4.

AIRBORNE ELECTROMAGNETIC METHODS

A. Becker
Ecole Polytechnique, Montreal, Quebec

Becker, A., Airborne electromagnetic methods; in Geophysics and Geochemistry in the Search for Metallic Ores; Peter J. Hood, editor; Geological Survey of Canada, Economic Geology Report 31, p. 33-43, 1979.

Abstract

The past decade has witnessed a number of major technical advances in the art of airborne electromagnetic (AEM) surveying. Although in most cases these took the form of improvements to AEM systems available in their basic form prior to 1967, they resulted in a substantial upgrading of data quality. In this context the Canadian airborne survey industry has introduced multifrequency and multicomponent operation, has reduced noise and drift levels and has increased the recording bandwidth of AEM equipment. It is only natural that the introduction of digital data recording accompanied these changes so that more sophisticated methods of data reduction and interpretation could be implemented.

Refined AEM equipment and superior EM data quality has now given practical meaning to the concept of electromagnetic mapping. The AEM method is thus no longer restricted to prospecting applications, but can serve as an essential component of a flying laboratory used for the indirect search for mineral deposits or for the resolution of problems in geological engineering. Thus, much progress has been made in recognition and automated interpretation of overburden response.

It is expected that these trends will continue so that reliable theoretical tools will soon be available for translating high quality airborne electromagnetic data into corresponding geological sections of the underlying terrane.

Résumé

Nous avons été témoins au cours de la dernière décennie de progrès techniques importants dans le domaine des levés électromagnétiques aéroportés. Bien que, dans la plupart des cas, ces progrès aient été des améliorations apportées à des systèmes de base existant déjà avant 1967, ils ont constitué un enrichissement important de la qualité des données. C'est ainsi que l'industrie canadienne des levés aéroportés a introduit des travaux à fréquences et à composantes multiples, a réduit les niveaux de bruit et de dérive et a augmenté la largeur de bande d'enregistrement. Il est bien normal que l'introduction de la technique d'enregistrement numérique des données ait accompagné ces changements; ainsi des méthodes plus perfectionnées de réduction et de décodage des données pouvaient être mises en oeuvre.

Du matériel amélioré et une qualité supérieure des données ont ainsi accordé une signification pratique au concept de la cartographie électromagnétique. Les levés aéromagnétiques aéroportés ne sont alors plus limités à la prospection: ils peuvent constituer un élément essentiel d'un laboratoire volant servant à la recherche indirecte de ressources ou à la solution de problèmes d'étude géologique. Ainsi, d'importants progrès ont été réalisés dans les domaines de l'identification et du décodage automatisé de réponses des morts-terrains.

Il est à espérer qu'à l'avenir ces tendances se poursuivent de sorte que l'on dispose bientôt d'outils théoriques véritables pour la traduction de données électromagnétiques aéroportées de haute qualité en des sections géologiques correspondantes du sol sous-jacent.

INTRODUCTION

In the decade that has elapsed since the last review of the state of the art in Airborne Electromagnetic (AEM) surveying by S.H. Ward in 1967 (Ward, 1970), the survey industry has concentrated on the refinement and modification of existing AEM systems rather than on the development of new systems based on new concepts. Most of the recent development efforts have been aimed at improving AEM system sensitivity and penetration through a reduction in noise level, at improving the system capability for definition of conductor geometry through the introduction of multi-component receivers, and at improving AEM system apertures for definition of conductor quality through the introduction of secondary field measurements at a number of simultaneously transmitted frequencies.

As they occurred, these innovations were reported by P.J. Hood in his annual review "*Mineral exploration trends and developments*" which appears each year in an early number of the Canadian Mining Journal (e.g. see Hood, 1978). The major capability in AEM systems is still located in Canada. For this reason, and because information on new AEM developments in Scandinavia and the Eastern World is difficult to obtain, the present review will concern itself principally with the North American scene.

Although no radical instrumentation changes were reported, the scope of application of the AEM technique has been considerably enlarged. In fact, the simple prospecting tool of ten years ago has evolved into a sophisticated mapping system whose multichannel information is recorded digitally for further computer processing on the ground. Our understanding of the electromagnetic induction process in a variety of geological environments has been considerably improved because high quality multi-frequency and/or multicomponent data are available. Thus, in addition to their main application in mineral exploration programs, airborne electromagnetic measurements are now also frequently used for the definition of geological parameters either as an aid to structural mapping or, in an engineering context, for mapping overburden. Finally, AEM systems are beginning to see service as part of a flying laboratory destined for the indirect detection of mineral deposits such as uranium mineralization which itself does not show an AEM response, but is sometimes associated with conductive marker horizons.

The progress made in improving AEM instrumentation quality and extent of applications was also accompanied by progress in the development of EM data interpretation methods. Thus the partial catalogues of scale model EM curves presented by Ward ten years ago were updated and completed for virtually all current AEM systems by West, Ghosh and Palacky (Ghosh and West, 1971; Palacky, 1978). Information is now available upon which a rational choice can be made for the deployment of a particular AEM system in a given environment. In parallel with this effort, new theoretical AEM tools were evolved for the automatic mapping of earth resistivity. It is expected that the trend towards the upgrading of EM interpretation methods will continue. As methods of numerical analysis for the calculation of the response of an arbitrarily shaped conductor to a dipole source become more accurate and economical, one can look forward to the replacement of the current techniques, which involve the use of master charts, by the direct inversion of the measured secondary field parameters into geological models.

TECHNICAL DEVELOPMENTS (1967-1977) IN AEM SYSTEMS

In spite of the fact that no radically new AEM system became operational during the 1968-1977 decade, the capability of the 1967 systems was considerably enlarged either through an updating and improvement of the electronics or through the addition of auxiliary data acquisition capability to the original system. Thus, today, as in 1967 (Ward, 1970), we still have a number of versions of the three basic AEM system types, namely rigid boom, towed bird, and VLF (Very Low Frequency-remote transmitter).

The most common system in the rigid boom category is the helicopter-towed coaxial configuration. In this type of AEM system the transmitter and receiver are rigidly supported in a plastic structure with a seven to ten metre separation between the two elements. The whole assembly is then suspended beneath the carrying platform on a cable which brings the secondary field information to the inphase and quadrature detectors and the recording apparatus located in the helicopter. If one includes in the above category, the new three-frequency coaxial Kenting-Scintrex Tridem (Bosschart and Seigel, 1974; Hood, 1978) system which is rigidly attached to the Canso aircraft that carries it, then it appears that this type of system is rapidly replacing the fixed-wing coplanar equipment which has seen much service since its inception more than twenty years ago. The current popularity of the helicopter AEM systems is probably related to the recent technological improvements that resulted in noise levels of the order of 1 ppm and a true "button-on" capability which is now available from a number of Canadian manufacturers. Although these AEM systems usually operate at a single frequency in the vicinity of 1kHz, at least two manufacturers offer a two-frequency version of this type of apparatus.

A further refinement to helicopter-borne, rigid-boom AEM systems was the introduction of the Dighem system which has a three-component receiver coil system (Fraser, 1972a). As illustrated in Figure 4.1, this type of system provides useful information on the strike and dip of small- and medium-sized conductors. The Dighem system has recently been further modified to contain two totally independent systems (one coaxial, one coplanar) within the same housing. This arrangement (Fraser, 1978a) facilitates recognition of conductor geometry.

Towed-bird AEM systems have also undergone considerable technological change during the past decade. In particular, as shown in Figure 4.2, the Barringer Input EM system (Lazenby, 1973) has been improved by its operators by increasing the transmitter power by 30 per cent for the Mark VI model. This simple change yielded a much improved signal-to-noise ratio, and permitted a decrease in the recording time constant, which resulted in an accompanying increase in anomaly resolution and depth of penetration. The new Mark VI installation has also been equipped with a digital recording system to take full advantage of improved data quality. In the frequency domain the McPhar F-400 two-frequency quadrature AEM system (Seiberl, 1975) has been modified to respond to a wider range of conductors by extending the capability of that system to five-frequency operation. The improved system, called Quadrem, which can be adapted to either fixed wing or helicopter operation operates at 95, 285, 855, 2565, and 7695 Hz. Typical data recorded by this system are shown in Figure 4.3. Another example of the current high level of technological achievement in towed-bird AEM systems is the new Hudson Bay EM-30 system constructed by Geonics Ltd. With this system it is possible to obtain inphase and quadrature data at a large coil separation in a compensated towed-bird configuration with a noise level lower than 200 ppm (Anonymous, 1977).

