร์ สูง การทดสอบการแปลความหมายโดยใช้แผนภูมิใหม่ ทำในสามพื้นที่เลือกสรร ที่มีตัวนำไฟฟ้า แตกต่างกัน คือ เป็น graphitic shale, pyrite-graphite vein และ saprolite ผลการแปลความหมาย พบว่า ค่าความนำไฟฟ้าและความลึกของตัวนำไฟฟ้า สอดคล้องกับผลการเจาะสำรวจ การประเมินคุณค่าของแผนภูมิใหม่ ทำโดยคัดเลือก พื้นที่ อ.สอง จ. แพร่ เป็นพื้นที่ทดลองทำการแปลความหมายใหม่ (re-interpretation) ผลการแปลความหมายใหม่จะแสดง พื้นที่ศักยภาพของแหล่งแร่ ใหม่ ที่ไม่ได้บ่งบอกไว้ใน แผนที่การแปลความหมาย ที่ทำมาก่อนแล้ว

Thesis Title Multiparameter Diagram for Interpretation of Electromagnetic Response in Uniform Conductive Host Media

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ABSTRACT

Airborne electromagnetic method (AEM) is used for searching the geologically potential areas of conductive minerals such as sulfide minerals or base metals. The main problem in the interpretation of the airborne electromagnetic survey in Thailand is due to the high conductivity of host rocks and overburden. As a consequence, the high response amplitude of in-phase and quadrature components have been observed, because of the rapid gain of the channelling current in the conductor flowing from the host.

The AEM interpretation generally uses an Argand diagram to find a conductance and depth of conductor. The previous diagram was created for the resistive host areas. Suitable diagram for a conductive host and overburden of this research was constructed by using the electromagnetic modeling software (VHPLATE F3D1.0/A) . The coplanar configuration of 912 Hz was selected to construct a conductive diagram. Two peaks anomaly of this configuration can be used to indicate the approximate dip and depth of a conductor by using the ratio of major and minor peaks and

a peak separation respectively. The new diagrams were constructed by varying the parameters of conductor and host which control the characteristic and amplitude of the anomalous profiles.

Comparison of the previous resistive diagram and the new conductive diagram shows the difference of conductance and depth of conductor. The high quadrature is the dominant pattern of the conductive diagrams. The interpretation tests were made for three target areas with three cases of conductor, graphitic shale, pyrite-graphite vein and saprolite.The conductance and depth of conductors are in good agreement with the drilling results. In order to evaluate the usefullness of the new diagrams, the re-interpretation of the Song area was made. This new interpretation map shows a new potential area which has not been delineated in the previous interpretation map.

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INTRODUCTION

An electromagnetic (EM) method is one of several exploration geophysical methods used to obtain information about the subsurface conditions of the earth. The EM methods have been designed to exploit the extreme conductivity contrast which often exists between concentrations of metallic minerals and the host rocks in which they occur. Most of metal massive sulfide ores are very conductive and provide a strong contrast to their host rocks, thus the EM methods are widely used in the prospecting of base metal ore deposits such as copper, zinc and lead.

Electromagnetic methods include an initially confusing variety of techniques, survey methods, applications, and interpretation procedures. All techniques involve the measurement of one or more electric or magnetic field component, using an "EM receiver", around some natural or artificial source of electromagnetic energy, the "EM transmitter".

Based on Maxwell's laws, an AC electromagnetic source induces secondary currents in conductive earth materials. These secondary currents generate secondary magnetic fields. The EM receiver measures both primary and secondary fields. Upon normalization by the input source or by the received primary field, either the secondary or the total (primary plus secondary) field response may be interpreted to yield the significant resistivity information.

A horizontal loop electromagnetic (HLEM) system is one of the EM techniques whose transmitter-receiver coil configuration is a coplanar system. The transmitter coil generates an audio frequency signal, the relative strength and phase of which are measured by the receiver. In the fields, the operator carries the loops in tandem along the traverse line, taking readings at specified locations. Anomalous values arise when conductivity inhomogeneities intervene to alter the electromagnetic coupling of the loops. This technique may be used particularly for any of several airborne or ground prospecting systems.

Airborne electromagnetic (AEM) surveys have been used since the 1950's as a rapid means for economically searching a large geologically potential area, in order to detect conductive zone of sulfide mineralization. Most of the AEM systems employ moving source configurations comparable to moving source systems used on the ground.

For the airborne electromagnetic survey in Thailand, three frequencies and two configurations were used, i.e. one vertical coaxial coil pair operating at 736 Hz and two coplanar coil pairs operating at 912 Hz and 4200 Hz respectively. The EM data were sampled at 0.25 second intervals employing a 0.1 second time constant. The survey was flown with a mean terrain clearance of 60 m and a traverse line spacing of 400 m. The EM sensor was towed with a 30 m long cable. A limited number of fill-in lines were also flown. The flight path was recovered using digital data combined with points identified on base maps from a 35 mm track film.

In this study, the airborne horizontal loop system was chosen, because of its popularity and familiarity. However, better understanding about the effects of conductive host are needed for the horizontal loop AEM systems.

Most of commercial AEM prospecting systems have interpretation nomograms. The nomograms are diagrams on which the measured parameters, such as in-phase and quadrature (out of phase) components are plotted for varying model conductivity and one or more geometrical factors, e.g. depth to the top, dip, thickness, etc. The model response diagrams available for most EM methods are those of the long, thin dike, a homogeneous host, and a layer simulating conductive overburden.

The interpretation of EM response follows two basic steps. The first step is to attempt to determine the characteristic of the profile anomaly. The second step is to measure the in-phase and quadrature amplitudes and to plot these amplitudes on the appropriate nomograms. From the characteristic of the anomaly and the diagram one can estimate the quality of a conductor, depth, dip, thickness and strike length of the anomalous body.

The procedures for interpreting data are based on model studies of EM response. The model data are prepared by one of the following methods:

1. Scale-model measurement, mostly on a model consisting of plate in free space (resistive host diagram).

2. Theoretical solution for the case of layered-earth, a perfect conductor in free-space.

3. Numerical methods, currently only practicable for a plate-like conductor in a uniform conductive half space.

Many massive sulfide ore bodies are steeply dipping and their a strike and depth extend much greater than their thickness. This has led to a wide acceptance of a thin vertical half-plane model (thin plate) in the quantitative interpretation of AEM anomalies (Ferneyhough, 1985).

In the past, scale modeling provided most of the data for the construction of free-space nomograms. Argand diagrams for a vertical metallic sheet excited and measured by a horizontal coplanar system are given by Ghosh (1972), Grant and West (1965), Wieduwilt (1962), and Podosky (1966). One method of the interpreted AEM data is that of Palacky and West (1973) where the six peak channel amplitudes are plotted on tracing paper using the logarithmic scale on the right-hand side of the nomogram.

Accurate numerical modeling methods for EM response of a plate in free space have been constructed by Lamontangne and West (1971) and by Annan (1974). Horizontal coplanar(HEM) response of typical host media (two-layered earth) has been computed by Patra and Mallick (1979), Frishknecht (1967) and Eadie (1979).

However, there are many geological situations where the overburden and host rock conductivity cannot be neglected. They are known to modify the free space- response considerably. Lowrie and West (1965), and Fraser and Ward (1967) simulated the conductive overburden by thin horizontal metallic sheets placed over the vertical target conductor and observed amplitude reduction and phase rotation of the anomaly. Thus, a conductor appears to be more conductive and more deeply buried than it actually is.

Whereas Lajoie and West (1976) obtained numerically, the Turam response of a thin vertical conductor in a conductive host, Hohmann (1975) computed some EM effects for scatters of low conductivity contrast and Walker (1988) computed the EM scattering by a plate in conductive media. The horizontal loop electromagnetic response of a thin plate in conductive earth have been calculated by Hanneson and West (1984). Up to now, no systematic study of the AEM response of a plate in a conductive host has yet been made, at least, to the best of my knowledge.

In Thailand, the general geological conditions are characterized by conductive host rocks. These conditions enhance the in-phase and quadrature values in the AEM responses. But, the AEM data interpretation using a resistive diagram may cause some error regarding conductance anomalies. The example of an interpretation map of AEM anomaly in Thailand is shown in Figure 1.1. A condition specified for this interpretation explained at the bottom of the map. The conductance was determined by using a vertical half plane model in free space, resistive host media, for data recorded at 736 Hz (KESILL, 1989c). The nomograms of the resistive host media are shown in Figure 1.2. Bedrock conductors were selected according to the in-phase and quadrature response of each anomaly. The conductance and depth of conductor can be determined by plotting the in-phase and quadrature response in this diagram. As a result, this could cause a ground follow-up survey to miss the potential ore target.

At present, none of the AEM interpretation is made properly according to a geological condition. This problem is known for years but the right diagram is not exist. A new approach is urgently needed to tackle this problem.

In this study, the multiparameter diagrams for interpreting the AEM anomalies due to a conductor buried in a conductive host media are constructed using the VHPLATE program based on the algorithm developed by Dr.Peter Walker (1994) of PetRos EiKon Inc., Ontario, Canada.

The usefulness of the new diagrams for the AEM surveys are as follows :

1. The problem in the interpretation of AEM data in the conditions where the conductor is embedded in a conductive host media can be eliminated.

2. The diagram enable the re-interpretation of the selected AEM anomalies of Thailand to be used as a target area for ground follow-up survey.

3. Quantitative interpretation of the AEM data in conductive host media in any tropical country, where deep weathering and ground-water saturation produce relatively conductive host rocks for conductive ore bodies, could be improved.

Furthermore, a qualitative interpretation of the AEM data can be achieved easily by comparing the AEM profile with the calculated profile over various types of conductor and host rock.

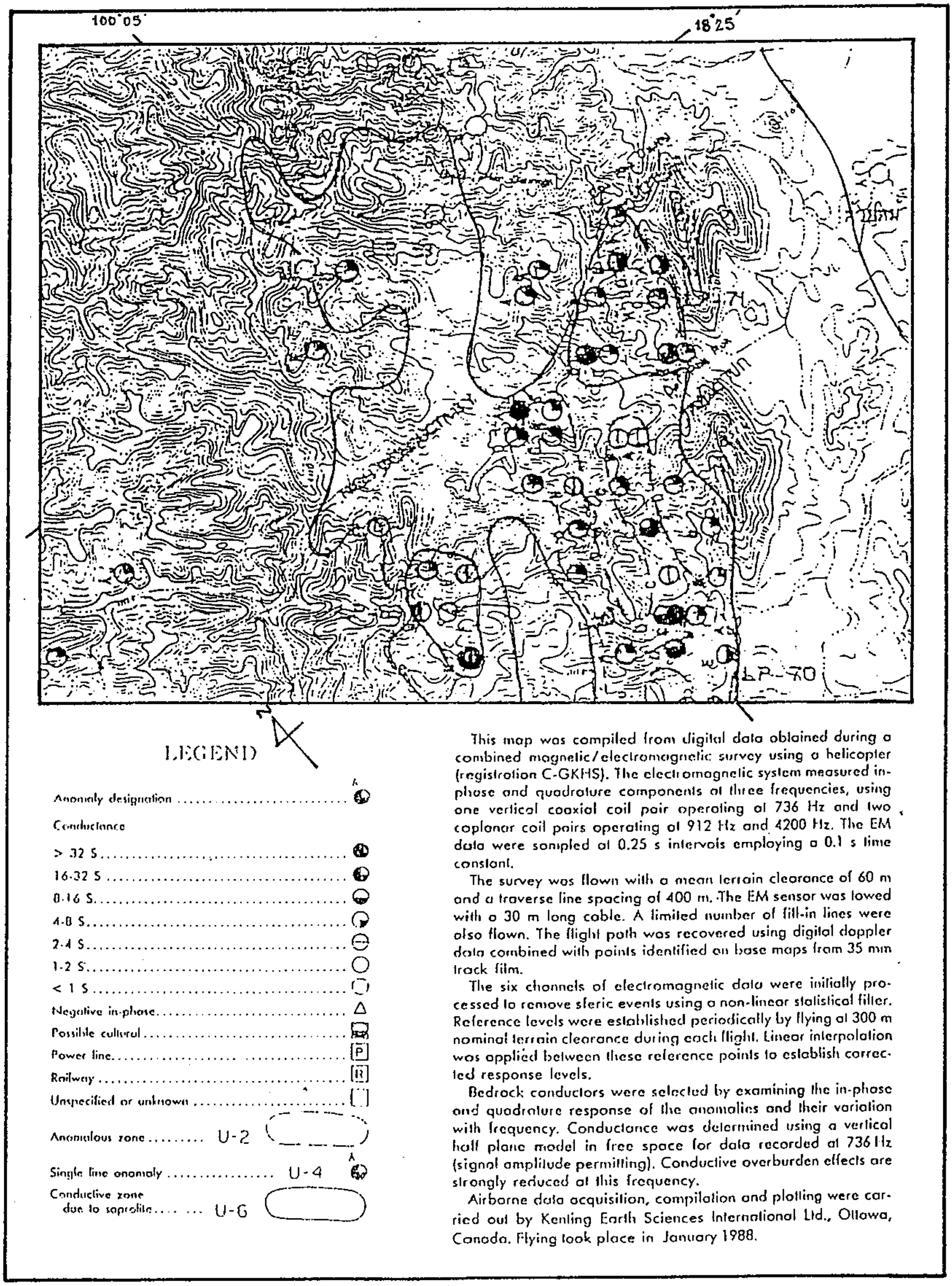


Figure 1.1 The example of the interpretation map of AEM survey in Thailand (KESIL, 1989c)

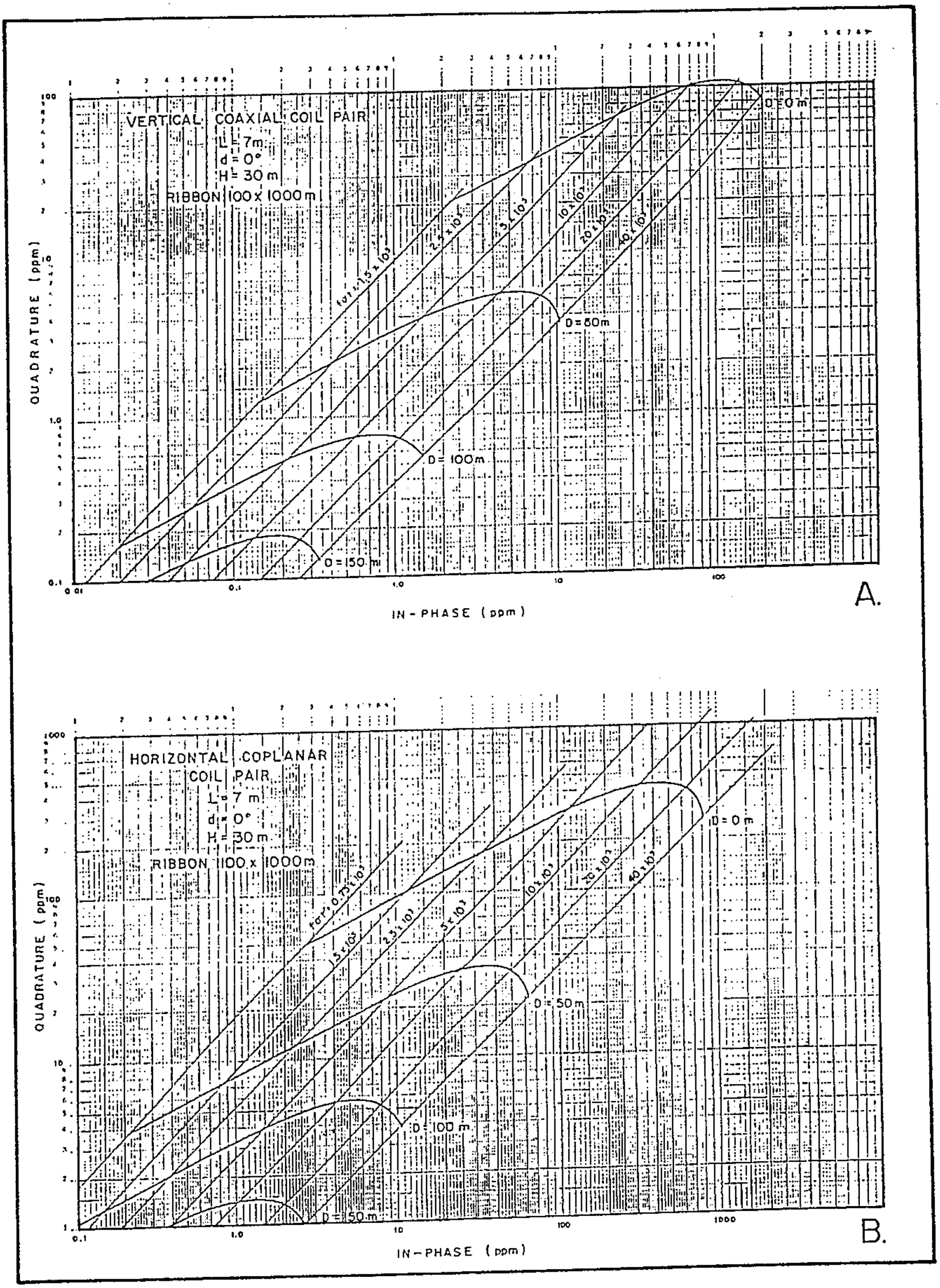


Figure 1.2 The resistive host diagrams for interpretation of AEM survey in Thailand (after Paterson, 1982)

CHAPTER 2
THEORY AND PRINCIPLES OF EM METHOD

2.1 The EM Response Theory

2.1.1 The normal response

The EM field vector in the frequency domain **F(r)** at a point **r** is related to the source dipole moment **s(r′)** by

$$\mathbf{F(r)} = \mathrm{G}(\mathbf{r},\mathbf{r}')\mathbf{s}(\mathbf{r}')$$

where G(**r**,**r′**) is a Green's function. In this case, **F** may be either an electric field **E** or a magnetic field **H**, the dipole moment s may be a current dipole **j** or magnetic dipole **m.**

On a horizontally stratified half-space, the Green's function is invariant under translation and rotation of the horizontal projection of the different vector **r**-**r′**, and in an infinite uniform space, it depends only on the magnitude of this vector. In order to simplify subsequent expression, the Green's functions are modified to have dimensions which are powers of length only. There result the definitions

$$\mathbf{E}_i(\mathrm{r}) = [g]_{ik}^{Ej}(\mathrm{r},\mathrm{r}')\mathrm{j}_k(\mathrm{r}')/\mathrm{d}(\mathrm{r}')$$
$$\mathbf{H}_i(\mathrm{r}) = [g]_{ik}^{Hm}(\mathrm{r},\mathrm{r}')\mathrm{m}_k(\mathrm{r}')$$
$$\mathbf{E}_i(\mathrm{r}) = [g]_{ik}^{Em}(\mathrm{r},\mathrm{r}')\mathrm{m}_k(\mathrm{r}')i\omega\mu(\mathrm{r}')$$

and

$$\mathbf{H}_i(\mathrm{r}) = [g]_{ik}^{Hj}(\mathrm{r},\mathrm{r}')\mathrm{j}_k(\mathrm{r}')$$

where (r) and μ(r) are the conductivity and permeability at the point r, respectively. The pairs of function $[g]^{Ej}$, $[g]^{Hm}$, and $[g]^{Em}$, $[g]^{Hj}$ have the dimension of $[L]^{-3}$ and $[L]^{-2}$, respectively. Summation over the repeated index k is implied in the equation to obtain the total value of each field.

The Green's functions, as normalized above, of any earth model have constant real values at the low frequency, static limit. They are functions of angular frequency ω and become complex as the frequency increases and eddy current becomes important.

The EM response of a uniform, horizontally stratified earth excited by an arbitrary source was studied extensively and derived both in frequency and time domain by Wait (1982). West and Edwards (1985) discussed the EM fields generated by some sources may be written as analytic expression; other case requires the numerical evaluation of integral transform. Furthermore, they noted that the EM field by assuming such routines available and they require a notation to describe an EM response.

2.1.2 The anomalous response

As follow the well-known, equivalent-source approach to analyze the effect of local conductivity variation within a normal layered earth, the inhomogeneity is replaced by an anomalous or scattering current distribution $\mathbf{J}^a$. The Ohm's law relationship in terms of $\mathbf{J}^a$, the total current density **J,** and the electric field **E** have alternative forms

$$\mathbf{J} = \sigma\mathbf{E} = \sigma_h\mathbf{E} + \mathbf{J}^a$$

and

$$\mathbf{J}^a = \sigma_a\,\mathbf{E} = k_\sigma\sigma_h\mathbf{E}$$

where σ and σ_h are the conductivity of the inhomogeneity and the host medium , respectively , and $k_\sigma = (\sigma - \sigma_h)/\sigma_h$.

An exactly analogous approach may be used for a permeable inhomogeneity, by describing it in terms of an induced magnetization

$$\mathbf{M}^a = k_\mu\,\mathbf{H}$$

where $k_\mu = (\mu - \mu_h)/\mu_h$

2.2 Principle of EM Response in Conductive Host Media

Electromagnetic survey systems are composed of two components, the transmitter to transmit the EM wave into the ground and the receiver to receive the signal from the ground.

The current in the transmitter coil generates a magnetic field which penetrates the earth and may be the conductive body. Current flows in the conductor in response to the induced electromagnetic force in accordance with the Biot-Savart law of induced current. These currents usually flow through the conductor in a plane perpendicular to the transmitter line of the magnetic force field unless restricted by the conductor's geometry. Current flow within the conductor generates a secondary magnetic field whose lines of force at the conductor are such that they oppose those of a primary magnetic field.

In a conductive host rock, the magnetic field from the transmitter induce the current flow in the host. The current in the host flows through the conductor in the parallel plane of the conductor. This current is called a channelling current that generates a secondary magnetic field whose lines of force surround the conductor as shown in Figure 2.1.

The two secondary magnetic fields from the inductive and the channelling current are combined to produce the resultant response. The receiver coil at some distances from the transmitter coil is therefore energized by the two fields: one from the transmitter (primary field) and the other from the resultant field (secondary field).

In summary, a conductor in resistive host media produces only a secondary magnetic field with an inductive response. A conductor in conductive host media, on the other hand, produces a secondary magnetic field from both the inductive and the channelling current.

