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COVER PHOTOS

Top Row (left to right)

Berner Oberland and Walliser Alps, Switzerland.
Traditional quarters, Ouagadougou, Burkina Faso.
Northern suburbs of Sydney (Manly), New South Wales, Australia.

Middle Row (left to right)

Rakaia River in the foothills of Southern Alps, New Zealand.
Sugar cane fields near Port-au-Prince, Haiti.
The village of Cornes-Forel, east of Lausanne, Switzerland.

Bottom Row (left to right)

North shore of the St. Lawrence River near Malbaie, Québec, Canada.
Wheat fields east of Calgary, Alberta, Canada.
The coast of the Gulf of Suez, Sinai Peninsula, Egypt.

(All photos by George J. Palacky)

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FOREWORD

The papers in this volume were presented at a workshop organized by the Geological Survey of Canada and held on 2-3 October 1985 at Camsell Hall in Ottawa. Despite the fact that it was not advertised, the meeting attracted 150 participants from 14 countries, and included most of the world's experts on airborne resistivity mapping.

The workshop consisted of four sessions: at the first, introductory papers and contributions defining the concept of resistivity mapping were presented. The first airborne electromagnetic systems were developed as tools for prospecting for massive sulphide deposits, and attempts are being made to broaden their application. Advanced systems are now capable of producing maps of apparent resistivity or in some cases even resistivity sections. The second session was dedicated to new systems, already in operation or in the final stages of development, and to novel applications as seen from the contractor's perspective. The third session focused on non-traditional applications, this time from the point of view of users. A panel discussion, providing an excellent view of the current state of the industry, formed the final session.

The workshop took place at a critical time for the airborne geophysics industry. The demand for services is down, mostly because of a slowdown in mineral exploration, and new applications have not yet been widely accepted by potential users. Therefore, a substantial effort, not only by contractors but also by other organizations, is needed to further develop and promote new applications. Until now Canadian companies have enjoyed a virtual monopoly on airborne electromagnetic surveys, and have carried out over 80% of such surveys worldwide. It is hoped that the application of the technicalities described in this volume will enable Canada to stay in the forefront of airborne resistivity mapping.

AVANT-PROPOS

Les textes du présent volume ont été présentés à un atelier organisé par la Commission géologique du Canada qui s'est tenu les 2 et 3 octobre 1985 à la salle Camsell à Ottawa. Même si aucune publicité n'a été faite, la réunion a attiré 150 participants de 14 pays dont la plupart sont des spécialistes mondiaux de levés aériens de résistivité.

L'atelier était divisé en quatre sessions : la première comportait des communications définissant le concept de levés de résistivité. Les premiers systèmes électromagnétiques aéroportés ont été mis au point pour faire la prospection des gisements de sulfure massif et certains essais visent à étendre leur application. Des systèmes élaborés sont actuellement capables de produire des cartes de résistivité apparentes et, dans certains cas, des coupes de résistivité uniforme. La deuxième session a été consacrée aux nouveaux systèmes, ayant déjà atteint le stade de l'exploitation ou les dernières étapes de la mise au point, ainsi qu'aux nouvelles applications telles que perçues par les entrepreneurs. La troisième session a porté sur les applications non classiques, cette fois du point de vue de l'utilisateur. Enfin, la dernière session qui a consisté en une réunion-débat a permis d'obtenir un excellent aperçu de la situation actuelle de l'industrie.

Cet atelier a eu lieu à un moment crucial pour l'industrie de la géophysique aérienne. Les demandes de services sont faibles, situation qui est en grande partie attribuable au ralentissement de l'exploration minérale et au fait que de nouvelles applications n'ont pas encore été largement acceptées par les utilisateurs potentiels. Par conséquent, il faudra que non seulement les entrepreneurs mais également d'autres organismes prennent des mesures importantes pour élaborer et promouvoir de nouvelles applications. Jusqu'à maintenant, les sociétés canadiennes possédaient le monopole des levés électromagnétiques aériens, ayant réalisé plus de 80 % de ces levés à travers le monde. Il reste à espérer que l'application des détails techniques d'écrits dans le présent volume permettra au Canada de demeurer à l'avant-garde des levés aériens de résistivité.

CONTENTS

INTRODUCTORY PAGES

SCIENTIFIC AND TECHNICAL REPORTS

APPENDICES

OPENING REMARKS

A.G. Darnley[1]
Geological Survey of Canada

The purpose of this workshop is to examine the options for systematic resistivity mapping, examine the present state-of-the-art, identify any necessary or desirable improvements, and summarize the reasons why such surveys are scientifically and economically important. This workshop, whilst marking a new beginning, also provides me with the opportunity to pay tribute to Len Collett's work over the past 25 years in establishing the Geological Survey of Canada's involvement and reputation in electrical methods.

It is significant that at a time when there is a general shortage of customers for airborne electromagnetic (AEM) surveys so many people in the industry should think it worthwhile to come to this meeting. Unfortunately there are no plans at present to launch a major government program involving airborne resistivity mapping in the near future. Any move to introduce airborne resistivity surveys could only be at the expense of the other methods currently being provided to satisfy various established needs. Since 1984 there has been a marked increase in the amount of government sponsored airborne survey work in Canada, compensating to some degree for the worldwide decrease in demand by the exploration industry. This work has been financed through a number of short term special programs including federal-provincial Mineral Development Agreements, the Frontier Geoscience and Offshore Bilateral Boundaries programs. In 1985 these have resulted in aeromagnetic gradiometer surveys in six provinces, involving both fixed-wing and helicopter work, and the extension of standard aeromagnetic surveys into far offshore areas. Also a limited amount of airborne gamma-ray spectrometry is being funded.

In the interests of economy and effectiveness I believe that the most likely means of introducing airborne resistivity surveys into the program of national systematic mapping will be as a component of a multiparameter survey system. The value of multiparameter airborne mapping has been well demonstrated in Finland and Sweden for a number of years, and I think we in Canada should learn from and build on their experience, which has been well documented.

Over the past two decades it has become increasingly obvious that it is not sufficient for geophysical and geochemical surveys to be limited to finding anomalies. Whilst anomalies will always attract the attention of anyone concerned with mineral exploration, anomalies form a very small percentage of the available information. The main mass of physical and chemical data should be used to map the geological environment in quantitative terms. There is a great need to use geophysics and geochemistry

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INTRODUCTION

A.G. Darnley[1]
Commission géologique du Canada

Le but de cet atelier est d'examiner les options qui s'offrent en matière de cartographie systématique par résistivité, de faire le point sur la technologie actuelle en ce domaine, de déterminer les améliorations nécessaires ou souhaitables et de résumer les raisons pour lesquelles les levés de ce type sont scientifiquement et économiquement importants. Tout en constituant un nouveau départ, cet atelier me fournit l'occasion de rendre hommage au travail qu'a accompli Len Collett depuis 25 ans pour établir la présence de la Commission géologique du Canada dans le secteur des méthodes électriques et asseoir la réputation de la Commission en cedomaine.

À un moment où l'on constate une pénurie générale d'usagers pour les levés électromagnétiques aériens (ÉMA), il est significatif que tant de représentants de l'industrie aient jugé utile de venir à cette réunion. Malheureusement, on ne prévoit pour l'immédiat aucun programme gouvernemental important comportant des travaux aériens de cartographie par résistivité. L'introduction de levés de ce genre dans un programme donné ne pourrait se faire qu'aux dépens d'autres méthodes actuellement appliquées pour répondre à divers besoins déterminés. Depuis 1984, le nombre de levés aériens patronnés par l'État est en hausse marquée au Canada, ce qui compense jusqu'à un certain point la baisse mondiale de la demande émanant de l'industrie d'exploration. Ces travaux sont financés dans le cadre de programmes spéciaux à court terme, notamment les ententes fédéraux-provinciaux de mise en valeur des minéraux, le programme géoscientifique des régions pionnières et le programme de levés dans les zones frontières au large des côtes. En 1985, ces programmes ont donné lieu à la réalisation de levés magnétiques par gradiomètre aéroporté et héliporté dans six provinces, en même temps qu'on étendait les levés aéromagnétiques traditionnels à des zones en mer. On réalise aussi un nombre limité de travaux de spectométrie aérienne par rayons gamma.

Pour des raisons d'économie et d'efficacité, je crois que l'insertion de travaux de levés aériens par résistivité dans le programme de cartographie systématique nationale se fera probablement dans le cadre de levés multiparamétriques. La valeur de la cartographie aérienne multiparamétrique est bien établie en Finlande et en Suède depuis plusieurs années et je crois que nous devrions, au Canada, tirer profit de l'expérience de ces pays, qui est bien documentée, et la perfectionner.

Depuis deux décennies, on se rend compte de plus en plus que les levés géophysiques et géochimiques ne doivent pas se limiter à la détection des anomalies. Certes, les anomalies attireront toujours l'attention de quiconque s'intéresse à l'exploration des minéraux, mais elles forment un très petit pourcentage des données disponibles. La grande masse des données physiques et chimiques devrait servir à cartographier l'environnement géologique en termes quantitatifs. Un grand besoin existe d'utiliser la géophysique et la géochimie pour obtenir des paramètres

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to provide objective discriminating parameters for mapping overburden and bedrock on a systematic basis. Effective mineral exploration is undertaken in the context of comprehensive geological exploration, and knowledge of geology should not be limited to what can be deduced from chance outcrops. Our target for the future should be to produce geoscientific maps, the reliability of which is not drastically controlled by the degree of visible bedrock exposure. This can only be done by recognizing lithologies and structures from their characteristic physical and chemical properties and by delineating discontinuities in these properties. In parallel with obtaining lithological and structural information about bedrock it is, of course, of great practical importance to have comprehensive information about the overburden which conceals the bedrock. Resistivity mapping can contribute substantially to the solution of these problems as part of a multiparameter system.

Canada is many times larger than Finland and Sweden where systematic multiparameter airborne mapping is in routine use. Even with enlightened and generous funding, multiparameter airborne mapping in Canada will necessarily have to be very selective in terms of areas to be covered, and it will require many decades to complete. It will entail the use of many different sets of instrumentation. Note that the aeromagnetic mapping of Canada has been in progress for almost 40 years, and is still incomplete! In order to allow systematic compilation and comparison of data it is essential that there are established and generally accepted units of measurement, reference standards and calibration procedures. This does not, and must not, preclude the steady improvement of techniques, depth of penetration, spatial resolution and sensitivity. A metre is a metre irrespective of whether it is measured with a tape or a laser beam. The fact that on one occasion a measurement is determined within ±10% whilst on another occasion it is determined to ±0.0001% does not imply that a common unit of measurement cannot be used. The adoption of standardized reporting formats will make it obvious which are the most sensitive and consistent measurement systems, and this is advantageous in the development and selection of new equipment. Once it is acknowledged that what many exploration geophysicists have dismissed as geological background noise is in fact useful information, then the necessity to adopt rigorous and consistent quantitative procedures becomes apparent. Airborne resistivity mapping entails advancing from the past where different AEM instrumentation systems have presented data in different formats, each format based on some arbitrary, ill-defined and difficult to reproduce datum.

Approximately 70% of Canada is presently covered by systematic aeromagnetic surveys, 25% by systematic radiometric, and 15% by systematic geochemical surveys. The establishment of standard procedures with respect to each of these methods has played a major part in establishing their validity and maximizing their usefulness. This systematization has not only benefitted Canada, it has also

objectifs pour cartographier le mort-terrain et la roche en place de façon systématique. Pour être efficace, l'exploration des minéraux doit se faire dans le cadre d'une exploration géologique étendue et la connaissance géologique ne devrait pas se limiter à ce qu'on peut déduire des affleurements observés çà et là. Notre objectif devrait être de produire des cartes géoscientifiques dont la fiabilité ne tienne pas essentiellement au degré d'exposition de la roche en place visible. On ne pourra y arriver que par un inventaire des données pétrographiques et des structures, à partir de leurs propriétés physiques et chimiques caractéristiques et en déterminant les éléments de discontinuité de ces propriétés. Parallèlement à la connaissance de la lithologie et de structure sur la roche en place, il est naturellement d'une grande valeur pratique de disposer de données complètes sur le mort-terrain qui cache la roche en place. La cartographie par résistivité peut contribuer substantiellement à la solution de ces problèmes dans le cadre d'un système à plusieurs paramètres.

Le Canada a une superficie plusieurs fois plus étendue que celles de la Finlande ou de la Suède, pays qui pratiquent systématiquement la cartographie aérienne à plusieurs paramètres. Même avec des fonds généreux et judicieusement employés, la cartographie aéroportée à plusieurs paramètres devra nécessairement s'opérer d'une manière très sélective au Canada et il faudra bien des décennies pour la mener à bonne fin. Elle exigera l'emploi d'un grand nombre d'instruments divers. On ne doit pas oublier que la cartographie aéromagnétique du Canada se poursuit depuis près de 40 ans et qu'elle n'est pas encore terminée! La compilation et la comparaison systématique des données exige absolument la définition d'unités de mesures, de normes de référence et de procédés de calibration communément admis. Cela n'empêche pas et ne doit pas empêcher d'améliorer constamment les techniques, la profondeur de pénétration, la résolution spatiale et la sensibilité. Un mètre demeure un mètre, qu'on le mesure avec un ruban ou avec un rayon laser. Le fait qu'une mesure soit, dans un cas, déterminée avec une précision de ±1 p.cent et, dans un autre, avec une précision de ±0.0001 p.cent, n'empêche pas l'emploi d'une unité de mesure commune. L'uniformisation de la présentation des rapports permettra de voir clairement quels sont les systèmes de mesurage les plus sensibles et les plus cohérents, ce qui facilitera la mise au point de nouveaux instruments et la sélection du matériel. Dès lors qu'on admet comme données utiles ce que bien des géophysiciens d'exploration écartaient comme bruits de fond géologiques, la nécessité d'adopter des procédés quantitatifs rigoureux et uniformes s'impose. La cartographie aérienne par résistivité suppose qu'on doit dépasser l'époque où différents systèmes d'instrumentation ÉMA présentaient des données sous des formes diverses, chaque forme étant basée sur un élément de donnée arbitraire, mal défini et difficile à reproduire.

Environ 70 p. 100 du Canada a fait jusqu'ici l'objet de levés aéromagnétiques, 25 p. 100, de levés radiométriques et 15 p. 100, de levés géochimiques systématiques. L'établissement de procédés normalisés pour chacune de ces méthodes a grandement contribué à établir leur validité et à maximiser leur utilité. Cette systématisation n'a profité qu'au Canada; elle a également encouragé l'adoption de la cartographie quantitative systématique dans d'autres pays. En revanche, la cartographie ÉMA ne couvre pas plus de 2 p. 100 du territoire canadien actuellement et encouraged the adoption of systematic quantitative mapping in other countries. In contrast, the present AEM coverage does not exceed 1% of the area of Canada, and it has been largely directed towards the detection of massive sulphides, in other words, anomaly seeking. Because of the costs involved it is unlikely that systematic airborne resistivity mapping, either on its own or as part of a multiparameter system, will be applied to more than 10 or 15% of the area of Canada in this century. Even this represents a large volume of work, sufficient to provide the airborne survey industry with business for many seasons into the future. This workshop is intended to bring us a step closer towards placing resistivity measurements on the map of Canada in a systematic and cost-effective manner.

elle porte en grande partie sur la détection des sulfures massifs, autrement dit sur la détection d'anomalies. Vu les coûts en cause, il est peu probable que la cartographie aérienne systématique par résistivité, réalisée d'une façon autonome ou dans le cadre d'un système multiparamétrique, couvrira plus de 10 ou 15 p. 100 de la superficie du Canada d'ici la fin du siècle. Cela représente néammoins un gros volume de travail, suffisant pour tenir occupée l'industrie des levés aériens pendant bien des saisons. Le présent atelier vise à nous rapprocher un peu plus de l'objectif consistant à inscrire les mesures de la résistivité sur la carte du Canada d'une manière systématique et efficace.

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G.J. Palacky

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G.J. Palacky

AIRBORNE ELECTROMAGNETICS AT CROSSROADS

G.J. Palacky[1]
Geological Survey of Canada

The first airborne electromagnetic (AEM) systems were developed in the 1950s in Canada. Their early development is treated by Collett in this volume. AEM surveys proved successful as a fast and cost-effective method of mineral exploration, particularly for volcanogenic massive suphides.

In the 1970s, the technique was increasingly applied outside Canada, where near surface conditions were unlike those encountered in the Canadian Precambrian Shield. Instead of the generally thin and rather resistive glacial cover typical of the Canadian Shield (with the notable exception of the Abitibi clay belt), the weathered layer was often thick and highly conductive. For example, in Australia, where many AEM surveys were flown at that time, the thickness of the weathered layer often exceeds 100 m. AEM surveys were less effective in such environments and alternate exploration techniques were applied.

Studies in several tropical countries, particularly Brazil, have shown that weathered layers forming over certain rock types produce characteristic AEM responses. This discovery resulted in the increased use of AEM techniques for geological mapping. Several types of mineral deposits are formed by weathering (lateritic nickel, manganese, gold, tin, bauxite, phosphates) and AEM techniques can be effectively used in their prospecting.

Other new applications of AEM techniques that are discussed in this volume include: groundwater exploration (identification of freshwater-saltwater interface), coal and lignite prospecting, mapping of hydrothermal alteration zones and lineaments, prospecting for kimberlites, geotechnical studies, agricultural investigations (salinization in irrigated areas), and offshore marine surveying (bathymetric charting). Even though these new applications of AEM techniques appear successful, the acceptance of EM as an exploration tool has so far been limited outside the mining community.

With the reduction of spending on mineral exploration, AEM activities have declined substantially in the Western world since 1981. Historically, Canadian contractors have carried out between 70 and 90% of AEM surveys in free-market and developing countries and because many of these contractors derive a substantial portion of their revenue from AEM surveying, the impact of the recent decline on the geophysical industry has been considerable. Based on data from annual Society of Exploration Geophysists (SEG) geophysical activity reports, Figure 1 shows two periods of high

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OÙ EN SONT LES SYSTÈMES ÉLECTROMAGNÉTIQUES

G.J. Palacky[1]
Commission géologique du Canada

Les premières systèmes électromagnétiques aéroportés (ÉMA) ont été mis au point au cours des années 1950 au Canada. Leurs débuts sont présentés par Collett dans le présent volume. Les levés ÉMA se sont révélés un moyen rapide et rentable d'exploration des minéraux, en particulier dans le cas des sulfures massifs volcanogéniques.

Au cours des années 1970, cette technique a été de plus en plus appliquée à l'étranger, en des endroits où les conditions superficielles étaient différentes de celles du Bouclier précambrien canadien. Au lieu de la couche glaciaire généralement mince et de haute résistivité qu'on trouve communément dans le Bouclier canadien (à l'exception notable de la zone d'argile de l'Abitibi), la zone d'altération était souvent épaisse et hautement conductrice. Ainsi, en Australie, où il se faisant beaucoup de levés ÉMA à cette époque, la zone d'altération dépassait souvent 100 m d'épaisseur. Les levés ÉMA étaient moins efficaces dans ces environnements et on appliqua d'autres techniques d'exploration.

Des études réalisées dans plusieurs pays tropicaux, en particulier au Brésil, ont montré que les zones d'altération formées sur certains types de roches produisaient des réponses ÉMA caractéristiques. Cette constatation a entrainé un usage accru des techniques ÉMA pour la cartographie géologique. Plusieurs types de gisements de minéraux se forment par altération (nickel latéritique, manganèse, or, étain, bauxite, phosphates) et on peut utiliser avec efficacité les techniques ÉMA pour leur prospection.

Le présent volume porte sur d'autres applications des techniques ÉMA, notamment dans les domaines suivants : prospection des nappes d'eau souterraines (détermination de l'interface entre les eaux douces et les eaux salées), prospection du charbon et du lignite, cartographie des zones d'altération hydrothermale et des linéaments, prospection des kimberlites, études géotechniques, enquêtes agricoles (salinité des zones irriguées) et levés au large des côtes maritimes (cartographie bathymétrique). Quoique ces nouvelles applications des techniques ÉMA se révèlent fructueuses, l'acceptation des systèmes ÉM comme instruments de prospection est encore restreinte, en dehors du secteur minier.

Parallèlement à la diminution des dépenses de prospection des minéraux, les activités ÉMA ont fléchi substantiellement dans le monde occidental depuis 1981. Par le passé, les entrepreneurs canadiens réalisaient de 70 à 90 p. 100 des levés ÉMA dans le monde occidental et dans les pays en développement. Comme un grand nombre de ces entrepreneurs tirent une part substantielle de leurs revenus de ce type de levés, la diminution récente des activités dans ce secteur a eu un impact considérable sur l'industrie géophysique. La figure 1, établie d'après les rapports annuels sur les activités géophysiques publiés par la Society of Exploration Geophysicists (SEG), montre deux périodes d'intense activité, au cours desquelles on a réalisé de 500 000 à 600 000 km linéaires de levés ÉMA par année. La première période a duré sept ans, de 1967

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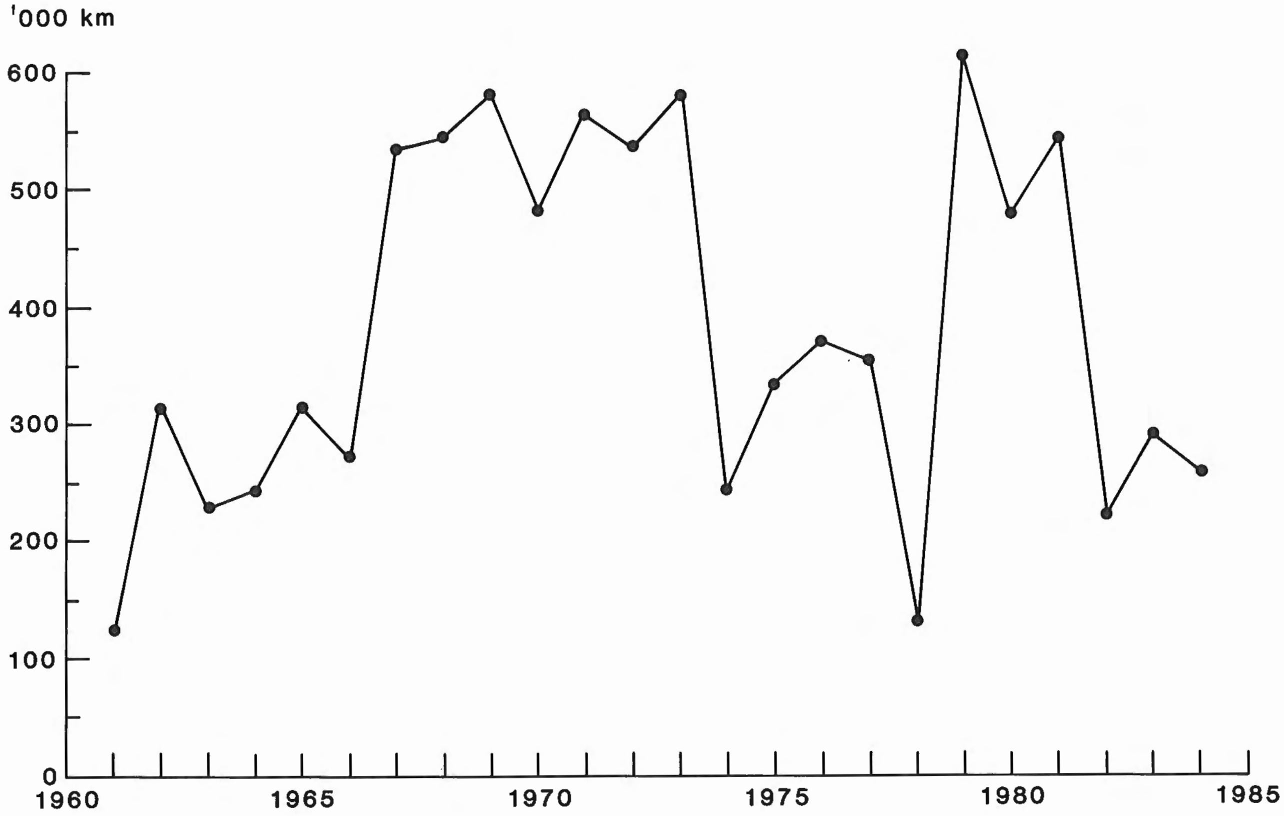

Figure 1. Quo vadis airborne electromagnetics? Surveys flown with AEM systems between 1961 and 1984. Based on data published annually by the Society of Exploration Geophysicists. The figures do not include surveys in socialist countries.

Figure 1. Fluctuations des levés aériens électromagnétiques de 1961 à 1984, d'après des données publiées annuellement par la SEG (Society of Exploration Geophysicists). Les chiffres ne comprennent pas les levés réalisés dans les pays socialistes.

activity when 500 000 to 600 000 line km of AEM surveys were flown per year. The first period, from 1967 to 1973 lasted 7 years, the second, from 1979 to 1981, only 3 years. Both coincided with periods of high mineral exploration activity. The average distance flown in the last three years (1982-84) is comparable to that during the exploration slump of the mid 1970s (about 250 000 line km). The probable reason is the accelerating decline in mineral exploration in North America. Unfortunately, the technique has not found sufficient acceptance in tropical developing countries, where the exploration activities still remain at a relatively high level (even though reduced in absolute terms).

From the limited amount of information available, one can assume that AEM surveying activities continue to rise in the USSR. China and India have recently acquired AEM systems from a Canadian manufacturer and have started to carry out their own surveys. Also geological surveys in several European countries operate AEM systems (Austria, Finland, Germany, Norway,

à 1973, la deuxième seulement trois ans, de 1979 à 1981. Les deux ont coïncidé avec des périodes d'intense prospection des minéraux. Le volume moyen des levés ÉMA réalisés au cours des trois dernières années (1982-1984) est comparable à celui du fléchissement marqué qu'à connu la prospection au milieu des années 1970 (environ 250 000 km linéaires). Cela tient probablement à la baisse accélérée de la prospection des minéraux en Amérique du Nord. Malheureusement, la technique n'a pas suscité suffisamment d'adhésions dans les pays tropicaux en développement, où les activités d'exploration demeurent à un niveau relativement élevé (tout en ayant diminué en chiffres absolus).

D'après les données limitées disponibles, on peut supposer que les travaux de levés ÉMA continuent d'augmenter en URSS. La Chine et l'Inde ont récemment acheté des systèmes ÉMA d'un fabricant canadien et commencé leurs propres levés. En outre, les commissions géologiques de plusieurs pays européens (Allemagne, Autriche, Bulgarie, Finlande, Norvège, Suède) exécutent des levés ÉMA avec des systèmes propres. Des travaux sont en cours en Australie pour l'élaboration d'un système ÉMA avancé en domaine temporel. Il est manifeste que le monopole dont disposaient pratiquement les sociétés canadiennes est en voie de rapide disparition.

Sweden). Development is underway in Australia to design an advanced time-domain AEM system. It is obvious that the virtual monopoly the Canadian companies had is disappearing fast.

During the period of consolidation in the 1960s, the cost of AEM surveys was relatively stable — the 1970 average was US $11.80 per km. During the inflationary 1970s, the survey cost accompanied the general price index, and at the end of the decade the average price was US $23.60 (in 1979). Surprisingly, in the 1980s, when the inflation was brought under control in Western countries, the US dollar price continued to climb — it doubled between 1979 and 1984 to US $47.10 per km. A nagging question: Is the technique becoming less cost-effective than alternatives, even in mineral exploration programs? (The survey costs quoted were obtained from SEG geophysical activity reports which use figures furnished by contractors and organizations conducting AEM surveys).

An interesting comparison can be made with other airborne geophysical techniques. In 1979, the peak year for AEM, 615 229 line km were flown worldwide, compared to 1 386 018 line km of magnetics and 95 302 line km of radiometrics. Five years later, the use of AEM declined 48%, while aeromagnetic surveying has more than doubled, to 2 829 012 km. Aeromagnetic surveys are now used in petroleum, mineral and groundwater prospecting. Despite the decline in uranium exploration activities, radiometric surveys are being more widely used for mapping purposes and showed an increase, to 128 534 km in 1984. While the cost of AEM surveys doubled between 1979 and 1984, the cost of aeromagnetic surveys decreased slightly from $12.74/km to $10.80/km (all prices are quoted in current US dollars, not adjusted for inflation). There was no significant change in AEM technology between 1979 and 1984. Companies operating in a shrinking market see their revenues decline and as a group have probably entered the vicious circle of less work and higher unit cost.

What can be done to increase the use of airborne electromagnetics? Potential new users must be made aware of its capabilities, new markets must be developed, contractors must offer AEM services for new applications as a cost-effective alternative to other approaches.

Hopefully, the Workshop on Airborne Resistivity Mapping has played a positive role in this process and has generated new ideas. In the technical program, we have attempted to focus on non-traditional applications for airborne electromagnetics and on new Canadian AEM systems in the final stages of development or testing. Even though the audience consisted mainly of specialists, highly knowledgeable in their field, papers have been included on the geological background and principles of AEM interpretation. Two papers authored by geophysicists from Finland and Quebec describe the

Au cours de la période de regroupement des années 1960, le coût des levés ÉMA est resté relativement stable. La moyenne de 1970 s'est établie à 11,80$ américains par kilomètre. Durant la période d'inflation des années 1970, le coût des levés a suivi l'indice général du coût de la vie et à la fin de la décennie, sa moyenne était de 23,60$ américains (en 1979). Fait étrange, au cours des années 1980, alors qu'on a réussi à juguler l'inflation dans les pays occidentaux, le prix par kilomètre a cependant continué à monter. Il a doublé de 1979 à 1984, passant à 47,10$ américains par kilomètre. D'où la question gênante suivante : la technique est-elle en voie de devenir moins rentable que les autres méthodes, même pour les programmes de prospection des minéraux ? (Les coûts cités sont tirés des rapports sur les activités géophysiques publiés par la SEG, qui utilise les chiffres fournis par les entrepreneurs et les organisations effectuant des levés ÉMA.)

On peut établir une comparaison intéressante avec les autres techniques de levés géophysiques aériens. En 1979, la meilleure année pour les levés ÉMA, on a fait 615 229 km linéaires de levés ÉMA dans le monde entier, comparativement à 1 386 018 km linéaires de levés aéromagnétiques et 95 302 km linéaires de levés radiométriques. Cinq ans plus tard, l'emploi des techniques ÉMA avait diminué de 48 p. 100 tandis que les levés aéromagnétiques avaient plus que doublés, passant à 2 829 012 km. Les techniques de levés aéromagnétiques sont actuellement employées pour la prospection du pétrole, des minéraux et des eaux souterraines. Malgré le fléchissement des activités de prospection d'uranium, les levés radiométriques sont plus largement employés dans les activités de cartographie géologique et ont augmenté, s'établissant à 128 534 km en 1984. Si le coût des levés ÉMA a doublé de 1979 à 1984, celui des levés aéromagnétiques a légèrement fléchi, passant de 12,74$ à 10,80$ le km (tous les coûts sont en dollars américains constants, non corrigés de l'inflation). La technique des méthodes ÉMA n'ont pas connu de changements notables de 1979 à 1984. Les entreprises, fonctionnant dans un marché en régression, voient leurs revenus baisser et, dans l'ensemble, elles sont probablement entrées dans le cercle vicieux du fléchissement de la demande accompagné de l'augmentation des coûts unitaires.

Quels moyens prendre pour augmenter l'emploi des techniques électromagnétiques de levés aériens ? Il faudrait renseigner les nouveaux utilisateurs éventuels sur leurs possibilités, ouvrir de nouveaux marchés. Il faudrait que les entrepreneurs offrent leurs services ÉMA à de nouvelles applications, comme options rentables par rapport à d'autres approches.

On peut espérer que l'Atelier sur la cartographie aérienne par résistivité aura joué un rôle positif dans ce processus et suscité de nouvelles idées. Nous avons cherché à centrer la partie technique du programme sur des applications non traditionnelles des techniques électromagnétiques de levés aériens et sur les nouveaux systèmes ÉMA parvenus aux derniers stades de développement ou au stade des essais. Même si l'assistance se composait principalement de spécialistes, très compétents dans leurs domaines, nous avons inclus des exposés sur les notions géologiques et les principes sous-jacents à l'interprétation des données ÉMA. Deux exposés ayant comme auteurs des géophysiciens de la Finlande et du Québec décrivent des programmes de couverture systématique utilisant des techniques ÉMA. Des programmes similaires existent également en Suède, en Norvège et en Ontario. Peut-être que l'avenir réside systematic coverage using AEM techniques. Similar programs exist also in Sweden, Norway, and Ontario. Perhaps the future lies in such a systematic approach using all available geophysical systems. The resulting data base can be used in assessment of mineral and groundwater resources. In the long run, systematic geophysical surveys may emerge as the most cost-effective means of geological mapping — by interpretation of geophysical data in advance of geological field work and checking of selected geophysical features in the field, rather than traditional traversing. Some of the questions concerning the future of airborne electromagnetics have been addressed during the Panel Discussion, whose proceedings are included in this volume.

dans ce type d'approche systématique utilisant tous les systèmes de levés géophysiques disponibles. La base de données ainsi produite pourrait servir à évaluer les ressources en minéraux et en eaux souterraines. À la longue, les levés géophysiques systématiques se révéleront peut-être le moyen le plus rentable de réaliser la cartographie géologique, grâce à l'interprétation des données géophysiques avant les travaux géologiques sur le terrain et à la vérification sur place de caractéristiques géophysiques choisies, au lieu de la méthode traditionnelle de parcours du terrain. Certaines questions sur l'avenir des techniques électromagnétiques de levés aériens ont été débattues au cours des tables rondes, dont les comptes rendus figurent dans le présent volume.

- 1 -

Development of the airborne electromagnetic technique

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Abstract

The idea of using airborne electromagnetic (AEM) systems for resistivity and geological mapping dates from the 1950s. In the Western World, AEM systems were developed for the main purpose of detecting massive sulphides. This paper attempts to record the chronological development of AEM systems. In the early years, the ideas emanated from Finland and Sweden and with foreign capital were transformed into operational systems in Canada. With the first AEM discovery of the Heath Steele lead-zinc deposit in New Brunswick in 1954, the usefulness of the AEM system was established. By 1970 there were approximately twenty AEM systems available. The INPUT® system has been the most popular system ever developed and today accounts for about 70% of all the AEM line km flown in the Western World. Since 1970, new developments or improvements on AEM systems have emphasized multifrequency capability, multicoil arrangements, and increased receiver sensitivity. Parallel to these developments, institutes in the USSR have developed AEM systems that are not unlike those operated in Canada and Europe. The characteristics of these systems are tabulated along with their closest Western counterparts.

Résumé

L'idée d'employer des systèmes électromagnétiques aéroportés (ÉMA) pour établir la résistivité et dresser des cartes géologiques date des années 1950. Dans le monde occidental, les systèmes ÉMA ont été mis au point principalement pour la détection des sulphures massifs. La présente étude a pour objet de présenter la chronologie du développement de ces systèmes. Les premières idées ont été élaborées en Finlande et en Suède et, grâce à des capitaux étrangers, elles ont été transformées en systèmes opérationnels au Canada. L'utilité des systèmes ÉMA a été établie à l'occasion de la découverte du gisement plombo-zincifère de Heath Steele, au Nouveau-Brunswick, en 1954. Ce fut la première découverte réalisée à l'aide des techniques ÉMA. En 1970, il existait environ 20 systèmes ÉMA. Le système INPUT® est devenu le système le plus répandu. Éviron 70 p. 100 de levés ÉMA du monde occidental se font actuellement avec ce système. Depuis 1970, les nouvelles techniques mises au point ou les perfectionnements apportées aux systèmes ÉMA existants ont porté principalement sur les systèmes à plusieurs fréquences, sur les dispositifs à plusieurs bobines et sur l'accroissement de la sensibilité des récepteurs. Parallèlement à ces travaux, des centres de recherche d'URSS ont élaboré des systèmes ÉMA assez semblables à ceux qui fonctionnent au Canada et en Europe. Les caractéristiques de ces systèmes sont présentées ici sous forme de tableaux où elles sont comparées à leurs contreparties occidentales les plus proches.

EARLY YEARS

In 1946, Hans Lundberg, a native of Sweden, put together the world's first airborne electromagnetic (AEM) system. It was a null-coupled coil system mounted entirely inside the cabin of a Bell helicopter. That summer, it was flown on a survey in northern Quebec and Ontario. It detected sulphides only when flying within 5 m of the top of the conductor. There was no quantitative basis for the prediction of the response of conducting bodies to an AEM system. In fact, it has been said, if there had been a study done, no AEM system would have been developed. Although the experiment failed, the idea did not.

During the mid-1940s, Stanley Davidson, a geologist with Stanmac Ltd., had been using a vertical-loop ground

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EM system to detect sulphides in the Sudbury Basin, Ontario. In 1946, he contacted a group of electronic engineers in Toronto to make the instrument more portable. The unit was modified, installed in cabooses and towed across frozen lakes in northern Manitoba. The configuration used led to the first AEM system to be used on a fixed-wing aircraft (Hanula, 1982, p. 141-142). The portable ground EM system was so successful that in 1949 the engineers (McLaughlin, Cartier, Perz, Harvey, Anthes and Robinson) decided to form a company, McPhar Geophysics Ltd. Before that time they were known as the McPhar group (McPhar is an acronym of the names of these engineers).

After the success of the ground EM system, Stanmac Ltd. commissioned McPhar to build an AEM system and install it in a wooden-skinned Anson (Fig. 1.1). This aircraft had been used for training during World War II. Test flights over the Whistle Mine near Sudbury proved successful. Probably as a result of high development costs Stanmac Ltd. went bankrupt. In 1949 Davidson approached Ralph Parker, International Nickel Co. of Canada Ltd. (INCO), who contracted McPhar to build an improved version of the AEM system. Two years later, the INCO system, which consisted of orthogonal coils in the transmitter and in the towed receiver, went into operation.

In 1952, McPhar Geophysics Ltd. carried out a ground vertical-loop EM survey in New Brunswick and discovered the Brunswick Number Six orebody near Bathurst. After this American Metals Co. (later AMAX Inc.) approached INCO for the use of their newly developed AEM system to search for lead-zinc massive sulphide deposits in New Brunswick. A year later, John Dowsett of INCO supervised an AEM survey over a major portion of the Bathurst-Newcastle area (Hanula, 1982, p. 162). The detected anomalies were drilled in 1954, resulting in the discovery of the Heath Steele lead-zinc deposit, about 65 km southwest of Bathurst (Fig. 1.2). This was the first AEM discovery in the world.

Development in Finland

In 1950 the Geological Survey of Finland made a bold decision to start a systematic airborne geophysical mapping of the whole country. Aeromagnetic surveys commenced in 1951 using a fluxgate magnetometer acquired from Canada. In 1953 a single frequency quadrature AEM system was developed by Maunu Puranen, Aarno Kahma, and Vaino Ronka. The Geological Survey started systematic AEM surveying a year later. Table 1.1 summarizes the AEM systems used in this coverage from 1954 to 1979 (Peltoniemi, 1982).

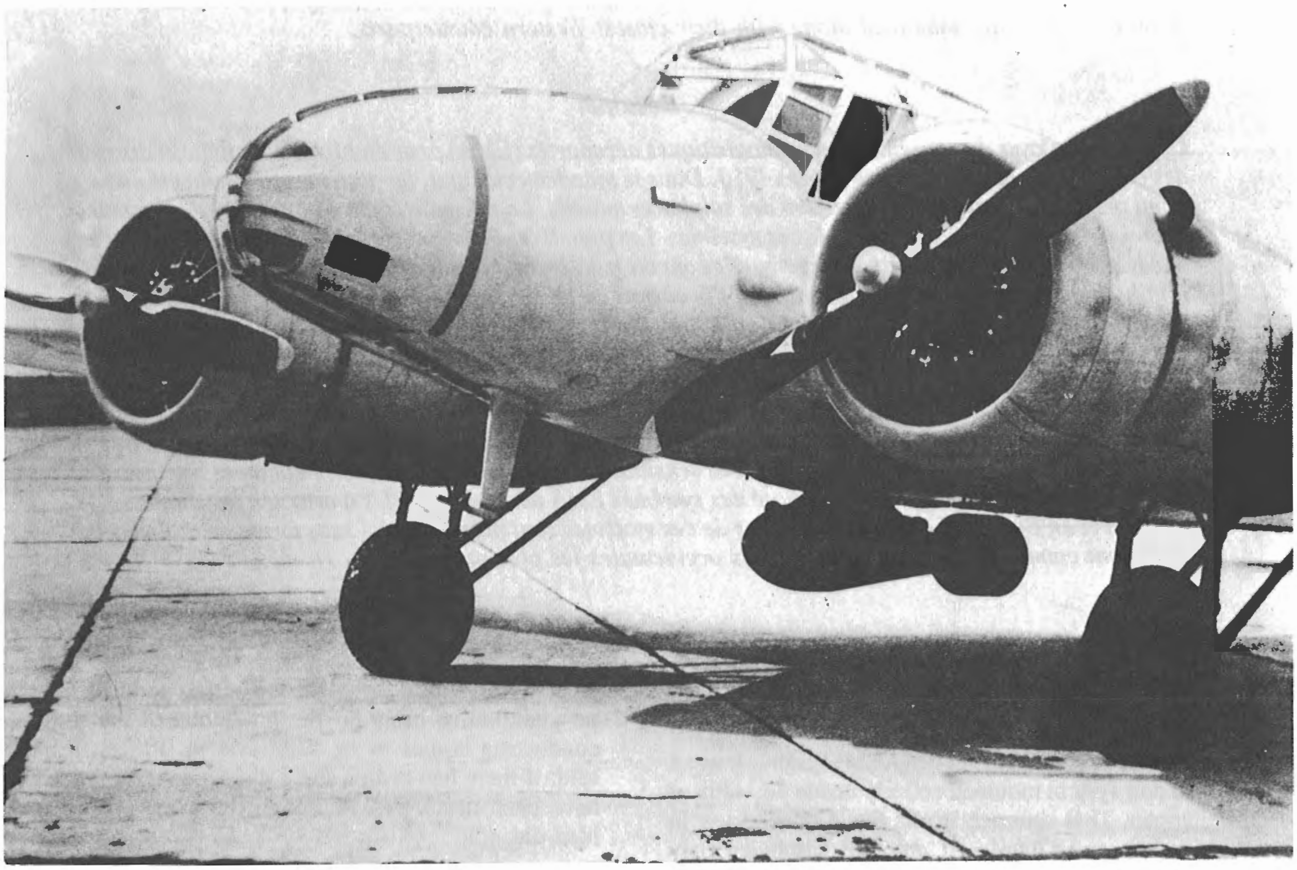

Figure 1.1. The first Canadian-built AEM system, North Bay airport, July 1948 (from Fountain and Bottos, 1970).

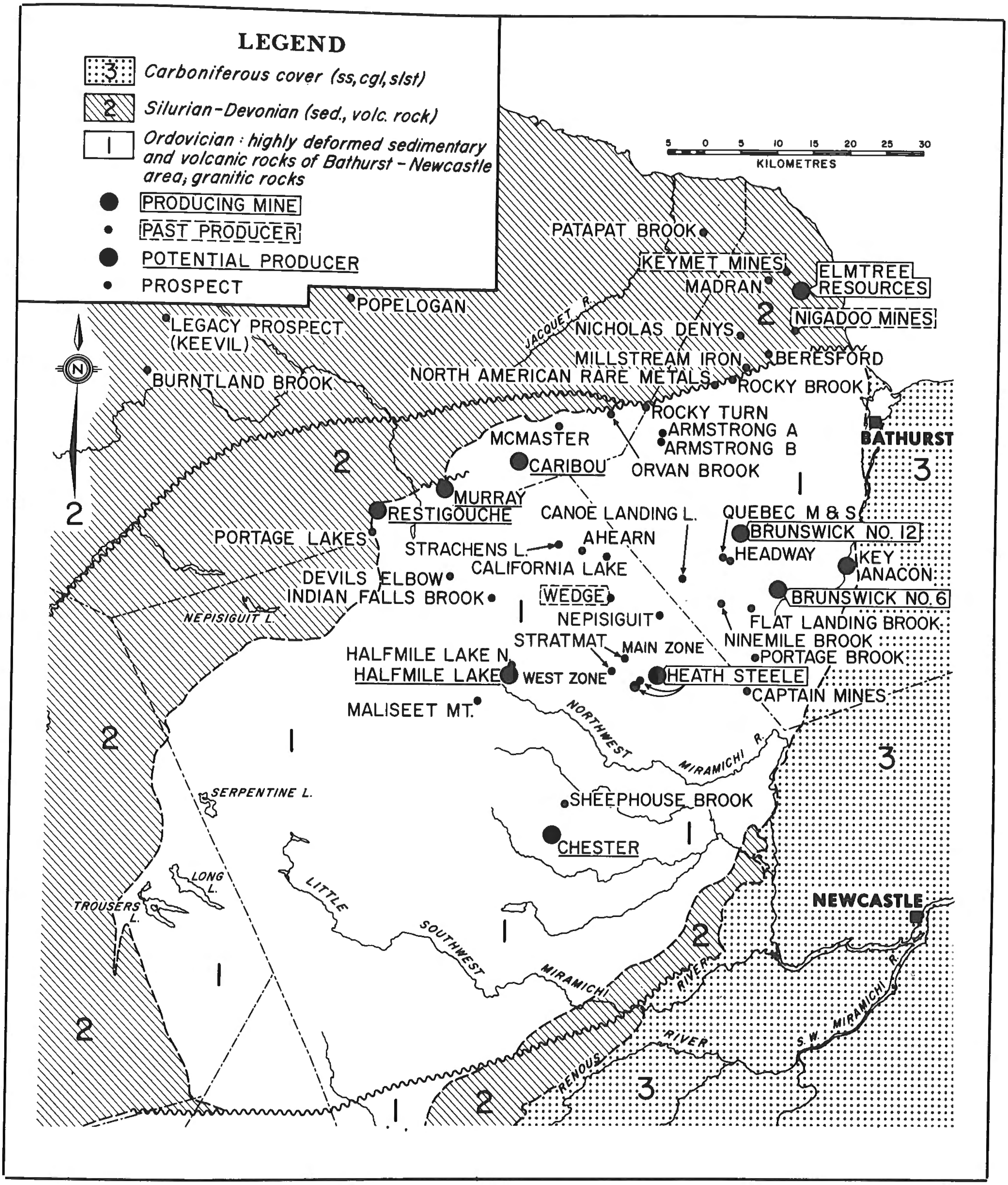

Figure 1.2. Bathurst mining camp, New Brunswick, where the first AEM discovery took place in 1954 (from Potter, 1985).

Table 1.1 Geological Survey of Finland: systematic mapping using AEM systems

Period	Aircraft	AEM system	Flight height	Line spacing
(a) Towed receiver				
1954-59	Lockheed Lodestar	Single f (Q) 390 or 410 Hz	150 m	400 m
1960-71	Lockheed Lodestar	Single f (IP, Q) 390, 410 or 820 Hz	150 m	400 m
(b) Rigid coil				
1972, 1980+	Twin Otter	Single f (IP, Q) 3220 Hz	30 m	200 m
1973-79	DC-3	Single f (IP, Q) 3220 Hz	30 m	200 m

IP = inphase component
Q = quadrature component
T = transmitter
R = receiver
x = coil axis in direction of flight
y = coil axis perpendicular to flight direction
z = coil axis vertical
Note: In case of VLF, x denotes radial field direction from transmitter and not the direction of flight.

Theoretical development

Prior to 1950, little had been published in the English literature about the response of a conductive body to an excitation frequency. The first article on the subject was written by Wait (1951) who described the behaviour of a conducting sphere in a time varying magnetic field (Fig. 1.3). This work led to the realization of the importance of measuring the in-phase as well as the out-of-phase (or quadrature) component. As a result, rigid-coil systems were designed after 1955 capable of recording the in-phase response, which is more sensitive to good conductors.

In the early 1950s, M. Puranen derived the in-phase and quadrature responses for a sphere, vertical plane, and a half-space (V. Ronka, personal communication, 1985). Most of this information is in the files of the Geological Survey of Finland, but has never been published in English.

Other developments

The discovery of the Heath Steele deposit in 1954 was the stimulus for a sustained period of development of fixed-wing and helicopter AEM systems. After successful work at the Geological Survey of Finland, A. Kahma came to Toronto in late 1953 to interest the Hunting Survey Corp. (formerly Aeromagnetic Surveys Ltd.) in a dual-frequency quadrature system (400 and 2300 Hz). Final tests with the system, which became known as the "Canadian" or "Hunting" Canso system, were completed in late 1954 (refer to Table 1.2). At that time V. Ronka started to design the Hunting helicopter EM system which was flight tested in the spring of 1955.

In the meantime, McLaughlin, Cartier, Robinson, Harvey and others formed Nucom Ltd. to develop instrumentation and carry out surveys for AMAX. In 1955, the company built a helicopter system and developed AFMAG (Audio Frequency MAGnetics), but the latter never became a reliable EM technique since the natural EM fields were too low to measure except during the summer months. Nucom Ltd. was bought out by AMAX in 1959.

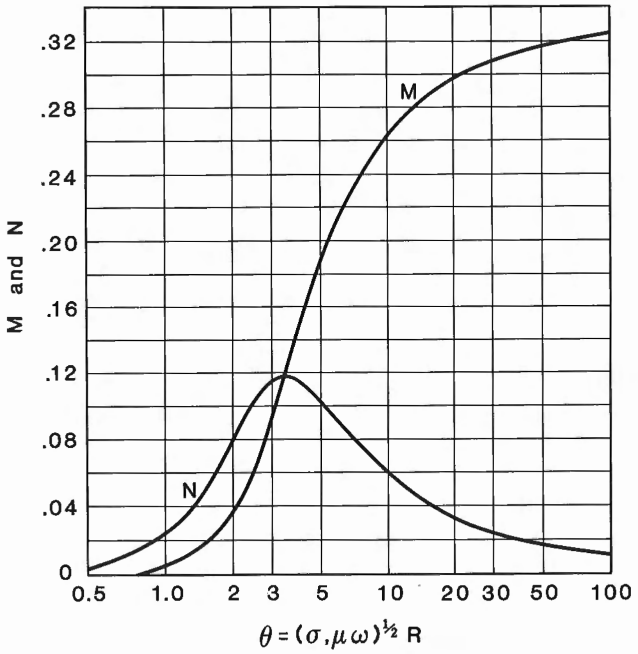

Figure 1.3. The first theoretical EM study applicable to mineral exploration. The variation of in-phase (M) and quadrature (N) components of the secondary magnetic field with frequency over a sphere (after Wait, 1951).

In 1954, A.B. Elektrisk Malmletning (ABEM) in Sweden developed a two-plane AEM system, which was designed by the same team from Finland responsible for the dual-frequency quadrature system (Puranen, Kahma and Ronka). Two years later, the ABEM system was operated under license in Canada by C.C. Huston and Associates and Lundberg Explorations Ltd. until 1960.

In 1956, Rio Tinto Canadian Explorations Ltd., introduced into Canada the Rio-Mullard coplanar fixed-wing system with coils installed on the wing tips of a Twin Pioneer aircraft. The equipment was acquired by Canadian Aero Service Ltd. five years later. About 1957, Aerogeophysics of Canada Ltd., an affiliate of Spartan Air Services Ltd., Ottawa, was flying an Anson equipped with a single-frequency quadrature system. The receiver was towed in a bird below the aircraft.

In the mid 1950s, Ken Ruddock, Newmont Exploration Ltd., had designed an in-phase and quadrature rigid-boom EM system, which was built by Varian Associates Ltd. in California. Canadian Aero Service Ltd. installed this system on a Canso aircraft in 1957 and a year later on a Sikorsky S-55 helicopter. By 1959, Texas Gulf Sulphur Co. used the Newmont-Varian system with a Bell G-2 helicopter.

In 1956, A.R. Barringer, Selco Exploration Ltd., started work on a radically new design for an airborne system, called INPUT (INduced PUlse Transient), which used a half-sine excitation of 1.5 ms duration followed by off-time, during which the EM response was measured. A large transmitting loop was mounted horizontally on a Canso aircraft and a horizontal-axis receiver was towed in a bird at the end of a 150 m cable. The first operational surveys commenced in 1959.

Table 1.2. AEM systems developed between 1950-60

(a) Towed bird systems				
	Coil	Measures	Frequency (Hz) or delay (ms)	Operation by
INCO-Anson	coplanar & coaxial	Amplitude differences	3 freq. 142 to 2430	1951
Hunting Canso (Aeromagnetic Surveys Ltd)	Tz, Rx	Q	400 & 2300	1954
ABEM (2 plane) Sweden	2 orthogonal (Ty, z; Ry, z)	IP, Q	800	1954
Nucom AFMAG	Cross coils	Tilt angle	90 & 330 150 & 590	1955
Aerophysics-Anson (Spartan Air Services)	Tz, Rx	Q	140	1957
Barringer INPUT	Tz, Rx	Transient 4 channels	0.45 to 2.0 ms	1959
(b) Rigid coil systems				
American Metals (Bell) (Nucom Ltd)	Tx, Rx	IP, Q	1000	1955
Hunting Helicopter (Bell) (Aeromagnetic Surveys Ltd)	Tx, Rx	IP, Q	4000	1955
Rio-Mullard (Otter)	Tx, Rx (coplanar)	IP, Q	320	1956
Canadian Aero S-55 (Varian/Newmont)	Tx, Rx	IP, Q	390	1958
Texas Gulf Sulfur (Bell G-2) (Varian/Newmont)	Tx, Rx	IP, Q	400	1959

IP = inphase component
Q = quadrature component
T = transmitter
R = receiver

x = coil axis in direction of flight
y = coil axis perpendicular to flight direction
z = coil axis vertical

Note: In case of VLF, x denotes radial field direction from transmitter and not the direction of flight.

During the 1950s some of the major mining companies developed their own systems. They were either copies or slight modifications of the existing systems. Besides the companies mentioned above (INCO, AMAX, Rio Tinto, Texas Gulf Sulphur, and Selco Exploration), Sherritt-Gordon Mines Ltd. in Canada and Anglo-American Corp. of South Africa used their own systems. An excellent review of this decade was published by Pemberton (1962).

PERIOD 1961-1970

During the first half of this decade, the development of AEM systems levelled off substantially with only improvements made to existing systems. One notable step forward was made by Barringer Research Ltd. when the INPUT Mark V became operational in 1965. In the following years, INPUT became the most widely used AEM system in the world, a distinction which prevails today.

Between 1967 and 1970, a number of new AEM systems were developed, including four helicopter systems (Table 1.3). Companies bringing out these systems were Sander Geophysics Ltd., Barringer Research Ltd., Scintrex Ltd. and Dighem Ltd. McPhar Geophysics Ltd. introduced two "button-on" airborne systems during 1967, the F-400 dual-frequency quadrature system and AFMAG AF-4 natural field cross-coil system.

During the 1960s four companies developed airborne VLF (Very Low Frequency) systems. Barringer Research Ltd. placed into service the RADIOPHASE® and the E-PHASE® units, McPhar Geophysics Ltd. the KEM cross-coil system, Lockwood Survey Corp. the EM-18, which was developed by Geonics Ltd., and Scintrex Ltd. introduced the Deltair system. The last named company also developed the Turair system which can be described as a fixed-source, semi-airborne, gradient measuring device.

By 1970, Canadian companies did 80% of all AEM surveys in the Western World (Paterson, 1973). It is interesting to note that three AEM systems (INCO, AMAX and Hunting) accounted for 20 of the 25 mines discovered until 1970, the remaining 5 made by the Rio-Mullard and INPUT systems. Paterson (1971) reviewed the characteristics of 12 of the approximately 18 systems that were used in routine exploration for massive sulphides.

PERIOD 1971-1980

At the commencement of this decade, it became evident that new advances in instrumentation had to be made to increase the survey effectiveness. Efforts were directed toward the improvement of signal-to-noise levels, introduction of multi-frequency measurements and signal processing to reduce acceleration effects in rigid-boom systems, and toward better anomaly resolution by decreasing time constants in the time-domain systems.

Table 1.4 lists chronologically the developments of the AEM systems during this period. Most of the systems employed 2 to 3 frequencies and were essentially improvements of existing systems. SOQUEM (Societé Québecoise Minière) developed a single-frequency light-weight system that could be installed on a small aircraft such as a Cessna. Barringer Research Ltd. and Questor Surveys Ltd. developed jointly the Mark VI version of INPUT with a time-constant instrument response reduced to 0.5 s. The Scintrex 3-frequency Tridem system, which was developed in 1972, was used for contract surveying two years later using an Otter aircraft. In 1977, Scintrex Ltd. and Kenting Earth Sciences Ltd. formed a joint venture to provide Tridem AEM services. McPhar introduced the F-500 three-frequency quadrature "button-on" system in 1973 and in 1975 Dighem brought out a two-frequency helicopter EM system (Dighem II).

In 1976, Barringer Research Ltd. announced the development of a new towed-bird AEM system, named COTRAN® (COrrelation TRANsient). The system consisted of a full-waveform transmitter with two receiver coils in the bird. The purpose of the development was to build a system superior to INPUT in sensitivity and depth of penetration and to classify geophysical targets in real time in terms of their time-constant spectra (Collett et al., 1983). Geonics Ltd. announced their helicopter rigid-boom EM system EM 33-2 and 3, McPhar produced a new 4-frequency Quadrem system for fixed-wing and helicopter installations, and Terra Surveys-Geoterrex Ltd. obtained an exclusive license from Hudson Bay Mining and Smelting Co. to operate the EM-30 AEM system, which was installed on a Beechcraft E-18-S with a horizontal-axis transmitter on the nose of the aircraft.

In 1977, the newly formed Herz Industries Ltd. and Vaino Ronka developed an airborne VLF system, Totem 1A, which measures the total field and the vertical quadrature component. Because of its small size, light weight, easy installation and simple operation, this system has become widely used in conjunction with other airborne geophysical methods in fixed-wing aircrafts and helicopters. In 1979, two more airborne VLF systems were developed, Scintrex SE-90 and Sander Geophysics VLF-EM 11.

In 1978, Scintrex Ltd. announced an improved HEM-802 two-frequency helicopter EM system, which could be transported by air freight and installed in a range of locally available helicopters. Geotech Ltd., which was formed in 1979, introduced a three-frequency helicopter system Geotech-3 with coaxial (945 and 5450 Hz) and horizontal coplanar (4100 Hz) coils in the same bird. In 1980, Geoinstruments Ky of Helsinki, Finland, installed a coaxial EM system (SLR-80) operating at 3700 Hz on an Aero Commander.

During the 1970s the use of AEM systems for resistivity mapping had not yet become a popular idea, but Fraser (1978) and Palacky (1981) led the way. From the tests and experiments that had been carried out it was realized that the AEM

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Table 1.3. AEM systems developed between 1961-1970

Year	Company	Description	Coil	Measures	Frequency (Hz) or delay (ms)
1967	Barringer	HEM/Questor	Tx, Rx or Rz	IP, Q	400 or 800
		Radiophase	Hy/Ez	IP, Q	VLF
	Sander	HEM	Tx, Rx	IP, Q	1000
	McPhar	AFMAG AF-4	Cross coils	Tilt Angle	140 & 470
		F-400, H-400	Tx, Rz	Q	340 & 1070
1968	Barringer	E-PHASE	Ex/Ez	Q	VLF
	Geonics	EM-18	Rz/Rz+y	IP, Q	VLF
	Scintrex	HEM-701	Tx, Rx	IP, Q	1600
		Scintrex/AiResource Otter	TX, Rx (coplanar)	IP, Q	320
	McPhar	KEM	Cross coils	Dip Angle	VLF
1970	Dighem	Dighem I	Tx, Rx, y, z	IP, Q	900 Hz
	Scintrex	Turair	Tz (ground) Rx, x	Ampl. Ratio	200, 400 & 800
				Phase Grad.	
		Deltair	Rx, x	Ample. Ratio	VLF
				Phase Grad.	

IP = inphase component
Q = quadrature component
T = transmitter
R = receiver
x = coil axis in direction of flight
y = coil axis perpendicular to flight direction
z = coil axis vertical
Note: In case of VLF, x denotes radial field direction from transmitter and not the direction of flight.

systems had to be very stable, i.e. low drift, and that a broad band of frequencies was necessary. Towards the latter half of the decade, one of the most significant advances was the improvement in data gathering capabilities due to microelectronic technology development. Until then AEM systems rarely recorded more than six channels of data.

PERIOD 1981-1985

The first half of this decade experienced a great deal of activity in improving the existing AEM systems, particularly with multifrequency capability and multicoil configuration. However, by 1985 the airborne geophysical survey industry had been affected by the decline in the demand for base metals. Since gold deposits became the exploration target, the AEM technique has increasingly been considered to be a tool of geological mapping and overburden thickness determination.

In 1981, Herz Industries Ltd. developed the Totem-2A, which records the same parameters as the Totem-1A, but at two VLF frequencies (Table 1.5). In 1982, Dighem Ltd. completed the development of Dighem III, which is an improved version of the Dighem II system with an added horizontal coplanar coil pair operating at 7200 Hz. Geotech Ltd. introduced the helicopter EMEX-1 boom system which consists of a coaxial-coplanar set operating at any combination of frequencies from 380 to 8000 Hz, and Questor Surveys Ltd. announced their helicopter INPUT Mark VI system. In 1983, Sander Geophysics Ltd. came out with a three-frequency helicopter EM system, EM3-A, operating at 1000, 4000, and 8000 Hz which was capable of mapping formations with resistivities up to 4000 Ωm. In 1984, Geoinstruments Ky of Helsinki introduced a two-frequency system (SLR-84) similar in design to the earlier SLR-80.

During 1985, Dighem announced a four-frequency Dighem IV and Geotech Ltd. a seven-frequency helicopter EM

Table 1.4. AEM systems developed between 1971-1980

Year	Company	Description	Coil	Measures	Frequency (Hz) or delay (ms)
1972	SOQUEM	Emal-19	Tx, Rx (coplanar)	IP, Q	625
	Barringer/Questor	INPUT MK 6	Tx, Rx	Transient 6 channels	0.1 to 2.0 ms
	Scintrex	Tridem	Tx, Rx (coplanar)	IP, Q	500, 2000, 8000
1973	McPhar	F-500	Tx, Rx	Q	340, 1070, 3450
1975	Dighem	Dighem II	Tx, z, Rx, z	IP, Q	900, 3600
1976	Barringer	COTRAN	Tz, Rx, z	Transient 5 channels	.03 to 2.43 ms
	Geonics	EM-33-2 & 3	Tx, Rx	IP, Q	300, 1500, 7500
	McPhar	Quadrem	Tx, Rz	Q	95, 285, 855, 2565, 7695
	Hudson Bay M&S	EM-30	Tx, Rx	IP, Q	380, 1225
1977	Herz Industries	Totem 1A	Rx, y, z	Total, Qz	VLF
1978	Scintrex	HEM-802	Tx, Rx,	IP, Q	735, 3220
1979	Geotech	Geotech-3	Tx, z, Rx, z	IP, Q	945, 4100, 5450
	Scintrex	SE-90	Rx, y, z	Ampl. x, y; IPz, Qz	VLF
	Sander	VLF-EM II	Rx, y, z	Ampl. x, y; IPz, Qz	VLF
1980	Geoinstruments (Finland)	SLR-80	Tx, Rx	IP, Q	3700

IP = inphase component
Q = quadrature component
T = transmitter
R = receiver
x = coil axis in direction of flight
y = coil axis perpendicular to flight direction
z = coil axis vertical
Note: In case of VLF, x denotes radial field direction from transmitter and not the direction of flight.

system. Geoterrex Ltd. had completed the development of Geotem, which is a time-domain towed-bird system, consisting of a large vertical-axis transmitting loop with a selectable fundamental frequency of 75, 90, 125, or 150 Hz and a half-sine current pulse. The completion of two new-generation systems was announced in the same year. Kenting Earth Sciences Ltd. introduced the software-controlled Sweepem system which was initially designed by KSEPL (Royal Dutch/Shell Exploration and Production Laboratories) in Rijswijk, Netherlands. A large transmitting loop (vertical axis) is driven by a pseudorandom sequence primary field with a frequency range of 50 to 5000 Hz. Two receiving coils are mounted in a towed bird. A-Cubed Inc. tested a fully digital AEM system (PROSPECT I) mounted on a fixed-wing aircraft with a high-drag bird in which 3 orthogonal receiving coils are mounted. Both developments are described in this volume.