The gap between the moving source methods described above and the fixed remote-source VLF EM methods is bridged by the Turair EM system in which Scintrex Ltd. has introduced a semiairborne EM system in order to attain the

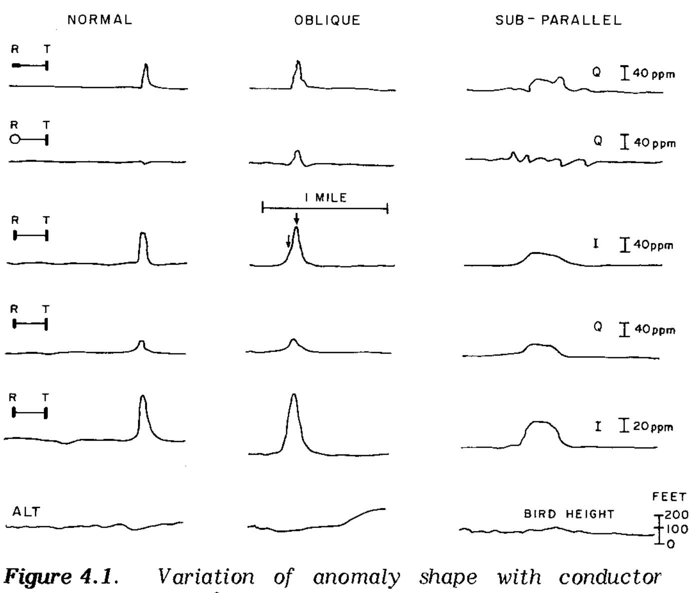

Figure 4.1. Variation of anomaly shape with conductor strike relative to flight direction; Dighem helicopter-borne EM system (after Fraser, 1972a).

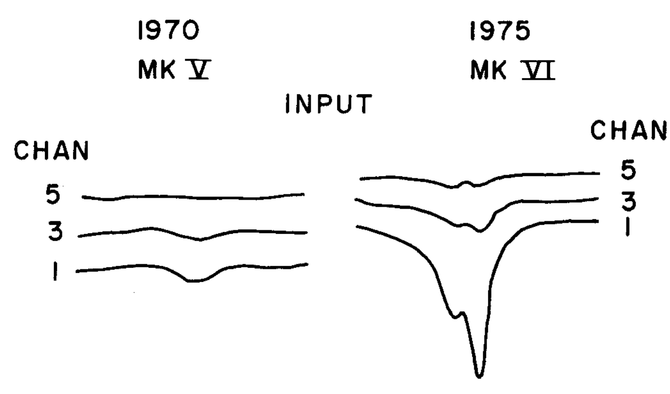

Figure 4.2. Improvement in signal quality over a given anomaly due to technological improvements; Input EM system (courtesy of Questor Surveys).

Contents

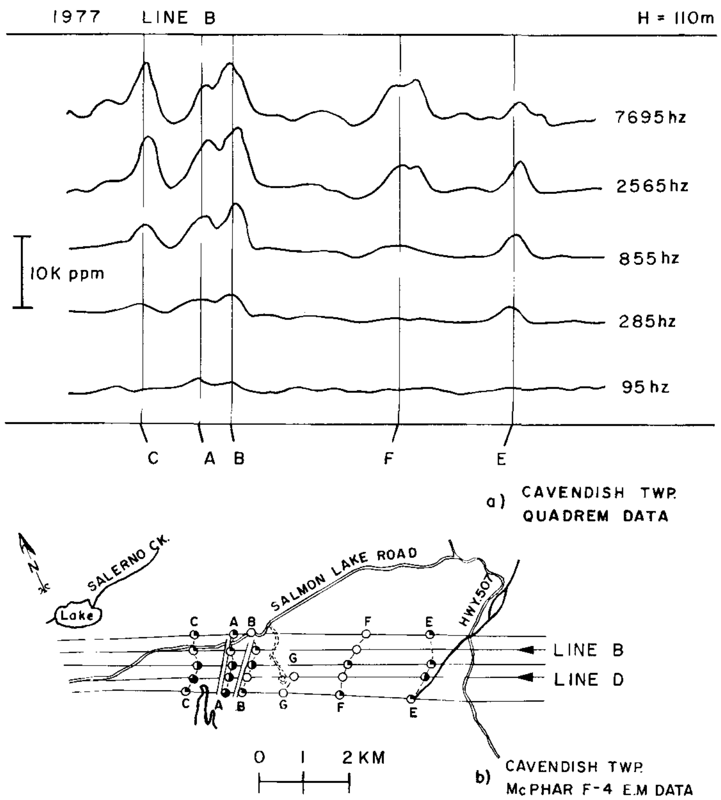

Figure 4.3. *Five-frequency quadrature EM data, McPhar Quadrem and F-400 AEM systems (courtesy of McPhar Geophysics).*

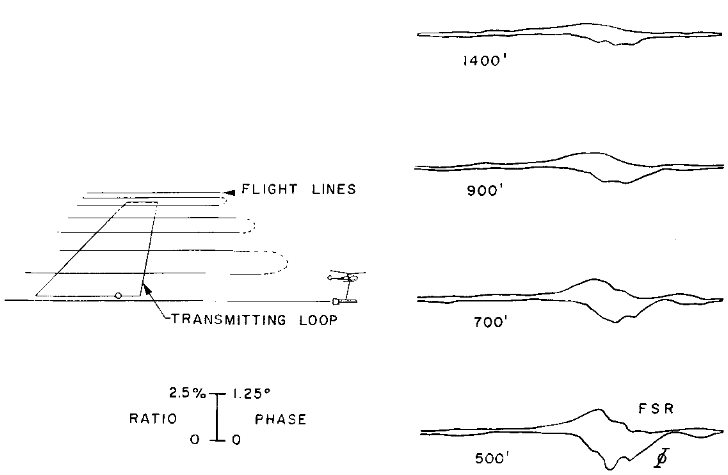

Figure 4.4. *Variation of Turair EM response as a function of altitude (courtesy of Scintrex Ltd.).*

depth of exploration capability of large-loop uniform primary-field ground systems such as the Turam system, while maintaining the efficient coverage of conventional AEM systems. The mode of operation of this equipment as shown in Figure 4.4 is entirely analogous to the conventional ground Turam system with the all important exception that the receiver coils, which can be set to measure the gradient of either the horizontal or the vertical EM field, are traversed across the survey area by helicopter on a short (3-10 m) rigid boom. The system operates in the audio frequency range.

The introduction of the first airborne VLF-EM system by Barringer in 1967 (Barringer, 1970) was closely followed by the development of a number of other airborne VLF-EM systems during the past decade. All the recent systems (Hood, 1974) resemble the AFMAG method (Ward, 1970) in that use is made of a remote VLF transmitter and conductors are detected by the presence of an anomalous vertical component of the secondary field. The Geonics and Scintrex VLF-EM systems measure directly the inphase and quadrature components of this quantity, with respect to the total horizontal EM field. The McPhar VLF-EM system, however, measures the tilt angle of the total field and the amplitude of the horizontal EM component.

Finally, it is appropriate to mention the trend in the use of integrated airborne geophysical survey systems. Although magnetic field data were always obtained simultaneously with EM data in airborne surveys, it is only recently that multisensor systems have begun to be fully utilized. An example of such an integrated aerogeophysical survey system is shown in Figure 4.5. The aircraft, a TU 206D Cessna, is equipped with a McPhar two-frequency F-400 EM system, a VLF-EM system, a magnetometer, and a gamma-ray spectrometer. For efficient processing, the large amounts of data generated by such an installation must be digitally recorded. Figure 4.6 shows data obtained with the Scintrex Tridem installation to illustrate this point. As our concept of base metal exploration evolves from one of anomaly hunting to that of geological mapping, installations such as these will become more and more common.

AEM INTERPRETATION

The electromagnetic scale model (Grant and West, 1965) still remains the most practical source of interpretation data for all AEM systems. As a result of a major research program at the geophysical laboratory of the University of Toronto (Ghosh and West, 1971), sufficient EM data were collected to establish the system response to a thin sheet model conductor for most Canadian airborne EM systems under a variety of flight conditions. While the degree to which the thin sheet model simulates a typical Canadian Shield massive sulphide deposit varies from case to case (Ghosh, 1972), it appears that this type of model is satisfactory for interpreting a fair percentage of the airborne EM anomalies encountered in practice. As shown by Ward (1970), individual scale model EM results may be summarized in the form of master charts which are used to translate the anomaly parameters (e.g. amplitude and phase) into conductor parameters (i.e. thickness-conductivity product and depth of burial).