2.3 Factors controlling an EM Response

The EM response of a buried conductor is influenced by many factors. These factors include the geometry and conductivity of a conductor and the host rock. The conductor is defined in terms of a plate because the plate shape simplifies the calculation of the EM response. The other factor that influence the EM response is the configuration of the transmitter and receiver coils.

2.3.1 Plate (Conductor)

The properties of the plate are defined by the induction number ($I^n = 2\omega\mu\tau a$) and the channelling number ($C^n=\tau/2ha$), where

$\tau =$ conductance of the conductor
$\omega =$ angular frequency ($= 2\pi f$)
$\mu =$ magnetic permeability

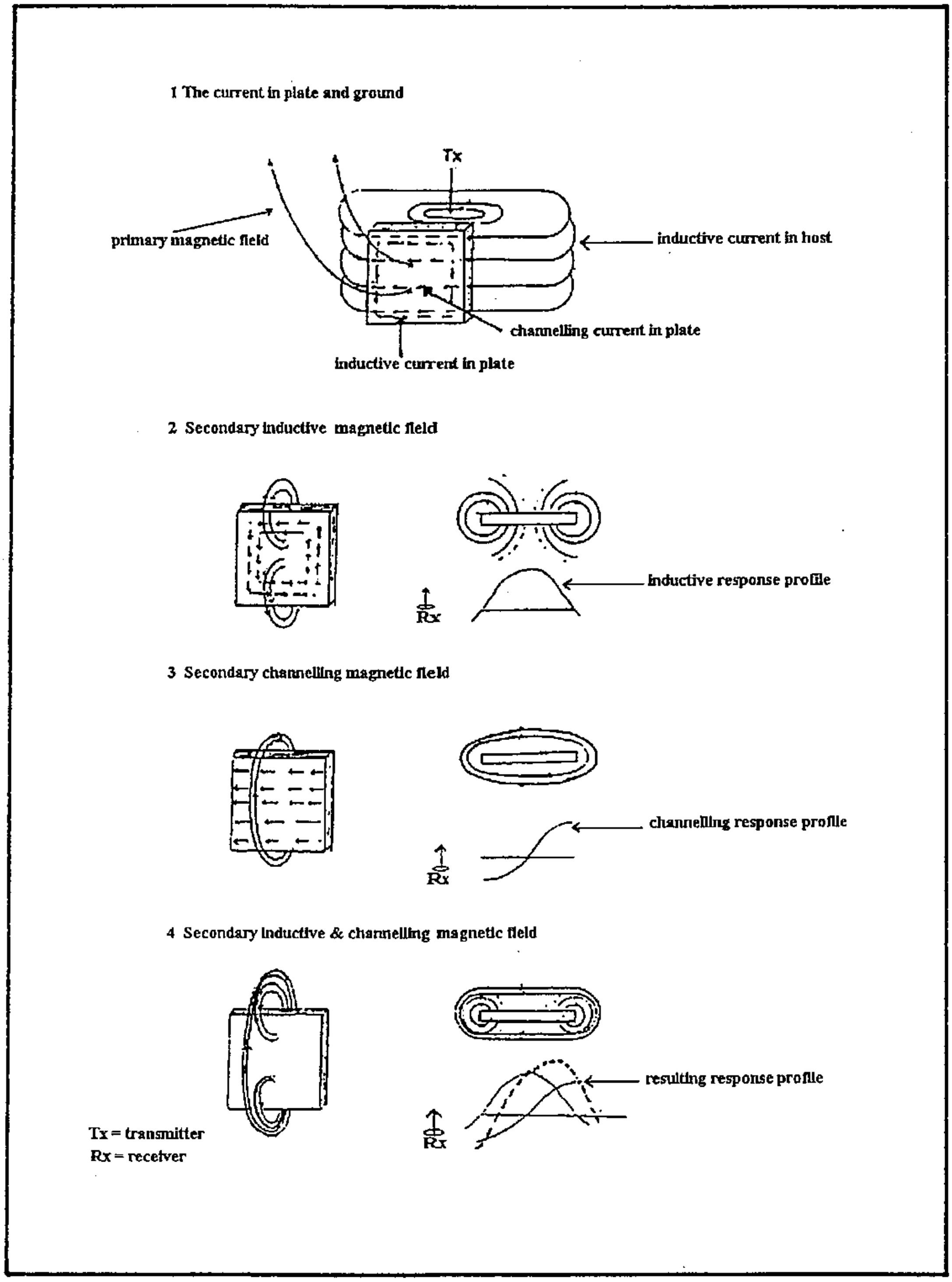


Figure 2.1 EM field and current about a plate in a conductive host medium

a = plate dimension
h= host conductivity

The induction number is proportional to the conductance of the plate, while the channelling number is dependent on the conductance of the plate and the conductivity of the host. The properties of the plate can be divided into the induction and the channelling properties and these properties can be separated into "unsaturated" and "saturated" properties (Figure 2.2).

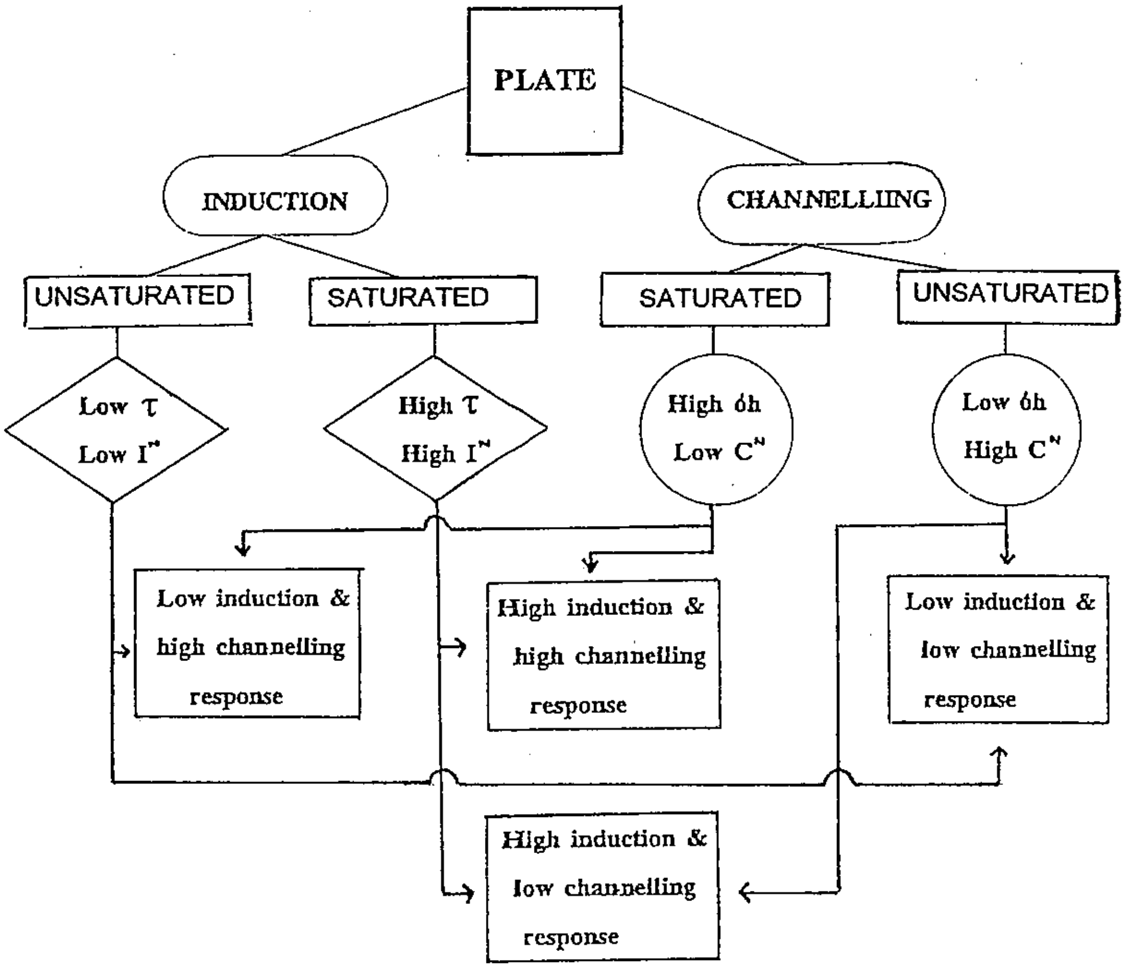
For the induction properties of the plate, the saturated and unsaturated properties are controlled by the induction number. The saturated induction property represents the high conductance plate or the high induction number. (assuming μ,ω,a are constant) The unsaturated induction property represents the low conductance of the plate or low induction number.

For the channelling property, the saturated and unsaturated properties depend on the channelling number. A plate with a high channelling number has the unsaturated channelling property. So the saturated channelling property indicates a low channelling number of the plate.

For the different plate properties the EM responses for the conductive host media have different induction and channelling responses. For example, in the plate that has a saturated induction and unsaturated channelling property, the EM response will have a high induction response and a low channelling response.

The induction and channelling response can be observed by the amplitude of in-phase and quadrature components. The induction response has a greater in-phase than quadrature component. The channelling response directly affects the quadrature component, but it has little effect upon the in-phase component.

Besides the property of the plate, the EM response is affected by the geometry of the plate, such as length, thickness, dip and depth. In a thick plate, there is a current flow in the thick dimension and the EM response at the position of plate will increase (Figure 2.3). The other properties concerning the EM response will be discussed in Chapter 4, where the profile characteristic is needed to represent a total EM response



τ = conductance
δh = conductivity of host
I^N = induction number($2\varpi\mu\tau a$)
C^N = channelling number($\tau/2\delta ha$)

Figure 2.2 Conductive plate properties in a conductive host

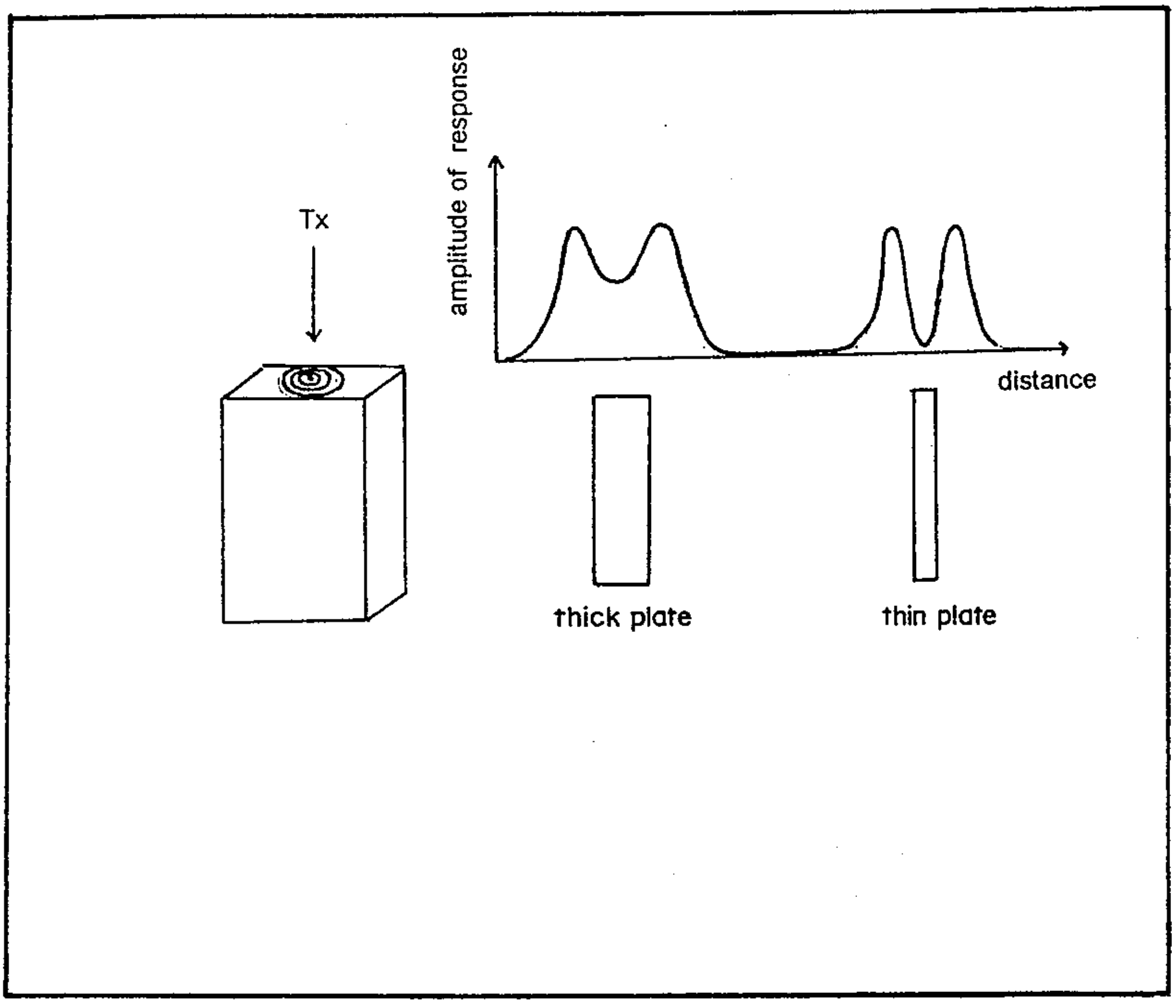


Figure 2.3 Effect of a thickness of a conductor on the EM response

2.3.2 Host

The host is defined by the response parameter of the host ($\gamma_h = \omega\mu\sigma_h t^2$), and can be divided into a saturated host (high γ_h) and an unsaturated host (low γ_h).

When an EM wave propagates through a saturated host, the induction current is induced in the host and flows parallel to the plane of the plate. This creates a channelling current and generates the secondary magnetic field (Figure 2.4). The amount of the current is controlled by the C^n

2.3.3 Source (Transmitter)

The source factors that affect the EM response are as follow:

1) **Primary magnetic field**: A high intensity primary magnetic field will induce a high current that generates a high EM response. In practice, the secondary magnetic field is measured in terms of a percentage the primary magnetic field to compensate for a varying intensity of the primary magnetic field.

2) **Frequency:** The EM response will increase to the maximum and remains stable when the frequency increases continuously .

3) **Direction:** The direction of a primary magnetic field has an effect on the shape of the anomaly profile (Figure 2.5).

Figure 2.5 A and B show that the position of the maximum coupling has two peaks near the plate when the direction of the primary magnetic field is vertical (coplanar coil configuration) and has only one peak at the position of the plate when the direction of the primary magnetic field is horizontal (coaxial coil configuration).

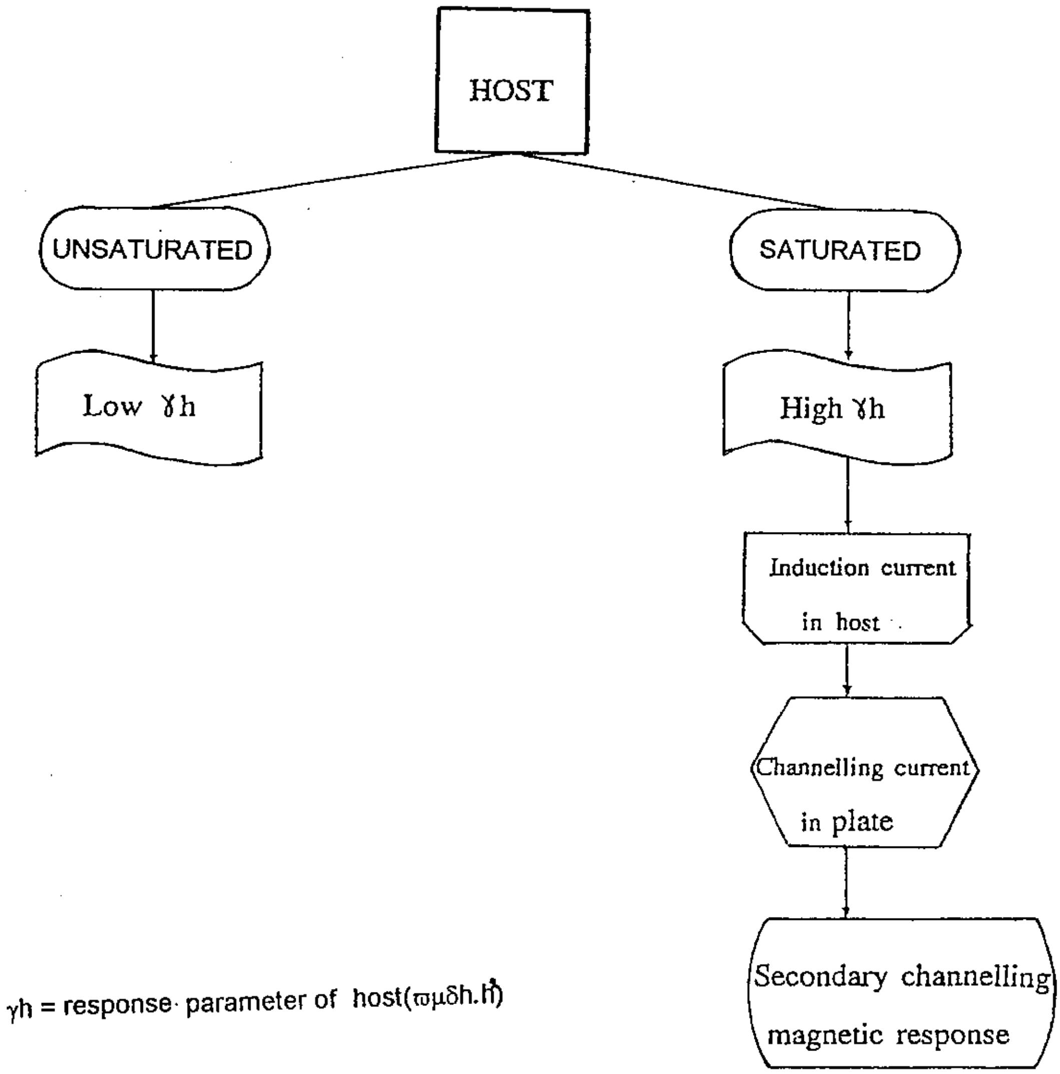


Figure 2.4 Host properties affecting the EM response

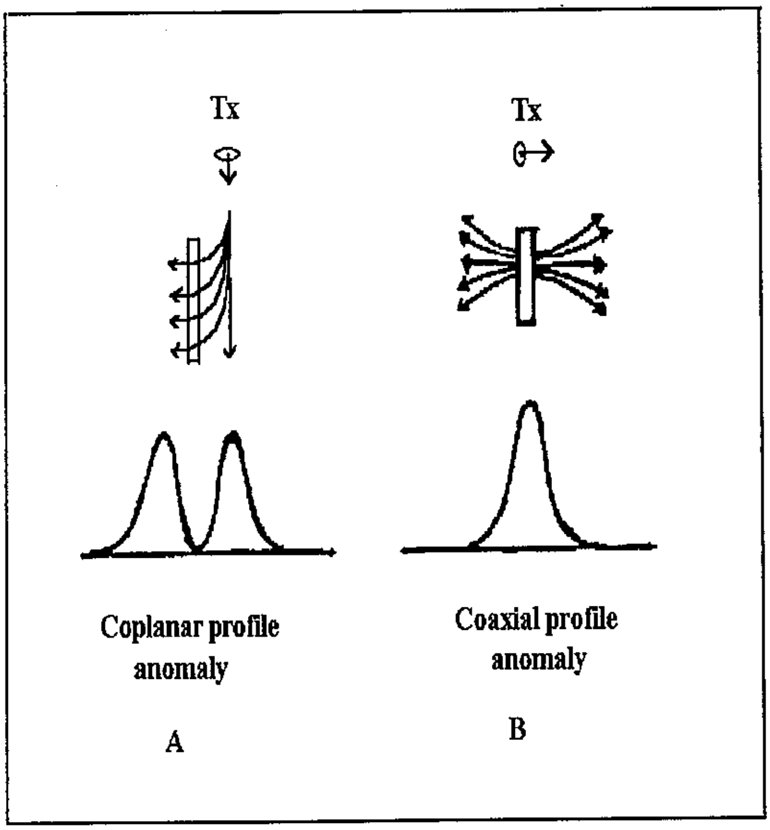


Figure 2.5 Orientation of the source affects the EM response

4) **Distance**: The distance of the transmitter from the plate affects the EM response in both horizontal and vertical directions.

The induction and channelling responses are affected by the horizontal distance from the source. The induction response is strong when the plate is placed near the source. On the other hand, the channelling response is strong when the plate is sitting far from the source (Walker, 1988).

2.3.4 Receiver

The orientation of the coil in a receiver affects the shape, amplitude and position of the EM response. Figure 2.6 shows that the induction, channelling, and resultant responses are different if different orientations of the receiver coil are employed.