Hood (1985) has compiled the most recent list of AEM systems that are available for purchase or as a contract service.

AEM developments in the USSR

Parallel to the development of AEM systems in Canada, Finland and Sweden, similar systems were developed in the USSR. The exact year when each system was put into operation is not known. Table 1.6 summarizes the AEM systems developed until 1980 as reported in the Geophysicist's Handbook on Electrical Exploration (Tarkhov, 1980). Before 1960, two AEM systems were developed, the semi-airborne BDK-70 and the VMP which was a two plane version of the Swedish ABEM rotary field method. In the case of BDK-70, a long grounded cable was used as the transmitter.

Table 1.5. AEM systems developed between 1981-1985

Year	Company	Description	Coil	Measures	Frequency (Hz) or delay (ms)
1981	Herz Industries	Totem 2A	Rx, y, z	Total, Qz	VLF, 2 frequencies
1982	Dighem	Dighem III	Tx, z, Rx, z	IP, Q	900, 900, 400/7200
	Geotech	EMEX-1	Tx, z, Rx, z	IP, Q	380, 933, 918, 5500
	Questor	HEM INPUT	Tz, Rx	Transient 6 channels	0.1 to 2.0 ms
1983	Sander	EM 3-A	Tx, z, Rx, z	IP, Q	1000, 4000, 8000
1984	Geoinstruments (Finland)	SLR-84	Tx, Rx	IP, Q	910, 7040
1985	Dighem	Dighem IV	Tx, z, Rx, z	IP, Q	900, 900/7200, 56 000
	Geotech	EMEX-2	Tx, z, Rx, z	IP, Q	7 frequencies 190-12 000
	Kenting/Shell	Sweepem	Tz, Rx, z	IP, Q or transient	14-32 frequencies 50-5000
	Geoterrex	Geotem	Tz, Rx, z	Transient 11 channels	0.1 to 2.0 ms

IP = inphase component
Q = quadrature component
T = transmitter
R = receiver

x = coil axis in direction of flight
y = coil axis perpendicular to flight direction
z = coil axis vertical

Note: In case of VLF, x denotes radial field direction from transmitter and not the direction of flight.

Table 1.6. AEM systems developed in USSR

Period (Approximate)	Description	Coil	Measures	Frequency (Hz) or delay (ms)
1955-60	BDK-70	T(grounded cable) Rx	IP, Q	81, 163, 244, 488, 976 (only 2 frequencies simultaneously)
1955-60	VMP (2 planes)	2-orthogonal (Ty, z, Ry, z)	$|H|$, $\Delta\varphi$	612, 1225, 2450 (only one frequency at a time)
1960-70	DIP-AD	Tz, Rx, z	$|Hx|$, $|Hy|$	312, 2500
1968-70	AMPP-2	Tz, Rz	Transient, 3 channels	125 Hz; 0.5–3 ms
1970-75	DIP-ZK	Tx, Rx (coplanar)	$|Hx|$, Q	625, 5000 (only one frequency at a time)

IP = inphase component
Q = quadrature component
T = transmitter
R = receiver
φ = phase

x = coil axis in direction of flight
y = coil axis perpendicular to flight direction
z = coil axis vertical
H = magnetic

Note: In case of VLF, x denotes radial field direction from transmitter and not the direction of flight.

The DIP-AD system developed in the late 1960s resembled the McPhar F-400 (fixed-wing) and H-400 (helicopter) systems. A horizontal loop was installed around the fuselage of the plane and two orthogonal coils were towed in a bird. About this time, a helicopter borne transient system, AMPP-2, was installed. The pulse repetition rate was 125 Hz and three channels were recorded with delay times from 0.5 to 3 ms. The DIP-ZK system introduced in the early 1970s was a coplanar wing-tip system, somewhat similar to the early version of the Tridem. Systematic AEM surveys have been conducted since 1977 in the Ural Mountains. The developments in airborne electromagnetics were discussed at a Symposium "Induction Electrical Prospecting" held in April 1984 in the USSR (Kamenecky and Yakubovsky, 1985).

CONCLUDING REMARKS

The development of AEM systems has taken place mostly in Canada since the first airborne test was carried out by Hans Lundberg in 1946. The demand for base metals provided a strong impetus to the AEM developments. Since much of Canada has geology favourable for mineral discovery and legislation has encouraged exploration and mining, Toronto and Ottawa became the pioneering centres for this development. By 1970, approximately 20 systems were used in routine exploration for massive sulphides and Canadian companies carried out 80% of all AEM surveys in the Western World. In 1985, 15 companies in Canada provided AEM systems for purchase or as a contract service. Because of the continuing low demand for metals, mineral exploration budgets were severely cut back by the mining companies, with a serious impact on the AEM community. The aim of this workshop is to assess our present status and to provide stimulation for "lateral" thinking in creating new applications which will eventually lead to future markets.

ACKNOWLEDGMENTS

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- 2 -

Geological background to resistivity mapping

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Abstract

Conductors detectable by airborne electromagnetic (AEM) systems include massive sulphides, graphite (both with conductivities in excess of 500 mS/m), and clays in alteration zones, weathered layers, and glaciolacustrine sediments (with conductivities between 5 and 500 mS/m). In principle, data obtained with multifrequency or broad-band AEM systems permit identification of these conductors. Massive sulphides, which have been the traditional exploration targets since the development of AEM methods in the 1950s, have been amply discussed elsewhere and are not treated in this paper in detail. The type of clay encountered in saprolite (thoroughly chemically weathered rock) depends on the lithology of the parent rock. Saprolites developing from mafic volcanic rocks are more conductive than those from felsic volcanic rocks or granite. AEM techniques can therefore be used for pseudogeological mapping in areas where the weathered layer has not been removed. Such situations exist locally in Canada, but generally they are more typical of non-glaciated terrains.

Conductivity of water depends on its mineral content (primarily NaCl). In coastal areas, AEM methods can be used to map the extent of salt-water aquifers. Salt water is significantly more conductive than fresh water (respective conductivities, 1-5 and 10-500 mS/m). Offshore, bathymetric charting can be performed with AEM systems. A recently developed AEM technology has the potential of monitoring thickness of sea ice in Arctic areas.

Résumé

Les conducteurs détectables par les systèmes électromagnétiques aéroportés (ÉMA) comprennent les sulfures massifs, le graphite, tous deux présentant des conductivités supérieures à 500 mS/m et les argiles situées dans les zones d'altération et les sédiments glaciolacustres, présentant des conductivités de 5 à 500 mS/m. En principe, les données obtenues avec les systèmes ÉMA à plusieurs fréquences ou à larges bandes permettent de détecter ces conducteurs. Les sulfures massifs, qui sont la cible la plus courante des explorations depuis la mise au point des méthodes ÉMA durant les années 1950, sont amplement étudiés ailleurs et la présente étude ne les traite pas en détail. Le type d'argile qui se rencontre dans la saprolite (roche où les minéraux lessivés primaires sont remplacés par minéraux argilitiques) dépend de la composition pétrographique de la roche saine. Les saprolites qui se forment à partir des roches volcaniques mafiques sont plus conductrices que celles qui se développent à partir des roches volcaniques felsiques ou du granit. On peut donc employer les techniques ÉMA pour établir une cartographie pseudogéologique dans les régions où les zones d'altération n'ont pas été érodées. Il existe des situations de ce genre en certains endroits au Canada, mais on les retrouve plus communément dans les zones non soumises à la glaciation.

La conductivité de l'eau dépend de sa teneur en minéraux (NaCl principalement). Dans les secteurs côtiers, on peut utiliser les méthodes ÉMA pour cartographier l'étendue des aquifères d'eaux salées. L'eau salée est sensiblement plus conductrice que l'eau douce (conductivités respectives de 1-5 et 10-500 mS/m). Au large des côtes, on peut dresser des cartes bathymétriques avec des systèmes ÉMA. Une technique ÉMA récemment mise au point permet de mesurer l'épaisseur des glaces de l'océan Arctique.

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INTRODUCTION

The first AEM systems were developed in Canada in the 1950s (Collett, 1986). Until recently, such systems have been used almost exclusively in prospecting for massive sulphide orebodies primarily of the volcanogenic type. The procedure of airborne EM and magnetic coverage followed by ground identification of conductors has been highly successful in Canada and numerous orebodies have been found. When attempts were made to use a similar approach in regions without previous glacial erosion, the technique was less successful. Frequently the response from the weathered layer was found to be much stronger than that from the target. The remedy pursued in the 1970s was to decrease the operating frequency of the system substantially, but this approach proved unsatisfactory. The presently widely accepted opinion is that AEM measurements should be carried out in a wide band or at multiple frequencies in order to identify responses from massive sulphides and weathered layers. This paper outlines the principal types of conductive inhomogeneities that can be detected by EM surveys.

Table 2.1 shows conductivity values (in mS/m) of common earth materials. The conductivities represent a typical range for the materials, but this physical property is highly variable, particularly in situ, and values outside these ranges can often be found. The table was compiled from a variety of sources (e.g. Angenheister, 1982) and generally, preference was given to values obtained in the course of field EM and resistivity measurements rather than to those derived from laboratory investigations. Conductivities over 500 mS/m are considered high. Materials falling into this category are massive sulphides, graphite, and salt water. The medium conductivity group (between 1 and 500 mS/m) includes a variety of materials — sedimentary rocks, unconsolidated glacial sediments, weathered layers, alteration zones, and fresh water. Most readers are probably well acquainted with the traditional application of AEM methods in prospecting for massive sulphides, but may not be familiar with other types of conductive inhomogeneities. This paper tries to fill the gap and focuses primarily on electrical response of clays, which occur in weathered layers, alteration zones, and glaciolacustrine sediments.

Table 2.1 Conductivity of some earth materials

	Conductivity mS/m
Massive sulphides	10^3–10^7
Graphite	500–10000
Alteration zones	10–500
Saprolite (mafic volcanic rocks, schist)	50–500
Saprolite (felsic volcanic rocks, granite, gneiss)	5–50
Mottled zone	0.5–5
Duricrust (canga)	0.03–0.5
Glaciolacustrine clays	10–200
Glacial tills	0.5–20
Gravel and sand	0.1–2
Sedimentary rocks	0.01–500
Igneous and metamorphic rocks	10^{-5}–1
Sea water	1000–5000
Fresh water	10–500
Sea ice	1–50
Permafrost	10^{-2}–2

BEDROCK CONDUCTORS

Until the late 1970s, only bedrock conductors were considered important and interpretable; other types were regarded as "noise". In mineral prospecting the aim was to recognize anomalies caused by massive sulphide deposits. Rule-of-thumb criteria were based on experience in the Canadian Precambrian Shield. Massive sulphides were presumed 1) to have high conductance, 2) to be isolated from other bedrock conductors, 3) to be small, and 4) to have a magnetic expression. Priorities in ground follow-up of AEM anomalies were commonly assigned on the basis of these four criteria. As Gaucher (1983) has demonstrated on data from Quebec, highly conductive sulphides with magnetic association are usually rich in pyrrhotite, but only seldom are of economic interest (with the exception of nickel-copper rich orebodies). Reed (1981) described the discovery of the Detour zinc-copper-silver deposit in Quebec, which is without magnetic association and poorly conductive (interpreted conductance of 5 S); because of this the AEM anomaly associated with the deposit was not followed up until 1974 even though it was detected 16 years earlier. The Casa Berardi gold deposit in Quebec was discovered by routine drilling for assessment purposes in 1981, even though an AEM survey of the area flown in 1974 detected the body (Tintor, 1986). Responses due to two isolated conductors of low conductance were recorded by the AEM system, but the anomalies were not followed up.

Since mid 1970s, case histories have been published of massive sulphide orebodies with no magnetic response (e.g. Webster and Skey, 1979; Whiteley, 1981). In terrains with a thick weathered layer, the EM response of massive sulphides may be obscured by anomalies due to conductive bands resulting from weathering of volcanic rocks. Even though the use of the four criteria mentioned above can be misleading, there still is a need for some guidelines to be used in the selection of AEM anomalies for ground follow-up. Typically, only 1 to 10% of anomalies will be tested by drilling. The best recommendation is to use integration of available geophysical, geological, and geochemical information. There are at least two ways to improve effectiveness of AEM data: by presenting them in several forms, in which one conductor type can be emphasized over another, and by performing statistical analysis of conductivities within a given formation. Thus "anomalies within anomalies" can be identified, which is particularly important in regions with conductive cover (Palacky and Sena, 1979).

For geological mapping and uranium prospecting, bedrock conductors other than massive sulphides are of interest. The most prominent EM anomalies in shield areas are caused by graphite and graphitic schists. Such conductors can be used as marker horizons to unravel the local stratigraphy. Unlike sulphides, whose conductivity varies substantially even over one deposit, physical properties of graphite are usually constant along a given trend. Detection of graphitic metapelites in Aphebian metasediments was the strategy used in prospecting for uranium deposits in the Athabasca Basin in Saskatchewan, because uranium is often concentrated near reducing graphitic basement (Saracoglu et al., 1983). The Cigar Lake orebody, which is covered by 415 m of resistive Helikian sandstones, is the deepest discovery so far using an AEM system (Fouques et al., 1986).

In frequency-domain AEM measurements, anomalies due to magnetite can easily be recognized by their negative in-phase response. In this case the magnetic susceptibility contribution outweighs conductivity. The EM response is determined by the "response parameter" (Grant and West, 1965), which is a product of conductivity, magnetic susceptibility, the system frequency, and dimensions (which in turn depend on the model used in interpretation and the type of EM system).

CLAYS

Many AEM anomalies are caused by water-saturated conductors, mostly clays, which appear in a variety of geological situations. Compared with the previously described materials, clays are not highly conductive (conductivity ranges between 5 and 500 mS/m). Clays concentrate in what geophysicists have been describing as "overburden". In the past anomalies caused by clays were considered a nuisance and dismissed as "noise". However, on closer examination one can extract significant information from this "noise".

In glaciated regions, clayey lacustrine sediments were formed after the retreat of glaciers (e.g. Lake Agassiz in Manitoba, Lake Abitibi in Ontario). Studies in Ontario (Pitcher, 1985) indicate that glaciolacustrine clays have a fairly constant conductivity (about 35 mS/m) and that EM surveys can be used to map their thickness. If the new generation of multifrequency (or wide-band) AEM systems succeeds in identifying the clay-till and till-bedrock interfaces, a significant new application will be born. Knowledge of subsurface bedrock topography is important in conducting geochemical programs (till sampling is presently used in gold exploration) and in various engineering projects (Fig. 2.1). Test AEM surveys for overburden mapping have been carried out in northeastern Ontario (Pitcher et al., 1984).

AEM mapping of lineaments, shear and fracture zones has been done successfully for many years, usually with the VLF technique. Mapping of tectonic features has become particularly important in Canada with the increase in gold exploration. Despite the frequent application it seems that very few researchers have tackled the fundamental problem — what makes the lineaments conductive? It is the writer's opinion that water-filled clays are the conductive material. Depending on the type of the feature, clays can be present along the entire plane of the shear zone (if they are a product of hydrothermal alteration), or only near the surface, forming a conductive wedge. The latter situation results from weathering along a weakened fracture zone. Formation of clays by hydrothermal activity is well known and one can use EM techniques to locate sources of hydrothermal activity (Hoover and Pierce, 1986). It is important to establish the clay origin before attempting quantitative interpretation of the detected EM responses. Generally, the half-plane model has been used in interpretation, but such approximation is not suitable in the case of wedge-like conductors.

In situ weathering produces clays which give clues about the local geology because their composition is a function of the bedrock lithology. Clays are highly conductive because of their ability to absorb water in their lattice, which depends on the clay mineralogy. It is this phenomenon which makes mapping of geological units feasible under certain circumstances. When dry, all clays are quite resistive (Angenheister, 1982).

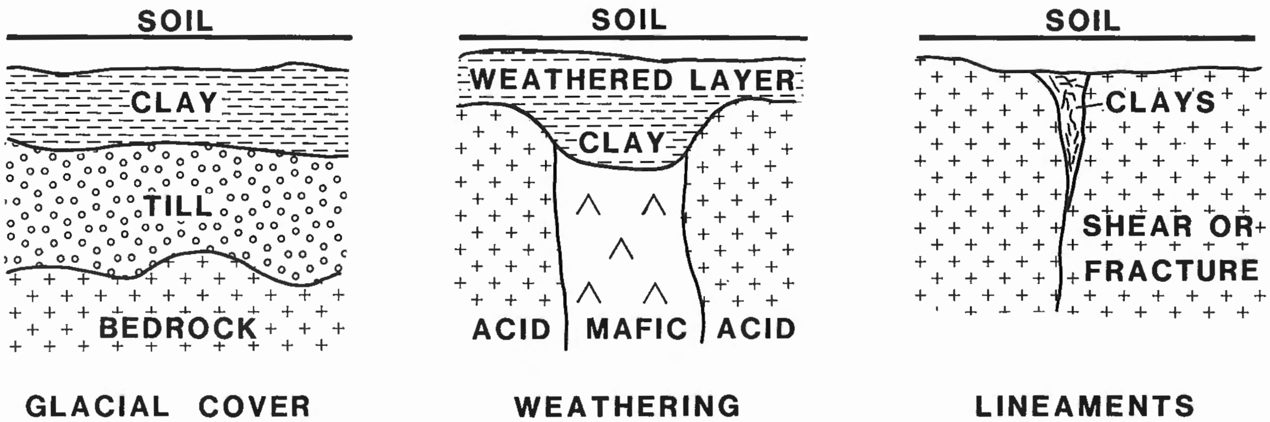

Figure 2.1. Schematic sketch of three situations in which clays commonly occur. Their detection is of importance in geological mapping and in prospecting for some resources (lateritic nickel, saprolite gold, bauxite, etc.).

Geologists distinguish two weathering mechanisms, physical and chemical (Ollier, 1969). The first, which causes mechanical destruction of solid rocks and creation of detrital cover, occurs primarily in arid and frigid regions. In all other regions chemical weathering is present and usually it prevails. The intensity of weathering increases with rainfall and temperature. Thus the hydrolysis process will be faster in tropical climates than in temperate ones. Nevertheless, it takes millions of years to create a thick weathered layer. In the absence of tectonic uplift and denudation or glacial erosion, the weathered layer will be preserved for millions of years. Therefore, there is not necessarily a correlation between the present-day climate and the thickness of the weathered layer. Conversely, by studying the properties of the weathered layer one can gain information about paleoclimates. Thick weathered layers have been observed in Australian deserts (over 150 m), Central Europe, and under thin glacial cover in Lappland, in regions where the present climates are not favourable for intense weathering. On the other hand, there are many tropical regions where the weathered layer is relatively thin because of continuing tectonic uplift (e.g. Central America, Jamaica). Therefore, one cannot speculate a priori about weathering patterns only by examining modern climatological maps.

Not all rock types are affected equally by weathering. Rocks with high content of resistant minerals, like quartz, are less affected by chemical weathering than those with an abundance of mafic minerals, which contain vulnerable elements like iron (Millot, 1970). Table 2.2 shows the vulnerabililty of the major plutonic and volcanic rock types to chemical weathering. The more easily weathered rocks (in the lower part of the table) contain more minerals that are replaced by secondary clays during the weathering process. The rock types are ordered according to their silica content (standard petrological nomenclature).

Sample weathering profiles are shown in Figure 2.2 for felsic and mafic rocks. From the bottom to top, we can identify several distinct layers: a) fresh rock, which is unaffected by weathering; b) zone of fractured rock, where the mineral composition is essentially the same as that of the parent rock (typically this zone is thick over granites); c) saprolite, where the original rock textures are still preserved by stable primary minerals and neoformed secondary clay minerals (formation of clays is more extensive over mafic rocks); d) leached (pallid) zone, which lies above the water table and where the clays are therefore less conductive; e) mottled zone, where the original rock textures are unrecognizable and the material becomes soft, and f) a ferruginous zone (duricrust, canga, cuirasse), which is hard and enriched in Fe minerals (hematite), but which may be missing in many areas. Clay minerals, such as chlorite, vermiculite, smectite and montmorillonite, which form over mafic rocks, are more conductive than sericitite and kaolinite which result from weathering of granites and gneisses (Butt, 1982).

Table 2.2 Standard classification of igneous rocks based on their silica content. The susceptibility of rock to weathering and saprolite conductivity increase with decreasing quartz content

	PLUTONIC	VOLCANIC	
QUATRZ ↑	GRANITE	RHYOLITE	↓ CONDUCTIVITY OF SAPROLITE
	SYENITE	TRACHYTE	
	QUARTZ DIORITE	DACITE	
	DIORITE	ANDESITE	
	GABBRO	BASALT	
	PERIDOTITE	ULTRAMAFITITE	

Resistivity or EM soundings can be used to obtain conductivity values of weathered layers. Peric (1981) reported from Burundi conductivity of saprolite formed over peridotite as being between 50-100 mS/m, leached zone (ferralite) 1.2 mS/m, and canga 0.15 mS/m. The respective thicknesses ranged from 20-40 m for saprolite, 7-20 m for ferralite, and 6 m for canga. In Goiás, Brazil, Palacky and Kadekaru (1979) found conductivity of 125 mS/m for a weathered layer formed over peridotite. Slightly lower conductivity values, 100 mS/m, were obtained for weathered amphibolite in Burkina Faso (Palacky et al., 1981). Saprolite formed over schists is less conductive and values of approximately 50 mS/m were reported from Burkina Faso (Palacky et al., 1981), Mali (Engalenc, 1978), and Pará, Brazil (Palacky and Kadekaru, 1979). Saprolite overlying granite appears more resistive, 14 mS/m in Burkina Faso (Palacky et al., 1981) and 15 mS/m in Bahia, Brazil (Palacky and Kadekaru, 1979). All values quoted were obtained from interpreted results of galvanic resistivity soundings which were converted to conductivity.

One can conclude that: 1) conductivity of saprolite depends on the parent rock, 2) conductivity values for a given lithology are fairly uniform not only within a given area, but on a global scale, 3) the more mafic the parent rock, the more conductive the saprolite. The third assertion has important implications for geological mapping — resistivity and EM methods appear to give results which correlate with the parent lithology.

AEM techniques may be more suitable for pseudogeological mapping than magnetic surveys in areas where lithological units do not have a sufficient susceptibility contrast. Because of its indirect character (an AEM technique is not "seeing" the rock but its weathered layer) the technique may be subject to many local limitations (absence of weathered layer because of uplift or glacial erosion). However, a duo of techniques (or possibly a trio, including gamma-ray spectrometry) would in any case be a more powerful mapping technique than magnetics alone.

Palacky (1981) published examples of application of AEM methods to geological mapping in Brazil. Figure 2.3 is a geological map of an area near the Araci gold mine in the Itapicuru greenstone belt (200 km NNW from Salvador, Bahia). The map of apparent conductivity derived from INPUT® AEM data is shown in Figure 2.4. In several areas resistivity soundings were carried out and the values obtained

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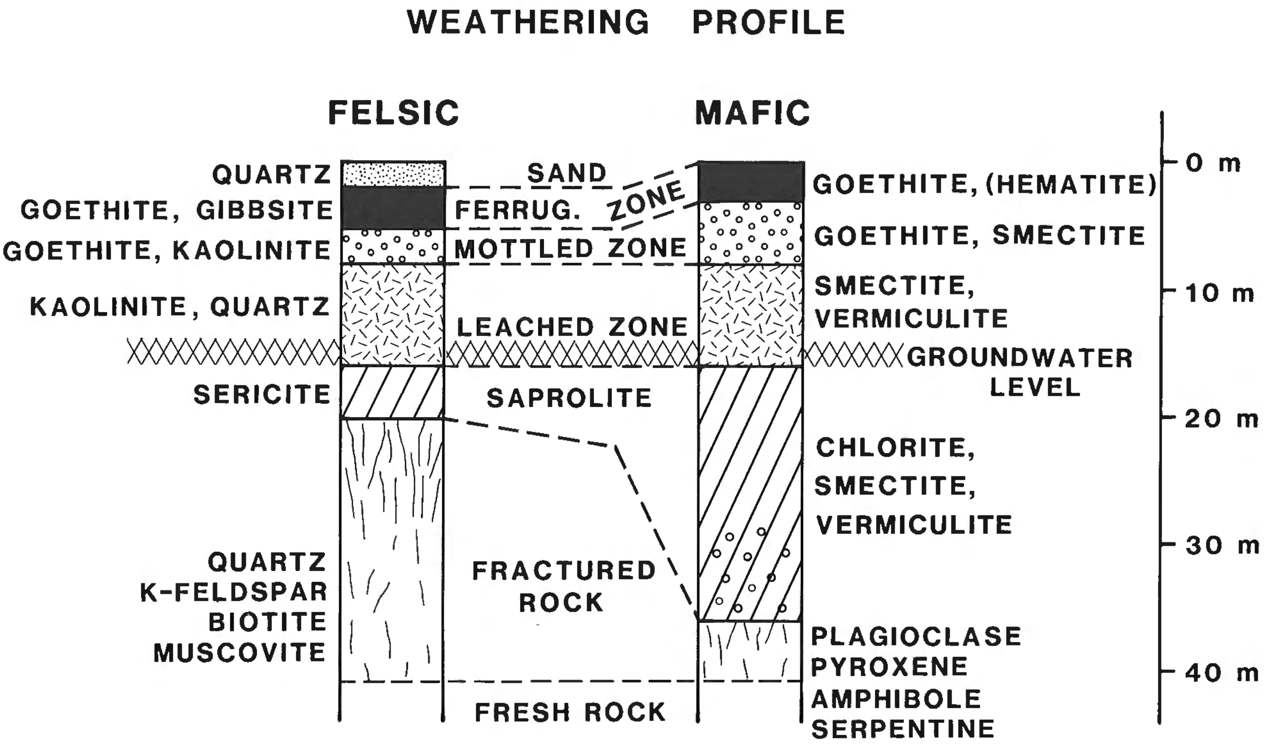

Figure 2.2. Weathering profiles over felsic and mafic rocks. The minerals most common for each layer (names in the centre column) are given on sides of the section. Mineral content of fresh rock and zone of fracturing are the same.

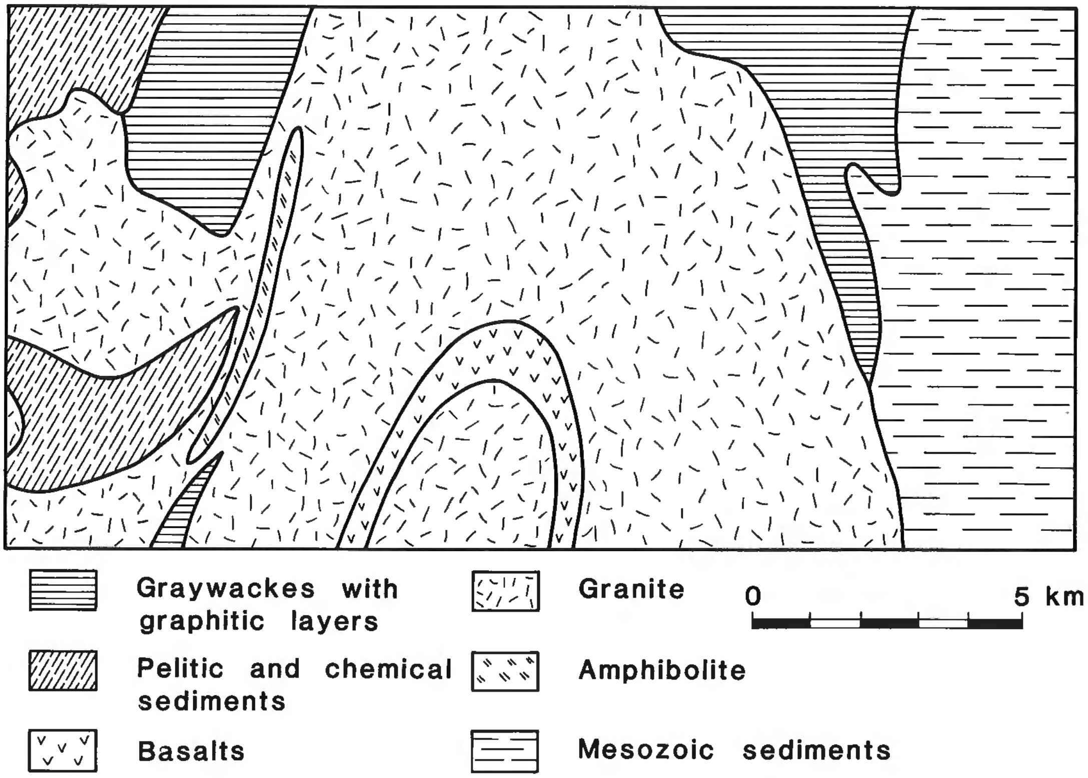

Figure 2.3. Geological map of a part of the Itapicuru greenstone belt (near the Araci gold mine) and its contact with Mesozoic sediments. State of Bahia, Brazil.

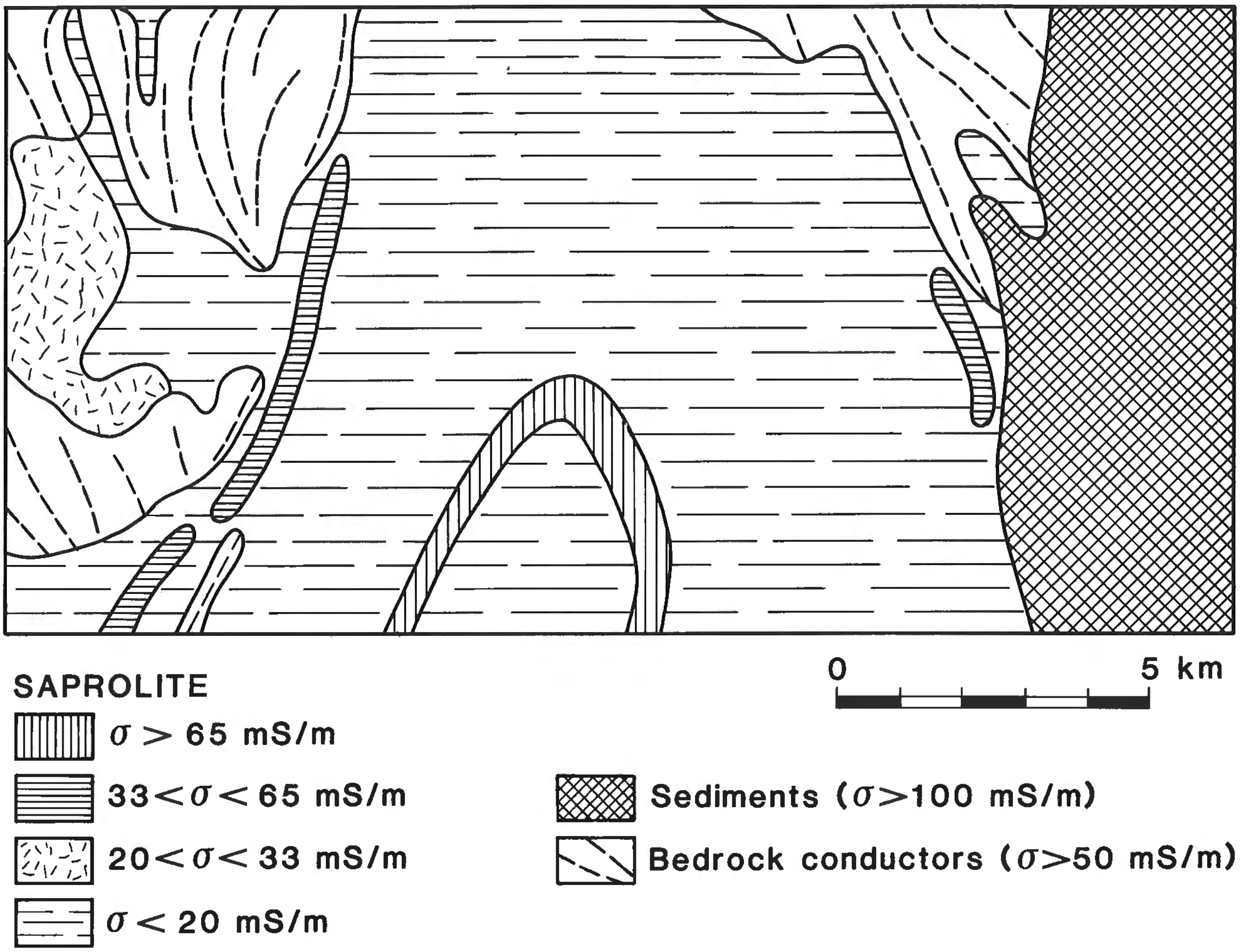

Figure 2.4. Map of apparent conductivity based on INPUT AEM data of the area shown in Figure 2.3. The conductive area in the east corresponds to Mesozoic shales. There are numerous bedrock conductors (graphite) in the Precambrian greywacke sequence. All other anomalies are caused by conductive saprolite.

from AEM and ground data were in agreement. Highest conductivity values (over 100 mS/m) were obtained over Mesozoic shales (Aliança Formation) which are highly conductive even when unweathered (Lima, 1979). In the shield, numerous anomalies (narrow in shape) are caused by graphitic layers within the greywacke sequence. Existence of some conductors was confirmed by drilling. The remaining anomalies appear to be related to saprolite, whose conductivity varies according to the underlying geology. The most conductive saprolite layers (over 60 mS/m) form over basalts, slightly less conductive layers were found over amphibolites. The INPUT response over granite was essentially zero, but resistivity soundings indicated conductivities of approximately 15 mS/m for the saprolite layer. One should add that there are very few outcrops in the area and that geological mapping is largely based on soil colour differences. This fact enhances the applicability of the AEM method to geological mapping in tropical regions.

Selective weathering permits the use of AEM techniques in diamond prospecting. The "yellow ground" forming over kimberlites is highly conductive (Macnae, 1979). In Africa, AEM surveys have been found to be more reliable exploration tools than magnetics. Several types of mineral deposits are related to the weathering process: bauxite, nickel laterites, saprolite gold (e.g. Serra Pelada, Brazil) and cassiterite (e.g. Central Goiás, Brazil). Even though marginally used to date, EM methods could be effectively applied in conjunction with geochemistry in prospecting for such orebodies.

The application of AEM surveys to general geological mapping in Canada depends to a large extent on the development and preservation of weathered layers. Recent geological studies have indicated that existence of such layers is more common in glaciated areas than thought previously (e.g. Veillette and Nixon, 1982). Figure 2.5 shows a geological map and INPUT AEM conductors from the Rice Lake greenstone belt in Manitoba (Dyck et al., 1975). Most of the area shown is underlain by granites of the Wanipigow River Plutonic Complex. Six AEM anomalies in the lower part of the map are associated with a peridotite body, whose outcrops have been mapped. The INPUT survey was flown with a horizontal-coil configuration and the type of response obtained resembles a horizontal ribbon rather than a vertical dyke. This suggests that the source of anomalies lies in a saprolite layer formed over peridotite. Petrophysical studies indicate that fresh peridotite is highly resistive (Angenheister, 1982).

WATER

Conductivity of water depends on its dissolved mineral content and temperature. The most common mineral dissolved in water is sodium chloride. Sea water conductivity varies substantially from sea to sea, e.g., the Red Sea has a very high salt content, the Baltic, very low. Measurements performed in the Atlantic Ocean indicated that 4 S/m can be assumed as a representative near shore conductivity value. Because this value remains constant over a given area (with the possible exception of tidal beaches), one can use AEM systems to measure the thickness of the water layer, and in this way perform bathymetric charting. So far only a few tests have been performed (Won and Smits, 1986; Becker et al., 1986), but the results appear encouraging. Accuracy of 1 m in water to a depth of 20 m has been achieved. Depth sounding capabilities of AEM systems can hopefully be extended to 100 m.

Another application (Fig. 2.6) of AEM technique which seems feasible is to measure the thickness of ice in Arctic regions (Holladay et al., 1986). Ice is more resistive than sea water (20 mS/m and 4 S/m, respectively). Repeated surveying of shipping lanes by helicopter EM systems would make passage by icebreakers safer. Fuel could be economized by selecting traverses with lesser ice thickness.

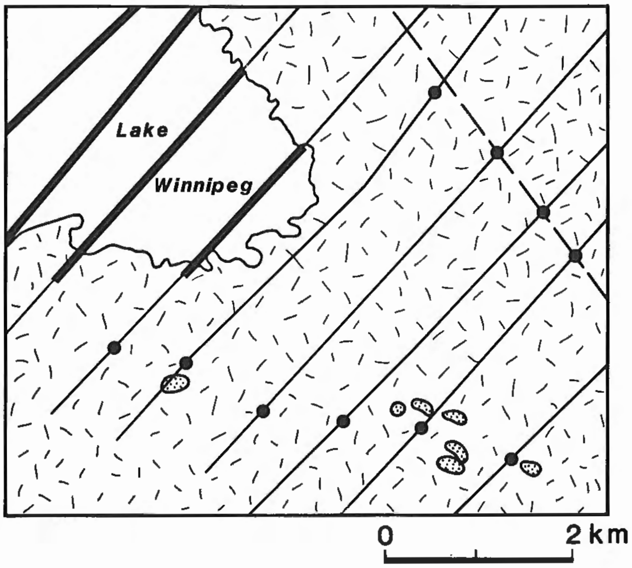

Figure 2.5. Geological map of area 5 of the Project Pioneer in Manitoba (after Dyck et al., 1975). The location of INPUT AEM anomalies is also indicated.

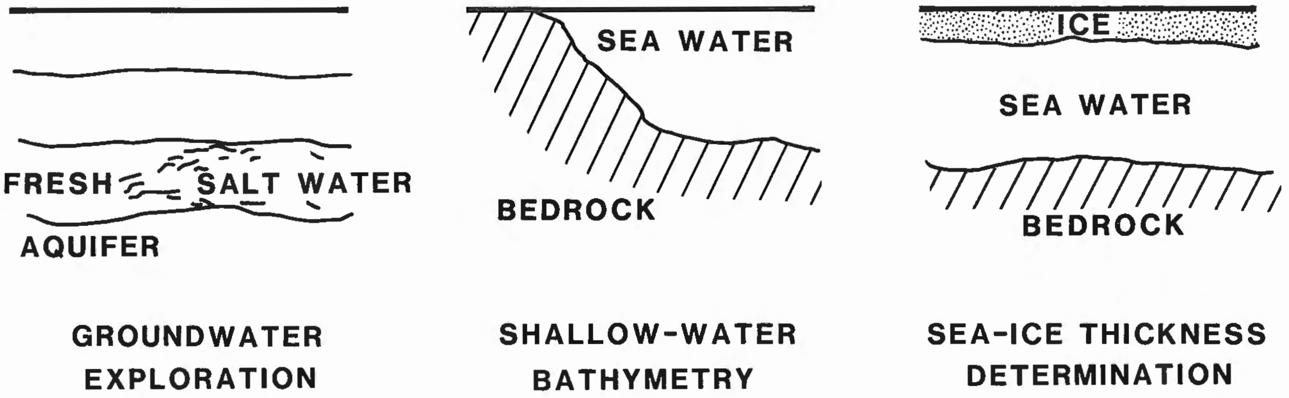

Figure 2.6. Situations in which mapping of salt water presence or its thickness has practical importance (groundwater exploration, shallow water bathymetry, and airborne ice-thickness measurements).

Conductivity measurements have been used to map the extent of salt water aquifers in coastal regions. Surveys have been carried out in various countries, in France as early as 1966 (Baudoin et al., 1970). Two surveys are reported in this volume (Johnson and Seigel, 1986; Sengpiel, 1986). Salinity increase in soils after years of intense irrigation causes fertility degradation. The problem is becoming serious in many regions of the world. AEM surveys can be used to map the extent of the affected areas (O'Connell and Nader, 1986).

Compared with prospecting for massive sulphides all applications mentioned in this section are still less common, but the potential volume of surveys related to other objectives may become in future larger than in mineral prospecting.

CONCLUSIONS

The AEM technique has the potential of becoming a versatile mapping tool. Anomalies are caused not only by bedrock conductors (sulphides, graphite, magnetite), but also by clays which are present in weathered layers, hydrothermally altered zones, and glaciolacustrine sediments. Multifrequency or wide-band AEM measurements should become an integral part of multiparameter geophysical surveys that are carried out in resource-inventory programs. Economic spinoffs would be of significance not only in mineral prospecting, but also in groundwater resource assessment. Systematic mapping programs are more cost-effective than one-purpose surveys. In offshore areas AEM systems can be used for bathymetric charting and in Arctic waters for monitoring of sea ice thickness.

ACKNOWLEDGMENTS

Discussions with colleagues at the Geological Survey of Canada (B.W. Charbonneau, T.J. Katsube, J. Mwenifumbo, A.R. Miller, K.A. Richardson) were useful during the preparation of this paper.

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- 3 -

Modelling of airborne electromagnetic response: present capabilities and future expectations

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Abstract

An ability to predict at least roughly what response should be expected from an electromagnetic (EM) exploration system when it is in the vicinity of a given configuration of conductors is fundamental to EM survey interpretation. Early interpretation procedures were based on a few elementary analytical models such as a uniform sphere in free space and a source on a conductive half-space, and on "type curve" studies carried out on scale models, mostly of dipping sheets. More recently, computing methods have improved to the point where models of somewhat greater complexity can be analyzed at reasonable cost. Complex models such as an arbitrarily shaped target-conductor in an arbitrary host medium are, however, still very difficult to handle, either computationally or in the scale-model laboratory.

Currently, computer modelling is a relatively straightforward way of obtaining the frequency or time-domain response of a controlled source EM system to an arbitrarily layered half-space, a sphere, a plate, or to a number of other simple shapes in an insulating host medium. With more difficulty and with more limitations, a simple target conductor in a host medium consisting of a uniformly conductive half-space or layer and half-space can be handled. Research trials on arbitrarily structured two-dimensional models (3d source) have shown promise. In the scale modelling laboratory, electronic advances have facilitated the modelling of time-domain EM systems. Modern computer plotting systems have made the production of systematic type curve sets more economical.

For situations where cost-effective modelling is possible, inversion methods have been constructed based on Marquhardt type iterative regression or on other methods. Where the number and range of free parameters in the model is limited and the observational data can be reduced to a few key characteristics, inversion by table look-up techniques is a very fruitful approach.

Résumé

Pour interpréter un levé électromagnétique (ÉM), il est essentiel de pouvoir prédire au moins approximativement quelle réponse attendre d'un système ÉM lorsqu'il est au voisinage d'une configuration de conducteurs. Les premiers procédés d'interprétation étaient basés sur quelques modèles analytiques élémentaires, p. ex. une sphère uniforme en espace libre et une source sur un demi-espace conducteur, et sur des études de "courbes types" effectuées sur des modèles à l'échelle, principalement des feuilles inclinées. Récemment, on a amélioré les méthodes informatiques si bien qu'on peut analyser des modèles d'une complexité un peu plus grande à des coûts raisonnables. Toutefois, les modèles complexes, p. ex. un conducteur-cible ayant une forme arbitraire dans un milieu arbitraire, sont encore très difficiles à manipuler, tant par calculs que sur des modèles à l'échelle en laboratoire.

Actuellement, l'élaboration de modèles par ordinateur est une façon relativement directe d'obtenir la réponse d'un système ÉM à source contrôlée dans le domaine des fréquences ou dans le domaine temporel a causée par un demi-espace des couches arbitraires, par une sphère, par une plaque ou par un certain

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nombre d'autres formes simples dans un milieu isolant. On peut, avec plus de difficultés et de limitations, manier un conducteur-cible simple dans un milieu uniformément conducteur en forme d'un demi-espace ou d'un tandem couche/demi-espace. Des essais théoriques sur des modèles à deux dimensions (source tridimensionnelle) arbitrairement structurés ont été prometteurs. Dans le laboratoire de modèles à l'échelle, des progrès électroniques ont facilité le modelage de systèmes ÉM à domaine temporel. Des systèmes modernes de traçage par ordinateur ont rendu plus économique la production d'ensembles systématiques de courbes types.

Dans le cas où un modelage rentable était possible, on a utilisé des méthodes d'inversion basées sur une régression itérative de type Marquhardt ou sur d'autres méthodes. Si le nombre et la gamme des paramètres libres du modèle sont restreints et qu'on peut ramener les données d'observation à quelques caractéristiques clés, l'inversion par des techniques de contrôle tabulaire est une approche très fructueuse.

INTRODUCTION

To discuss the modelling of airborne EM response, it is useful to classify AEM applications into 3 categories:

1. Search for unusually conductive features in a comparatively resistive host medium.
2. Areal conductivity mapping, particularly of surficial materials.
3. Identification and interpretation of complicated conductivity structures.

Interpretation concepts and techniques differ depending on the category of the problem being investigated, but all involve determination of model responses. The basic models for the first two applications are:

1. Discrete uniform conductors in free space.
2. Horizontally layered earth models.

The third category includes all cases which are too complicated for 1 or 2 to be applied. By and large, our present capabilities in modelling are reasonably satisfactory for categories 1 and 2, but *tour de force* efforts are still required for the more complicated cases.

There are two basic methods of response modelling: numerical evaluation of mathematical solutions to the EM equations, and measurement on scale models. Both methods have been used since the inception of EM geophysical exploration, and both methods are still strongly limited in the cases they can handle adequately. Neither method has supplanted the other. The great advances of recent years in computing capability have lead to corresponding advances in computational techniques of EM modelling, and evaluation of analytical solutions is being supplanted by direct numerical solution methods. In the scale modelling laboratory, electronic advances have made measurement much less laborious than formerly.

Conceptual distinctions between airborne and ground EM are only marginal, insofar as interpretation and modelling are concerned. However, it is an annoying feature of all controlled source EM methods that modelling studies are necessarily specific to a single type of EM system. In this short review, I concentrate initially on what modelling is available to assist AEM interpretation. Unfortunately, most recent modelling developments have focussed on ground EM, but they could certainly be applied to AEM if there is enough need. They are discussed under new developments.

The main distinction between ground and airborne EM interpretation is in the quantity of data to be analyzed and the level of detail or resolution expected in the interpreted output. The large amount of data usually acquired, coupled with the limited spatial information provided by a usual airborne survey grid having a line separation of, say, 400m (not to mention any other possible limitations of the airborne survey) means that interpretation must concentrate on simple methods which reliably can give a rough idea of subsurface conductivity in the survey area, rather than on elaborate model fitting exercises directed to obtaining detailed information about specific anomalies.

PRESENT STATUS

Conductive targets in free space

Much routine interpretation of AEM surveys for conductive target location has been based on the following models consisting of a single homogeneous conductor in free space:

1. Dipping thin half-plane.
2. Dipping rectangular plate.
3. Sphere.

Currently, responses to these models are most easily obtained by computation, but most early AEM interpretation methods were in fact developed from a computed solution for a perfectly conductive half-plane (e.g., Wesley, 1958; Wieduwilt, 1962) and scale model studies on plates of finite conductivity (e.g., Grant and West, 1965; Ward, 1967; Ghosh, 1972; Palacky, 1974). Several organizations have their own computer models for such cases, but accessible programs well known in Canada are the Annan/Dyck program PLATE and the Nabighian/Dyck program SPHERE available from the University of Toronto (Dyck et al., 1980). Weidelt (1983) has developed a method for modelling a half-plane of finite conductance.

Interpretation concepts based on free-space conductor models have really not changed much in the last two decades. The well known review by Ward (1967) is still an excellent introduction to current practice. The vertical half-plane model serves as a basic reference point because of its simplicity (only two parameters, depth to top and surface conductance) and its widespread applicability to interpreting data from the greenstone belts of glaciated shields. Other studies show the general effects of shortened strike and depth extent, dip and strike angle, etc., and the ability to resolve multiple conductors. What has happened in the interim is that similar kinds of study have been made for new types of EM systems. The fixation with plate-like models continues, although some attention has been given to interpreting compact massive conductors with a sphere (Lodha and West, 1976; Best and Shammas, 1979). In retrospect, it seems clear that availability of a practical modelling capability has as much influence on what models are used in interpretation as any *a priori* consideration of actual ground structure.

Layered earth models

The formal mathematical solution for the EM response of layers has been well known for more than sixty years. The horizontal spatial variation of the field in (r,θ) or (x,y) coordinates is Fourier transformed to horizontal wavenumber domain. For a dipole transmitter, the angular (θ) variation of the various EM field components is always simple for a dipole type of source, so the Fourier representation is usually written as one or possibly a very few terms in which radial wavenumber is the only transform variable. General solutions of the transformed equations are easily obtained for any number of layers, either in explicit algebraic form or as a recursion relationship. Source terms are likewise easily written explicitly. Solutions for the fields in space domain are then obtained as the Hankel inverse transform of an algebraically computable function which describes the source and the layering. Solutions for transient responses require a further inverse Fourier or Laplace Transform.

Although responses to certain simple models such as a uniform half-space have long been relatively easy to evaluate for airborne EM configurations (e.g., Wait, 1955, 1958), it was some time before similar results could be obtained for the time-domain INPUT® system (e.g., Morrison et al., 1969). However, development of algorithms such as the Fast Hankel Transform (Koefoed et al., 1972; Anderson, 1979; Johansen and Soerensen, 1979) and Exponential Fourier Transform (Lamontagne, 1975; Holladay, 1982) have now made it relatively easy to calculate layered earth response for any kind of layering or EM coil configuration in frequency or time domain. Nevertheless, such programs are not trivial to code, and occasionally suffer from accuracy problems. In general, AEM responses are much easier to calculate than ground EM cases because the height of the system introduces an exponential convergence factor into the Hankel inverse transform. There is now little excuse for an AEM interpreter not to have a convenient layered earth modelling program available for his system.

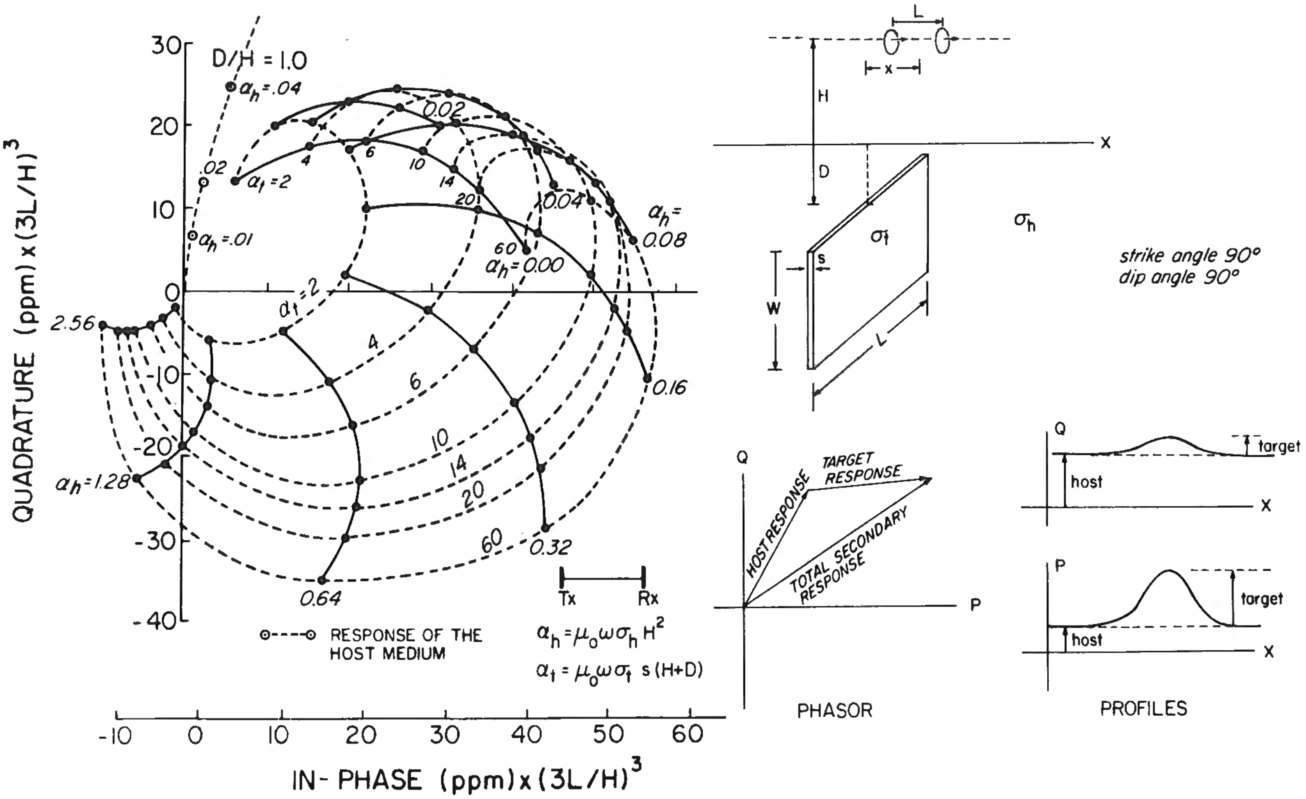

Figure 3.1. Effect of a uniformly conductive host medium on the local anomaly observed by a helicopter EM system over a vertical plate-like target conductor. Note that anomaly strength is measured from the regional (host) response level. Host response is also plotted for small values of the host medium's response parameter. Note how the target anomaly is enhanced from the free space value in amplitude as the host conductivity increases, and is then phase rotated and attenuated at higher conductivities (Ferneyhough, 1985).

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Complex models

In only a few cases has the response of a complex model been studied systematically over a range of parameter values for a practical EM system, either by scale model or mathematical methods. One example is the vertical plate conductor in a conductive half space with or without an overburden layer (Lajoie and West, 1976; Hanneson and West, 1984). This is an important model for base metal exploration, but still is of limited applicability because it lacks geometrical flexibility and is expensive and cumbersome to use. The most interesting results are the filtering effect of the overburden and overlying half-space on the plate anomaly (relative to a free-space case) and the enhancement of the plate anomaly by currents channelled from the host region whenever the host is sufficiently conductive. Figure 3.1 shows the twin effects of a uniform host medium as seen by a frequency-domain helicopter EM system. Figure 3.2 shows the equivalent results for a time-domain AEM system. They were calculated by Ferneyhough (1985) using an extended version of Hanneson's program.

The effect on the response of an underlying target conductor situated in a resistive host medium, of an overburden not in contact with the target is known to be principally a phase rotation. Ferneyhough (1985) has shown that such an overburden can easily be introduced approximately into most free-space conductor models, at least for calculation of the peak anomaly amplitude. The procedure is just to find a frequency-domain filter function using a layered earth algorithm and apply it to the free-space results, before converting to the time-domain if that is required. Figure 3.3 gives an

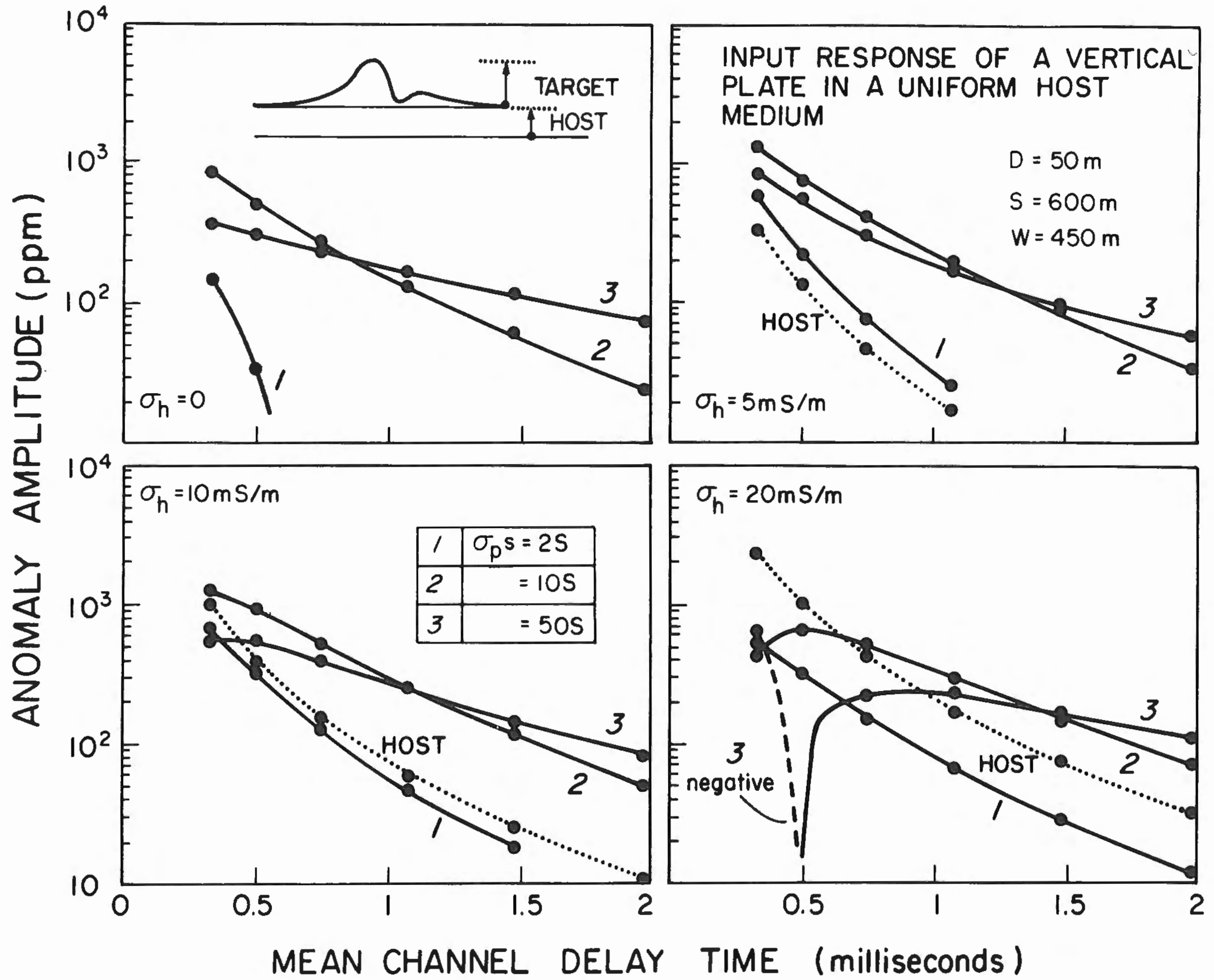

Figure 3.2. Effect of a uniformly conductive host medium on the INPUT response of a vertical plate. Anomaly amplitude is measured relative to the host response level, and the host response is plotted separately. Note how increasing the conductivity of the host medium adds to the target response a component which has a decay rate similar to the host medium, and supresses or even reverses the early time target response (Ferneyhough, 1985).

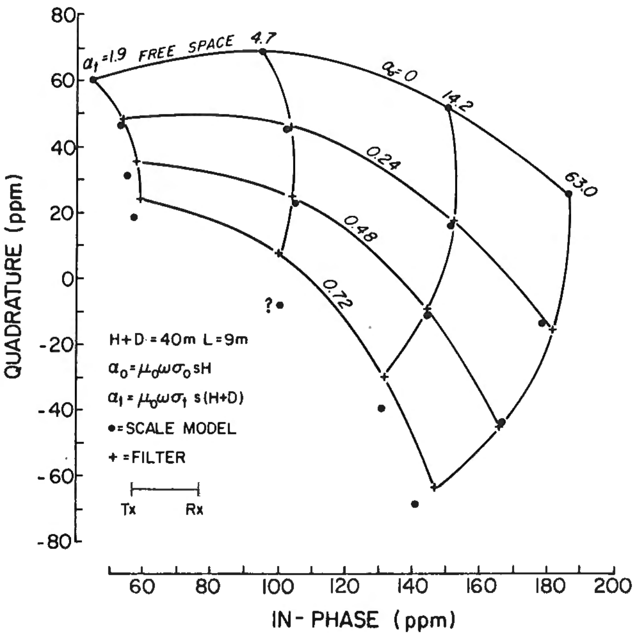

Figure 3.3. The effect of a conductive overburden layer on the reponse of target conductor in an insulating subspace, modelled as a simple filtering process. Here the filter for a thin sheet overburden has been applied to free space HEM model data from Ghosh (1972), and the result can be compared with analogue scale model data where an overburden layer is included. The filter theory provides a reasonably good estimate of the overburden effect, but becomes progressively less accurate when the overburden becomes more conductive (Ferneyhough, 1985).

example for frequency-domain helicopter EM and Figure 3.4 gives a simplified example for a time-domain system.

The effects of host rock and overburden on the response of a helicopter EM system are not much different qualitatively than on a ground horizontal-loop EM. Their manifestations in a time-domain system with an INPUT waveform are, however, somewhat paradoxical. The conductive host medium and overburden of course contributes a strong additional component to the total response. More surprisingly, its filtering effect on the target component of the response not only reduces the early time target response but makes it negative. This comes about mainly because the receiver output is proportional to the time derivative of magnetic field. The secondary magnetic field from the target is initially supressed by the shielding effect of the overburden, and then its growth phase produces a negative voltage in the receiver coil. The negative response was demonstrated on model data by Palacky (1974).

Inverse methods

The classical method of interpreting AEM data has been the Method of Characteristics whereby some key characteristics of an anomaly are defined and measured and then compared with graphs (called interpretation diagrams or characteristic curves) which relate the same characteristics to the parameter values of a simple model. The simplest and best known AEM example is the helicopter EM response characteristics of a vertical half-plane model (Fig. 3.5), where the anomaly characteristics are just the peak in-phase and quadrature amplitudes which are related to the model parameters depth-to-top and conductance. Palacky and West (1973) introduced an interpretation technique based on peak amplitudes for 6 measured channels for the INPUT system.