Model studies are also extremely valuable as they permit the determination of the effects of special conditions such as the superposition of conductive overburden over the target conductor. This particular effect is illustrated in Figure 4.7 which shows the change in response of a vertical sheet conductor to a standard helicopter EM system as a function of overburden conductance. In this case, providing the overburden is not overly thick, its effect is mainly observed as a phase rotation so that the detected conductor appears to be of a better quality and at a somewhat greater depth than it actually is. At the cost of considerable additional effort, scale model EM experiments can also provide information on the effects of conductive host rock. Finally, with the same tool one can also investigate the effects of deviations of conductor geometry from the ideal "infinite" thin sheet model in current use.

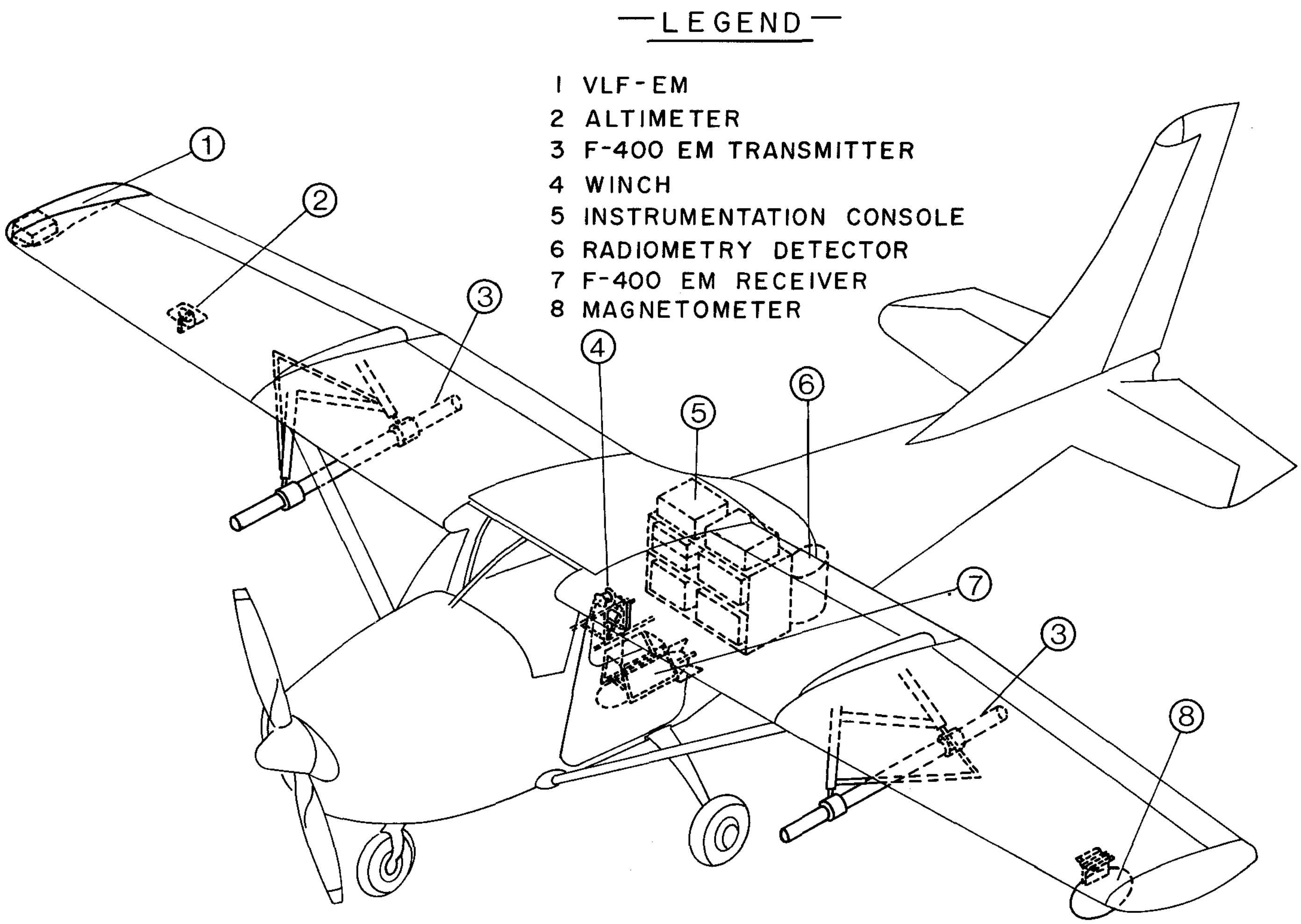

Figure 4.5. *Integrated airborne geophysical survey system (courtesy of McPhar Geophysics).*

In recent years, however, improved multifrequency AEM data and/or data obtained with two different AEM systems over a given conductor have revealed that the classical thin sheet model anomalies can differ appreciably from those actually observed in the field. Consider two particular cases which illustrate this fact. The first concerns the Sturgeon Lake orebody in Ontario and was first reported by Ghosh (1972). As shown in Figure 4.8, the anomaly recorded by a small scale helicopter EM system indicates a high quality conductor while the anomaly obtained with a large scale two-frequency quadrature AEM system indicates a medium quality conductor. The other case relates to the anomaly recorded by a fixed-wing, three-frequency Tridem AEM system over the New Insco deposit in the Noranda area of Quebec. When the AEM data (Fig. 4.9) is plotted on the appropriate interpretation chart (Fig. 4.10), it becomes evident that the apparent quality and depth of the conductor is roughly inversely proportional to the frequency of measurement as both quantities increase with decreasing frequency. Palacky (1978) has reported similar effects over a number of Canadian ore deposits only to confirm the occasional inappropriateness of the thin sheet model.

Although scale model EM experiments provide the basis for a qualitative understanding of the differences between the observed AEM field data and the laboratory infinite thin sheet model, it is unlikely that sufficient scale model data will ever be generated for the proper analysis of observable field anomalies. It is more probable that development of airborne EM data interpretation in future years will evolve through computer modelling. Computer programs for modelling two-dimensional VLF EM anomalies are already available and in reasonably common use (Vozoff, 1971; Telford et al., 1977). In addition, complete theoretical model VLF EM data sets have been generated and are available to the user (Vozoff and Madden, 1971). Computer anomaly modelling for a dipole source such as is used in AEM exploration, however, is still far from perfected. While recent efforts in this direction (e.g. Meyer, 1976) show much promise, the available programs lack accuracy and, above all, are very costly to execute (Anonymous, 1978).

AEM SYSTEM EVALUATION

An evaluation of AEM systems has been carried out by N.R. Paterson (Paterson, 1971) who found that the overall quality of performance for a given AEM system as an anomaly detector could be determined as a function of six major factors, namely: penetration, sensitivity, discrimination, resolution, aperture, and lateral coverage. Space does not allow a full discussion of all of these factors, but at least two factors, penetration and sensitivity, should be considered. Both are defined with reference to the signal-to-noise ratio variation with depth of burial in free space of a high quality conductor. Penetration is the depth at which this ratio is

Contents

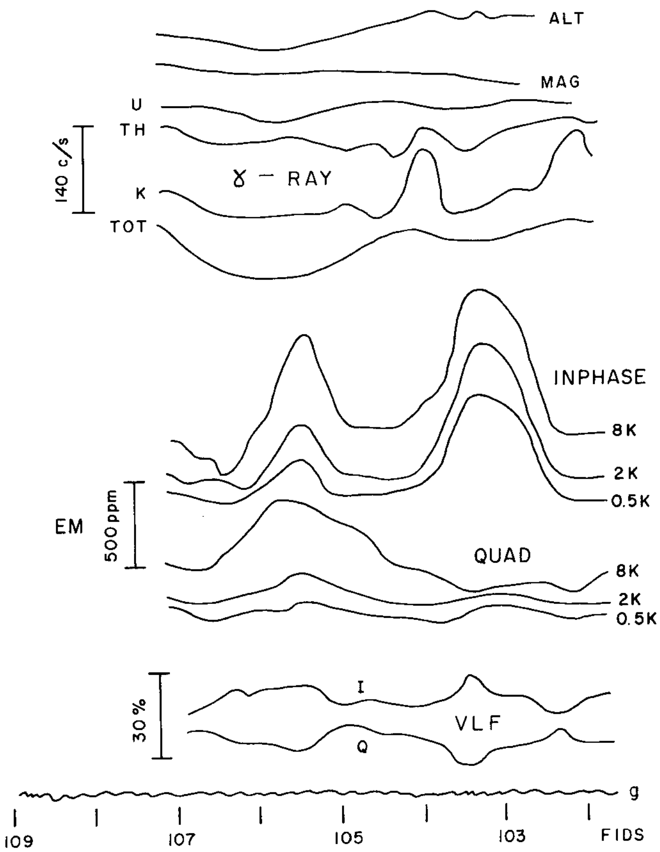

Figure 4.6. Typical data output for an integrated airborne geophysical mapping system (courtesy of Scintrex Ltd.).

