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5.

GROUND ELECTROMAGNETIC METHODS AND BASE METALS

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Abstract

The electromagnetic method of prospecting for base metals has been used successfully since the early 1920s. Its application has been marked by spectacular success and by dismal failure. Despite three decades of intensive research on the electromagnetic method, it still suffers from severe limitations of interpretability. These have gradually diminished over the last decade and probably will diminish much more rapidly over the next decade as the method encompasses more frequencies, more transmitter-receiver configurations, hardware of greater flexibility, in-field data processing, plus exceptionally sophisticated methods of data interpretation. We should expect the electromagnetic method to contribute to our knowledge of the three-dimensional distribution of electrical resistivity in the subsurface but we should not expect it to offer means for discriminating between specific minerals. Accordingly, we are concentrating on means for separating the responses of the various elements in the geoelectric section and on determining the geometries of these elements. On the other hand, a combination of electromagnetic and induced polarization methods could be mineral specific. The past, the present, and the future of the ground electromagnetic method are all discussed within this framework. This contribution is concerned only with active ground electromagnetic systems. The outlook is optimistic.

Résumé

La prospection par méthode électromagnétique en ce qui a trait aux métaux non précieux est utilisée avec succès depuis le début des années 1920. Son usage a été marqué de succès spectaculaires et d'échecs lamentables. Malgré trente années de recherches poussées sur la méthode électromagnétique, cette dernière est encore affligée de sérieuses limites de décodage. Ces limites ont diminué graduellement au cours de la dernière décennie et elles continueront probablement à décroître encore plus rapidement au cours des dix prochaines années à mesure que la méthode comporte des fréquences plus nombreuses, davantage de dispositions d'émission — réception, du matériel d'une plus grande souplesse d'emploi, un traitement sur place des données, de même que des méthodes exceptionnellement perfectionnées de décodage des données. Nous devrions nous attendre à ce que la méthode électromagnétique contribue à nous faire connaître la répartition tridimensionnelle de la résistance électrique dans le sous-sol, et non pas à ce qu'elle offre des moyens de distinguer des minéraux précis. En conséquence, nous portons notre attention sur différents moyens de séparer les réponses des divers éléments de la section géoélectrique et d'établir la géométrie de ces éléments. De plus, une utilisation combinée des méthodes électromagnétiques et de polarisation induite pourrait se prêter à la distinction des minéraux. Le passé, le présent et l'avenir de la méthode électromagnétique terrestre sont tous analysés à l'intérieur de ce cadre. L'étude s'intéresse ici seulement aux systèmes électromagnétiques terrestres "actifs". La perspective est optimiste.

INTRODUCTION

In applying the active ground electromagnetic method to the search for massive sulphide deposits of base metals, one can only expect to detect the ore if its signature is distinctive from those of the halo of disseminated noneconomic sulphide mineralization, the weathered and fresh host rock, adjacent faults, shears, and graphitic structures, overburden and surface and buried topography. Figure 5.1 depicts the sources of signatures in a typical exploration problem.

In the last decade we have learned that the separation of anomaly (signature of ore deposit) from geological noise (combined signatures of disseminated halo, host rock, faults and shears, graphitic structures, overburden, and topography) is not easy. To attempt this separation we utilize a broad band of frequencies, we employ several transmitter-receiver separations and we employ several transmitter-receiver configurations.

If the various elements of the earth, depicted in Figure 5.1, responded independently of one another, the problem of separation of anomaly from geological noise would be much simplified. Unfortunately the elements react with one another to complicate the problem. For example, any source of electromagnetic waves will induce currents in the host rock. When a massive sulphide deposit is emplaced in this host, it causes the currents to be deflected into it on account of its lower resistivity. Current gathering by an inhomogeneity thereby occurs. Current gathering usually increases the anomaly due to the massive sulphide but it also modifies its response to make it appear deeper and of higher resistivity. Quantitative interpretation of electromagnetic data is, therefore, usually seriously hampered. What can be done about this and related problems? In this paper an attempt is made to expose both the optimum approach and the current practical approach to these problems. In the process I hope to indicate current and future advantages and limitations of the ground electromagnetic method.

Although not an objective in the past, the principal current objective of the electromagnetic method is to develop an ability to detect each element of the geoelectric section so that the resistivity environment surrounding the assumed ore may be assessed. In this fashion, for example, the massive sulphide ore can be distinguished from disseminated noneconomic mineralization in a volcanogenic environment.

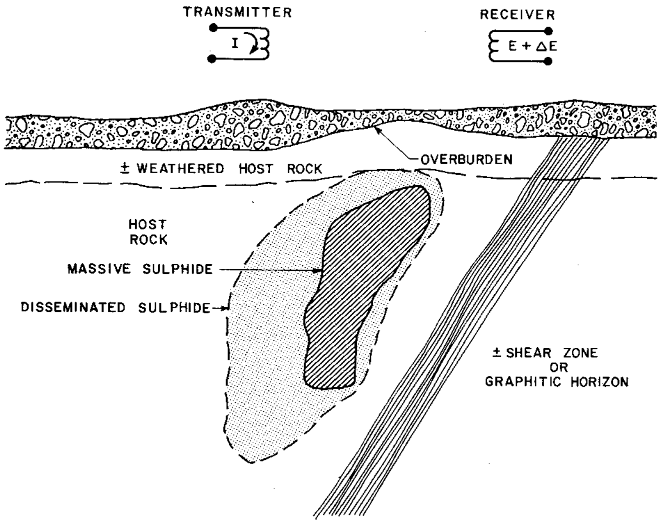

Figure 5.1. *The elements, of a generalized three-dimensional earth, which contribute to the signature obtained with an electromagnetic prospecting system.*

Recent papers which address the problems encountered by the electromagnetic method when faced with a real earth in which overburden, host rock, surface topography, buried topography, a disseminated halo around a massive sulphide body, faults, shears, and carbonaceous or graphitic structures all might be included are: Lowrie and West (1965), Roy (1970), Sarma and Maru (1971), Gaur, Verma, and Gupta (1972), Gaur and Verma (1973), Scott and Fraser (1973), Ward et al. (1974a), Ward et al. (1974b), Hohmann (1975), Lamontagne (1975), Palacky (1975), Verma and Gaur (1975), Spies (1976), Lajoie and West (1976), Lajoie and West (1977), Lodha (1977), Ward et al. (1977), and Braham et al. (1978). We refer the reader to them for details but summarize their conclusions in Table 5.1.

DATA ACQUISITION

Domain of Acquisition

Electromagnetic data are always collected as a time series describing an electromagnetic field at a point P and a time t as in Figure 5.2. The resulting data may be processed and interpreted in the frequency domain (fD) or in the time domain (tD). In (fD) the spectrum of the waveform is viewed through some frequency window (passband) as in Figure 5.2a while in (tD), the transient decay of an impulsive waveform is viewed through some time window (passband) as in Figure 5.2b. Observations at discrete frequencies or at discrete times are most commonly made. There is no

Table 5.1

Summary of effects of extraneous features in electromagnetic search for massive sulphides

Feature	Effect	Interpretation problem
Overburden	rotates phase decreases amplitude	depth estimates invalid σ t estimates invalid
Host rock	rotates phase increases amplitude for shallow conductors increases or decreases amplitude for deep conductors changes shape of profiles fall-off laws change	depth estimates invalid σ t estimates invalid dip estimates invalid
Surface and buried topography	introduces geological noise	depth estimates invalid σ t estimates invalid dip estimates invalid may obscure sulphide anomalies
Halo	rotates phase increases amplitude	depth estimates invalid dip estimates invalid σ t estimates invalid
Weathered host rock	introduces geological noise	obscures sulphide anomalies may invalidate all quantitative interpretation
Faults, shears, graphitic structures	introduces geological noise	obscures sulphide anomalies may invalidate all quantitative interpretation

NOTE: σ t — conductivity-thickness product of massive sulphide body.

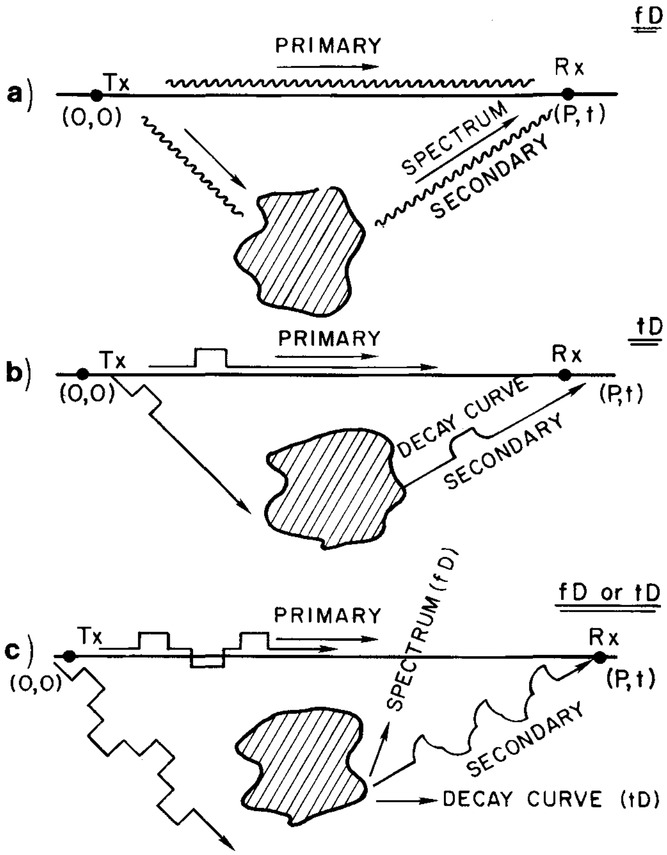

Figure 5.2. *Schematic of (a) frequency domain, (b) time domain, and (c) combined time domain/frequency domain processing of a signature from a base metal deposit by an electromagnetic system.*

particular reason why one transmitted waveform cannot be processed and interpreted in the frequency domain, in the time domain, or in both domains simultaneously as in Figure 5.2c.