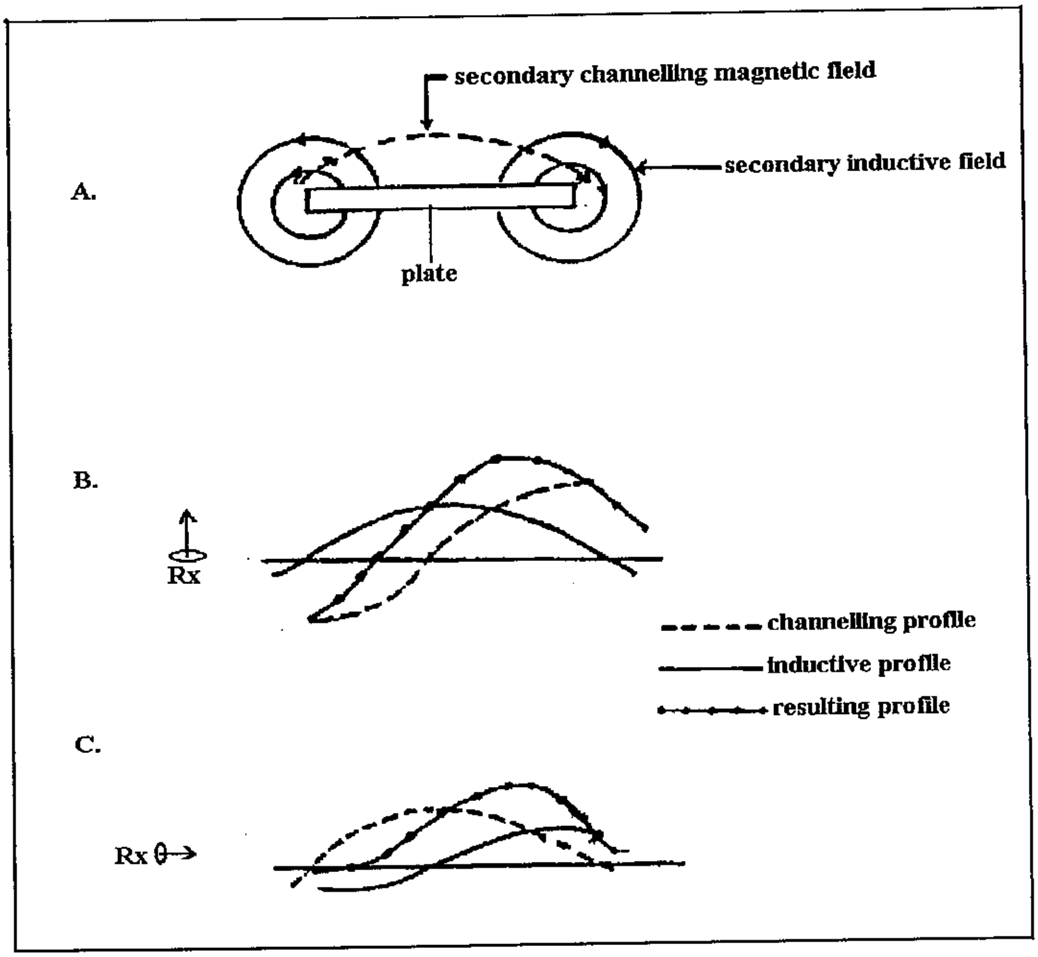


Figure 2.6 Orientation of the receiver as it affects the EM response profile

A) Secondary magnetic field in the plate

B) EM response profile measured on the vertical coil receiver

C) EM response profile measured on the horizontal coil receiver

CHAPTER 3
VHPLATE PROGRAM

Considering the EM response discussed in the preceding chapter, numerical model algorithm can be used to demonstrate its phenomena. Many numerical EM made algorithm were presented by various authors (e.g. Lamontange and West (1971), Annan (1974) and Eadie (1979)). Anyway, VHPLATE program was selected to use in this study.

VHPLATE program is the version of a modeling program which has been developed by Peter Walker in his doctoral thesis. This program allows the user to model a single conducting plate in a layered host medium in frequency domain. The advantage of the program is the unlimitation of the geometry of the target. Both low and high contrast targets can be modeled accurately.

The VHPLATE is an integral equation solution which robustly models electromagnetic scattering when the currents are purely inductive, purely galvanic (or channelling) or combination of the two currents.

THE INDUCTIVE MODE:

In the inductive mode, currents flow in vortices as illustrated in Figure 3.1.

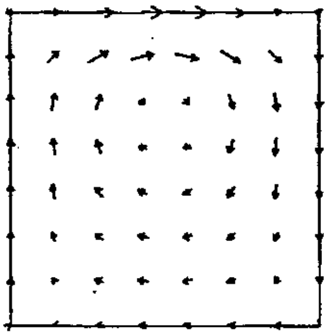


Figure 3.1 Currents flow in inductive mode

The inductive mode is often assumed to dominate the response on a thin plate. Unfortunately, this assumption can only be relied upon when the plate lies in extremely resistive environments. Induction is strongly controlled by the coupling of the magnetic field with the target. Because of this, the induction can vary along a profile in a moving source system.

THE CURRENT CHANNELLING MODE:

In the current channelling mode, current flows in from the host medium and through the conductor as illustrated in Figure 3.2 .

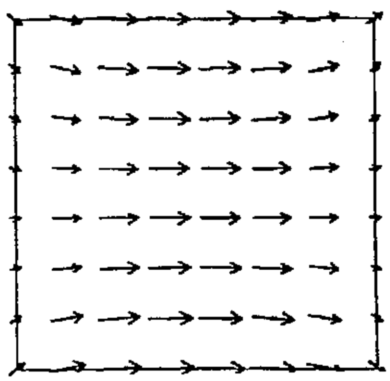


Figure 3.2 Currents flow in channelling mode

The channelling mode is often assumed to be insignificant on a thin plate, but can co-exist with induction and sometimes dominates it. Channelling is controlled by the coupling of the electric field with the target. Because of this, it can also vary along a profile in different manner from induction in moving source systems.

The electromagnetic response is calculated from a thin dipping plate which is buried in one of a number of layers. The plate is rectangular, and may give an aspect ratio from 1:1 to 9:1. It may be given an anomalous conductance and Cole-Cole polarization parameters. The plate must be more conductive than the surrounding medium it resides in. Each of the layers can have a different thickness, conductivity, electrical permittivity and magnetic permeability.

VHPLATE can be used to model inductively dominated responses from massive sulfides in the most resistive crystalline rocks, current channelling dominated response in highly weathered conductive environments, and the interaction between the two modes. In many cases, it is difficult to know whether the response is dominated by induction or current channelling, even when the source used is a ground source such as in IP surveys. Similarly, a loop source which is associated with the inductive response can generate the large current channelling response in the conductor, depending on the target- source coupling and host rock resistivity.

3.1 The Calculation of VHPLATE

VHPLATE is an integral equation solution, and so has elements in common with other integral equation solutions such as those developed at the University of Utah (Hohmann, 1975). In all such solutions, the integral equation represents the volume of the ground with anomalous conductivity. The conductivity structure is chosen to be simple enough that incident fields inside it can be calculated either analytically or quasi-analytically. In practice, this has limited the background to either a whole space, two half-spaces, or two half-spaces with layers.

The integral equation specifies how the anomalous conductivity alter the current flow in the ground from the current distribution that would flow naturally in the background medium. To do this, the electric fields at selected points inside the anomalous conductivity are calculated and fed into the integral equation solution. The output of the integral equation solution is the current pattern, the scattered field associated with the presence of the anomalous conductivity can be calculated.

Like all other integral equations, the scattered fields in the VHPLATE are calculated by first assigning points in the plate where the incident electric field is to be found. In the current version, the incident electric field is found at 41 points equally distributed in both of the two larger dimensions of the plate. These input electric fields are then used to compute the scalar potential, magnetic field and then the scattering current distribution on the plate using the basis of polynomials ranging continuously from order 0 through 5 inclusively. The solution should be accurate for the case where the incident electric field and all computed quantities can be accurately represented by the polynomial basis; i.e. when the incident field does not vary too drastically over the plate. Such a situation, for example, could occur when a dipole transmitter is located in close proximity to the plate(Walker,1994).

3.2 Steps in Construction of the diagrams

3.2.1 Calculation of the EM response by using the VHPLATE program

For the calculation of the EM response, the parameters which control the EM response will be selected. The three important groups of parameter are the instrument systems, the conductors and the host rocks. The instrument systems includes waveform (frequency or time domain), coil configuration (coplanar or coaxial), coil separation and source position. The conductor parameters encompass conductance (conductivity-thickness), depth, dip, strike and dimension. The last parameter is the conductivity of the host rocks which is very important for the EM response of the conductor buried in conductive host media.

The steps in the calculation of EM responses by the VHPLATE are as follows:

1) **Parameters input** : This step is devised for the user to design the study models and select the parameters in calculating the EM responses of the models. When the parameters are varying, the different profiles of the EM responses can be observed. The input parameters include :

- waveform input,
- layered earth input,
- plate input,
- profile input,
- response specification input,
- normalization input,
- plotting input

2) **Calculation of the EM response** : After the input step, the program should now start executing. One of the first operation it undertakes is to perform some simple checks on the input parameters to ensure that they are correct. If not, the program will terminates with an error message. If the input parameters are correct , the program will calculate the EM response based on the input parameters. The results will be saved into an output file, vhaplate.ans or vh.dat.

3.2.2 Application of the VHPLATE program for constructing the conductive host diagram

To plot the EM response result, the file vh.dat will be selected. Via the Grapher or MicroSoft Excel program, the profile of the EM responses will be shown along the line with sampling interval controlled by the input parameters. The different characteristics of the EM profiles can be observed and studied when the input parameters are changed.

After the profiles with varying parameters are plotted, then the maximum response amplitudes of in-phase and quadrature are selected and collected. A diagram will be created by plotting the collected data of a group of parameters. The flow chart of the construction procedure of the diagram is shown in Figure 3.1. Within the dash-blocked section, the application of the VHPLATE program is outlined and then the conductive host diagram is made.

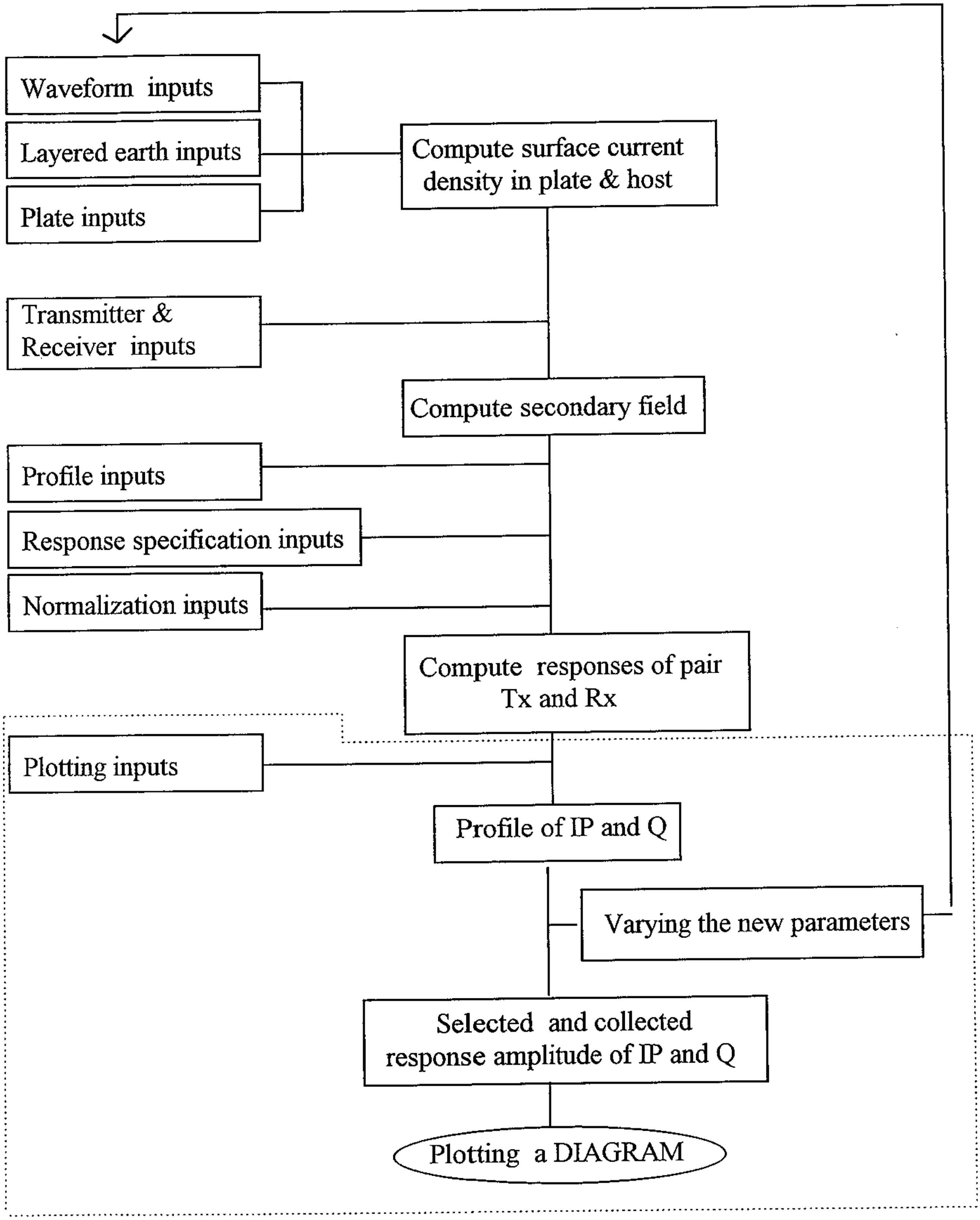


Figure 3.3 Flow chart of created diagram steps.

CHAPTER 4
CHARACTERISTIC OF AEM RESPONSE PROFILES

Airborne electromagnetic (AEM) surveys have been used since the 1950's as a rapid mean to economically explore any large geologically potential area to detect conductive zone of sulfide mineralization. In addition to their main application in base metal exploration programs, AEM systems are frequently used for structural mapping or in an engineering context, mapping overburden. AEM surveys are also used for the indirect detection of a mineral deposit such as uranium mineralization which is sometimes associated with conductive marker horizons.

Most AEM systems employ moving source configurations comparable to moving source systems used on the ground. The main limiting factors in AEM system is the differential movement and coil configuration between the transmitter and the receiver which cause the large voltage induced in the receiver by the primary magnetic field to vary with position, making detection of small secondary components difficult. Two solutions have been used to overcome this problem, namely, coaxial and coplanar coil configurations

Since both coaxial and coplanar coil pairs are symmetric about a vertical axis, the flight direction does not affect the response. Thus, one needs only to compute profiles for conductor dipping at an angle of 90°, assuming that the conductor is geometrically thin.

Maximum coupling between a vertical dipping conductor and coaxial coil occurs when the coils are directly placed above the upper edge of the conductor. A single symmetric anomaly is obtained for both the in-phase and quadrature component .

In case of coplanar coils, maximum coupling occurs when the coil pair is located at some distance from the conductor. Coplanar coils do not couple with a vertically dipping conductor when placed directly above it's upper edge, provided the conductor is geometrically thin. Thus a profile with two symmetric shoulder peaks and a central trough of zero amplitude is obtained. The amplitude of the coaxial peak and the coplanar shoulder peaks are almost identical.

In order to calculate the AEM response of thin rectangular plates in free space, the use was made of a FORTRAN computer program

(PLATE) developed by A.V. Dyck and others at the Department of Physics, University of Toronto (Dyck et al., 1980).

In this thesis, the EM response profiles of the thin plate(conductor) buried in a conductive host media are calculated by the FORTRAN computer program called VHPLATE. This program was developed by Peter W.Walker (1988). In addition, the diagram for interpreting the AEM data was shown only in the coplanar coil (HLEM) configuration, a most suitable configuration for examining a vertically oriented structure.

4.1 Model Study

The study model and the instrument system are conformed with the specifications for the AEM surveys in Thailand as follows :

1. **Instrument system**
   -frequency: 912 Hz
   -coil configuration: coplanar coil
   -coil separation : 6.43 m.
   -source position : +30 m.

2. **Conductor**
   -conductance : 100 seimens
   -depth : 30 m.
   -dip : 90°
   -strike : 90°
   -dimension (strike and dip extent) : 100*100

3. **Host rock**
   -conductivity : 0.01 seimens/meter

The parameters of the conductor and host rock are varied. For each calculation the instrument system parameters are fixed.

4.2 HLEM Profile Characteristics

The HLEM profiles consist of the background and the anomalies. The anomaly is commonly the peak of high amplitude of the in-phase (IP) and quadrature (Q) components. The characteristics of HLEM profile anomalies include :

-amplitude of IP & Q
-ratio of IP/Q
-position of peak
-width of peak (half of maximum value)
-slope of a shoulder peak

If the parameters of the conductor and host rocks are changed, the characteristics of HLEM profiles will change accordingly. This can be explained by the electromagnetic process.

4.2.1 Conductance of the conductor

Conductivity-thickness is defined as a conductance. Generally, sulfide minerals have high conductance. This means that they have a high conductivity because the study models are assumed to be thin.

Figure 4.1 shows that the characteristic of the HLEM profile changes when the conductance increases from 30 to 100 seimens. The amplitudes and ratios of IP & Q increase because the EM responses are dependent on the conductance properties.

4.2.2 Depth of the conductor

If the depth of a conductive plate increases, then, the width (half maximum amplitude between the two peaks) of anomaly also increases (Figure 4.2).

At a shallow depth, the profiles show a high amplitude with high ratio of IP and Q and a narrow peak separation. At a greater depth, the opposite is observed; i.e. the profile show low amplitude, low ratio of IP/Q and a larger peak separation.

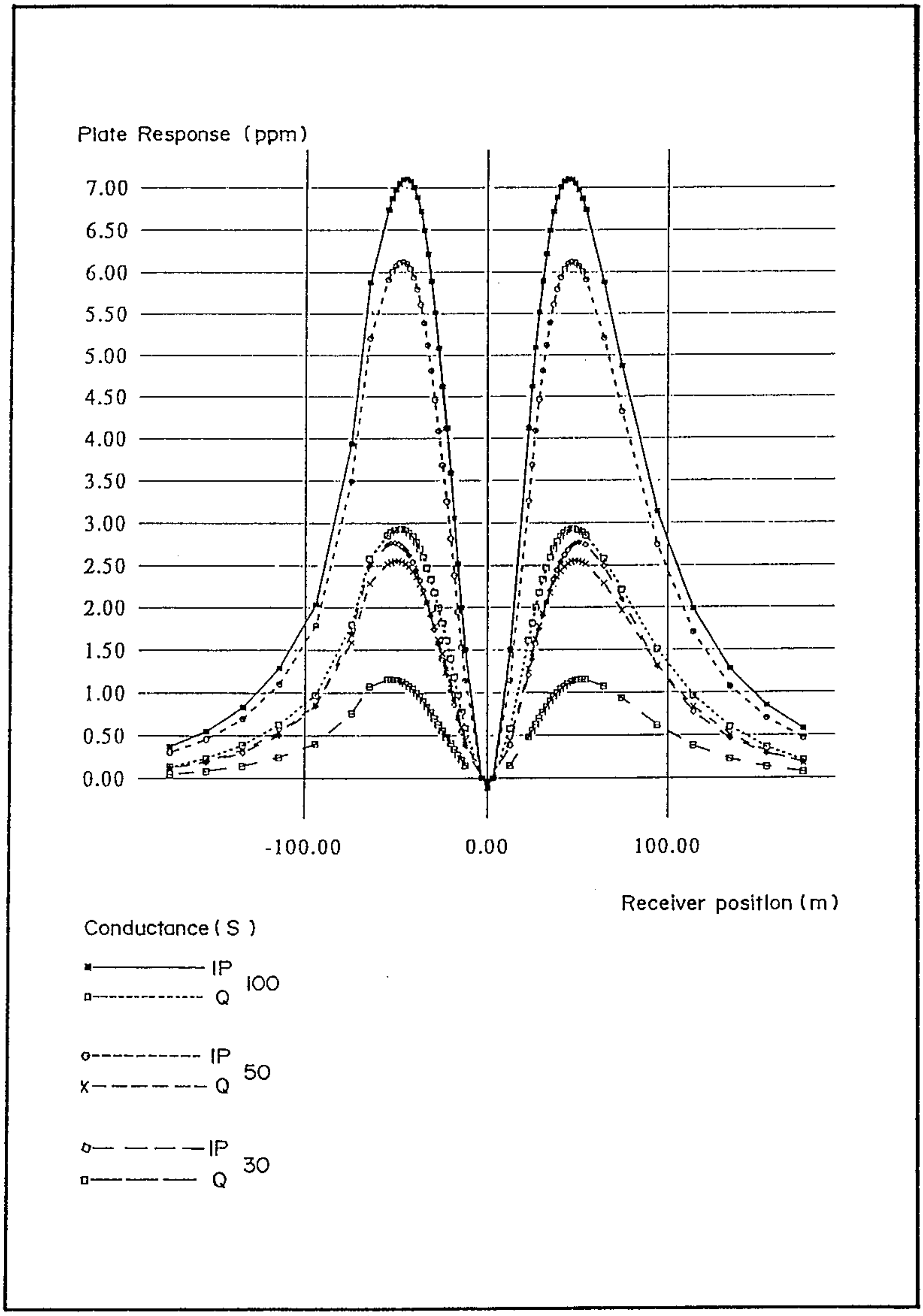


Figure 4.1 Characteristics of the HLEM profile over a vertical plate at different conductance

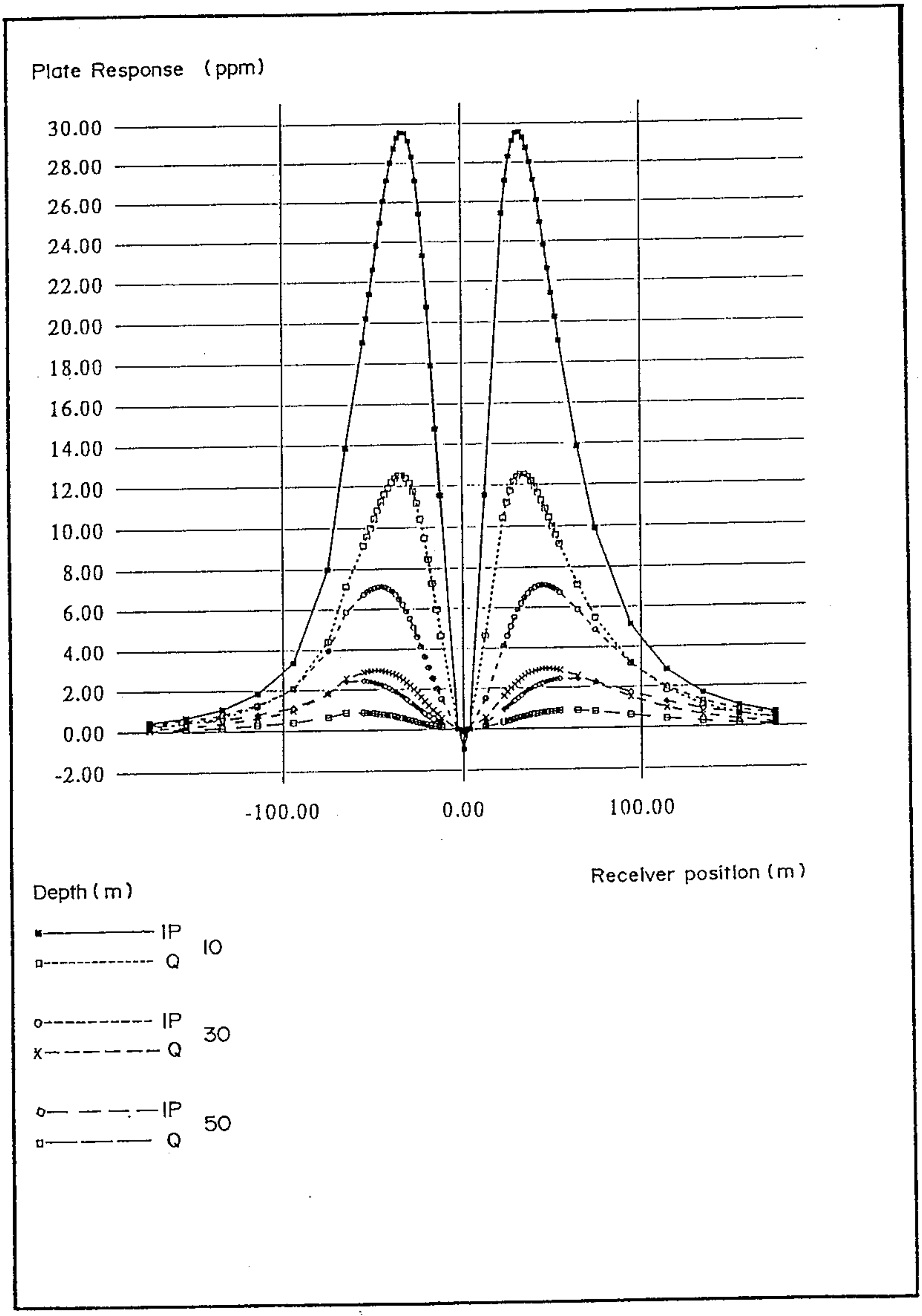


Figure 4.2 Characteristics of the HLEM profile over a vertical plate at different depth

Figure 4.3 shows lines of magnetic flux from the transmitter intersect the conductive plates at different depths which explains the characteristics of the profiles discussed in the next paragraph.