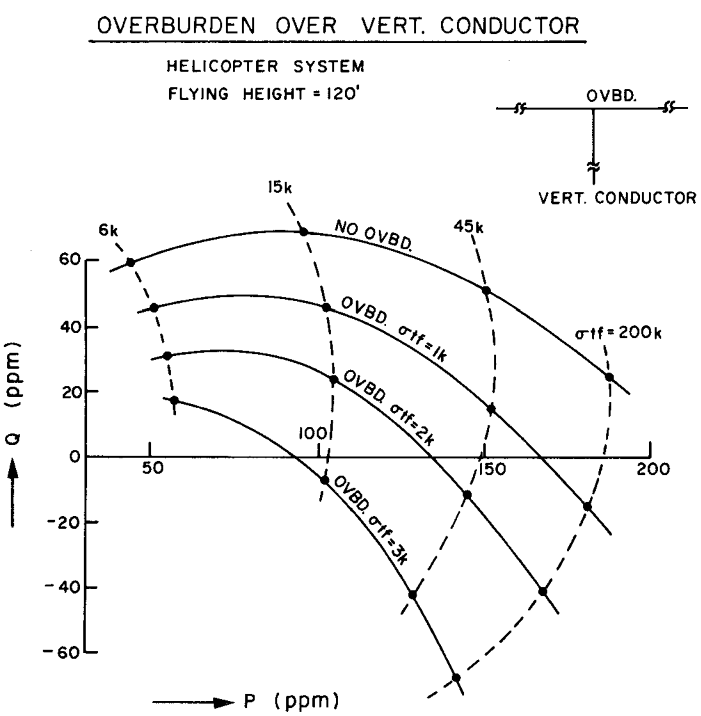

Figure 4.7. Change in response of a vertical sheet conductor to a standard helicopter coaxial EM system as a function of overburden conductance; P is inphase response and Q is quadrature response (after Ghosh, 1972).

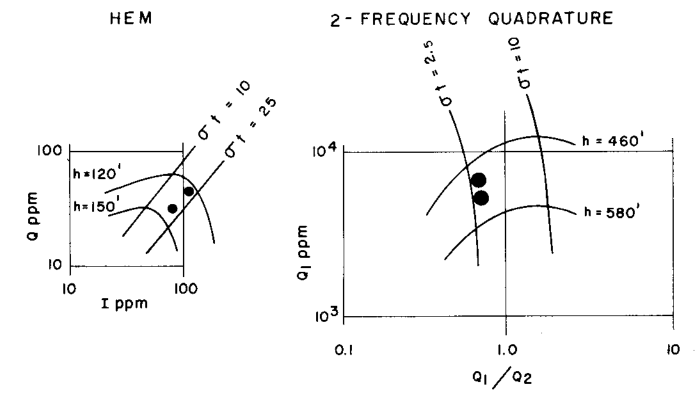

Figure 4.8. Variation of "apparent" conductor quality with AEM system scale; Sturgeon Lake orebody, Ontario (after Ghosh, 1972).

four, while sensitivity is defined as the actual value of this ratio for a conductor at surface. These quantities are graphically illustrated in Figure 4.11 which was compiled from scale model EM data. It should be noted that the effective penetration of an AEM system is not an absolute quantity and should be checked during the progress of a survey to establish its effectiveness. This is so because the noise of the AEM system can vary with survey conditions, especially if geological noise is taken into consideration. From a practical point of view, one can get a better appreciation between these two system attributes by comparing actual field data flown with different AEM systems over the same conductor. For instance, Figure 4.12 contrasts data obtained with two different McPhar AEM systems over the Cavendish test range in southern Ontario. The data clearly indicate the superior sensitivity of the KEM apparatus over the F-400 AEM system which is known to have better penetration.

APPLICATIONS

Today, as in the past, the principal application of AEM methods is to discover discrete conductive mineralized zones in the underlying bedrock. The geographical arena for the proper deployment of AEM systems has, however, been considerably enlarged as a result of much improved equipment. Thus AEM surveys in areas of deep overburden or in areas of moderately deep but quite conductive overburden, which were previously considered unsuitable for AEM, are now being successfully carried out. In view of this, the industry's remarkably consistent discovery rate of about two orebodies per year is not unduly surprising.

In addition to the expanding role of AEM in the direct discovery of conductive deposits, the last decade witnessed the firm establishment of the practice of airborne electromagnetic mapping. This practice can be divided into two distinct processes. The first involves the delineation of geological features by detecting the conductive material which they contain. An example of this type of application of the AFMAG system was given by Sutherland (1970). Similar information can be obtained with VLF-EM systems such as the Barringer Radiophase, for which typical data from the Noranda area of Quebec is shown in Figure 4.13. Finally, good use can also be made of active AEM systems for this purpose. As an illustration of such an application, Figure 4.14 indicates the association of Input EM anomalies with a fault system in the Lake Wanipigow area of southeastern Manitoba because of the presence of conductive serpentinite (Dyck et al., 1975).