The Method of Characteristics is easily extended to take account of slightly more complicated situations, such as the strike angle at which the flight path crosses the conductor, dip, etc., and may readily be automated by storing the characteristic curves as tables in a computer and obtaining the parameter values of the model from the observed values of

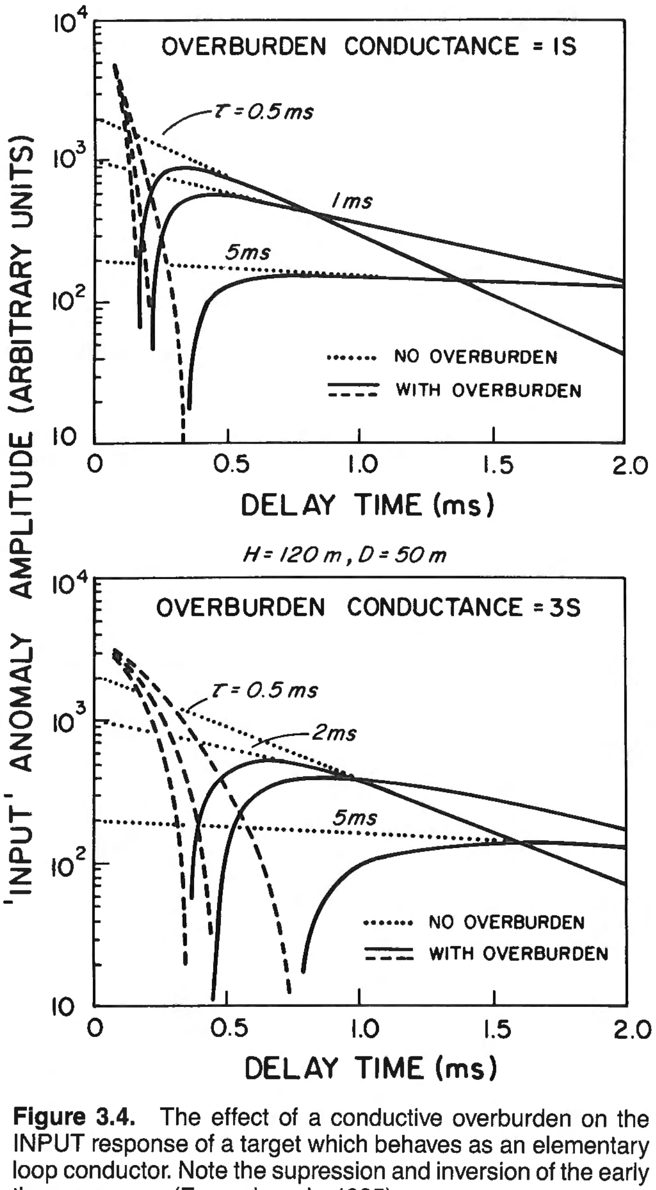

Figure 3.4. The effect of a conductive overburden on the INPUT response of a target which behaves as an elementary loop conductor. Note the supression and inversion of the early time response (Ferneyhough, 1985).

anomaly characteristics by table look-up and interpolation. Figure 3.6 gives some examples of interpretation diagrams for plate models. De Moully and Becker (1984) described such interpretation approach for the INPUT system.

The method of characteristics is based on finding *n* unknown model parameters from *n* measured characteristics. Error limits can be assigned in the inversion process, but problems of ambiguity and mismatch are glossed over. The problem may be somewhat remedied if a non-linear, iterative, least-squares regression approach is taken using the Marquhardt algorithm or one of its relatives (Glenn et al., 1973). Layered earth modelling algorithms for frequency domain EM systems are simple enough to be used in this way, when the quality and variety of data acquired by the AEM system warrant it.

UNDER DEVELOPMENT

Computer methods

Many different numerical modelling methods have been tried, with varying degrees of success and practicality. Hohmann (1985) has provided a very useful review. In general, modelling of EM response (which must necessarily be of 3-dimensional fields if it is to be compared with controlled source AEM field data) has proved to be more difficult than for resistivity or other potential field methods. Difficulties arise from the diffusive nature of the EM field, the rapid geometrical attenuation of field strength with distance from the source, and the dualistic physics of EM induction in complicated media (the electric field being generated both by charge on boundaries and by changing magnetic field). Few

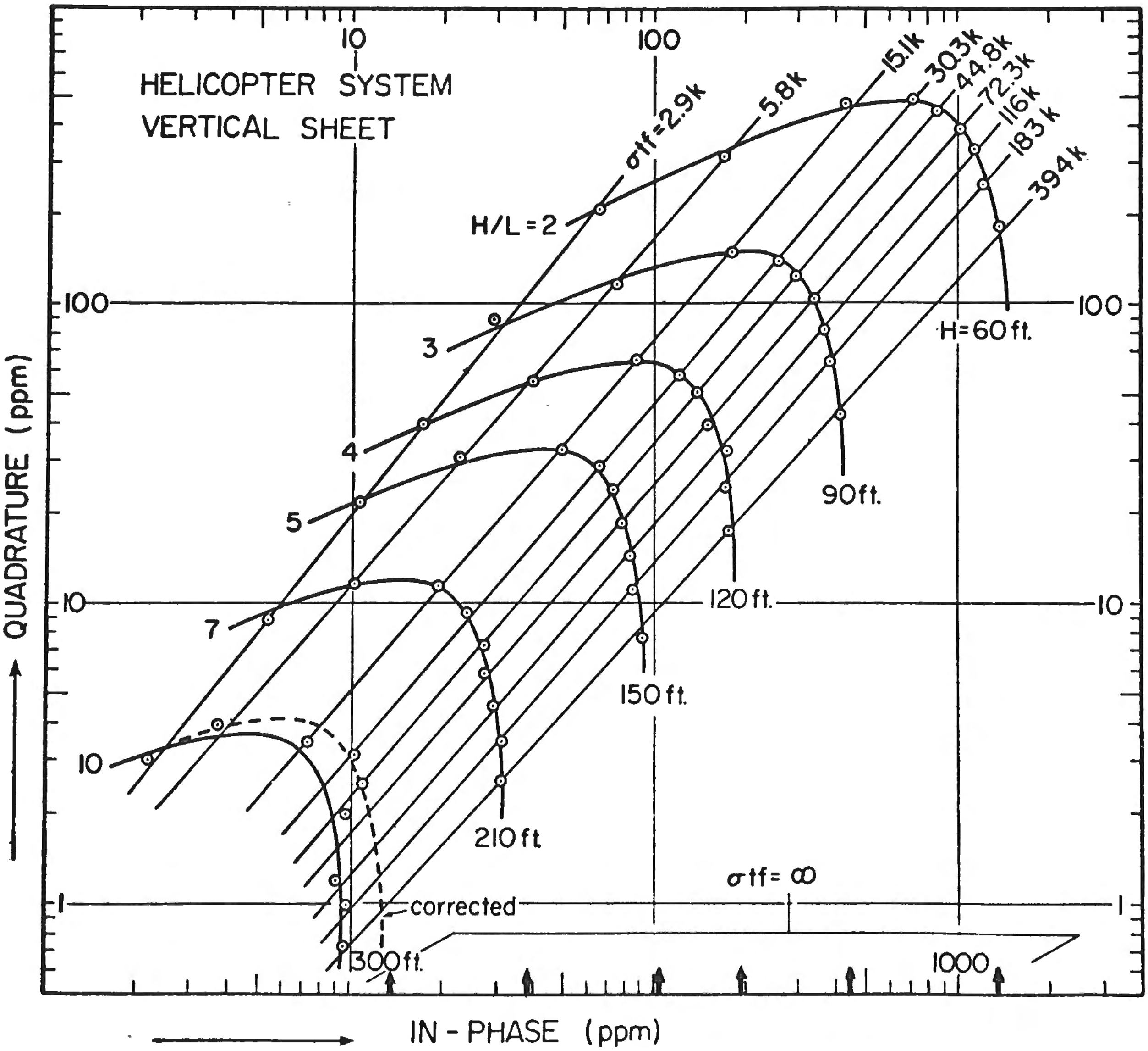

Figure 3.5. HEM anomaly characteristics for a vertical half-plane model, from Ghosh (1972). Peak in-phase and quadrature anomaly amplitude is related to depth-to-top and conductivity-thickness of the model.

methods have been able to deal with all three problems simultaneously and at the same time be simple, economical and robust.

There are three basic methods for numerical solution of the EM equations: integral equation, finite difference/finite element, and hybrid methods. They differ in how general a model may be analyzed and are illustrated in Figure 3.7. The integral equation method is the most restrictive in model design, requiring the model to consist of a limited region of uniform anomalous conductivity superimposed on a simple background medium. The FD/FE method allows a general specification of the model, but it is very slow to execute and often has accuracy problems. The hybrid method is an attempt to combine the better features of both.

Researchers at several institutions have constructed various kinds of model and run a few test cases with them (e.g., Best et al., 1985; and for a list *see* Hohmann, 1985), but I am not aware of any extensive parametric studies yet made with them which are applicable to AEM. However, I think they will soon (2-3 years) offer practical though not inexpensive modelling capability to AEM interpreters. The methods of numerical modelling which show the most promise of practicality in the near future are those that limit the form (integral equation methods) or the dimensionality of the conductivity model. So-called 2½ models (2d earth model, 3d EM source fields) permitting arbitrary conductivity structure have been successfully analyzed using FD/FE or hybrid methods.

An example of a freely structured model of reduced dimensionality that is approaching practicality is a thin horizontal sheet of arbitrary and variable conductance. It can be used to study the AEM response of a patchy overburden. Smith (1985) has developed numerical methods for simulation of frequency or time-domain EM response of this model

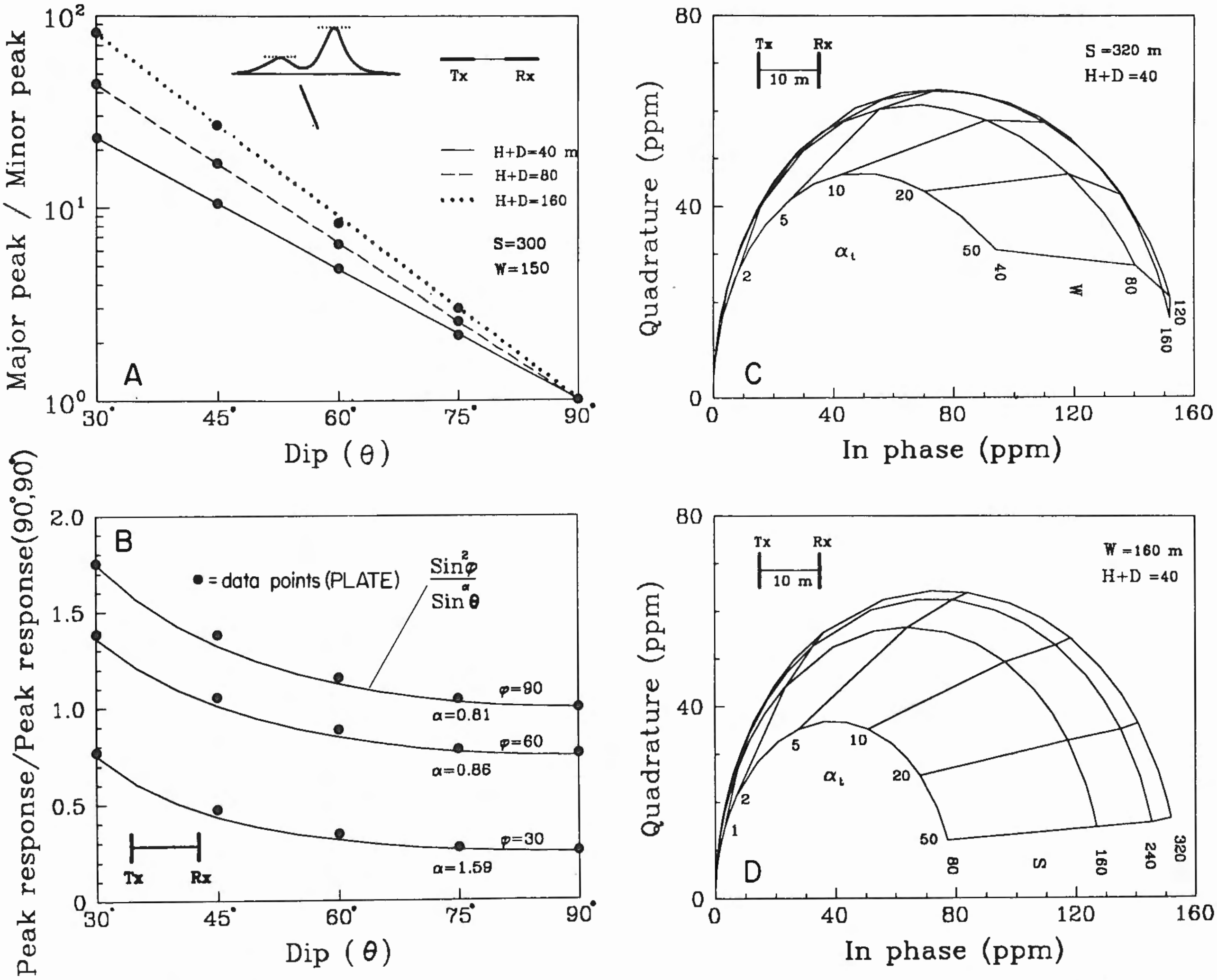

Figure 3.6. HEM anomaly characteristics for a thin plate target. Figures A and B show one way of handling dip and strike angles. Dip can be estimated from the asymmetry of the coplanar coil system's anomaly (A) and strike from the correlation of anomalies on adjacent lines. B then is used to correct the observed coaxial coil anomaly amplitudes before application of Figure 3.5. C and D show, for one flight height and geometry, how the effects of dip extent (W) and strike extent (S) affect the response (Ferneyhough, 1985).

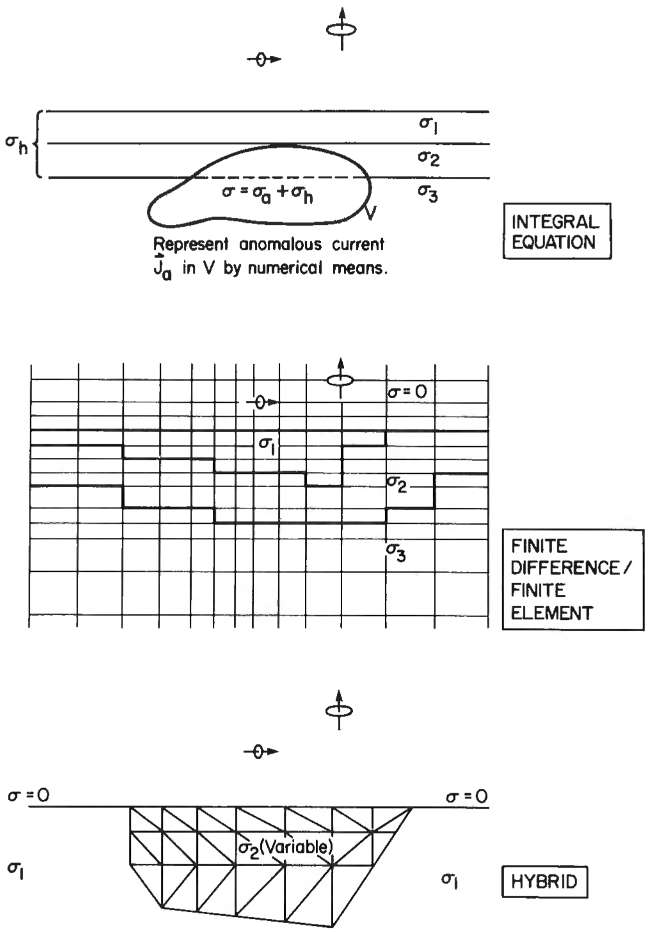

Figure 3.7. Discretizations for numerical modelling by the integral equation, FD/FE, and hybrid methods, shown for a two-dimensional ground structure. For the IE method, the host medium must be simply layered, and the anomalous region must be of simple shape and uniform anomalous conductivity. The FD/FE method discretizes all of the space occupied by the EM fields, using rectangular (FD) or more complex (FE) grid cells. The hybrid method discretizes a limited region and inserts it into a very simple host region.

(Fig. 3.8). The technique is computationally intensive, requiring an array processor for economical use, but otherwise reasonably robust and accurate. Extreme conductance contrasts are a limitation.

Scale modelling

The limitations of the scale modelling laboratory are of long standing. It is difficult to make a good contact between different types of material except for a solid immersed in a liquid which can lead to unwanted IP problems at interfaces if modelling is done at low frequencies (Guptasarma, 1983). Some modelling of uniloop TEM has been done with cast metals (e.g., Spies, 1980) but thermal contraction can be a problem. Also, it is laborious to make systematic changes in conductivity of model conductors; frequency is the only easily changed intrinsic parameter. Furthermore, there are very large gaps in the conductivity spectrum of easily available materials (Fig. 3.9). These factors combine to make scale modelling most useful for investigating those problems where a universal conductive host medium is not required and where computer modelling is not applicable. Examples might be investigations of complicated shapes or multiple conductors.

Where an electrolytic host medium is to be used and the modelling laboratory has limited dimensions, it often becomes necessary to use frequencies in the high kHz-low MHz range. Modern wide-band differential amplifier and analogue-to-digital conversion technology as used in current digital oscilloscopes has certainly made accurate phase and amplitude or time-domain measurement routinely feasible in this part of the spectrum where it was formerly difficult. It has been demonstrated that composites of intermediate conductivity between strong electrolytes and sintered carbon can be made by mixing graphite or similar materials in a self-setting plastic, but it is difficult to achieve satisfactory homogeneity without industrial scale manufacturing facilities. It seems likely, however, that suitable materials in the range of 10^3–10^4 S can be found or manufactured, if there is sufficient interest and need.

A *state of the art* versatile modelling laboratory with computer driven positioning and computerized data logging reduction and plotting can now be put together from purchaseable components and some custom engineering of a few items such as the model EM system coils and the transmitter drive circuits. The cost is in the neighbourhood of $200 000. Effective production of data output would be more the work

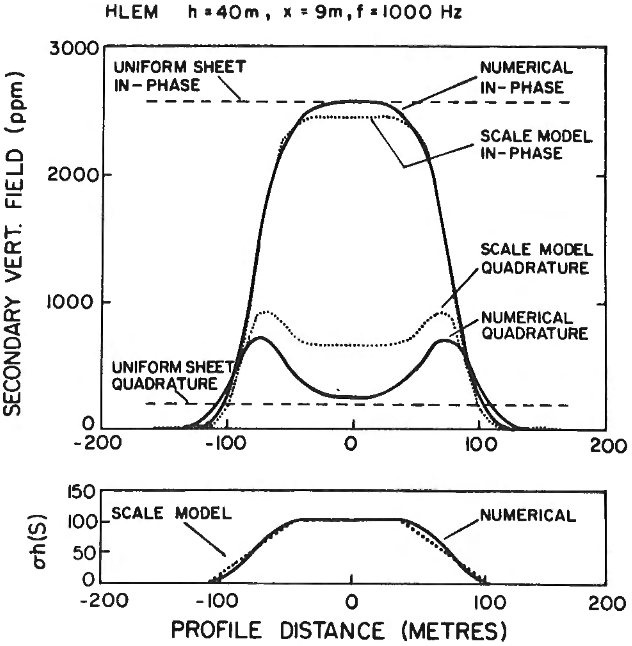

Figure 3.8. Test of a method for calculating numerically the HEM response of a thin overburden of laterally varying conductance. The example shows the response of a conductive strip of overburden with tapered edges. The scale model results were over a relatively thick sheet, and this accounts for most of the differences between the calculated and measured data (Smith, 1985).

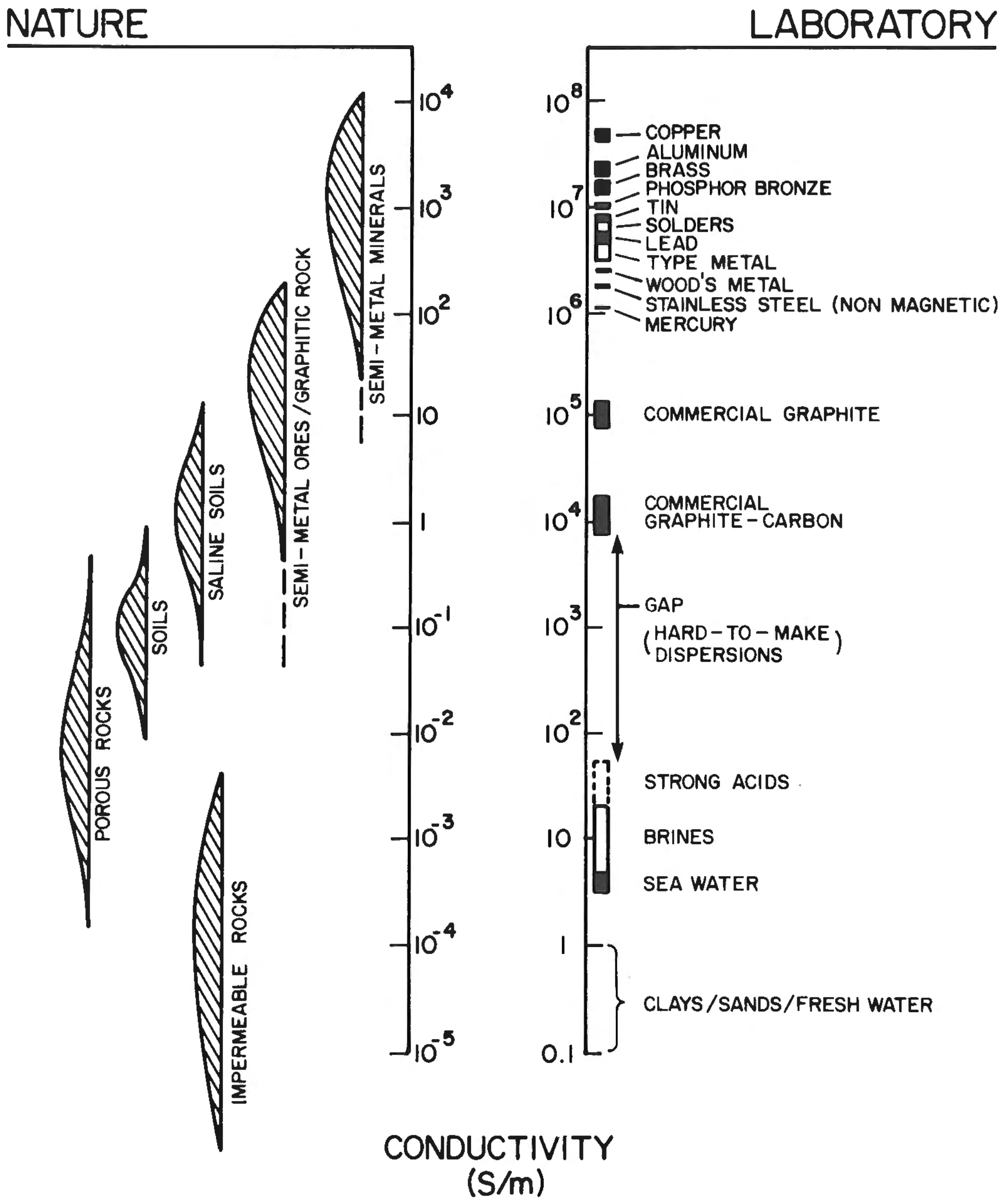

Figure 3.9. Conductivities of materials useful for scale model studies of geophysical EM problems.

of a skilled professional rather than graduate students. There is no doubt in my mind that the necessary modelling data to solve many interpretation problems could be produced from such a facility at very moderate operating cost, if the geophysical industry felt the need were great enough to warrant the setup expense.

OUTLOOK

Numerical modelling is indeed the way of the future. One cannot, however, expect numerical methods to solve all modelling problems. Scale model studies will remain a cost-effective and even the sole method of tackling some problems for a long time. The ideal of a completely flexible computer modelling package where any EM system can be specified and any arbitrary picture of ground conductivity can be modelled is still a long way off, either from a technical or an economic point of view. Generalized inversion of data onto such a general model is even further in the future, if it is even possible or desirable. Nevertheless, we can expect to see computer modelling of a number of new and useful idealized field situations soon become available.

Given the considerable expense of developing and running complex computer modelling programs and also the amount of intelligent supervision required to make sure that the output data are reliable, practical use of these models in inversion and interpretation will be obtained by carrying out comprehensive *a priori* model studies and then creating a numerical data bank from each study that can be interpolated by computer for arbitrary input values of the model parameters. The data interpolation computer program then may serve as the basic forward modelling algorithm for an automated inversion method.

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- 4 -

Inversion of airborne electromagnetic data for overburden mapping and groundwater exploration

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Abstract

The airborne electromagnetic (AEM) method has been increasingly used in geological mapping, exploration for coal and lignite, geotechnical studies, and groundwater prospecting. The most meaningful way of interpreting AEM surveys conducted for such applications is to invert the measured data and obtain estimates of conductivity and thickness of the important subsurface layers. An analytical method based on singular value decomposition (SVD) was developed for a three-layer model, which is under normal circumstances the most realistic in the above mentioned situations. The algorithm provides stable, geologically meaningful solutions and can deal with real situations, such as the disappearance of the conductive upper layer.

The inversion method has been tested on approximately 4000 line km of data obtained in the course of AEM surveying in Africa and North America. Examples are shown of inversion of two-frequency helicopter EM data from Tanzania, where the objective was to map the surface of unweathered bedrock. In Canada, 3-frequency helicopter EM surveys were conducted as a part of the nuclear fuel waste management program where one of the tasks was to map the thickness of glacial sediments and the topography of the underlying Precambrian. In western USA, helicopter EM surveys have been used to determine the depth to water table in semi-arid areas. In the three mentioned surveys (and several others) the inversion algorithm provided the desired answers at a relatively modest cost. Continuous inversion of AEM data appears to be a powerful tool for many new applications.

Résumé

La méthode des levés électromagnétiques aériens (ÉMA) est de plus en plus utilisée pour la cartographie géologique, la prospection du charbon et du lignite, les études géotechniques et la prospection des eaux souterraines. La façon la plus valable d'interpréter les levés ÉMA effectués pour ces applications consiste à inverser les données mesurées pour obtenir des estimations de conductivité et d'épaisseur des couches importantes du sous-sol. Une méthode analytique basée sur la décomposition de la valeur unique (DVU) a été élaborée pour un modèle à trois couches, ce qui correspond le plus, en conditions normales, aux situations sousmentionnées. L'algorithme fournit des solutions stables et géologiquement significatives et peut traiter des situations réelles, comme la disparition de la couche conductrice supérieure.

La méthode d'inversion a été testée avec des données recueillies sur environ 4000 km linéaires par levés ÉMA en Afrique et en Amérique du Nord. Nous donnons des exemples d'inversion de données ÉM mesurées par hélicoptère sur deux fréquences, en Tanzanie, pour cartographier la topographie de la roche en place non altérée. Au Canada, des levés ÉM sur trois fréquences ont été effectués par hélicoptère dans le cadre du programme de gestion des déchets de combustibles nucléaires. L'une des tâches consistait à cartographier l'épaisseur des sédiments glaciaires et la topographie des couches précambriennes sous-jacentes. Dans l'Ouest des États-Unis, des levés ÉM par hélicoptère ont servi à determiner la profondeur de la nappe phréatique dans des zone semi-arides. Pour les trois levés mentionnés (et plusieurs autres), l'algorithme d'inversion a fourni les réponses voulues à un coût relativement modique. L'inversion continue des données ÉMA semble être un instrument puissant se prêtant à bien des applications nouvelles.

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INTRODUCTION

There is a growing realization that the traditional role of airborne electromagnetics (AEM), which is to search for discrete metallic conductors, fails to utilise the full potential of modern surveying and interpretation methods. At the same time the need for technological assistance in the areas of environmental studies and groundwater exploration has become acute, even critical (Paterson and Bosschart, 1987). Starting in the early 1970s (Dyck et al., 1974; Fraser, 1978) resistivity mapping has become an increasingly popular byproduct of routine AEM surveys. Palacky (1981) illustrated the application of simple resisitivity mapping to lithological interpretation. More recently (Paterson et al., 1982; DeMoully and Becker, 1984) examples have been published of applications of AEM to a wide range of exploration and geotechnical problems, including:

1. Mapping buried layers of coal, lignite, tar-sands and other deposits of nonmetallic minerals.
2. Determining depth to unweathered bedrock for geotechnical, alluvial prospecting and groundwater purposes.
3. Searching for and delineating groundwater aquifers and hot brine (geothermal) deposits.
4. Measuring water depth and ice thickness in bathymetric and hydrographic sounding.

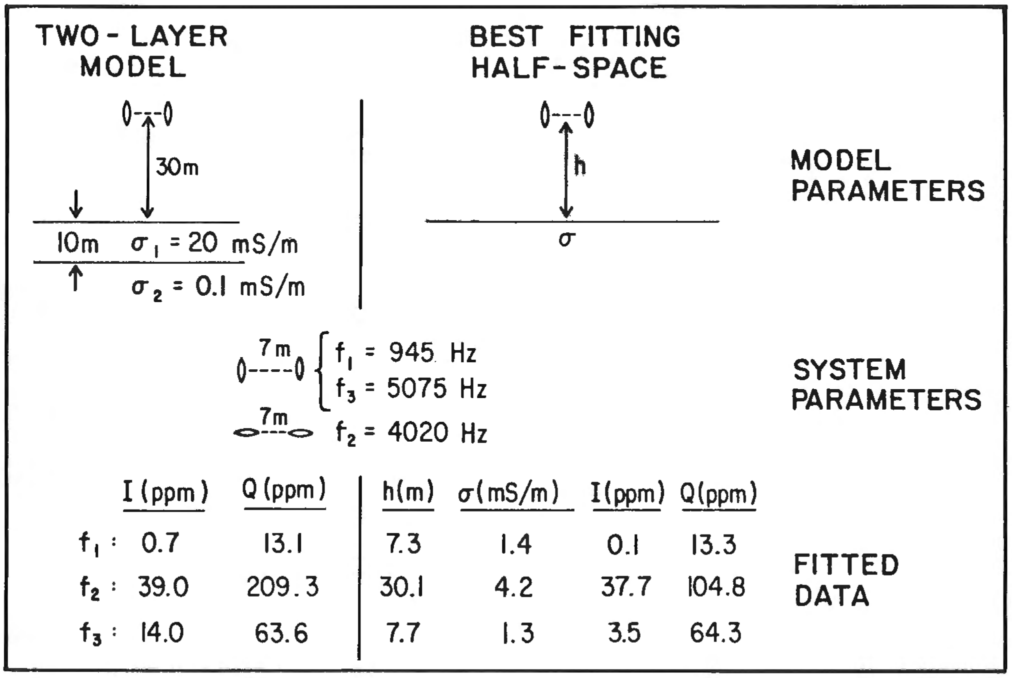
Currently a great deal of effort is being spent on the problem of inverting AEM data in order to provide meaningful information for the above applications. Most methods use some form of table look-up and interpolation procedure. This paper describes an analytical method based on singular value decomposition (SVD) and illustrates its application by means of a number of geotechnical and groundwater case histories.

CONDUCTIVE EARTH MODELS

For all of the above applications the first decision to be made is the choice of geological/physical model. Obviously the simpler the model the better in terms of instrumental constraints and economy of computer modelling. Thus the half-space model has been a popular choice.

Intuitively, one would think that the "apparent conductivity" of a half-space, measured at a number of frequencies simultaneously along a continuous profile, would yield pseudo-sections that could be employed in much the same manner as those derived from electrical resistivity and magnetotelluric (MT) soundings. Unfortunately, the problem is not that simple. The inherent difficulty is that, unless the earth happens to be electrically homogeneous, it is unlikely that an apparent conductivity can be found that will exactly fit the observed AEM data. Stated simply, the problem is overdetermined. Given a minimum of three measured data, e.g. height, and in-phase and quadrature response, and only one unknown, the half-space conductivity, it will generally be impossible to fit more than one of the two AEM measurements.

Figure 4.1 illustrates this difficulty. Given a typical geological situation in Canada, namely a relatively conductive



	I (ppm)	Q (ppm)	h(m)	σ(mS/m)	I(ppm)	Q(ppm)
f_1 :	0.7	13.1	7.3	1.4	0.1	13.3
f_2 :	39.0	209.3	30.1	4.2	37.7	104.8
f_3 :	14.0	63.6	7.7	1.3	3.5	64.3

Figure 4.1. Comparison of actual two-layer and best fitting half-space AEM responses.

overburden over a resistive bedrock, measurable values of in-phase and quadrature AEM responses are obtained at normal coil elevations and operating frequencies. If the ground is assumed to be a half-space, each channel of information provides a different value of apparent conductivity (as it does, for example, in MT). However, the added problem here is that, in order to fit at least one of the AEM measurements, it is necessary to allow the height above the conductive half-space to vary. Thus, the model is not only changing from one channel to the next, but it fails to approximate in geometry or conductivity the real ground. Most importantly, the model provides no information on the overburden, which is often the layer of greatest interest.

Faced with this difficulty all the interpreter can do is to record an apparent depth (positive or negative) to the hypothetical half-space and use this information in a qualitative fashion, together with the apparent conductivity, to suggest what might really be going on under the surface.

In practise, half-space inversion methods seldom employ more than one channel, since the concept of variations in apparent depth with frequency and/or coil configuration is difficult to treat in a meaningful way. In our studies we have found the half-space model to have limited application except in very restricted areas where, for example, a thick clay layer is overlain by dry surficial deposits such as sand or gravel. Here, the apparent depth can be of direct value in measuring the alluvial thickness.

n-layer earth

Another popular model in electrical resistivity and MT sounding is the n-layer one-dimensional earth. This is clearly a useful model for most of the applications we have mentioned. True, the real earth is not strictly one-dimensional, but the effects of variations from one-dimensionality are usually recognizable in the solution. A more serious limitation is imposed by the number of independent measurements that are needed to solve for the parameters of an n-layer earth. If each layer is assumed to have a thickness t and a conductivity σ, the minimum number of channels of AEM information (assuming in-phase and quadrature data, in the frequency domain) required to obtain a solution, is equal to the number of layers. In practise, because of the ambiguities inherent in many situations, the number of independent AEM measurements required is very much greater than the number of model parameters. Even if these could be provided, it is doubtful whether meaningful fits would be obtained for models of more than 3 or 4 layers. The problem of inverting data sets of such magnitude is one that we would hestitate to attempt on a routine basis.

3-layer earth

Faced with these dilemmas most workers have chosen to simplify the earth to a 3-layer model, as shown in Figure 4.2. The model actually consists of a conductive layer over a resistive halfspace, but a third layer can be added over the conductive one if it is assumed to be highly resistive. Paterson et al. (1982) and DeMoully and Becker (1984) described inversion techniques in the frequency domain and time domain respectively for this relatively simple and useful model. In the remainder of this paper we examine the requirements of an effective inversion procedure, as illustrated by results from recent AEM surveys.

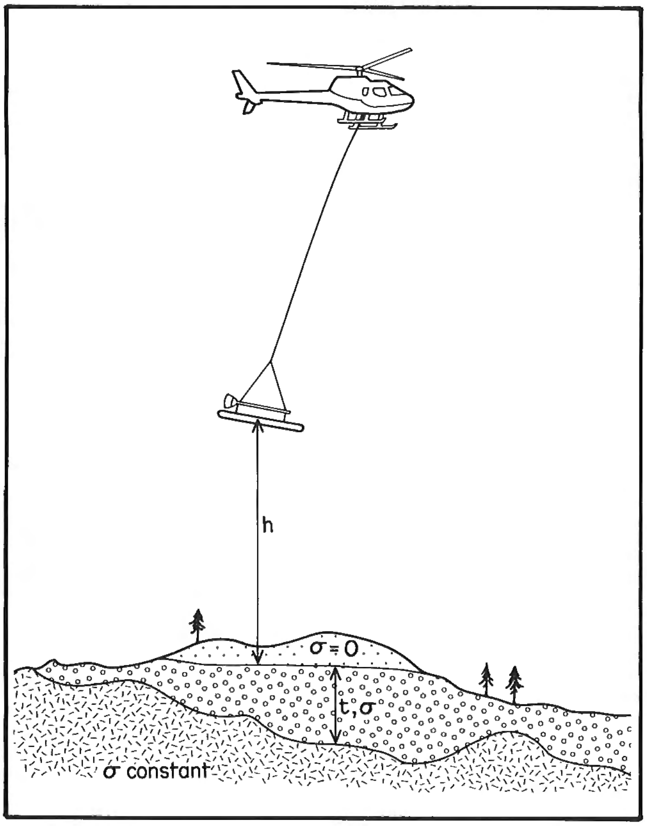


Figure 4.2. Three-layer conductive earth model.

AEM INVERSION

We have noted that, in general, the problem of fitting a model to AEM data is generally an overdetermined one. Unlike most overdetermined problems in physics, however, each independent measurement or set of measurements cannot be relied upon to yield an approximation to the same solution. Because of the failure of the model to exactly resemble the real earth, and because the measurements are made at different frequencies and/or coil configurations, each measurement can generally be counted upon to offer a different solution.

What is needed, therefore, is a method of optimizing the model fit to all of the available measured data. Subsidiary requirements of the scheme include the following:

1. Because, even if the model exactly fits the earth, some parameters are "well determined" and others are not, it

is necessary to obtain a measure of the relative importance of each parameter to the model fit. For example, a high degree of correlation often exists between the conductivity and the thickness of the conductive layer. If the two are solved independently, it is clearly important to know how much each of these parameters can vary without affecting the solution.

2. Since the model does not, in general, exactly represent the real earth, it is useful to know which of the measured data are fitted well and which are not. For example, if the lower frequencies are fitted better than the higher ones, it is probably because of the presence of conductive inhomogeneities in the near-surface.
3. Since not all of the measured data have the same accuracy, it is desirable to be able to place error limits independently on each measurement. In this way, for example, the geophysicist can improve the fit to the measurements that are of most geological significance, while de-emphasizing those that would respond most to the inhomogeneities of least importance.
4. As in the case of most inversion procedures, it should be possible to assign a tolerance to each model parameter, within which the fit is deemed to be acceptable. This is necessary in the interest of economy and also to ensure that the less important parameters are not fitted at the expense of others that are more geologically significant.
5. Finally, the inversion method must be robust and economical. The AEM method produces, typically, six or more values of EM response and an elevation above ground every 50-60 m along each profile. A relatively small survey of 600 line km contains 12 000 measurement sets requiring inversion. Obviously, the inversion method must involve minimum interaction by geophysicist and the least possible CPU time.

With the above objectives in mind, we decided in 1981 to adopt the method of SVD or eigenfunction analysis, based on work by Edwards et al. (1981) and Wiggins (1972). This method allows the inherent ambiguities of the model-fitting procedure to be described in a physical way, and has proved to be a reliable method for a variety of applications, including the layered earth conductivity model (Inman et al., 1973). A complete description of the inversion procedure is given by Reford et al. (1985), but the illustration in Figure 4.3 may be useful.

Given a set of measured data, d_1, d_2.....etc., which are assumed to be functions of a combination of a number of model parameters p_1, p_2.....etc., a decomposed model is derived involving a new set of eigendata and eigenparameters – linear combinations of the original data and the individual model parameters. Fractional changes in the eigendata are related to fractional changes in the eigenparameters through a linear combination of a set of partial derivatives.

The properties of these eigenparameters are such that the effects of fractional changes in the individual model parameters on the measured data are independent of one another and can therefore be identified and determined.

It is also an important property of the eigenparameters that in the inversion process the model parameters having little importance in the solution are given little weight or are ignored completely, depending upon the tolerances assigned. Thus a rapid convergence is effected even when one or more of the model parameters is poorly determined.

An example of SVD analysis of AEM data is given in Figure 4.4, the model being that described in Figure 4.1 Before the SVD process is applied the eigendata are scaled in two ways. Each datum is assigned a standard error of unity; hence, the standard error in each independent eigenvector is the reciprocal of its associated eigenvalue. Parameters defined by eigenvectors with errors greater than about 0.3 are considered not significant in their contribution to the EM response. Secondly, the parameters p_i (Fig. 4.3) are redefined, for the purposes of the analysis, as the logarithms of the layer parameters (H-height, RHO-resistivity, D-thickness). Hence,the physical meaning of each eigenvector is defined by the product of the contributing layer parameters, not the sum (i.e. log D − log RHO = log (D/RHO)). Also, the standard error in each eigenvector becomes the fractional error in the derived layer parameter.

In Figure 4.4, despite poor starting parameters the program converged in 6 iterations to fitted parameters within 10% of those of the model. The rms errors in the fitted data are

EIGENFUNCTION ANALYSIS

ANY GIVEN MODEL

$$d_i = F_i \; (p_1 \, , p_2 \; \ldots\ldots p_n)$$

where d_1, d_2 ....etc. are DATA points
and p_1, p_2 ....etc. are layer PARAMETERS (t or ρ)

LINEARIZATION

$$\delta d_1 = a_{11} \, \delta p_1 + a_{12} \, \delta p_2 \ldots\ldots \text{etc.}$$
$$\delta d_2 = a_{21} \, \delta p_1 + a_{22} \, \delta p_2 \ldots\ldots \text{etc.}$$
$$\text{etc.}$$

where a_{11}, a_{12}.... etc. are computed PARTIAL DERIVATIVES

DECOMPOSED MODEL

$$\delta \bar{d}_1 = \bar{a}_1 \, \delta \bar{p}_1$$
$$\delta \bar{d}_2 = \bar{a}_2 \, \delta \bar{p}_2$$
$$\text{etc.}$$

where $\bar{d}_1$, $\bar{d}_2$ ....etc. are linear combinations of d_1, d_2....etc;
and $\bar{p}_1$, $\bar{p}_2$ ....etc. are linear combinations of p_1, p_2....etc;
the independent EIGENDATA and EIGENPARAMETERS

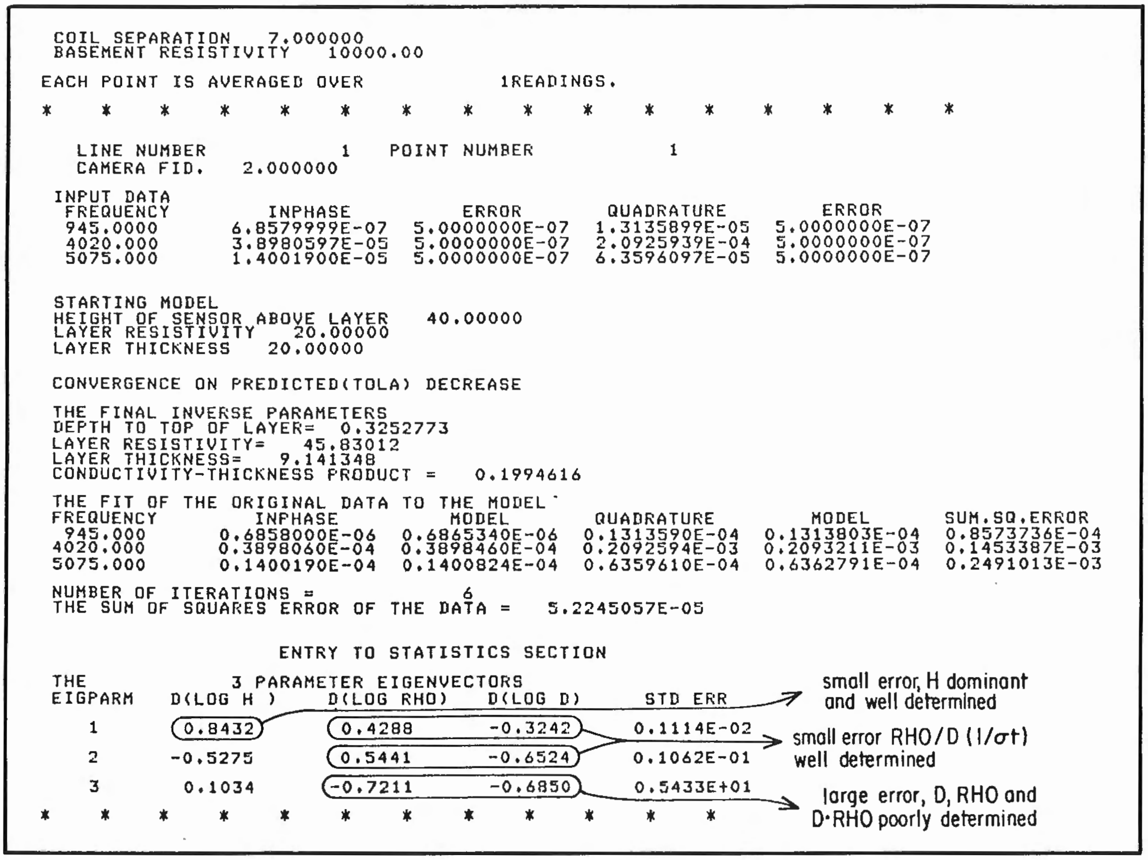
APPLICATION

GIVEN fractional measurement errors in d_1, d_2 ....etc;
WE FIND fractional errors in the INDEPENDENT $\bar{p}_1$, $\bar{p}_2$... etc.

PHYSICS

IDENTIFY the significance of $\bar{p}_1$, $\bar{p}_2$ .... etc.

Figure 4.3. The SVD method of eigenfunction analysis.



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 COIL SEPARATION   7.000000
 BASEMENT RESISTIVITY   10000.00

EACH POINT IS AVERAGED OVER           1READINGS.

*    *    *    *    *    *    *    *    *    *    *    *    *    *    *    *

   LINE NUMBER             1   POINT NUMBER            1
   CAMERA FID.   2.000000

 INPUT DATA
  FREQUENCY        INPHASE         ERROR        QUADRATURE        ERROR
  945.0000      6.8579999E-07  5.0000000E-07  1.3135899E-05  5.0000000E-07
  4020.000      3.8980597E-05  5.0000000E-07  2.0925939E-04  5.0000000E-07
  5075.000      1.4001900E-05  5.0000000E-07  6.3596097E-05  5.0000000E-07


 STARTING MODEL
 HEIGHT OF SENSOR ABOVE LAYER   40.00000
 LAYER RESISTIVITY   20.00000
 LAYER THICKNESS   20.00000

 CONVERGENCE ON PREDICTED(TOLA) DECREASE

 THE FINAL INVERSE PARAMETERS
 DEPTH TO TOP OF LAYER=  0.3252773
 LAYER RESISTIVITY=   45.83012
 LAYER THICKNESS=   9.141348
 CONDUCTIVITY-THICKNESS PRODUCT =   0.1994616

 THE FIT OF THE ORIGINAL DATA TO THE MODEL
 FREQUENCY         INPHASE          MODEL         QUADRATURE         MODEL        SUM.SQ.ERROR
  945.000       0.6858000E-06  0.6865340E-06  0.1313590E-04  0.1313803E-04  0.8573736E-04
 4020.000       0.3898060E-04  0.3898460E-04  0.2092594E-03  0.2093211E-03  0.1453387E-03
 5075.000       0.1400190E-04  0.1400824E-04  0.6359610E-04  0.6362791E-04  0.2491013E-03