Attempts to design optimum waveforms have been made in recent years. Thus, the UTEM system (Lamontagne and West, 1973) was designed to transmit a triangular waveform and receive its derivative, a square waveform. Pseudo random noise generators (Quincy et al., 1976) and sweep-frequency generators have also been proposed. Enhancement of signal-to-noise ratio is the reason for selecting these latter waveforms.

Regardless of the method of data processing and interpretation, the signal sensed at the receiver (R) is a superposition of a primary field (including the effects of a homogeneous earth) and a secondary field (reflected from a subsurface inhomogeneity).

Coil Configurations

Roving Coil Pairs — Fixed Orientations

The transmitting coil (T) may be oriented with its axis vertical (called a vertical magnetic dipole or a horizontal loop) or with its axis horizontal (called a horizontal magnetic dipole or a vertical loop). If a horizontal magnetic dipole is used its axis may be pointed at the receiver (R) or be orthogonal to this direction. Three orthogonal transmitting coil orientations are thus possible. Similarly, three orthogonal receiving coil orientations are possible.

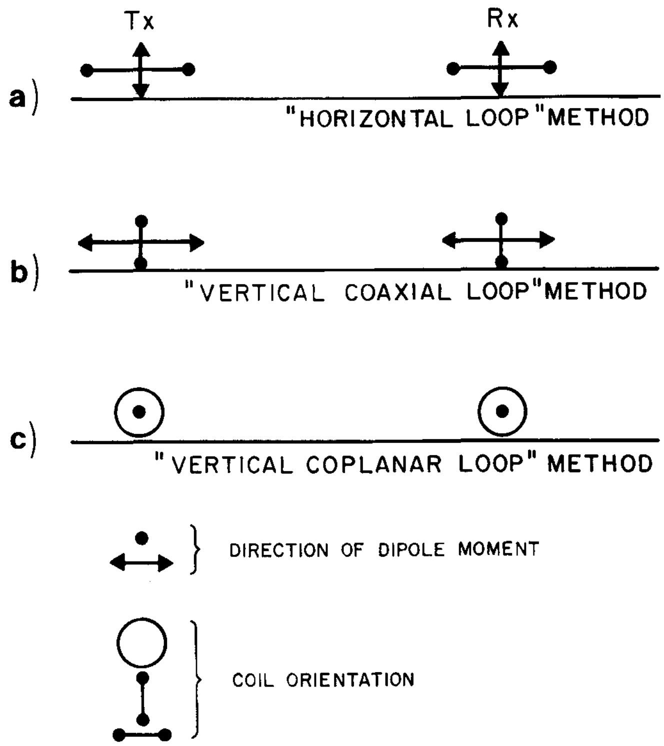

Figure 5.3. *Coil configurations employed in (a) horizontal loop, (b) vertical coaxial loop, and (c) vertical coplanar loop methods of electromagnetic prospecting.*

In the so-called horizontal loop EM method both the receiving and transmitting coils have their axes vertical and the coil pair is transported, with constant coil separation, in-line in a direction normal to strike as in Figure 5.3a. Commercially available equipment which utilizes this configuration is listed in Table 5.2 (after Hood, 1977).

In the vertical coaxial loop EM method (Fig. 5.3b) both the receiving and transmitting coils have their axes horizontal, in-line, and the pair is transported, with constant coil separation, a) in-line in a direction normal to strike, or b) broadside in a direction normal to strike. Any one of the coil systems listed in Table 5.2 could be used in this configuration but this is not routinely done.

In the vertical coplanar loop EM method, the receiving and transmitting coils have their planes vertical and common and the pair is transported in-line with constant coil separation, in a direction 45 degrees to strike as in Figure 5.3c. This latter configuration is not used commonly but any one of the systems of Table 5.2 could be used this way. The need to traverse at 45 degrees to strike in order to obtain significant response usually mitigates against use of this configuration.

Roving Coil Pairs — Rotatable Orientations

In the Crone shootback method (Crone, 1966), the receiving and transmitting coils are interchangeable in the sense that each is used both as a receiver and as a transmitter. The remarkable advantage of the method is that the effects of elevation differences between transmitter and receiver are eliminated. Two variations of it, the Crone horizontal and vertical shootback methods are used (Crone, 1966, 1973). With each, the orientation of the transmitting coil is fixed with its axis at some angle to the horizontal or to

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Table 5.2

Commercially available horizontal loop ground electromagnetic equipment

Manufacturer (C)– Canada	Model designation	Frequency of operation in Hertz	Coil separation in metres	Dipole moment in amp turns sq. mtr (in m^2)	Component measured I/P– in Phase O/P– Out of Phase	Readout device	Range of readings	Read-ability	Weight (kg)	Power source
ABEM (Sweden)	Demigun	880 & 2640	30,60,90, 150&180	50/880Hz 20/2640Hz	I/P & O/P	2 Dials	0-160%I/P ±80%O/P	±0.5%	23.2	D or Nicad cells
Apex Parametrics (C)	Max Min II	222,444, 888,1777 & 3555	30,60,90, 120,180, & 240	150/222 & 444Hz 75/888Hz 50/1777Hz	I/P & O/P	2 Dials +Tiltmeter	±100%I/P ±100%O/P	±0.5%		3 x 6V Cells
Geonics (C)	EM 17	1600	30,60,90 & 120	24	I/P & O/P	Meter (self-indicating)	±100%I/P	±0.5%	12.61	C cells --Rx
	EM17L	817	50,100, 150 & 200	24(reduced) 48(normal)			±50%O/P	±0.25%	13.4	D cells --Tx
McPhar (C)	VHEM	600 & 2400	30,60,90, or 40,80	60/600Hz 18/2400Hz	I/P & O/P	Dial & Headset	±100%I/P ±100%O/P	±0.5%	8.2	9v--Rx D cells --Tx
Scintrex (C)	SE-600	1600	60 or 90	27	I/P & O/P	Dial & Headset	±100%I/P ±50%O/P	±0.5%	15	6 & 13.5v cells

the vertical. The receiving coil, however, is rotated about an axis normal to the traverse line until a minimum signal is obtained at which time the tilt of the plane of the receiving coil, from the horizontal or from the vertical, is recorded. Two readings, taken at each observation stop with first one coil as transmitter then the other, are averaged. Elevational effects in the tilt angle reading are thus eliminated. The reader is referred to the literature for specific operational details. Figure 5.4 illustrates the two variations.

In the vertical loop broadside method, the transmitter is transported along one traverse line while the receiver is moved in unison along an adjacent traverse line. At each point of observation the transmitting coil is placed in that vertical plane which contains the location of the receiver as in Figure 5.5. The receiving coil is then rotated about an axis normal to the traverse line until a minimum signal is obtained, at which time the tilt of the plane of the receiving coil from the horizontal is recorded.

Fixed Transmitter, Roving Receiver

With the rotating vertical loop method the transmitting coil (T) is erected at a fixed position within the survey area (Fig. 5.6a) while the receiving coil (R) is carried systematically on traverse lines adjacent to it and oriented normal to strike. The plane of the vertical loop is oriented for each observation so as to contain the point of observation. Commercially-available equipment which utilizes this configuration is listed in Table 5.3 (after Hood, 1977).

For the coaxial vertical loop method, illustrated in Figure 5.6b, the axis of the transmitting coil is oriented normal to strike and the receiving coil is carried along the line of the axis of the transmitting coil. This is not a standard technique but has been used with success where tried (Ward et al., 1974b; Pridmore, 1978).

A fixed horizontal loop (or coil with its axis vertical) is used where large transmitting coil moments are required. When the loops are tens of metres in diameter or less, the transmitting loop is fixed at the end of a traverse line and the receiver traversed in increments along that line. Then the transmitting coil is moved to an adjacent line and the process repeated. Commercially available systems which use this technique are listed in Table 5.4 (derived from the data of Hood, 1977 and Buselli and O'Neill, 1977).

With the frequency-domain Turam method a large rectangular transmitting coil, hundreds or even thousands of metres to a side, is laid out on the ground and the field strength ratio and phase difference are recorded between a pair of receiving coils 30 m to 100 m apart. With the time-domain Russian MPP01 and the Australian Sirotem system, a single rectangular loop 50 m to 200 m to a side, is used first as a receiver, and at appropriate time delays, then as a receiver. Sirotem also offers the opportunity for use of separate transmitter and receiver loops separated by 100 m to 200 m.

The Crone Pulse EM (PEM) method uses a small, i.e. tens of metres, transmitting coil separated from the receiving coil by 30 m to 100 m. Typically, the transmitter

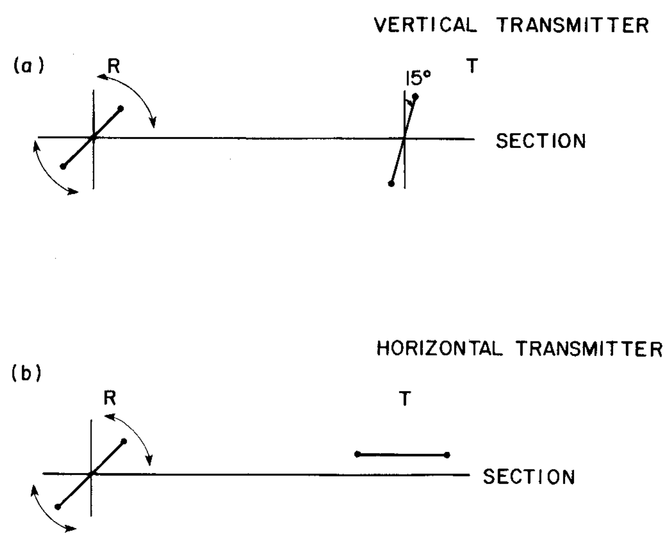

Figure 5.4. Crone Shootback configurations.