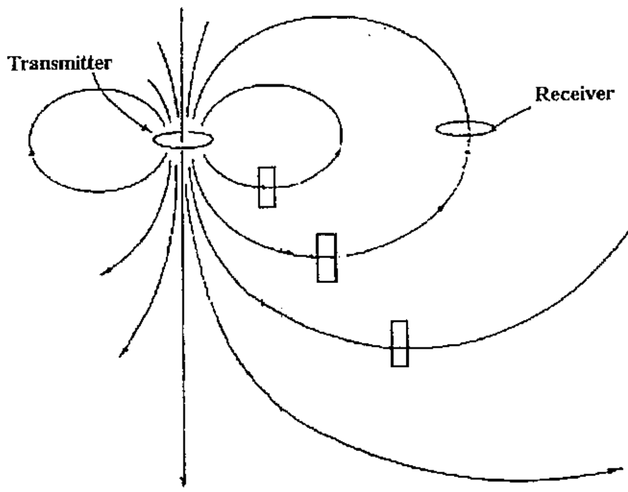


Figure 4.3 Sketch diagram of the magnetic flux intersects the conductor at different depth.

The maximum coupling of magnetic flux with a shallow depth conductive plate is closer to the transmitter than that of the greater depth. The peak separation of a high amplitude anomaly is, therefore, narrow, in contrast to that of the greater depth.

4.2.3 Dip of the conductor

The characteristics of the profiles are controlled by the electromagnetic process, as shown in Figure 4.4 (a and b).

Figure 4.5 shows the characteristics of the HLEM profiles that are affected by the dip of the conductive plate.

When the angle of a conductive plate is 90°, the peaks are symmetric. If the dip of the conductor ranges from 30° to less than 90°, major peak and minor peak are observed. If the dip of conductive plate is 30° or less, only one peak of anomaly is observed. This single peak is similar to the anomaly of a coaxial configuration, but with different slopes of the shoulder peak.

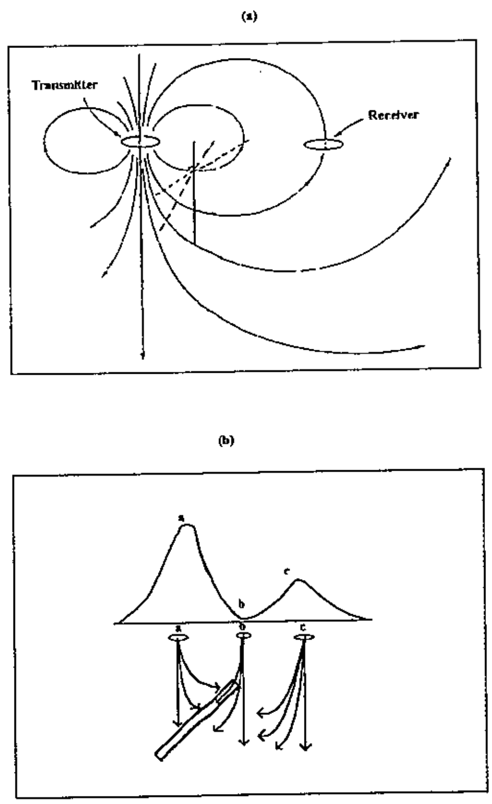


Figure 4.4 Sketch diagram of the magnetic flux intersect the conductor at different dips.

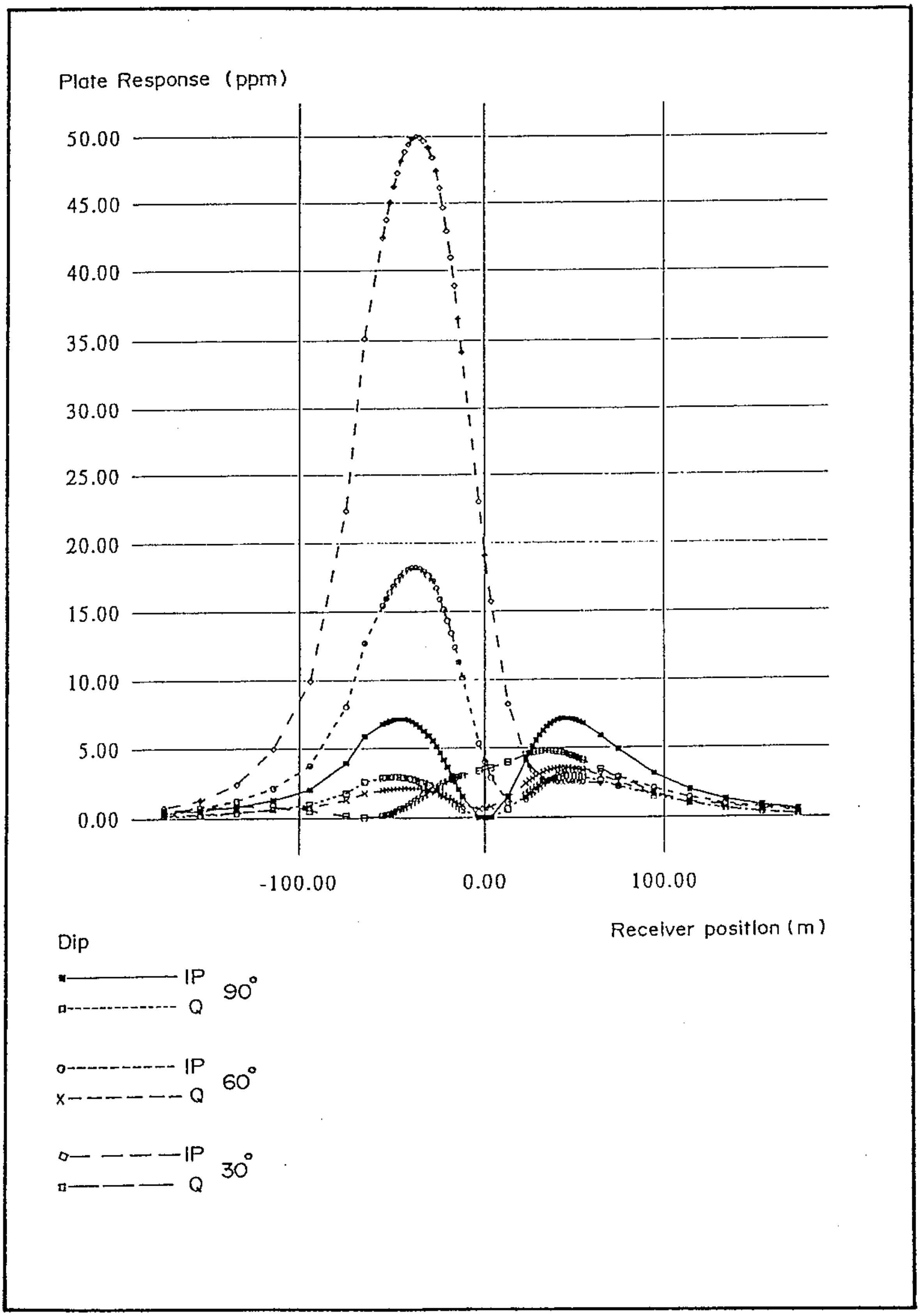


Figure 4.5 Characteristics of the HLEM profile over a vertical plate at different dips

The sketch diagrams show the magnetic flux intersect the plate at different dips (Figure 4.5a). When the plate is dipping vertically, then the symmetric peaks have low amplitude because the maximum coupling between the magnetic flux and plate is further away from the transmitter, so the intensity of magnetic flux decreases.

When the transmitter is moving along the dipping plate (Figure 4.5 b), at position **a**, the lines of magnetic flux are perpendicular to the conductor, thus, the high amplitude peak (major peak) is shown. At position **b**, the lines of the magnetic flux are almost parallel to the conductor, showing the low amplitude response. At position **c**, the lines of the magnetic flux crossing the conductor are far from the transmitter, so, a medium amplitude peak (minor peak) is detected. Thus, a conclusion can be drawn that the major peak indicates the dip direction of the conductor.

4.2.4 Strike of the conductor

For a resistive host rock, decreasing the strike angle from 90° to 30°, increases the anomaly width. The width increase as $1/\sin\theta$, where θ is the strike angle (Ferneyhough,1985).

The coupling between the coplanar coils and the conductor is practically independent of the strike angle, such that the anomaly amplitude is not quite altered. This is the most useful parameter in locating conductors whose strikes are almost parallel to the flight line (Fraser,1979).

In case of conductive host rocks, Figure 4.6 shows the effect of a strike angle to the EM response. Decreasing the strike angle from 90 to 30° decreases the amplitude and ratio of IP/Q.

In order to explain this effect, the lines of magnetic flux in plan view are shown in Figure 4.7.

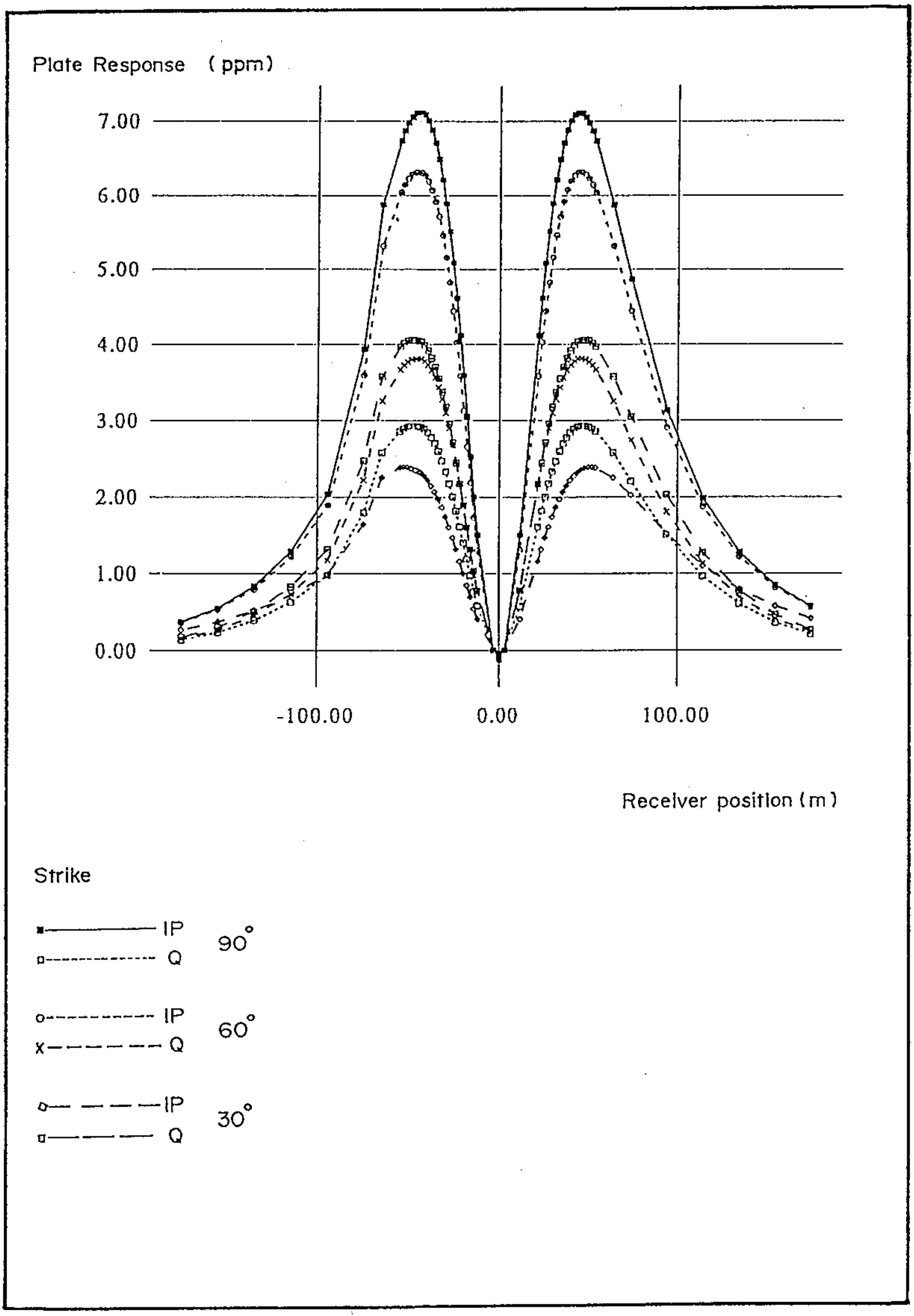


Figure 4.6 Characteristics of the HLEM profile over a vertical plate at different strikes

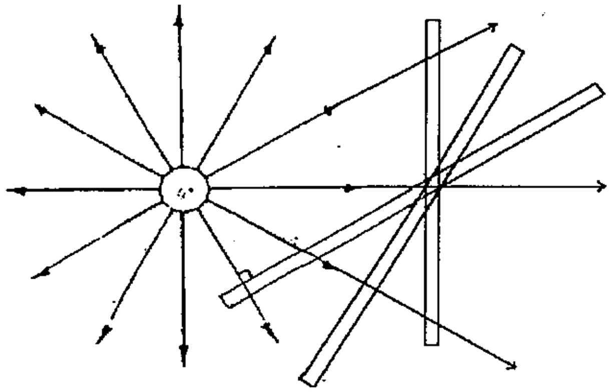


Figure 4.7 Sketch diagram of the magnetic flux intersect the conductor at different strikes.

When the strike angle is 90°, there is the maximum coupling between the coplanar coil and conductor. So, the maximum amplitude can be observed.

4.2.5 Dimension of the conductor

Dimension of the conductor (dip extent and strike extent) is dependent on the EM response. Figure 4.8 shows the high amplitude peaks for a large dimension and low amplitude peaks for a small dimension.

However, the height of the transmitter from the conductor also has significant effect to the EM responses.

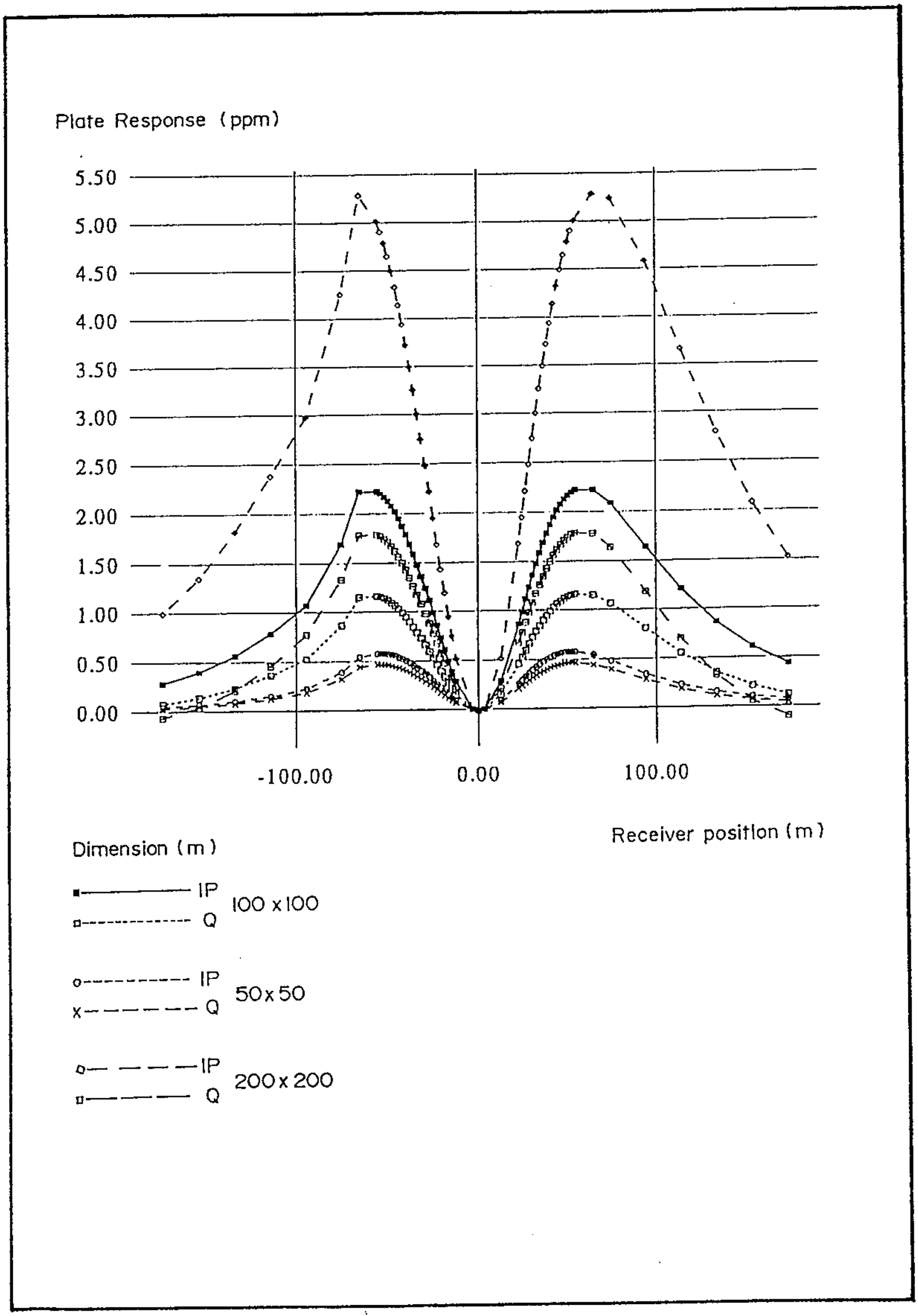


Figure 4.8 Characteristics of the HLEM profile over a vertical plate at different dimensions

For a high source, the dimension of the conductor is proportional to the EM response, for a low source, the dimension of the conductor does not affect the EM response, as shown in Figure 4.9 .

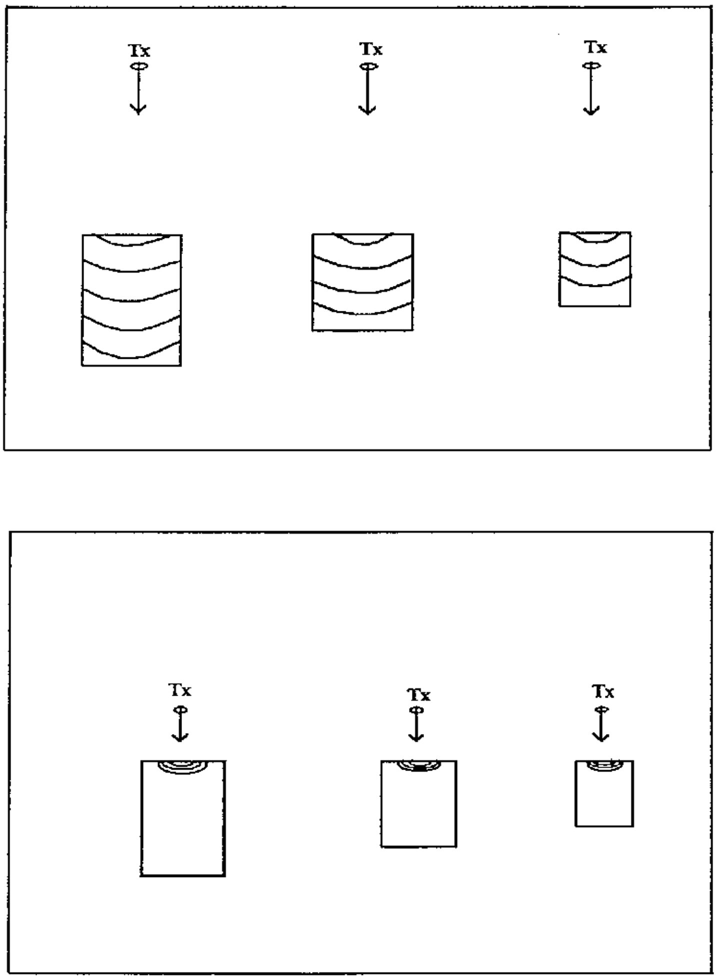


Figure 4.9 Sketch diagram of the eddy current in plate at different dimensions and height of source.