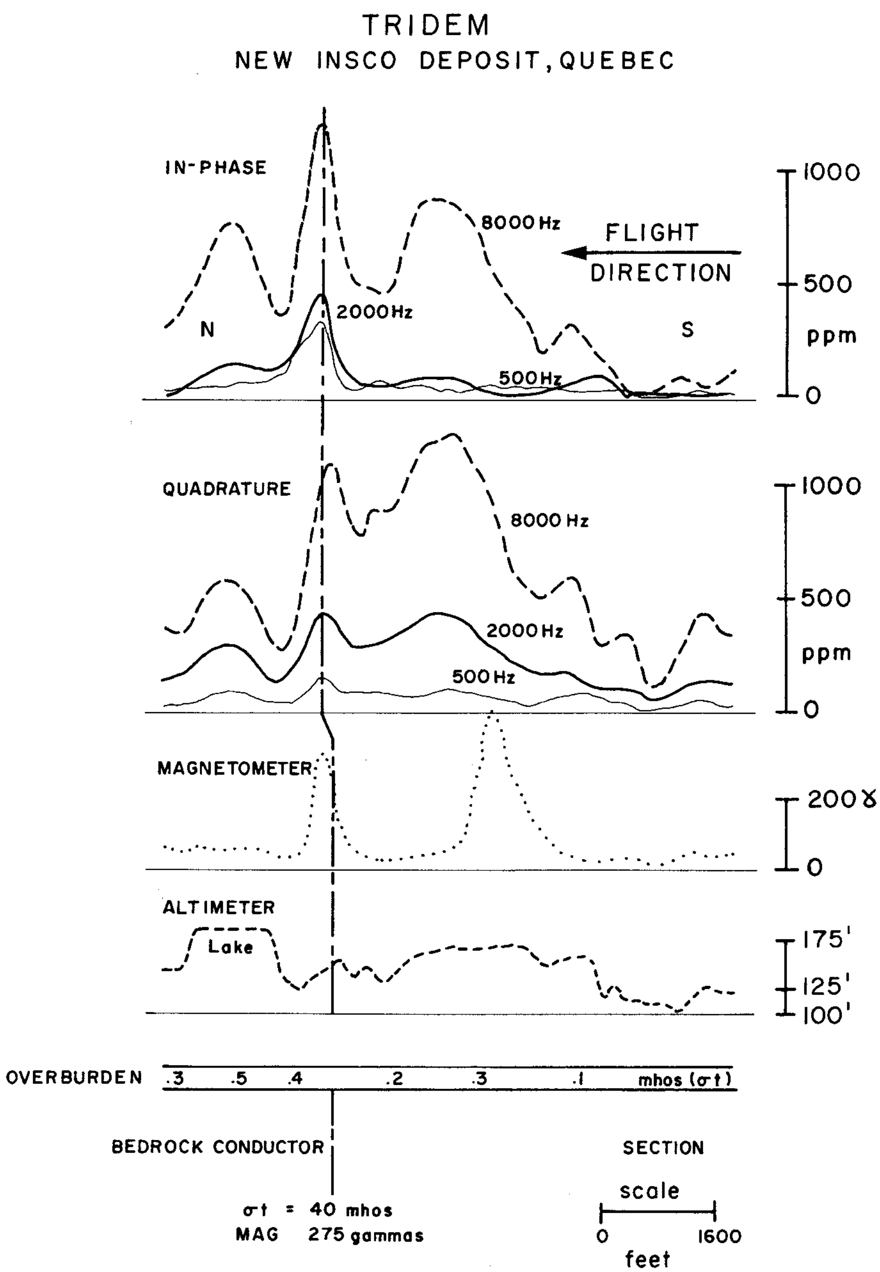

Figure 4.9. *Three-frequency Tridem EM data over New Insco Deposit, Quebec (courtesy of Scintrex Ltd.).*

The second AEM mapping application relates to the establishment of overburden parameters from the continuously recorded EM data. As pointed out by Seigel and Pitcher (1978) and Fraser (1978b) this procedure can be very useful for

i) Definition of bedrock conductors in mineral exploration surveys;

ii) Location of nonmetallic mineral deposits (e.g. lignite and kimberlite);

iii) Mapping and differentiation of surficial materials for civil engineering purposes.

In the first case, quantitative estimates of overburden parameters facilitate the interpreter's task of choosing between surficial conductivity anomalies and those likely to be caused by bedrock conductors. In the last case, the derived overburden parameters can be used in the selection of road sites and pipeline routes.

The basic techniques utilized in the automatic interpretation of AEM data to calculate overburden parameters involve the digital recording of the field data, the definition of suitable field data parameters and the calculation of ground parameters for a particular assumed model. The last step is done most efficiently through the use of table look-up routines on discrete data sets which are precalculated and stored in the computer. This was the approach taken by Dyck et al. (1974), Becker and Roy (unpubl. rep.) and most recently by Fraser (1978b) and Seigel and Pitcher (1978).

The EM interpretation procedures summarized above can be best illustrated with reference to some actual field data. The examples will be taken from surveys sponsored by the Geological Survey of Canada which were made with the Input (Dyck et al., 1974) and the Tridem (Seigel and Pitcher, 1978) AEM systems. Both surveys were carried out in the Hawkesbury area near Ottawa, Ontario where geological knowledge allowed the assumption of a single layer of conductive overburden (mainly clay) over a resistive half-space composed of limestone.

Typical 11-channel, vertical-axis receiver, Input EM data obtained over one line in the Hawkesbury area is shown in Figure 4.15. At each point along the survey line the observed data are summarized by defining the average amplitude and decay rate of the observed secondary field transient. These two parameters are then entered into an interpretation chart of the type shown in Figure 4.16 that is stored in a computer memory. The output is a reliable estimate of the conductivity-thickness product of the overburden and, in cases where the clay is exposed at surface, reliable estimates of the upper layer resistivity. Typical output for the data of Figure 4.15 is shown in Figure 4.17, where the airborne EM data are compared with DC resistivity data obtained independently. The DC resistivity spreads were spaced at about 2 km intervals. Thus, the airborne EM data, which are continuous, show much greater detail. As the overburden mapped in this area consists mainly of material whose resistivity was found to be about 3 ohm metres, the thickness of overburden here can, in places, extend to depths of the order of 75 m.

A similar procedure can be used to interpret overburden properties from data obtained with the Tridem system (Becker and Roy, 1977). Once again, Figure 4.18 shows a typical profile obtained along line 208 in the Hawkesbury area. Here the original digitally-recorded AEM data was replotted to show the variation of secondary field amplitude and phase at each of the three operating frequencies which are 0.5, 2 and 8 kHz. Figure 4.19 shows the type of chart used for automatic interpretation of Tridem data. In this

Contents

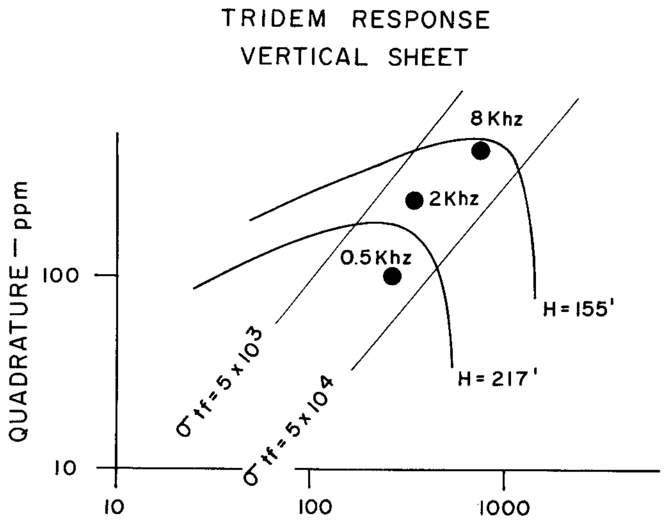

Figure 4.10. *Interpretation of three-frequency Tridem data.*

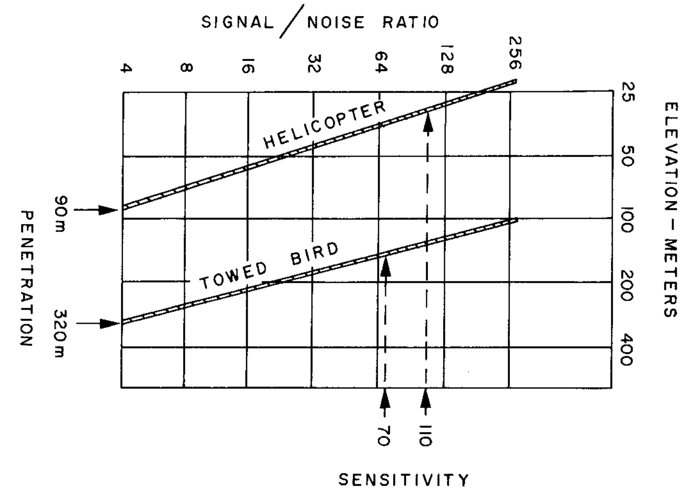

Figure 4.11. *Signal-to-noise ratio as a function of elevation for helicopter-borne and fixed-wing towed-bird AEM systems (after Paterson, 1971).*

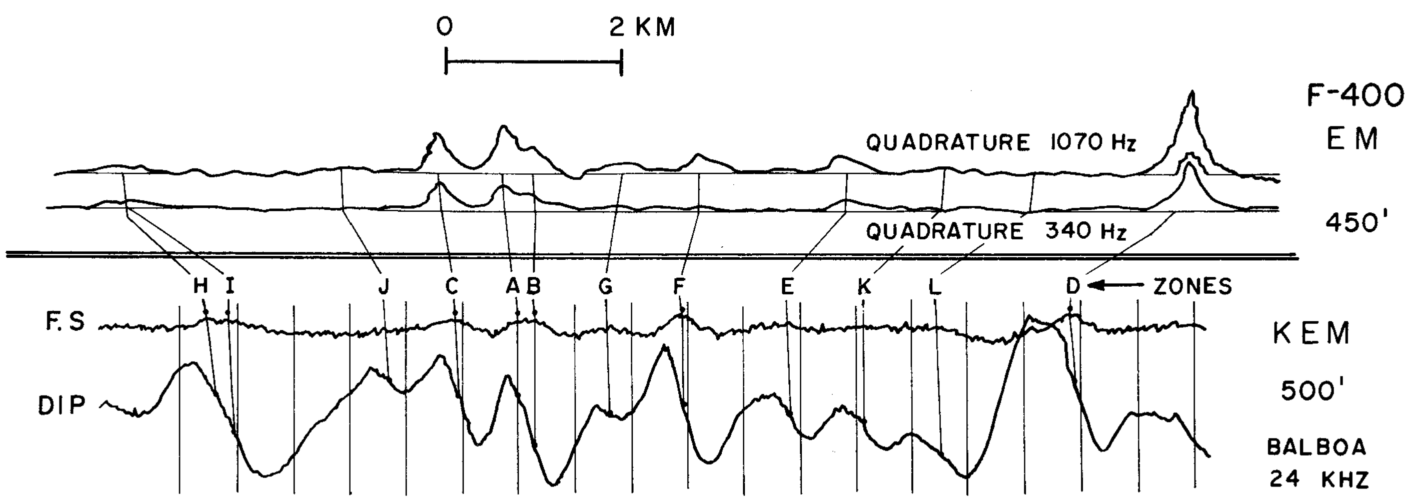

Figure 4.12. *Comparative data for VLF-EM and F-400 AEM systems, Line D, Cavendish Test Range, Ontario (courtesy of McPhar Geophysics).*