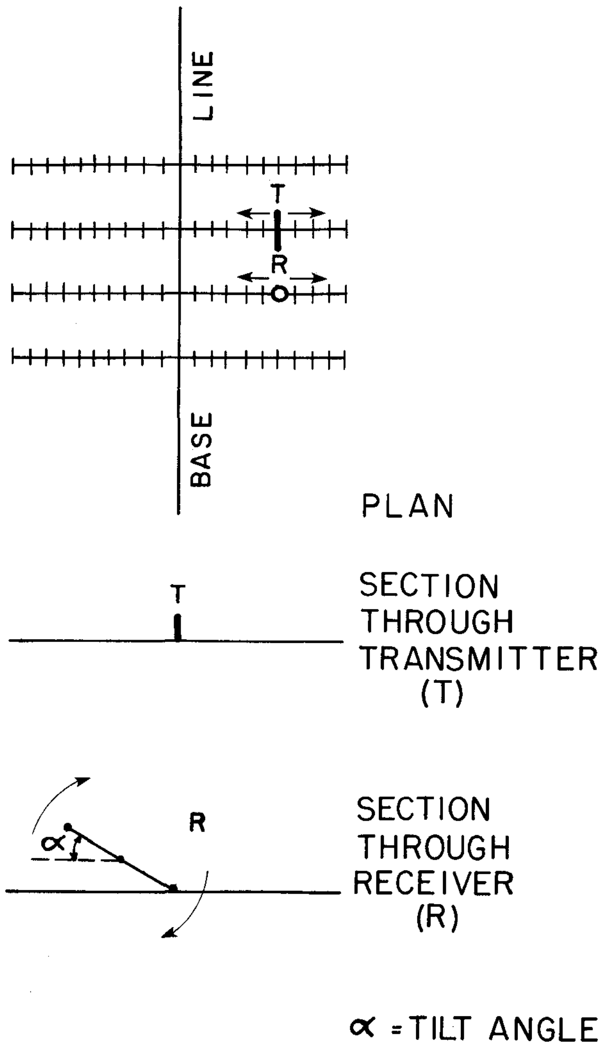

Figure 5.5. *Coil configuration for vertical-loop broadside EM method.*

and receiver are moved in unison along a traverse line so that this method could be listed under the section on roving coil pairs.

The Newmont EMP system, not available commercially, uses a large fixed rectangular transmitting loop, hundreds of metres to a side. The received signals are the three orthogonal components of magnetic field recorded at 32 discrete time channels after termination of each transmitted current pulse (Nabighian, 1977).

It can be argued that the larger the loop the larger the potential for exploring to greater depths. The basis for this argument is that in the small dimensional limit the loop is a dipole, whereas in the large dimensional limit the loop becomes four line sources. Fields from a dipole fall off as $1/r^3$ whereas fields from a line source fall off as $1/r$. Coupled with the attractiveness of using larger loops for greater depth of exploration is an opposing factor which is that a loop couples best with a body of its own dimensions and hence only very large targets would be excited optimally by very large loops.

The theoretical computations of Lajoie and West (1976) confirm this analysis in a general way but indicate that the optimum source dimension depends upon the overburden and

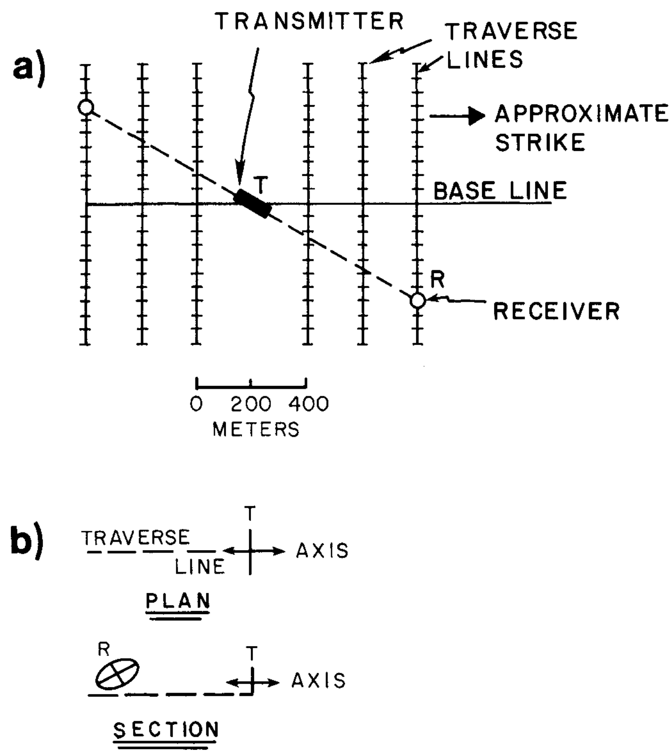

Figure 5.6. *(a) Survey procedure for vertical rotating-loop EM method, (b) orientation of projection of ellipse of polarization on vertical plane passing through axis of transmitter.*

host rock resistivities as well as upon the dimensions of the inhomogeneity. Figure 5.7a, b, c (after Lajoie and West, 1976) show two models and their respective phasor diagrams. The in-phase (IP) and quadrature (Q) amplitudes are normalized with respect to the vertical component of the primary magnetic field intensity on the surface, directly over the plate. Note that the largest percentage anomaly occurs for a 1000 m to 2000 m loop for model 5 while it occurs from a 250 m x 500 m loop for model 6.

Decades of Frequency Required to Separate Geological Signal from Geological Noise

If the earth responded as a single body, the anomaly to which it gave rise with any electromagnetic system would, as a function of frequency, trend from a low frequency asymptote to a high frequency asymptote in about three decades of frequency. Zone B at the Cavendish Test Site in southern Ontario, seems to respond this way to a vertical axial coil operating over the frequency range 10^2 to 10^5 Hz. Figure 5.8 contains plots of a) the tilt of the major axis of the projection of the ellipse of magnetic field polarization on a vertical plane passing through the axis of the transmitting coil, and b) the ratio of the minor to major axis of this projection of the ellipse of magnetic field polarization. These two quantities are referred to as tilt angle and ellipticity, respectively. Three decades of frequency also encompass the low and high frequency asymptotes for horizontal loop excitation as Figure 5.8 reveals. All curves are both smoothly varying and slowly varying. If the response of a sulphide body was always so simple and predictable, then only two or three frequencies spread over a decade or two, would be needed to learn all there is to know, electrically, about the sulphide body. Indeed, until ten years ago this was the common assumption.

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Table 5.3

Commercially available dip-angle ground electromagnetic equipment

Manu- facturer	Model designation	Frequency of operation in Hertz	Maximum coil separa- tion in metres	Dipole moment in amp. turns sq. m. & weight (kg)	Transmitter power source	Weight of receiver (kg)	Readability of clino- meter	Bandwidth of receiver system	Remarks
Crone Geophysics	CEM (shootback)	390,1830 & 5010	200	45inm^2/390Hz 30inm^2/1830Hz 18inm^2/5010Hz 10kg with batteries	3 x 6 volt lantern batteries	11	±0.5°	5Hz/390Hz 15Hz/1830Hz 30Hz/5010Hz	Transreceiver Units for Shootback & vertical-loop
	VEM	390 & 1830	700	1100inm^2/390Hz 900inm^2/1830Hz 20kg with battery	12 volt/ 24 amp hr. Gel battery	6	±0.5°	5Hz/390Hz 15Hz/1830Hz	Hi powered Vertical loop
McPhar	REM	1000 & 5000	200	60inm^2/1000Hz 15inm^2/5000Hz 4.5kg	Hg cells	2.4	±0.5°	20Hz/1000Hz	
	VHEM	600 & 2400	200	60inm^2/600Hz 18inm^2/2400Hz 4.1kg	300 cells	3.8	±0.5°	13Hz/600Hz	Horizontal loop also
Scintrex	SE-600	1600	300	27inm^2 8 kg	2 x 6 volt cells	5.5	±0.5°	10 Hz?	Horizontal loop also

Table 5.4

Commercially available fixed horizontal loop electromagnetic equipment

Domain	Manu- facturer	Model designation	Parameters measured	Frequency of operation in Hertz	Power Output	Power source (mg=motor generator)	Readout device	Weight (kg)	Remarks
Time	Crone Geophysics	Pulse EM (PEM)	8 samples of secondary field 1 sample of ramp voltage	Equivalent 18 to 1060 Hz	Max 450W	2 x 12v 20 amp.hr Gel batt.	Meter	21	Moving Tx- loop system
	Geonics	UTEM	Vert. magnetic & Hor. electric fields	10 time slots -base freq. 7 to 90 Hz		1.5kw Mg	Meter or digital tape deck	60	Large loop
	Geoex.	SIROTEM	Vert. Mag. field	12 to 32 time slots 0.25 ms to 180 ms	Max 176W	22v 10 amp.hr Nicads	Printer Output	20	Single or Double Loop Configura- tion Moving Loops Choice of Sizes
Frequency	Geoprobe	Maxi-probe EM 16	Vert. & Hor. Mag. field Hor. elec. fields	2^n(n=0 to 9), 1k, 2k,4.1k,8.2k, 16.4k,32.8k,41k	2100W	6Hp Mg	Meter	116	
	Scintrex	SE-77/ TSQ-2M (Turam)	Field Strength Ratio & Phase diff.	35,105,315, 945 & 2835	500W	3 HP Mg	Automatic Meter Display	42	Reads harmonics of trans- mitted square wave
	Geotronics	EMR-1/ GT20A	32f	10 to 10 000 Hz	20Kw	Mg	Meter	R.10 Kg	Coherent super without carried reference