4.2.6 Conductivity of the host

This parameter is very important for the EM response of the conductor buried in conductive host media. The effect of the conductive host on the EM response is two folds :

1) The secondary magnetic field is produced not only by an induced vortex circulation as in the free space case but also by an additional type of current flow. The additional current pattern is a galvanic circulation which passes through the boundary of the target conductor and is, in every respect, similar to the secondary current field observed in the DC resistivity when a conductive region is situated in a conductive host. This current produces a response at the receiver which is geometrically very similar to the one that would be produced by a static magnetometric resistivity survey. The effect is commonly known as a current channelling or current gathering. Generally, the strength of the galvanic part of the response varies directly with the conductivity of the host medium.

2) Both the primary field in reaching the target and the secondary field in reaching the receiver are phase shifted or delayed in time by the low-pass frequency filtering effect of the host medium. The discussion of this effect is explained in Ferneyhough (1985).

Figure 4.10 shows the characteristics of the profiles which have been affected by varying the host-conductivity. The shape of the profiles that have the same conductance are different. So, in case of the EM profiles in a conductive host medium, the consideration of a conductivity of host rocks is very important for the interpretation.

The conclusions of the HLEM profile characteristic of a good conductor buried in conductive host-rocks in the model study can be made as follows:

1. The induction and channeling response and the distance between a source and a conductor control the amplitude of IP and Q,

2. The position of the peak is controlled by the position of the maximum coupling between the line of magnetic field and a conductor,

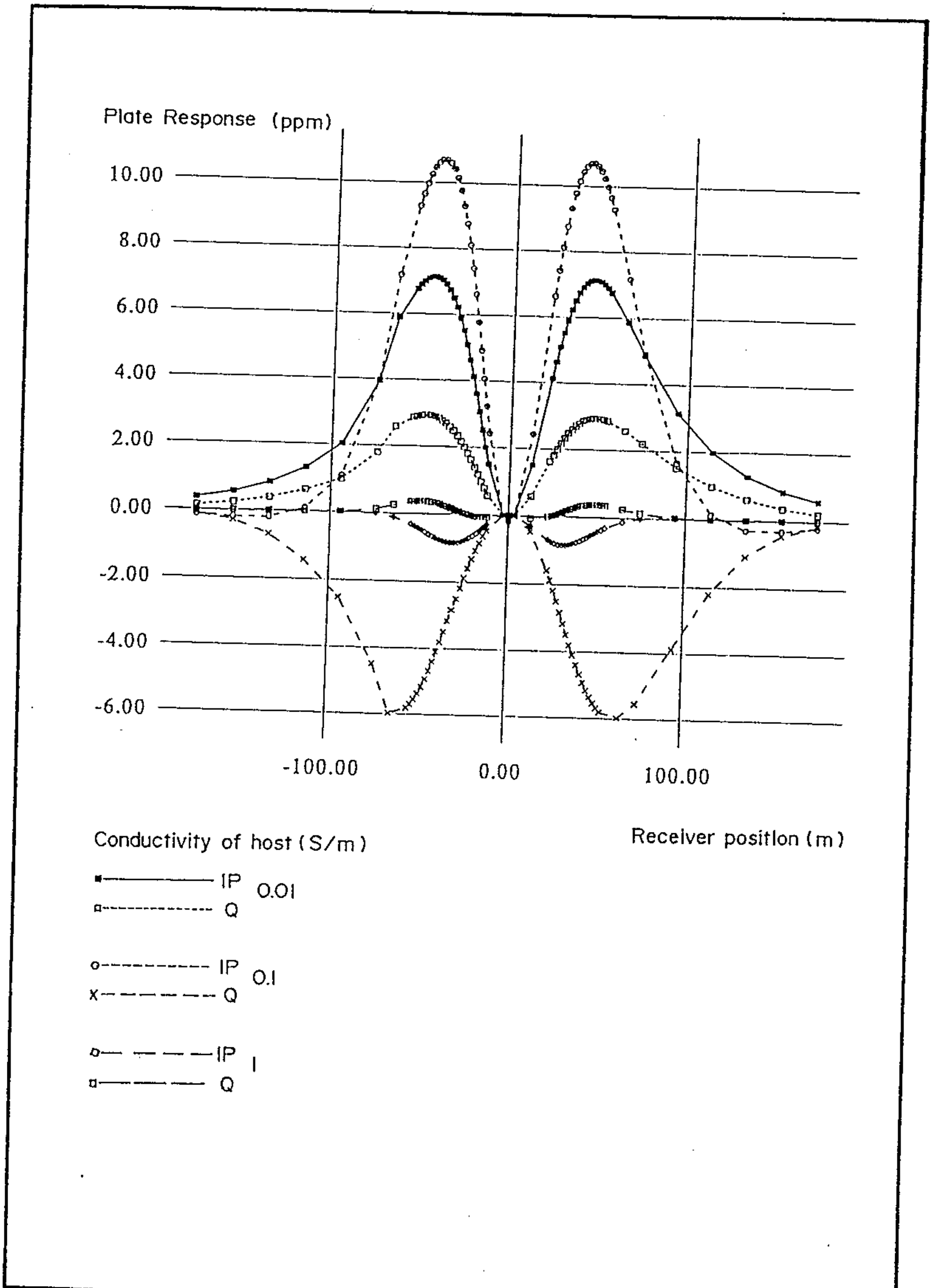


Figure 4.10 Characteristics of the HLEM profile over a vertical plate at different conductivity of host

3. The depth of a conductor controls the width of the peak and the peak separation,

4. The slope of a shoulder peak and the major and minor peaks are controlled by the dip of the conductor,

5. The configuration of the transmitter and receiver controls the shape of anomaly.

The profile characteristic discussed in this chapter will be used to construct an interpretation diagram. The diagram will be made in order to show a relationship between a conductor, with various geometric parameters, and the conductivity of the host rock. The newly created diagram will be described as a conductive host diagram.

CHAPTER 5
CHARACTERISTICS OF CONDUCTIVE HOST DIAGRAMS

The output data of an airborne electromagnetic survey are stacked profiles of two components, the in-phase and quadrature (out of phase). In an area of resistive host rocks, the anomalous profiles in coplanar systems characterized by two peaks over a thin sheet conductor dipping over 30°.

In Chapter 4, different AEM anomalous profiles of various parameters have already been shown. The characteristics of these profiles are related to some important parameters of the conductor such as depth, dip and conductance. In conductive areas, the characteristics of the profiles are complicated due to the effect of the host rock conductivity and/or conductive overburden layers.

The relationships between the conductivity of the host and the depth, dip, and response of the conductor are discussed in this chapter. New diagrams produced from various parameters are explicitly compared as well.

5.1 The Influence of the Host Conductivity to the Depth and Dip of the Conductor

As shown in Chapter 4, the response amplitude of the anomalous profile may indicate the depth, dip, and conductance of the conductor and the conductivity of the host. The height of an amplitude peak represents high conductance or shallow depth, low dip, high conductivity of the host. Since the response amplitudes are affected by many parameters mentioned previously, the interpretation of a conductor buried in a conductive host must be done with caution.

In case of the conductor depth, the other important feature of the profiles besides the high amplitude of a peak is the separation of the two in-phase peak anomalies. From Figure 4.2 in Chapter 4, the large peak separation is related to the deeply buried conductor and vice versa.

Figure 5.1 indicates that the relationship between the peak separation and the depth of conductor is linear. For a conductive host medium, the graph shifts downward as being affected by the host conductivity.

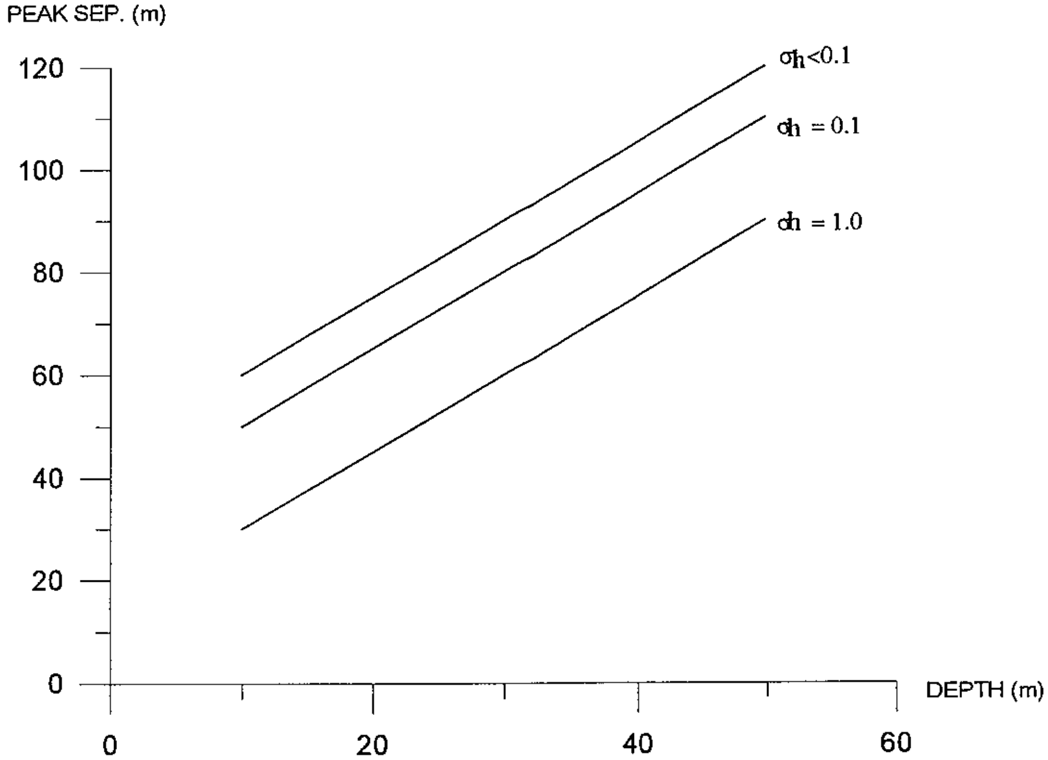


Figure 5.1 Graph showing the relationship between peak separation of anomalous profile and depth of conductor.

In addition, the dip of the conductor, the ratio of in-phase amplitude of two peaks can probably be used to indicate the dip of the conductor. For vertical conductor (dip 90°), the two peaks are symmetric so that the ratio of the two peaks equals 1. When the conductors are not vertical, the two peaks are asymmetric and the dip of conductor can be determined by the ratio of major (M) to minor (N) peak. However, when the dip is less than 30°, the profile shows only one peak, so the dip of conductor cannot be determined by the two peak ratio.

If the conductors are located at different depths, the ratio of M/N changes. Figure 5.2 shows the relationship between the ratio of M/N and the depth. As shown, the ratio of M/N decreases if the depth increases.

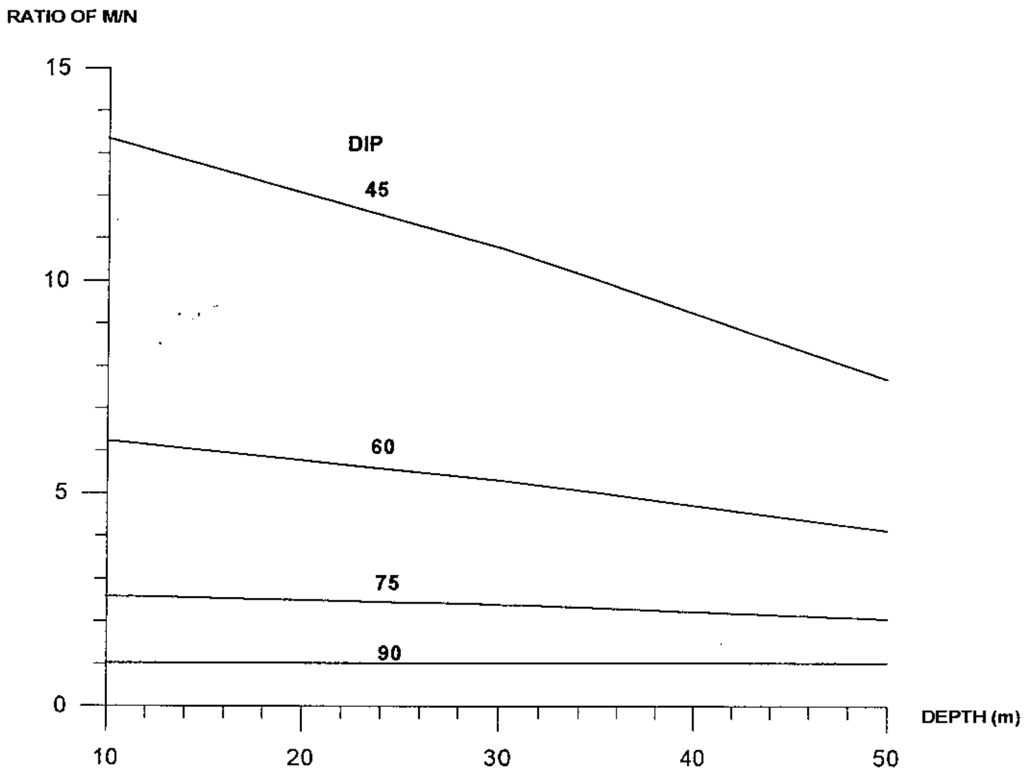


Figure 5.2 Graph showing the relationship between ratio of M/N of anomalous profile and dip of conductor.

In an area of a conductive host, a host conductivity will also affect the ratio of M/N. Figure 5.3 is a plot of the host conductivity versus the ratio of M/N. When the conductivity of the host increases, the ratio of M/N decreases. All the lines are appareantly converged and become parallel to the line representing a vertical conductor from a host conductivity of 0.05 S/m onward.

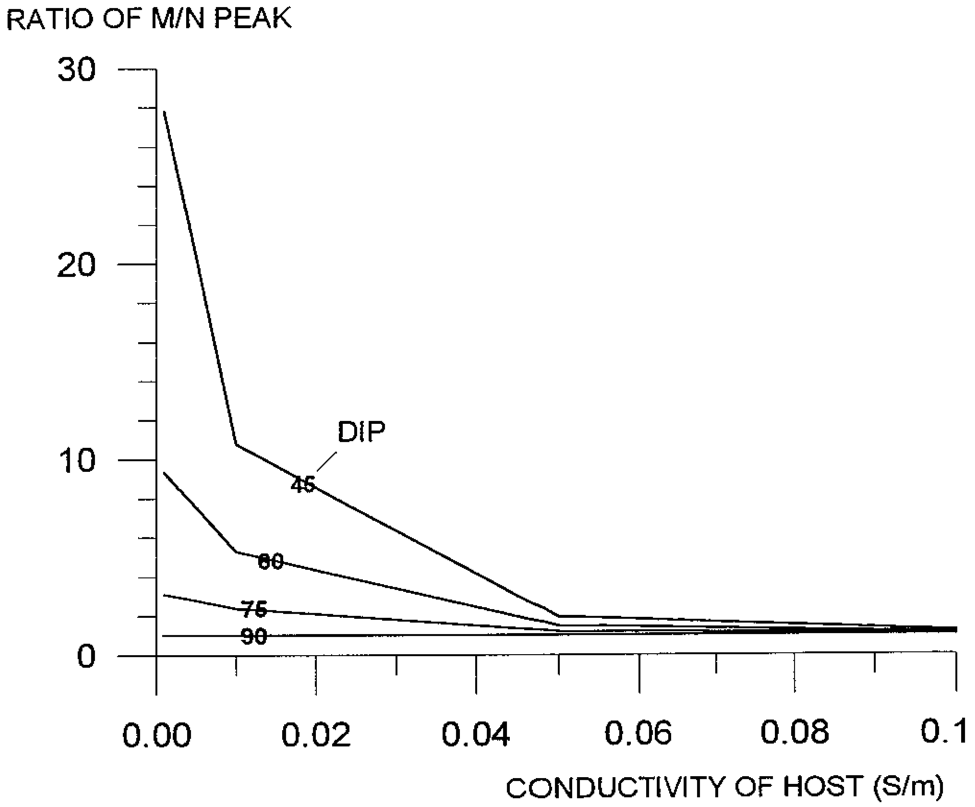


Figure 5.3 Graph illustrating the relationship between ratio of M/N of anomalous profile and the host conductivity

It should also be noted that, the depth and the conductivity of the host do not affect the M/N ratio of the vertical conductor (dip 90°). Thus, in the AEM profiles where the surveys are over the deep conductor or in the high conductive area, the symmetric peak will be observed .

5.2 Effects of the Conductance of a Conductor and the Host Conductivity to the Responses

Figure 5.4 shows the relationship between the conductance of the conductor (plate), the conductivity of the host and the plate response.

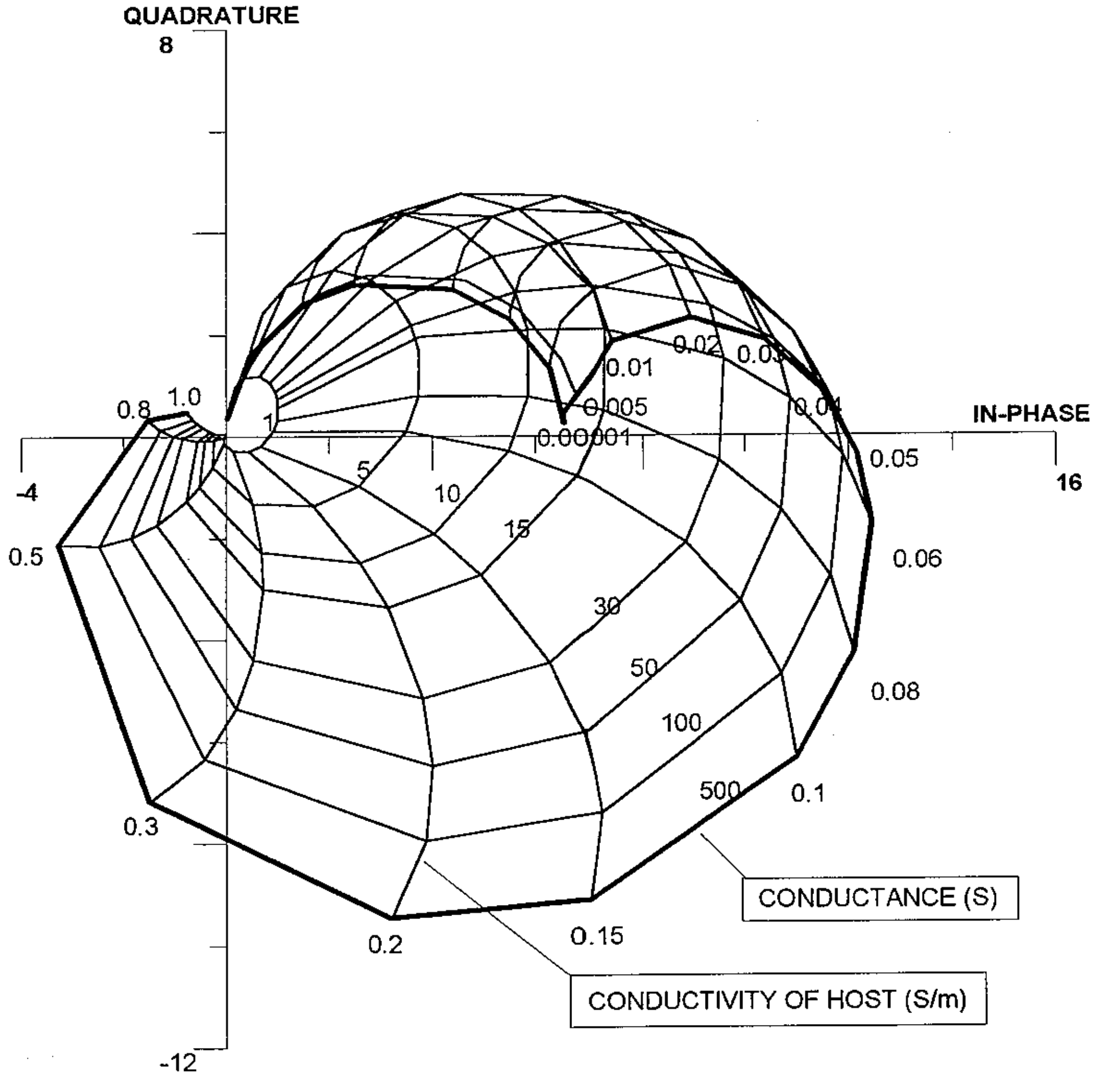


Figure 5.4 Diagram showing the relationship between the conductance of the conductor and the conductivity of host as it affects the response amplitude

When the conductivity of the host increases continuously, the in-phase and quadrature values will shift from quadrant 1 to quadrant 4 around the origin. The sign of the in-phase and quadrature values will change accordingly in each quadrant. Increasing the host conductivity results in an increase of the quadrature values. This relationship can be explained such that when the host conductivity initially increases, the amplitude increases and the phase of the plate response slightly increases by addition of the channelling response to the normal inductive response. Further increase in the host conductivity continues to enhance the amplitude of the total plate response but the phase angle starts to decrease due to the result of the low-pass frequency filtering effect of the host medium.

5.3 Comparison of the Scattering and Layered Earth Responses

All parameters of the plate model are used to calculate the response along the selected line over the target model using the VHPLATE. The response data are plotted as profiles of in-phase and quadrature amplitude values along with the location of the transmitter and receiver movement.

The electrical current generated in the plate consists of the induced current caused by the transmitter and the channelling current which flows from the ground (host). These two types of current then act as the scattering field in the plate. The VHPLATE calculates not only the scattering field but also the scattering and layered earth fields. In practice, the second response (scattering plus layered earth) is more appropriate to the AEM surveys than the first reponse as the resistive host rocks are not common in Thailand. Figure 5.5 shows the difference between the two responses (scattering and scattering plus layered earth) calculated by the VHPLATE. The amplitude of the total response of the scattering plus the layered earth is higher than the scattering response only, resulting in the shifting of the profile from the background. However, if only the amplitude of the residual response is considered then the amplitude of the scattering plus the layer earth response is similar to the amplitude of the scattering response. Creating the interpreted diagram, the maximum amplitude of the anomaly peak is plotted against the conductance and depth. This new diagram is based only on the in-phase and quadrature of the scattering response.