 NUMBER OF ITERATIONS =              6
 THE SUM OF SQUARES ERROR OF THE DATA =    5.2245057E-05

                       ENTRY TO STATISTICS SECTION

 THE                  3 PARAMETER EIGENVECTORS
 EIGPARM    D(LOG H )     D(LOG RHO)     D(LOG D)       STD ERR
    1        0.8432        0.4288         -0.3242       0.1114E-02
    2       -0.5275        0.5441         -0.6524       0.1062E-01
    3        0.1034       -0.7211         -0.6850       0.5433E+01
*    *    *    *    *    *    *    *    *    *    *    *
```

small error, H dominant and well determined

small error RHO/D (1/σt) well determined

large error, D, RHO and D•RHO poorly determined

Figure 4.4. Statistics for a three-channel AEM inversion.

less than 0.01%. The eigenparameter matrix shows height H to be dominant in the solution and well-fitted; RHO/D (1/σt) to be of next importance and well-fitted; and D, RHO and D•RHO to be of least importance and poorly fitted.

Applying this technique to real survey data was no simple task. It was decided early on to use as starting parameters for each measurement set the fitted parameters of the previous set. This procedure worked well when all parameters were well determined. However, when two of the parameters become strongly correlated, such as the conductivity and thickness of a thin conductive layer, the parameters would often wander aimlessly, giving poorer starting values for each subsequent inversion. Means had to be provided to jog the "sleepy" parameters so that they would respond to the fitting process and still remain within geologically reasonable limits. Also, the problem of disappearance of the conductor, for example a pinch-out of a conductive overburden in an outcrop area, had to be dealt with. Does the program see the outcrop as the new conductive layer and, if so, how does it deal with the overburden when it appears again along the profile? This problem was solved by switching automatically from the 3-layer to the half-space model in such situations, and continuously testing the data until the surface layer reappeared. Other difficulties were experienced and were dealt with by one means or another.

Various versions of our SVD frequency domain inversion method have been applied to surveys in North America and Africa. A total of approximately 4000 line km of survey data have been processed and compiled in profile and/or contour form. The following examples illustrate the applications in a number of different environments.

EXAMPLES

The first commercial application of the inversion method was on a two-frequency helicopter EM data set from Tanzania. Here, the objective was to map the surface of the unweathered bedrock in order to assess the contribution of overburden to the AEM response and to identify bedrock conductors of possible economic interest. Figure 4.5 shows a typical profile, raw and interpreted. The inversion method proved relatively forgiving of base-level errors in the raw data, a severe problem in most surveys of this type. Furthermore, by adjusting the base-levels on one or two profiles from each survey flight so as to minimize the deviations between the measured and fitted data, excellent agreement could be obtained between model fits on intersecting profiles. The example illustrates

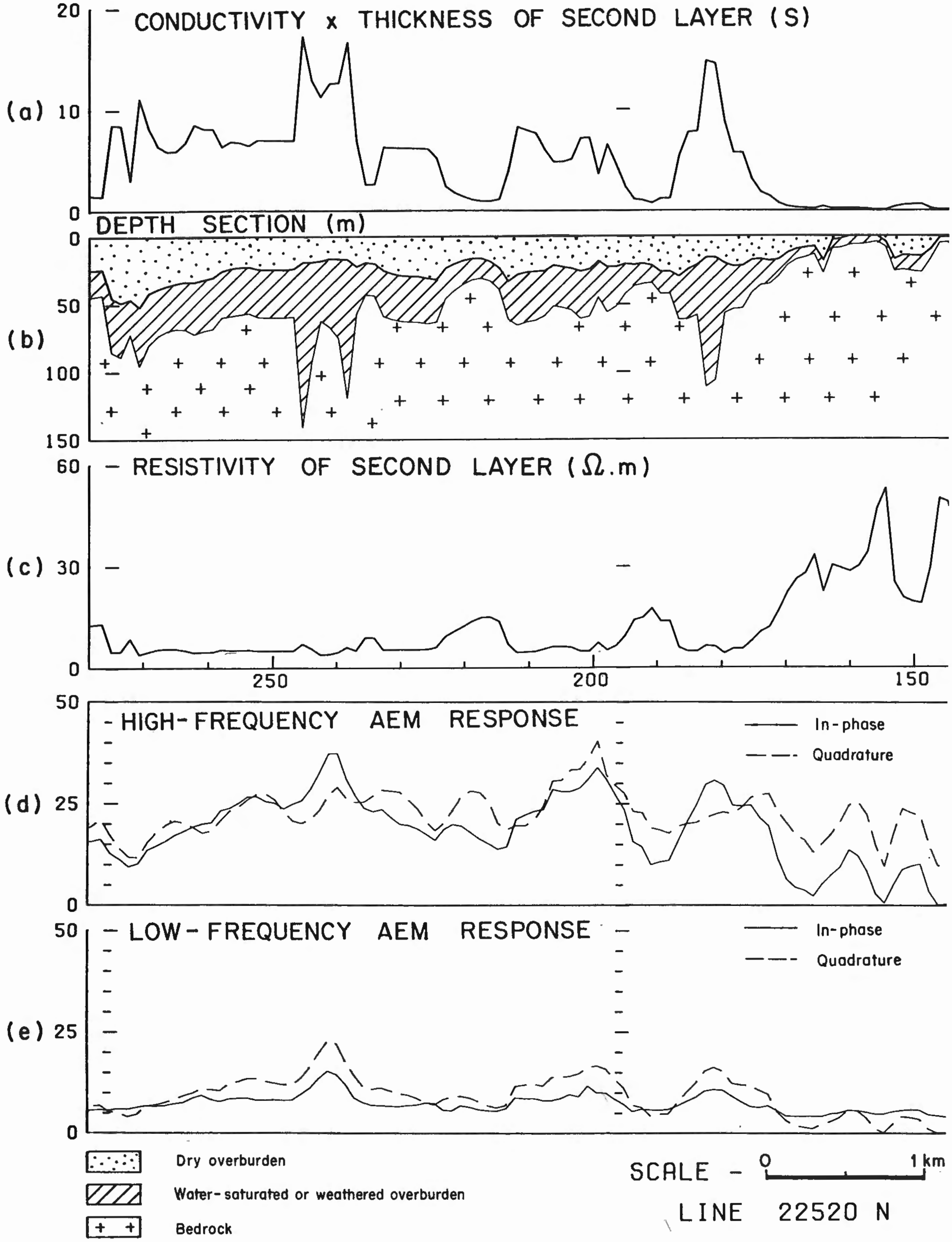

Figure 4.5. Three-layer inverison of two-channel helicopter EM data, Tanzania. Stacked profiles showing raw AEM data (d, e) and computer-derived geological interpretation (a, b, c). Apparent thickness spikes (a, b) probably represent shallow bedrock conductors – possibly faults.

how spikes in the apparent conductive layer thickness (and peaks in the rms error profile, not shown in the figure) point to probable bedrock conductors. Also of interest is the ability to delineate the conductive weathered zone, or saprolite layer, of major interest as a potential source of groundwater in many areas.

The method has been applied to overburden mapping in several areas in Canada, including a 3-frequency helicopter EM survey of the East Bull Lake nuclear fuel waste management research area, 200 km west of Sudbury, Ontario (Fig. 4.6, 4.7). Here, the depth of overburden, occurring mainly in narrow, glacially scoured depressions, are presented in profile form, together with plan contours of overburden conductance. Fault-controlled gulleys, of particular interest to the study team, were again recognized by conductance or thickness spikes and large rms errors in the fitted data. Other applications in Canada have included surveys to determine the depth to, and approximate thickness of, the conductive regolith overlying Archean basement under the Athabasca sandstone.

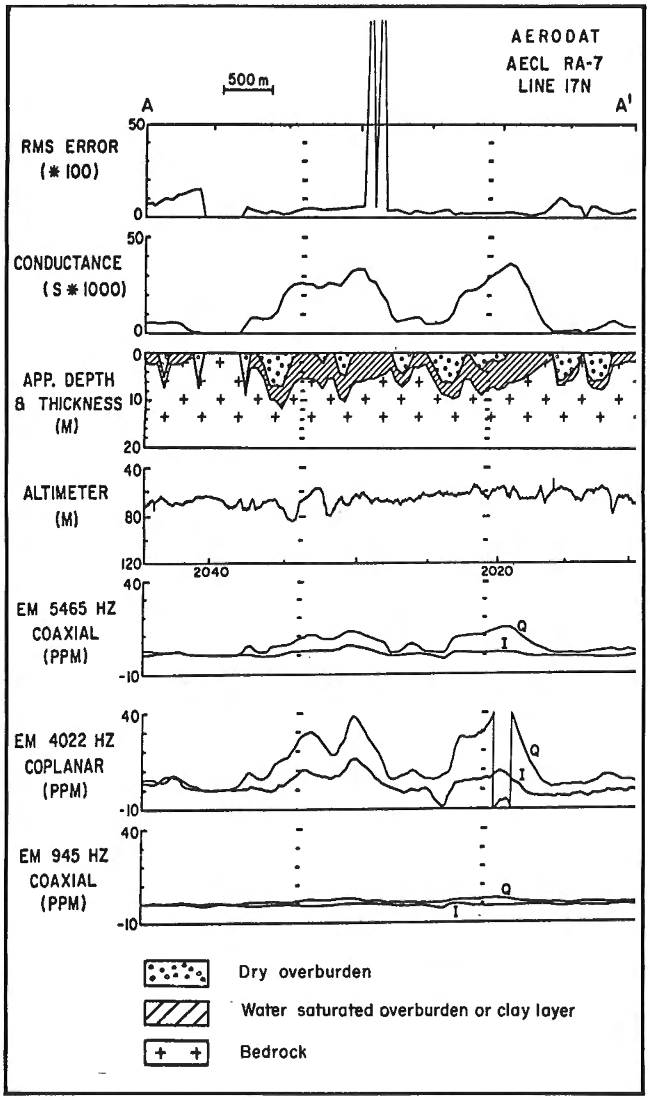

Figure 4.6. Application of AEM to overburden mapping at the East Bull Lake nuclear fuel waste mangement research area, near Massey, Ontario: Stacked profiles of 3-frequency helicopter EM response and 3-layer interpretation. Rms errors spikes indicate local bedrock conductivity, possibly faulting.

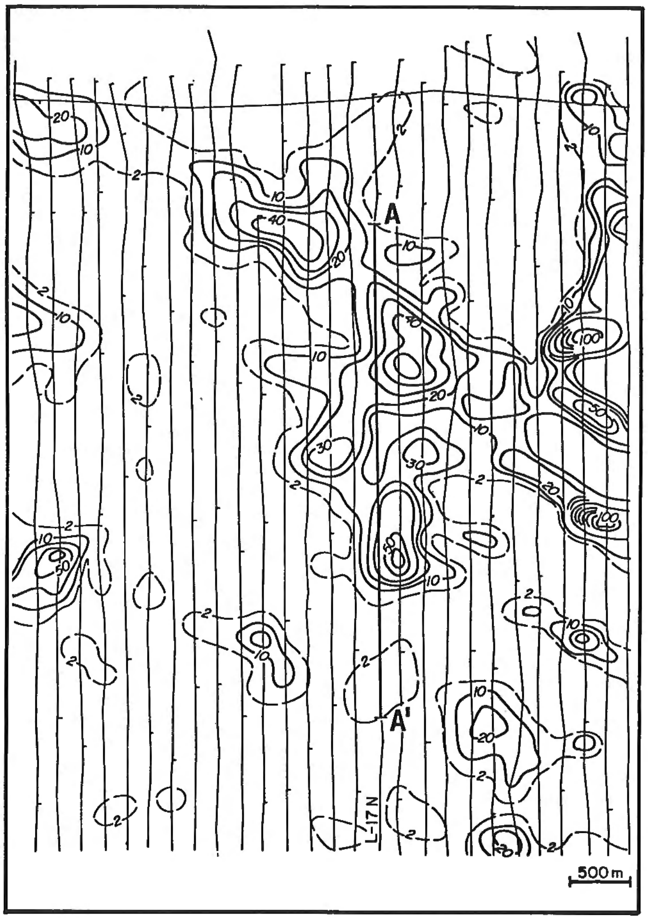

Figure 4.7. Contours of conductance (in S) of the water-saturated layer derived from the EM data.

The final example is from a two-frequency helicopter EM survey for groundwater in the Western USA (Fig. 4.8, 4.9). In this case contour maps were prepared of depth, thickness, conductivity, and conductance of the conductive layer. The depth map in Figure 4.8 shows a water table varying in depth from less than 15 m to more than 100 m from the ground surface. Shallower areas include several mapped springs; the deeper areas are mainly under the higher ground. Wells occur, for the most part (Fig. 4.9), on or close to regions of high conductance, probably indicating a thicker water layer or locally higher porosity. Several zones of high conductance, occurring in areas of relatively shallow depth, are of potential importance.

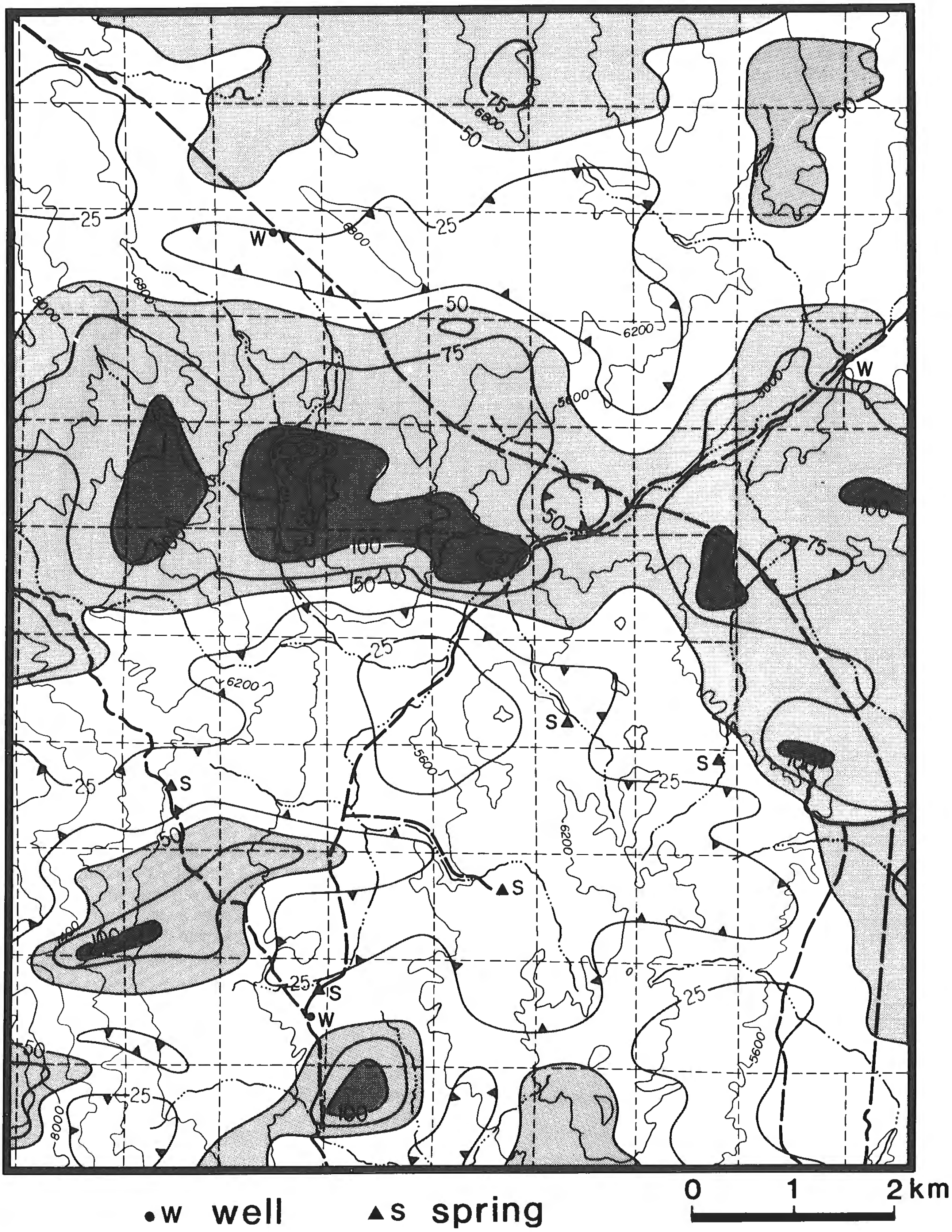

Figure 4.8. Groundwater survey, Western U.S.A. Contours of depth in metres to water table derived from two-channel helicopter EM data. Note occurrence of surface springs and seasonal drainage in some areas of shallow water table. Where the depth is large, springs are rare and probably seasonal.

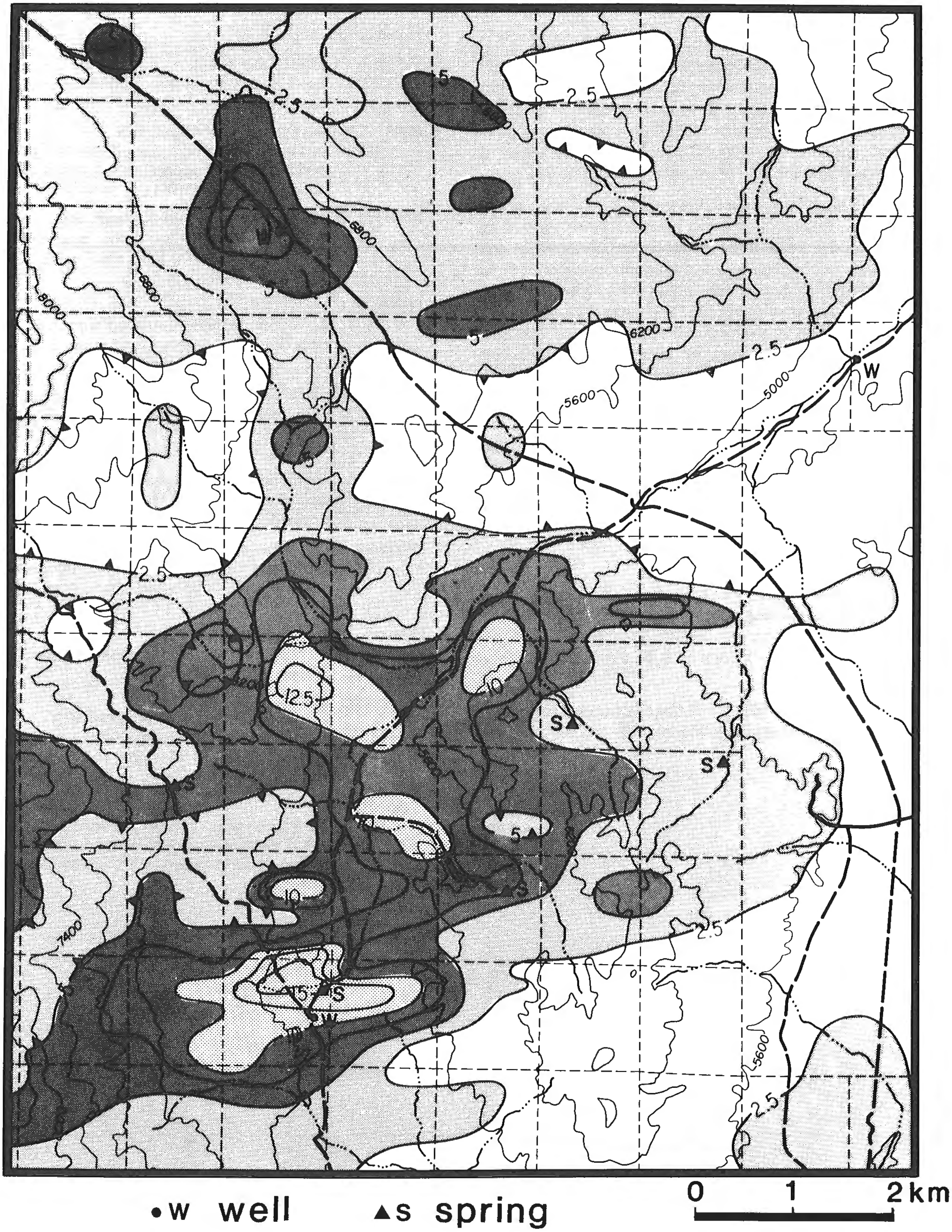

Figure 4.9. Groundwater survey, Western U.S.A. Contours of conductance (in S) of water-layer derived from two-channel helicopter EM data. Wells are generally close to zones of higher conductance probably indicating a thicker water layer or higher porosity.

CONCLUSIONS

Modern AEM survey and interpretation methods are useful for a wide variety of conductivity mapping purposes. A multilayered model is necessary in most areas and in nearly all applications if geologically meaningful results are to be obtained. An inversion method based on SVD eigenvector analysis has been found to be effective in a variety of terrains.

Using a three-layer model, the top layer of which has zero conductivity, estimates of depth to and conductance of the second layer are found to be generally well determined and, given good survey data and a reasonably one-dimensional earth, accurate to better than about 10%. The individual parameters t and σ of the conductive layer are often poorly determined and, in the limiting cases of very thin or very thick (or conductive) layers, may be indeterminate. The conductivity-thickness product σt can be used to derive satisfactory approximations of thickness over limited areas for many applications.

Continuous inversion of AEM data appears to be a powerful tool for many overburden mapping, geotechnical and groundwater purposes.

ACKNOWLEDGMENTS

The work carried out by Paterson, Grant & Watson Limited and described in this paper was supported by an ETDF grant from the Ontario Ministry of Natural Resources. The original computer program was written by R.N. Edwards, University of Toronto.

We thank Atomic Energy of Canada Limited for permission to show the example in Figures 4.6 and 4.7.

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- 5 -

Dighem resistivity techniques in airborne electromagnetic mapping

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Abstract

The pseudo-layer half-space model is commonly used to produce apparent resistivity maps from helicopter electromagnetic (EM) data. The model yields an apparent resistivity which is unaffected by errors in altimetry since flight height does not enter the resistivity equations. This is important because the measured altitude frequently is wrong due to the presence of trees and irregular topography.

The Dighem IV helicopter EM system typically operates at frequencies of 900, 7200, and 56 000 Hz. This allows apparent resistivity maps to be made for each of these frequencies. The apparent resistivities for the three frequencies provide a qualitative means of resistivity sounding.

A recent innovation is the use of a two-layer inversion technique to provide a simplified resistivity section, from helicopter EM data. A specialized model has been developed, called the pseudo-layer two-layer model, which is unaffected by errors in altimetry.

The applications of airborne resistivity are many, for example, Dighem surveys have been flown for base and precious metal exploration, geothermal mapping, exploration for kimberlites, shallow sea bathymetric mapping, fresh water detection, and general geological mapping for radiation waste disposal and other engineering programs.

Résumé

Le modèle de pseudo-couches dans un demi-espace est couramment employé pour produire des cartes de résistivité apparente utilisant des données électromagnétiques (ÉM) mesurées par hélicoptère. Le modèle donne une résistivité apparente insensible aux erreurs d'altimétrie, car l'altitude n'intervient pas dans les équations de résistivité. C'est là une caractéristique importante, car l'altitude mesurée est souvent fausse à cause de la présence des arbres et de la topographie irrégulière du terrain.

Le système héliporté Dighem IV fonctionne généralement aux fréquences de 900, 7 200, 55 000 Hz. Cela permet d'établir des cartes de résistivité apparente pour chacune de ces fréquences. Les résistivités apparentes obtenues à ces trois fréquences permettent d'établir qualitativement un sondage de résistivité.

Une innovation récente consiste à appliquer une technique d'inversion pour deux couches qui fournit une coupe simplifiée de résistivité à partir de données ÉM obtenues en hélicoptère. On a élaboré une modèle spécialisé, appelé modèle de pseudo-couche à deux couches, sur lequel les erreurs d'altimétrie n'ont pas d'effet.

Les applications des levés aériens par résistivité sont nombreuses. Par exemple, les levés Dighem servent à l'exploration de métaux communs ou précieux, à la cartographie géothermique, à la prospection des kimberlites, à la cartographie bathymétrique des hauts-fonds marins, à la détection des nappes d'eau douce et à la cartographie géologique générale appliquée à l'élimination des déchets radioactifs et à d'autres programmes d'études techniques.

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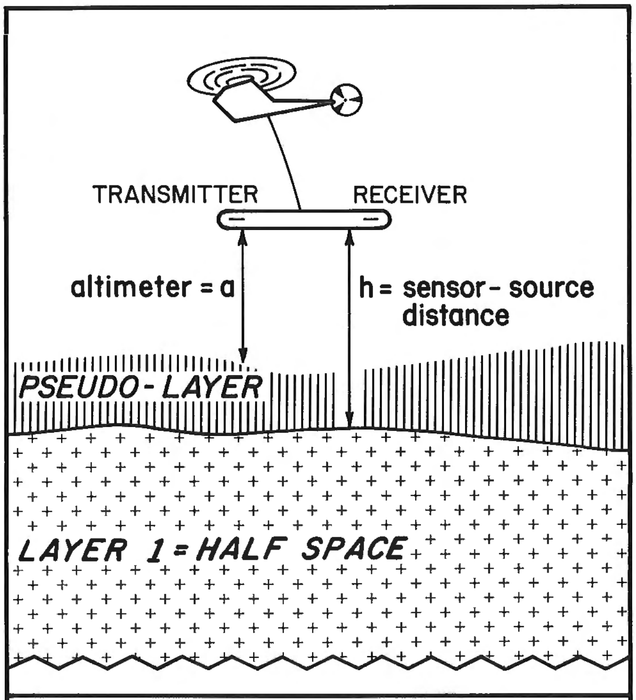
COMPUTATION OF RESISTIVITY FROM HEM DATA

The pseudo-layer half-space model (Fig. 5.1) is commonly employed for apparent resistivity mapping when using towed-bird helicopter EM (HEM) 'systems (Fraser, 1978). Such systems employ maximum-coupled transmitter-receiver coil pairs. The coil pairs are oriented in both the vertical coaxial and horizontal coplanar positons in modern HEM systems (e.g., Fraser, 1979). Resistivity can be computed from any coil pair. For horizontal layers, the horizontal coplanar coil pair is to be preferred (Sinha, 1973). Only the horizontal coil orientation will be considered herein (Fig. 5.1).

The system Dighem III, for which field examples will be shown, has 2 horizontal coplanar coil pairs operating at frequencies 900 and 7200 Hz and one vertical coaxial coil pair, whose frequency can be varied between 385 and 7200 Hz depending on the target and the environment.

The pseudo-layer half-space model actually represents a two-layer case. The resistivity of the upper layer is infinite, and the resistivity of the lower layer is that of the conductive earth or half-space.



LAYER	RESISTIVITY	THICKNESS
PSEUDO	∞	?
1	?	∞

Figure 5.1. Configuration of the Dighem system with horizontal coplanar coil pair. Definition of the pseudo-layer half-space model.

In essence, the resistivity is obtained as a function of inphase and quadrature channels of the horizontal coils. The distance h from the bird to the conductive earth is obtained as a by-product of the resistivity calculation. Discrepancies between distance h and bird altitude "a" are ascribed to a fictitious, highly resistive upper layer. This model provides resistivities which are free of an altitude dependency, since altitude does not enter into the resistivity equations. The model may be called a "pseudo-layer" half-space because the pseudo-layer is merely an artifice to account for discrepancies between the measured altitude "a" and the computed distance h. The nature of the pseudo-layer depends on the physical conditions of the survey area. The thickness of the pseudo-layer may be a measure of tree height in a dense forest, or the thickness of resistive permafrost in Arctic areas, or the thickness of a resistive gravel deposit overlying a clay substratum.

NIGHT HAWK TEST RANGE DATA

Figure 5.2 shows horizontal coplanar EM survey data over the Night Hawk test range in Ontario. For a summary of geophysical surveys at the test range see references in Pitcher (1985). The wide graphitic conductor is irregularly shaped and is buried beneath 85 m of glacial deposits which consist mainly of sands. The resistivity of the sands is estimated to be 300 Ωm and the graphite 1 Ωm from Dighem survey data. The resistivity of the host rock is probably well in excess of 3000 Ωm based on Dighem resistivity responses over barren outcrop areas in the region.

For the Dighem III data of Figure 5.2, the conductor response is most prominent on the 900 Hz inphase channel. The two lower channels are the apparent resistivity from the half-space model, computed for two frequencies, 900 and 7200 Hz. The apparent resistivities are 16 Ωm over the conductor for 900 Hz and 200 Ωm for 7200 Hz. These resistivity channels show that the penetration is much better at the 900 Hz frequency, into the graphite, than that at 7200 Hz, where the response of the higher frequency is determined mainly by the overlying sands.

A recent innovation is the use of a two-layer inversion technique to separate the response of overburden from that of the bedrock. We have developed a specialized model which we term the pseudo-layer two-layer model (Fig. 5.3).

As in the case of the previously discussed half-space model, the sensor-source distance h in the pseudo-layer two-layer model is an unknown. A dense tree cover would result in the airborne altimeter "a" understating the distance h, so h must be treated as an unknown. There are four unknowns, comprising two resistivities and two thicknesses, for the three media of Figure 5.3.

The Night Hawk conductor, due to its width, fits a two-layer case reasonably well. The coplanar EM channels over

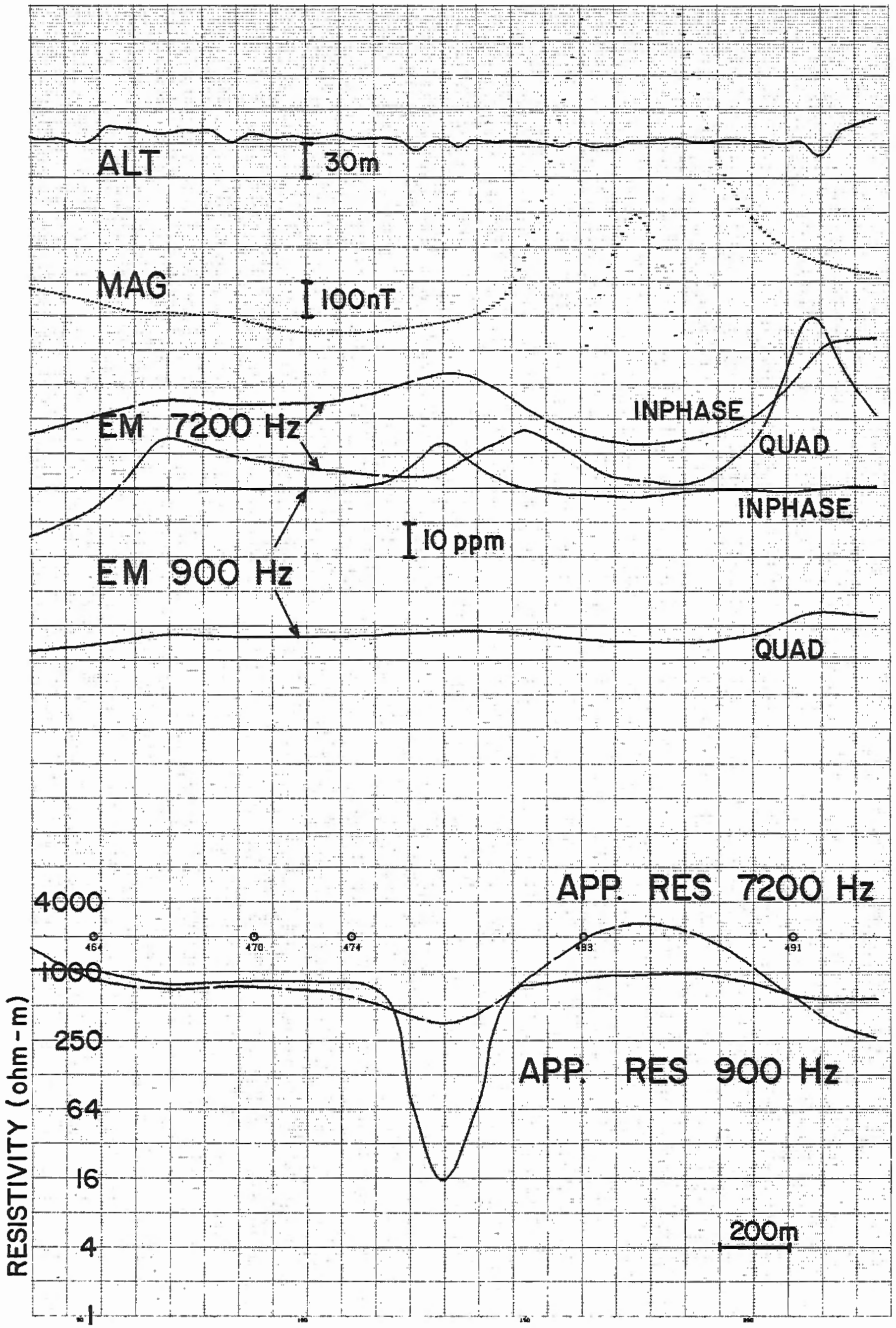


Figure 5.2. Dighem III survey data over the Night Hawk test range (top) and resistivity calculated using the pseudo-layer half-space model (bottom). ALT-altimeter, MAG-total field magnetometer, EM-horizontal coplanar-coil EM response at two frequencies, inphase and quadrature, RES-computed resistivity.

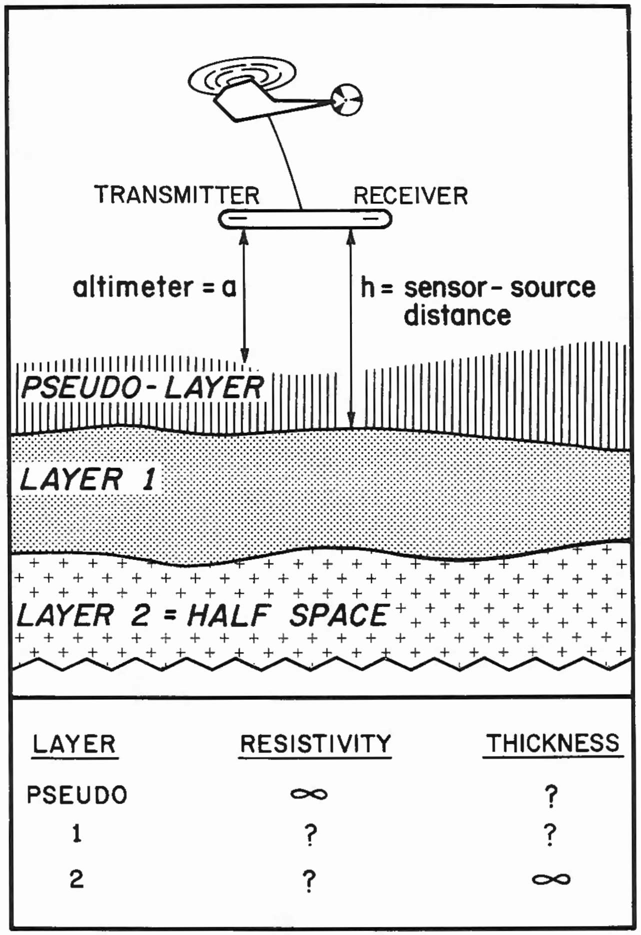


Figure 5.3. Dighem system with horizontal coplanar coil pair over pseudo-layer two-layer model.

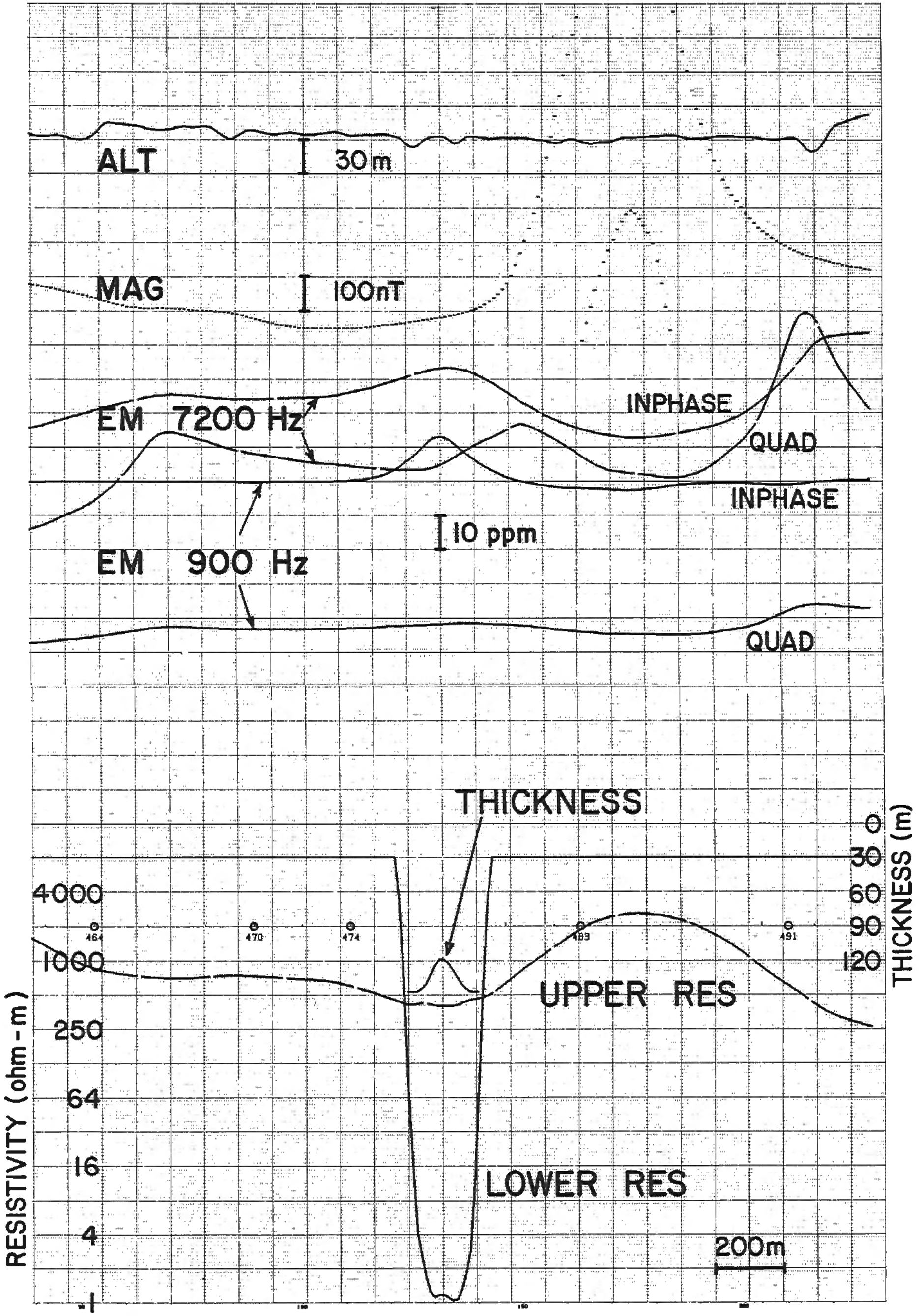


Figure 5.4. Dighem III survey data over the Night Hawk test range (top), and resistivity calculated using the pseudo-layer two-layer model. Explanation of symbols as in Figure 5.2.

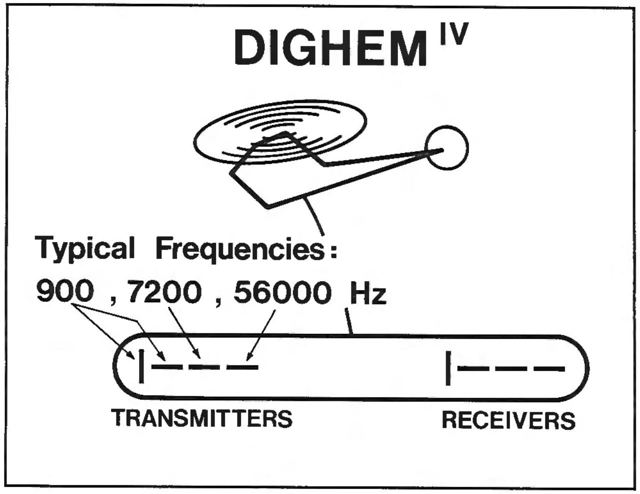


Figure 5.5. Configuration of the Dighem IV system, which has 3 horizontal coplanar coils (suitable for resistivity sounding) and one vertical coaxial coil pair.

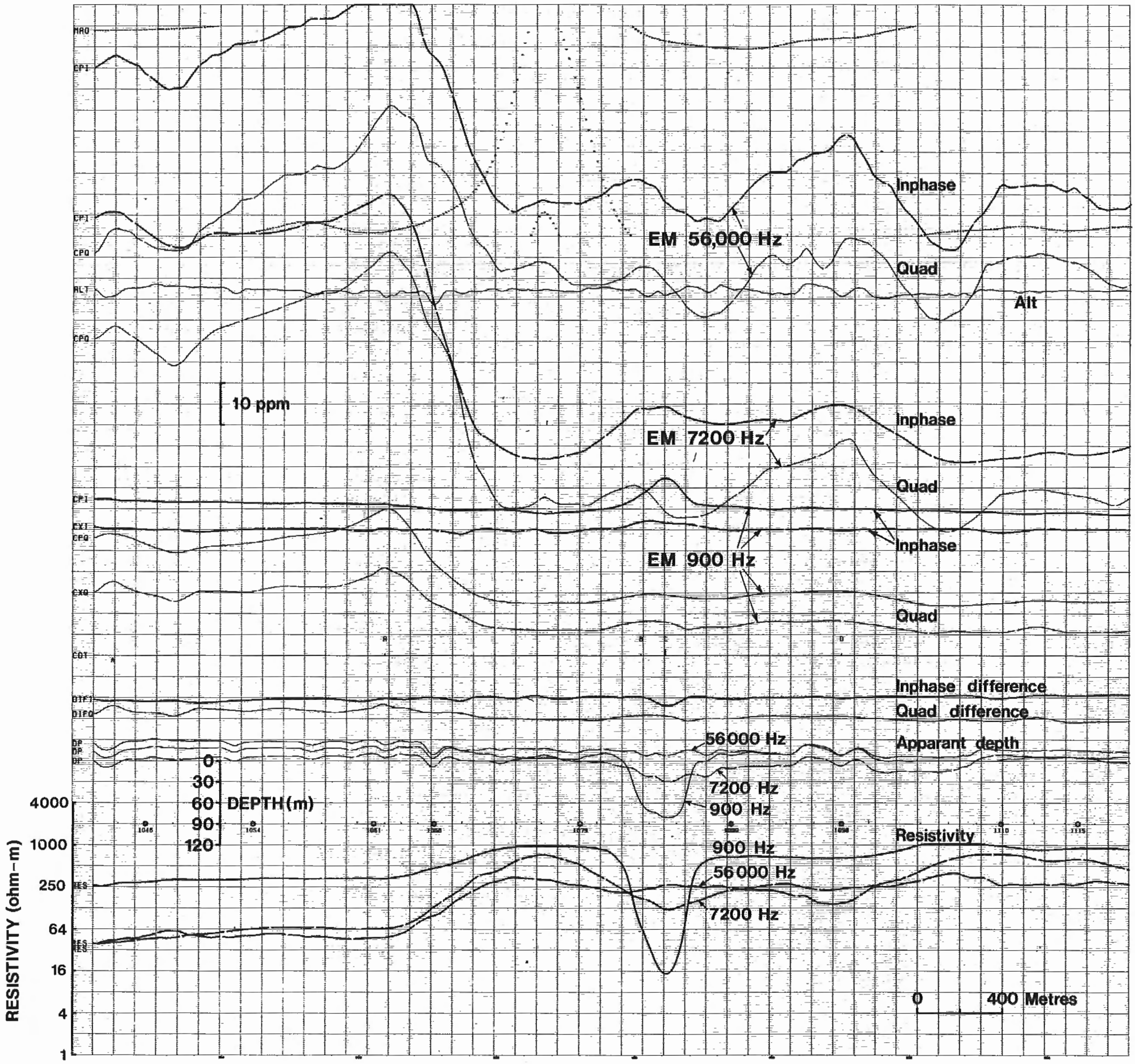


Figure 5.6. Dighem IV data over the Night Hawk test range. EM channels are shown for horizontal coplanar coil pairs at 3 frequencies and vertical coaxial coil at 900 Hz. At the bottom, difference channels, computed apparent depth and resistivity are shown for all three frequencies. The Night Hawk conductor is indicated by the prominent resistivity anomaly at 900 Hz.

the Night Hawk conductor are shown in the upper half of Figure 5.4. The results of the two-layer resistivity inversion are shown in the lower half of the figure. The conductor is seen to have a resistivity of 1 Ωm and it is surrounded by highly resistive rocks (saturated at 8000 Ωm). The upper glacial layer has a resistivity of about 300 Ωm. The interpreted depth to the conductor is 120 m, rather than the true value of 85 m; the error presumably arises because the conductor does not appear infinitely wide to the EM system. In general, however, the inversion seems to be quite satisfactory in this case. It has a greatly increased dynamic range over the half-space method. For example, the half-space resistivity at 900 Hz (Fig. 5.2) was 16 times higher over the graphitic conductor than the 1 Ωm resistivity of Figure 5.4.

IMPROVED MAPPING SYSTEM

We have recently added another tool to our resistivity mapping technology, the Dighem IV system, which has three horizontal coplanar coil-pairs (Fig. 5.5). The fourth coil-pair, with a vertical coaxial orientation, provides a geometric analysis of conductors. In the following discussion, let us consider only the resistivity-sounding array provided by the horizontal coplanar coils.

The frequencies increase from 900 Hz in steps of 8, comprising 900, 7200, and 56 000 Hz. The system can map half-space resistivities up to 20 000 Ωm. It allows more accurate inversions than the previously developed Dighem III system which lacks the high frequency coil pair.

Figure 5.6 shows an example of Dighem IV data over the Night Hawk test range. The EM channels are shown in the upper half of the figure, and the corresponding half-space resistivities are shown in the lower half.

On the resisitivity profiles, the graphitic conductor can be seen best at the lowest frequency of 900 Hz. It does not give any response on the resistivity profile at 56 000 Hz. Such a result is desirable. This is because the bedrock conductor can be separately defined more reliably if the high frequency defines only the cover. The geologically useful result is a superior definition of a highly conductive target under moderately conductive cover.

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- 6 -

Airborne EM instruments operating at VLF and higher frequencies

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Herz, A., Airborne EM instruments operating at VLF and higher frequencies in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 55-61, 1986.

Abstract

Airborne VLF measurements are now commonly performed as a part of multiparameter airborne geophysical surveys. Present VLF instruments are light-weight, reliable, and easy to install and operate. Their addition to the airborne geophysical package increases only marginally the survey cost, yet the data are extremely useful in geological mapping. Total-field VLF data are usually presented as contour maps.

In the past, attempts have been made to conduct airborne resistivity mapping at VLF and higher (up to 1 MHz) frequencies. The E-PHASE was the first system capable of generating contour resistivity maps, but the lack of information at the lower end of the audiofrequency spectrum prevented it from becoming a widely used airborne mapping tool.

Presently, airborne VLF systems are manufactured by 3 Canadian companies. The parameters measured differ slightly in each case. VLF sensors can be installed on a wing tip, nose stinger, lower helicopter frame, or a towed bird.

Résumé

On effectue couramment des mesures par systèmes aéroportés fonctionnant en VLF, dans le cadre de levés géophysiques multiparamétriques aériens. Les instruments VLF actuels sont légers, fiables et faciles à installer et à manier. Leur inclusion dans l'instrumentation géophysique aéroportée n'augmente que très peu le coût des levés, tout en fournissant des données extrêmement utiles à la cartographie géologique. Les données VLF du champ total sont ordinairement présentées sous forme de cartes en courbes.

Par le passé, on a essayé de réaliser des travaux de cartographie aérienne par résistivité à fréquences VLF et plus élevées (jusqu'à 1 MHz). Le système E-PHASE a été le premier qui ait permis produire des cartes de résistivité en courbes, mais le manque de données à l'extrémité inférieure du spectre d'audiofréquence le empêche de devenir un instrument de cartographie aérienne courant.

Trois sociétés canadiennes fabriquent actuellement des systèmes VLF aéroportés. Les paramètres mesurés diffèrent légèrement d'un système à l'autre. On peut installer les détecteurs VLF en bout d'aile dans le nez de l'appareil, sur le cadre inférieur d'un hélicoptère ou sur un tube remorqué.

INTRODUCTION

Radio signals in the MHz range were used for geological mapping already in the 1930s, but at that time only on experimental basis (Cloos, 1934). Measurements at very low frequencies (VLF) – between 15 kHz and 25 kHz – became a practical exploration tool in the 1960s when Vaino Ronka designed the first portable VLF apparatus. The Geonics EM-16, as it was called, is a light-weight instrument (1.6 kg) which measures tilt angle and ellipticity of the magnetic component of the VLF field. The instrument is still in use and it has been consistently outselling other EM ground units. The VLF technique became practicable after the completion by the U.S. Navy and other powers of a network of powerful transmitters which were designed for communication with submarines. The VLF method, which does not require its own transmitter, could thus become the fastest and the least expensive EM technique. Another attractive feature of VLF measurements is the ease of theoretical solutions for a number of models. The plane-wave excitation is much easier to handle theoretically than dipole or large-loop sources.

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EARLY AIRBORNE VLF SYSTEMS

The first operational airborne VLF system was developed by McPhar Geophysics Ltd. of Toronto in the early 1960s. It was called KEM and it used a pair of cross coils which measured horizontal-field strength and tilt angle. No measurements of the quadrature component were recorded. The instrument was rather simple and susceptible to errors in dip angle measurements, which resulted from pitch movement of the aircraft.

Geonics Ltd. of Toronto designed an airborne version of the successful EM-16. The instrument (EM-18) measured the vertical in-phase and quadrature components of the secondary magnetic field as a percentage and phase of the horizontal vector. A vertical gyro was used for correction of the aircraft pitch.

AIRBORNE RESISTIVITY MAPPING

The most ambitious VLF project was undertaken from 1969 to 1973 by Barringer Research Ltd. of Toronto. The company designed two airborne systems, RADIOPHASE® and E-PHASE®, which should have established the technique as an aid to geological mapping at par with magnetics and radiometrics.

The RADIOPHASE system used three orthogonal coils to measure the magnetic components of the magnetic VLF field and a vertical whip antenna to measure the vertical component of the electrical field. Because of its poor coupling with the ground, the vertical electrical component could be used as phase reference to correct the magnetic components for aircraft movement and variable transmitter intensity (Barringer and McNeill, 1970). Data were presented as vectors along profiles and contour maps of the in-phase component of the horizontal magnetic field. Anomalies were caused by surficial features (changes in overburden thickness), shear zones and bedrock conductors.

The second system, E-PHASE, was more widely used than RADIOPHASE and it was in use until 1979. Fifteen years ago, the existing AEM systems were not considered suitable for airborne resistivity mapping (Sinha, 1973) and the VLF techniques were thought highly promising for this task. The E-PHASE measures the in-phase and quadrature components of the horizontal electric field and the in-phase component of the vertical electric field. The ratio of the quadrature component of the horizontal electrical field and of the in-phase component of the vertical electrical field is called wave tilt. As Sommerfeld (1909) showed this quantity can be used to calculate earth resistivity.

As in galvanic resistivity measurements, one postulates apparent resistivity, which can be calculated for all measured points along the flight line. Measurements were carried out simultaneously at 3 frequencies, one in the VLF band (15 to 25 kHz), one in the LF band (200 to 400 kHz), and one in the MF band (550 kHz to 1.1 MHz). In the last band, non-directional radio beacons (NDB) located at airports or AM broadcast stations (BCB) were used. Three profiles of apparent resistivity were generated by digitally processing the raw data and resistivity maps were compiled for 3 frequencies. An example from a survey near Wadena, Saskatchewan, is shown in Figure 6.1. The three-frequency data could be used to interpret thicknesses and resistivities of up to 3 layers assuming horizontal stratification (Fig. 6.2). The E-PHASE scheme can be cited as the first successful application of digital data processing in AEM surveying. All operations were automated: digital recording, data correction, resistivity calculation, map gridding and plotting, and semi-automated inversion of the data to produce resistivity sections (Palacky and Jagodits, 1975).

While the E-PHASE was a technical success, it did not become one of the leading AEM techniques in terms of the mileage flown. In the context of this Workshop on Airborne Resistivity Mapping, it is interesting to note that the technique was marketed as "airborne resistivity". In the days when most efforts went into designing deeper penetrating AEM systems for massive sulphide exploration, the E-PHASE pursued the concept of a shallow penetration technique applicable primarily to Quarternary geological mapping. Numerous surveys in various parts of North America were successful in identifying lithological changes in shallow sediments.

PRESENT AIRBORNE VLF TECHNIQUES

The history of the last 20 years shows that VLF systems are viewed as a valuable accessory tool in multiparameter surveys, but are not accepted as a primary airborne geophysical technique. The demand is for reliable light-weight instruments that would be insensitive to changes in aircraft movement and remain virtually maintenance-free.

At present, airborne VLF systems are manufactured by Scintrex Ltd. and Herz Industries Ltd. of Toronto, and Sander Geophysics Ltd. of Ottawa. The Scintrex SE-99 is similar to the previously described Geonics EM-18, but in addition to the vertical magnetic component, it also measures the horizontal vector amplitude of the VLF magnetic field. The coils are compensated for aircraft pitch using level sensors. The Sander Geophysics VLF system has three orthogonal coils. A vertical gyro is used for aircraft movement compensation. Multichannel measurements are recorded and inflight processed by an onboard computer.

Herz Industries Ltd. developed two airborne VLF systems, Totem-1A (Fig. 6.3) and Totem-2A. Both are lightweight and easy to install in an aircraft or a towed bird. Figures 6.4-6.6 show installations of the sensors on a wing tip and nose stinger (for fixed- wing planes) and a helicopter. While the Totem-1A was designed to operate at one frequency (operator selected), Totem-2A can simultaneously record VLF signals at two frequencies. This improvement is significant as it permits a better coverage using two transmitters. It is a known fact that conductors must point in the direction of the transmitter to produce optimum response. Other strikes result in degradation or even disappearance of VLF response. If the

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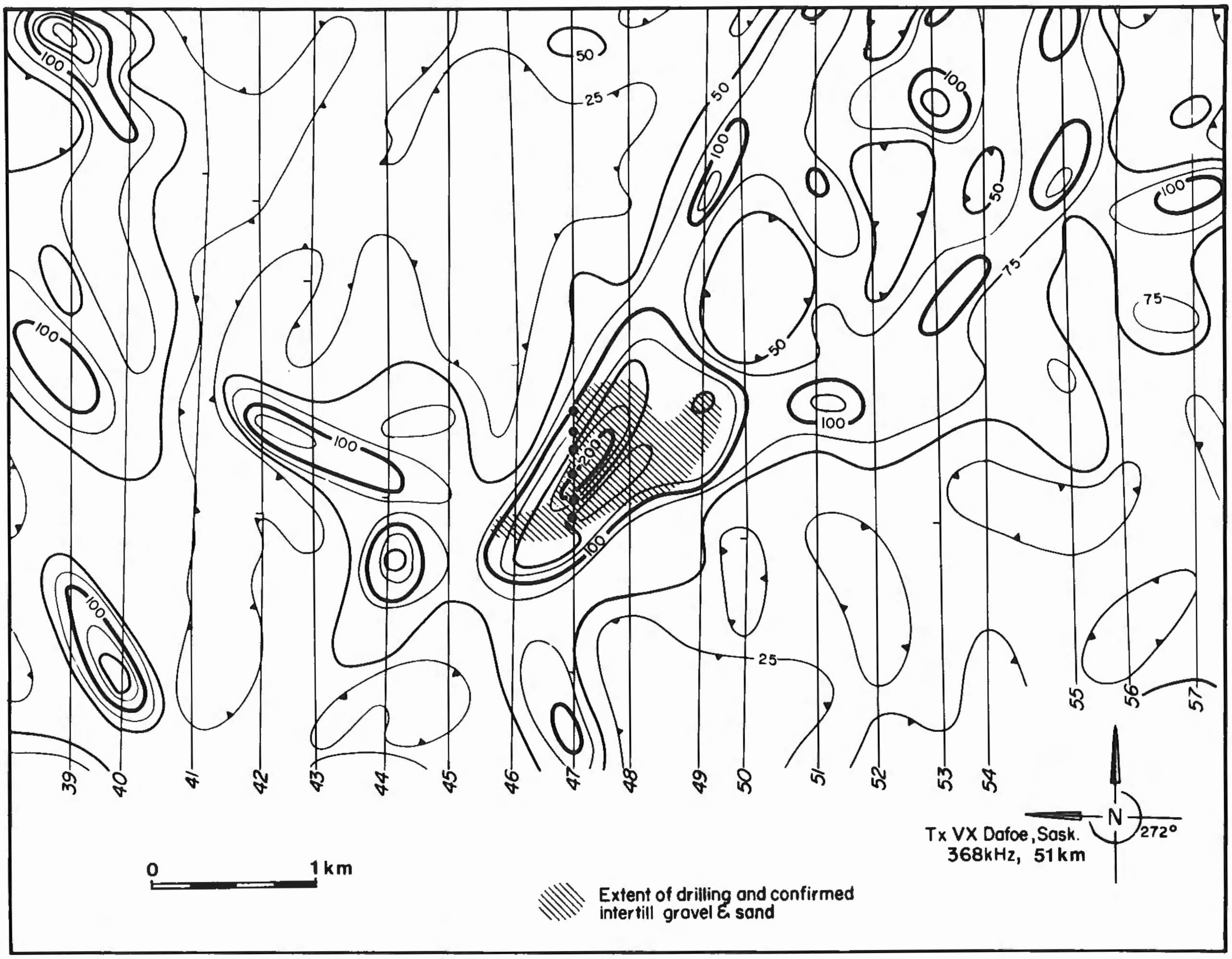

Figure 6.1. Map of apparent resistivities obtained with the E-PHASE system near Wadena, Saskatchewan (frequency used 368 kHz). The shaded area indicates a gravel deposit found as a result of this survey (from Palacky and Jagodits, 1975).

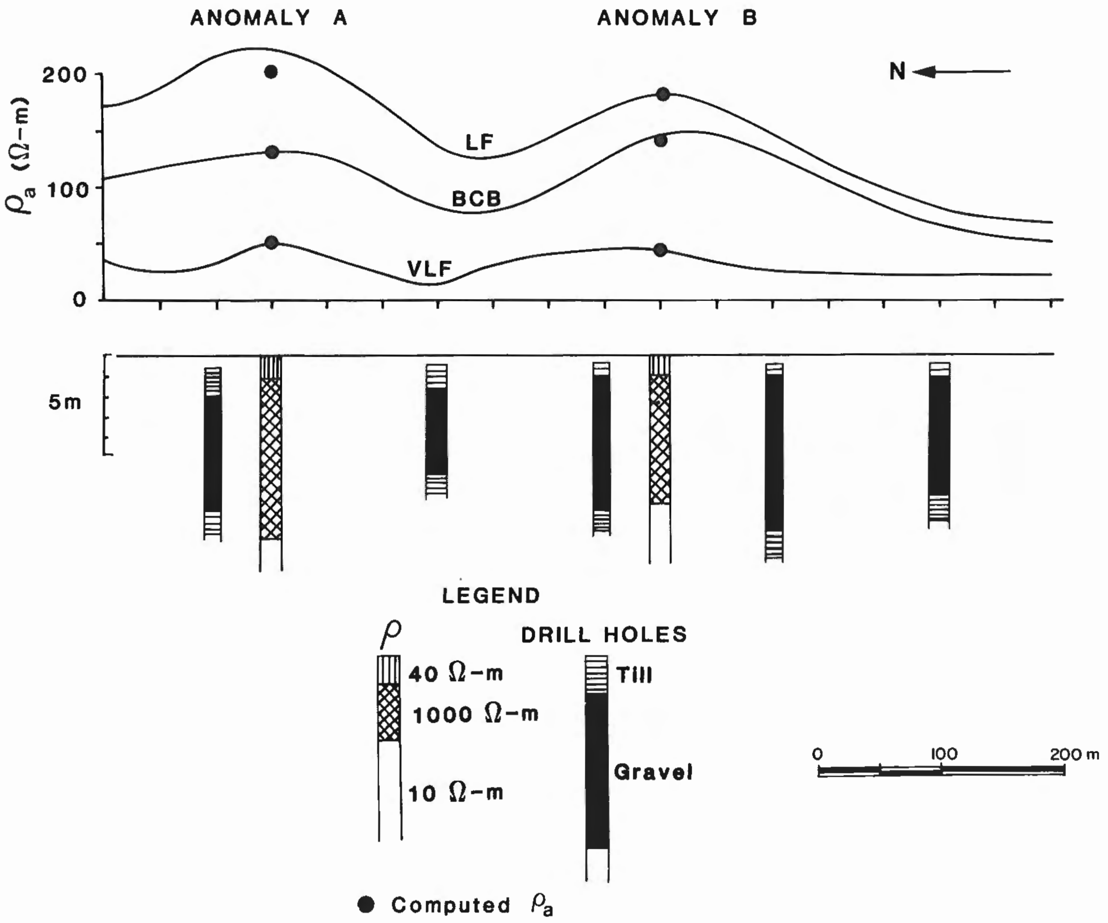

Figure 6.2. E-PHASE response at 3 frequencies along Line 47 (indicated in Fig. 6.1). Interpretation of AEM data is shown for 2 anomalies, along with logs of 5 drillholes (from Palacky and Jagodits, 1975).

Figure 6.3. Totem-1A VLF receiver consisting of 19-inch rack-mounted console, the receiving coils, preamplifier unit, and interconnecting cables.

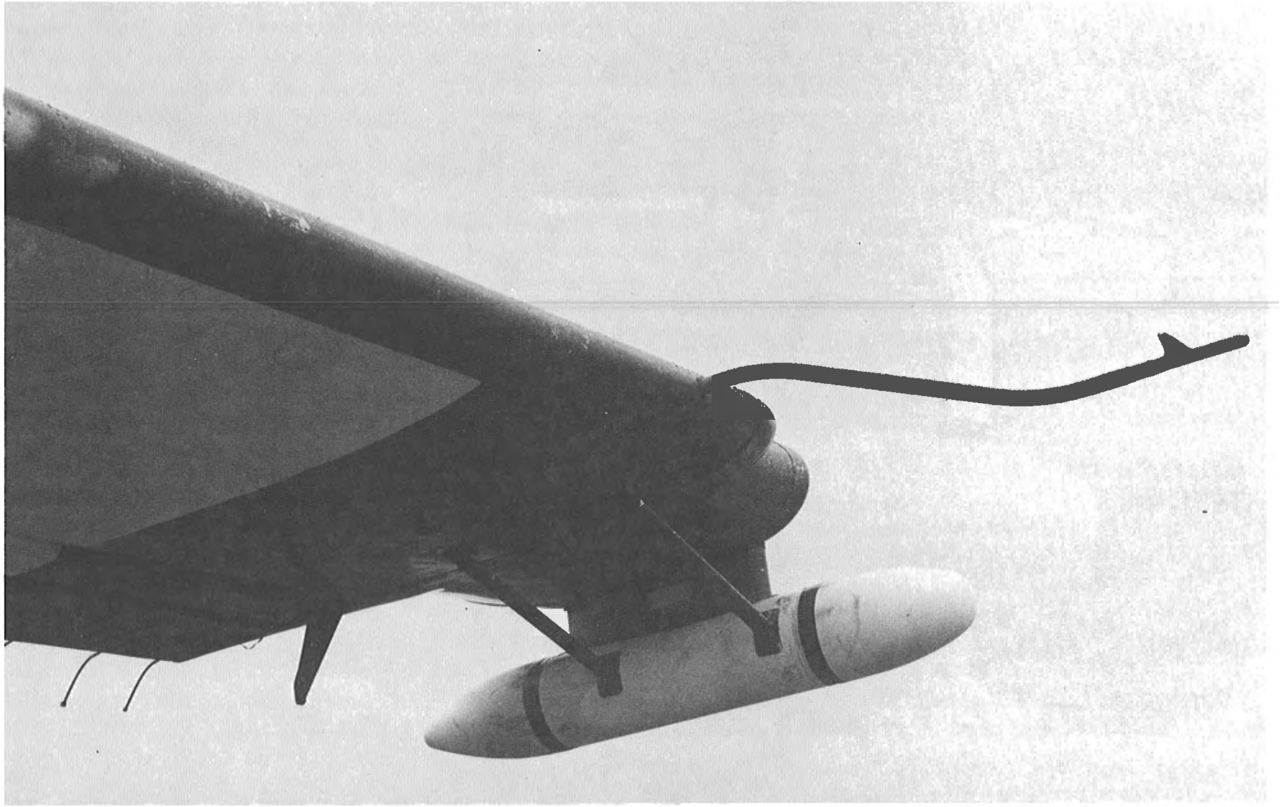

Figure 6.4. Wing-tip installation of Totem-2A receiving coils (courtesy of Geoterrex Ltd. of Ottawa).

Figure 6.5. Nose-stinger installation of Totem-2A receivers (courtesy of Geosurveys International Ltd. of Nairobi).

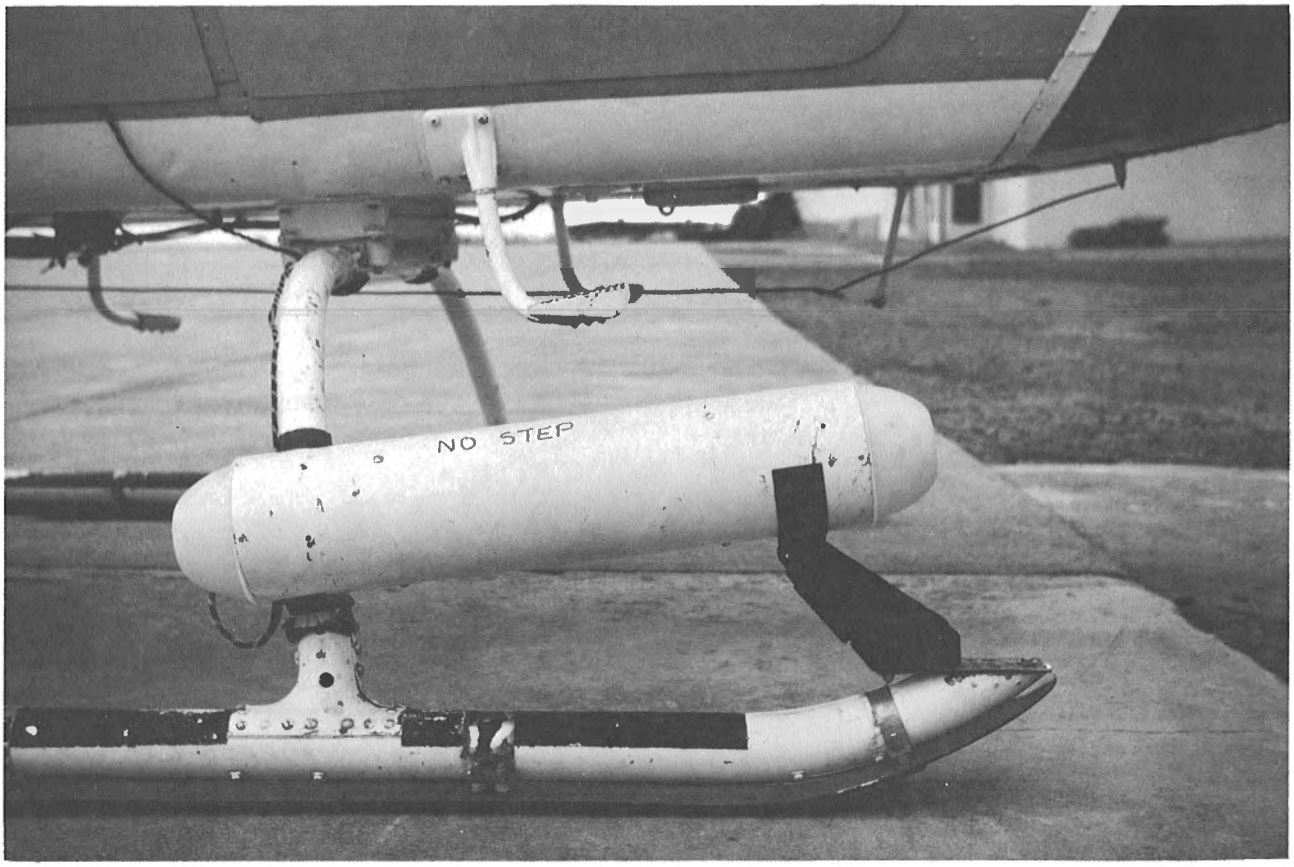

Figure 6.6. Helicopter installation of Totem-2A receivers (courtesy of Placer Exploration Ltd. of Vancouver).

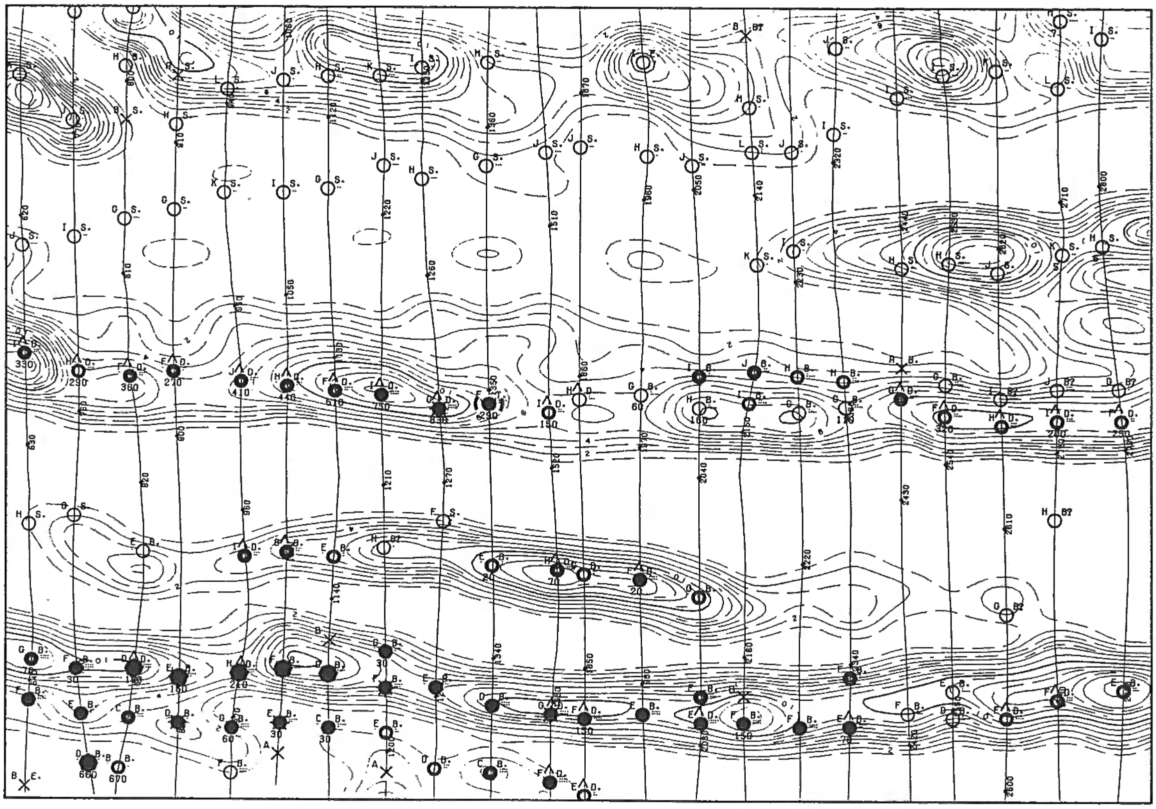

Figure 6.7. Contour map of total field VLF response from Utik Lake, Manitoba. Also shown are locations of conductors obtained in the course of a helicopter EM survey (courtesy of Westmin Resources Ltd. and Dighem Surveys and Processing Inc. of Mississauga).

directions to the two transmitters are mutually perpendicular, good coupling with at least one can be expected, thus assuring a good coverage of the survey area. Totem-2A has three orthogonally mounted coils which measure the total field strength and the vertical quadrature component of the magnetic VLF field. No external correction is required for aircraft pitch, roll, and yaw.

The airborne VLF data are usually recorded digitally, and several sets of maps can be produced (2 quantities measured at 2 frequencies). Figure 6.7 shows total-field VLF data from Utik Lake, Manitoba. The survey area is located in a Precambrian greenstone belt, where iron-formations and graphitic conductors have been identified. Conductors appear as anomaly highs; on the example also the results of a helicopter EM survey are shown (circles indicating location of conductors).

CONCLUSION

The airborne VLF technique is widely used in airborne geophysical surveying. Usually, it is an inexpensive add-on in multiparameter surveys. However, the low cost does not imply low utility of the data. Hundreds of thousands, perhaps millions of line kilometres of airborne VLF surveys all over the world have demonstrated the usefulness of the technique in geological mapping.

ACKNOWLEDGMENTS

I thank Geosurveys International Ltd. of Nairobi, Geoterrex Ltd. of Ottawa, and Placer Exploration Ltd. of Vancouver, for supplying photographs of their installations, and Westmin Resources Ltd. and Dighem Surveys and Processing Inc. of Mississauga, for examples of VLF surveys. G.J. Palacky of the Geological Survey of Canada provided information on the RADIOPHASE and E-PHASE systems.

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- 7 -

Development of the PROSPECT I airborne electromagnetic system

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Annan, A.P., Development of the PROSPECT I airborne electromagnetic system in *Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 63-70, 1986*

Abstract

PROSPECT I® is a new fixed-wing, towed-bird system which is being developed for airborne conductivity mapping applications. This paper presents the design philosophy and describes the design features. The system is now in the initial test-flying stages.

The PROSPECT I system has an operating frequency band from a few 10s of Hz to over 10 kHz. A 3-component, vector-field towed bird which has been designed for high stability and position tracking provides the multi-component data essential for motion compensation and target geometry descrimination.

Automated data handling and anomaly selection form an integral part of the system design. Examples of automated anomaly selection using existing AEM data are presented.