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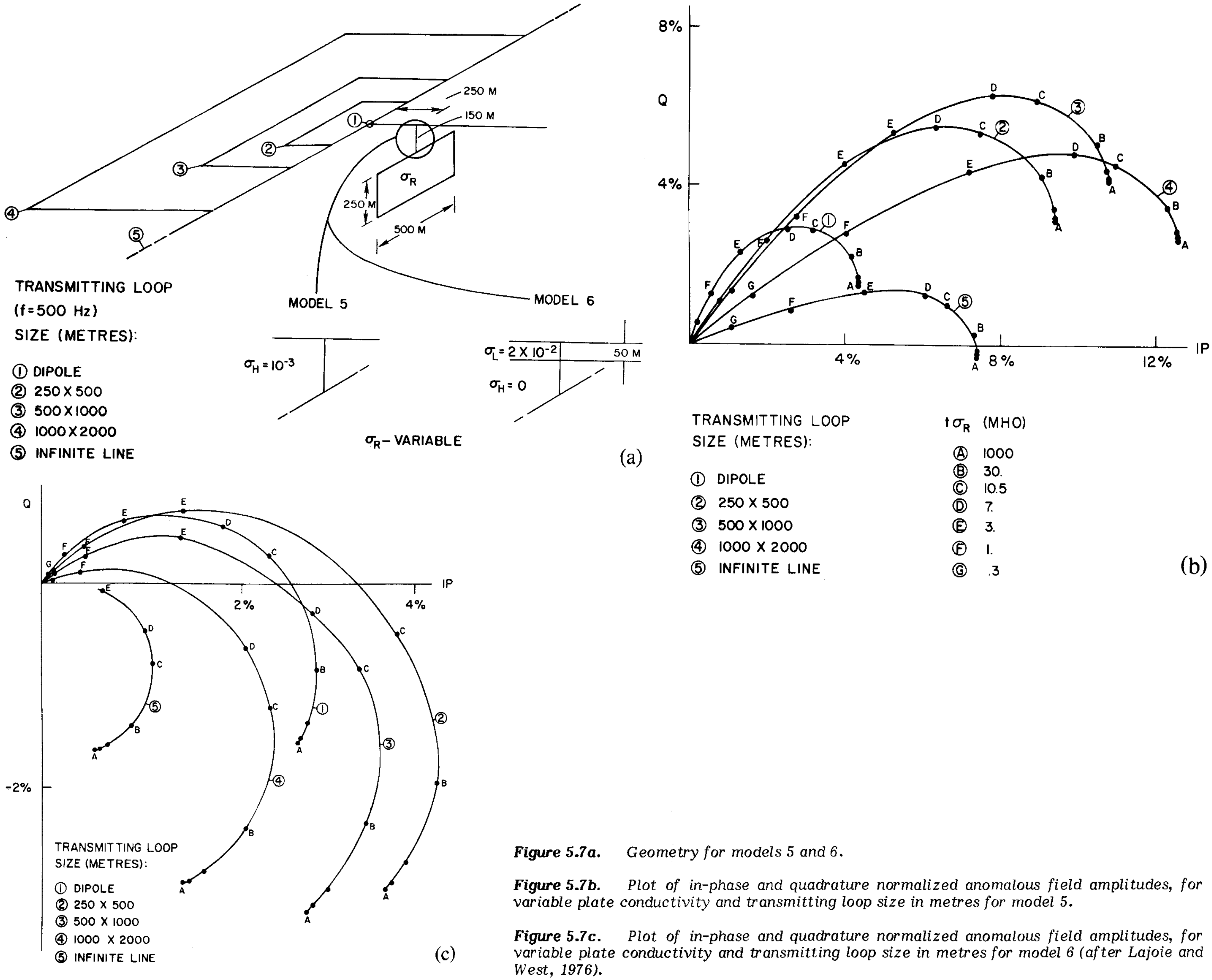

Figure 5.7a. *Geometry for models 5 and 6.*

Figure 5.7b. *Plot of in-phase and quadrature normalized anomalous field amplitudes, for variable plate conductivity and transmitting loop size in metres for model 5.*

Figure 5.7c. *Plot of in-phase and quadrature normalized anomalous field amplitudes, for variable plate conductivity and transmitting loop size in metres for model 6 (after Lajoie and West, 1976).*

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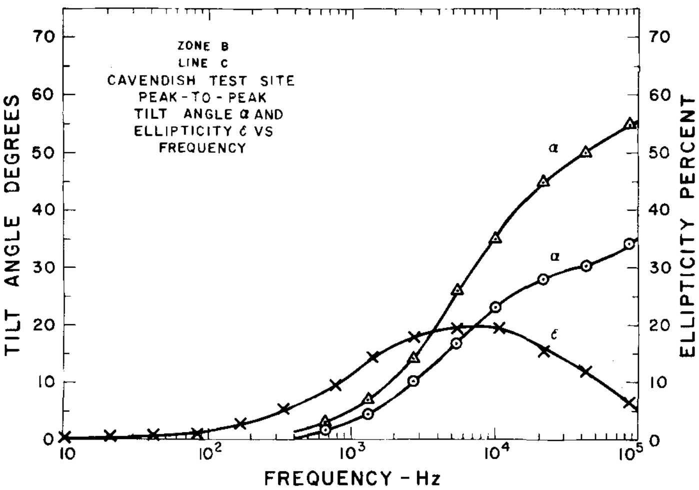

Figure 5.8. Peak-to-peak tilt angle ⊙ and ellipticity X for the vertical axial coil; and peak tilt angle ▲ for the horizontal coil. All are plotted against frequency for Zone B, Cavendish Test Site (after Ward et al., 1974b).

However, the earth can behave in a most unusual manner as a function of frequency when not only the sulphide body, but the host rock, the overburden and the other elements of the general earth also contribute in the frequency window used. This is illustrated in Figure 5.9 in which plots of ellipticity and tilt angle over Zone A of the Cavendish Test Site are contained. With vertical axial coil excitation, the tilt angle trends from asymptote to asymptote over four decades of frequency while the ellipticity at 10^5 Hz is at the high frequency asymptote, but never does reach a low frequency asymptote four decades below this. With horizontal coil and vertical rotating coil excitations the tilt angle at 10Hz is at the low frequency asymptote but the high frequency asymptote is never reached. The latter two curves are not at all smoothly varying or even slowly varying.

It should be evident from the previous illustration that at least four decades and preferably five decades of frequency (1Hz to 10^5Hz) are required to understand the earth. The commercially available systems listed in Tables 5.2 and 5.3 at most use 1+ decades and hence are not suited to use over complex earths. On the other hand, the systems of Table 5.4 use two to four decades of frequency or of spectrum and hence are to be preferred for complex earths. About four frequency or time samples per decade are necessary to assure delineation of rapid changes of response with frequency. The Sirotem system has a capability for about 10 time samples per decade but this high sampling rate may not be necessary.

Combined Resistivity, Induced Polarization, and Electromagnetic Surveys

Conventional and Inductive Measurement of Resistivity

The distribution of true resistivity of a homogeneous, layered, generally inhomogeneous, or layered earth in which local inhomogeneities exist may be estimated from apparent resistivity data acquired during routine surveys with electrode arrays such as the Schlumberger or dipole-dipole arrays. As discussed later, the data may be interpreted in terms of one-, two-, and three-dimensional earth models. References on this subject include Al'pin et al. (1966), Keller and Frischknecht (1966), Kunetz (1966), Van Nostrand and Cook (1966), Bhattacharyya and Patra (1968), Madden (1971), Roy and Apparao (1971), and Telford et al. (1976).

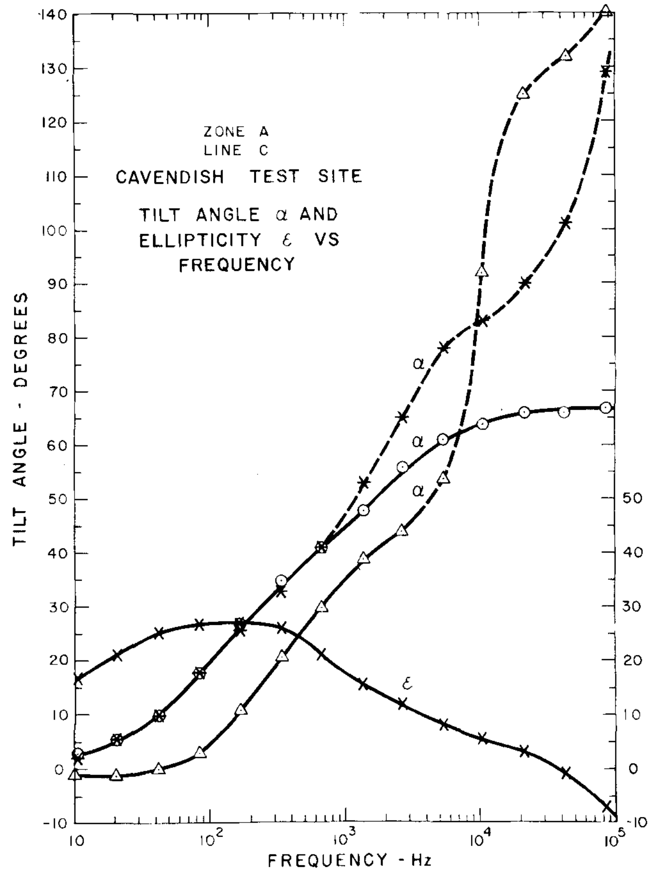

*Figure 5.9. Peak-to-peak tilt angle ⊙ and ellipticity X for the vertical axial coil; peak-to-peak tilt angle * for the vertical rotating coil; and peak tilt angle ▲ for the horizontal coil. All are plotted against frequency for Zone A, Cavendish Test Site (after Ward et al., 1974b).*

Apparent resistivity can be measured readily with an inductive electromagnetic system as has been noted by Keller and Frischknecht (1966), Frischknecht (1967), Vanyan (1967), Dey and Ward (1970), Ryu et al. (1970) and others. However, the feasibility of inductive measurement of the distribution of true resistivity in a two- or three-dimensional earth has only recently been recognized (Parry, 1969; Hohmann, 1971; Swift, 1971; Hohmann, 1975; Lamontagne, 1975; Lajoie and West, 1976; Dey and Morrison, 1977; Pelton, 1977; Rijo, 1977; Pridmore, 1978; and others). Pridmore (1978) demonstrates how the resistivity distribution of a homogeneous or layered earth may be recognized despite the presence of one or more inhomogeneities.