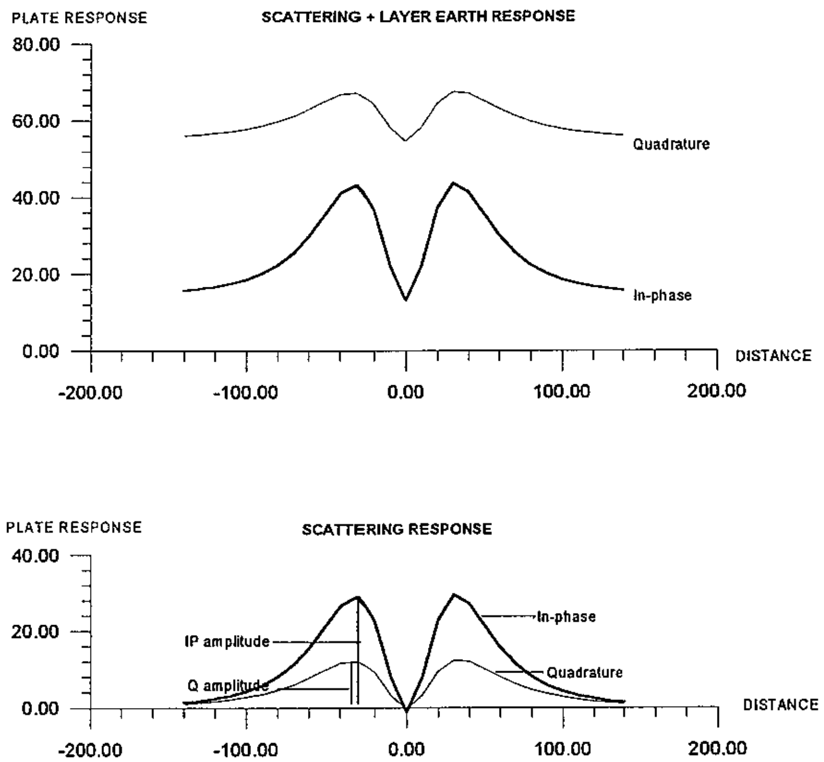


Figure 5.5 Comparison of scattering response and scattering plus layered earth response.

5.4 Model Diagram Study

In order to study the new diagram, the model diagram (the base diagram) is needed. It is constructed for the condition of the conductive host rock incomparison with the non-conductive host rock. The parameters of the base diagram are as follows:

frequency : 912 Hz.
configuration : coplanar
coil separation : 6.43 m.

source height : 30 m.
resistivity of host(ρ) : 100 Ωm
dip extent : 100 m.
strike extent : 100 m.
dip angle : 90°
strike angle : 90°

Most of the system parameters conform with the airborne electromagnetic survey conditions in Thailand .

The diagram is constructed by plotting the amplitude of the in-phase values versus the quadrature values at the maximum peak of the calculated profile. The conductance varies from 5-100 seimens (Ω^{-1}) and the depth varies from 10 to 50 meters.

5.5 Comparison of Conductive and Resistive Host Diagrams

The diagram for a conductor buried in the resistive host ($\rho = 1\times10^8$ Ωm) is shown in Figure 5.6 .

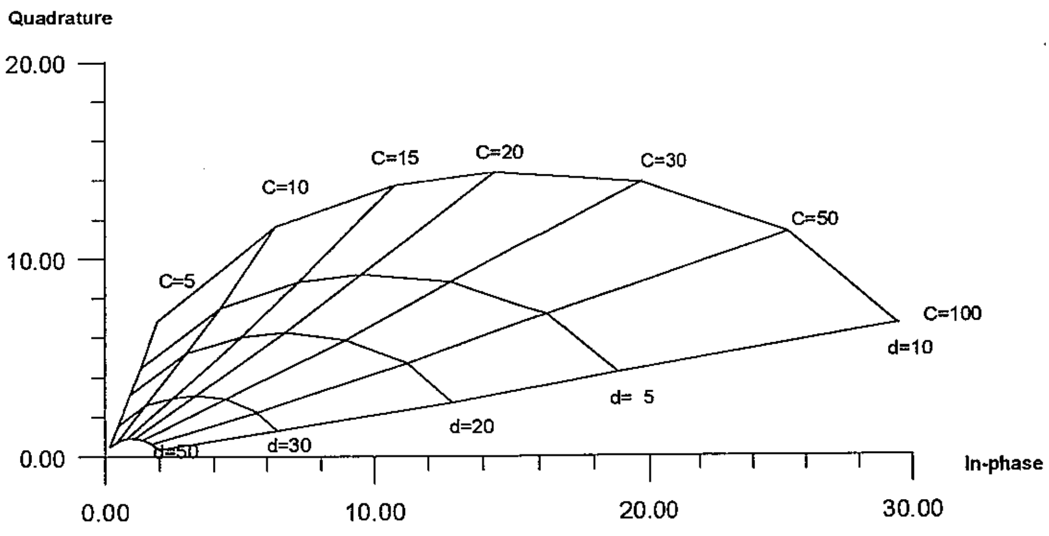


Figure 5.6 Diagram for a conductor buried in the resistive host ($\rho = 1\times10^{8}$ Ωm)

High conductance is represented by the high in-phase and low quadrature amplitudes. The curve or pattern of the diagram is close to the in-phase axis, especially for the high conductance.

When the depth is taken into consideration, it is shown that at shallow depth, the amplitude response is high. When the depth is greater than 50 meters the amplitudes of in-phase and quadrature components are very small. This is common in Thailand, where the profile is rarely shows significant amplitude response, although there is a definitely high conductive bedrock at a 50 meter depth.

Figure 5.7 shows the diagram for a conductor buried in a conductive host (ρ =100 Ωm). The pattern of the diagram shifts from the in-phase axis toward the quadrature axis indicating a high quadrature amplitude of the response. On the other hand, the channelling response also increases in the conductive host. Therefore, the quadrature amplitudes are higher than those shown in the diagram for a resistive host rock.

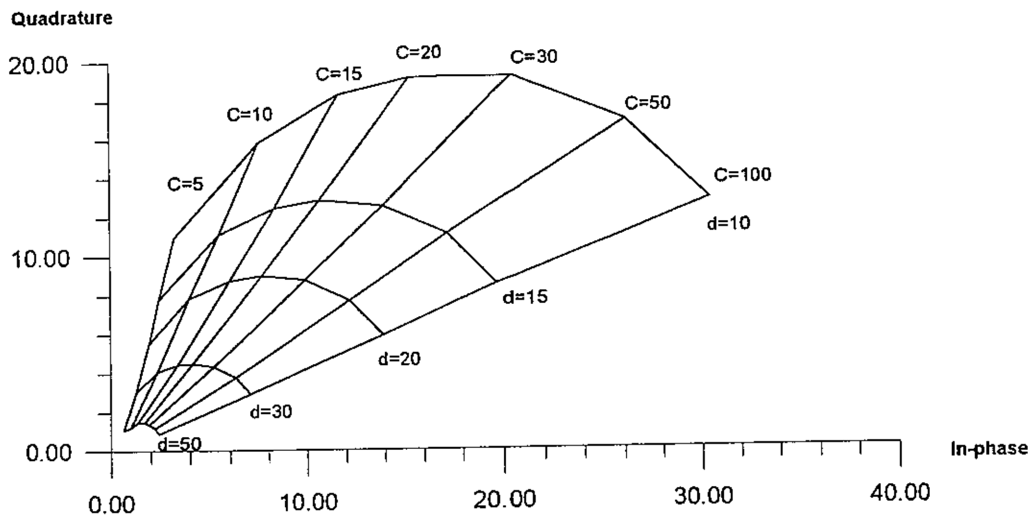


Figure 5.7 Diagram for a conductor buried in the conductive host ($\rho = 100\ \Omega m$)

In order to compare various diagrams for a the conductive host , the diagram in Figure 5.7 is selected as the base diagram.

The conductive top layer is common in Thailand, especially in a flat area. Figure 5.8 shows the diagram with the conductive top layer (ρ =50 Ωm) and the conductive host (ρ =100 Ωm).

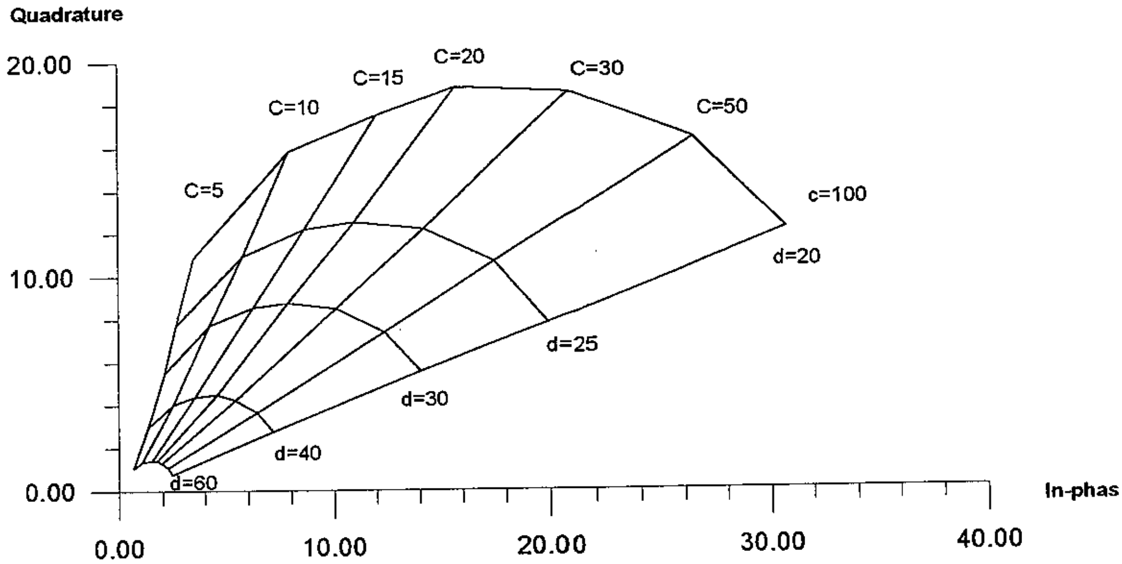


Figure 5.8 Diagram of a conductor buried in the conductive host ($\rho = 100$ Ωm) with the top layer ($\rho = 50$ Ωm)

The general pattern of this diagram is similar to that of the base diagram except the depth of the buried conductor. In the diagram, when the depth of the conductor is 20 meters, the responses are close to those of a conductor without a conductive layer located at a depth of 10 meters. Considering the response at the same depth, the amplitude response of the conductor beneath the conductive layer are about twice greater than that of a conductor without a conductive layer. In order to interpret the AEM response in this case , the geology of the target area has to be considered. The effect of the depth is very important to the size of the responses.

When the dip of a conductor is taken into account, the anomaly profile shows an asymmetric peak . In order to construct this diagram, the maximum amplitude of the major peak is selected because at a low dip (< 30°) the anomaly profile shows only the major peak. Figure 5.9 and Figure 5.10 correspond to the cases where the dip is less than 90°.

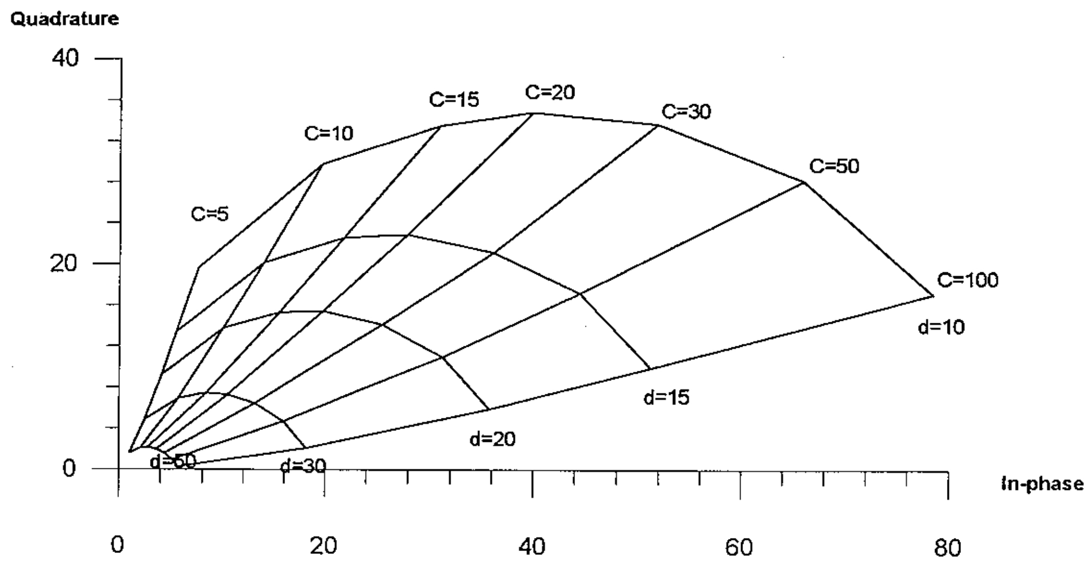


Figure 5.9 Diagram of a conductor buried in the conductive host ($\rho = 100$ Ωm) with the dip 60°

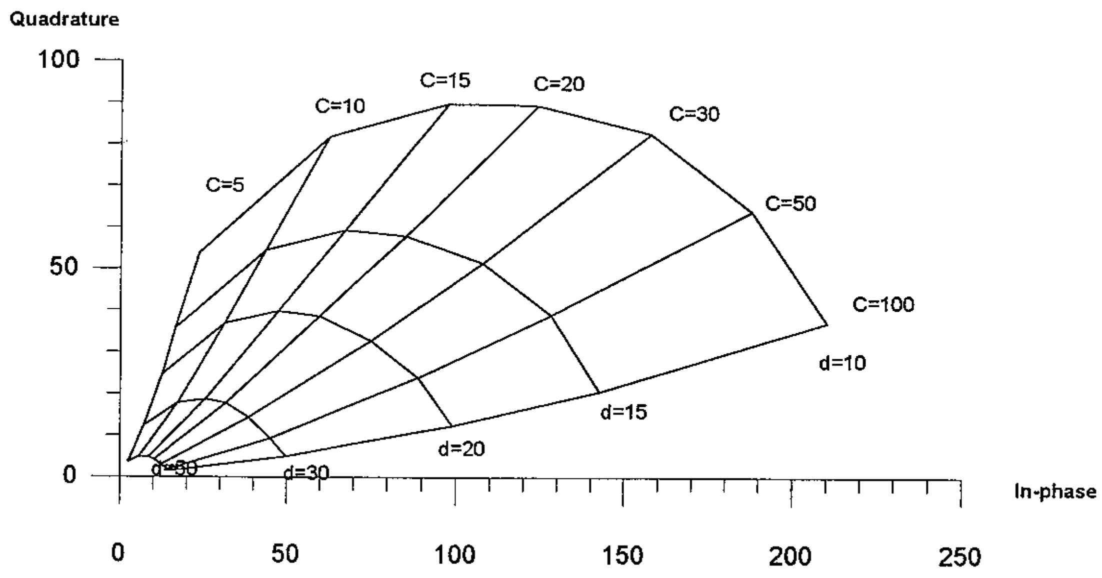


Figure 5.10 Diagram of a conductor buried in the conductive host ($\rho = 100$ Ωm) with the dip 30°

Consider Figure 5.9 (60° dip) , the amplitude responses are twice higher than those presented in the base diagram. The diagram for a 30°

dip conductor (Figure 5.10) shows that the amplitude responses are seven times higher than those shown in the base diagram. Thus, for the single peak AEM anomaly (<30° dip) , the amplitude response must be very high. This interpretation will be erroneous if the interpretation is conducted based on the resistive host diagram.

Figure 5.11 shows the diagram for the conductor in the lesser conductive host (ρ =1000 Ωm).

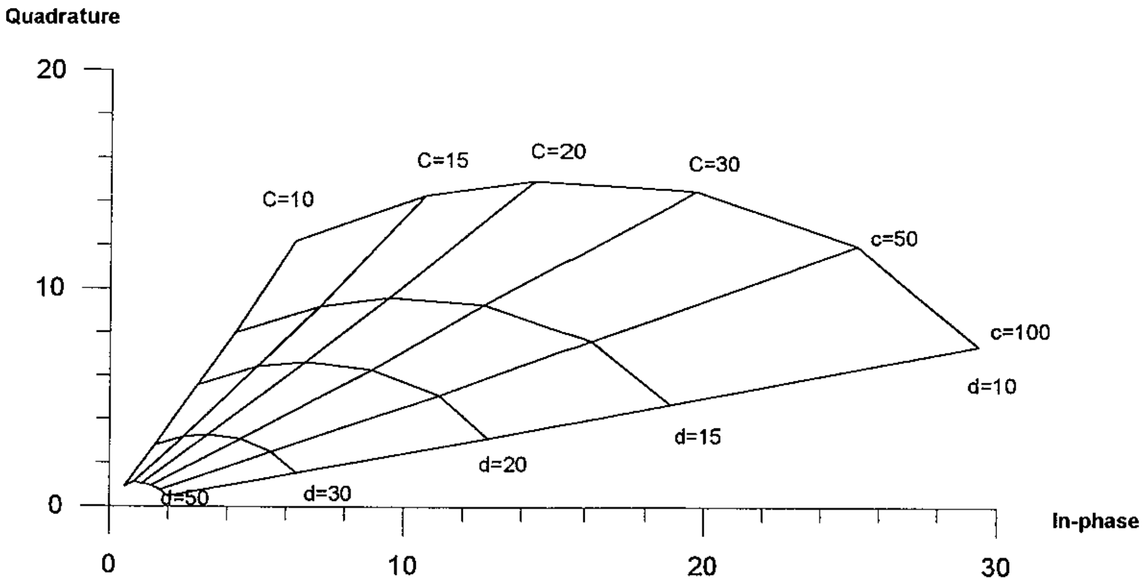


Figure 5.11 Diagram of a conductor buried in the conductive host (ρ = 1000 Ωm)

The pattern of diagram is close to the in-phase axis because of the high conductive contrast between the conductor and the host. If the conductor underlie the conductive layer (ρ= 100 Ωm), as shown in Figure 5.12 these will corespond to the very high response at the same depth. Therefore, the qualitative interpretation of AEM anomaly should reveal the depth of the conductor which will be useful in considerly the response and the set up plan in the geophysic ground follow-up surveys.

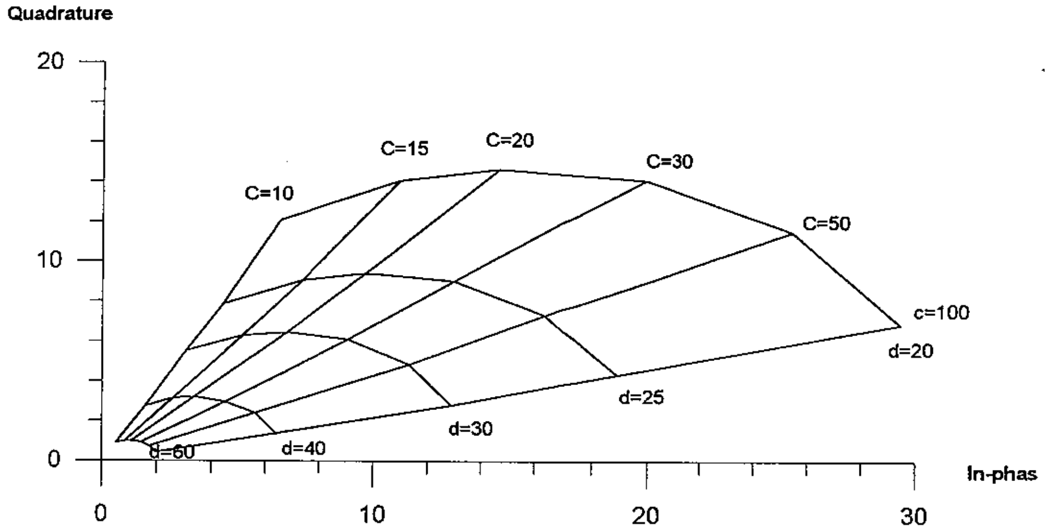


Figure 5.12 Diagram of a conductor buried in the conductive host (ρ = 1000 Ωm) with the top layer (ρ =100 Ωm)

The AEM profile anomalies usually show the continuity of the peak. The long strike extent is equal to or greater than 400 meters since the separattion of the AEM survey line conducted in Thailand is 400 meters.

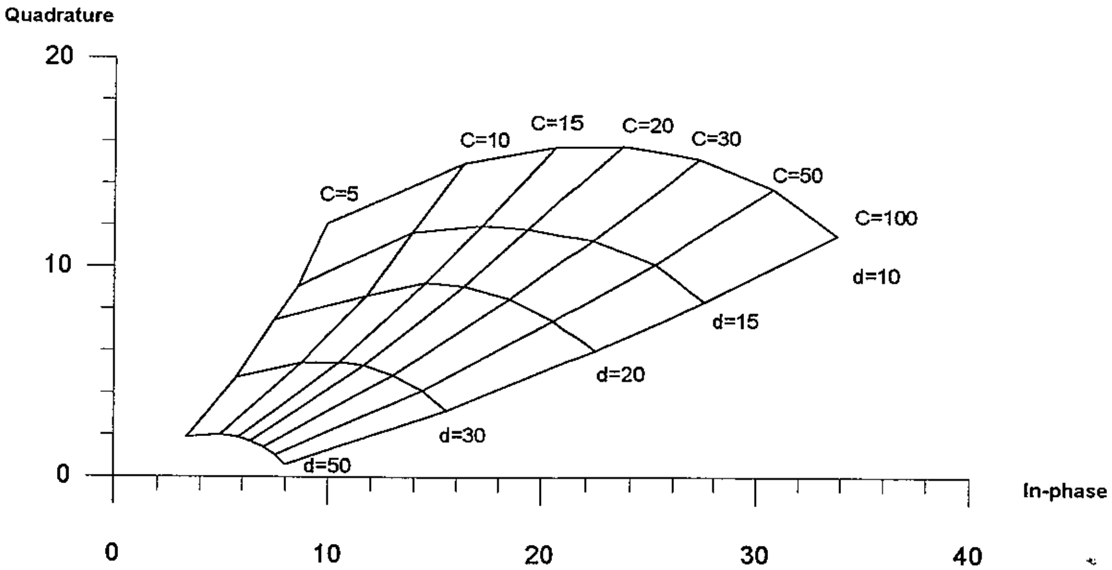


Figure 5.13 Diagram of a conductor buried in the conductive host (ρ = 100 Ωm) with strike extent 1000 m.