Résumé

Le système PROSPECT I® est un nouveau système monté sur avion avec un tube remorqué qu'on est à mettre au point pour des applications de cartographie aérienne par conductivité. La présente étude en expose les principes de conception et en décrit les caractéristiques théoriques. Le système est actuellement au stade des premiers essais en vol.

Le système PROSPECT I utilise une bande de fréquences allant de quelques dizaines de Hz à plus de 10 kHz. Un tube à 3 bobines à champ vecteur, conçu pour une haute stabilité et le traçage de la position, fournit les données à plusieurs composantes essentielles à la correction du mouvement et à la discrimination géométrique de la cible.

Le traitement des données enregistrées par ordinateur et la sélection automatisée des anomalies font partie intégrante de la conception du système. L'étude présente des exemples de sélections automatisées des anomalies utilisant des données ÉMA existantes.

INTRODUCTION

The concepts underlying the PROSPECT I system have been fermenting with its developers for the past decade. The first major action toward the development of the system took place approximately 3 years ago when A-Cubed Inc. was established. Its founding members set out with the objective of doing for airborne EM surveying what had been done for seismic data acquisition 20 years ago, namely, to provide state-of-the-art totally digital systems with quantified measurements throughout.

PROSPECT is an acronym for **P**eriodically **R**epeated **O**utput **SPECT**rum which reflects the nature of the transmitter and signal processing components. The system is designated PROSPECT I to indicate that this is the first embodiment of the fundamental design principles which have been used in this new series of EM systems.

The development of a modern EM system requires rationalization of:

1) The physical embodiment of the system.
2) The operational logistics of running the system.
3) The data handling and interpretation of results obtained with the system.

This paper reviews each of these aspects of system development. In the case of the PROSPECT I system, the stage of physical embodiment has now been completed. The system is

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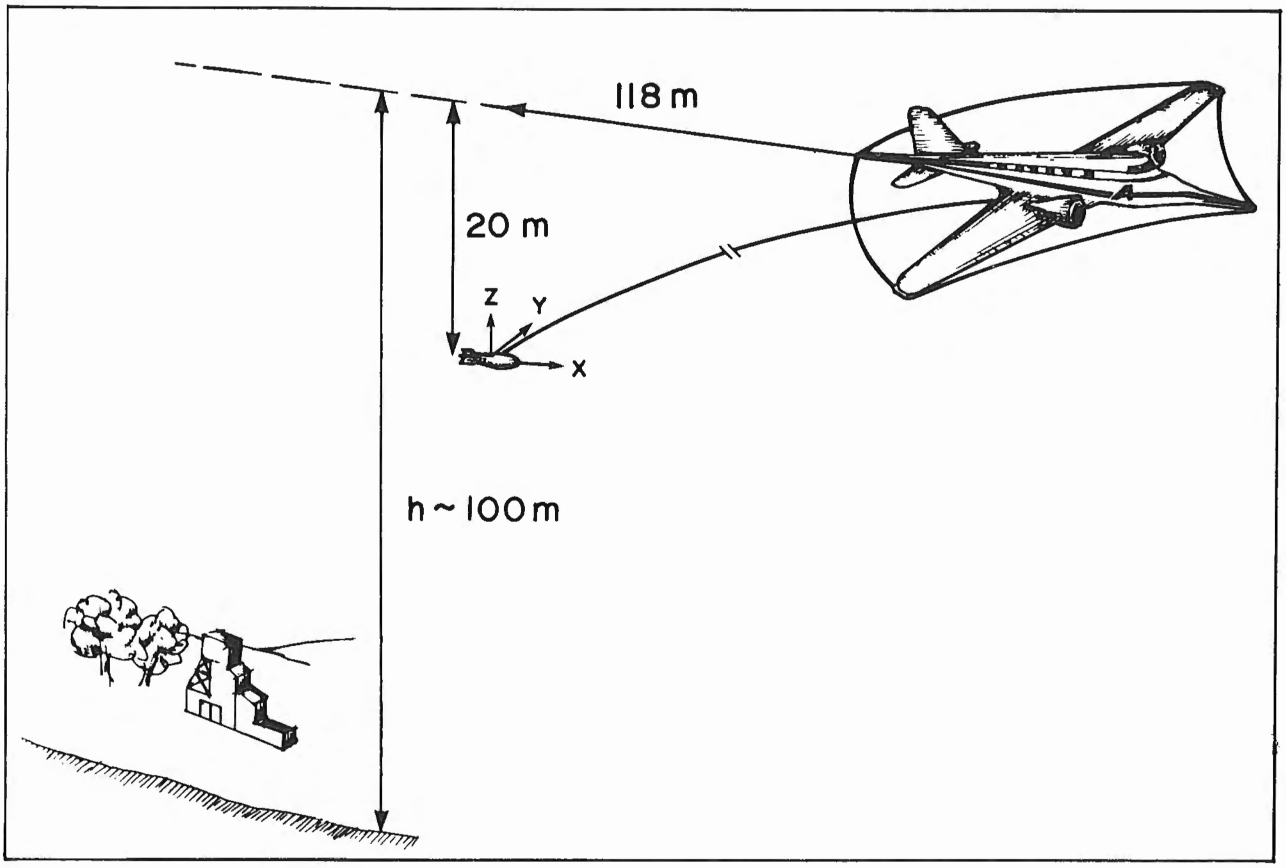

Figure 7.1. Illustration of the PROSPECT I system geometry and airborne platform. The orthogonal receiver signal components are **x, y** and **z** where **x** is aligned with the flight direction, **z** is vertically up and **y** is selected to complete a right-handed co-ordinate system.

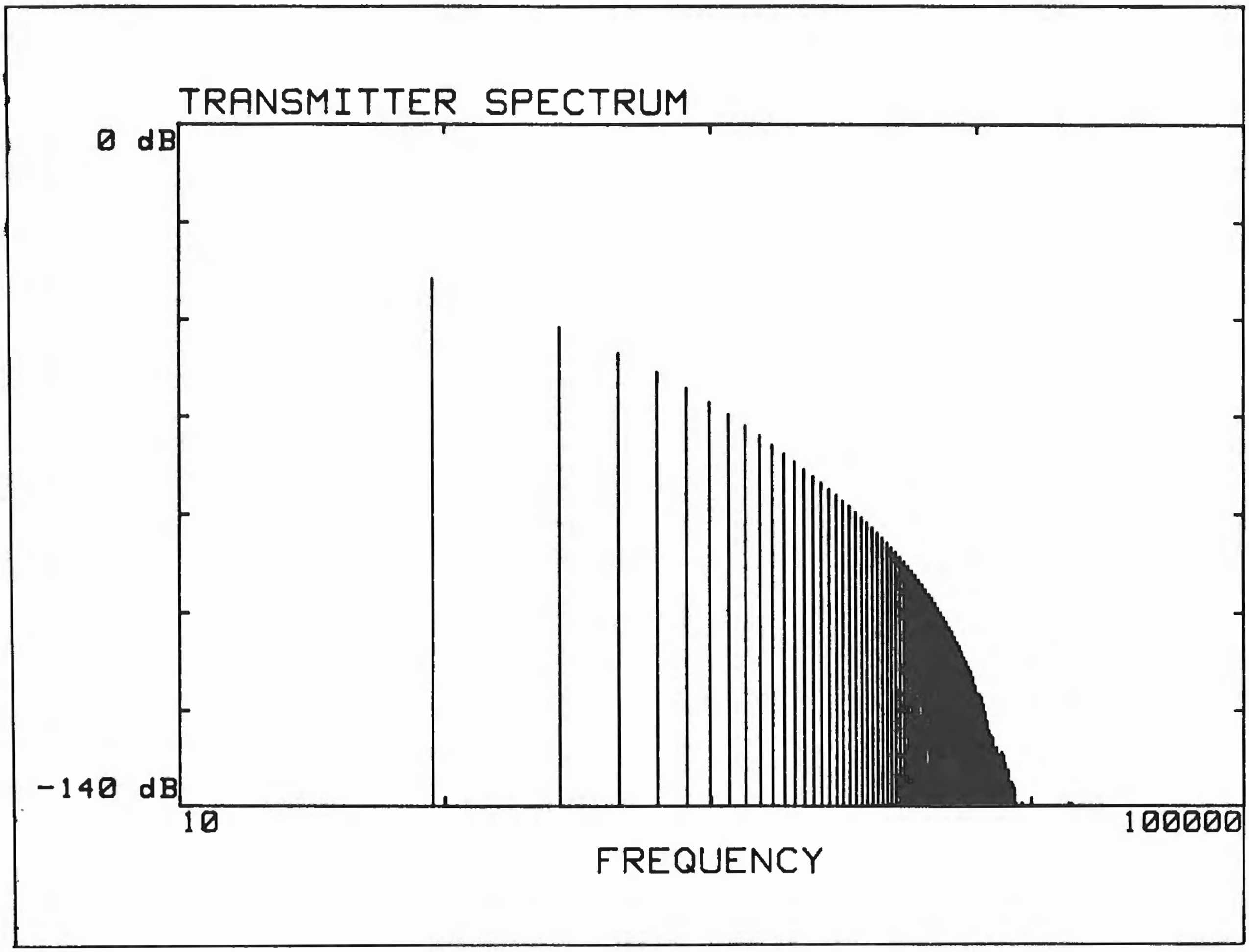

Figure 7.2. Typical PROSPECT transmitter line spectrum as measured with the digital receiver employing a 5 kHz 10th order anti-aliasing filter.

now constructed and is being initially tested in the air. The latter two aspects have been addressed throughout the development cycle and will continue to be given important consideration as the system moves from testing into production.

SYSTEM DESIGN PRINCIPLES

Each of the three main aspects of an EM system presents its own goals and objectives. Compromises have to be made between engineering practicality and geophysical utility. The primary objective of the PROSPECT system design has been to assemble a precision geophysical tool which reproduces the ground response with fidelity. In the area of physical embodiment which encompasses the instrumentation and physical construction of the system, the basic design principles were modularity, flexibility, and fidelity. For the operational aspect of the system, the costs of assembly and operation, the reliability, and the minimization of operator intervention were at the fore. For the geophysical aspect of the system, which encompasses data reduction and interpretation, the objectives were penetration, discrete target discrimination, conductivity mapping, and automated data handling.

System platform configuration

The fundamental decision in developing an airborne EM system is to settle on the platform and system configuration that one is going to use. This step involves examination of the geophysical requirements of the system and the practical constraints of available aircraft. The PROSPECT I system was designed as a fixed-wing, towed-bid (FWTB) system for the following reasons.

i) FWTB systems have the maximum penetration of any system configuration.

ii) FWTB systems have a large ground footprint which is extremely useful for regional reconnaissance.

iii) The operational costs of fixed wing platforms are less than helicopters.

iv) FWTB systems have superior target discrimination because of their greater power-bandwidth capability.

v) The state-of-the-art of FWTB systems is still primitive and there is tremendous room for improvement.

Two factors viewed as limitations of FWTB systems are the spatial resolution and target positioning accuracy. These limitations are the result of outdated technology or methodology and not an inherent feature the FWTB configuration.

A major problem with a towed-bird system is bird motion. For discrete bump detection it is not a major problem. For resistivity mapping or detecting discrete bedrock targets in a conductive environment, it is a critical item to be considered. The problems of bird motion have been presented by Annan (1983, 1984).

The PROSPECT I system has been mounted on a DC-3 aircraft as sketched in Figure 7.1. This aircraft gives long range, large size, and economic performance. The liability of such a platform is that it is an old aircraft.

Transmitter design

Designing the PROSPECT I transmitter required going back to the fundamentals. The objective was to achieve a transmitter which had a clean spectral distribution and which could be operated down to very low frequencies. The current PROSPECT I transmitter has no bottom end on its operational frequency. The lowest frequency of operation is limited only by the speed at which the aircraft flies. In other words, one transmit cycle cannot be too long, otherwise the speed of the aircraft motion over the ground will average the signal over too large a spatial distance. The practical lower limit for operating frequency is typically in the 30 to 100 Hz range.

An example of the spectral distribution of the transmitter system being operated in one mode of operation is shown in Figure 7.2. The spectrum in this case varies inversely with frequency. This transmitter spectral distribution is designed to achieve approximately equal signal-to-noise across the operating bandwidth. The general behaviour of the atmospheric noise spectrum is shown in Figure 7.3. The high-frequency bulge in the atmospheric noise spectrum is due to "spherics" which are eliminated by sophisticated digital signal processing.

Towed-bird receiver

The towed-bird system which has been developed is unique and proprietary. The bird is currently towed at a distance 120 m behind and below the aircraft as shown in Figure 7.1. The towed-bird unit measures all three vector components of the field. As indicated in previous work on bird motion effects, it is imperative that the total vector field be obtained if compensation for bird motion is to be undertaken systematically.

Size constraints and aerodynamic system bandwidth limit the operation of the towed-bird system to an EM bandwidth of approximately 10 Hz to 20 kHz in the current implementation. This bandwidth is a design cut-off limit based on requirements for the PROSPECT I system and not a fundamental hardware limitation.

Digital EM receiver

The heart of the PROSPECT I system lies in its digital receiver technology. The system is operated under computer control. The receiver is a four-channel wideband, digital signal acquisition unit. Four channels of analogue signal can be acquired at sampling rates of up to 100 kHz. Figure 7.4 shows a block diagram of the receiver system.

The four channels of data are currently assigned to transmitter current and the 3 signals from the towed bird. These sampled data are fed to an array processor which removes the system transfer function, and reduces the data to a format for real-time display. The real-time signal processing steps are outlined in Figure 7.5.

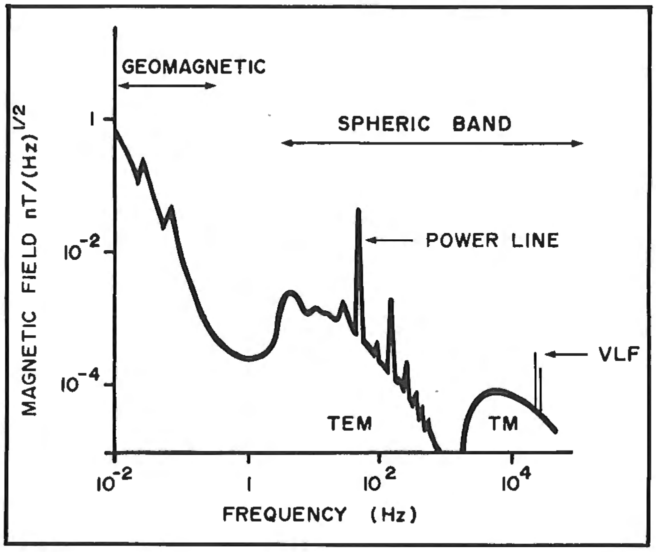

Figure 7.3. The general electromagnetic noise spectrum encountered by AEM survey systems.

The functional bandwidth of the receiver is DC to 10 kHz. Changes in bandwidth can be accomodated by changes in the clock rates and the anti-aliasing filters used in the signal preconditioning circuitry.

The PROSPECT I system is digitally controlled and is completely reconfigurable for a wide variety of measurements. For example, a complete-self-calibration of the system is carried out under computer control. Diagnostic signals are injected at numerous points along the signal path, re-acquired by the computers, and analyzed for stability, integrity and fidelity.

For testing and debugging bird operation and defining other system noise sources, the receiver has proved invaluable. Monitoring of motion-induced noise from a towed-bird sensor over a period of a few minutes and utilization of spectral analysis of these data defines the natural aerodynamic oscillaton frequencies of the bird system. These frequencies are exactly those predicted from an aerodynamic analysis of the bird suspension system. Examples of the use of a digital EM receiver were presented by Annan and Lobach (1985).

Data acquisition and peripheral instrumentation

The MIDAS (Modular Interactive Data Aquisition System) has been uniquely designed to support the EM receiver's wide bandwidth and large-volume data generation capabilities. A block diagram of MIDAS is shown is Figure 7.6. The heart of MIDAS is a general-purpose, multi-tasking mini-computer which supports a wide variety of peripherals. The system has been designed to be totally modular and reconfigurable. For example, the current MIDAS survey mode configuration is handling approximately 25 000 bytes of data per second. Any channel of information can be displayed via menu driven user control.

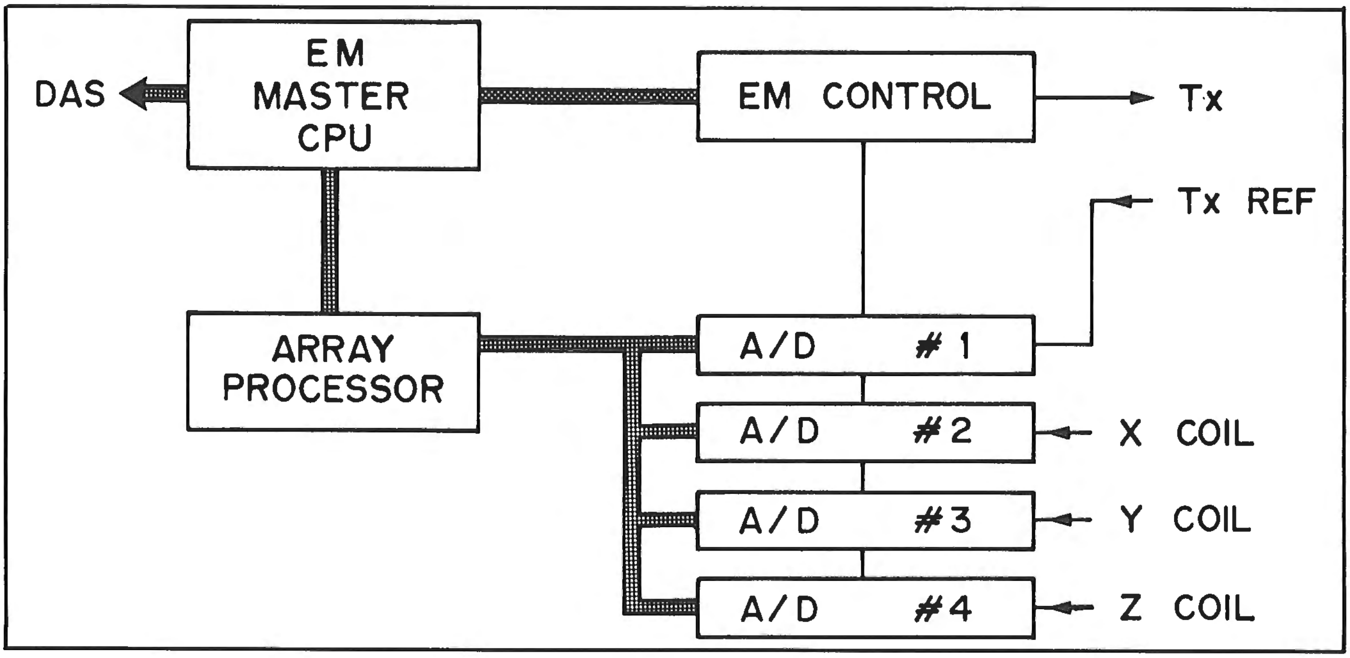

Figure 7.4. The block diagram of the PROSPECT I four-channel, wideband, digital EM receiver. The receiver controls all system timing and co-ordinates transmitter operation in addition to its wideband signal acquisition functions. Each A/D unit consists of analogue signal pre-conditioning circuitry in addition to analogue to digital signal conversion.

DATA PROCESSING AND DISPLAY

The PROSPECT system permits measurement of the ground transfer function over a frequency range of a few tens of Hz to over 10 kHz. The output of the system is the transfer function uncontaminated by DC level offsets, unknown calibrations, and system drifts. One of the major problems with such a system is the manner of data presentation. One has 3 components of data to display with an enormous bandwidth of information to convey.

Choices of display are either the time domain or the frequency domain. The current PROSPECT data are being displayed in the time domain as the windowed step response of the ground as illustrated in Figure 7.7. For those familiar with the UTEM system on the ground, PROSPECT I provides the same type of data presentation (West et al., 1984).

In order to convey a feeling for system performance, standard interpretation aids have been generated for first-order data analysis. The PROSPECT I response over a conductive half-space is shown is Figure 7.8 for varying ground conductivity. The superior bandwidth of the PROSPECT system produces improved performance in target discrimination based on conductivity. Needless to say, the additional geometrical information from the multicoil receiver system is also very useful for discrete target analysis and discrimination.

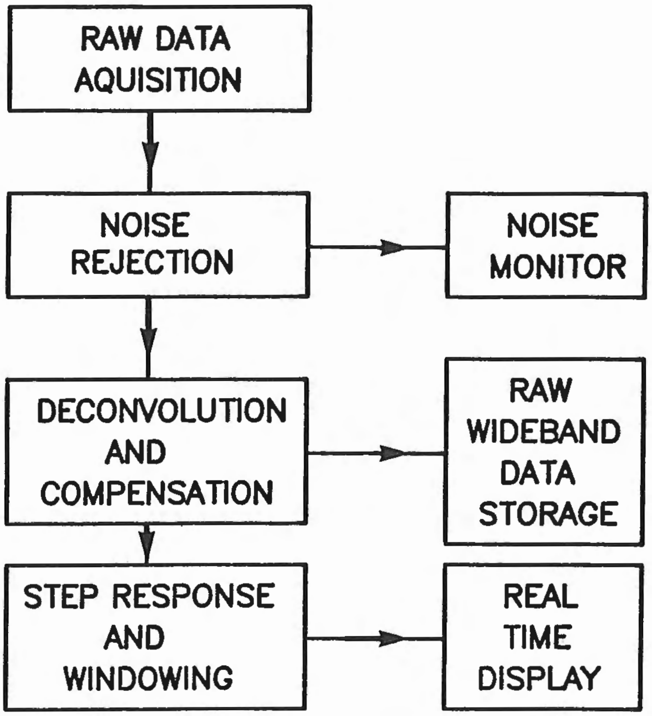

Figure 7.5. The major elements of the real-time signal processing carried out in the PROSPECT I digital AEM receiver.

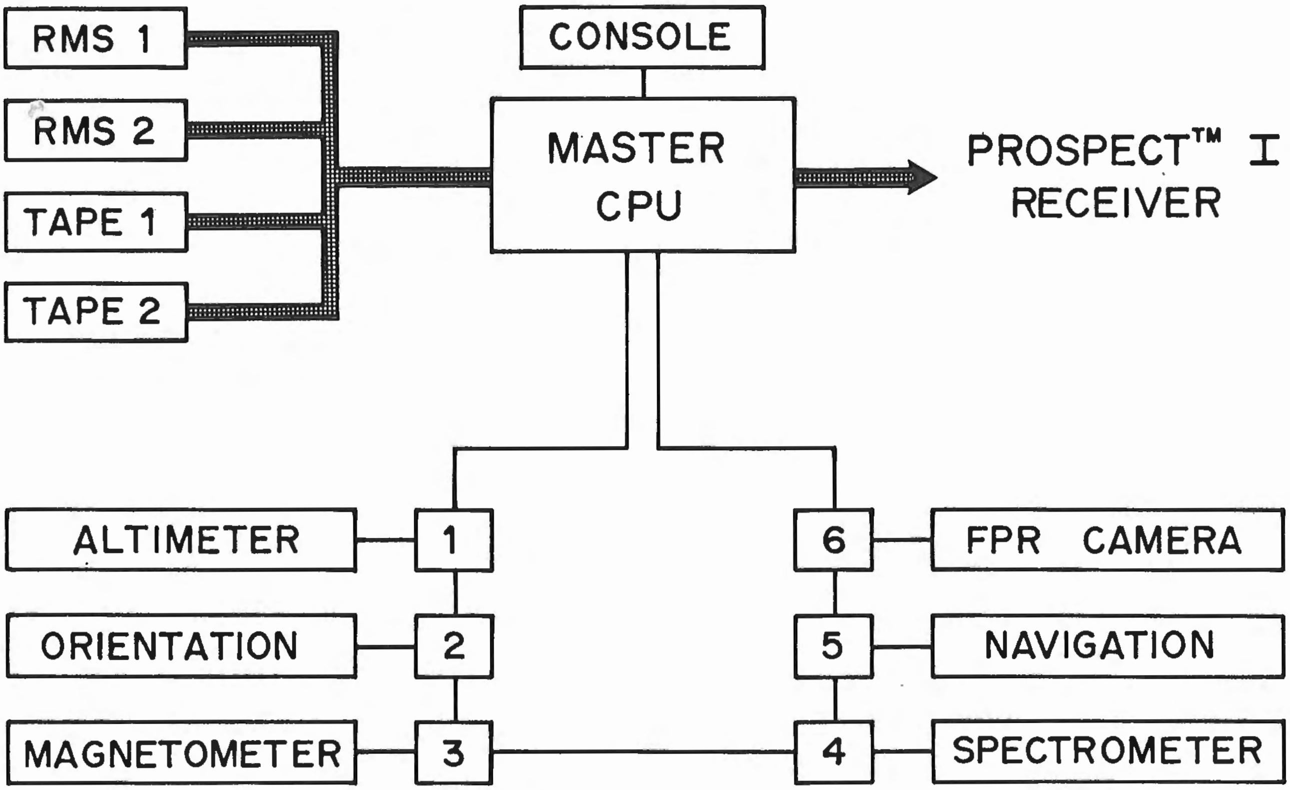

Figure 7.6. The block diagram of the MIDAS (Modular Interactive Data Acquisition System) developed to provide flexible, reconfigurable data display and recording capabilities for the PROSPECT I system.

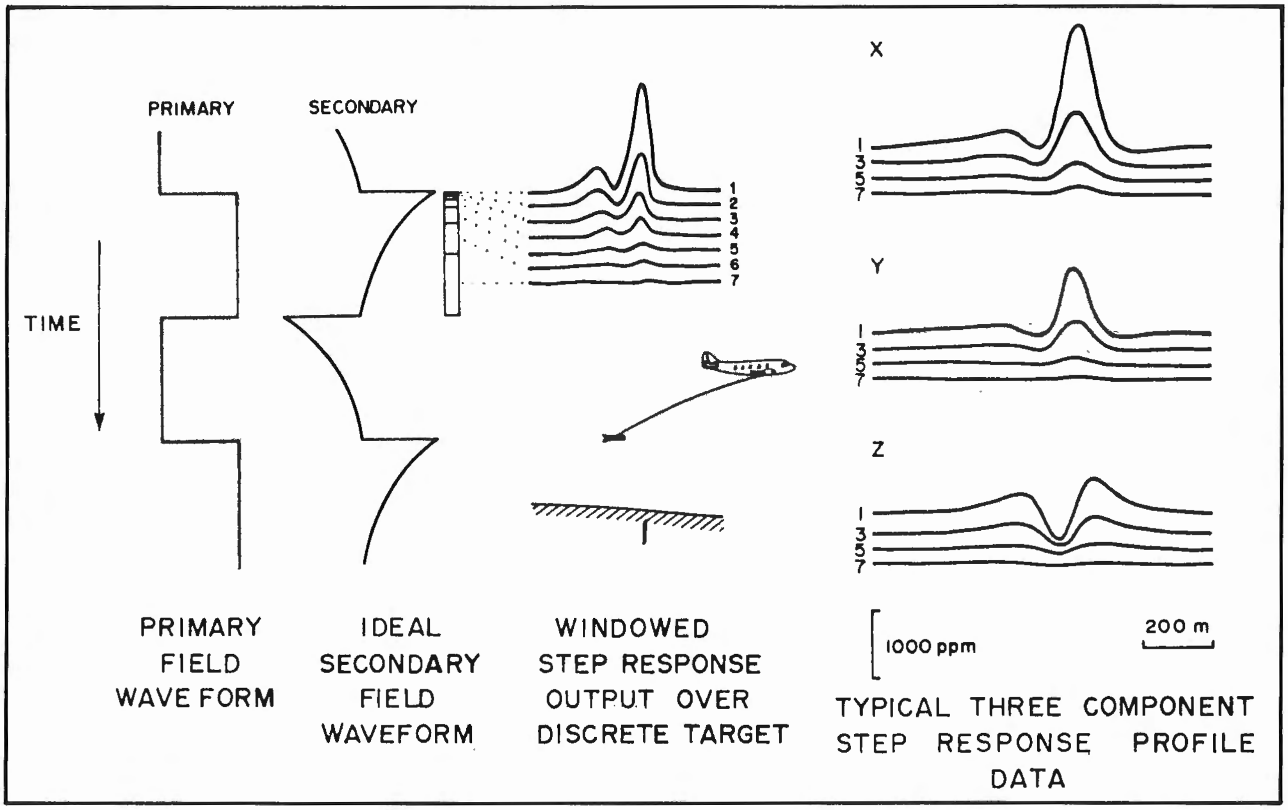

Figure 7.7. This diagram shows the transformation of deconvolved time domain step response data into chart profile format. The full waveforms shown on the left are windowed at logarithmically spaced time intervals to generate the profile format results shown in the centre and on the right for the multiple coil receiver.

DATA HANDLING AND INTERPRETATION

The key to success of any system is how data are presented to the user. The data presentation methods that have been used for towed-bird AEM data in the past decade have vastly limited the utilization of the data. There is a wealth of information which lies in existing towed-bird EM data which has not been extracted. Systematic attempts to improve data presentation and to extract more quantitative results lead to better data collection practices and technology.

A-Cubed has systematically undertaken to address this subject just as thoroughly as the rest of the system development. For experimental purposes and design of data processing and presentation techniques, procedures for processing Input AEM data in a systematic manner have been developed which allow automated anomaly selection and discrimination by computer (Vaughan, 1985). Figure 7.9 shows an automatically reduced data set displayed in stacked profile form.

CONCLUSIONS

The PROSPECT I system is now well down the development path. From the geophysical viewpoint, however, it is just at the starting gate in terms of operation, data handling, and data

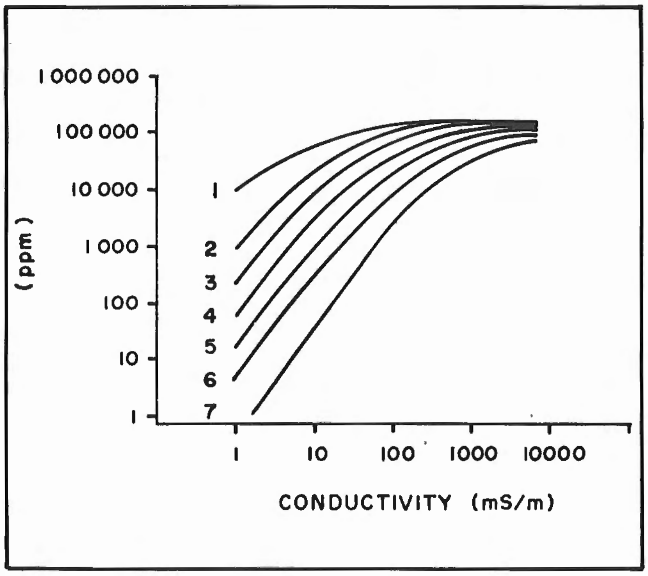

Figure 7.8. Plot of the logarithmically windowed PROSPECT I step response for the system flying at an altitude of 120 m over a conductive half-space of varying conductivity. This nomogram displays the secondary field response for the **x** component receiving coil.

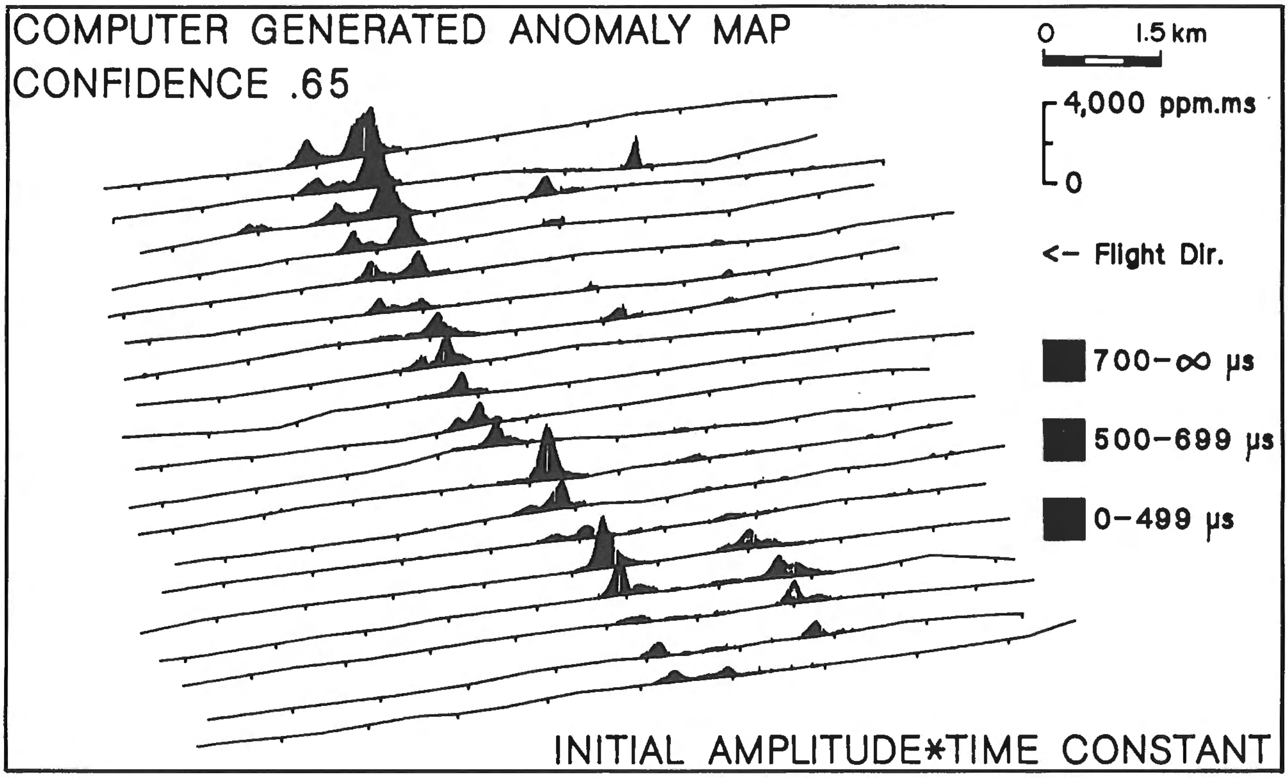

Figure 7.9. Example of a computer generated anomaly map displaying stacked profiles of the initial amplitude – time constant product for a standard set of INPUT AEM data. Anomaly quality (confidence) has been used to window the data for features with a 0.65 confidence level. The colour display allows time constant to be superimposed on the amplitude information.

presentation. A tremendous amount of design, thought and effort has gone into the system. Over the next 3 years this same kind of effort will be expanded on bringing the system into a state where it is a viable, commercially usable system.

As one can plainly see, the PROSPECT I system maximizes the utilization of computer technology. There is no doubt that this is the way of the future and systems that do not operate this way will not be able to compete in the market place of the future.

ACKNOWLEDGMENTS

The development of the PROSPECT I system has been a tremendous team effort. Numerous people have been involved in the systems design and development. The superb efforts by Gary Black and Dave Leggatt have been essential in putting the system together. Real-time software development has been directed by John Lobach and data handling and interpretation efforts have been conducted by Chris Vaughan.

In addition to the efforts of all the individuals at A-Cubed Inc., I would also like to acknowledge financial and/or technical support received from the National Research Council of Canada, the Ontario Geological Survey ETDF program, and Anglo-American Corporation.

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- 8 -

The Sweepem airborne electromagnetic system

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Best, Melvyn, E. and Bremner, T.G.T., The Sweepem airborne electromagnetic system in *Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 71-77, 1986*

Abstract

Sweepem, a new towed-bird AEM system has been developed during the last few years. It is a multifrequency, multicoil system with a large dipole moment (1.2×10^5 Am^2) capable of measuring in-phase and quadrature responses at as many as 30 frequencies. Conversely, Sweepem can provide the band limited impulse response of the earth in the time-domain. The emitted waveform is a pseudo-random sequence whose parameters are controlled in flight. They are adjustable and can be optimized for the specific survey area.

A new algorithm allows for correction of the effect of bird motion on the in-phase response. The in-phase component is corrected in real time, resulting in approximately equal noise levels for the in-phase and quadrature responses.

Some results over a graphite zone near Senneterre, Quebec, are shown. Although they are preliminary, they show the high quality of this multifrequency system when compared to other frequency-domain towed-bird systems.

Résumé

Le système Sweepem est un nouveau système ÉMA à tube remorqué mis au point ces dernières années. C'est un système à plusieurs fréquences et à plusieurs bobines comportant un moment dipole étendu (1.2×10^5 Am^2). Il peut mesurer des réponses en phase et en quadrature sur une gamme pouvant atteindre jusqu'à 30 fréquences. Inversement, le Sweepem peut donner la réponse d'impulsion de la duration limitée par rapport au sol, pour le domaine temporel dont il s'agit. La forme d'onde émise est une séquence pseudo-aléatoire dont les paramètres sont contrôlés en cours de vol. Les paramètres sont ajustables et peuvent être optimisés en fonction du secteur particulier du levé.

Un nouvel algorithme permet de corriger les effets du mouvement du tube sur la réponse en phase. La composante en phase est corrigée en temps réel, ce qui se traduit par des niveaux de bruit approximativement égaux pour les réponses en phase et en quadrature.

L'étude présente les résultats obtenus au-dessus d'une zone de graphite près de Senneterre, Québec. Ces données sont préliminaires, mais elles montrent la haute qualité de ce système à plusieurs fréquences comparativement aux autres systèmes ÉMA à tube fonctionnant dans le domaine de fréquence.

INTRODUCTION

The Sweepem system resulted from the work of many geophysicists and engineers (Zandee et al., 1985). Royal Dutch/Shell Laboratories developed the basic hardware and processing design while Shell Canada Ltd. supplied the interpretation software. Finally, Kenting Earth Sciences Ltd. mounted the system into the Canso aircraft and is continuing to test it under operating conditions.

The Sweepem is a towed-bird AEM system with two orthogonal receiver coils in the bird. The transmitted current waveform is a pseudo-random sequence (PRS) with adjustable parameters to govern the frequency bandwidth and the number of frequencies. Thus the frequency spectrum can be

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[2] Kenting Earth Sciences Ltd., 380 Hunt Club Road, Ottawa, Ontario K1G 3N3.

adjusted to specific survey requirements. The system can operate either in frequency-domain or time-domain mode.

The present system covers the frequency band between approximately 50 and 5000 Hz. Depending on the parameters in the PRS sequence, the number of frequencies can vary from 14 to 32 (or more).

A new algorithm allows for the correction of bird motion and hence in-phase and quadrature or the equivalent time-domain responses can be obtained after corrections from the raw data. The processed in-phase and quadrature responses have approximately equal noise levels.

The design parameters for this system were developed after extensive modelling (Best et al., 1985). The main features are:

1. Measurement of in-phase and quadrature response using the bird correction algorithm.
2. Adjustable frequency spectrum between 50 and 5000 Hz. A slight modification to the present hardware can extend the upper frequency limit to 10 kHz.
3. Two orthogonal receiver coils which measure the magnetic field directly.
4. A large transmitter dipole moment (1.2×10^5 Am^2 rms).

HARDWARE AND EQUIPMENT

Figure 8.1 is a schematic diagram of the overall system. The receivers are mounted in a fibreglass bird, which is towed approximately 45 m behind the aircraft by a kevlar reinforced fibre optics cable (Figure 8.2). As the cable contains no metal, coupling with the earth's magnetic field and stray eddy currents on the aircraft are minimal. The cable transmits digital data at a very high rate (i.e. a large band width).

A PDP 11/23 (MINC) CPU is programmed to handle the data manipulation and control. An FPS 100 array processor is attached to this system to allow real-time processing of correlations and Fast Fourier Transforms (FFT). There is only a several second delay between the actual measurement of the signal by the receivers and the final display on a strip-chart recorder.

The transmitter emits any PRS combination of square waves under computer program control. The fixed rise time of 100 μs determines the upper limit of the frequency range. The wide wingspan (30 m) and the rigid structure of the Canso aircraft provide an ideal frame for mounting the large transmitter loop needed to generate a large dipole moment.

The receiver coils are part of an electronic feedback system which determines the magnetic field (B) instead of the usual first derivative (dB/dt). This means that the low frequency end of the spectrum is not degraded as is the case with normal coils. Inside the bird the signals are filtered, converted from analogue to digital, and then to optical signals.

Presently, the bird is approximately 45 m behind and 40 m below the aircraft at a normal cruising speed of 100 knots. This geometry is still being modified as the system develops. In the aircraft the received signals and the measured values for the transmitter current are stored in the array processor memory and processed after some averaging.

PROCESSING SEQUENCE

The waveform emitted by the transmitter is a pseudo-random sequence. The waveform is characterized by the length of the basic clockpulse (T) and one additional integer number (N) (Duncan et al., 1980). Figure 8.3 shows a typical current waveform for $N=4$. The sequence is repeated after 2^N-1 clock pulses. We have chosen the value of N to be 4 for most of our applications. Figure 8.4 shows the frequency spectrum of the PRS sequence in Figure 8.3. All peaks are equidistant, their spacing and total number solely determined by the value of T and N. The frequency spectrum is generally chosen so that no frequency is too close to 60 Hz and its harmonics.

The first step in the processing sequence is to calculate auto- and cross- correlations between the transmitter and receiver signals. These correlations are then Fourier transformed using an FFT algorithm and a frequency deconvolution applied to remove the transmitter response and the total instrument response of the system. These responses are averaged over 0.5 s.

The in-phase and quadrature responses are available at all frequencies present in the PRS spectrum. The aircraft chart recorder plots a subset of these while all the data are recorded on digital tape for further processing. Additional processing includes analysis of the data as phasor plots or as band limited impulse responses in the time domain.

BIRD MOTION CORRECTION

Bird motion causes large distortions in the in-phase response because of relative changes in the primary signal between the transmitter and receiver coils. Consequently, such noise can be larger than the secondary signals of interest. We have developed a new method of correcting the measured data for the bird motion.

The correction is based on the presence of a DC component in the PRS spectrum. As no ground response is present at 0 Hz frequency, fluctuations in the measured DC value are related to the bird motion. In practice, this so-called DC component, which is measured by the feedback coils, contains frequencies up to some maximum depending on the filters and the PRS sequence used. A typical value for the maximum frequency is 15 to 20 Hz. This means that good conductors will have a response in the DC channel. We have found that the combination of two receiver coils reduces this effect due to different coupling between the earth response and the bird-motion response. The bird motion shows up opposite in sign while the secondary signals have the same sign.

Examples of corrected in-phase and quadrature responses for the vertical receiver are given in Figures 8.5 and 8.6. Six frequencies ranging from 500 Hz to 4500 Hz and the altimeter trace are shown. The survey was flown near Senneterre, Quebec.

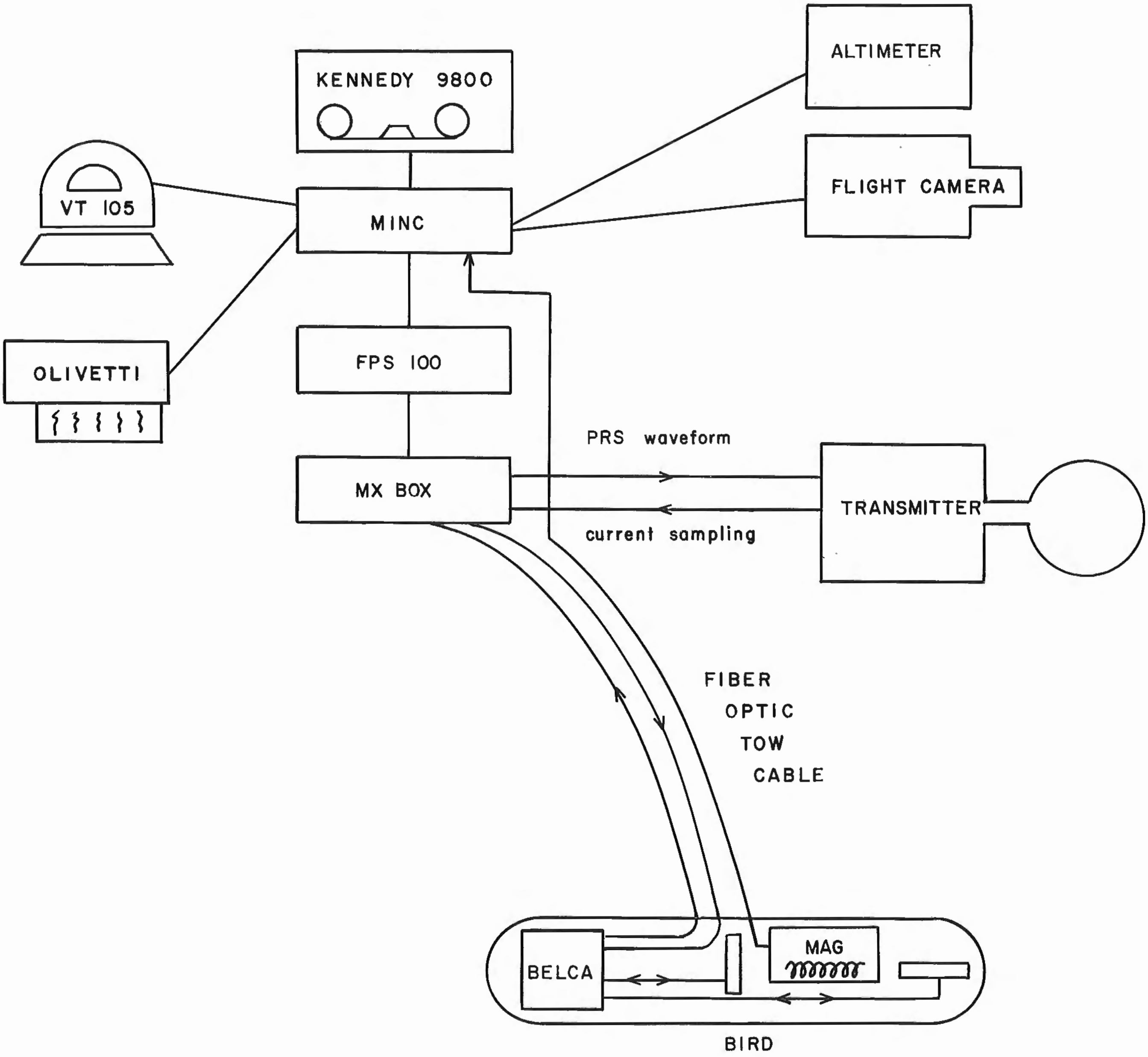

Figure 8.1. Schematic diagram of the Sweepem system installation in a Canso PBY aircraft. The bird is towed on a fiber-optic cable. A magnetometer is installed in the bird. The BELCA box consists of electronics for filtering, A/D conversion and electrical to optical conversion.

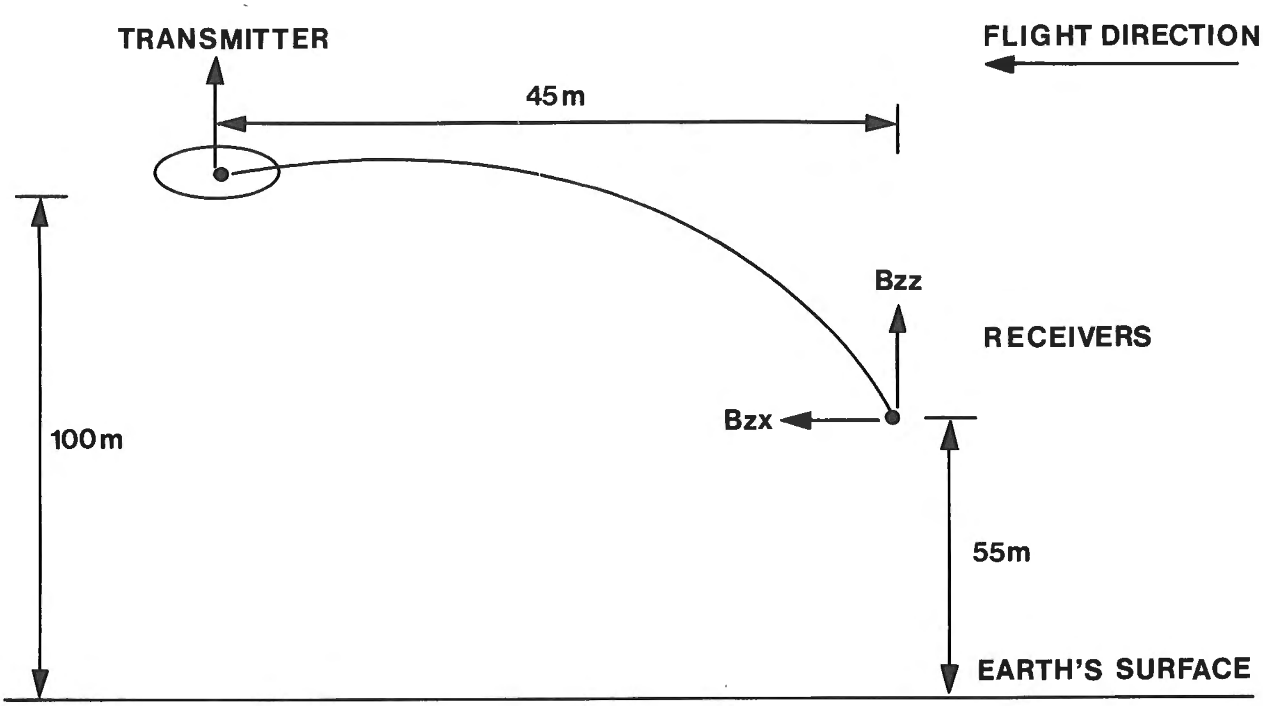

Figure 8.2. Geometrical configuration of the Sweepem system. The horizontal and vertical separations have not finalized and may be changed after completion of test surveys.

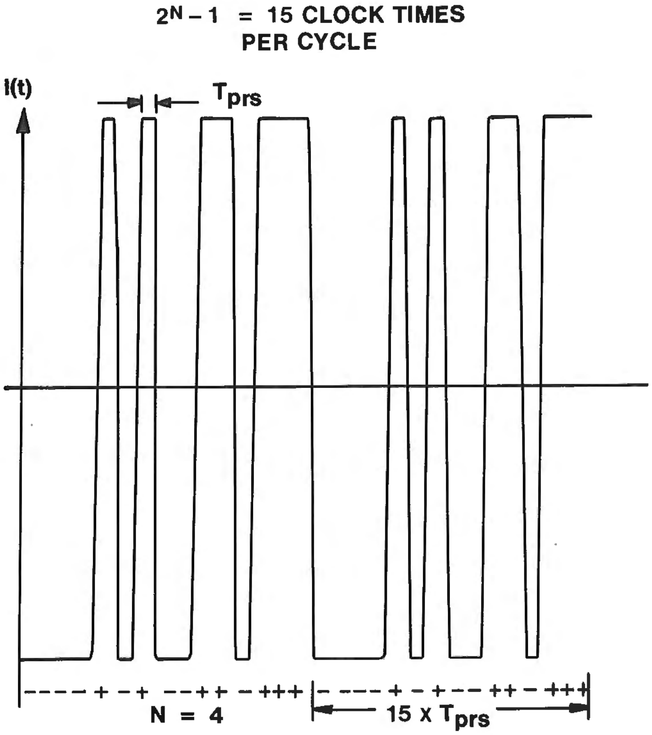

Figure 8.3. Current waveform of the PRS sequence for N=4. There are 15 clock pulses before the waveform is repeated. The shortest time can never be less than the clock time.

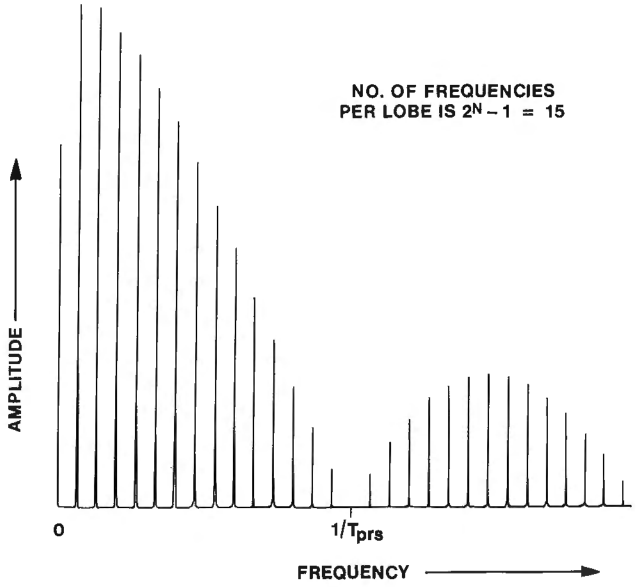

Figure 8.4. Frequency spectrum of the PRS sequence given in Figure 8.3. The frequencies are equally spaced with the first zero at 1/clock time. There are 2^N-1 frequencies in each lobe. Note the large DC component in the frequency spectrum.

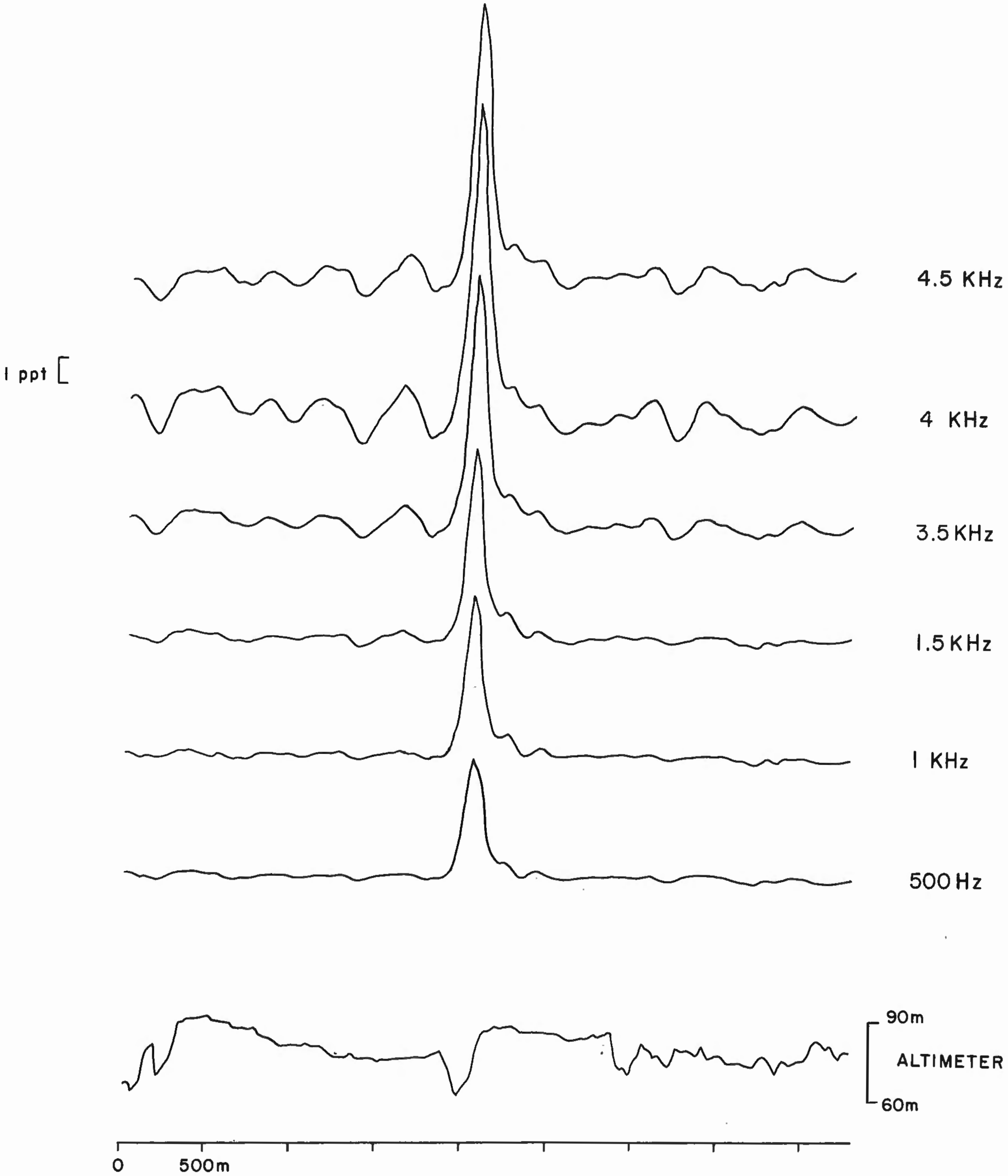

Figure 8.5. In-phase response for the horizontal-coil receiver from a test survey flown near Senneterre, Quebec. The digital sampling rate for these data was 90 μs. Although not shown here, the digitally stored data have been properly normalized for input to the resistivity inversion program.

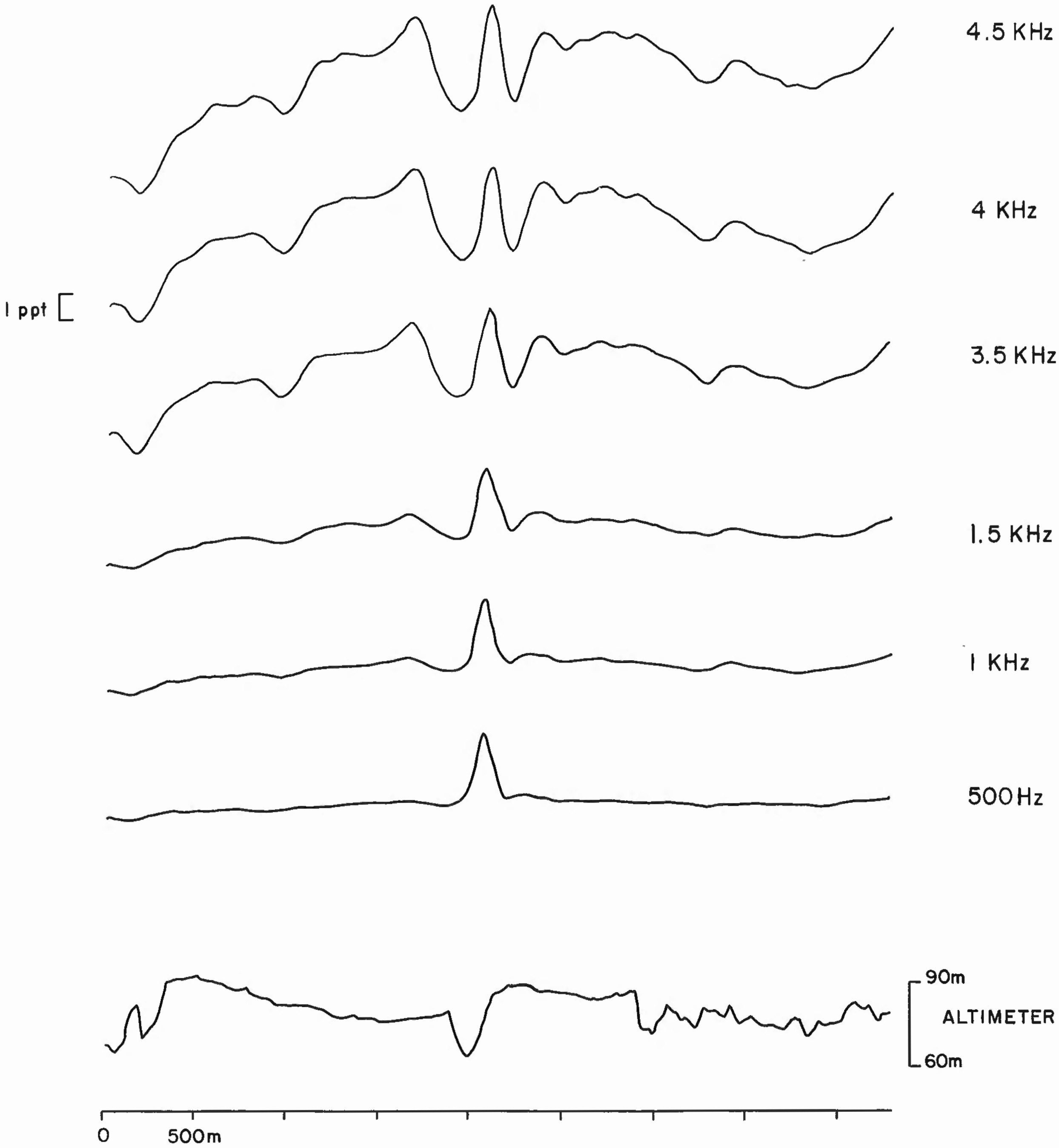

Figure 8.6. Quadrature response for the horizontal-coil receiver, Senneterre, Quebec. See Figure 8.5 for comments.

INTERPRETATION

Presently, our interpretation consists of a series of forward and inverse frequency-domain modelling packages, although there is no inherent reason why similar time-domain modelling packages could not be used. Indeed, one of the reasons for developing this system was to allow flexibility between time-domain and frequency-domain.

A major component of the interpretation package is an inverse program for one- and two- layer resistivity models. The forward program uses the Hankel transform method (Anderson, 1979) where explicit kernels are computed for one- and two- layer cases. The inverse package uses the Marquardt algorithm (Marquardt, 1963) which is a non-linear ridge-regression technique. These two programs have been coupled together to provide a first-pass interpretation package.

The input to the program consists of the in-phase and quadrature components of both receiver coils over the entire frequency range for each fiducial. Editing facilities are provided to eliminate noisy frequencies or incorrect fiducial values. Options are also available in the inverse program for statistically weighing the data according to their quality.

The output from the best fit at fiducial n is used as input to fiducial n + 1. This makes the procedure very fast and effective once the initial model has been determined. If the parameters of the overburden and/or bedrock are changing rapidly between fiducials (i.e. 25 to 50 m on the ground) and a significant change exists in the receiver values, then this procedure of using the last set of best fit values as the initial model for the next fiducial will cease to be time efficient. The inversion will continue but at a slower pace. Areas of rapid change are usually associated with near-surface overburden effects on bedrock conductors. The method tends to flag such areas by the number of iterations that were necessary to obtain a good fit.

The output from the inversion program consists of the best fit parameters for a one- to two- layer earth plus an estimate of the statistical fit to the data and the number of iterations that was required for that fit. Profiles of overburden resistivity and thickness (one or two layers) and bedrock resistivity are provided as well as contour maps of the same data.

These profiles and maps can be used to isolate areas of unique conductivity. Also, the statistical and iteration parameters can be contoured and used to flag areas where the layer model is inappropriate. These regions can then be investigated individually. Forward and inverse packages for a multi-layered earth (Best et al., 1985), a free space sphere (Best and Shammas, 1979) and a free space plate (Annan, 1974) are available to aid the interpretation.

The average time to invert a typical fiducial with 2 receiver components (both in-phase and quadrature) and 19 frequencies (i.e. 76 data points) was between 6 and 8 s on a UNIVAC 1100/83 system. We have found that a line 8 km long, which has approximately 150 fiducials, can be inverted in 5 minutes. This is without any obvious optimization or tuning. We believe that proper optimization will reduce this time in order to permit integration of the inversion program and the field computer system. The data will then be processed in the field after each flight.

CONCLUSIONS

The Sweepem has been developed as an AEM system with a large transmitter dipole moment and a large frequency bandwidth. The present design provides also the flexibility to modify the hardware and the data processing sequence with minimum effort. The original bird-motion correction represents a breakthrough in fixed-wing, towed-bird surveying as it permits accurate measurement of in-phase and quadrature components.

The multifrequency and multicoil nature of the system makes it an ideal tool for resistivity mapping and detection of deep conductors. As more data are collected and interpreted, the full potential of the Sweepem system will be realised.

ACKNOWLEDGMENTS

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- 9 -

The Aerodat multigeometry, broadband transient helicopter electromagnetic system

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Abstract

A multigeometry, broadband helicopter electromagnetic system has been developed by Aerodat Ltd. Its flight testing is expected to begin in early 1986. The transmitter consists of two concentric coils, 6 m in diameter; one with its axis vertical, the second with its axis in the direction of flight. The receiver, which is located at the centre of the transmitter loops, consists of 3 orthogonal coils. Both the transmitter and the receiver are mounted in a bird towed 30 m below the helicopter. The two transmitter loops are energized with a transient pulse of a unique shape on a time shared basis. The pulse length is digitally controlled to provide a variable bandwidth. Computer modelling has been carried out for plates in various geometric situations. The wealth of data generated by this novel system will permit less ambiguous interpretation in complex geological situations.

Résumé

La société Aerodat Ltd. a mis au point un système électromagnétique héliporté à géométrie multiple et fonctionnant sur une bande étendue. Ses essais en vol sont prévus pour le début de 1986. L'émetteur comporte deux bobines concentriques de 6 m de diamètre, l'une à axe vertical, l'autre axée dans le sens du vol. Le récepteur, situé au centre des bobines de l'émetteur, consiste en trois bobines orthogonales. L'émetteur et le récepteur sont montés sur un tube remorqué à 30 m au-dessous de l'hélicoptère. Les deux bobines de l'émetteur sont chargées par une impulsion périodique d'une forme particulière sur la base d'un partage du temps. La longueur de l'impulsion est contrôlée numériquement de façon à fournir une largeur de bande variable. La réponse ÉM a été calculée par ordinateur pour des plaques en diverses situations géométriques. La quantité des données obtenues par ce nouveau système permettra une interprétation moins ambiguë dans le cas de situations géologiques complexes.

INTRODUCTION

In 1982 Aerodat Ltd. initiated the development of a new helicopter electromagnetic (HEM) system. The objective was to design a button-on system with the following features:

1) A receiver consisting of 3 orthogonal induction coils.
2) At least 2 orthogonal transmitter axes.
3) A wide response band.

A receiver consisting of 3 orthogonal coils is a vector device capable of measuring both the amplitude and the direction of the secondary magnetic field. A multi-geometry transmitter is one capable of transmitting a primary field in any one of 3 orthogonal directions. The system under construction is one transmitter coil short of the full complement as shown in Figure 9.1. Current HEM systems consist of coaxial and coplanar configurations (Fraser, 1979). Several ground EM systems now have 3 axis receivers but are limited to transmitter loops lying on the ground (McNeill, 1980).

The broadband concept can best be explained in a response diagram (Fig. 9.2). This is a plot of the inphase and quadrature components of the secondary EM field versus the response parameter of a given anomaly type. The curves plotted are for a simple L-R circuit, but their general form is similar for a wide range of geological models. The response

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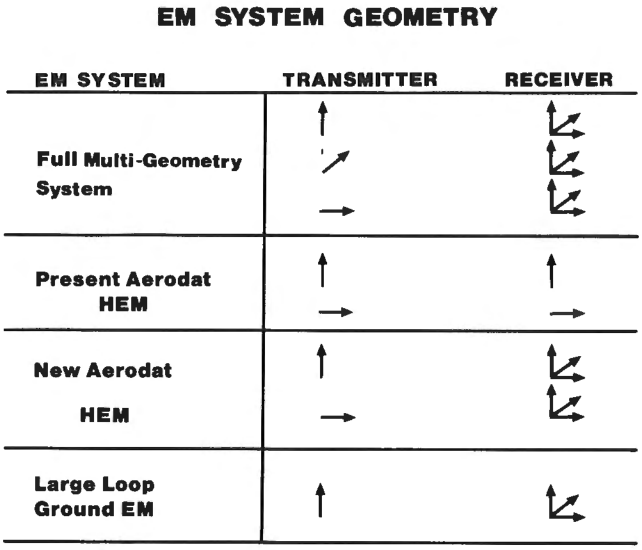

Figure 9.1. Transmitter/receiver coil configurations for an ideal multigeometry system, two Aerodat systems, and ground EM.

parameter is a product of conductivity, magnetic permeability, system frequency and two dimensions of the system and/or of the target (Grant and West, 1965).

A diagnostic region is indicated for the central curve set. It is a region, here arbitrarily defined as one decade, in which variations in signal amplitude can be most accurately measured. Below the lower response parameter limit the signal level falls rapidly for both components. Above the high limit of the indicated band the inphase component reaches saturation, and hence it becomes insensitive to changes in the response parameter value. The quadrature component decreases to values below noise limit.

A system with a range of frequencies one decade apart would ensure that for any given response parameter at least one observation would be made within the diagnostic region. For example, if ground resistivities ranged from say $10^{-1}\Omega$-m to $10^{-5}\Omega$-m, six frequencies would be required to span the bandwidth.

OBJECTIVES OF THE MULTI-GEOMETRY BROADBAND CONCEPT

Resistivity is a 3-dimensional variable; it may change with depth reflecting various geological strata or laterally across a dyke or contact. In the case of a massive sulphide deposit, the resistivity distribution is truly 3-dimensional. Interpretational models of increasing sophistication have been developed for quantitative interpretation of horizontal strata, dipping sheets, and spheres. If the chosen model is appropriate to the geological situation, reasonable quantitative determination of resistivity and dimensions can be expected. At this interpretive stage the spectral resolution of a broadband system has its greatest value. In a typical mineral exploration program, however, the initial problem of model identification may be the most difficult. The multi-geometry transmitter can provide information sensitive to the geometry rather than the resistivity of the target. This additional parameter greatly improves the interpretability of broadband data.

A multi-geometry transmitter is currently available on HEM systems but not on fixed-wing AEM systems (Fraser, 1979). The concept is easily illustrated by the case of a thin vertical conductive sheet in free space beneath a horizontal dipole transmitter (upper part of Fig. 9.3). Optimum coupling is achieved with the transmitter directly over the target. Null coupling occurs at the two lateral locations shown. In the case of a vertical dipole transmitter, (lower part of Fig. 9.3) the reverse occurs: Null coupling occurs over the target with optimum coupling occurring to the sides. This substantial contrast in inductive coupling between the two transmitter orientations provides excellent interpretive basis for model identification.

Aerodat has approached the multi-geometry objective with a non-traditional bird designed to meet the electrical/electronic requirements of the system (Fig. 9.4). The two outer rings, the transmitter loops, are 6 m in diameter. At the centre of the bird are 3 orthogonal receiver coils surrounded by two smaller scale transmitter loops. These are part of the main transmitter loop but create a field of reverse polarity to partially protect the receiver from the strong primary field. The bird structure has been designed by a team of aeronautical engineers. Wind tunnel testing and computer modelling were carried out prior to full scale construction.

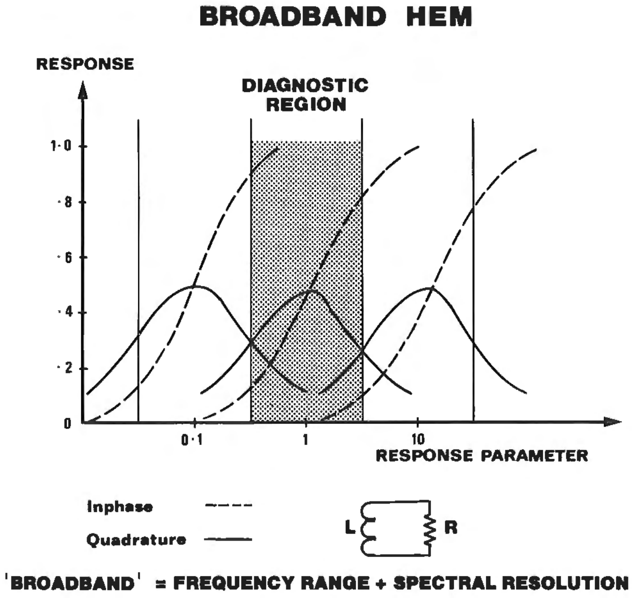

Figure 9.2. Response diagram for a simple L-R target. The diagnostic region is arbitrarily indicated as one decade.

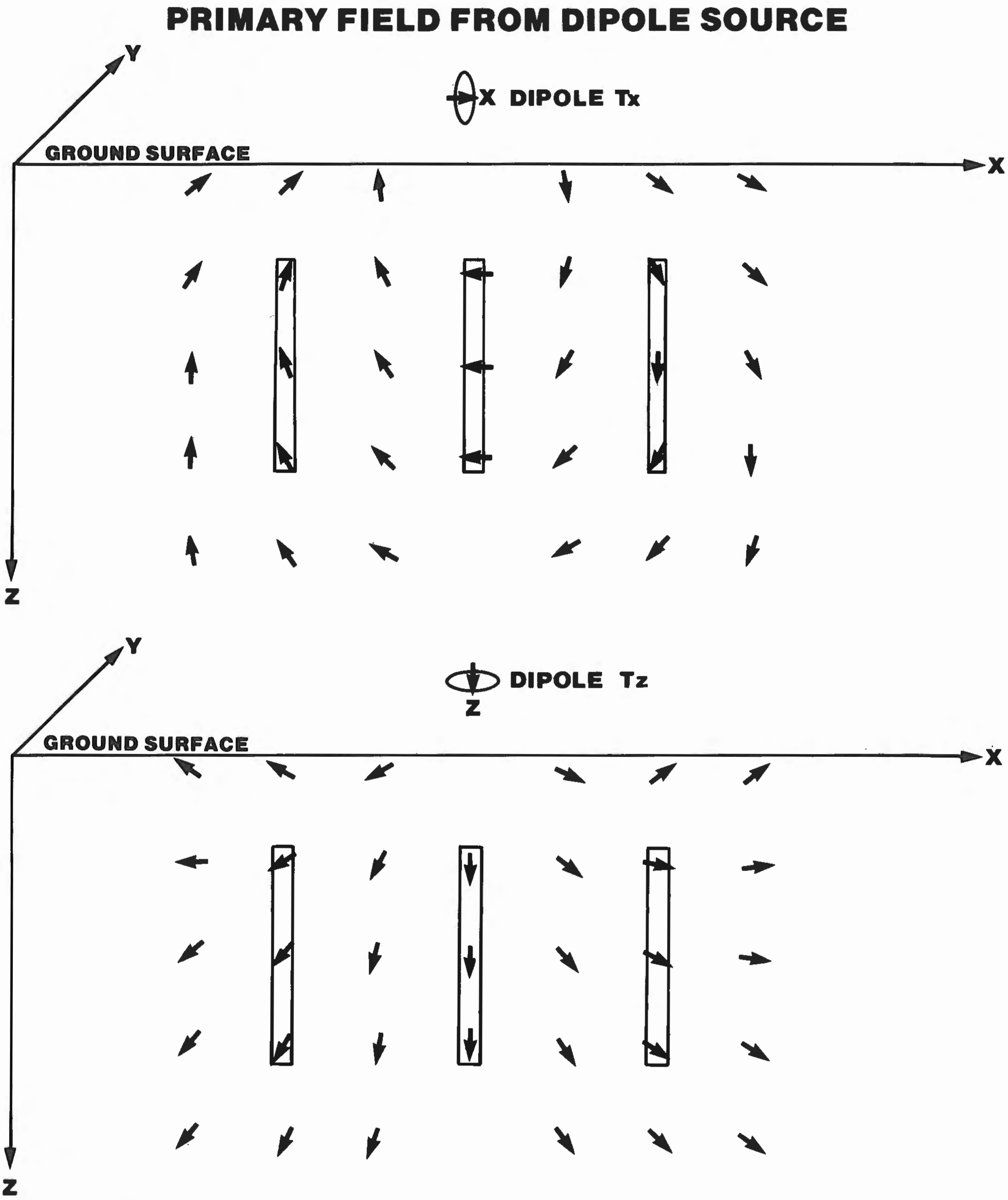

Figure 9.3. Inductive coupling depends on the geometry of the dipole source and the conductor position. At the top, horizontal dipole transmitter, at the bottom, vertical dipole transmitter.

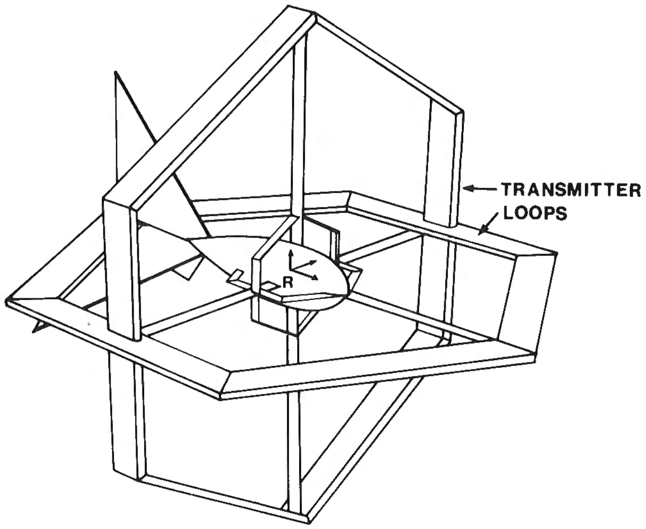

Figure 9.4. The Aerodat bird consists of two rigidly mounted transmitters and a 3-component receiver. The diameter of the transmitter loop is 6 m.

BROADBAND TRANSMITTER DESIGN

The Aerodat current pulse used in the new system is initiated by a quarter sine rise to 200 A and followed by a period of steady current flow (Fig. 9.5). The pulse is terminated by a ⅜ sine rise to 280 A prior to falling to zero. The duration of the steady current flow is variable and digitally controlled. The rate of the pulse truncation is determined by both the peak current and the transmitter loop inductance. The current levels indicated together with the selected transmitter coil design yield a fall off from the 200 A level to zero in 70 μs. Alternate transmitter configurations might be considered in the future that would reduce the shut off time to about 20 μs albeit with a reduced transmitted moment.

An initial appreciation of the waveform can be gained by plotting the induced current in the simple L-R target against time for different time constants τ (Fig. 9.6). For comparison, the half-sine waveform which is used by the INPUT AEM system is also shown. For each τ the ground current starts in a negative direction but more slowly for the more resistive target. During the period of steady current flow, the induced emf is zero and attenuation of the ground current begins; rapidly for small τ, slowly for large τ. The transmitter shut-off drives the current in a positive direction and the decay starts again at $t=o$, the start of the signal measurement period. It is interesting to note that the induced current profile for large τ closely follows the form of the primary field. For small τ and higher resistivity, the current profile resembles the derivative of the primary field.

For small τ the reverse current flow that follows the pulse turn-on is of little significance at $t=0$; it has decayed to an insignificant amount. The amplitude of the signal at $t=0$ is related only to the sharpness of the pulse truncation. However, for larger τ, this negative current flow from the turn-on is still present at the turn-off and would be subtracted from the final signal amplitude at $t=0$. An increase in the pulse duration can reduce this negative impact of turn-on from turn-off by allowing more time for attenuation.

As noted above, it is the amplitude of the secondary field or the induced target current at the end of the pulse that most clearly reflects the signal level to be measured. In Figure 9.7

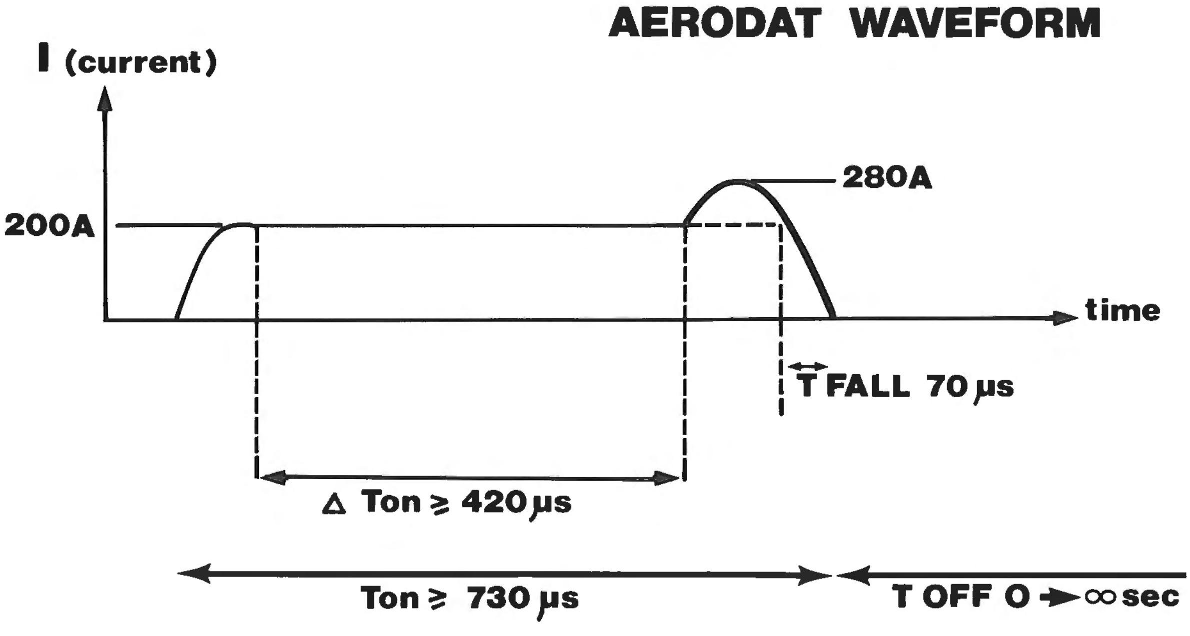

Figure 9.5. Aerodat transient current waveform.

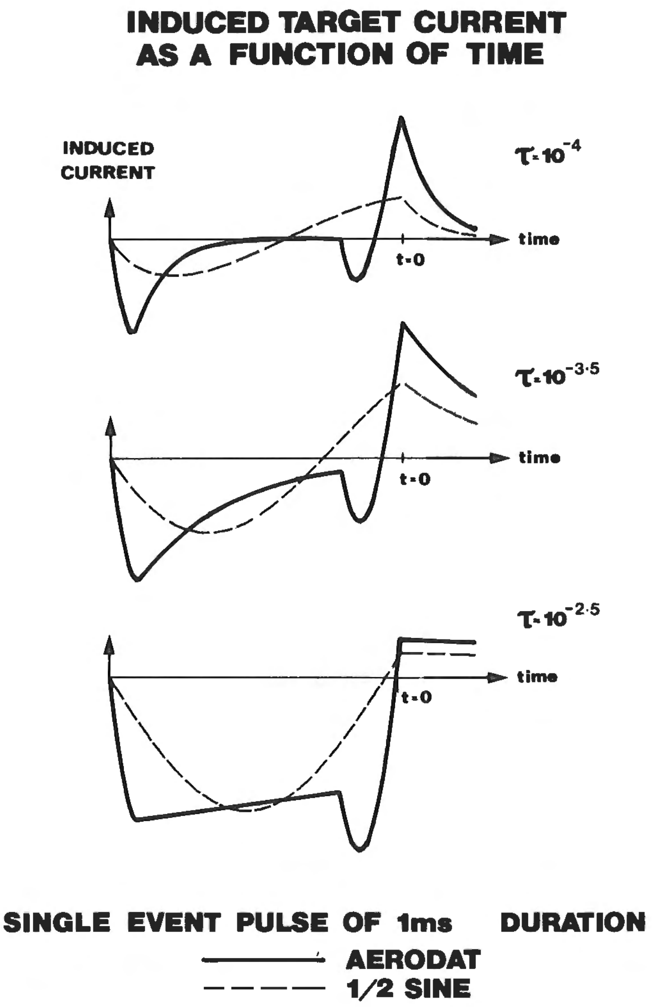

Figure 9.6. Induced current flow in a target as a function of time for various time constant τ. Aerodat and half-sine (INPUT) pulse responses are compared.

this amplitude is plotted as a function of the time constant of the target. Similar graphs for the INPUT AEM system were published by Becker et al. (1984). The pulse duration is 1 ms, repeated every 3.5 ms in opposite polarity. The limiting effect for small τ is due to the finite steepness of pulse truncation and at large τ it is due to the finite pulse length. The truly broadband step current function described earlier would provide a constant amplitude independent of τ. The variable pulse duration provided for in the Aerodat system permits modification of large τ response without modification of the low limit.

It is possible to draw a parallel between transient and frequency domain bandwidth. Noting that the centre of the response band for an L-R circuit occurs when $\frac{WL}{R} = 1$, frequency may be defined as $\frac{1}{2}\pi\tau$. This conversion is illustrated in Figure 9.8 in which the diagnostic region has been set at the 50% amplitude level. With a 2 ms pulse duration, the transmitted bandwidth by this definition is 65 to 4550 Hz. The operational bandwidth is larger and the receiver has a uniform response from 100 to 10 000 Hz.

To appreciate the full operating range of the system other factors must be considered. For example, the repetition rate of the transmitted waveform is important. As the repetition rate is increased, the number of measurements increases with the ensuing improvement in the signal-to-noise ratio. In resistive areas, the repetition rate can be simply increased at the operator's console to improve the high-frequency response, but with some accompanying loss at the low-frequency end. Flight testing of the system is necessary before the limits on this form of flexibility can be properly assessed.

RESULTS OF COMPUTER MODELLING

The number and spacing of receiver time gates is not yet confirmed and will await flight testing. To provide an idea of what may be expected from the system, modelling has been done using the University of Toronto PLATE program (Dyck, 1980).

The receiver window boundaries were set to 0.035, 0.07, 0.14, 0.28, 0.56, 1.12, and 2.24 ms, to provide 6 channels of output. The conductive plate was 300 m in strike length, 150 m in depth extent with a conductance of 64 S.

Figure 9.9 illustrates the system response for a vertical plate striking 90° to the flight line. Arrows indicate the relative orientation of the transmitter and receiver dipoles. The top row is for a transmitter dipole aligned in the direction of flight. The bottom row is for the vertical dipole transmitter. The response in each of the 3 orthogonal receiver coils is presented from left to right. The graphic amplitude of the profiles has been normalized in all cases. Due to the complete symmetry of the model there is no response on the receiver coil whose axis is perpendicular to the flight line.

Figure 9.10 illustrates the response for a plate dipping 45°. Note the clear asymmetries reflecting the dip and the coplanar null corresponding with coaxial maximum.

Figure 9.11 shows the responses obtained over a horizontal ribbon. At early times (the higher amplitude channels), strong edge effects exist due to significant current concentrations at the edge of the sheet. At later times, the edge effects disappear in the coaxial and coplanar pairs as the induced current distributes itself more evenly throughout the ribbon.

Figure 9.12 shows the response for a vertical plate striking at 45°. In this case the receiver coil oriented perpendicular to the direction of flight is no longer null coupled and provides useful information on the strike.

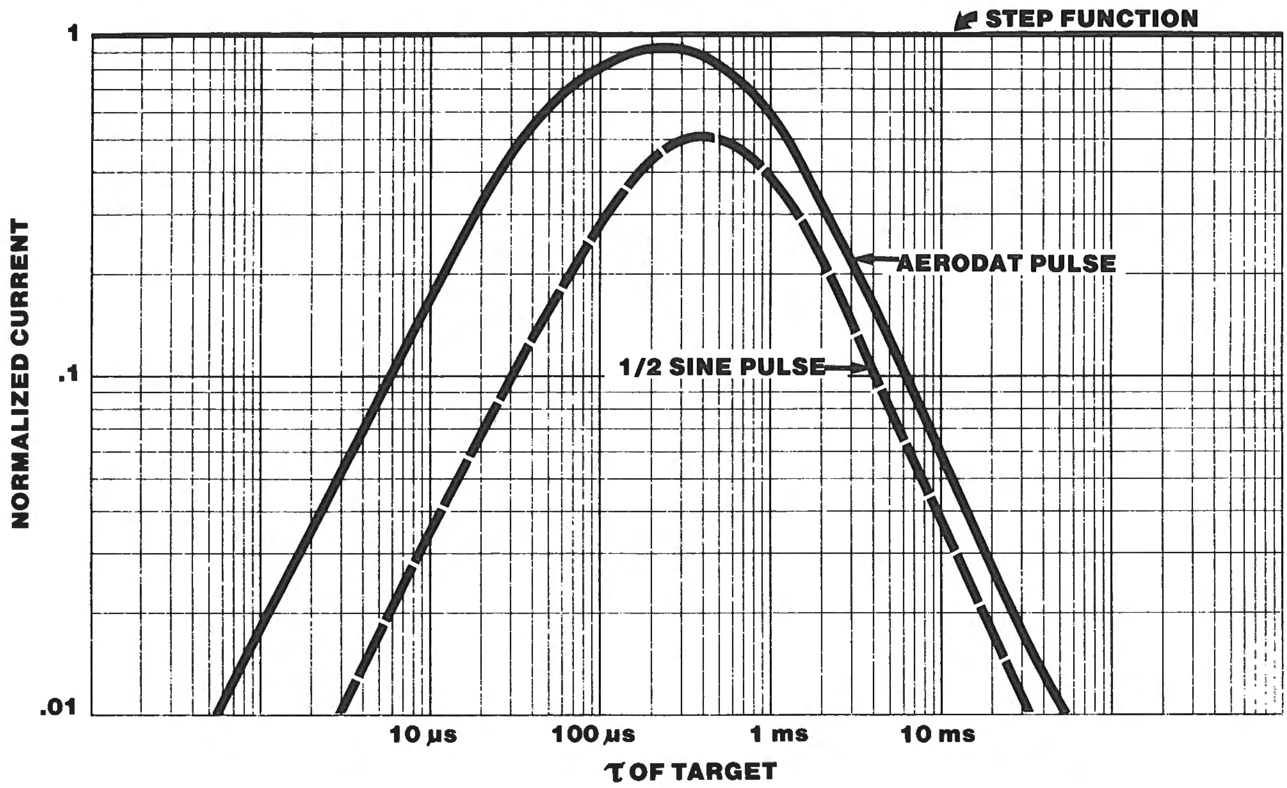

Figure 9.7. Peak induced current as a function of time constant τ. The inductive coupling factor is assumed to be unity for all waveforms. The amplitude of the step, peak half-sine amplitude, and steady current flow amplitude of the Aerodat waveform are equal.

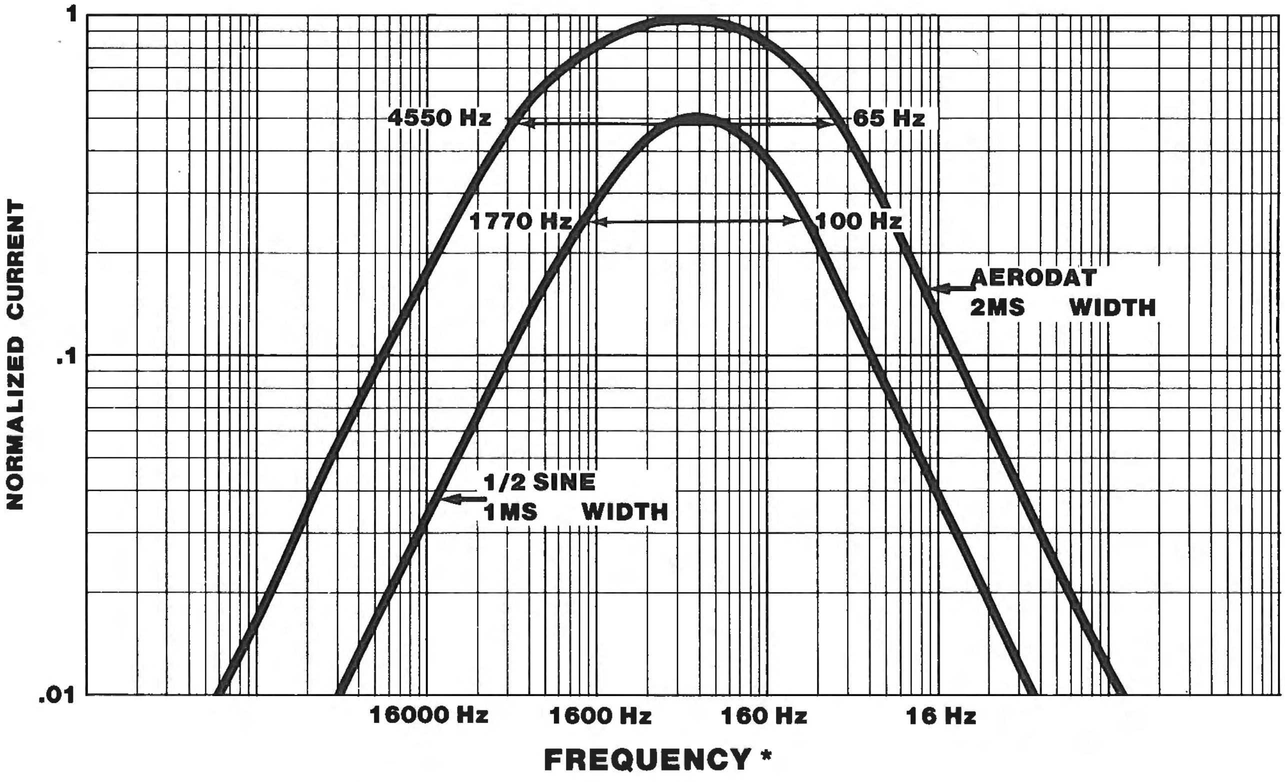

Figure 9.8. The same as Figure 9.7 but with τ converted to frequency by the process noted in the text. The "bandwidth" indicated has been arbitrarily set at 50% of peak response level.

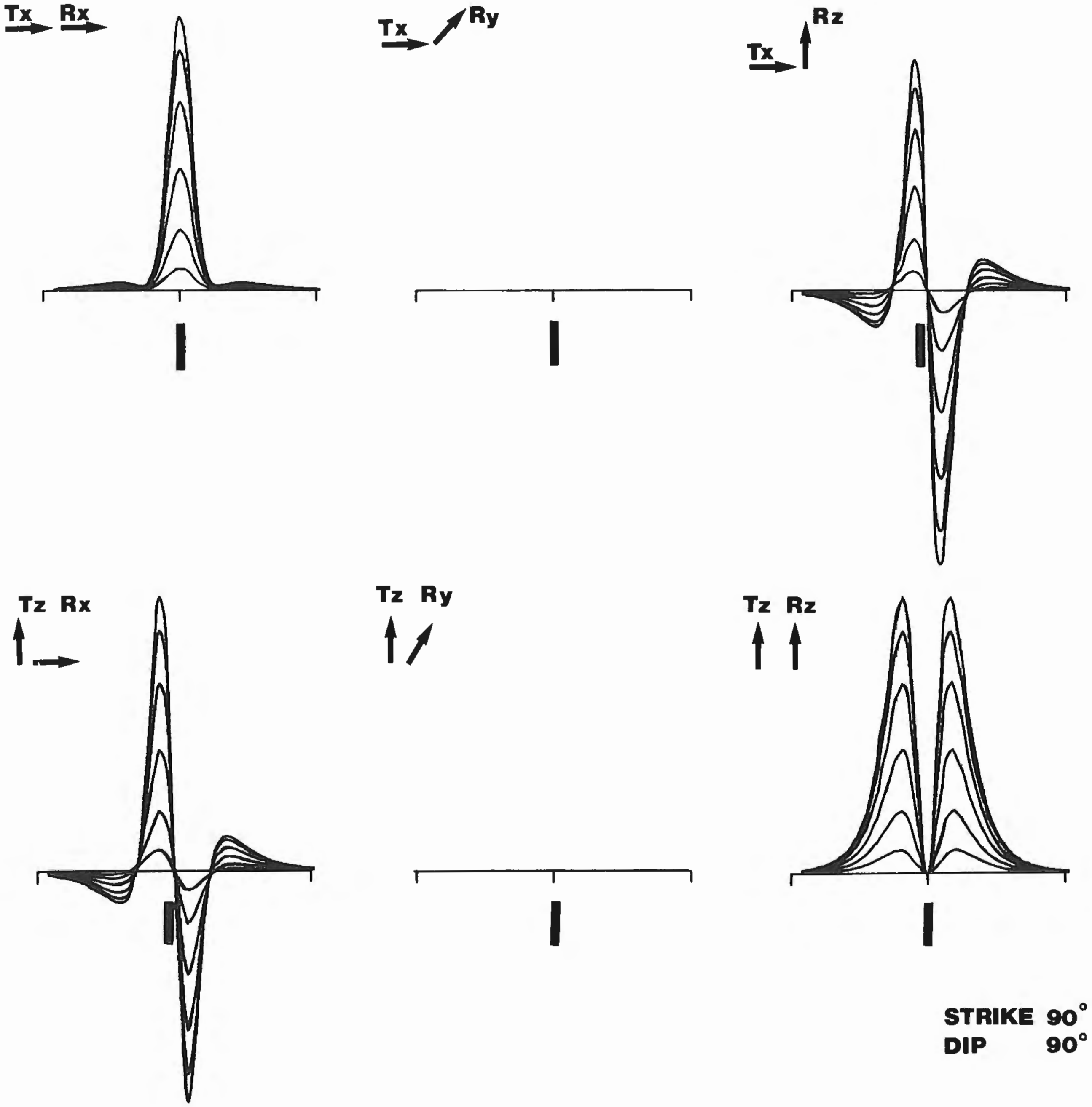

Figure 9.9. Model responses for a thin rectangular plate, 300 m strike extent and 150 m depth extent, conductance 64 S. All amplitudes normalized to the peak response of the earliest channel. Plate strike and dip are 90°.

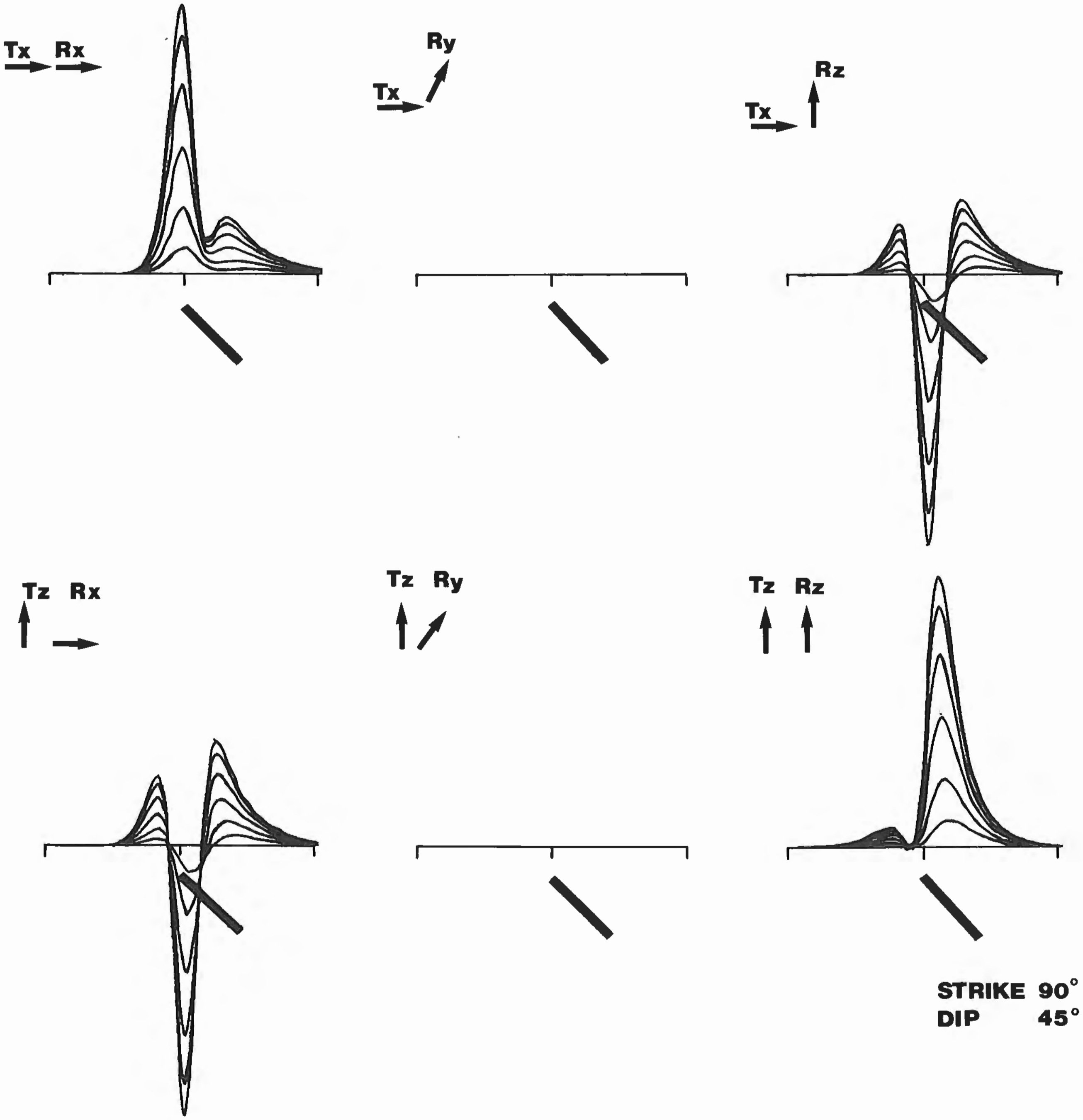

Figure 9.10. The same as Figure 9 but with a plate dip of 45°.

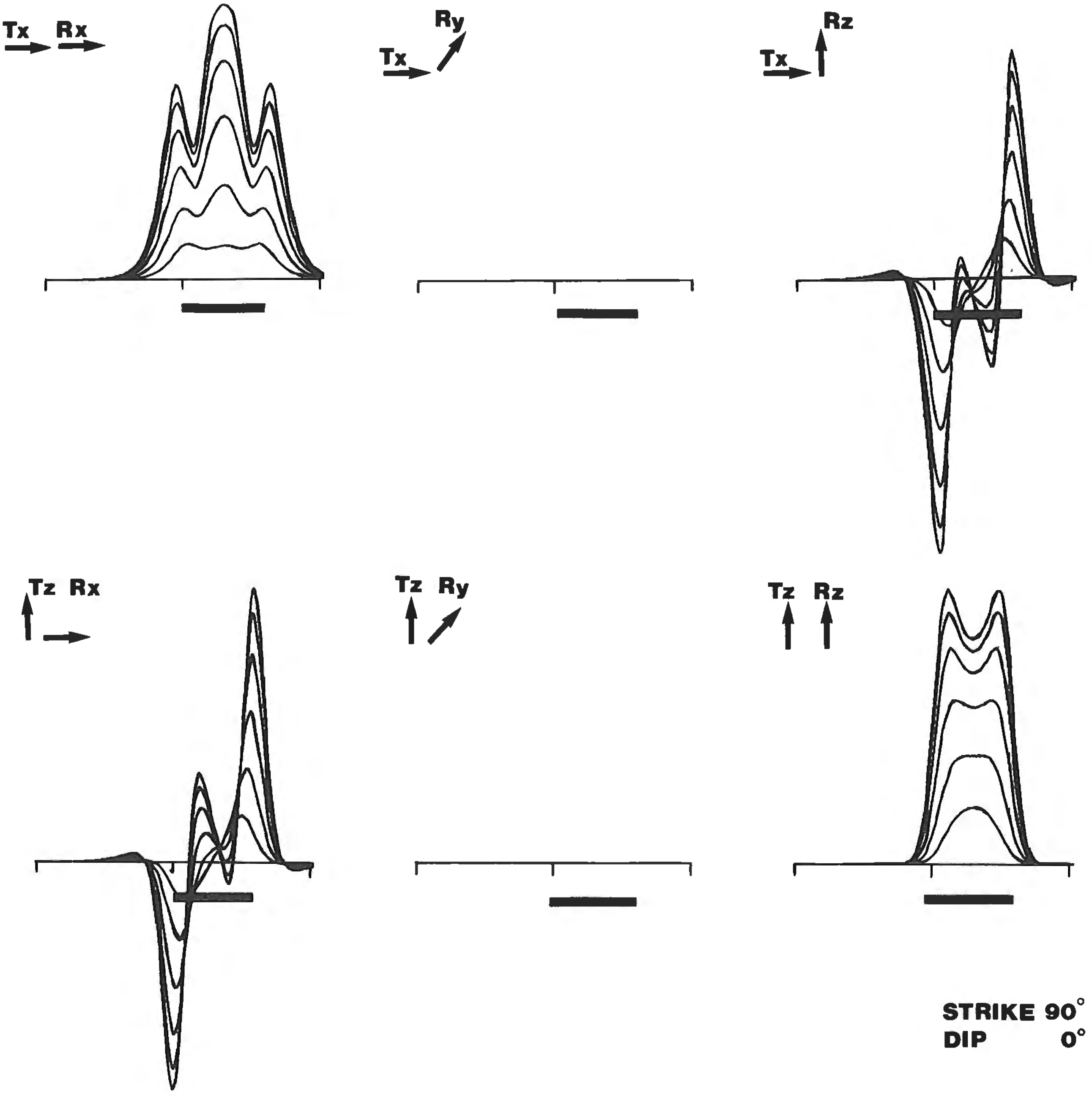

Figure 9.11. The same as Figure 9.9 but with a plate dip of 0° (horizontal ribbon).

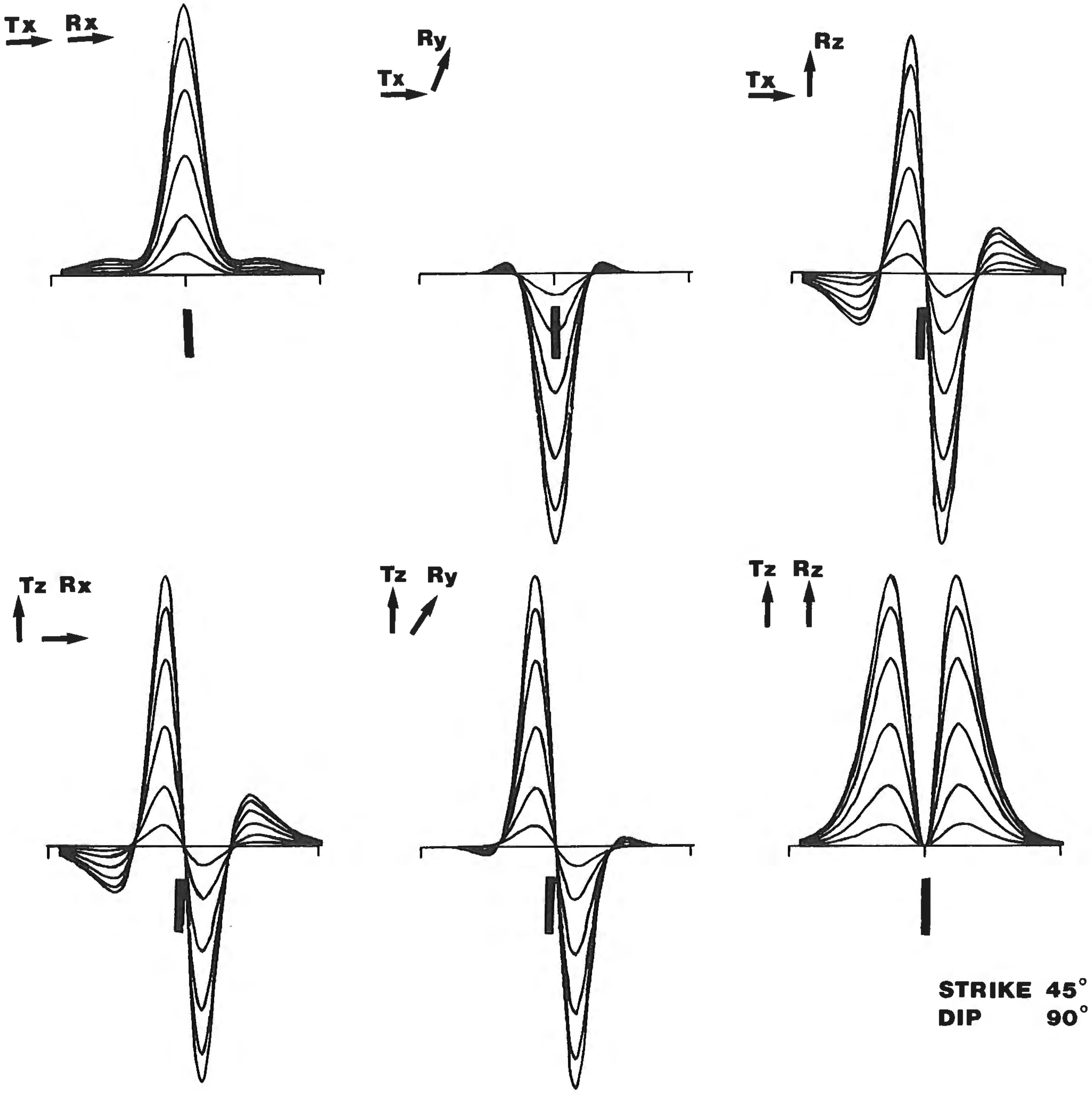

Figure 9.12. The same as Figure 9.9 but with a plate strike of 45°.

SUMMARY

The Aerodat HEM system has been designed to provide maximum interpretative information. The multi-geometry transmitter/receiver configuration provides indication of the geometry of the conductor and thereby aids in the selection of a suitable model for interpretation. The broadband nature of the transmitted waveform ensures that a wide range of resistivities can be measured with a sufficient spectral resolution to calculate the dimensions and resistivities associated with the particular conductor.

ACKNOWLEDGMENTS

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- 10 -

Application of multifrequency helicopter electromagnetic surveys to mapping of sea-ice thickness and shallow-water bathymetry

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Abstract

Airborne ice-thickness and bathymetry measurements can be made with a multifrequency, high-precision, low-drift airborne electromagnetic system. Estimates of ice and water thickness and of the conductivity of the ice, water and bottom sediments are constructed using inversion techniques for a layered-earth model. The Singular Value Decomposition method employed in the inversion can be used to provide estimates of parameter error for a given example; these were found to be acceptable for typical model parameter ranges. The effects of noise and certain types of systematic error in the measuring system were simulated numerically in order to explore the errors that they would introduce to the interpretation. Systematic errors such as miscalibration and baseline drift were found to be the most serious, since they are difficult to distinguish from the effects of water depth and conductivity changes. In contrast, effects due to misorientation of the EM system can be corrected for if the misorientation is measured during flight, while the severe errors associated with incorrect altitude estimates can be reduced to acceptable levels by continuous measurement of the bird altitude using a high-precision laser altimeter mounted in the bird itself. AEM systems incorporating these design considerations have been constructed and flight tested in the Maritimes and elsewhere for Canadian and U.S. government agencies. Further testing under Arctic conditions is scheduled for early 1986.

Résumé

On peut réaliser des mesures aériennes bathymétriques et de l'épaisseur des glaces avec un système électromagnétique aéroporté à plusieurs fréquences, de haute précision et à faible dérive. On fait des estimations de l'épaisseur de la glace et de l'eau ainsi que de la conductivité de la glace, de l'eau et des sédiments du fond à l'aide de techniques d'inversion établies pour un modèle de sous-sol en couches. La méthode de la décomposition de la valeur singulière employée dans l'inversion peut servir à fournir des estimations de l'erreur paramétrique pour un exemple donné; ces estimations se sont révélées acceptables pour des gammes typiques des paramètres du modèle. On a simulé numériquement les effets du bruit et de certaines erreurs systématiques intervenant dans le système de mesurage afin d'étudier les erreurs qu'ils pourraient introduire dans l'interprétation. Les erreurs systématiques, p. ex. une calibration erronée et la dérive de la ligne de base, se sont révélées les plus graves, car elles sont difficiles à distinguer des effets des fluctuations de la profondeur de l'eau et de la conductivité. En revanche, les effets dus à la mauvaise orientation du système ÉM peuvent être corrigés, si cette mauvaise orientation est mesurée en cours de vol, tandis qu'on peut ramener à des niveaux acceptables les erreurs graves liées à des estimations inexactes de l'altitude, en mesurant constamment l'altitude du tube à l'aide d'un altimètre laser de haute précision monté sur le tube. Des systèmes ÉMA comportant ces composantes ont été testés en vol dans les Maritimes et ailleurs pour le compte d'organismes gouvernementaux canadiens et américains. On prévoit réaliser d'autres tests, dans les conditions arctiques, au début de 1986.

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INTRODUCTION

The determination of ice properties and water depth in shallow marine environments is now seen as an important application of the airborne electromagnetic (AEM) method, made possible by the advent of systems which combine large bandwidth, high sensitivity, large dynamic range, low drift and stable calibration with high-precision altimetry and bird attitude control. This paper indicates some of the considerations that apply to the design of the EM hardware and survey methodology.

Two components of the problem can often be distinguished. Bathymetry per se is the determination of water depth, although some measure of bottom conditions is often desired. In practice, AEM bathymetry provides a depth estimate, but normally requires the estimation of water conductivity as a separate parameter. The conductivity of the sediments at the sea bottom affects the response in very shallow water and thus may have to be included in the interpretation as well. Airborne ice measurement (AIM), a somewhat better-conditioned problem, seeks to estimate the thickness and conductivity of sea ice over deep water. In many situations, seawater in ice-covered areas will be shallow enough to require solution of the more general problem of through-ice bathymetry (TIB).

Conventional bathymetry in open water is normally carried out by relatively small launches carrying echo sounders. Such craft can work in shallow water and around rocks and other obstructions. When sea ice is present, conventional bathymetry becomes much more difficult and expensive, since icebreakers might be the only craft capable of entering the area. Thick ice accumulations preclude all possibility of bathymetry from surface vessels, as the greatest ice thickness that can be continuously broken is on the order of 1 m. A number of methods have been proposed and tested for rapid reconnaisance TIB, but all have been found to be prohibitively expensive, unreliable, and/or slow. The standard approach at present is to sample ice thickness and water depth at widely spaced points using echo sounders on the ice surface.

By contrast, AEM bathymetry can be performed over large areas using helicopter or fixed wing systems. Dense grids of accurately positioned TIB data can be gathered rapidly and processed into preliminary maps on site. It is anticipated that such data will be useful not only to hydrographers in chart preparation, but to oil companies seeking shallow water with stable bottom conditions for drilling sites, reflection seismic contractors and others requiring safe surface routes over thick ice, and salvage or rescue teams searching for conductive wreckage in shallow water.

The approach that has been used in this paper is based on generalized linear inverse theory as applied to nonlinear regression problems. In particular, the Singular Value Decomposition (SVD) method (Lancsoz, 1961) using damping and cutoff of singular values (Jupp and Vozoff, 1975) has yielded valuable insights into the electromagnetic TIB problem. The SVD method provides a clear mathematical framework for stable, efficient model fitting, estimates of parameter importance and error, identification of equivalence problems such as conductivity-thickness ambiguity, and an indication of importance of individual data channels to the determination of a given parameter.

The paper is organized in two sections. The first deals with the idealized problem of bathymetry with and without ice, including the importance of model parameters to the response and the choice of frequencies at which data should be obtained. The second examines the practical problem: the shortcomings of the one-dimensional model, typical sources of error in AEM methods and examples of the effects these can have on the interpretation of survey data.

THE IDEALIZED PROBLEM

The basic model used in this section consists of a conductive layer of seawater, with or without relatively resistive ice cover, over a moderately conductive bottom. In Figure 10.1, this model is represented schematically. Note that although there are 5 parameters present in this model, not all will necessarily be sought in a given situation.

The SVD approach clearly shows that in general the parameters in the linearized response of an electromagnetic model tend to factor out into groups called parameter eigenvectors, each associated with a so-called "singular value" which provides an estimate of the importance of the eigenvector to the response. A useful feature of the AEM TIB method is that the parameters separate remarkably well with proper design of the measurement with respect to frequencies and flight elevation: for a given singular value, the corresponding eigenvector often consists almost entirely of a single parameter's contribution. This simplifies the task of analysis considerably. The frequencies and base model parameters chosen for this study were f=50, 200, 1000, and 10000 Hz, representing the minimum goals of the Geotech Through-Ice

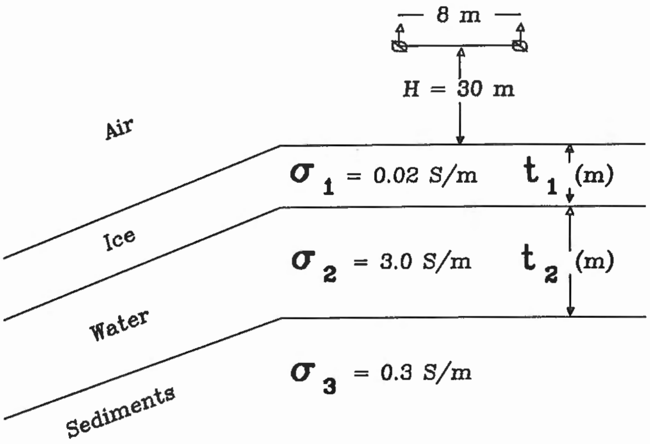

Figure 10.1. Schematic sketch of layered earth model used for interpretation of through-ice bathymetry (TIB).

Bathymetry System (TIBS). Horizontal coplanar coil arrangements were chosen for all frequencies to simplify assessment of the contributions of different frequencies. The model conductivities were chosen to be $\sigma_1 = 0.02$ S/m for ice where present, $\sigma_2 = 3$ S/m for seawater, and $\sigma_3 = 0.3$ S/m for bottom sediments, which represent fairly typical values for these parameters. The flight elevation is taken as a "known" parameter in this paper, for reasons that will be explained in the next section. If it were left free, it would certainly be the best-determined parameter in the model, while the other parameters would be somewhat less well-resolved.

One way of presenting the results graphically is to plot the error for a given parameter as a function of one of the model parameters. This can be estimated by the SVD method for a given noise level in the measuring system and its environment. The noise is estimated at 1 ppm. The parameter error estimates scales linearly with the noise level, but the error estimate for a given parameter will remain constant with respect to the error estimates for the other parameters.

In Figure 10.2, parameter error is plotted as a function of water depth t_2. Note that the relative error estimate is nearly constant at 0.08% for the water conductivity σ_2: the water conductivity is a very well-determined parameter for a wide range of water depths. The water thickness error estimate is also nearly constant at about the 1% level in shallow water, but starts a rapid increase at 40 m, which is about 1 skin depth at the lowest frequency (50 Hz). These results suggest a 10% depth error level at 80 m, which may be somewhat optimistic. The error estimate for the bottom conductivity σ_3 is greater than 1% for water depths greater than about 10 m. For this figure, ice thickness and conductivity were not included as the ice thickness was set to negligible levels to emphasize the bathymetric parameters.

Figure 10.3 presents results for the AIM problem: the parameter errors are plotted as a function of ice thickness. Note the near-constant behaviour in all parameters except for the ice thickness t_1, for which thicker ice has lower relative error. The error estimate reaches 1% for $t_2 = 0.3$ m. The rather complicated behaviour of this error estimate for very thick ice is mainly due to the presence of equivalence problems. Such thick ice rarely occurs at sea, except in large pressure ridges or icebergs.

The main conclusions that can be drawn here are that the important parameters for through-ice bathymetry under "normal" circumstances are the water conductivity σ_2, water thickness t_2 and ice thickness t_1, with ice and bottom conductivities becoming important under some circumstances. It should be noted that precise estimates of ice conductivity are not critical to most users, since hard, multiyear ice and soft, first year ice have substantially different conductivities which should be easily resolvable.

The same type of analysis can be applied to the "data eigenvectors" produced by the SVD to yield estimates of data importance or "information density". These results are hard to display in a simple format. However, the conclusions reached are essentially as expected on the basis of rule-of-thumb arguments: the lowest useful frequency available is dictated not so much by what is desired by the interpreter as by design considerations like weight and power requirements for the system hardware. The maximum depth of reliable interpretation is between one and two skin depths at that frequency. At somewhat less than one skin depth, the water thickness information is in the inphase, conductivity information in the quadrature of the lowest frequency. The choice of the highest frequency should be based on the precision required in ice properties: frequencies well over 10 kHz are required for reliable ice conductivity estimates, while frequencies lower than 10 kHz are satisfactory if only the thickness of the ice is desired. At 10 kHz, the ice conductivity information is in the quadrature. Intermediate frequencies are again dictated partially by weight and power considerations at the low end, and their distribution should reflect design goals for the system: more low frequency data is required for fairly deep water bathymetry.

PRACTICAL AEM BATHYMETRY

The simple, one-dimensional model is in some cases a gross approximation to the actual situation. The seawater can exhibit salinity, layering, or lateral variations caused by fresh water influx from rivers or runoff. Ice tends to be layered and laterally variable in its conductivity and other properties and its surface is often rough.

Water layering tends to be fresh water on top of salt water. In such a case, the fresh water would show up as an increase in apparent ice thickness if the salinity contrast is large. Lateral variations in water conductivity tend to be small, although ice conductivity can vary substantially over short distances owing to the presence of fissuring and other structural heterogeneity. Water depth and ice thickness can be approximated by successive one-dimensional interpretations along a survey line with excellent results (compared to ground truth information) except near unusually sharp two-dimensional or three-dimensional structures: ice layering and surface roughness in particular are smoothed out somewhat by the nature of the EM measurement. While this reduces the accuracy of spot thickness and conductivity estimates for the model, it increases the reliability of the estimate as averaged over the footprint of the EM system. Sharp relief will be blurred and distorted, but the degree of misfit also increases to warn the interpreter that a complicated structure may exist. Experience indicates that bottom dips of several degrees are easily tolerated by inversion methods.

Typical sources of error in helicopter EM surveys include noise, such as sferics and microphonics, and electronic noise in the measuring system. Calibration errors in amplitude and phasing can produce systematic errors in the data that are hard to distinguish from the response of a slightly different model. Baseline drift is an especially difficult problem to eliminate, and once again can bias both amplitude and phase measurements. Distortions in EM response can also be caused by bird attitude variations such as pitch and roll, which should be monitored continuously to allow correction at the interpretation stage. The attitude of the bird also affects

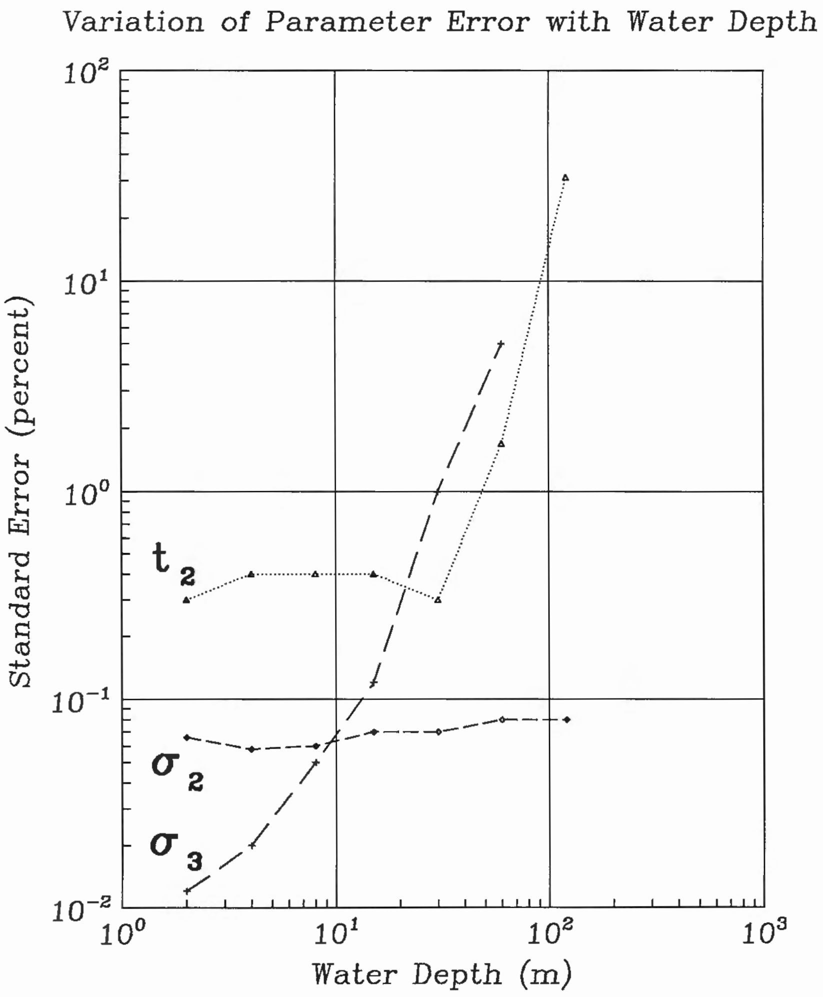

Figure 10.2. Estimated parameter error levels for the bathymetry problem as a function of water depth. All other model parameters were held constant.

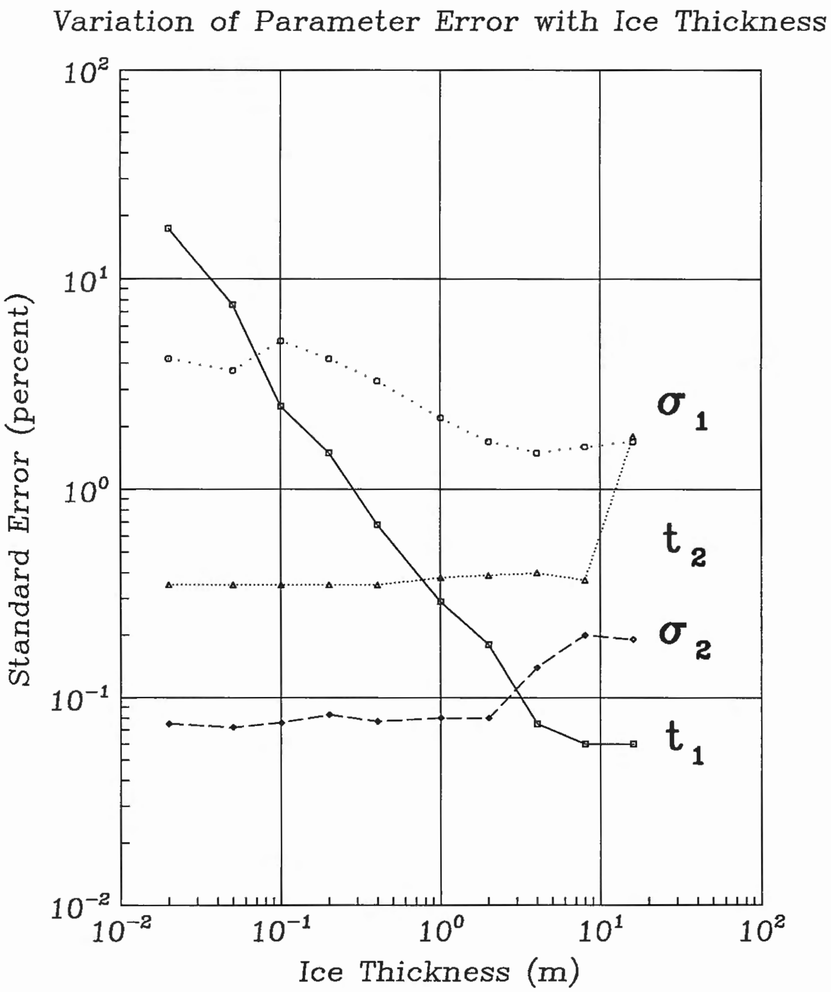

Figure 10.3. Estimated parameter error levels for the ice measurement problem as a function of ice thickness. All other model parameters were held constant.

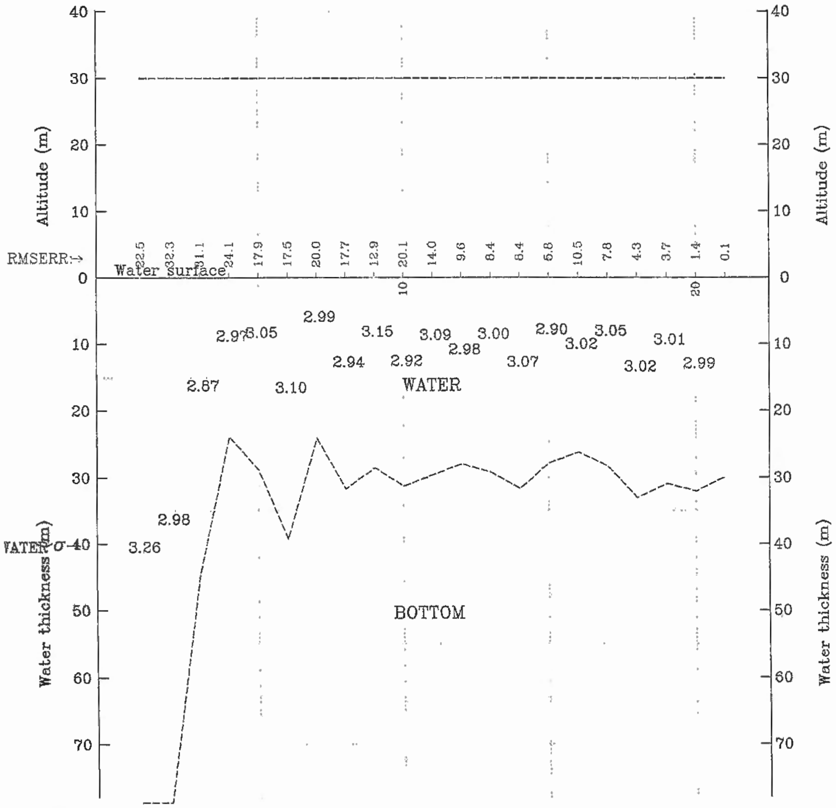

Figure 10.4. Interpretation of a synthetic data profile for the base model; random noise was added to data before interpretation. Standard deviation of noise ranges from 100 ppm at left of the profile to 0 ppm at right.

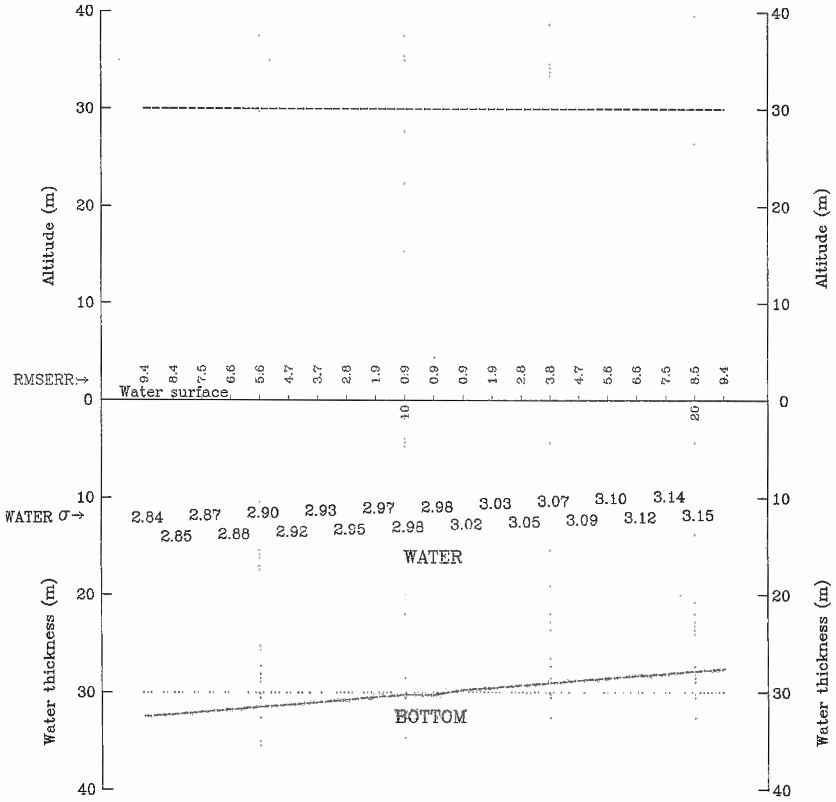

Figure 10.5. Interpretation of a synthetic data profile for the base model: a severe (±2%) calibration error was simulated by multiplying all data at each station by a constant. The constant ranges from 0.98 at left of figure to 1.02 at right.

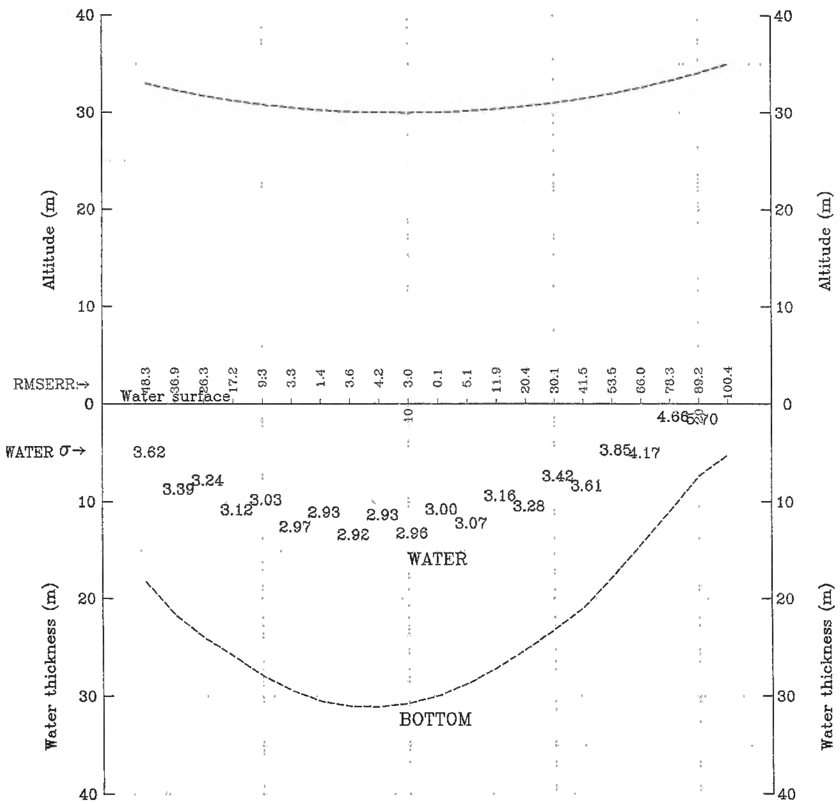

Figure 10.6. Interpretation of a synthetic data profile for the base model calculated for a range of ±20 degrees of pitch and roll: pitch and roll range from +20 degrees and −20 degrees, respectively at left to −20 and +20 degrees at right. No corrections were made for bird attitude.

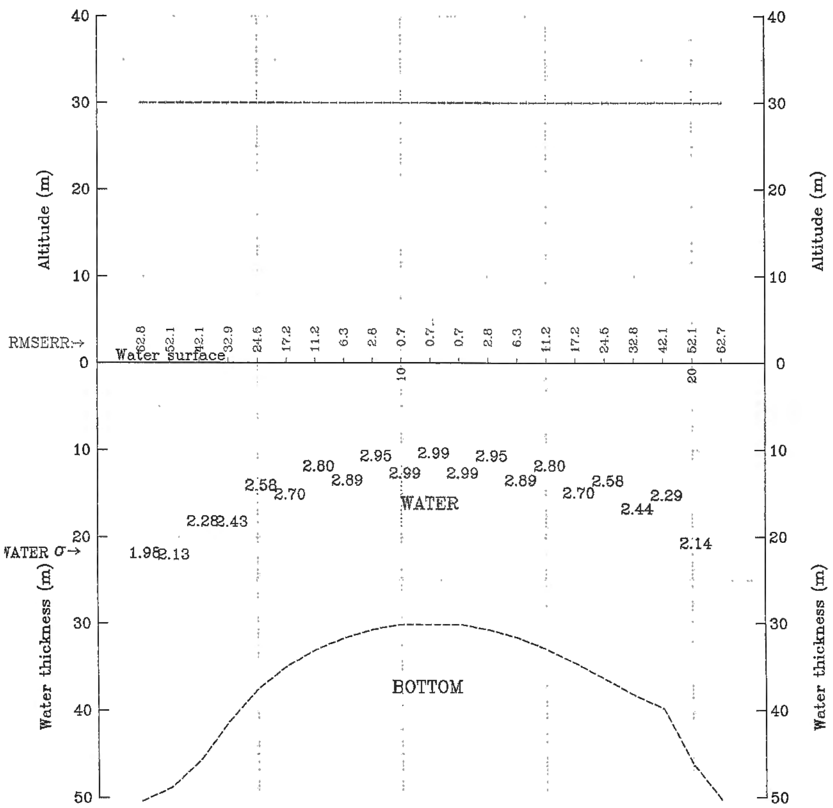

Figure 10.7. Interpretation of a synthetic data profile for the base model calculated for a range of ±20 degrees of pitch and roll. The apparent altitude was corrected for bird orientation, but the EM results were not.

altitude estimates based on laser altimetry from the bird. Such laser altimeters provide a highly accurate alternative to conventional radar devices, which typically have accuracies of a few meters in 30 m over water and even worse over ice and snow. Since radar altimeters are normally mounted in the aircraft, static and dynamic errors in the estimated bird altitude will be observed much of the time. Laser altimeters, on the other hand, tend to be small devices with accuracies of 10 cm or less in 30 m. Since they sense the distance to any reflective surface, they are ideal for use over ice and snow. Their size and low power levels make it practical to mount them in the EM bird, and their tight beam makes correction of the measured altitude for attitude variations straightforward.

In the next few figures, examples of how such errors would be treated by the inversion process are given. The base model for this study consists of a 30 m water layer of conductivity 3 S/m overlying a bottom layer of conductivity 0.3 S/m, with a bird altitude of 30 m. Synthetic forward models for several related models have been computed using a layered-earth forward model (Holladay, 1981) which has been augmented by a 55 point linear filter provided by D.E. Boerner, and a variety of error types have been superimposed

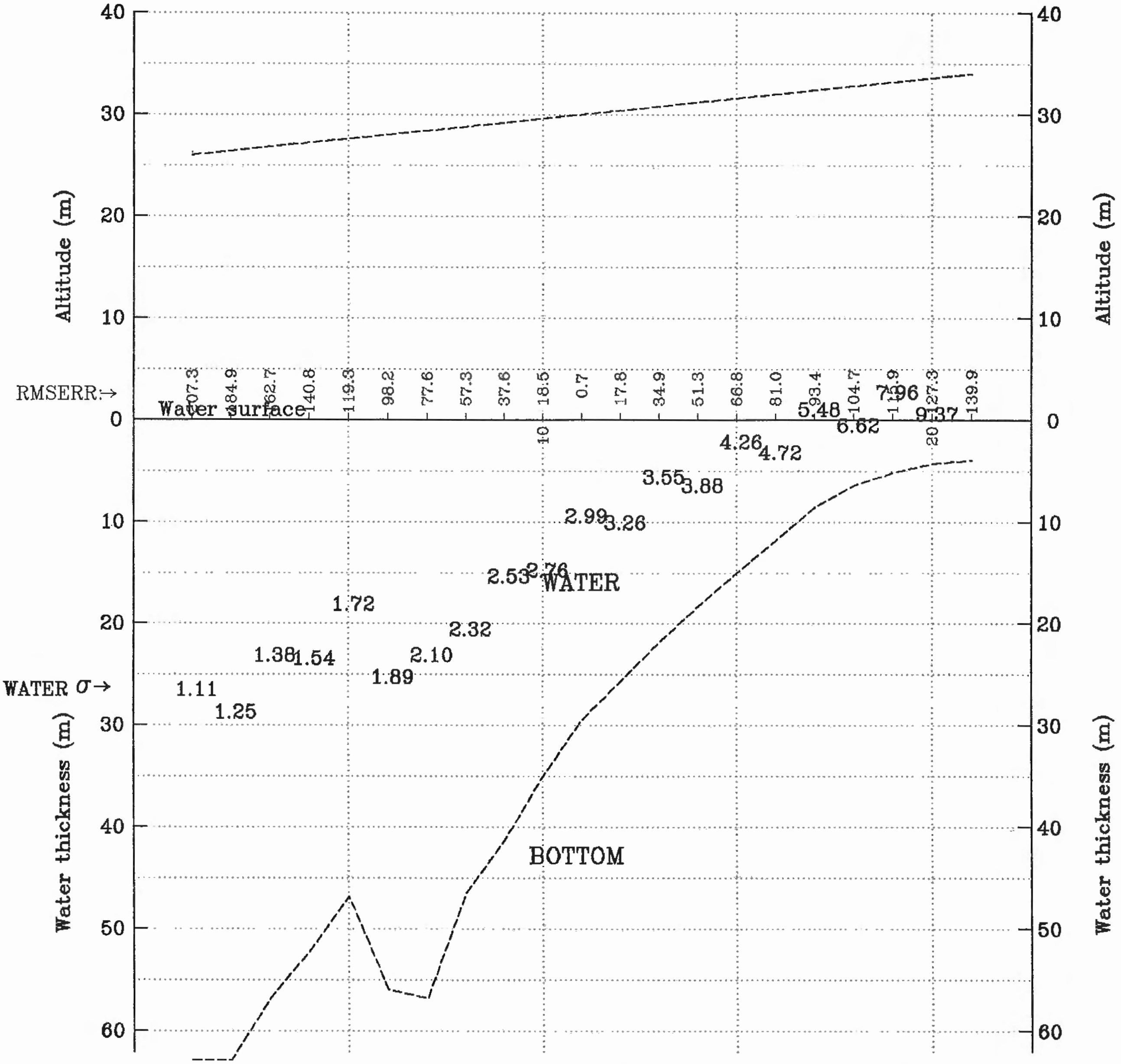

Figure 10.8. Interpretation of a synthetic data profile for the base model: Altimeter error was simulated by adding a constant to the altitude; this constant ranged from −4 to +4 m from left to right.

on these model responses. In the absence of error, the inversion proceeds quickly and gives excellent agreement with the original model. When error is included, the number of iterations required is increased and a larger misfit is observed at the end of the fitting process.

For the first example, random Gaussian-distributed noise with a known standard deviation was added to the synthetic response of the base model: the in-plane and quadrature at each frequency had an independent amount of noise added. The inversion routine was then run using this noisy response as data. Figure 10.4 displays the result of one such run, in which the standard deviation of the added noise was varied from 100 ppm at left to 0 ppm at the right as a linear function of position. To be rigorous, one would have to repeat this procedure many times and construct an envelope of inversion results for a given noise level. As expected, a fluctuation in interpreted parameter values is observed, mainly in the water depth. The conductivity estimates remain fairly steady even with large errors the depth estimate.