Inductive Induced Polarization (IIP)

Bhattacharyya (1964) computed the transient response of a loop antenna placed on a polarizable half-space but drew no inferences concerning the possibility of measuring induced polarization inductively. Dias (1968) indicated that detection of the induced polarization phenomenon was possible via broadband inductive electromagnetic methods. Hohmann et al. (1970) presented evidence that suggested that IIP was not feasible. Ward (1971a) argued that the tests of Hohmann et al. were not conclusive. Lamontagne (1975) presented field experimental evidence that IIP might indeed be possible. Pridmore (1978) has examined the problem both theoretically and by field experiments but is unable to reach a firm conclusion pro or con. As of early 1978 we can only conclude that IIP is theoretically and experimentally possible but we cannot yet assert that its use can be made probable let alone assure that it can be made economically feasible.

Extracting Resistivity, Induced Polarization, and Electromagnetic Data from a Broadband Dipole-Dipole Resistivity Survey

In conventional surveys designed to measure resistivity and induced polarization simultaneously, an unwanted contribution arises from inductive electromagnetic coupling between transmitting and receiving dipoles (see, for example: Sunde, 1949; Millet, 1967; Hohmann, 1973; Zonge and Wynn, 1975; Summer, 1976; Pelton, 1977). Most practitioners of the induced polarization method attempt to remove the inductive electromagnetic contribution from the data base. My colleagues and I, however, note that there is information about the earth in this data base and hence we advocate its use.

Epilogue

There seems to be information about resistivity and induced polarization in broadband electromagnetic surveys while there also appears to be inductive electromagnetic data inherent in broadband resistivity/induced polarization surveys. A merging of previously disparate technologies is now resulting from this awareness. Coherent detection systems utilizing in-field digital processors, combined with sophisticated and expensive computer modelling, may permit exploitation of this merging. Alternatively, successive application of the electromagnetic method and the induced polarization method, regardless of specific array geometries, may permit three-dimensional mapping of resistivity by electromagnetic methods (e.g. Hohmann, 1975) and specific mineral identification by linear or nonlinear induced polarization methods (e.g. Pelton, 1977; Klein and Shuey, 1978).

DATA PROCESSING

Until the last several years, processing of electromagnetic prospecting data has been entirely analog. Zonge (1973), Lamontagne and West (1973), Jain and Morrison (1976), Snyder (1975, 1976), Nabighian (1977), Buselli and O'Neill (1977), Hohmann et al. (1977) have presented descriptions of in-field digital processors which are being or might be applied to ground electromagnetic receiving systems. The in-field microprocessor permits a range of preprogrammed software applications including stacking, filtering, coherent harmonic detection, spectral storage, and spectral weighting. Cassette-recording systems rather than conventional tape decks, as recording media, provide the convenience of in-field or field camp same-day processing and even first-cut interpretation of data using processors such as the Hewlett-Packard 9825A. The costs of such processors and of computers in general will probably decrease rapidly during the next several years.

With these relatively inexpensive luxuries we are now dynamically changing the design of field surveys as the accumulated data warrant. No longer need we send a crew back to the field to obtain a missing data point or data profile or to repeat inadequate or noisy data. Now we know in the field or in the camp whether or not our data is adequate to meet our objectives.

This greater flexibility in the field is gradually leading to simultaneous collection of multichannel data such as n frequencies, m time samples, or r receiver locations. While simultaneous multiple receiver locations are now used commonly with advanced resistivity/induced polarization systems, they have yet to appear with ground electromagnetic systems. They will!

If we are to probe deeper for metallic sulphides via electromagnetic methods we must be able to utilize a broad spectrum, to employ more than one mode of excitation, to enhance the electromagnetic signal relative to natural or artificial electromagnetic noise, and to facilitate in-field processing and preliminary interpretation. Only by using in-field digital processors can we hope to accommodate all of these functions simultaneously.

The basic elements of a microprocessor-controlled electromagnetic receiver might include:

1. a multichannel analog front-end with gain and filtering automatically or manually controlled using the microprocessor,
2. an analog-to-digital converter,
3. an ultra-stable precision interval timer and synchronous clock locked to an identical clock which drives the transmitter,
4. a microcomputer, and
5. a keyboard and display unit.

The transmitter used most commonly with these receivers produces alternate cycles of reversed square wave although programmable waveform processors are available for complete generality of transmitted waveform. The microcomputer can be programmed to process the received signal in the time domain via stacking, in the frequency domain via synchronous demodulation, or both. The important point here is that software algorithms control the particular transmitted waveform and received signal processing scheme and these can be changed at will.

DATA INTERPRETATION

Introduction

If the earth is horizontally plane-layered it is referred to as a one-dimensional (1D) earth. If it exhibits extended strike length, locally, it is referred to as a two-dimensional (2D) earth. Both of these simplistic models are used today. Realistically, however, any base metal environment is three-dimensional (3D) in that any electrical parameter varies significantly over tens or hundreds of metres in all three dimensions. Interpretation proceeds by establishing models of the earth, calculating or finding in a catalogue the electromagnetic signatures of the models, selecting a model whose signature best approximates that observed, and then implying that this selected model is a reasonable representation of the real earth. Further, 3D models employed to interpret field data ideally must include all of the elements of the real earth, i.e. massive sulphide mineralization, halo of disseminated mineralization, fresh host rock, weathered host rock, overburden, faults, shears, graphitic zones plus surface and buried topography as in Figure 5.1. This task of modelling is a formidable one, the absence of which has led to the drilling of overburden anomalies (Fountain, 1972; Scott and Fraser, 1973, for example).

Interpretation of electromagnetic data can be accomplished by either forward or inverse methods. With the forward method, a catalogue of signatures is prepared with which observed signatures are compared by visual inspection

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or are matched with computed signatures by trial and error. The catalogues may be developed by scaled physical modelling, by analytic solution, or by numerical approximation. With the inverse method, observed signatures are automatically compared with numerically derived signatures via computer; the difference between the two is minimized in a least-squares sense and the ambiguity of interpretation is assessed statistically.

The Forward Method of Interpretation

Scaled Physical Modelling

For years we have used metallic sheets to simulate thin ore veins, metallic spheres to simulate equidimensional ore deposits, or slabs of carbon/graphite to represent tabular base metal deposits in scaled physical models. The variety of geometries of such models is great. Until about ten years ago, we modelled the earth by placing sheets, spheres or slabs in air and totally ignored all of the other elements of the real earth (Ward, 1971b). That we were successful with application of the electromagnetic method when using such crude models of interpretation is surprising. Ward et al. (1974a) reviewed some scaled physical modelling of the early 1970s that clearly indicated the need to take account of host rock and overburden. Many data from model tank measurements are now available in the literature.

The difficulty of physically modelling a real earth with all its complexities has deterred many from pursuing this method of forward modelling. Ward (1967) discussed the problems faced by the scaled physical modeller of that time. These problems led many of us, including me, to emphasize numerical solutions and to use scaled physical modelling only for checks on theoretical solutions. Perhaps it is time, given new materials, new perspectives, and greater imagination, to reconsider the use of scaled physical models not only as stand-alone data sets but also as data sets against which numerical models may be checked. The difficulty, computer limitations, and costs of analytic and numerical forward solutions may force us in this direction.

Analytic Solutions

Analytic solutions for a variety of simple earth models are available. These include:

1. electric or magnetic dipoles over a homogeneous earth (Wolf, 1946; Wait, 1953, 1955; Quon, 1963; Pridmore, 1978),

2. electric or magnetic dipoles over a layered earth (Wolf, 1946; Wait, 1958; Quon, 1963; Frischknecht, 1967; Ward, 1967),

3. a uniform alternating magnetic field incident upon a sphere or cylinder in free space (Wait, 1951, 1952; Negi, 1962; Ward, 1967),

4. magnetic dipoles near a spherical body in free space (Nabighian, 1971; Lodha and West, 1976; Best and Shammas, 1978), and

5. magnetic dipoles near a sphere in a conductive half-space (Singh, 1973).

These solutions are important in themselves because they serve as basic guides for interpretation. More importantly, of late, they serve as devices for checking the validity of the more flexible and more general numerical solutions which have entered the scene since the early 1970s.

A fundamental result using an analytic solution was obtained by Pridmore (1978). He demonstrated that reduction of magnetic field amplitude was more dependent upon geometric fall-off from a finite source than it was upon attenuation in a lossy medium.

Numerical Solutions

Hohmann (1977), in a publication of limited distribution, made an excellent analysis of the state-of-the-art of interpretation of resistivity, induced polarization, and electromagnetic data. In the next few paragraphs I shall draw heavily from that document.

In recent years solutions have been found to previously intractable electromagnetic boundary value problems (Coggon, 1971; Hohmann, 1971; Parry and Ward, 1971; Swift, 1971; Vozoff, 1971; Dey and Morrison, 1973; Lee, 1974; Hohmann, 1975; Lajoie and West, 1976; Stoyer and Greenfield, 1976; Rijo, 1977; and Pridmore, 1978). The earliest of these articles dealt with two-dimensional inhomogeneities in the fields of line sources; this is a true 2D problem. The article by Stoyer and Greenfield (1976) describes a two-dimensional inhomogeneity in the field of a three-dimensional source (the 2D-3D problem) while the articles by Lee (1974), Hohmann (1975), Lajoie and West (1976), and Pridmore (1978) described a three-dimensional inhomogeneity in the field of a three-dimensional source (the full 3D problem).

Four methods have been used to achieve numerical solutions to two- and three-dimensional problems:

1. finite difference,
2. network analogy,
3. finite element,
4. integral equation.