Figure 5.13 shows the diagram for a conductor having the strike extent of 1000 meters. The pattern of the diagram is different from the other diagrams mention earlier. It should be noted that at the depth of 50 m, the in-phase values are larger than the quadrature values, although the conductance is low. Figure 5.14 shows the case where the strike angle is 60°, the amplitude response increases but the pattern of diagram is almost identical.

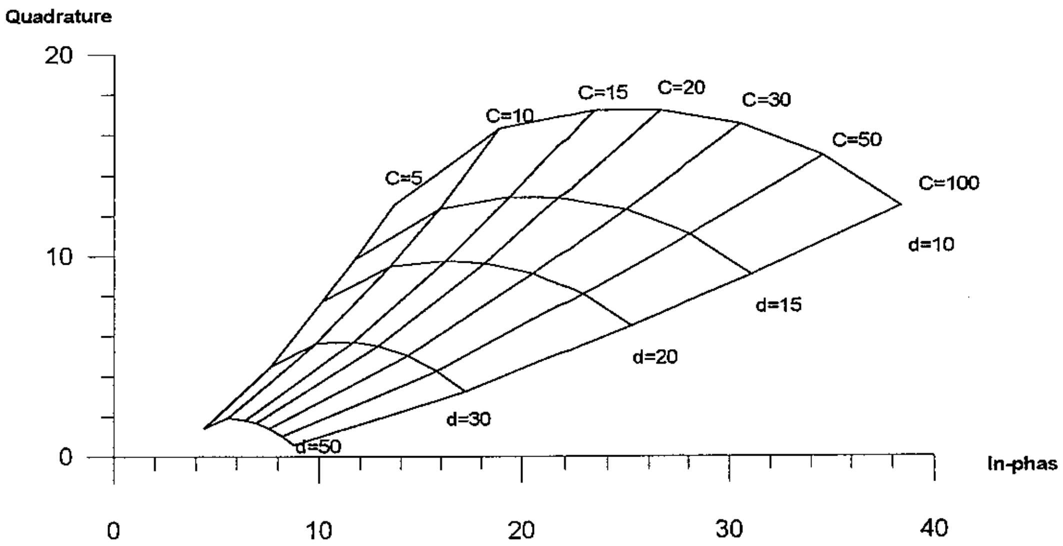


Figure 5.14 Diagram of a conductor buried in the conductive host (ρ = 100 Ωm) with 1000 m strike extent and 60^0 stike angle

5.6 The conductive Host Diagram

The new diagrams for interpretation the AEM anomaly in the condition of a conductive host are shown in the Appendix. A coplanar configuration system and a frequency of 912 Hz used in the calculation of these diagrams are conform with those used in the AEM survey in Thailand. The diagrams are constructed using the general electrical properties of rocks and minerals shown in Table 5.1.

Table 5.1 Electrical properties of some rocks and minerals

CONDUCTOR	CONDUCTIVITY(S/m)
massive sulfide	**1-100**
graphite	**0.1-10**
HOST ROCK	**RESISTIVITY(Ωm)**
intrusive rocks	**1000-100000**
extrusive rocks	**500-10000**
metamorphic rocks	**100-10000**
sedimentary rocks	**50-1000**
LAYER	**RESISTIVITY(Ωm)**
unconsolidated soil	**10-100**
saprolite	**3-300**

(Summarized from Telfold et.al.,1986 and Palacky,1988)

The diagrams shown in the Appendix are as follows:

Resistivity of top layer (Ωm) : 50,100
Layer thickness(m) : 10
Resistivity of host (Ωm):1000,10000
Dip angle (degree) : 90,30
Strike angle (degree) : 90
Strike extent (m) : 500,1000
Dip extent (m) : 100
Conductance (seimens) : 5,10,15,20,30,50,100
Depth (m) : 10,15,20,30,50

CHAPTER 6
INTERPRETATION AND EVALUATION

In order to prove the merit of this conductive host diagram, an evaluation is made from the proved data. Qualitative and quantitative interpretation is discussed in various aspects. Furthermore, the reinterpretation of the former target area, using a conductive host diagram, is made and the new target area is outline

6.1 Interpretation

An AEM interpretation is generally divided into two steps, i.e. qualitative and quantitative interpretations. The qualitative interpretation is conducted by considering the characteristics of stacked profiles. Response amplitudes of in-phase and quadrature component are the main indicators of the quality of a conductor. A diagram constructed using the geologic condition of the target area is used for the quantitative interpretation to determine the electrical property (conductance) and the geometry (depth and dip) of the conductor.

6.1.1 Interpretation procedure

In an interpretation of AEM survey data, stacked profiles of various frequencies are used. In practice, an AEM survey can be made with various frequencies and coil configurations to cover the expected depth. With the same coil separation, a low frequency and a coplanar coil configuration can penetrate deeper than a high frequency and a coaxial coil configuration. Considering the condition of a conductive host, the depth of penetration depends on the conductivity of the material and time rate (frequency) of change of the primary field. In order to clarify the variation in depth penetration of the current, the concept of skin depth (δ) is used. Fields and currents decay exponentially with distance in a conducting medium, falling to 1/e of their values at the surface in a distance termed δ , where

$$\delta = 1/ [\pi f \mu\sigma]^{1/2}$$

f and σ are the frequency and conductivity of the medium, respectively (Parasnis, 1986) and δ denotes the skin depth of the conductor.

The AEM system used in Thailand employed three frequencies in two coil configurations as given in Table 6.1

Table 6.1 Airborne electromagnetic system configurations in Thailand

Frequency (Hz)	Coil Pair Configuration	Coil separation (m)	Output Filter Time Constant (sec)
736	vertical coaxial	6.43	0.1
912	horizontal coplanar	6.43	0.1
4200	horizontal coplanar	6.42	0.1

As shown in Table 6.1, the skin depth of penetration of 736 Hz vertical coaxial and 912 Hz horizontal coplanar configurations are apparently similar to that described above. The data from the 4200 Hz frequency is generally used to calculate the near surface resistivity.

The electromagnetic system, transmitter and receivers were housed in an 8 m long bird and towed on a 30 m long cable from the cargo hook. The magnetometer sensor was housed in a separate 2 m long bird towed at approximately 10 m below the helicopter. A towed bird installation was used to minimize the undesired magnetic and electrical effects arising from the helicopter.

The AEM raw data were shown as stacked profiles (Figure 6.1) plotted using an electrostatic plotter at 1: 50,000 horizontal scale. The following information as represented :

-EM noise 736 Hz In-phase and Quadrature (ppm)
-Power Line Detector (mV)
-EM-Coaxial 736 Hz In-phase and Quadrature (ppm)
-EM-Coplanar 912 Hz In-phase and Quadrature (ppm)
-EM-Coplanar 4200 Hz In-phase and Quadrature (ppm)
-Apparent Resistivity (ohm.m)
-Total Magnetic field (nT) and Radar Altimeter (m)

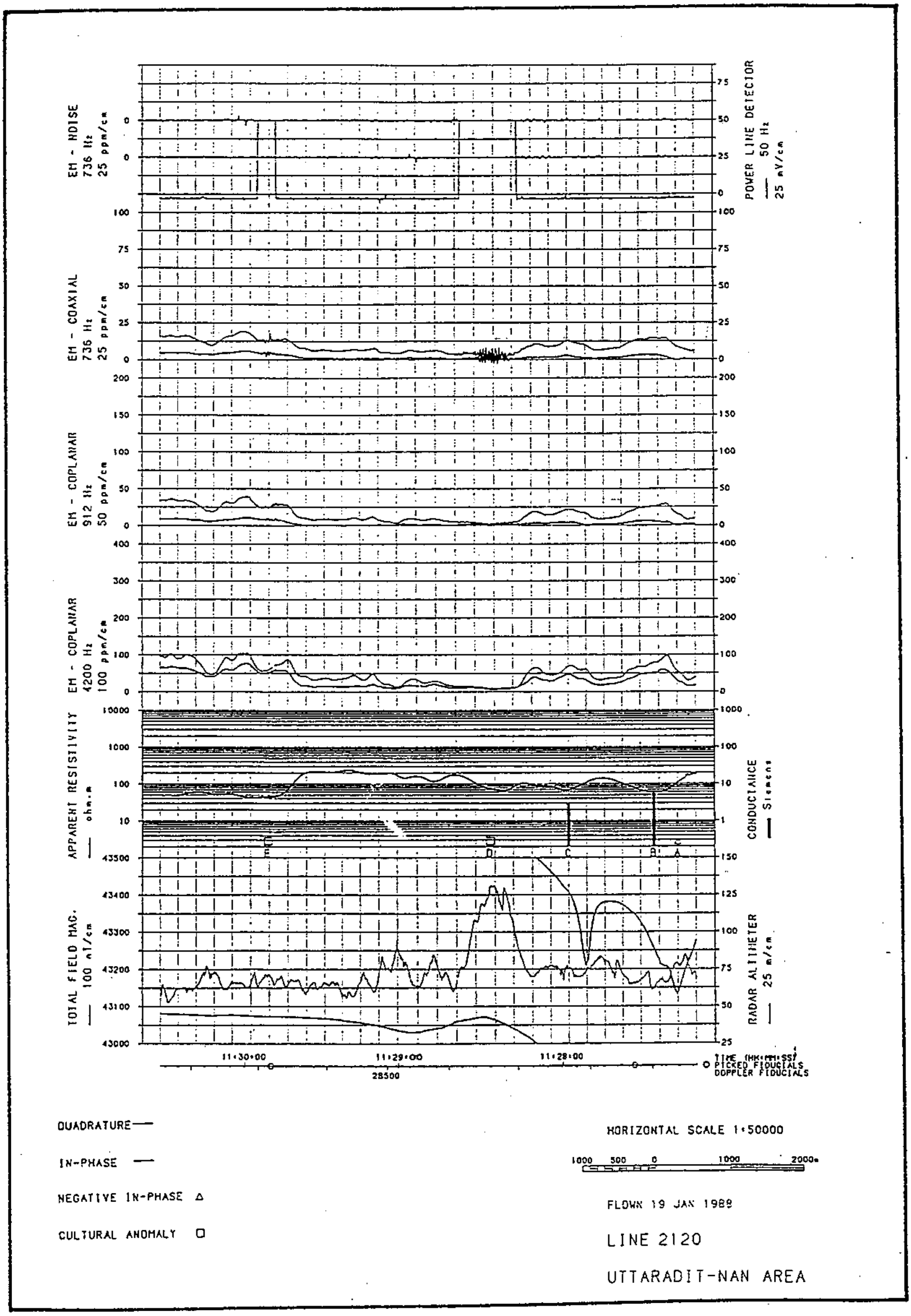


Figure 6.1 Stacked profile of AEM survey in Thailand (KESIL, 1989b)

Profiles were plotted in a continuous format for the particular traverse line concerned.

In Figure 6.1, the shift of stacked profiles from the zero level is observed especially in high conductive area. The profile shows total secondary field consisting of both scattering and the layered earth fields. The AEM anomalies are shown as "peaks" at different locations on the profile.

In order to interpret AEM profile anomalies, the peak selected from a distinct characteristic is used. In this work, the interpretation diagram is constructed from the EM-coplanar 912 Hz profile. The amplitude is measured from a maximum peak to the background of each component.

6.1.2 Suitable diagram

AEM responses are controlled by a number of parameters of conductor and host so that diagrams are constructed under various parameters conditions to approximately cover different target areas. For each target area, some of the parameters should be known beforehand in order to select suitable diagram for the interpretation. The parameters that can be evaluated from the target area are as follows :

1. Resistivity of host rock

In general, the area selected for the AEM survey should be complemented with the geologic map furnished with information about the rock types and their distribution. The resistivity of host rocks can be predicted from the geology of the target area using Table 5.1.

2. Resistivity and thickness of the layer

Other information, e.g. the age of rock units, is also shown in the geologic map. The Quaternary deposits represent the unconsolidated sediments commonly distributed in the flat areas. The resistivities of unconsolidated sediments (layer) are shown in Table 5.1. The relative thickness of the Quaternary sediments can be obtained from the topographic map. The sediments in a flat area should be thicker than those in an area close to a mountain. Another way to obtain the information about the resistivity of such layer is to find out from the 4200 Hz airborne resistivity map.

3. Strike and strike extent of conductor

For each area, all flight paths of stacked profiles are shown together. Strike direction can be observed from the continuation of peaks on neighboring line surveys. Since, the line survey spacing is 400 m, the strike extent can be determined.

4. Dip and dip extent of conductor

As described in Chapter 4, the approximate dip can be determined using the M/N ratio. The dip extent should not be greater than 100 m.

In coplanar system, a single peak anomaly profile may be caused by the following sources : a thin sheet with dip less than 30°, a thick vertical conductor, a narrow horizontal layer, and a spherical conductor. In order to define the source, the shape of anomalies of coaxial and coplanar configurations is used. Figure 6.2 shows the difference of peak anomaly in various cases of coaxial and coplanar systems.

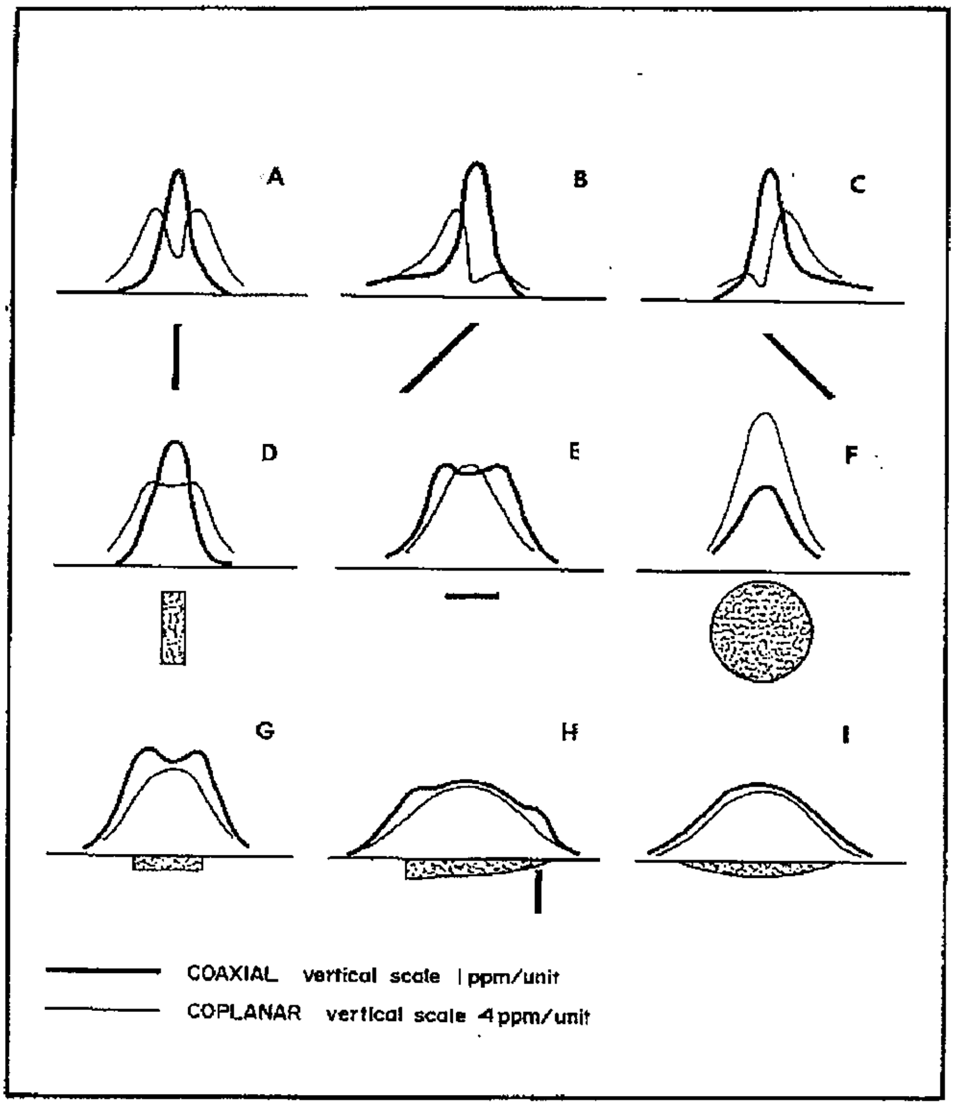


Figure 6.2 HEM response profile shape as an indicator of conductor geometry

When the suitable diagrams are selected and the amplitude of in-phase and quadrature are measured, the conductance and depth of a conductor may be determined by plotting the amplitudes. However, the standard diagrams constructed in this study cannot be used everywhere. The best way to interpret AEM anomaly is to construct the diagram for different sets of selected target area.

6.2 Test and Evaluation

In testing and evaluating the new diagrams for interpretation of the AEM anomalies, the subsurface condition of the target area should be known. Drillings have been carried out by the Department of Mineral Resources (DMR) in the following target areas (Figure 6.3) :

1. Khao Khee Nok (KKN)
2. Doi Pha Pok (DPP)
3. Khao Kai Fa (KKF)

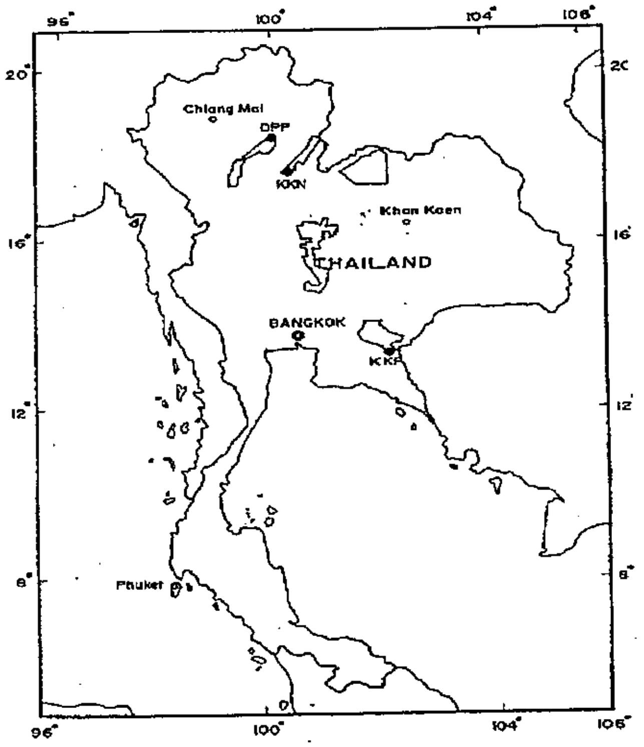


Figure 6.3 Location map of Khao Khee Nok (KKN), Doi Pha Pok (DPP), and Khao Kai Fa (KKF) areas.

6.2.1 Khao Khee Nok area (KKN)

This area is located in the Uttaradit-Nan suture zone of the Uttaradit province.

The geology of the KKN area is characterized by the Permain limestone overlain by volcaniclastic rocks (rhyolitic tuff, breccia and andesitic rock). The uppermost layer is the Permo-Triassic sedimentary sequence. The intrusive granite and contact metamorphic rocks are observed in this area (Sukvattananunt and Prasittikarnkul, 1985). The topographic map of the KKN area is shown in Figure 6.4 .

On AEM stacked profiles and a resistivity map of the KKN area are shown in Figure 6.5 and Figure 6.6, respectively.

6.2.1.1 Qualitative interpretation

The continuous peaks are observed on three flight lines in Figure 6.7. In line 980 (Figure 6.7A), the anomaly peak shows a good conductor because the in-phase amplitude is higher than the quadrature amplitude. The anomaly of coaxial configuration (736 Hz) shows two small peaks that may represent two close tabular conductors or may represent the effect of a horizontal conductor. The depth of the conductor is likely to be shallow because of the very high amplitude response.

At line 1000(Figure 6.7B), the anomaly is shown as a spiky peak that may represent a thin sheet conductor. The amplitude response is smaller than that at line 980 which indicates a shallow conductor. The ratio of M/N indicates that the conductor dips about 30-45° toward the west.

At line 1020(Figure 6.7C), the lowest amplitude indicates the deepest conductor and/ or the thin top layer and/or highly resistive host rocks. The ratio of M/N suggests that the conductor dips about 45-60°.