case, the thickness of the conductive layer is determined by the difference in phase angle of the secondary field between the extreme frequencies. The quality of the conductor is defined by the phase angle at the central frequency and its depth of burial by the amplitude data. The results of such an interpretation are shown in Figure 4.20, which is an automatic plot of the overburden conductance along Line 208 in the Hawkesbury survey where it is less than about 10 mhos, and a plot of the ground conductivity as well as the thickness of the resistive drift cover (if any) where the overburden appears as a homogeneous half-space. By compiling a series of such profiles, one can construct a terrane map for the Hawkesbury survey area as shown in Figure 4.21. Here the shaded area, which is bounded by the conductivity contour of 0.03 mhos/m, corresponds to resistive sands, tills, and limestone outcrop. The hatched area bounded by the 10 mho conductance contour corresponds to a thick (30 m) layer of conductive clay. The unshaded zone represents the area of transition between these two conductivity values. It is interesting to note that similar results for the Tridem interpretation were obtained by Seigel and Pitcher (1978) using a technique which differed in many details from the one described above.

FUTURE DEVELOPMENTS IN AEM METHODS

Future research in AEM technology will aim at developing systems that will more readily discover mineralized zones under the thick conductive cover found in many tropical areas. As the quest for increased efficiency in difficult survey conditions is pursued, AEM instrumentation will become more sophisticated and complex. One example of a step in this direction is the unique single-coil EM system invented by H.F. Morrison and W. Dolan which is now under

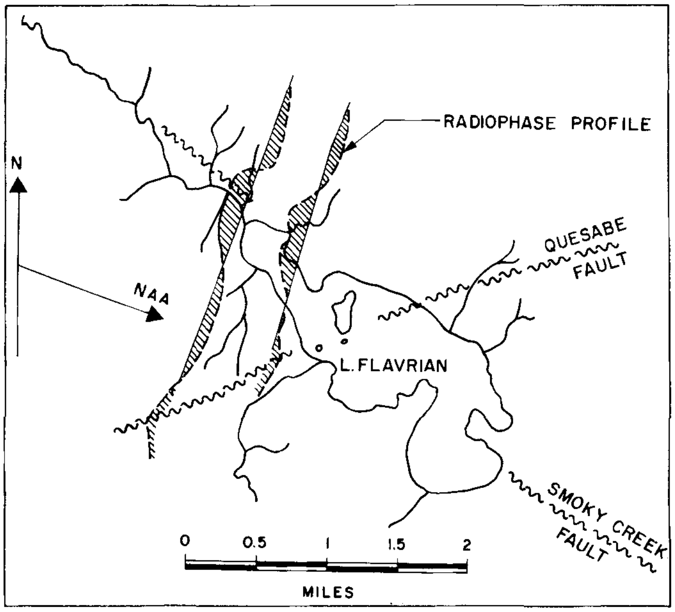

Figure 4.13. *Example of Radiophase AEM data; Noranda area, Quebec (courtesy of Quebec Department of Natural Resources).*

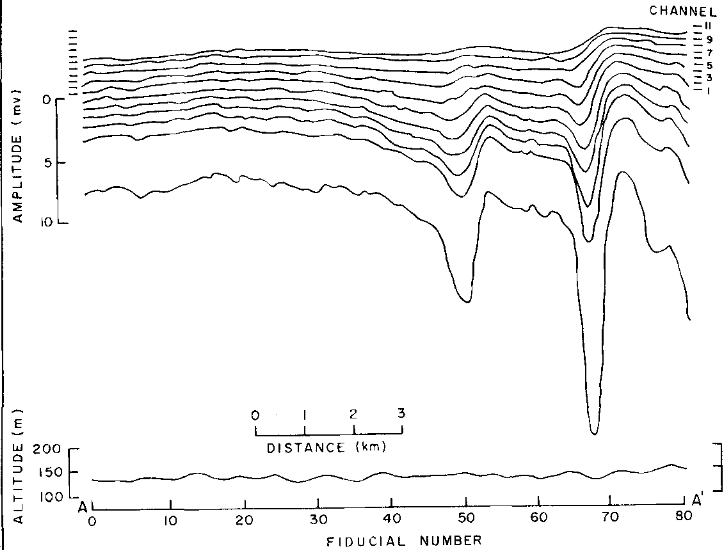

Figure 4.15. *Typical 11-channel, vertical-axis receiver Input EM response over a conductive overburden layer; Hawkesbury area, eastern southeastern Ontario (after Dyck et al., 1974).*

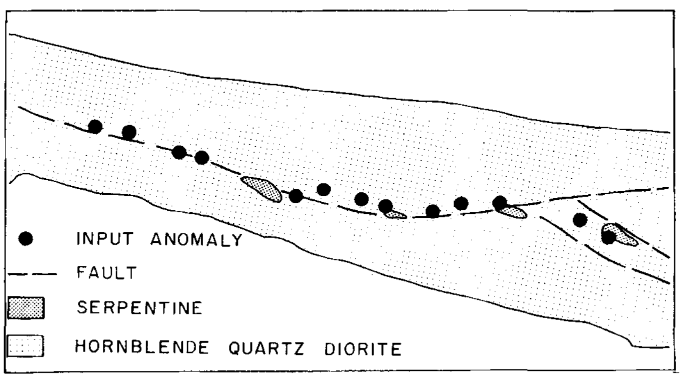

Figure 4.14. *Structural mapping with the Input EM system; Lake Wanipigow area, southeastern Manitoba (after Dyck et al., 1975).*

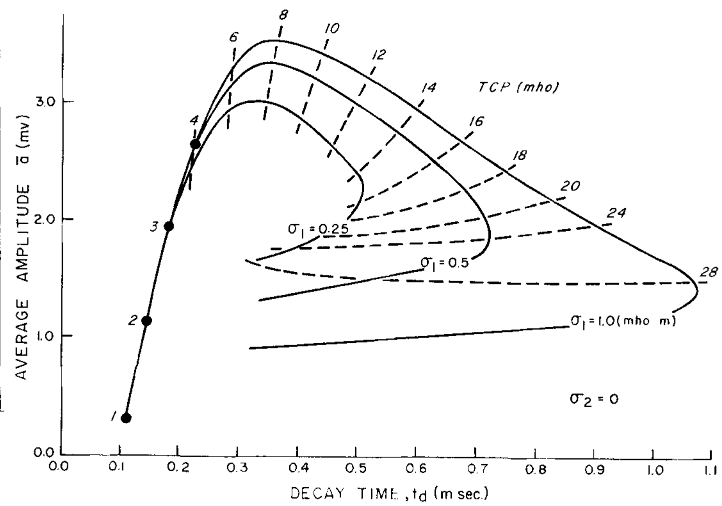

Figure 4.16. *Overburden parameter interpretation chart (after Dyck et al., 1974).*

construction at the Berkeley campus of the University of California (Morrison et al., 1976). This system (Fig. 4.22) detects anomalies by measuring minute changes in resistance of the single transmitter/receiver immersed in liquid helium in an especially constructed cryostat so that the coil winding is superconducting. The principal advantage of this type of apparatus is its ability to operate at extremely low (40 Hz) frequencies and thus to detect deep conductive zones covered by a highly conductive overburden. Another ongoing endeavour is the development of the Cotran AEM system by Barringer Research Ltd. (Barringer, 1976). Although the present concept for Cotran does not involve any departure from the conventional fixed-wing transmitter-receiver embodiment of an AEM system, the design differs radically from standard practice as the detector electronics are replaced by a microcomputer which continuously correlates the received time-domain EM signal with a prestored set of expected secondary field transients. It is probable that such sophisticated signal detection will result in improved system performance.