In Figure 10.5, a severe calibration problem is modelled by multiplying all data at a given station by a constant, whose value ranges from 0.98 to 1.02 over the profile, giving ±2% error in overall calibration over the length of the profile. Coherent error as in this example should be the worst case, since incoherent error (i.e. different errors for the in-phase and quadrature at each frequency) would tend to cancel out in the inversion step. This type of error distorts the model in a fairly linear way in which ±2% error gives ±10% error in depth and ±7% error in water conductivity. Station 11 in the centre of the profile is the 0 error point: the slight kink in interpreted water depth is due to the inversion routine accepting the previous station's model as acceptable without iteration. Baseline drift was also modelled by adding a variable offset to the data in the in-phase and quadrature at each frequency, coherently as before. The results strongly resemble those for calibration error: ±100 ppm drift gives ±10% error in depth and ±7% error in water conductivity.

Figure 10.6 shows the effects of bird attitude on the EM system due to the mixing of coupling modes and errors in estimated altitude caused by misorientation of the laser altimeter, which is mounted rigidly to the bird, while Figure 10.7 gives results for the case in which the altitude values have been corrected. In both examples, pitch and roll vary through ±20 deg. In Figure 10.6, no altitude or EM system correction has been applied to data generated for a misoriented bird. There is a clear altitude deviation from the "true" value of 30 m of from 10 to 15% for 20 degrees pitch and roll to zero at zero pitch and roll at the centre of the profile. The asymmetry is due to the noncentral position of the altimeter in the bird. The water thickness estimate is reduced much below the "true" value of 30 m at large pitch and roll values where the conductivity estimate is exaggerated. In Figure 10.7, where the altitude has been corrected, the water thickness is exaggerated by some 60% for 20 degrees of pitch and roll, while its conductivity is underestimated by about 30%.

Finally, Figure 10.8 shows the effects of ±4 m of altitude error about the "true" altitude of 30 m. Once again, station 11 represents the error-free condition, while 4 m have been subtracted from the altitude on the left side of the profile and added on the right. Even for ±1 m of altitude error (3%), the effect is substantial: the interpreted water thickness is altered by about 10 m or 30%, and the water conductivity estimate is out by about 15%. Of course, the altitude could be determined as a parameter, but this leads to an undesirable loss of resolution in the other parameters. However, if only radar altimeter data are available, there is little choice.

CONCLUSIONS

Through-Ice Bathymetry (TIB) using a helicopter EM system is theoretically capable of water depth estimation to < 10% for water depths less than 2 skin depths, and to about 0.3% for water depths less than 1 skin depth, given 1 ppm noise levels for an 8 m bird. The water conductivity must be determined jointly with the thickness, unless it is known to be uniform and stable in the survey area both laterally and as a function of depth. Water conductivity is a well-determined parameter, with estimated error levels of 0.08%. The accuracy of the conductivity estimate for saturated bottom sediments depends on the thickness of the water: levels of 1% or better may be possible for water depths of 20 m or less.

Ice thicknesses can be estimated to the order of 2% or better error for ice thicknesses over 0.1 m, while ice conductivity estimates to the order of 4% are possible even with 10 kHz as the highest frequency used, and will be more accurate if higher frequencies are available. The presence of even 8 m of ice does not significantly degrade water thickness or conductivity estimates.

One-dimensional interpretation is an acceptable approximation under most circumstances, given the spatial averaging performed by an AEM system. Where such an interpretation is not valid, clear indication is usually given by the inverse program that the model fits poorly.

Errors must be kept strictly under control. As noise can generate substantial errors in the more weakly determined parameters, it is mandatory to reduce the noise due to the measuring system to well below natural noise levels. This, however, is difficult to achieve at low frequencies. The effects of incorrect calibration and baseline drift are especially serious because they may distort the interpretation without generating strong misfits between the model and the data. Altitude and attitude errors can be controlled by means of suitable altimetry, pitch and roll sensors.

This paper has addressed some of the issues that were encountered during the development of the Geotech TIBS and AIM systems. Clearly, airborne bathymetry and ice property measurement are techniques which can be implemented with existing technology and interpretation methods. Case histories will be published as the survey data are released.

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- 11 -

Application of the airborne electromagnetic method for bathymetric charting in shallow oceans

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Won, I.J. and Smits, K., Application of the airborne electromagnetic method for bathymetric charting in shallow oceans; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 99-106, 1986.

Abstract

An experimental airborne electromagnetic (AEM) survey was carried out in the Cape Cod Bay area (Massachusetts, USA) to investigate the potential of extracting bathymetric information over a shallow ocean. A commercially available Dighem III AEM system was used for the survey without any significant modification. The helicopterborne system operated at 385 and 7200 Hz, both in a horizontal coplanar configuration. A concurrent ground truth survey included extensive acoustic profiles, as well as spot water conductivity measurements.

The interpreted bathymetric profiles show excellent agreements with corresponding acoustic depth profiles up to one (possibly more) skin depth of the source frequency. It is envisioned that with further improvements in hardware and software, the bathymetric resolution may extend beyond the skin depth. AEM data can also produce (as byproducts) conductivity profiles of both seawater and bottom sediments that may find potential applications in various offshore geotechnical engineering works.

Résumé

On a effectué un levé électromagnétique aérien (ÉMA) expérimental dans la baie de Cape Cod (Massachusetts, É.-U.) pour examiner la possibilité d'obtenir des données bathymétriques sur les fonds océaniques peu profonds. Le levé a été fait avec le système ÉMA Dighem III sans modification importante. Ce système héliporté fonctionnait aux fréquences de 385 et 7 200 Hz, toutes deux émises à partir de bobines coplanaires horizontales. En même temps, on a effectué un levé de vérification au sol qui comprenait des profils acoustiques étendus ainsi que des mesures aléatoires de la conductivité de l'eau.

Les profils bathymétriques interprétés des données ÉMA montrent d'excellentes concordances avec les profils acoustiques correspondants, jusqu'à concurrence d'une (et peut-être plus d'une) profondeur de pénétration de la fréquence d'origine. On croit que moyennant d'autres perfectionnements du matériel et du logiciel, la résolution bathymétrique s'étendra peut-être au-delà de la profondeur de pénétration. Les données ÉMA peuvent également fournir (à titre de sous-produit) des profils de conductivité de l'eau de la mer et des sédiments du fond, qui pourraient trouver des applications dans divers travaux géotechniques au large des côtes.

INTRODUCTION

The Naval Ocean Research and Development Activity (NORDA) has been investigating a possible application of the airborne electromagnetic (AEM) method to the bathymetric charting in a shallow ocean. There is a strong Navy requirement for a rapid airborne and cost-effective shallow-ocean bathymetric method capable of supplementing or even replacing the traditional shipborne acoustic sounding methods, which are time-consuming and often not suited to shallow coastal areas. Periodical and repetitive bathymetric mapping of shallow-ocean regions with heavy

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traffic is necessary for monitoring bottom sediment movements, ship lane maintenance, and a variety of geotechnical operations, as well as for routine charting.

TEST SURVEY IN THE CAPE COD BAY

The test survey area and the AEM flight lines are shown in Figure 11.1. All flights and ground truth surveys were performed during a 3 day period in June 1984. The AEM system used was a commercially available Dighem III, described in detail by Fraser (1978, 1979, 1981). The system was equipped with two horizontal coplanar coil pairs operating at 385 and 7200 Hz. Both pairs had an 8 m coil separation (an additional coaxial coil pair operating at 900 Hz was deactivated due to an electronic malfunction).

The sensor platform, or bird, towed by a Sikorsky S58T twin-engine helicopter using a 30 m cable, maintained an average altitude range between 40 and 50 m above the sea surface. The aircraft altitude was measured by a radar altimeter (Sperry Model 220 mounted on the aircraft) that had a manufacturer-specified accuracy of 5%. A total of about 200 line km AEM data consisting of 13 segment profiles was obtained in three sorties in a less than 7 h period. The sampling rate was 1 s, corresponding to about 50 m along the ground track (about a 50 m/s ground speed). The maximum water depth in the survey area is about 40 m, according to the bathymetric chart (NOAA Chart 13 246).

The flight plan included data collection before and after each profile at an altitude of about 270 m to calibrate the zero-level signal of the receiver coils. In addition, three short calibration flights were made in a location about 15 km east of the Cape, where the bathymetric chart indicated water depth in excess of 60 m. These data were intended to be used for determining the absolute calibration constants for amplitude and phase of each coil pair on an assumption that the water body below may be considered a uniform conductive half-space. It turned out, however, that this calibration method is not accurate enough for the bathymetric processing. As discussed later, both zero-level signal and amplitude/phase calibration constants are derived from a small portion of each actual flight line data.

Figure 11.2 shows a raw AEM data profile accompanied by a corresponding radar altimeter profile along Line 5021 (see Fig. 11.1 for location). Clearly, the AEM data are overwhelming correlatable with variations in altitude. A very crude indication of water depth may be observed from the ratio of the quadrature component to the inphase component of the 385 Hz data: the ratio increases with a decreasing water depth. Unfortunately, this relationship is highly nonlinear. Even though the aircraft altitude is maintained mostly within a 10 m range (between 40 and 50 m), the corresponding variations of the AEM responses amount to more than 500 ppm. Owing to the high water conductivity, errors induced by inaccurate altimetry pose a critical problem. At a 45 m bird altitude, a 1% altitude change at a given water depth of 10 m generates amplitude differences of 22 ppm at 385 Hz and 33 ppm at 7200 Hz. It can also be shown that, for a 1 m depth change at the same water depth of 10 m, the predicted amplitude differences amount to only 10 ppm at 385 Hz and 0 ppm at 7200 Hz.

Since the employed radar altimeter has a specified accuracy of 5%, it soon became evident that the radar altitude cannot be trusted for the bathymetric processing. Instead, a new algorithm was developed to use the 7200 Hz response to derive the electromagnetic altitude during the inversion process. The new altitudes thus derived show fairly random zero-biased differences (with respect to the radar altitudes) whose rms amounts to about 2-3%.

It was originally planned to employ a Del Norte navigation system supported by three ground transponders. Because excessive distances caused poor reception, a Loran-C system was installed on site with a makeshift arrangement of a printer that produced co-ordinates at a 5 s interval. These were later interpolated to produce 1 s interval co-ordinate data corresponding to the AEM data rate.

A ground truth bathymetric survey concurrent with the AEM flights was carried out using an acoustic depth sounder. A total of about 120 line km of depth profiles was obtained, which covered about 60% of the AEM flight area. Unfortunately, due to many practical reasons, the flight lines and the ship track did not coincide and were often more than 500 m apart. Therefore, the best available ground truth still reflects another interpolated approximation unless the bottom topography fluctuates rapidly, the ground truth is considered to be accurate within 1 to 2 m.

Spot measurements of water conductivity were made at eight different locations along the ship track at a 3 m depth. They ranged between 4.0 S/m and 4.12 S/m. While these values may be fairly representative for deep water, there are considerable uncertainties over very shallow water (<3 m) where water temperature may rise significantly during the day (particularly during sunny days in June, as in this case). A mere 4°C difference in the water temperature at a given salinity can result in as much as a 10% change in water conductivity. Unfortunately, no ground truth measurements were made during the survey to confirm this possibility.

INTERPRETATION

The high conductivity of seawater (between 3 and 5 S/m, depending on salinity and temperature with no fresh-water inlets) severely restricts the ability of EM waves to penetrate the water. Bathymetric range and resolution are, therefore, primarily governed by the source frequency. Figure 11.3 shows the skin depths in a frequency range between 40 Hz and 40 kHz for assumed water conductivities of 2, 3, 4, and 5 S/m.

For the employed frequencies of 385 and 7200 Hz and seawater with a conductivity of 4 S/m, we may, therefore, expect skin depth of 12.8 and 3.0 m, respectively. From Figure 11.3 the source frequency obviously should be less than 100 Hz to achieve a depth range of 50 m or more.

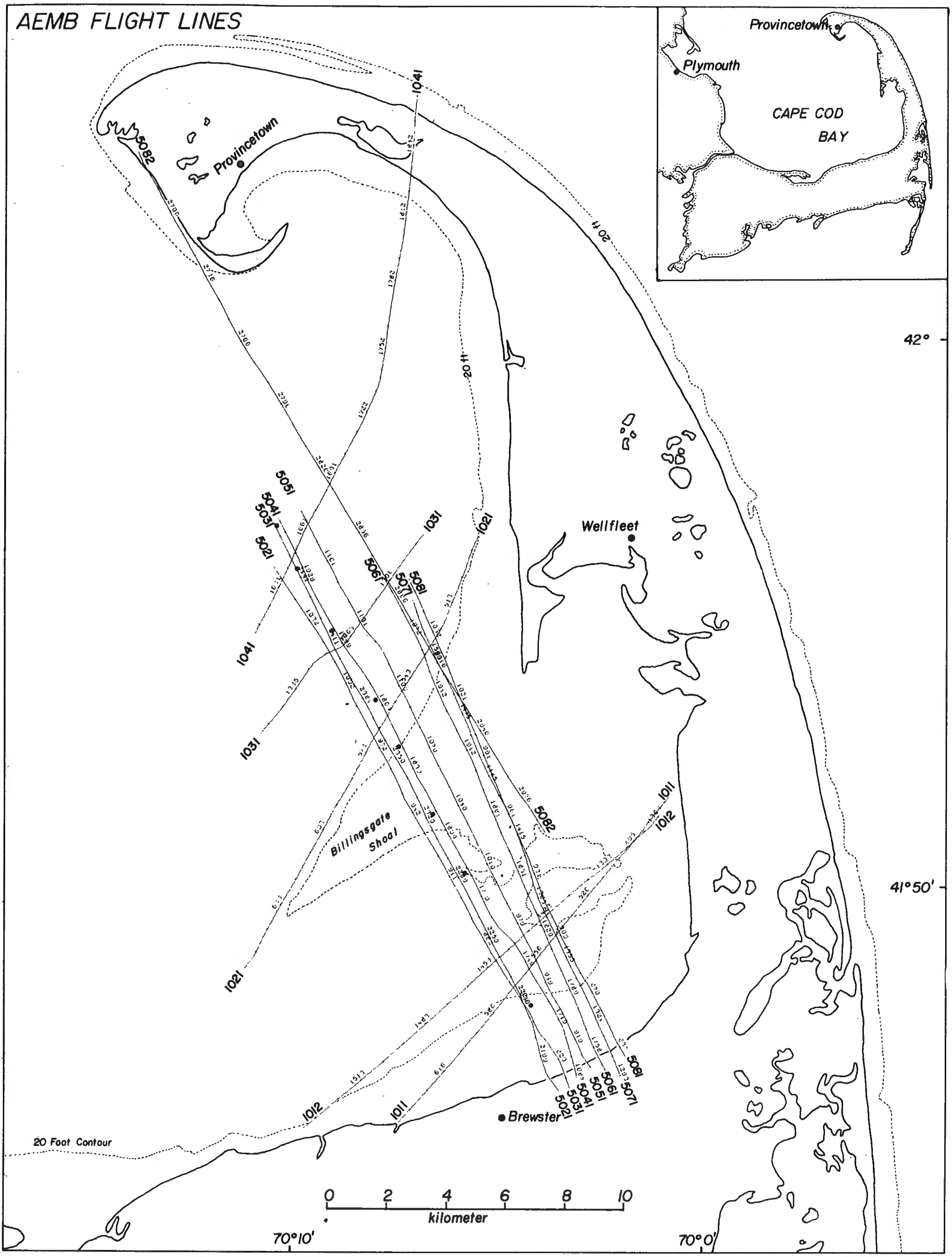

Figure 11.1. Cape Cod Bay test area and AEM flight lines. The line numbers are shown at the end of each line. Small numbers along the flight lines are fiducials.

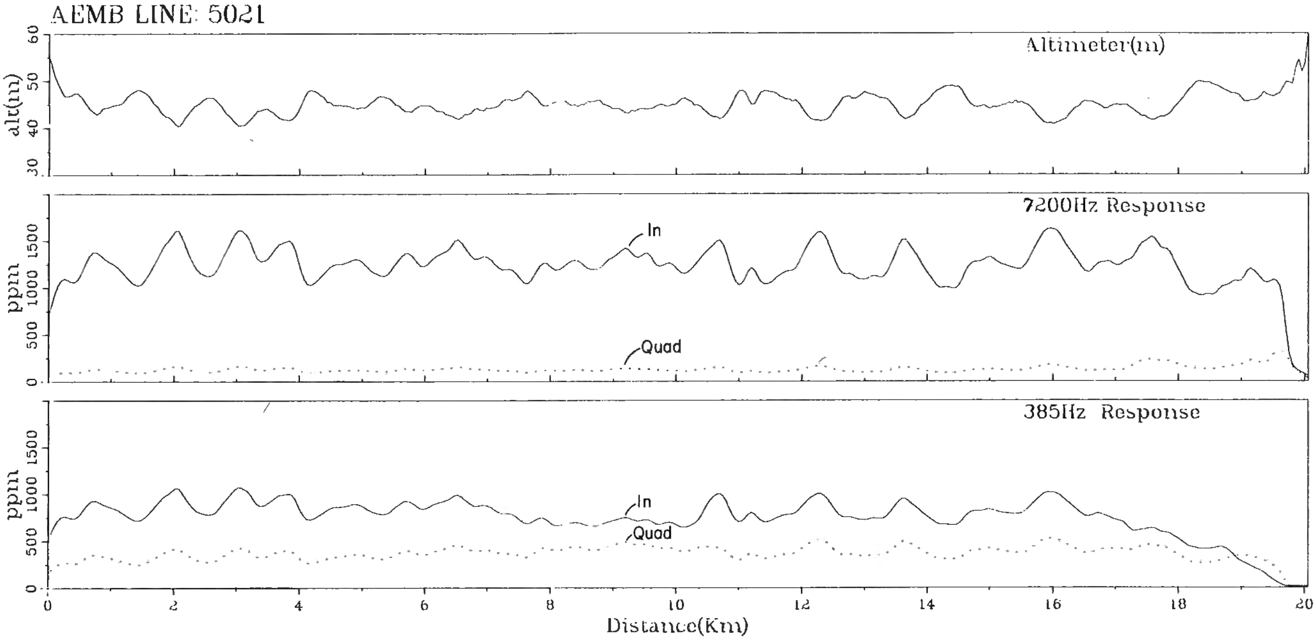

Figure 11.2. Raw AEM data (inphase and quadrature for two frequencies, 385 and 7200 Hz) and radar altitude data (flight line 5021).

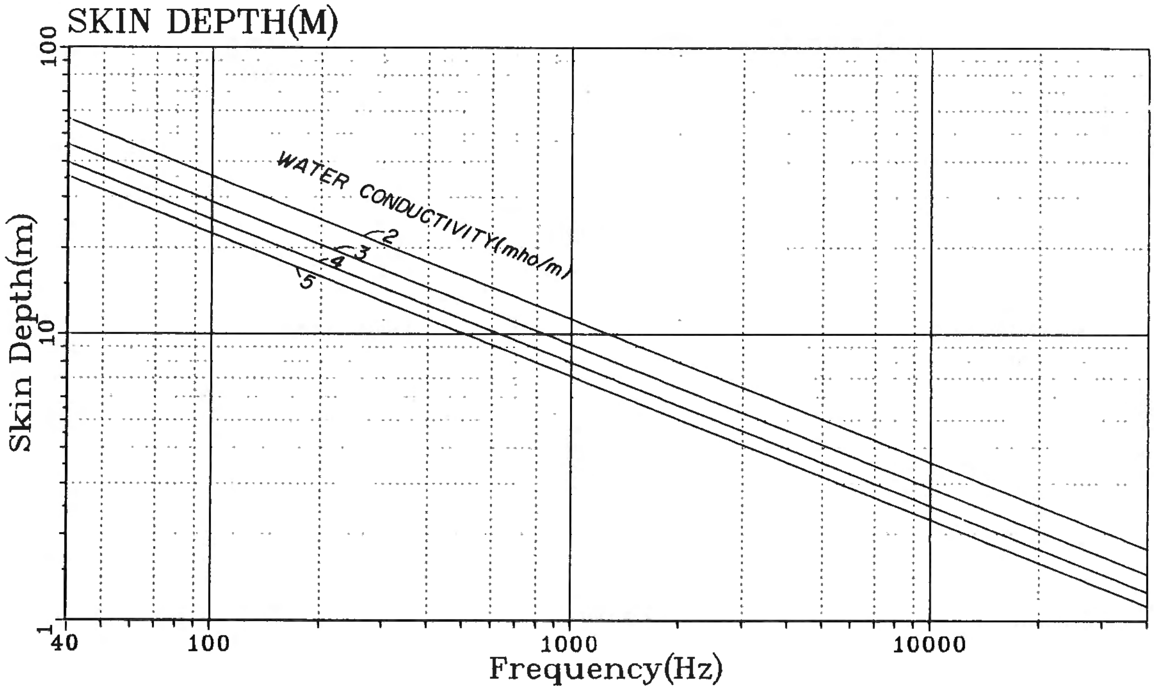

Figure 11.3. Skin depth as a function of frequency for seawater with conductivity between 2 and 5 S/m.

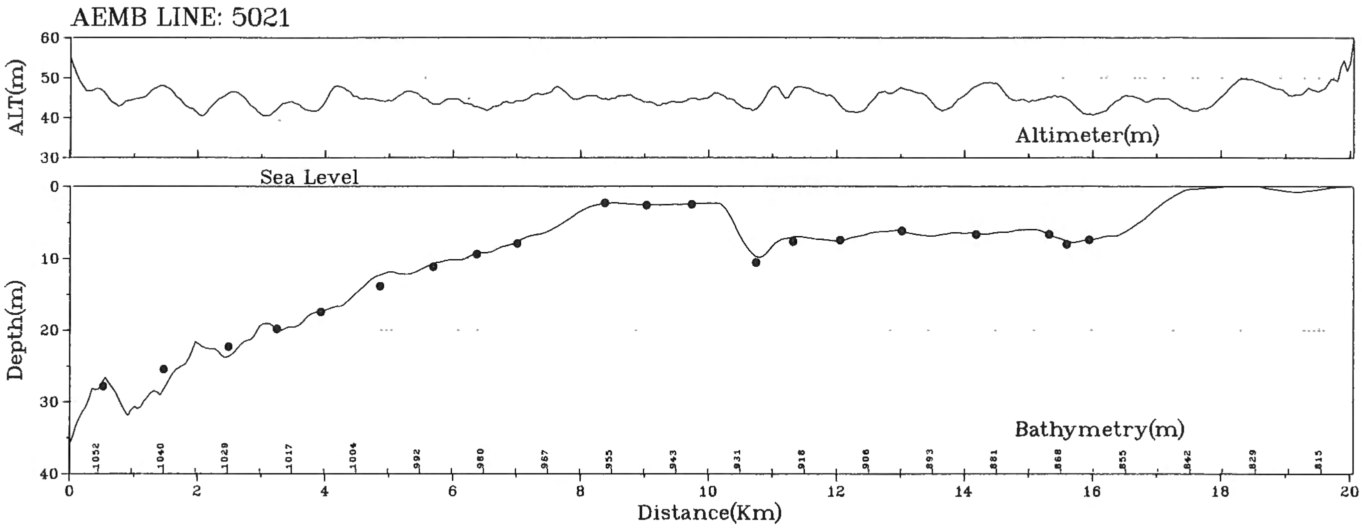

Figure 11.4. AEM bathymetric profile for line 5021 after applying an 11 point running average filter. Solid circles represent depths obtained by acoustic soundings.

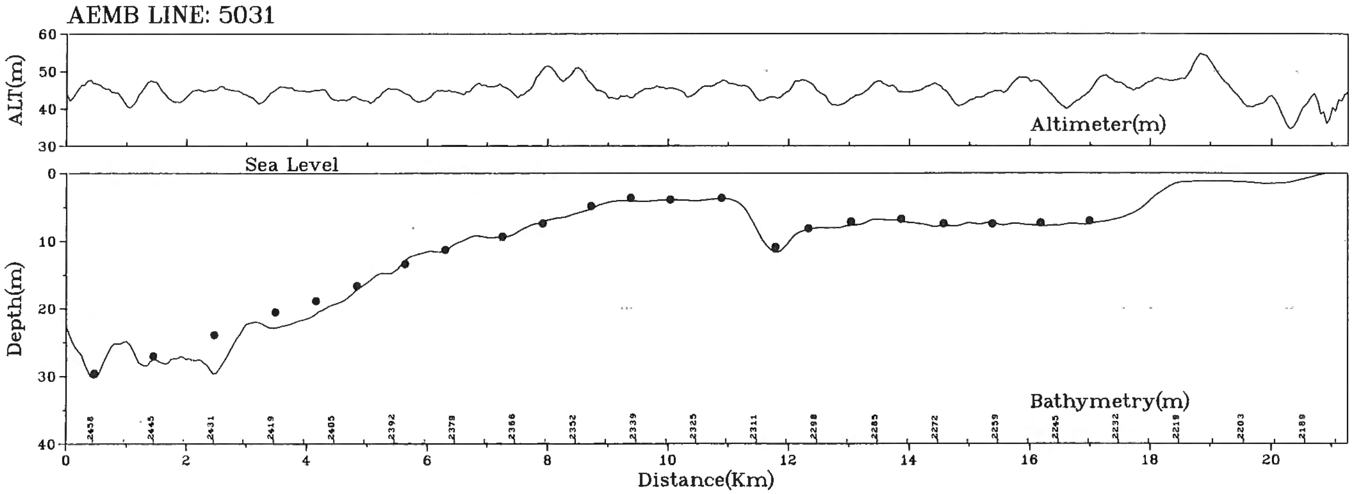

Figure 11.5. AEM bathymetric profile for line 5031 and acoustic depths (solid circles).

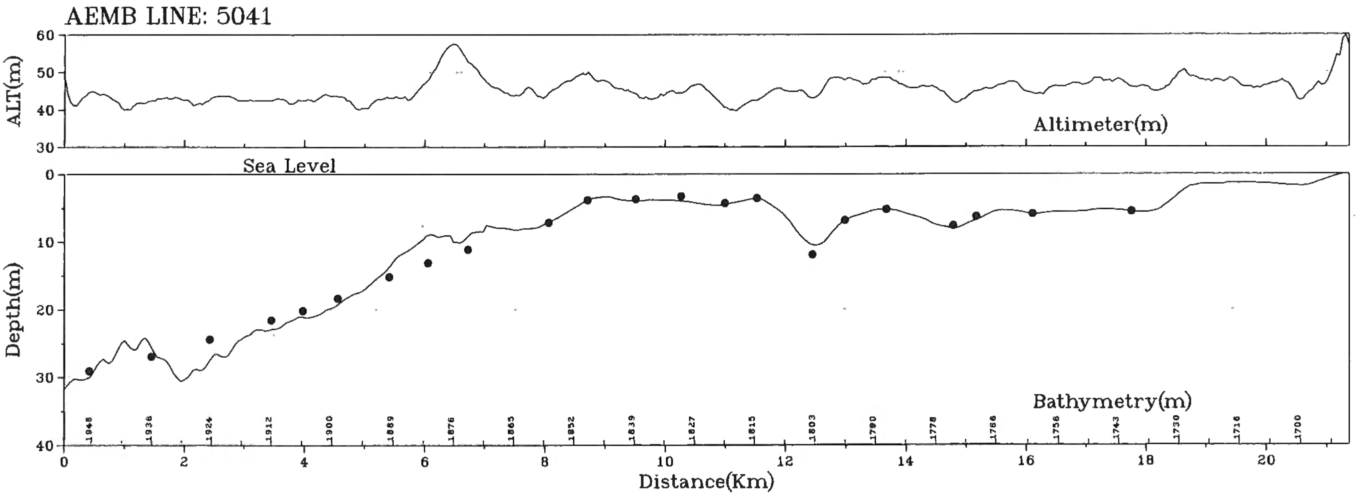

Figure 11.6. AEM bathymetric profile for line 5041 and acoustic depths (solid circles).

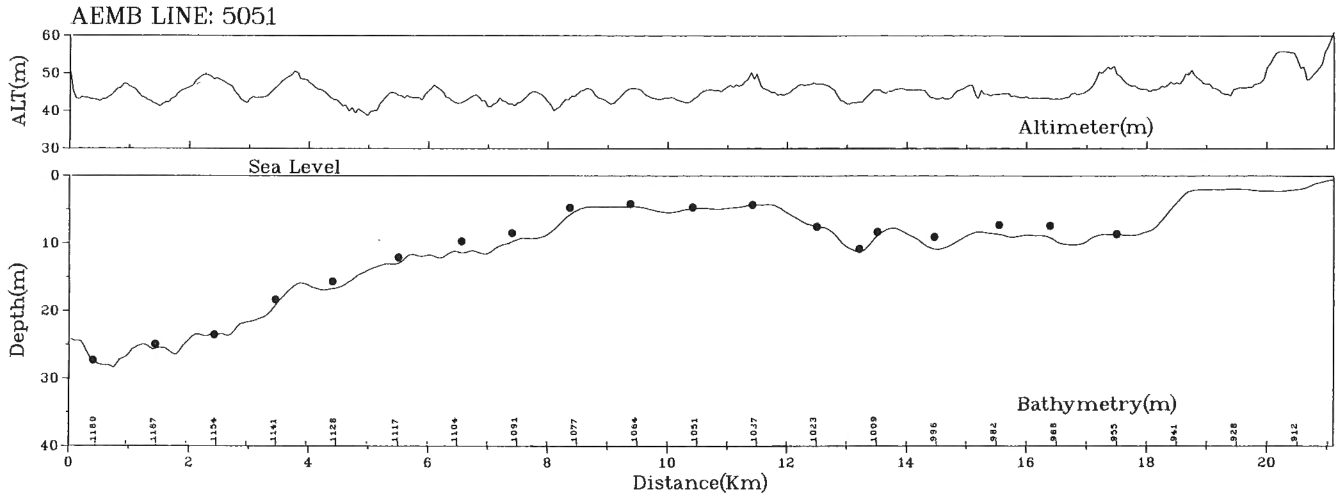

Figure 11.7. AEM bathymetric profile for line 5051 and acoustic depth (solid circles).

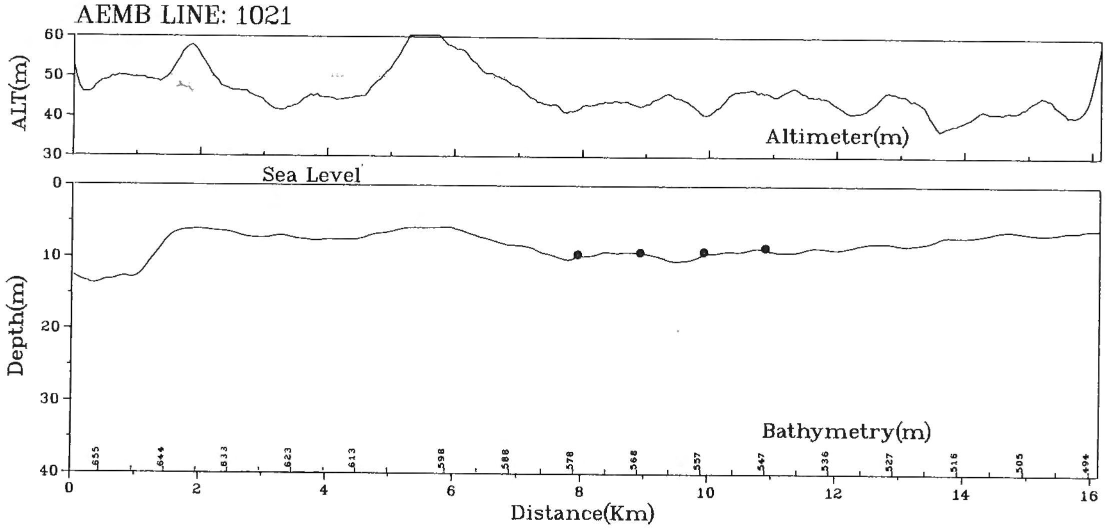

Figure 11.8. AEM bathymetric profile for line 1021 and acoustic depth (solid circles).

The Cape Cod test data were initially interpreted and reported by Fraser (1985) using a least-squares algorithm by Anderson (1979). Subsequently, the data were reprocessed at NORDA using a different Marquardt least-squares algorithm, notably Subroutine ZXSSQ in the IMSL package. The inverted bathymetry in both cases agreed approximately in trends with known bathymetry but showed a considerable static bias that often exceeded 5-10 m. Further careful inspection of the least-squares inversion results leads us to the following conclusions.

1) Computer inversion time is unacceptably long: one-point inversion of the two-frequency data consumes from 5 s to 1 min on a VAX 11/780 computer, even when the water depth is the only sought parameter, while all other parameters are prescribed and fixed.
2) AEM response is too sensitive to the bird altitude to accept the specified 5% accuracy of the radar altimeter used for the survey.
3) Both the water and the sediment conductivities must be allowed to float albeit in constrained ranges.

The AEM bathymetric profiles reported here are derived from yet another method: analytical solutions of simultaneous nonlinear equations. At each data location, we have four measured quantities; i.e., inphase and quadrature components at two frequencies. From this data set we derive exact solutions of four parameters: water depth, water conductivity, sediment conductivity, and electromagnetic altitude. When unconstrained, the solutions are exact (since the number of knowns and unknowns is the same), resulting in zero residuals regardless of data error. However, severe data error may produce physically unacceptable solutions (e.g. negative depth or conductivities). While the least-squares methods (in which the number of knowns is usually much more than that of unknowns) may produce a stable solution set from a noisy data set (even though its rms error may be high), the present analytic approach is understandably sensitive to data error. Under this circumstance, a low-pass filtering of the inverted profile is justifiable to countermeasure the random data errors.

An inversion algorithm using a modified Newton-Raphson method is then applied to the data. Initially, we derive the sensor altitude and water conductivity from the 7200 Hz data and, subsequently, water depth and bottom conductivity from the 385 Hz data. Inversion time for deriving all four parameters amounts to 0.5 to 2 s on a VAX 11/780 computer. The analytic method, as in the least-squares method, also requires initial guesses and, to ensure physically acceptable solutions, reasonable solution constraints. The constraints used for the final processing of the Cape Cod data follow.

1) Water conductivity (σ_1): 3-5 S/m
2) Sediment conductivity (σ_2): 0.01-2 S/m
3) Water depth (d): 0-50 m
4) Altitude (b): positive

Spot measurements of water conductivity at a 3 m depth at eight locations ranged from 4.0 to 4.12 S/m. No bottom sediment conductivity data are available. However, an extensive in situ study by Hulbert et al. (1982) off the Florida coast showed a common range of 0.4 to 1.4 S/m within the first 5 m depth, decreasing only slightly with increasing depth of burial.

The inversion process is initiated as follows. For the very first point, we prescribed starting values of σ_1 = 4 S/m, σ_2 – 1 S/m, d as read from the hydrographic chart, and b as indicated by the radar altimeter. Once the process starts, the solution set a the present location is prescribed as the initial parameters for the next location. Thus, after the first data point of a profile, the interpretation becomes completely autonomous.

We present only the bathymetric results. Presentation of other parameters will be dealt with in a separate report. It is noted, however, that (1) the derived electromagnetic altitude is well within ±1 m of the radar altitude (less than the manufacturer-specified 5% error), (2) water conductivity is mainly 4 ±0.2 S/m except for very shallow-water regions, and (3) bottom sediment conductivity ranges between 0.5 and 1.5 S/m in most profiles.

RESULTS

Figure 11.4 shows the interpreted AEM bathymetry for Line 5021 (see Fig. 11.1 for location). The solid line represents the water depth inferred from the AEM data. Solid circles denote the depths determined from acoustic profiles. Depths are computed at approximately 50 m intervals. Small numerals at the bottom are the flight line fiducials representing every 20th data point. The profile length is about 20 km.

The agreement is excellent up to a water depth corresponding to about one skin depth (12.8 m) of the 385 Hz signal. In fact, the agreement up to this depth is well within the interpolation accuracy of ground truth data. Below the skin depth we notice progressively degrading resolution resulting in oscillatory bathymetric profiles.

In essence, the oscillatory behaviour is a direct result of the decreasing signal-to-noise ratio with respect to the altitude uncertainty. At a 20 m depth, for instance, the maximum theoretical 385 Hz response (against an infinitely deep water) is expected to be about 10 ppm, while a mere 0.2 m error in altitude will result in the same amount of difference in

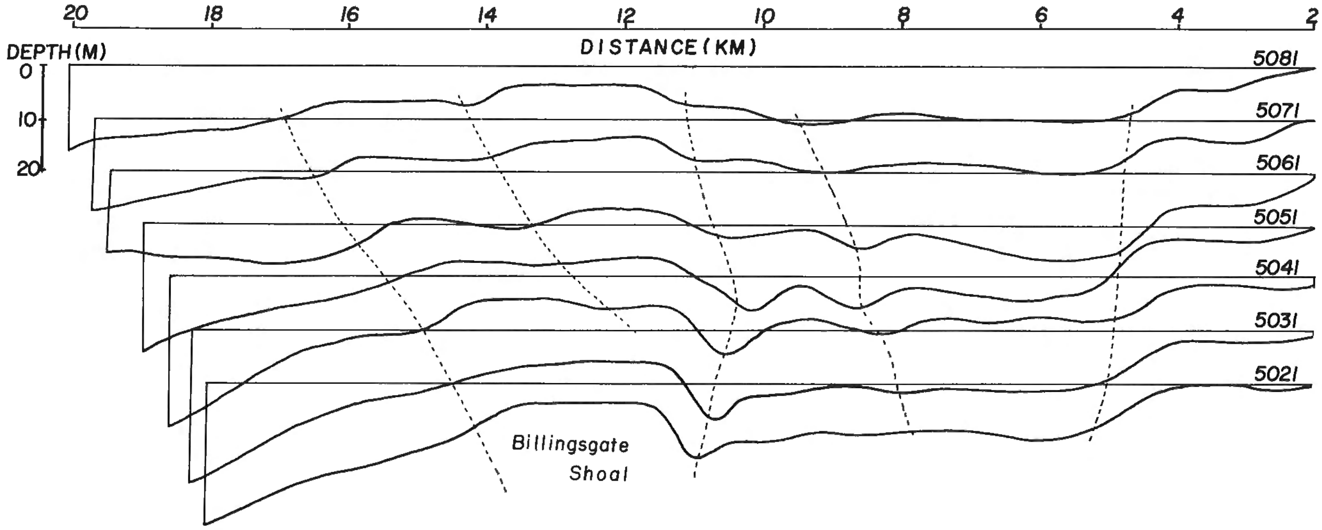

Figure 11.9. A composite of seven bathymetric profiles from the Cape Cod Bay area.

response. Since the bathymetric errors appear to be random, yet strongly correlated with the aircraft altitude, we tentatively conclude that the error sources are likely related to the altimeter resolution and to such bird attitude uncertainties as pitching and yawing associated with the aircraft altitude variations. The bird attitude will be monitored in the future using inclinometers whose output can be incorporated into the interpretation.

Such an oscillatory behaviour can sometimes be suppressed if we use instead a least-squares inversion method when a sufficient number of redundant measurements is available. The resultant solutions in this case will carry large rms errors, yet may give a deceptively smooth solution profile (errors never die; they simply become hidden in the process). The present analytical inversion method produces zero-residual solutions that fit the observed data regardless of the measurement errors. Although the two approaches are equivalent in the sense of error budgeting, the analytical inversion method appears to be superior in field logistics and in computational speed. Figures 11.5-11.8 show additional AEM bathymetric profiles produced by the above described procedure.

A composite of seven AEM profiles is shown in Figure 11.9. We notice striking details of the sea bottom morphology showing subtle trends and developments of slopes, trenches, and shoals. The fact that each profile is independently derived and yet shows remarkable correlations with neighbouring profiles renders further credence to the AEM results.

CONCLUSIONS

From our experience through the Cape Cod AEM bathymetry experiment, we summarize some of the error sources that degrade the bathymetyric resolution.

1) Calibration errors: amplitude, phase and zero level.
2) Error in the interpretive ocean model, particularly assuming the vertically homogeneous bottom sediment layer.
3) Altimeter error.
4) Measurement error due to pitching and yawing of the bird (negligible up to 10° if the bird altitude is 50 m or higher).
5) Ground truth interpolation error due to noncoincidence of tracks by boat and aircraft.
6) Electronic measurement noise.

Most of the above error sources can be significantly reduced through improvements in equipment and interpretation software.

It is envisioned that with additional research and development efforts, the AEM method will be able to produce accurate bathymetric charts over a shallow ocean (perhaps up to 100 m in depth). Compared with the traditional acoustic sounding techniques, the AEM method can provide an order-of-magnitude faster survey speed at a reduced cost and thus yield a synoptic knowledge of ocean-bottom topography. With improved interpretation schemes, even a real time data processing appears to be a realizable goal.

In addition, the method has potential applications to remote measurements of electrical conductivities of ocean water and bottom sediments. The bottom sediment conductivity, in particular, is closely related to certain mechanical characteristics, such as compaction rate, porosity, density, and (indirectly perhaps) sediment types, which carry broad geotechnical implications for many offshore activities.

ACKNOWLEDGMENTS

Airborne electromagnetic data used in this report were obtained under a NORDA contract by Carson Geoscience Co., Perkasie, Pennsylvania, employing Dighem III AEM system furnished by Dighem Surveys and Processing Inc., Mississauga, Ontario. Special appreciation is expressed to Joseph Heckelman of the National Oceanic and Atmospheric Administration for co-ordinating the deep-water ground truth survey. Shallow-water ground truth data were obtained under NORDA contract by the Woods Hole Oceanographic Institution. Jim Dodd (U.S. Geological Survey, Woods Hole) provided emergency on-site help in installing a Loran-C navigation system upon the failure of the originally planned Del Norte transponder navigation equipment. We also thank Doug Fraser of Dighem Surveys and Processing Inc., for many helpful discussions.

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- 12 -

Airborne bathymetry and sea-bottom profiling with the INPUT airborne electromagnetic system

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Becker, A., Morrison, H.F., Zollinger, R. and Lazenby, P.G., Airborne bathymetry and sea-bottom profiling with the INPUT airborne electromagnetic system; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 107-109, 1986.

Abstract

A specialized automated simple inversion technique was developed for the interpretation of airborne time-domain electromagnetic (AEM) offshore data obtained in coastal areas. This method was tested on a limited amount of data that was acquired in Canada with the Barringer/Questor Mark VI INPUT® AEM system along a 28 km long flight traverse off the coast of Cape Breton Island in Nova Scotia. An analysis of the data and comparison of the results with the available bathymetric charts indicates that the data can be interpreted to an accuracy of about 10% or 2 m in areas where the depth of sea water does not exceed 20 m. A second test off the coast of New Brunswick showed that reasonably good bathymetric estimates could be obtained to about 50 m of water depth.

Résumé

On a élaboré une simple technique spécialisée et automatisée d'inversion pour l'interprétation des données de levés électromagnétiques aériens (ÉMA) obtenues en domaine temporel au large des côtes. Cette méthode a été testée sur une quantité limitée de données obtenues au Canada avec le système ÉMA Mark VI INPUT® de Barringer/Questor, sur un parcours linéaire de 28 km au large de l'île du Cap-Breton, en Nouvelle-Écosse. Une analyse des données et une comparaison des résultats avec les cartes bathymétriques disponibles montrent qu'on peut interpréter les données avec une précision de ±10 p.cent, soit ±2 m, dans les zones où la profondeur de la mer ne dépasse pas 20 m. Un deuxième test au large des côtes du Nouveau-Brunswick a montré qu'on peut obtenir des estimations bathymétriques raisonnablement bonnes jusqu'à une profondeur d'environ 50 m.

INTRODUCTION

Traditionally, airborne electromagnetic (AEM) systems have been used for the detection of distinct subsurface conductors. As equipment quality improved all of the state-of-the-art apparatus could also be employed for mapping ground conductivity. Thus Dyck et al. (1974), Whiting (1983) and DeMoully and Becker (1984) have reported the use of the towed-bird, time-domain INPUT system for mapping the conductivity and thickness of surficial materials. Similar applications of frequency-domain apparatus were reported by Fraser (1978) for the Dighem helicopter system and by Seigel and Pitcher (1978) for the fixed-wing Tridem system. Evidently, the data interpretation techniques used for geological interpretation can be readily adapted for the purposes of airborne bathymetry. Indeed, the feasibility of using a conventional AEM system for bathymetry was confirmed by Morrison and Becker (1982). Their analysis of conventional survey systems shows that the INPUT system appears to be particularly well suited for the task, because under ideal conditions it can resolve a 40 m depth of seawater to better than 3% and a 60 m depth to about 15%.

In parallel with improvements in data quality, the last decade has also witnessed the evolution of appropriate theoretical methods for data analysis. Because of the amount of data that needs to be interpreted it is impractical to use classical inversion techniques (c.f. Glenn et al., 1973) for the analysis of time-domain AEM data. Instead, as shown by

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Zollinger et al. (1985), the field data can be best interpreted using automated, noninteractive, nomogram fitting techniques based on the assumption of very simple geological models.

SURVEY PARAMETERS

The survey data were acquired with the Barringer/Questor Mark VI INPUT system in its standard configuration (horizontal-axis receiver positioned 100 m behind and 70 m below the aircraft). A two ms pulse was used to induce transient eddy currents in the seawater. The decay of the secondary magnetic fields was measured with a conventional six-channel detector. For detail of the configuration and wave form see O'Connell and Nader (1986).

The first test survey was done by Questor Surveys Ltd. of Mississauga, Ontario, in conjunction with a mineral survey near Cape Breton Island, Nova Scotia. The data relates to a single 27 km long flight line which is oriented roughly east-west and crosses the mouth of the Lennox Passage. The centre of the line is located at 45° 35′ N, 60° 50′ W. Detailed bathymetry for this area is available as shown on two Canadian Coastal charts for St. Peters Bay (No. 4275; 1:30000 and No. 4308; 1:37500). The survey line was repetitively flown six times. The data were acquired at altitudes of 180, 210, and 240 m in both east and west directions. In addition to analogue records, the flight data, including altimeter and magnetometer values, have also been recorded in digital form on computer compatible magnetic tapes. Thus the data are readily accessible for automated interpretation on a high speed digital computer. On survey, the aircraft maintains a speed of about 193 km/h or 53 m/s. The detector output is scanned twice a second so that the data interval corresponds to a linear distance of about 27 m.

A second test survey, done with the same equipment, was carried out near Pokesudie Island in New Brunswick. This 30 km line commenced at 47° 45′ N, 64° 39.5′ W and was flown on along a N 50° W azimuth. It extended over deep water at the NW end and thus allowed us to evaluate the system performance to a water depth in excess of 40 m.

DATA INTERPRETATION

In interpreting offshore AEM data it is reasonable to assume a single layer model made up of conductive seawater overlying a very resistive halfspace of bottom sediments and basement rocks. The problem is further simplified by considering the conductivity of seawater to be constant at 4 S/m, and by assuming that the bottom is infinitely resistive. The only unknown parameter, depth of seawater, may be determined by comparing the observed EM transients to a table of theoretical values computed for various depths of seawater.

In areas of very high surficial conductivity, the amplitude of the secondary field transient is a very sensitive function of

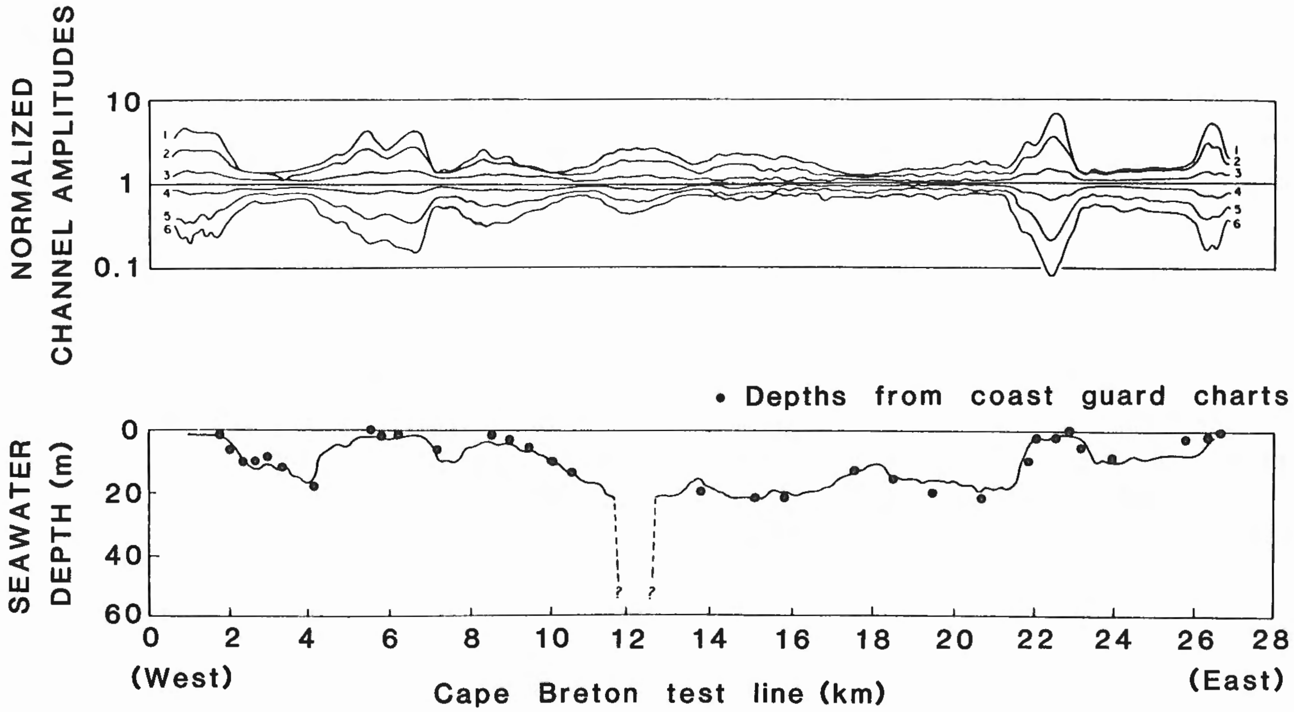

Figure 12.1. Example of a survey from an offshore area near Cape Breton, Nova Scotia. The INPUT AEM data were obtained at a flight height of 210 m. At the top are INPUT amplitudes normalized to geometric means of Channels 3 and 4. At the bottom, sea bottom depth interpreted from AEM data (solid lines) and published bathymetry information (dots).

the system elevation and geometry. The transient shape, however, is relatively insensitive to these effects and it is mainly related to the thickness and conductivity of the surficial layer. Thus an optimal data interpretation technique for this problem should rely on the relative channel amplitudes rather than on their absolute values. A method of data interpretation based on these principles was recently described by Zollinger et al. (1985). It was found that normalizing the data by the geometric mean of Channel 3 and Channel 4 amplitudes one could derive satisfactory bathymetric estimates from the survey results.