6.2.1.2 Quantitative interpretation

The continuous peak anomaly of three flight lines shows the 90° strike angle. Strike extent for three lines should not be shorter than 800 m. The resistivity of the top layer, from the resistivity map (Figure 6.6), is about 50 ohm-m. The parameters used to create the diagram are as follows :

Resistivity of top layer 50 ohm.m
Layer thickness 10 m .
Resistivity of host rock 1000 ohm.m
Strike angle 90°

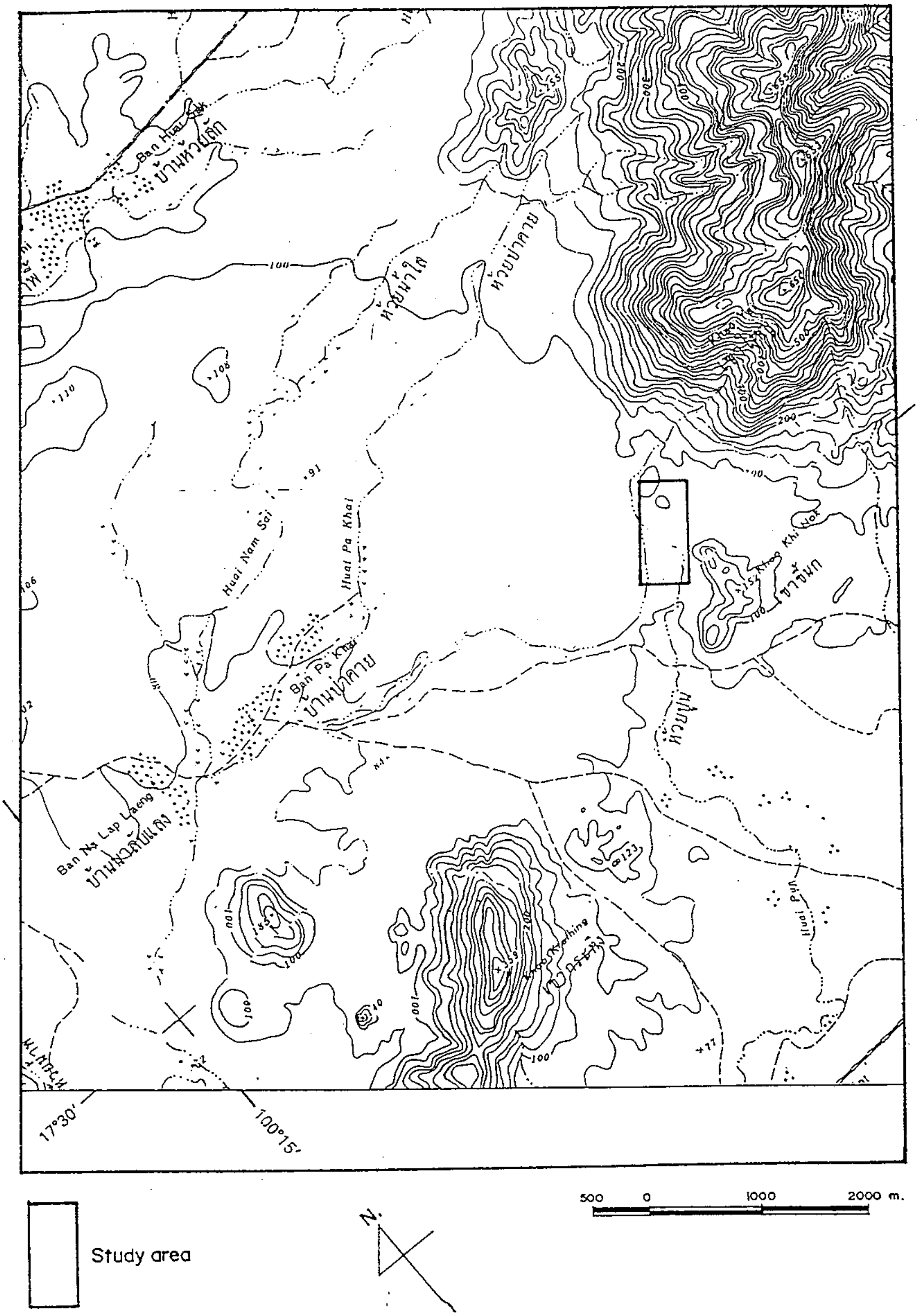


Figure 6.4 Location and topographic map of Khao Khee Nok area

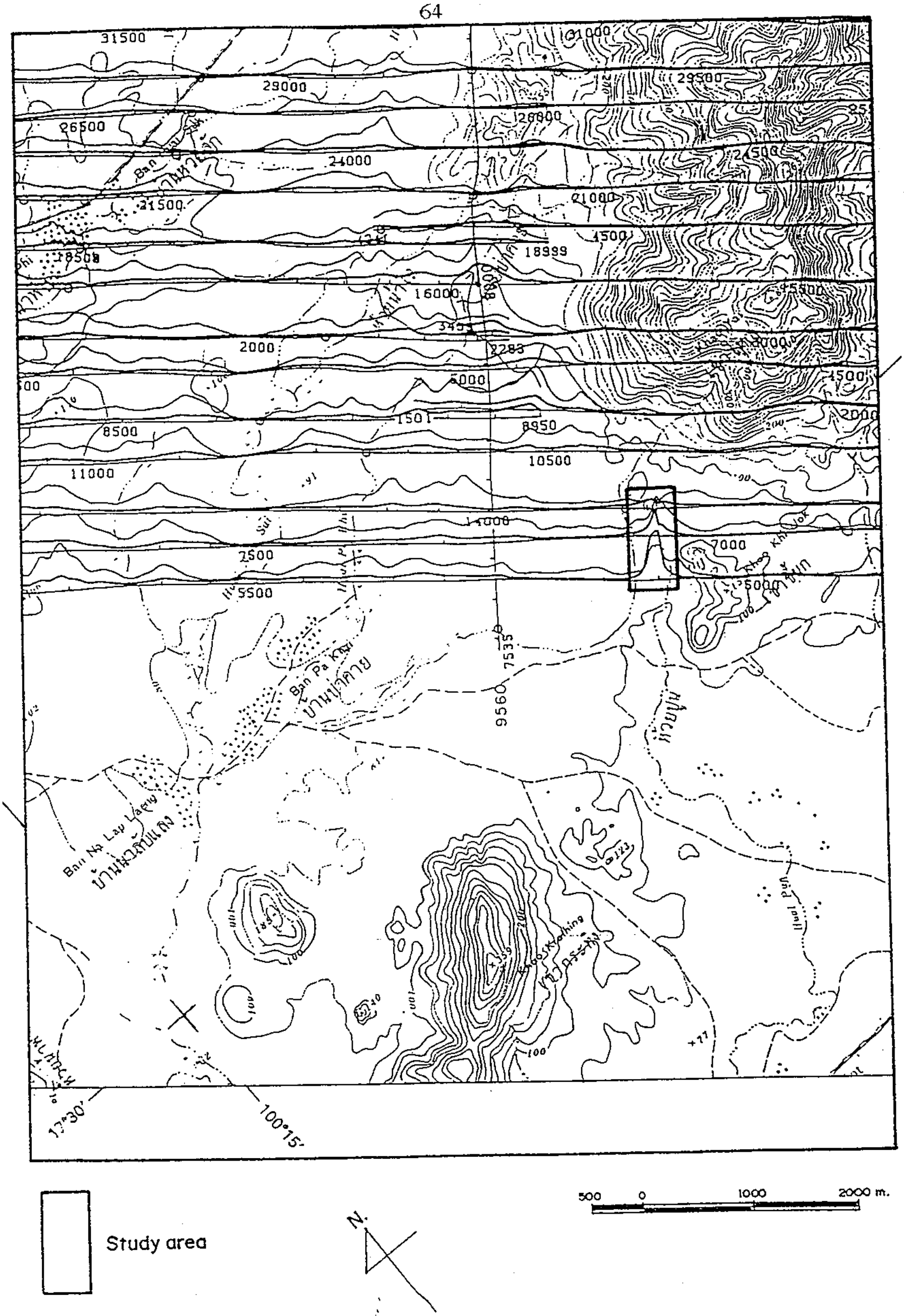


Figure 6.5 AEM stacked profiles of 912 Hz-coplanar configuration over the Khao Khee Nok area (KESIL, 1989b)

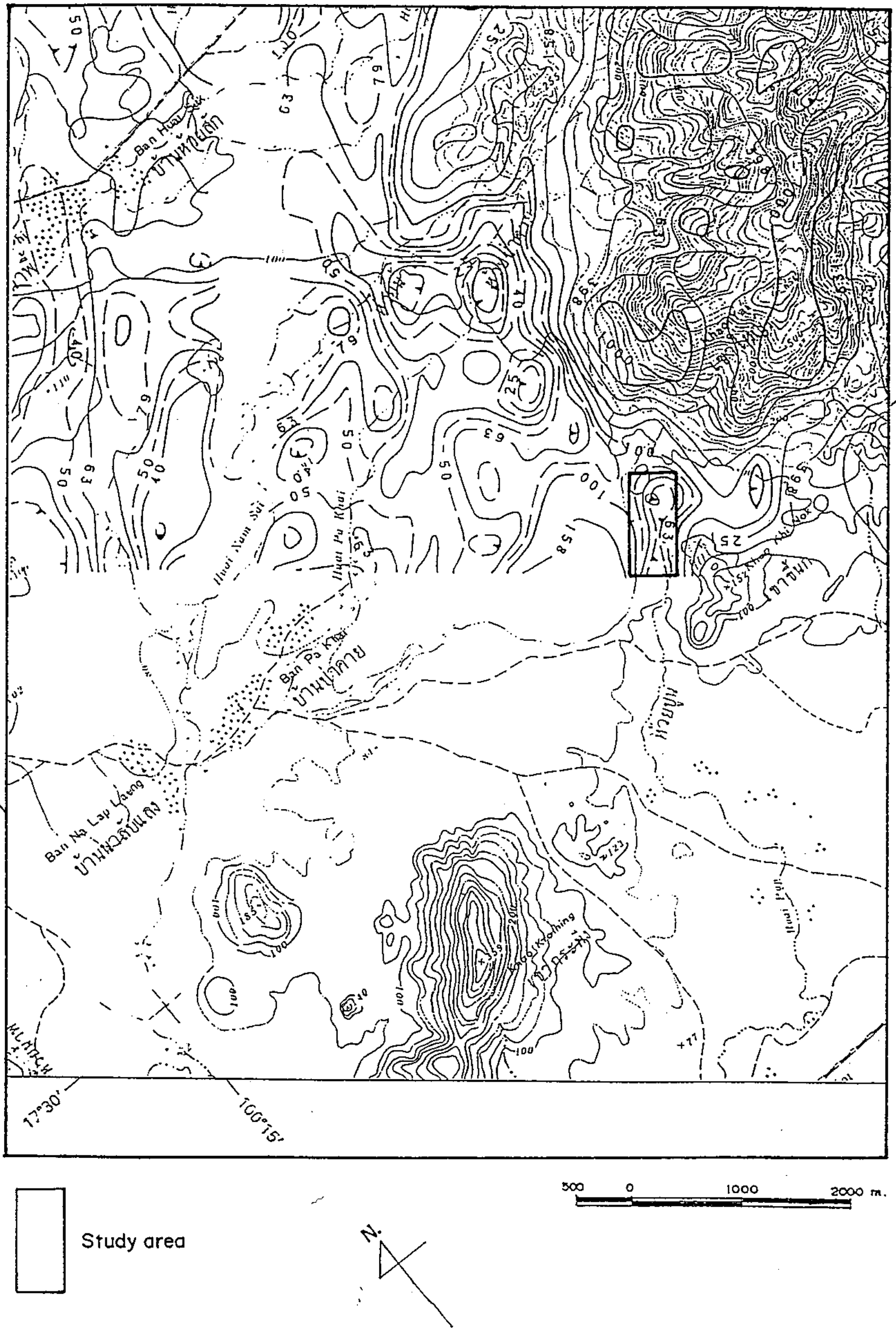
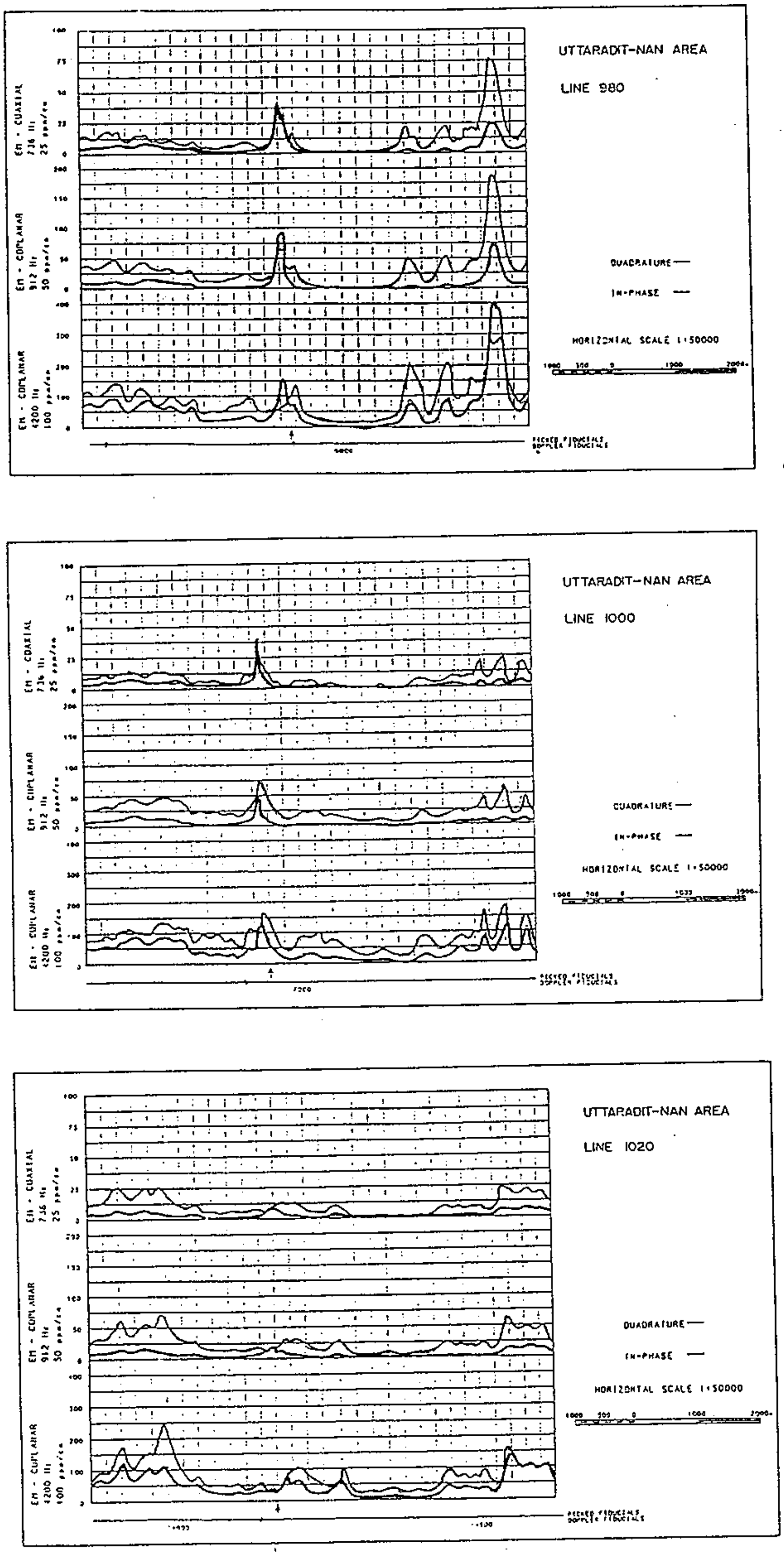


Figure 6.6 Resistivity map of Khao Khee Nok area (KESIL, 1989b)



A.

B.

C.

Figure 6.7 Stacked profile of line 980 (A), 1000 (B) and 1020(C) in Khao Khee Nok area (KESIL, 1989b)

Dip angle 30-45°
Strike extent 800 m
Dip extent 100 m

The diagram prepared for the interpretation of the KKN area is shown in Figure 6.8.

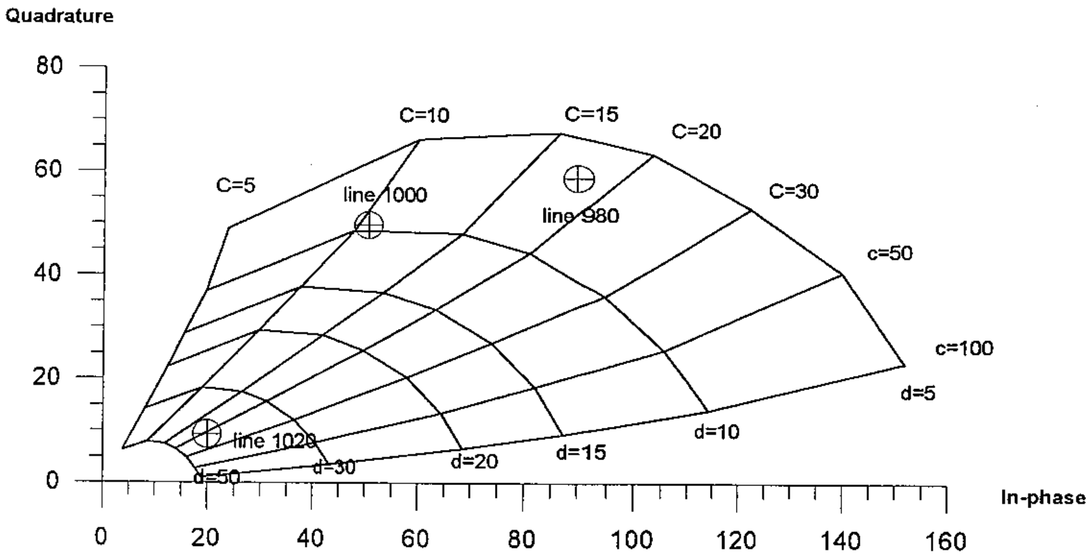


Figure 6.8 Interpreted diagram and response amplitude plots of Khao Khee Nok area

In the diagram, the mark points ⊕ indicate the amplitudes of in-phase and quadrature of each line. Considering the amplitude plots, at line 980 the highest amplitude shows the lowest depth. The conductance is about 18 seimens. At line 1000, the lowest conductance is observed and the depth of the conductor is about 10 m. At line 1020, the amplitudes of in-phase and quadrature are smaller than the other lines, but in the diagram the highest conductance is shown at the greatest depth. So, the high amplitude does not indicate the high conductance. The interpretation about the depth of conductor should be done with caution. The conclusions of quantitative interpretation of the KKN area are as follows:

1. The conductance of the conductor varies from 10 to 20 siemens,
2. The depth of the conductor varies from 7 m to 40 m on line 980 to line 1020.

6.2.2 Doi Pha Pok area (DPP)

This area is located in the contact metamorphic zone, east of the Permo-Triassic volcanic sequence in Phrae Province. The host rocks in this area are composed of schist and amplibolites adjacent to the volcanic rocks (mainly rhyolitic tuff). These units were metamorphosed by the late Triassic granitic intrusion (Phuthiang and Manoi, 1991). The topographic map and location of the DPP area are shown in Figure 6.9 .

Figures 6.10 and 6.11 show stacked profiles of coaxial 736 Hz and coplanar 912 Hz over the DPP area.

6.2.2.1 Qualitative interpretation

Consider the peak in line 8120 (Figure 6.12A) which is marked by the symbol ↑, the large anomaly indicates a large conductive zone (formation)which represents a wide conductor, or many close conductors. On the right-hand side, the conductive overburden is shown by the shift of the profile from the zero level. The amplitudes of in-phase and quadrature are not prominent due to the broad anomaly. At line 8141(Figure 6.12B), the continuous anomaly is not clear because the in-phase and quadrature are shifted from the zero level in a large zone. The peak anomaly on the left-hand side is more apparent.

6.2.2.2 Quantitative interpretation

The continuous anomaly of coaxial is clearer than that of coplanar. The strike angle is about 60° and strike extent is about 500 m. The dip of one peak indicates 30° dip with 100 m dip extent. This area is in the mountain that has a thin conductive overburden. The resistivity of the top layer from the resistivity map (Figure 6.13) is 100 ohm-m. The parameters used to create diagram should are as follows :

Resistivity of top layer 100 ohm-m
Layer thickness 5 m
Resistivity of host rocks 10000 ohm-m
Strike angle 60°
Dip angle 30°

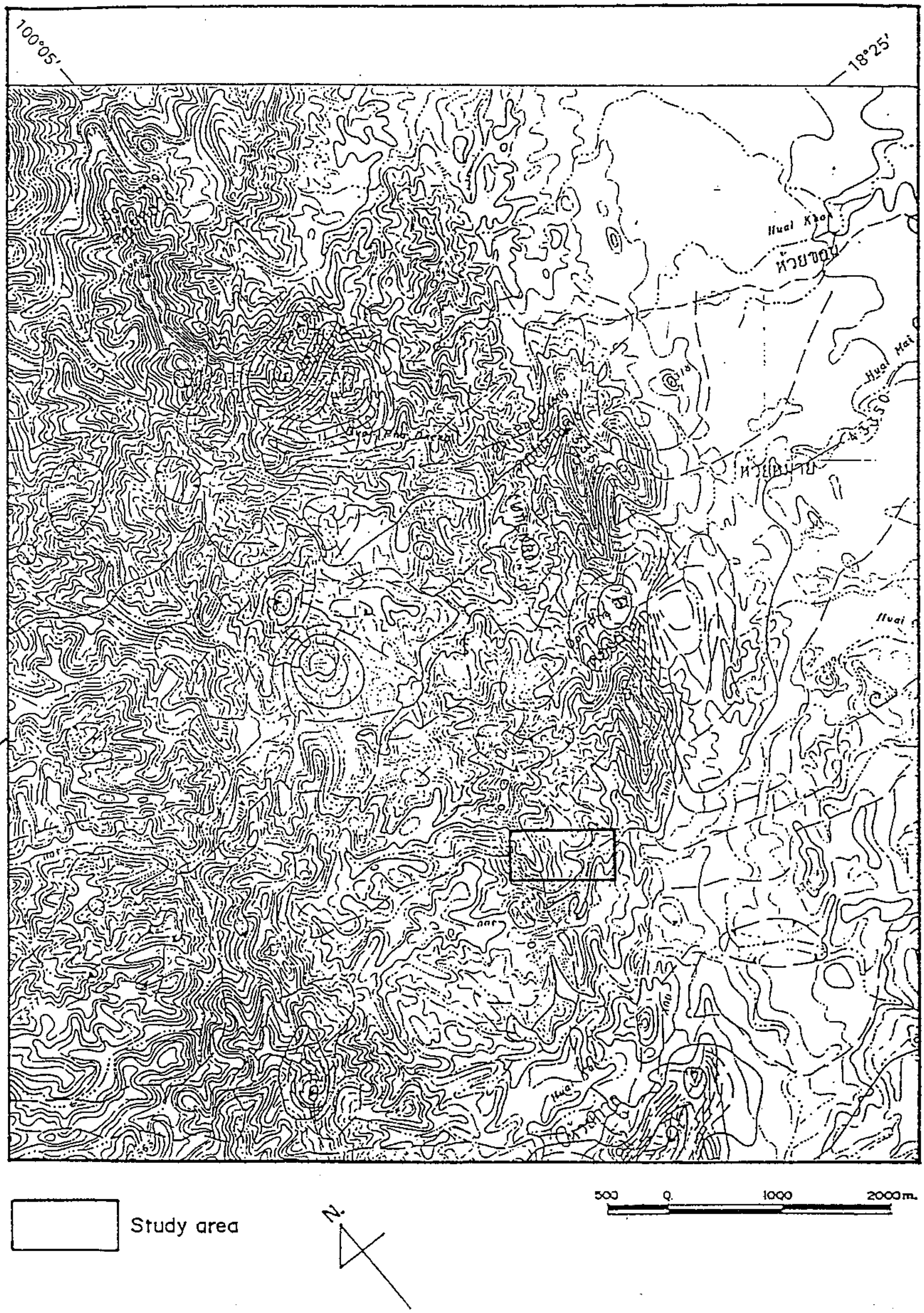


Figure 6.9 Location and topographic map of Doi Pha Pok area (KESIL, 1989c)