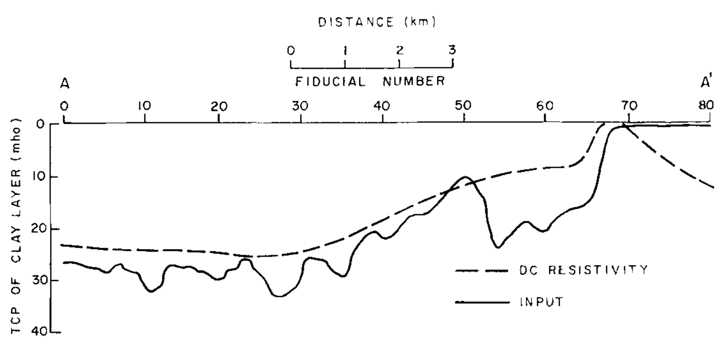

Figure 4.17. *Comparison of interpreted thickness — conductivity products for surficial layer obtained by Input EM and DC resistivity surveys; Hawkesbury area, southeastern Ontario (after Dyck et al., 1974).*

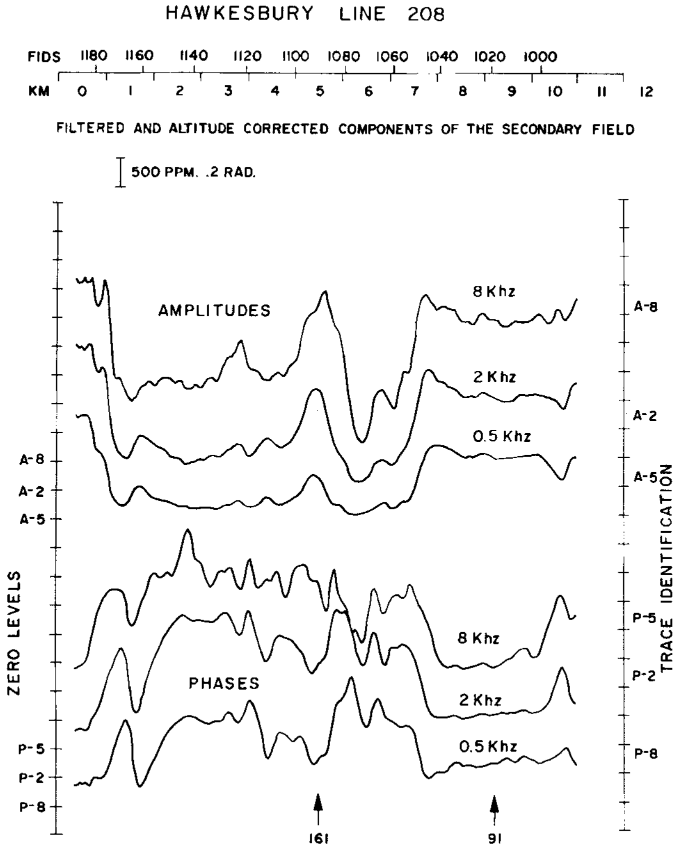

Figure 4.18. Typical Tridem response over a conductive overburden layer, Line 208, Hawkesbury area, southeastern Ontario.

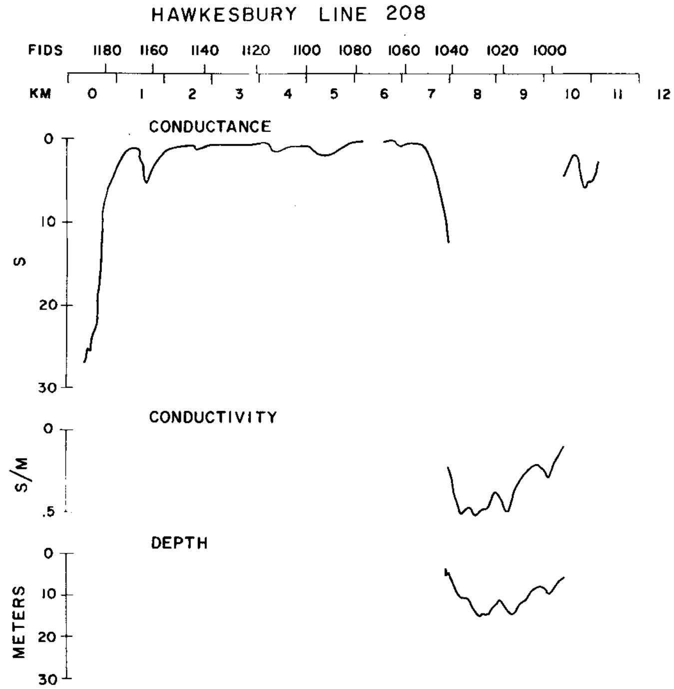

Figure 4.20. Computer-derived interpretation of overburden parameters; from Tridem data; Line 208, Hawkesbury area, southeastern Ontario (after Becker and Roy, 1977).

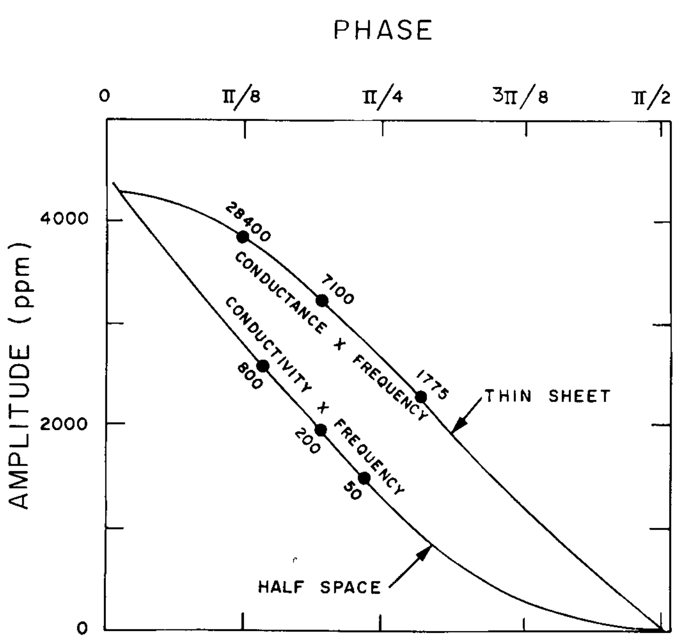

Figure 4.19. Interpretation chart for the calculation of overburden parameters from Tridem AEM data (after Becker and Roy, 1977).

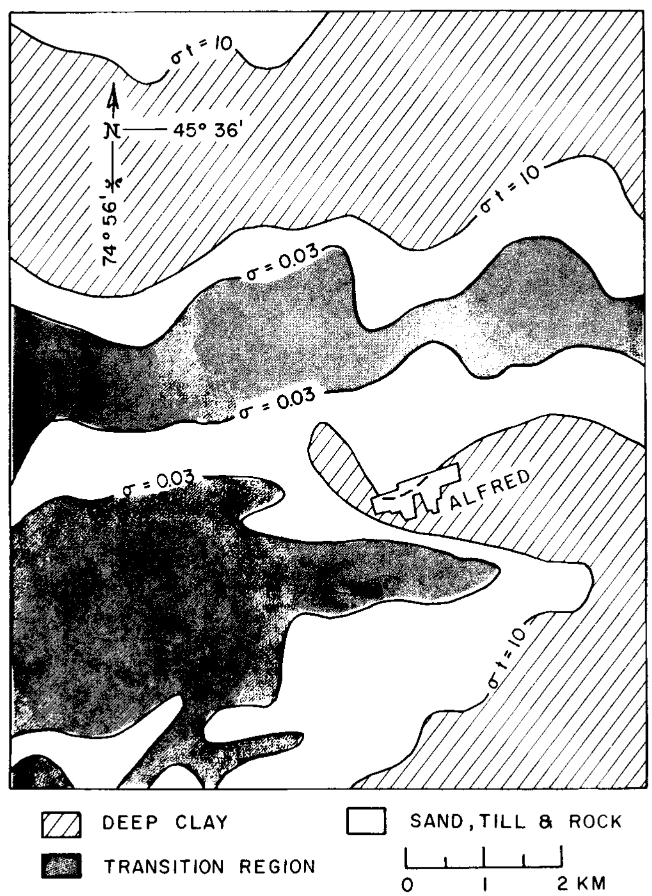

Figure 4.21. Terrane map of the Hawkesbury survey area, southeastern Ontario (after Becker and Roy, 1977).