These four methods all use the method of moments (Harrington, 1968) to solve an equation of the form

$$L(f) = g \tag{1}$$

where L is a linear operator, g is a known source term, and f is an unknown field function. The unknown f is approximated by

$$f = \Sigma_n \alpha_n f_n \tag{2}$$

in which the α_n are constants and the f_n are referred to as basis functions. If (2) is to be an exact solution then its right hand side must be an infinite summation and the f_n form a complete set of basis functions. For approximate solutions, (2) is usually a finite summation based on an incomplete set of basis functions. If we substitute (2) in (1) we obtain

$$\Sigma_n \alpha_n L(f_n) = g \tag{3}$$

An inner product $\langle f,g \rangle$ and a set of vector weighting functions W_m, are defined for the problem. If we then take the inner product of (3) with each W_m we obtain

$$\Sigma_n \alpha_n \langle W_m, L(f_n) \rangle = \langle W_m, g \rangle \tag{4}$$

This set of equations can be written in matrix form as (Harrington, 1968)

$$\left[\ell_{mn}\right] \left[\alpha_n\right] = \left[g_m\right] \tag{5}$$

where

$$\ell_{mn} = \begin{bmatrix} \langle W_1 L(f_1) \rangle, & \langle W_1, L(f_2) \rangle & \cdots\cdots \\ \langle W_2, L(f_1) \rangle, & \langle W_2, L(f_2) \rangle & \cdots\cdots \\ \cdots\cdots & \cdots\cdots & \cdots\cdots \end{bmatrix} \tag{6}$$

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$$[\alpha_n] = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad (7)$$

and

$$[g_m] = \begin{bmatrix} \langle W_1,g \rangle \\ \langle W_2,g \rangle \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad (8)$$

When the matrix (1) is nonsingular its inverse $[\ell^{-1}]$ exists and under this circumstance the α_n are given by

$$[\alpha_n] = [\ell^{-1}_{mn}][g_m] \quad (9)$$

When the α_n are substituted in (2), the unknown field function f is obtained.

For methods (1), (2), and (3), L is a second-order differential operator, while for method (4) it is an integral operator. For each method one must choose effective basis and weighting functions. The articles referenced earlier illustrate how these choices are made. The particular choice $W_n = f_n$ is known as Galerkin's method.

For purposes of comparison, the four methods may be divided into two groups: differential equation (1, 2, 3) and integral equation (4). The differential equation solutions are simple to construct and result in large banded matrices. Because the fields in the entire earth are modelled on a grid or mesh with the differential equation methods, these methods are preferable for modelling complex earths. This is in contrast to the integral equation method in which unknown fields are required only in the anomalous parts of the earth. The net result is that integral equation solutions are less expensive per unit of accuracy (than differential methods) where the earth contains only a few regions of differing physical properties; the resulting matrices, though full, are smaller than those for the differential methods. Of the differential methods, the finite difference and network methods are easier to program, while the finite element method can handle more complex geometrics. This short discourse on the over-riding method of moments and on comparisons between finite difference, network analogy, finite element, and integral equation are made a) to illustrate the similarities between each of the four methods and b) to point out that differences exist, on a cost per unit accuracy basis, between them. Rijo (1977) showed that the network analogy and finite element methods led to identical matrices but, facility to handle complex earths was quite different with the two methods.

The state-of-the-art in forward solutions for the electromagnetic scattering problem is shown in Table 5.5 opposite.

Table 5.5

Current progress in forward solutions by numerical methods

	2D	2D-3D	3D
Finite difference	x	[x]	[x]
Network analogy	x		
Finite element	x		x
Integral equation	x	[x]	x

[ ] denotes an unchecked algorithm.

Integral-equation 3D algorithms are inexpensive but are applicable to simple earths involving only one or two inhomogeneities. Finite element solutions are expensive but are applicable to complex earths. To illustrate the two methods, calculations of field quantities for the model of Figure 5.10 have been made with each of them. Figure 5.11 (after Hohmann, 1975) shows a horizontal-loop EM profile of real and imaginary components for background conductivities of 0.01 mhos/m and 0.0033 mhos/m. The effect of current gathering in the inhomogeneity is greater for the background of highest conductivity as expected.

Figure 5.12 (after Pridmore, 1978) shows tilt angle and ellipticity profiles measured with a roving receiver and a fixed transmitter. The background conductivity for this example was 0.033 mhos/m, so high that the ellipticity anomaly due to the inhomogeneity is very small. The tilt angle anomaly is not terribly diagnostic of the inhomogeneity because of the high background conductivity.

Figures 5.11 and 5.12 establish that full three-dimensional problems can be solved numerically. Each integral equation profile cost about US $30.00 while each finite element profile cost about ten times that much. On the other hand, a much more complex earth model could be treated by the finite element method at essentially the same cost. Note that each of Figures 5.11 and 5.12 were produced for a single frequency only. The costs for modelling broadband data obviously become excessive. The only economical means of treating such problems is via use of a dedicated computer, such as a DEC11/60, which is allowed to

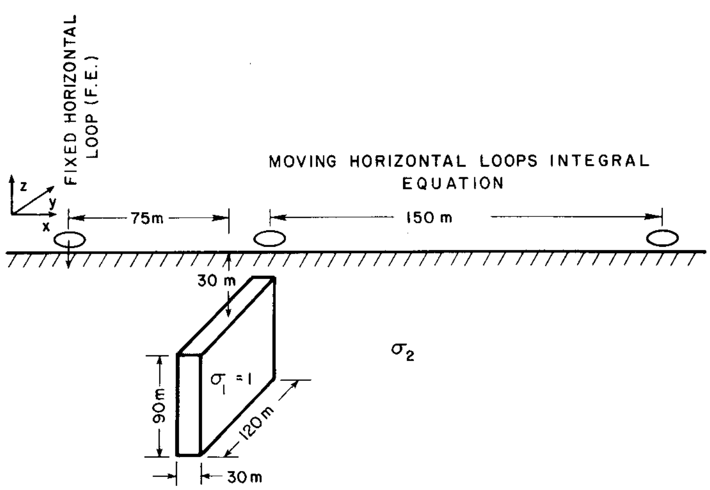

Figure 5.10. Geometry of the three-dimensional model used in producing Figures 5.9 and 5.12.

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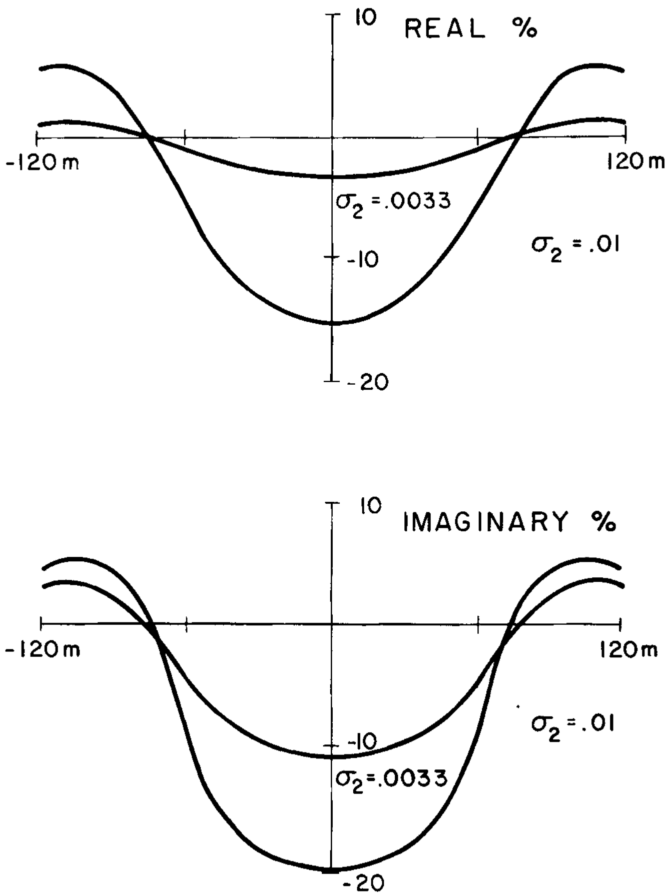

Figure 5.11. Horizontal loop EM profiles for the model used in Figure 5.10; frequency = 1000 Hz.

grind away at the problem at small operating cost. A special computer might be designed specifically to treat these problems at an even lower cost.

The algorithms of Hohmann and Pridmore cross check very well provided the conductivity contrast between inhomogeneity and host is not too large. For high contrasts and shallow depths to the top of the inhomogeneities, convergence problems force either error in computations or astronomical costs, again unless a dedicated computer is used.

The Inverse Method of Interpretation

While numerous algorithms exist for the inversion of resistivity and magnetotelluric data in terms of a layered earth, such is not the case for active source electromagnetic methods. Glenn et al. (1973), Glenn and Ward (1976), Ward et al. (1976), and Tripp et al. (1978) are the only published papers on the subject at the time of writing. Pridmore (1978) has applied this algorithm to estimate the mean conductivity of a half-space adjacent to a massive sulphide base metal deposit. Because of its limitation to a 1D earth, this particular algorithm is expected to be of minimal applicability in base metal exploration.

So far, no 2D or 3D inverse algorithms for active electromagnetic methods have been produced. The cost of applying them, if developed, may be prohibitive. However, some form of computer interactive inversion will be required if we are to derive the maximum possible information from EM data.