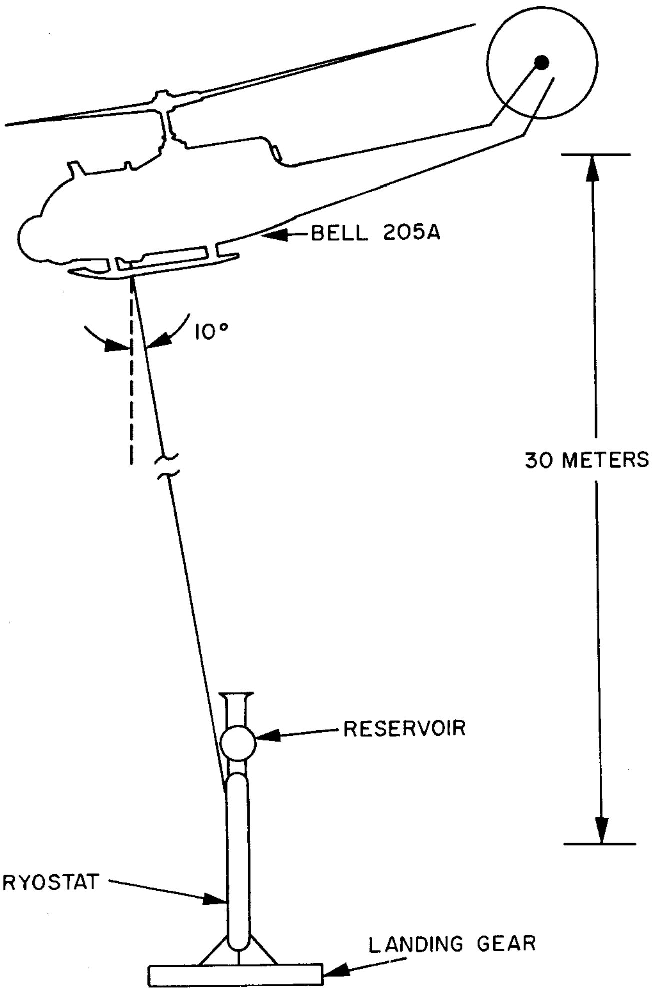

Figure 4.22. *Synoptic representation of the single-coil cryogenic EM system.*

Finally, it now appears, as a result of work in a number of laboratories, that electromagnetic systems can interact with nonconductive but magnetic minerals (Olhoeft and Strangway, 1974). Although the influence of magnetic susceptibility on the inphase component of the secondary field has been clearly demonstrated (Fraser, 1972b), it has only recently become feasible to measure the absorption of electromagnetic energy by magnetic minerals by detecting the subsequent influence of this process on the quadrature component of the secondary EM field. It is expected that as airborne EM measurements are made at increasingly lower frequencies, the magnetic interaction effects will allow some degree of differentiation between different minerals associated with the observed anomalies.

CONCLUSION

Because of time and space limitations only the highlights made in the technology and practice of airborne electromagnetic surveying during the past decade have been mentioned in this review. As the technical quality and scope of the AEM instrumentation improved, new methods of interpretation were developed so as to take full advantage of the increased amounts of data generated. It is expected that this trend to improve AEM interpretation techniques will continue and intensify in the future. Thus, it is conceivable that the final result of future airborne electromagnetic surveys will no longer be an "anomaly map", but rather a detailed geological section of the subsurface formations.

ACKNOWLEDGMENT

I am much indebted to the many individuals, companies, and organizations who have supplied me with the data that have made this review possible. Part of the work reported was done under National Research Council Grant A7472.

REFERENCES

Anonymous
1977: HBED's unique EM-30 system; Can. Min. J., v. 98 (8), p. 41.

1978: Workshop on modelling of electrical and electromagnetic methods, May 1978, Earth Science Division, Lawrence Berkeley Laboratory, University of California, 203 p.

Barringer, A.R.
1970: Regional reconnaissance techniques applied to exploration; in Mining and groundwater geophysics, L.W. Morley, ed., Geol. Surv. Can., Econ. Geol. Rept. no. 26, p. 202-210.

1976: Geophysical prospecting method utilizing correlation of received waveforms with stored reference waveforms, U.S. Patent 3,950,695.

Becker, A. and Roy, J.
1979: Descriptive interpretation of Tridem data relating to the Hawkesbury area, Ontario by Scintrex Limited; Geol. Surv. Can., Open File 605, Pt. 2.

Bosschart, R.A. and Seigel, H.O.
1974: The Tridem three-frequency airborne electromagnetic system; Can. Min. J., v. 95, April, p. 68-69.

Dyck, A.V., Becker, A., and Collett, L.S.
1974: Surficial conductivity mapping with the airborne Input system; Can. Min. Metall. Bull., v. 67 (744), p. 104-109.

1975: Input AEM results from Project Pioneer, Manitoba; Can. J. Earth Sci., v. 12 (6), p. 971-981.

Fraser, D.C.
1972a: New multicoil aerial electromagnetic prospecting system; Geophysics, v. 37 (3), p. 518-537.

1972b: Magnetite ore tonnage estimates from an aerial electromagnetic survey; Geoexploration, v. 11, p. 97-105.

1978a: Geophysics of the Montcalm Township copper-nickel discovery; Can. Min. Metall. Bull., v. 71 (789), p. 99-104.

1978b: Resistivity mapping with an airborne multicoil electromagnetic system; Geophysics, v. 43, no. 1, p. 144-172.

Ghosh, M.K.
1972: Interpretation of airborne EM measurements based on thin sheet models; unpubl. Ph.D. thesis, University of Toronto, 195 p.

Ghosh, M.K. and West, G.F.
1971: AEM analogue model studies; Norman Paterson & Assoc. Ltd., Toronto.

Grant, F.S. and West, G.W.
1965: Interpretation theory in Applied Geophysics; McGraw-Hill, New York.

Hood, P.
1974: Mineral exploration trends and developments in 1973; Can. Min. J., v. 95 (2), p. 163-214.

1978: Mineral exploration trends and developments in 1977; Can. Min. J., v. 99 (1), p. 163-214.

Lazenby, P.G.
1973: New developments in the Input airborne EM system; Can. Min. Metall. Bull., v. 66, p. 96-104.

Meyer, W.H.
1976: Computer modelling of electromagnetic prospecting methods; unpubl. Ph.D. thesis, University of California, Berkeley, 207 p.

Morrison, H.F., Dolan, W., and Dey, A.
1976: Earth conductivity determinations employing a single superconducting coil; Geophysics, v. 41 (6A), p. 1184-1206.

Olhoeft, G. and Strangway, D.W.
1974: Magnetic relaxation and the electromagnetic response parameter; Geophysics, v. 39 (3), p. 302-311.

Palacky, G.J.
1978: Selection of a suitable model for quantitative interpretation of towed-bird AEM measurements; Geophysics, v. 43 (3), p. 576-587.

Paterson, N.R.
1971: Airborne electromagnetic methods as applied to the search for sulphide deposits; Can. Min. Metall. Bull., v. 64, p. 29-38.

Seiberl, W.A.
1975: The F-400 series quadrature component airborne electromagnetic system; Geoexploration, v. 13, p. 99-115.

Seigal, H.O. and Pitcher, D.H.
1978: Mapping earth conductivities using a multi-frequency airborne electromagnetic system; Geophysics, v. 43, no. 2, p. 563-575.

Sutherland, D.B.
1970: AFMAG for electromagnetic mapping; in Mining and Groundwater Geophysics/1967; L.W. Morley, ed., Geol. Surv. Can., Econ. Geol., Rept. no. 26, p. 228-237.

Telford, W.M., King, W.F., and Becker, A.
1977: VLF mapping of geological structure; Geol. Surv. Can., Paper 76-25, 13 p.

Vozoff, K.
1971: The effect of overburden on vertical component anomalies in AFMAG and VLF exploration; Geophysics, v. 36 (1), p. 53-57.

Vozoff, K. and Madden, T.R.
1971: VLF Model suite; Private edition, Lexington, Mass., 2000 p.

Ward, S.H.
1970: Airborne electromagnetic methods; in Mining and Groundwater Geophysics/1967; L.W. Morley, ed., Geol. Surv. Can., Econ. Geol. Rept. no. 26, p. 81-108.