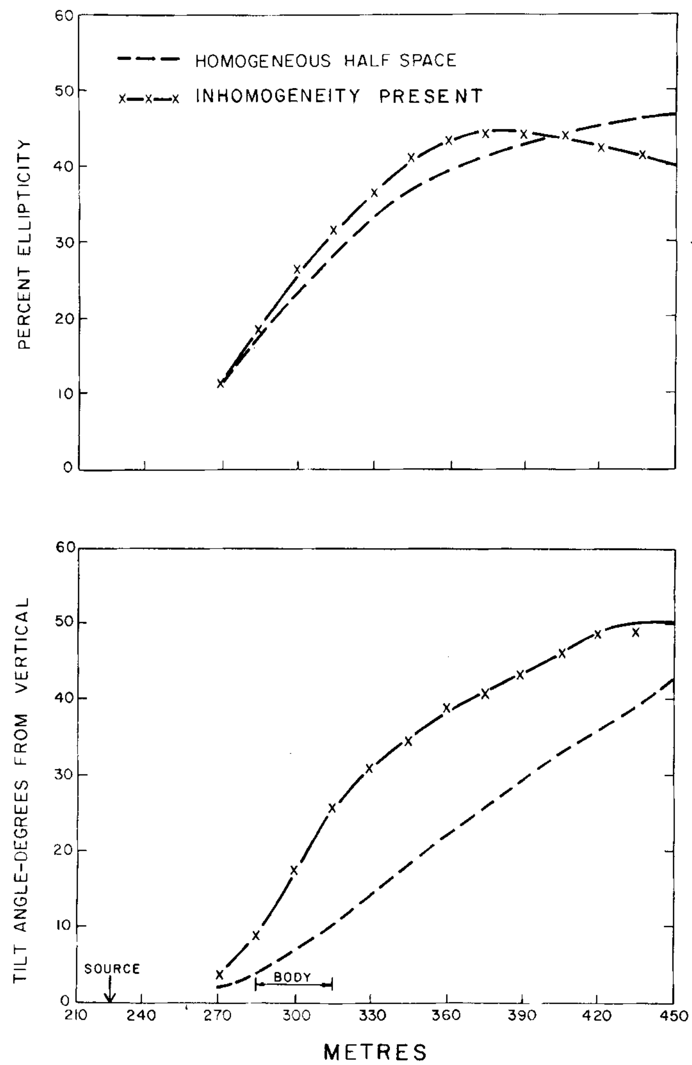

Figure 5.12. Tilt angle and ellipticity for fixed horizontal-loop EM transmitter for the model in Figure 5.10; frequency = 1000 Hz.

RECENT RESULTS WITH BROADBAND EM SYSTEMS

A few examples of the application of broadband electromagnetic methods follow. No attempt at completeness in terms of specific methods, specific geological problems, or specific geographical areas is attempted.

Cavendish Test Site, Frequency Domain

Ward et al. (1974b) obtained broadband frequency domain electromagnetic data over the Cavendish Test Site in Ontario. Figure 5.13 shows some of their data. The transmitter-receiver configuration used to obtain the data was the vertical coaxial coil method referred to earlier. The contours in frequency-distance space clearly reveal the existence of Zones A and B and also reveal that Zone A has a higher conductivity-thickness product than Zone B because the response commences at lower frequencies. The effects of overburden, host rock, and disseminated halo are not obvious in this form of data presentation, for this particular case history. However, Figure 5.9 clearly reveals that either the host rock or the overburden is contributing to the response at frequencies in excess of 10^4 Hz.

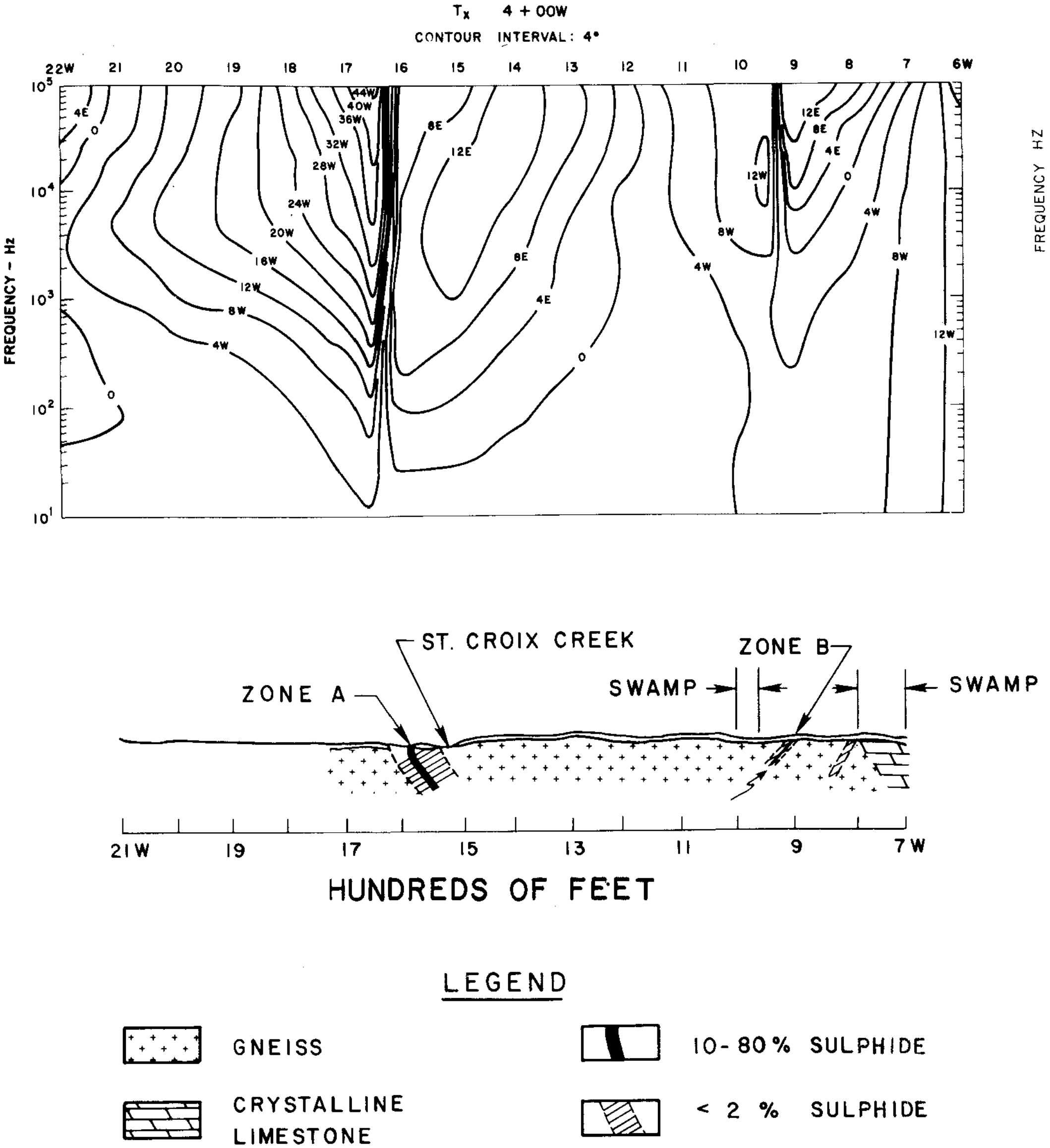

Figure 5.13. *Contours of tilt angle, in frequency-distance space, for measurements near a vertical axial coil located at 4+00W on Line C at the Cavendish Test Site, Ontario, Canada.*

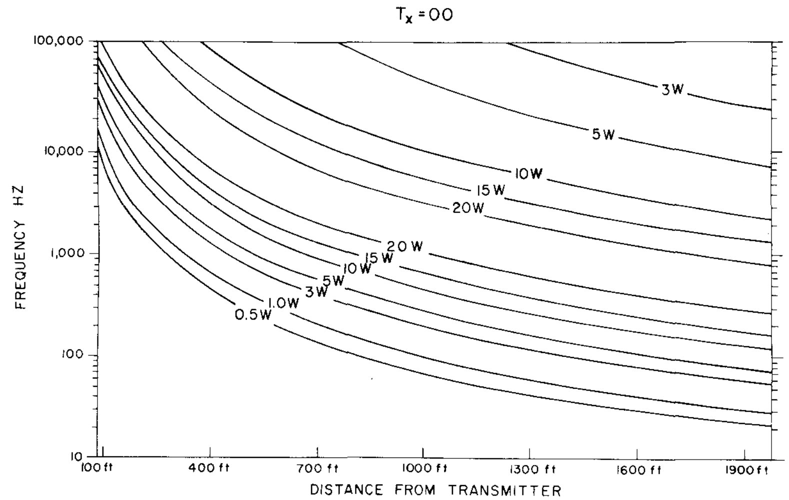

Figure 5.14. *Contours of tilt angle, in frequency-distance space, computed for a homogeneous half-space of conductivity 0.01 mhos/m relative to a vertical axial coil located at 0+00.*

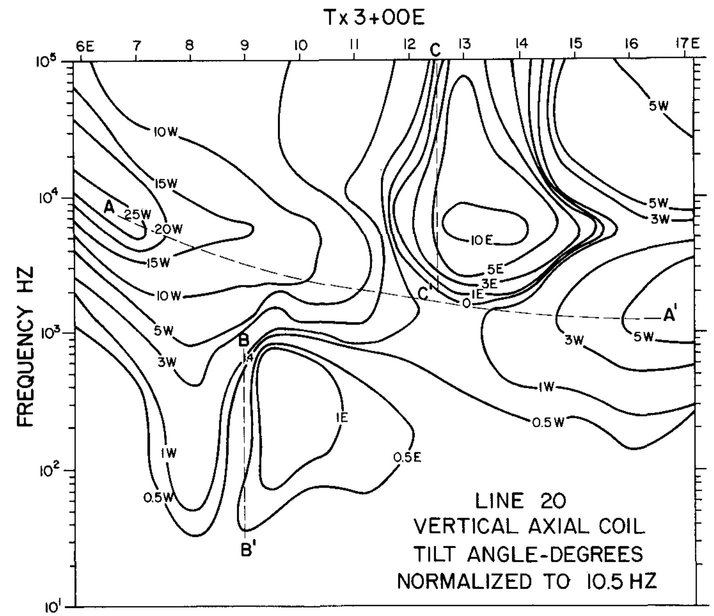

Figure 5.15. *Contours of tilt angle, in frequency-distance space, observed at a site in California where massive sulphides, disseminated sulphides, and a conductive host rock are present. A-A', B-B' and C-C' indicate trends of half-space, massive sulphide, and disseminated sulphide responses, respectively.*

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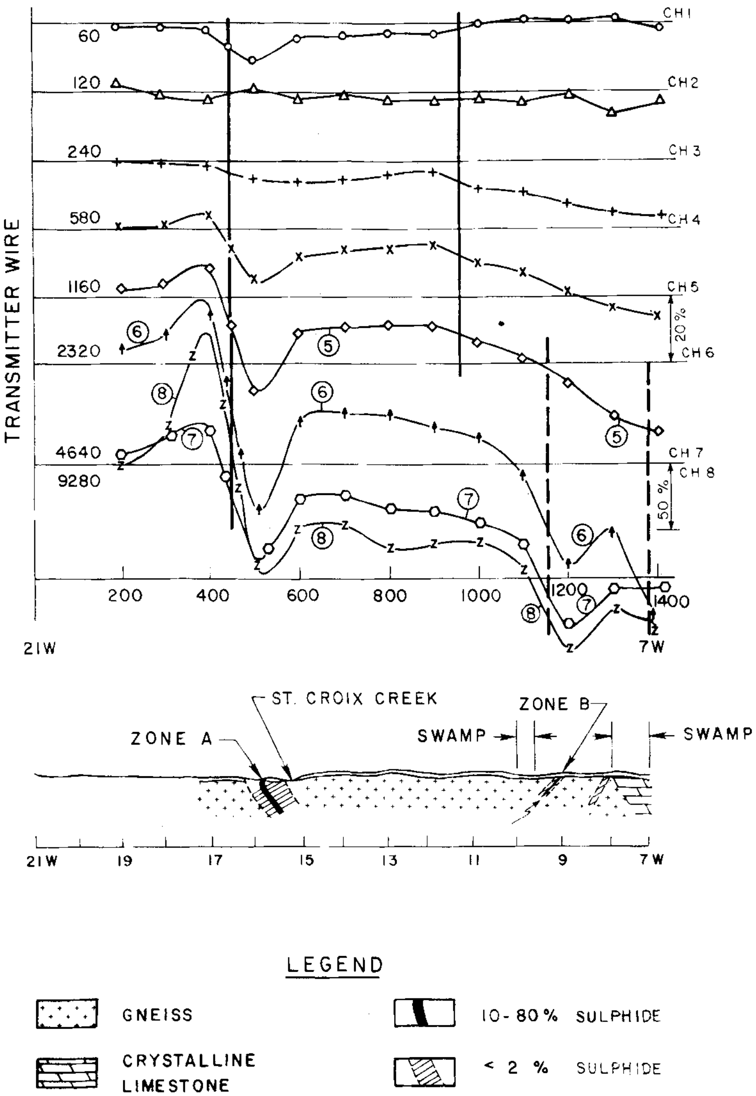
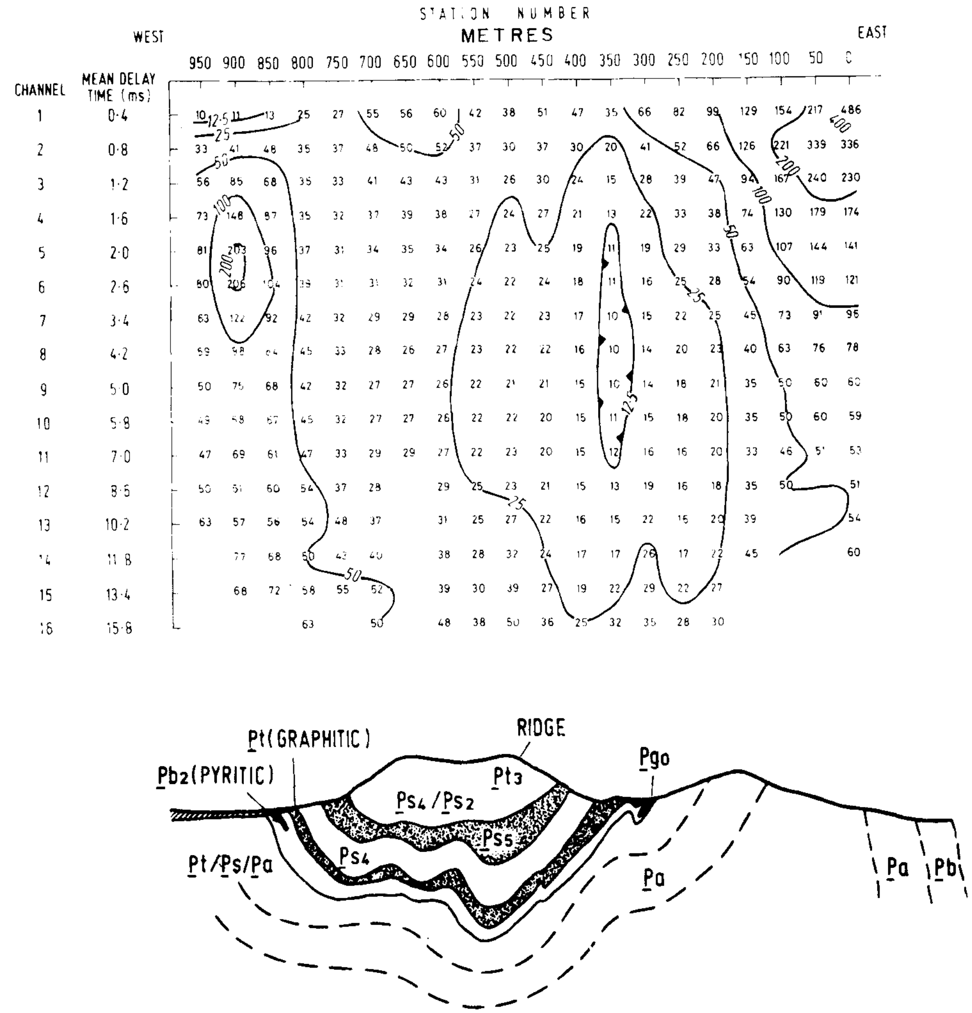


Figure 5.16. Profiles of seven channel UTEM time-domain response on Line C of Cavendish Test Site, Ontario, Canada (after Lamontagne and West, 1973).



Pb - albitalite;

Pgo - gossan. subsurface it changes to Pb2 which contains pyrite - conductive;

Pt - graphitic siltstone - conductive;

Ps5 - chiastolite schist - conductive;

Ps4 - andalusite schist (occurs in patches);

Ps2 - quartz muscovite schist (predominant lithology on ridge).

Figure 5.17. Apparent resistivity plotted in time-distance space as derived from data obtained over the Willyama complex, South Australia, using the Sirotem system (after Geoex Pty. Ltd., 1977).

The ability of a broadband system to evaluate the conductivity – thickness products of two adjacent zones in a resistive environment is brought out by this case history. The location of each conductor is indicated by a change of sign of tilt angle, in frequency-distance space, of vertical contours.

Theoretical Response of a Homogeneous Half-Space, Frequency Domain

Figure 5.14 (from Pridmore, 1978) shows the computed contours of tilt angle in frequency-distance space for a coaxial vertical-loop method. Broad, sweeping, semihorizontal contours of tilt angle in frequency-distance space are diagnostic of a homogeneous earth (or of a horizontally-layered earth, Pridmore, 1978).

California Test Site, Frequency Domain

When conductive overburden, a weathered layer, and conductive host rocks are encountered, tilt angle response combining the diagnostic features of Figures 5.13 and 5.14 is to be expected. Thus Figure 5.15 illustrated the half-space or layered half-space response (A-A') superimposed upon the response of an inhomogeneity of relatively high conductivity-thickness product (B-B') plus the response of an inhomogeneity of relatively low conductivity-thickness product (C-C'). The latter two responses arise in massive economic sulphides and in disseminated non-economic sulphides, respectively (Pridmore, 1978).

Cavendish Test Site, Time Domain

Figure 5.16 contains the early time-domain results obtained by Lamontagne and West (1973) over the Cavendish Test Site.

This time domain data clearly illustrate that Zone A is of higher conductivity-thickness product than Zone B, in accordance with the frequency domain results presented earlier. The transmitter was a large horizontal loop.

Willyama Complex, South Australia

Figure 5.17 contains a plot of apparent resistivity in time-distance space as obtained with the Sirotem system. The transmitting and receiving loops were coincident and were 100 m square. The loop was placed at 50 m intervals to obtain the data points of Figure 5.17. The boundaries of the conductive section of the syncline are indicated at 150W and 850W. The zone is most conductive under 350W which is the position of the conductive sediments at the depth of maximum response of the loop configuration. Near surface variations in resistivity are reflected in the variations at short time delays such as the low resistivities to the far west over thick conductive soil cover (Geoex Pty. Ltd., 1977). The ability of a broadband electromagnetic system to indicate the complexity of a geoelectric section is brought out by this example. Later results with Sirotem, illustrating penetration through a 90 m conductive cover to detect a massive sulphide body, are given in McCracken and Buselli (1978).

CONCLUSION

I have attempted to illustrate in this article what is being done and what will be done with electromagnetic systems designed to search for base metals. The newer systems currently in use, and especially those of the future, will obtain information on the parameters of the real three-dimensional earth. Failure to evaluate geological "noise" as well as geological "signal" will deter our attempts to search deeper for smaller base metal deposits. The variables to be employed are many and interrelated. We must be exceptionally clever if we are to make significant strides in our quest.

A new hardware item to look for in industrial use in the near future is a three-component cryogenic magnetometer which currently exhibits flat response from D.C. to 10^2 Hz at a sensitivity of 10^{-5} γ/Hz. Extension of the passband to 10^3 Hz is in the prototype stage, while extension to 10^4 Hz is on the drawing board. These exceptionally sensitive receivers permit three-component, and gradient of three-component, magnetic field measurement in an extremely compact package of about 12 kg weight. The accompanying in-field digital processing hardware is about 10 kg weight. If this in-field instrumental capability can be combined with a 3D interpretative capability via digital computer, then the electromagnetic method shall have achieved a viable status.

ACKNOWLEDGMENTS

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