EXPERIMENTAL RESULTS

Normalized data for one traverse of the Cape Breton flight line are shown in the upper part of Figure 12.1. The data were acquired at an altitude of about 210 m. The lower part of the illustration shows the interpreted bathymetry. The corresponding published bathymetry from Canadian Coastal Charts of St. Peter's Bay (#4275 and #4308) is also plotted for comparison with the interpreted data. The agreement between the interpreted AEM depths and the published bathymetry is quite good, generally agreeing within 2 m when the water is less than 20 m deep. As anticipated, the short wave length variations in the survey data that relate to amplitude changes were removed from the interpreted section by the normalizing procedure. The single major discrepancy between the interpreted section and the conventional bathymetry occurs near km 12 where we traversed the Lennox Passage. This relatively narrow feature is probably filled with saturated unconsolidated sediments which from an electrical point of view cannot be distinguished from seawater. It is also possible that the depths in the Lennox Passage at this point are not accurately charted.

CONCLUSION

By using a simple one layer model and an efficient table lookup scheme, large volumes of offshore AEM data may be interpreted accurately and inexpensively in terms of seawater depth. This technique could make AEM surveys a viable alternative to other methods for obtaining bathymetric data. Although the accuracy of AEM bathymetry is limited in deep waters by the "skin depth" at the pulse repetition frequency, this new method of obtaining bathymetric data appears to be very useful in coastal waters.

ACKNOWLEDGMENT

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- 13 -

Conductive layer mapping by computer processing of airborne electromagnetic measurements

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O'Connell, M.D. and Nader, G.L., Conductive layer mapping by computer processing of airborne electromagnetic measurements; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 111-124, 1986.

Abstract

The full potential of computer processing of geophysical data could only be realized with the advent of digital recording of AEM measurements. In the late 1970s, Geoterrex Ltd. started to pursue the concept of airborne conductivity mapping and to produce resistivity or conductivity maps from INPUT® AEM data. Several computer programs were developed in 1982-83 to automatically transform the AEM measurements using a conductive layer model. The presently used routine determines conductivity, thickness, and depth of burial, assuming that the layer is near surface (within 200–400 m) and that all adjacent layers are highly resistive.

Three field examples are presented from Australia. The first two (Kyancutta, S.A., and Esperance, W.A.) provide interpretation of the layer thickness of conductive sediments and the location of paleochannels that may be of economic importance (lignite). The third example from East Perenjori, W.A., illustrates airborne resistivity mapping of soil salinization in a water catchment area.

Résumé

La pleine utilisation des moyens de traitement informatique des données géophysiques n'a pu être obtenue qu'avec l'arrivée de l'enregistrement numérique des mesures ÉMA. À la fin des années 1970, Geoterrex Ltd. a commencé à appliquer la notion de cartographie aérienne par conductivité et à produire des cartes de résistivité ou de conductivité sur la base de données ÉMA recueillies par l'INPUT®. Plusieurs programmes informatiques ont été élaborés en 1982-1983 pour transformer automatiquement les mesures obtenues par ce système utilisant le modèle de couche conductrice. La méthode actuellement utilisée détermine la conductivité, l'épaisseur et la profondeur d'enfouissement, dans l'hypothèse que la couche se trouve près de la surface (à 200–400 m) et que toutes les couches adjacentes ont une haute résistivité.

L'étude donne trois exemples de travaux réalisés sur le terrain en Australie. Les deux premiers (Kyancutta, Australie du Sud, et Esperance, Australie de l'Ouest) présentent une interprétation de l'épaisseur de la couche des sédiments conducteurs et indiquent l'emplacement de paléocanaux qui peuvent avoir une importance économique (gisement de lignite). Le troisième exemple (East Perenjori, Australie de l'Ouest) illustre des travaux de cartographie aérienne par résistivité concernant le degré de salinité du sol dans un bassin de rétention des eaux.

INTRODUCTION

In the late 1970s Geoterrex Ltd recognized the potential of INPUT® as a geological mapping tool following several surveys to map fresh/salt water interfaces (Hetu, 1978). Dyck et al. (1974) showed the usefulness of INPUT for surficial conductivity mapping. Palacky (1981) gave an example of the system's application to geological mapping in the Itapicuru greenstone belt in the State of Bahia, Brazil.

With the advent of digital recording, it has become possible to derive computer generated resistivity profiles and contour maps from INPUT data. Dyck et al. (1974) described a method to obtain resistivity values using average amplitudes

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and decay times. The technique did not, however, yield any depth information. Fraser (1978) illustrated a computer routine for obtaining depth and conductivity for a multicoil helicopter EM system (Dighem). Seigel and Pitcher (1978) reported on a computer procedure that was able to simultaneously solve for depth, conductivity and thickness for a buried conductive layer over an infinitely resistive substrate. Based on the work of the aforementioned authors it is generally concluded that it is possible to perform resistivity mapping using an airborne electromagnetic (AEM) system. In this paper the principles of a computer processing routine developed at Geoterrex in 1982-83 will be outlined with the results from three test surveys from Australia to illustrate the application of AEM surveys to geological mapping.

THE INPUT AEM SYSTEM

INPUT is a time-domain AEM system, which has been in operation since the mid-1960s. In the configuration used by Geoterrex Ltd, the transmitter is a six-turn, vertical-axis loop attached to the aircraft generating a peak current of approximately 300 A to give a maximum dipole moment of 453 600 Am^2. The receiver is a small coil that is towed in a bird 107 m behind the aircraft and 80 m below (Fig. 13.1). The waveform of the current in the transmitter is a series of alternating half sine pulses of width approximately 1 ms and at a repetition rate of 144 Hz. There is an "off" time of 2.47 ms to record ground response (Figure 13.2). The induced voltage in the receiver coil is shown in Figure 13.2 as a time derivative of the transmitted wave form and the ground response. There are twelve channels to record ground response with the first channel starting 100 μs after turn off of the primary pulse and the last channel ending just prior to the start of the next pulse.

AUTOMATED INTERPRETATION OF INPUT DATA

Several data processing schemes were tested during the initial development. In the first approach, data were fitted to either a thin sheet or half-space Palacky nomogram giving depth and conductance or conductivity. The response curves for the nomograms were generated by a modified version of the University of Toronto Layered-Earth program (Holladay, 1981). To use the nomogram (Fig. 13.3), the user compares the logarithm of measured field amplitudes to the theoretical response by moving the data across and up or down to obtain the best fit (Palacky and West, 1973). Because it was time consuming the procedure was of rather limited use. It became necessary to derive an automated method that would accurately resolve the parameters for a range of thicknesses and conductivities for the conductive layer. We tested the horizontal layer interpretation routine of Dyck et al. (1974) in combination with the thin sheet and half-space Palacky nomograms. The software gave good results (Whiting, 1983), but only when the conductor was at or very near to surface.

It was then decided to fit the data to a set of nomograms that would vary from a thin sheet to a half space; a similar technique was also employed by DeMoully and Becker (1984). These nomograms would be stored in the computer in table form. A typical data processing sequence is shown in Figure 13.4. Initially the INPUT data are fitted to the 1 m thick layer nomogram (such as the one in Figure 13.3). The program then computes a conductance (σt) which corresponds to the minimum of the rms error versus conductance curve. The minimum rms error (designated RMS_1) is stored and the best estimate of depth is then read directly from the depth versus conductance curve. In the example shown in Figure 13.4, the conductance is 5 S and the depth is 170 m below the aircraft. These values are stored along with RMS_1 and the procedure is repeated for all the nomograms up to a thickness of 160 m. The best estimate of thickness corresponds to the minimum in the rms versus the thickness curve for all layers. For the

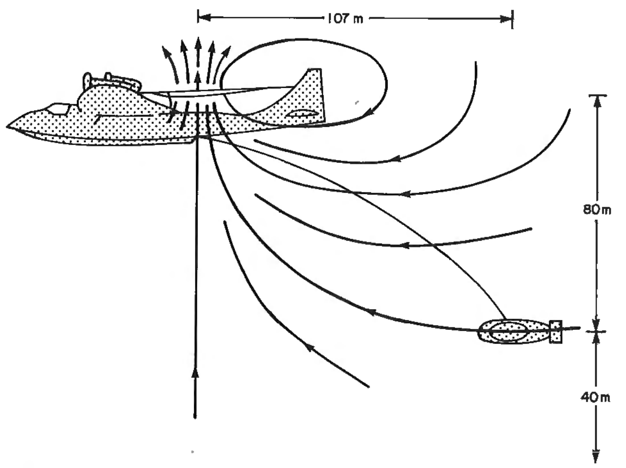

Figure 13.1. INPUT configuration used by Geoterrex Ltd.

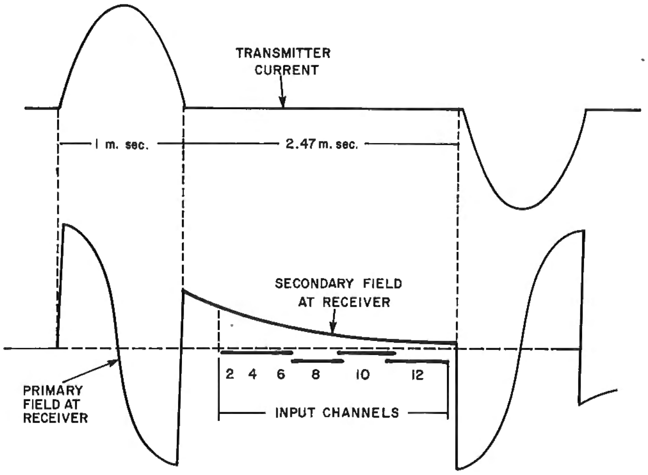

Figure 13.2. Transmitted INPUT waveform and the measured signal in the receiver.

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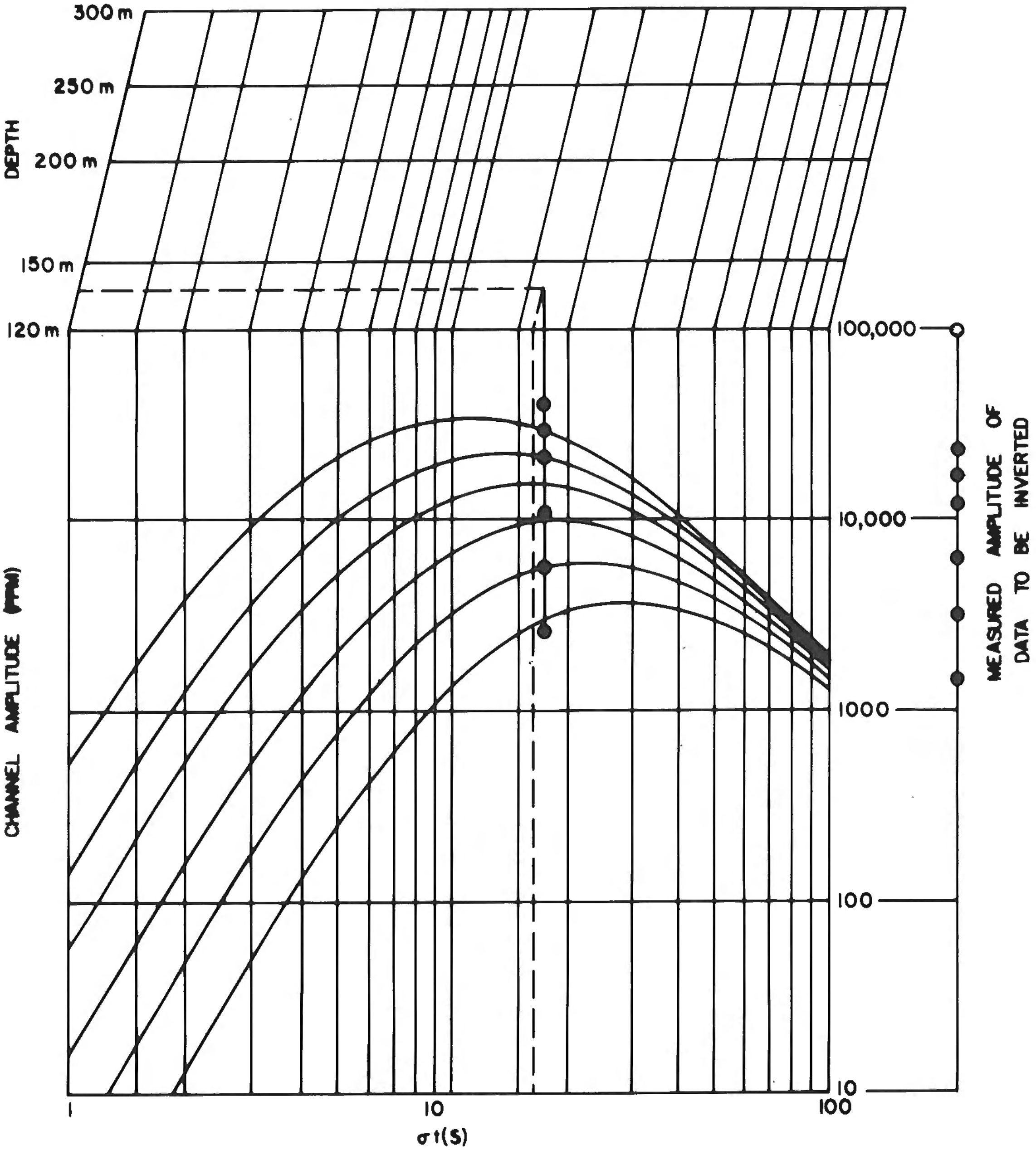

Figure 13.3. Palacky nomogram for a 1 m thick layer.

example in Figure 13.4, the minimum error is at a thickness of 90 m, the conductance is then 10 S, and the depth is 150 m below aircraft (the sequence of graphs is (a) to (e)).

Conductivity can be derived from thickness and conductance. The depth of burial is obtained by subtracting the value of the radar altimeter from the depth below aircraft. The main source of error in the depth estimates is related to the variable separation between the transmitter and receiver. In INPUT configuration the receiver is not always in its expected flying position behind the aircraft. The bird is constantly moving both vertically and horizontally about its mean position. These oscillations are normally only in the order of several metres and are manifested in the inversion routine as an error of up to 5 m, occasionally yielding slightly negative depths (i.e. above surface). For interpretational purposes these negative depths are considered to be at surface.

The routine discussed above was tested with a variety of data sets. A test with a wedge model having a resistivity of 10 Ωm and varying in thickness from 10 to 160 m is shown in Figure 13.5a. The synthetic data are a sequential combination of one dimensional layer models with no noise added. The second model, shown in Figure 13.5b, is a dipping layer 40 m thick with a resistivity of 10 Ωm. This dipping layer can also be equated to a horizontal layer where there is a large variation in the flying height of the aircraft. The described routine was able to recover the data sets with a good degree of accuracy. The resistivity values are resolved to within 5% and

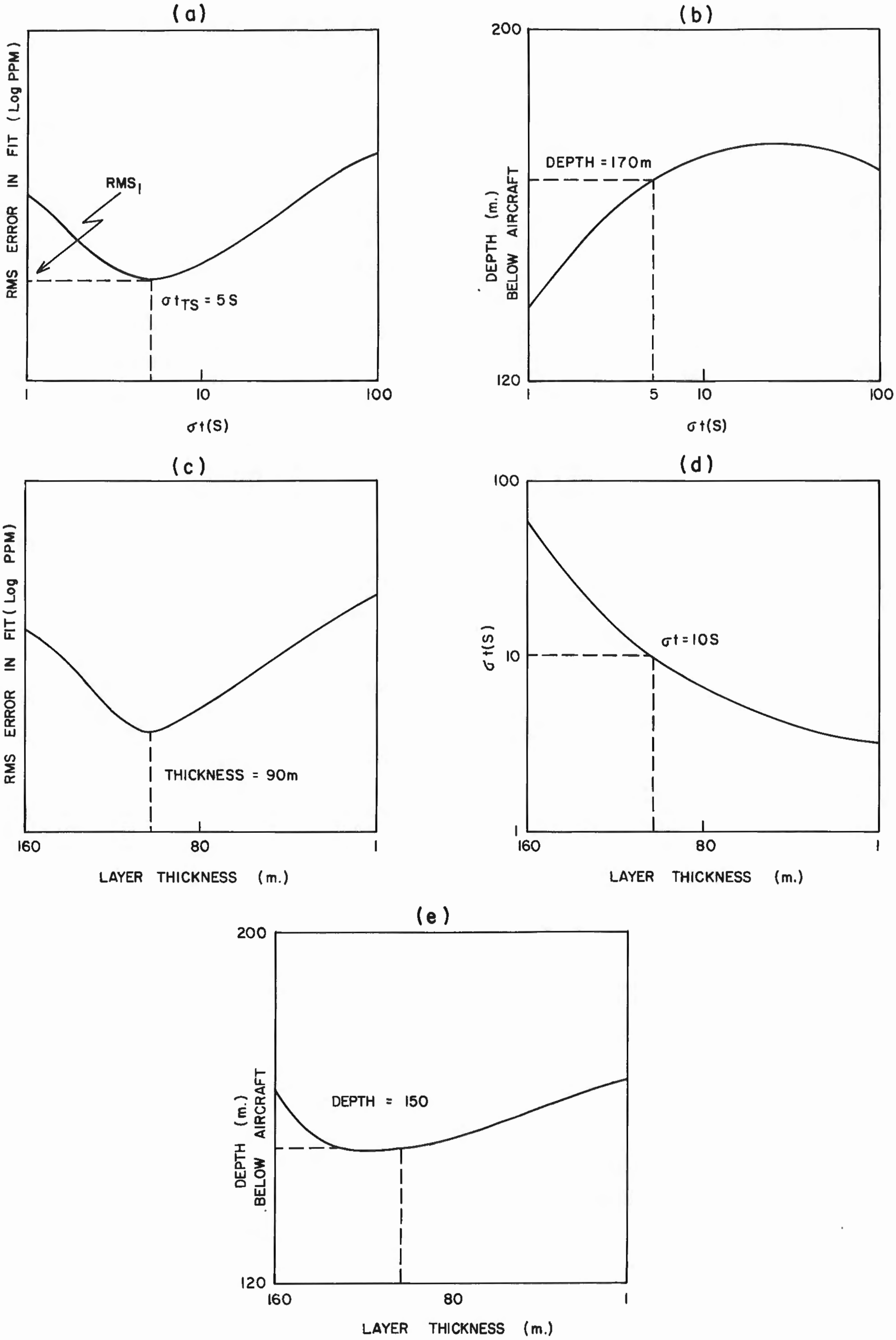

Figure 13.4. Data processing sequence for a conductive layer.

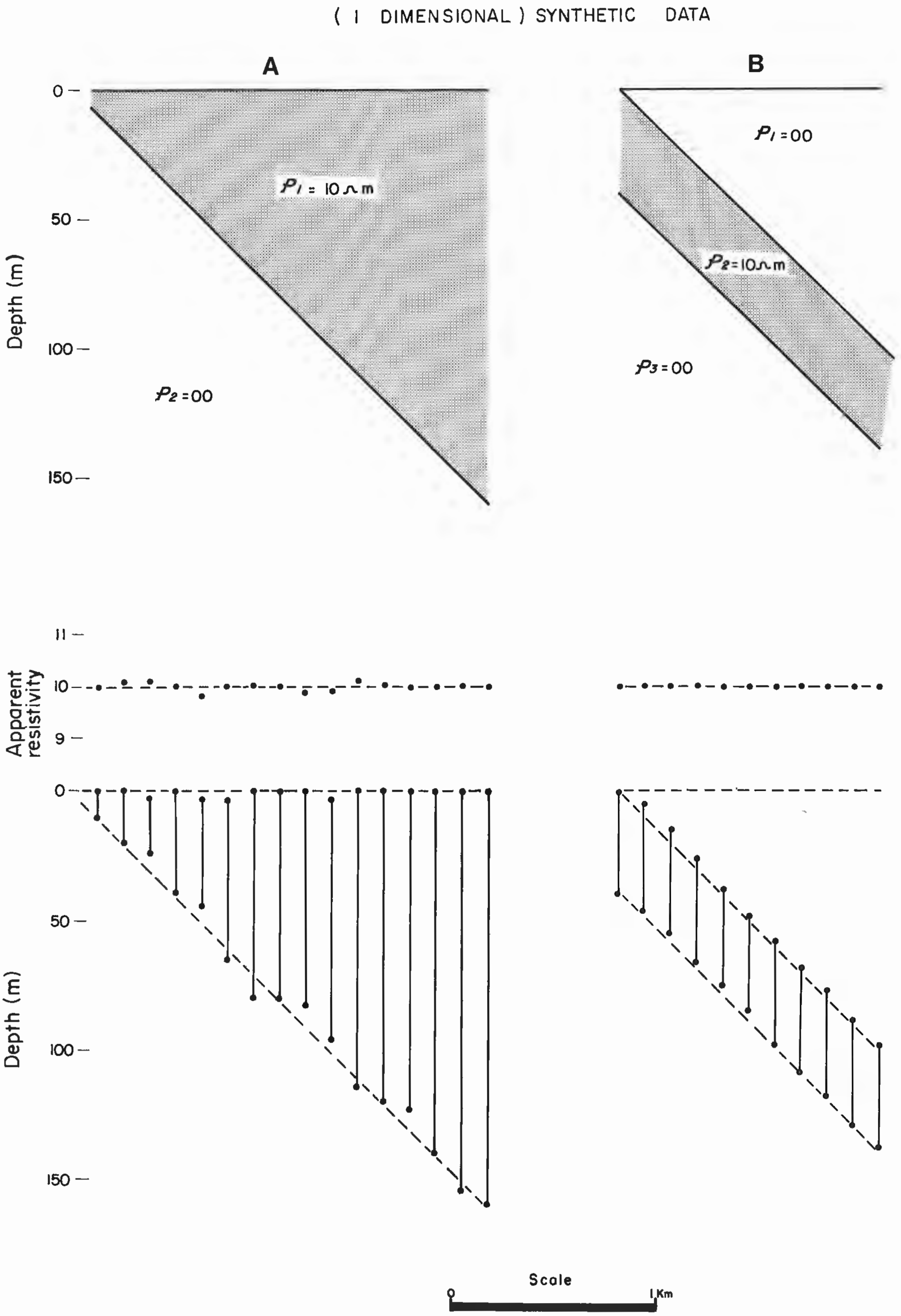

Figure 13.5. A) The wedge model and the results of automated data interpretation. B) The dipping layer model and the results of automated data interpretation.

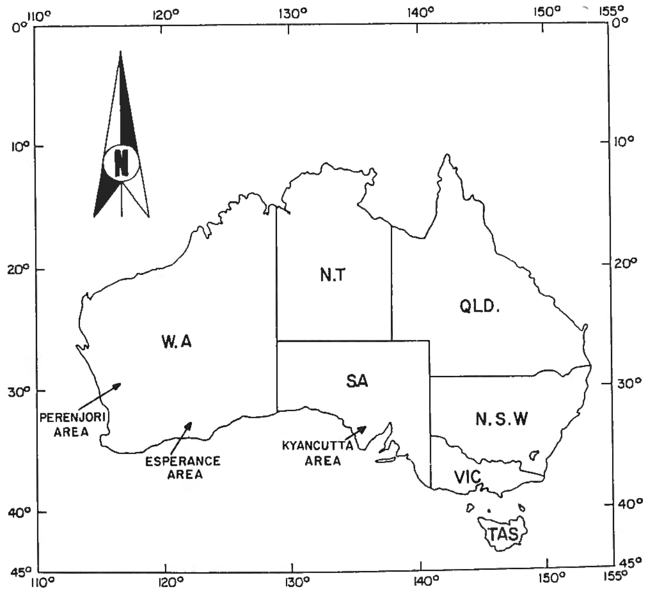

Figure 13.6. Location of survey areas described in the paper.

the thickness and depth values to within 7 m. The resolution aperture of the routine is typically 1 to 80 S and up to depths of 200 m for a half space and 400 m for a thin sheet.

FIELD EXAMPLES – PALEOCHANNELS

In many sedimentary basins throughout the world, coal, gold, uranium and some base metals occur in buried channels or small basins. Geophysical techniques, notably seismic, gravity, and electrical methods, have been successfully used in the search for paleochannels and basins. Only in recent years has the AEM method become a viable technique for achieving equally satisfactory results.

Kyancutta, Eyre Peninsula, South Australia

In the Eyre Peninsula of South Australia (Fig. 13.6). Cenozoic fluviatile sediments, eolian sands and calcrete overlie early Proterozoic and Archean metasediments. Exploration throughout this region has been concentrated on kimberlite targets as well as Tertiary channels which may host sedimentary uranium mineralization or economic deposits of brown coal.

A 200 km INPUT/magnetic profile was flown in 1984 across the Eyre Peninsula from Bairds Bay to the township of Kimba. A section of this profile, taken from an area near latitude 33°30′S and longitude 135°40′E, is shown in Figure 13.7. The twelve INPUT channels show broad variations that can be attributed to lithological changes along the profile. The geology along this section is known to consist of conductive Tertiary sediments overlying a more resistive Precambrian basement.

The results of the automatic processing scheme on this data set are shown in traces 15, 16 and 17 in Figure 13.7. The computed parameters of apparent resistivity, depth and layer thickness provide a one-dimensional interpretation of a layered earth. For this example, a highly conductive (1 Ωm), 40 m thick surface layer has been mapped between fiducials 420500 and 422000. Possible paleochannels are included within this horizon, typified by the change in layer thickness at fiducial 421950.

A major sedimentary channel or basin (4 km wide) with a maximum thickness of approximately 150 m dissected by a basement high is centred at fiducial 419750. Across this zone trace 15 shows a marked increase in the layer resistivity. Also shown is the Bouguer gravity profile obtained from government maps, which indicates a corresponding prominent low of 5 mgal, implying a major basement depression. It is important to note that the density of gravity stations was not detailed enough to verify the presence of the basement high as indicated by the EM measurements.

Esperance, Western Australia

The geology of the Esperance region consists of a Tertiary sequence of conductive sands and clays unconformably overlying resistive Precambrian basement which is composed of granites and metamorphic schists. Within the Tertiary sequence, there are known occurrences of lenticular lignite which are hosted in basement depressions (Fig. 13.8). An INPUT survey located at latitude 33°30′S and longitude 121°45′E (Fig. 13.6) was flown on behalf of Western Collieries with the object of mapping these basement depressions, i.e. areas of thicker cover. The procedure and results of this test survey were described by Whiting (1983) and are summarized below.

Results of six DC electrical soundings that were taken across partial sections of a basement depression are shown as conductivity versus depth plots in Figure 13.9. These plots indicate that there is only one conductive layer starting at surface, which overlies an electrically resistive basement. The dashed lines in Figure 13.9 represent the drillhole depth to basement. Electrical techniques are unable to separate the equally conductive clays of the Tertiary sequence and of the weathered layer overlying the basement. For the purposes of this work the absolute differences between depth values obtained by electrical surveys and from drillholes were not of real importance, considering that the relative changes in those values remained quite similar. The results suggest that an AEM system would be useful for mapping the apparent thickness of the Tertiary sequence and for outlining channels possibly bearing lignite.

The survey results are best illustrated by the INPUT response on one line that was flown over several paleochannels (Fig. 13.10). The upper trace in the figure is the altimeter measurements followed by six traces of AEM recordings and the computed apparent resistivity. In the bottom trace, the dashed line represents the interpreted depth to basement and the solid line is the drillhole depth to basement with the clay/lignite layers shown. Figure 13.10 illustrates the capability of our routine to resolve layer thickness and resistivity. This is indicated by significant variations in the layer thickness with little or no change in the layer resistivity. In effect, the

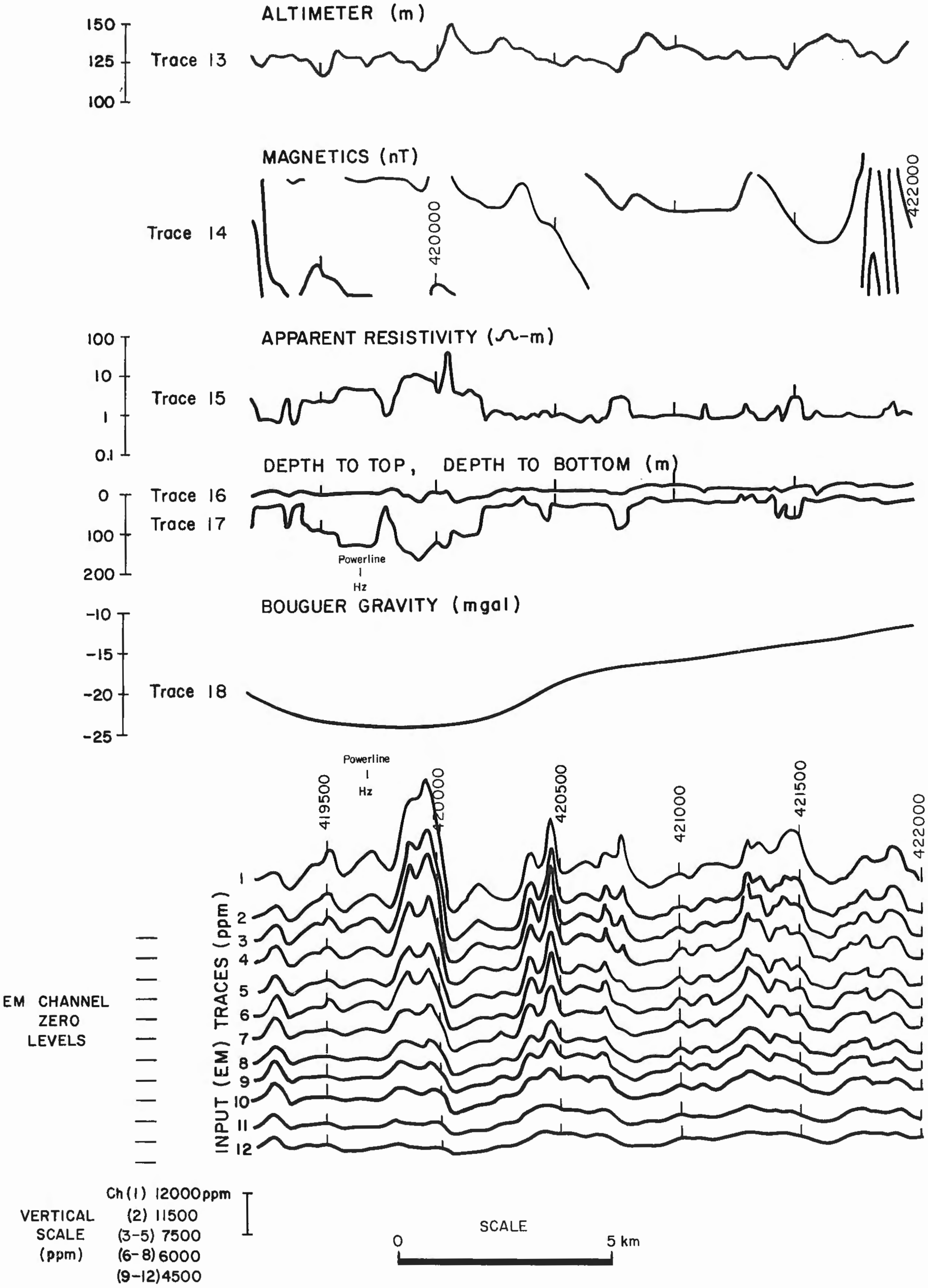

Figure 13.7. Measured INPUT data and interpreted parameters (apparent resistivity, depth) for Kyancutta, S.A. Also shown are the simultaneously measured magnetic data and the results of a ground gravity survey.

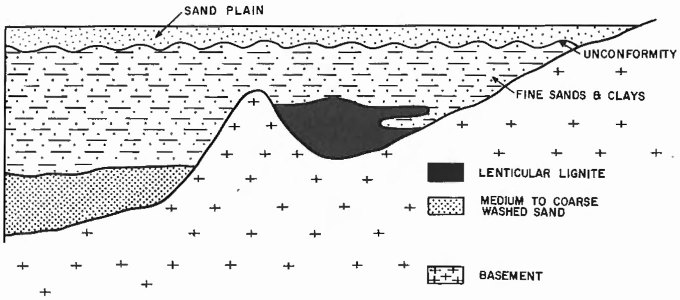

Figure 13.8. Geological section of the Tertiary sequence, Esperance, W.A. (after Whiting, 1983).

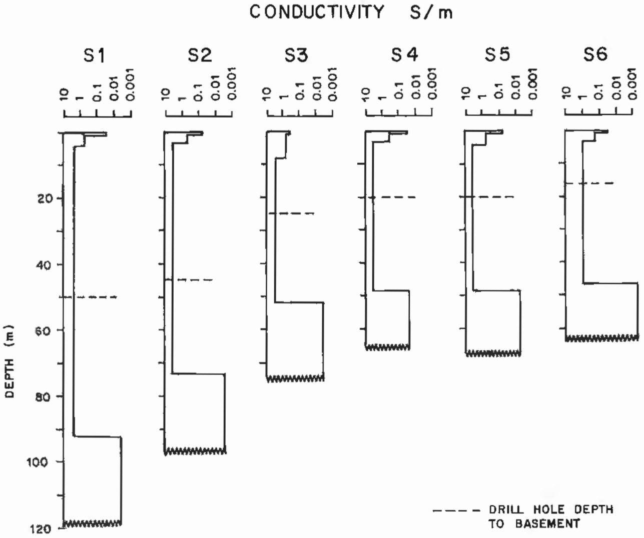

Figure 13.9. Drillhole and conductivity section, Esperance, W.A. (after Whiting, 1983). The apparent resistivity values interpreted from soundings were converted to conductivities. The depths determined from soundings are larger, because the technique cannot distinguish electrically conductive Tertiary sediments and weathered layer.

computed resistivity has remained uniform which is consistent with the results of DC electrical soundings in Figure 13.9. The overall interpreted depth to basement shows correctly the relative changes. The comparison between the interpreted and drillhole depth to basement is excellent.

Figure 13.11 shows the depth to basement contours for the test area as computed from the AEM data. Also outlined are the nine east/west survey lines and the location of lignite deposits (basins A, B, and C). The original lignite discovery is situated in the southern section of basin A. Delineation of the north trend from geophysical interpretation resulted in the discovery of lignite deposits to the north (dashed lines).

The depth contour lines resulting from the follow-up drilling program are shown in Figure 13.12. The drilling confirmed the north trend of basin A and the presence of lignite. Drilling completed in basin B resulted in the discovery of a previously unknown deposit of lignite, while drilling in basin C revealed scattered lignite occurrences. In a direct comparison of depths, the computed depths from the AEM data are consistently greater than the drillhole depths, but accurately reflect the relative changes in the depth.

FIELD EXAMPLE – SALINITY MAPPING

Salinization of land is a common problem in arid regions throughout the world. Australia, U.S.A., Pakistan, the Middle East, and Africa lose millions of dollars each year as a result of production losses due to the effects of salinization. Salinity hazards may develop through various means, such as irrigation, excessive water evaporation, or recharge imbalances, to name a few (Garland and Duff, 1984). An example of salting developed from a confined aquifer is illustrated in Figure 13.13. Such an aquifer has a fresh water intake or recharge area on high ground and an outlet or discharge area of salt laden water lower down. The outlet may be in the foothills or plains where soil salting will result as the salt laden waters are released.

To identify areas affected by salting, ground geophysical techniques, such as electrical resistivity and EM profiling have been employed. These methods permit the definition of areas of high conductivity and hence, by inference, areas of high soil salinity. An AEM survey will map an equivalent area in a much shorter time than ground techniques.

East Perenjori, Western Australia

The East Perenjori catchment area, where several geophysical studies were conducted is located at latitude 29°30′S and longitude 116°35′E (Fig. 13.6). The soil distribution and predominant soil groupings in the area (Fig. 13.14) were mapped by the Western Australian Department of Agriculture (WADA). The soil cover consists mainly of sandy loams and clays with varying textures. The dominant soil type is a brown-red sandy loam unit which trends northeast into highly saline soils around a salt lake and clay pan area.

The contour map (Fig. 13.15) shows the soil conductivity in the top 30 cm of soil as measured by the WADA in 1983. The conductivity was measured in the field with a DC Wenner array using a very small electrode spacing. The DC results show that within this small catchment there has been a buildup of saline ground water near the surface which has occurred mainly in the centre of the catchment due to a recharge-discharge imbalance. The strong linear trend along the axis of the catchment correlates well with the major brown sandy loam soil trend shown in Figure 13.14.

In 1984 Geoterrex Ltd. flew an INPUT survey across the Perenjori area. The results reported by Butt (1985) give an excellent illustration of the use of AEM in a resistivity mapping mode. The apparent resistivity contours across the area as calculated from the AEM data are shown in Figure 13.16. Survey lines were flown east-west at a line spacing of 1.5 km and a mean aircraft clearance of 120 m. The apparent

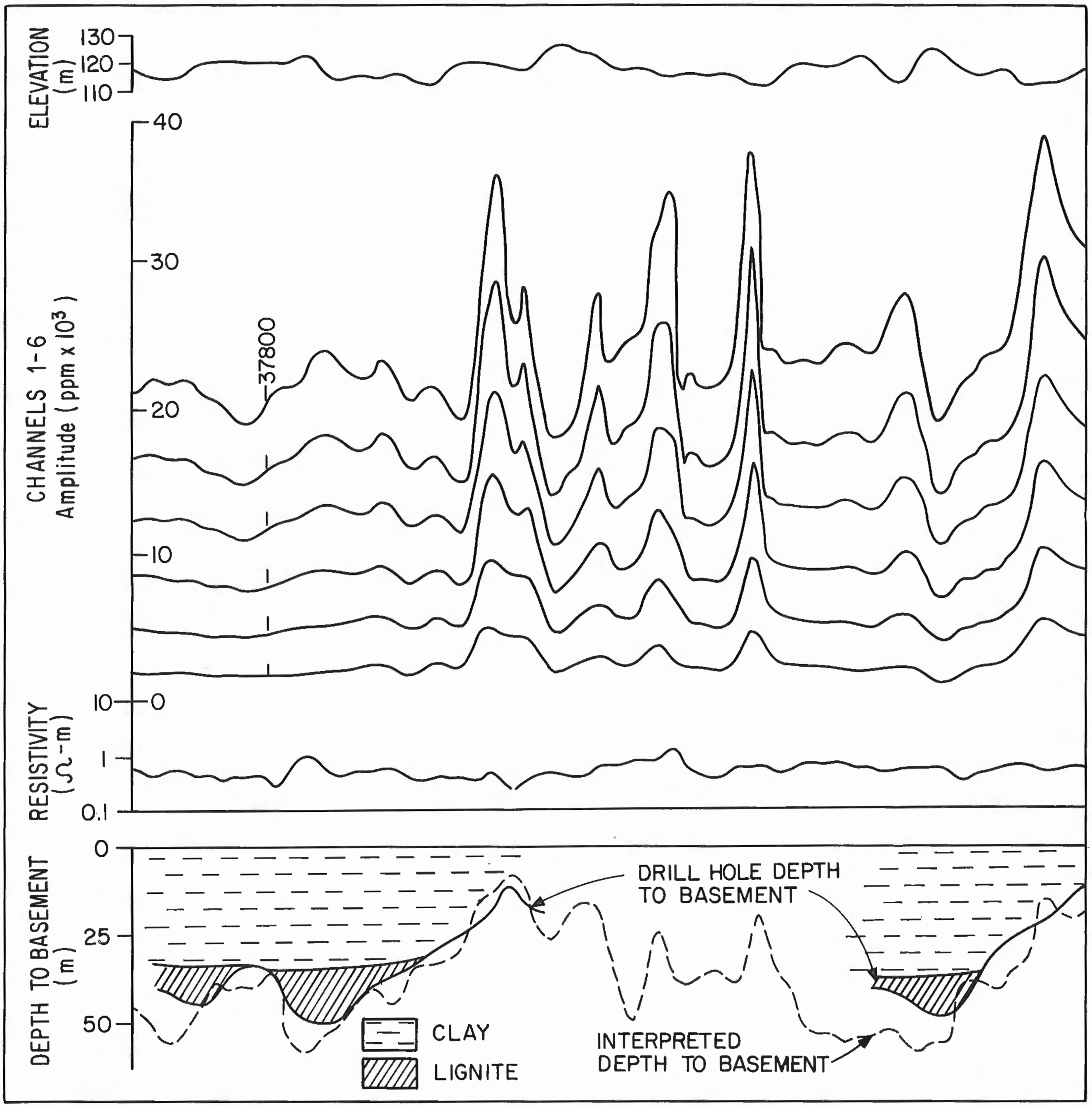

Figure 13.10. Record of INPUT data (6 channels), flight elevation, and calculated resistivity, Esperance, W.A. At the bottom, geological section with depth contours interpreted from AEM data and values obtained from drilling. As explained in the text, calculated values include the electrically conductive weathered layer and are consistently larger than drillhole data (after Whiting, 1983).

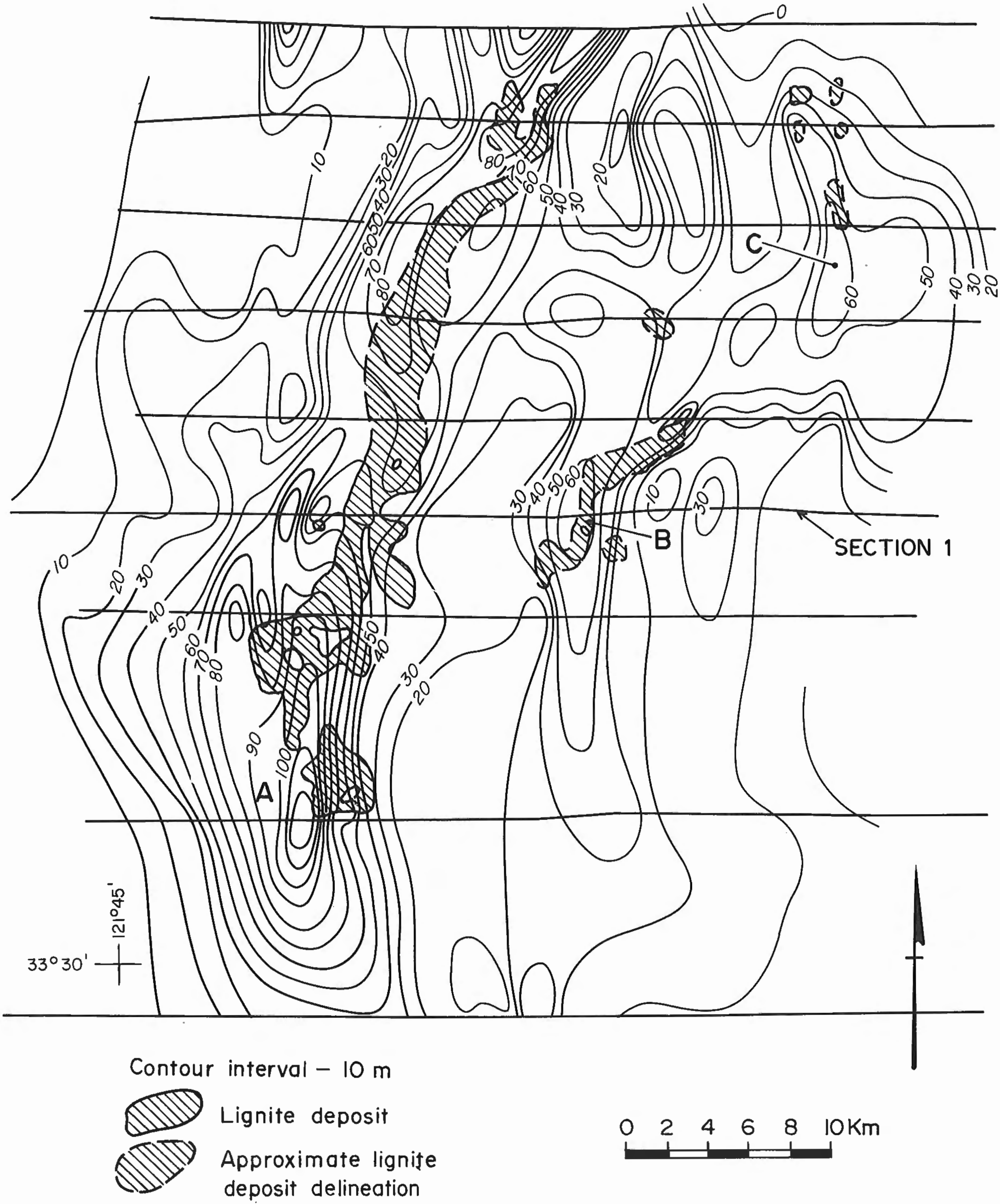

Figure 13.11. Interpreted depth to basement contours derived from Input data, Esperance, W.A. (after Whiting, 1983).

Figure 13.12. Drillhole depth to basement contours, Esperance, W.A. (after Whiting, 1983). The drillhole data give the depth to the weathered bedrock, whereas the AEM data indicate the depth to the fresh bedrock.

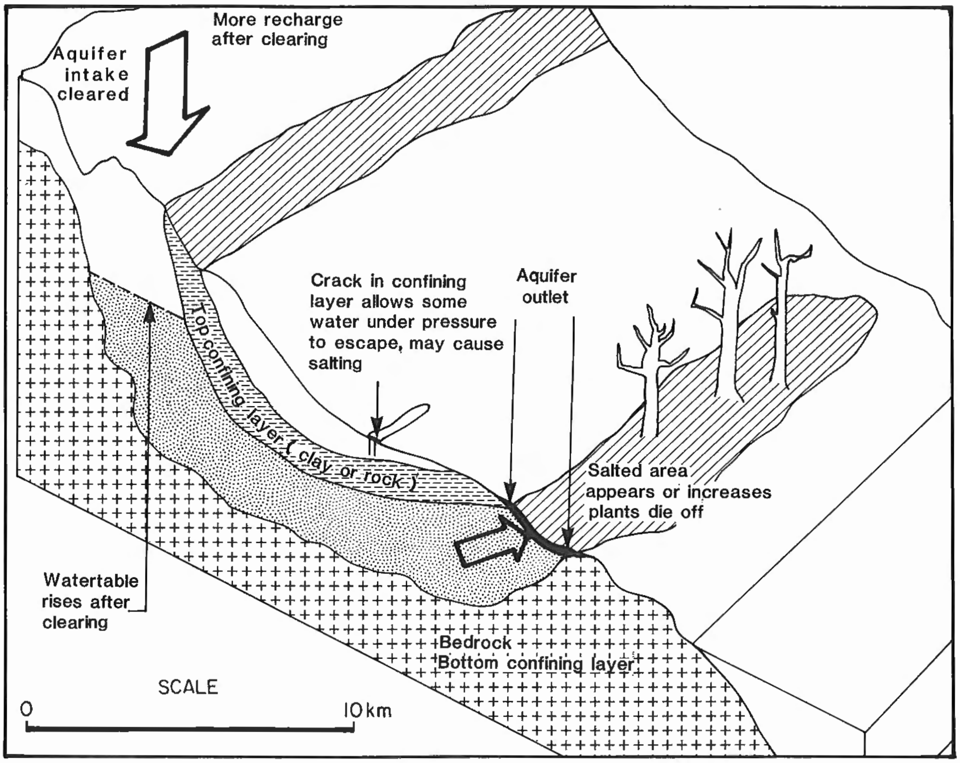

Figure 13.13. Confined aquifer salting after clearing of the intake area (after Garland and Duff, 1984).

resistivity values were determined from AEM data by matching to a half-space model. The contour map shows a low resistivity trend (5-10 Ωm) through the axis of the catchment area. While the general correlation between this map and the soil conductivity is excellent, the airborne data appear to be sensitive to the bulk of the ground water salinity distribution, which is the ultimate cause of, but is not identical to, the shallow soil salinity distribution (Butt, 1985). Even with the wide flight line spacing chosen, the AEM resistivity contours still provide good detail and bear a strong relationship to the soil distribution of the Perenjori catchment area. Obviously, a tighter line spacing would have allowed for the delineation of smaller, isolated saline pockets.

CONCLUSIONS

We have presented a method of computer interpretation for time-domain AEM data. Three field examples have demonstrated the application of computer derived parameters (apparent resistivity and thickness) to specific geological targets.

The first area (Kyancutta, S.A.) is characterized by a layer of conductive material with significant variations in both the layer resistivity and its thickness. The example from Esperance, W.A., illustrates a single layer of uniform conductivity with pronounced changes in the thickness of the layer. The final example from East Perenjori, W.A., shows a half-space of varying conductivity. In all three cases the computer routine was able to provide accurate and reliable results. An analysis of synthetic data shows the routine to be capable of estimating thickness, depth, and conductivity with a typical error of 7 m for the thickness and depth parameters and 5% for conductivity.

The processing routine does have some limitations. It is restricted to a single conductive layer with a minimum resistivity contrast of about 3:1 or more. In areas of rapid changes in conductivity, thickness, or depth (e.g. presence of a fault or vertical conductor), the accuracy of the determined parameters deteriorates. Although such changes may not accurately represent the geology they can be utilized to delineate major structural trends within a horizontally layered geological environment.

With the development of new processing techniques large quantities of time-domain AEM data can be routinely processed. Meaningful resistivity contours can be produced and in favourable geological environments fixed-wing time-domain AEM systems should be considered as a cost-effective method for resistivity mapping. Also, with the advent of high-speed digital acquisition systems such constraints as excessive instrument drift, noise and poor system calibrations will be minimized. This will provide significant improvements in the quality of AEM measurements and the end products.

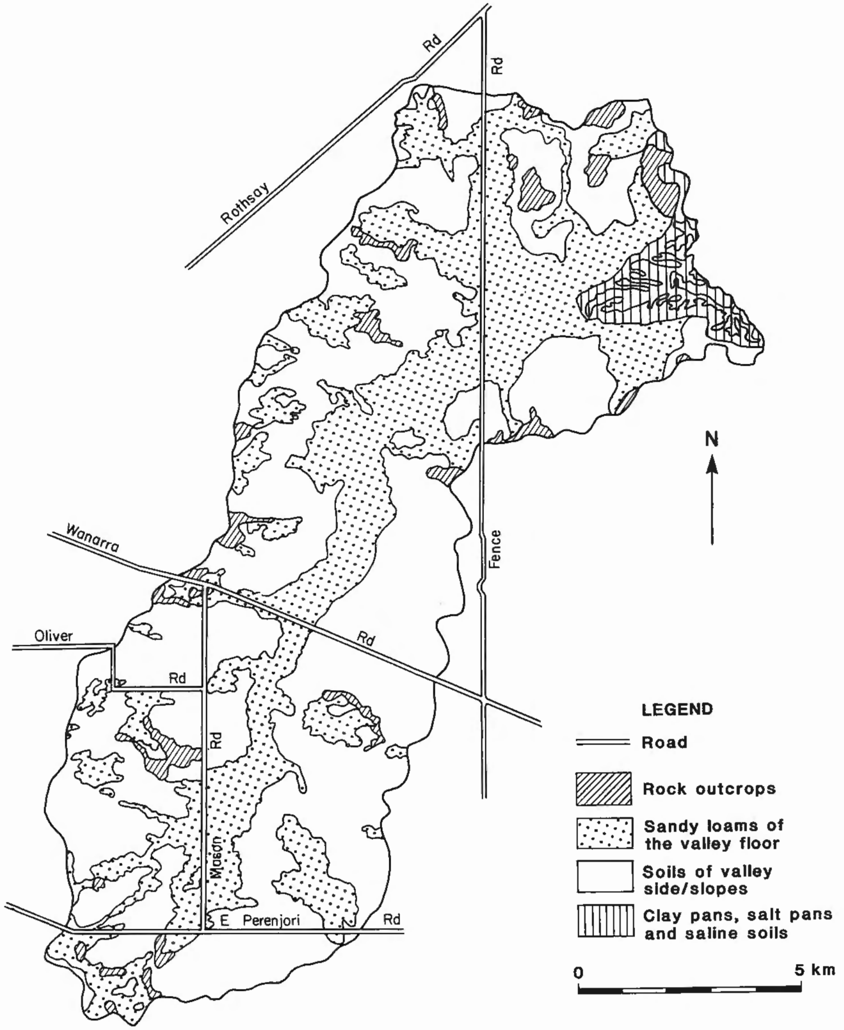

Figure 13.14. Soil map of the East Perenjori catchment area, W.A.

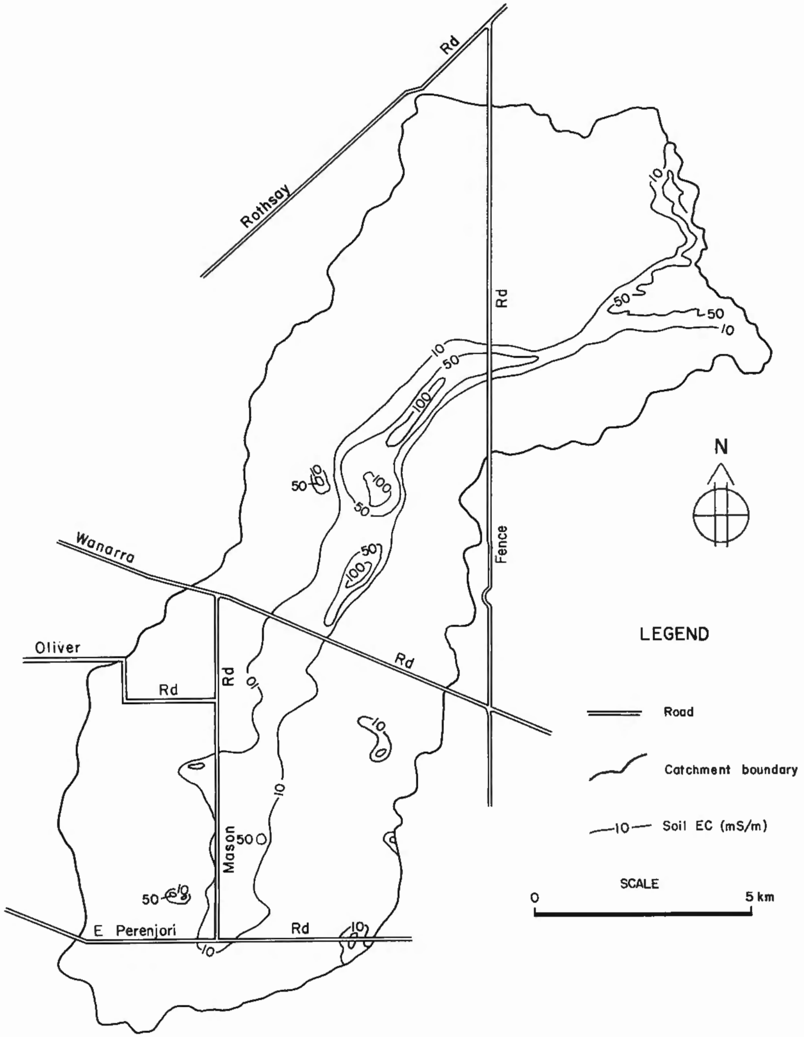

Figure 13.15. Soil conductivity map obtained by ground resistivity measurements in the East Perenjori catchment area, W.A. (after Butt, 1985).

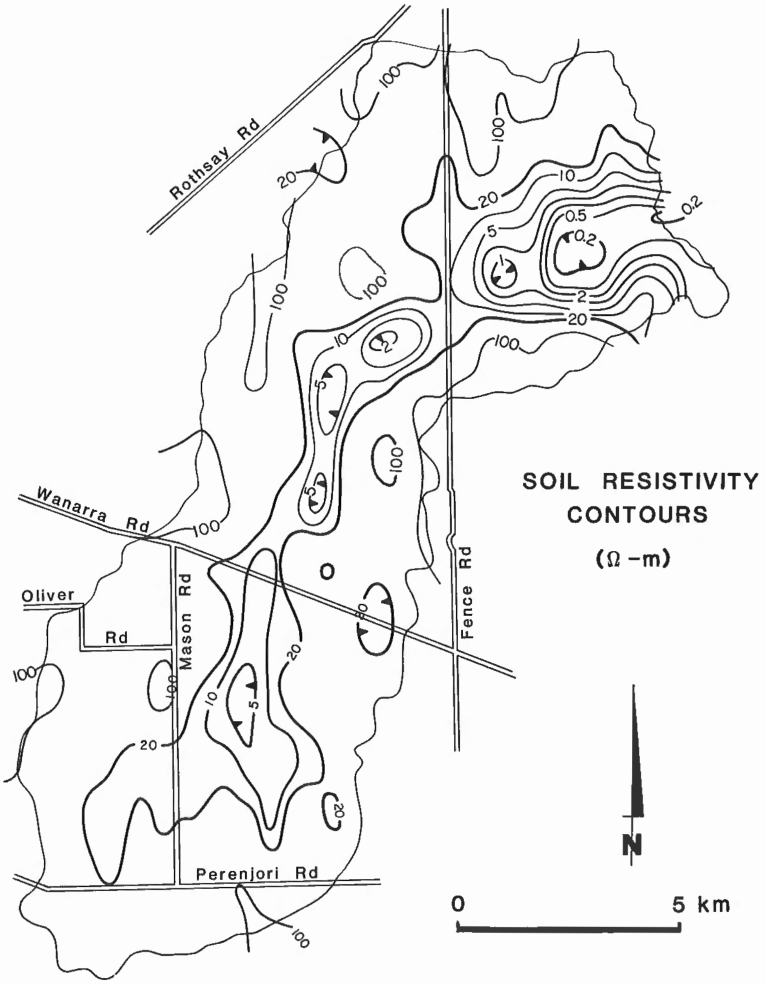

Figure 13.16. Apparent resistivity map derived from INPUT data, East Perenjori, W.A. (after Butt, 1985).

ACKNOWLEDGMENTS

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Tridem resistivity mapping for natural resources development

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Johnson, Ian M. and Seigel, Harold O., Tridem resistivity mapping for natural resources development; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 125-129, 1986.

Abstract

The fixed-wing Tridem airborne EM system, which was developed by Scintrex Ltd., operates at three frequencies (520, 2020 and 8020 Hz). The most common coil configuration has been vertical coplanar with transmitter/receiver coils mounted at the wing tips. The system has been operated in Canada, China, and various parts of Africa.

Examples are shown of resistivity (and conductivity) maps produced from Tridem survey data. In James Bay lowlands the system was used to outline a lignite deposit near Onakawana, Ontario. A survey flown near Mombasa, Kenya, was successful in mapping the boundary between fresh-water and salt-water aquifer. In prospecting for kimberlites the AEM results were found more diagnostic than those of magnetics alone. The plane operated by the Ministry of Geology and Mineral Resources in China has been used in a number of surveys with various applications.

Résumé

Le système ÉM aéroporté Tridem monté sur avion, mis au point par Scrintrex Ltd., fonctionne sur trois fréquences (520, 2 020 et 8 020 Hz). La configuration des bobines la plus courante est coplanaire verticale, les bobines de l'émetteur/récepteur étant installées en bout d'ailes. Le système a été utilisé au Canada, en Chine et dans diverses régions d'Afrique.

L'étude donne des exemples de cartes de résistivité (et de conductivité) compilées avec des données obtenues par le Tridem. Dans les basses-terres de la baie James, le système a servi à délimiter un gisement de lignite près d'Onakawana, Ontario. Un levé aérien près de Mombasa, Kenya, a permis de cartographier avec succès l'interface des aquifères d'eau douce et d'eau salée. Lors de la prospection de kimberlites, les résultats des données ÉMA se sont révélés d'une plus grande utilité diagnostique que ceux obtenus avec les mesures magnétiques seulement. L'avion utilisé par le ministère de la Géologie et des Ressources en minéraux de la Chine a servi à la réalisation de plusieurs levés aux applications diverses.

INTRODUCTION

The Scintrex Tridem system is a three-frequency airborne electromagnetic (AEM) system operating at 520, 2020 and 8020 Hz. Transmitter and receiver coils are normally mounted at the wing tips of the de Havilland Twin Otter aircraft. The three sets of coils are held in vertical coplanar geometry with a coil separation of 21 m. The Tridem system records the inphase and quadrature components of the secondary magnetic field. They are measured as a fraction (in parts per million) of the primary field at the receiver.

The Twin Otter configuration is the most recent in a series of installations stretching back to the early 1970s. Earlier versions were installed on a Single Otter. In the late 1970s, a coaxial version of the system was operated by Kenting Earth Sciences Ltd. of Ottawa. Twin Otter Tridem systems are currently in operation by Geosurvey International Ltd. of Nairobi and by the Ministry of Geology and Mineral Resources of the People's Republic of China. Another system built for the Geological Survey of India is expected to be in operation in 1986.

The instrument development has been characterized by regular improvements in the system design. Included have

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been reduction in short and long wavelength noise and the introduction of accelerometers and temperature monitors. All Tridem systems have, at one time or another, collected data which have been later processed to some type of resistivity maps. However, this type of processing is not routine. The total survey coverage achieved by Tridem systems of all types is in excess of 500 000 line km. Of this less than 2% has been presented in resistivity map form, but this percentage is likely to increase with demand. Costs for such processing, which has become routine, can be an acceptably small fraction of standard survey costs.

JAMES BAY LOWLANDS, CANADA

The area is one of flat lying Mesozoic and Cretaceous unconsolidated sediments with known lignite deposits near surface. An orientation/test airborne EM survey was flown in 1976 over a known lignite field near Onakawana with a Single Otter system. Resistivity maps indicated a reasonable correlation between lignite and low resistivity areas (Seigel and Pitcher, 1978). A more extensive (8000 line km) program was undertaken in 1978 using the Kenting Tridem system which had coils mounted in vertical coaxial geometry (nose-tail configuration).

A portion of the earlier results are shown in Figure 14.1. The calculation of apparent conductivity is based on a two-layer model and was determined for each of the three frequencies. The information was combined by extrapolation to low frequency in order to focus on the physical properties most diagnostic of the target at hand – the conductivity of the second layer (Pitcher and Barlow, 1979, and Pitcher et al., 1980).

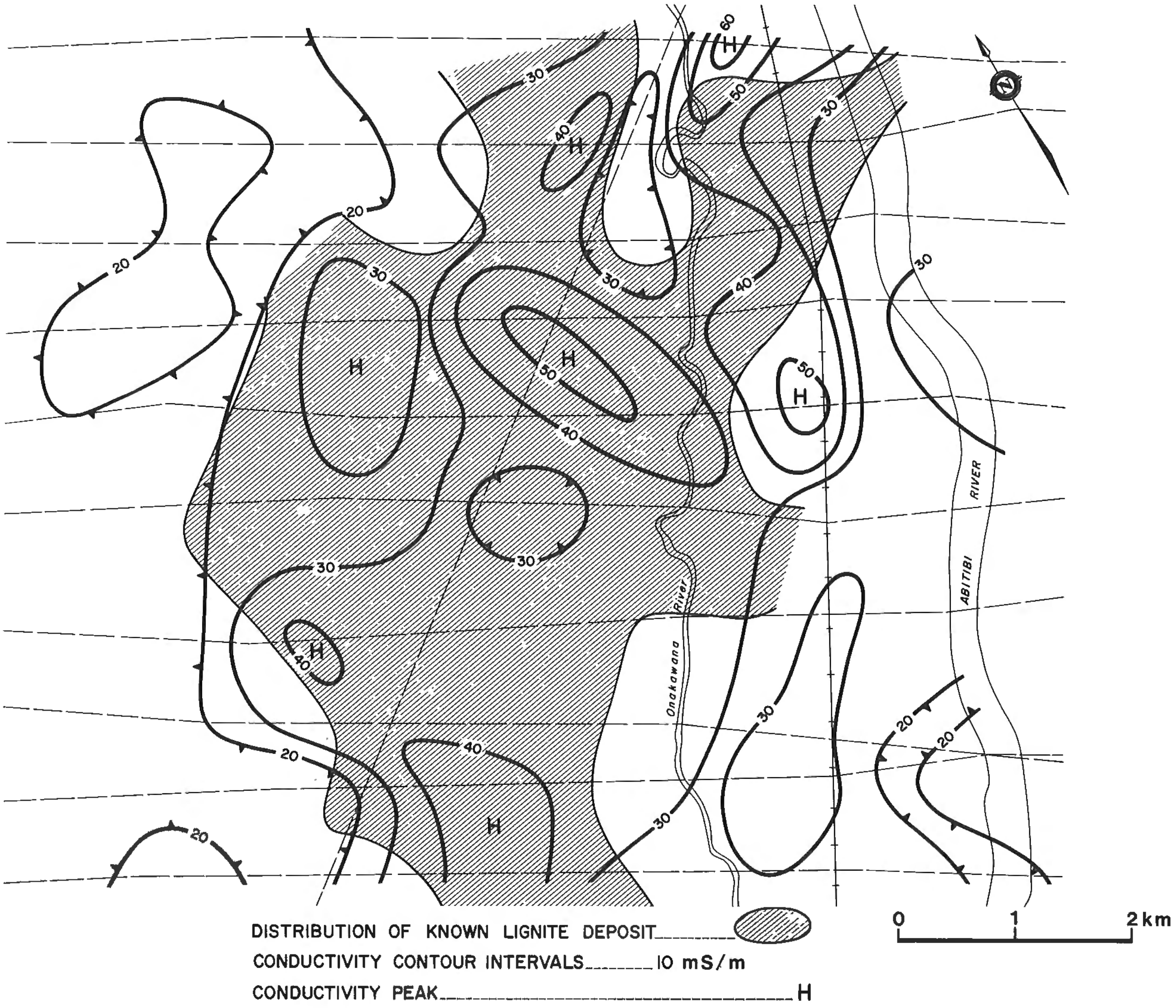

Figure 14.1. Apparent conductivity map from a Tridem survey flown in 1976 over a portion of the James Bay lowlands near Onakawana, Ontario. Distribution of known lignite deposits is shown superimposed (from Seigel, 1979).

The results in Figure 14.1 show a good correlation between areas of high conductivity (i.e. greater than 30 mS/m) and known deposits of lignite which are overlain by a conductive fine clay horizon. These results indicate that the mapping of near-surface lignite deposits associated with clays is possible using an AEM system and a suitable data processing and presentation strategy.

As noted by Pitcher et al. (1980), the method was limited by the inaccuracies of the reduction process of the raw EM data to a true zero, by the simplicity of the model used, and by the similarity in conductivity between lignite and clays. Of these, the reduction process is potentially the most critical in that such processes are designed around the noise characteristics of the system. Early AEM systems were designed to search for near vertical targets and consequently paid little attention to "drift". The quality of inversion of AEM data to resistivities and thicknesses relies upon minimal system noise at all frequencies.

PEOPLE'S REPUBLIC OF CHINA

The Ministry of Geology and Mineral Resources began survey work with a Twin Otter based Tridem system in 1980. Since that time some 50 000 line km have been achieved. The system has been used in the following exploration/mapping programs.

1. Reconnaissance AEM surveys for volcanogenic massive sulphide deposits (principally copper).
2. Exploration for kimberlites. Magnetic-electromagnetic-radiometric signatures thought to be due to kimberlites are being investigated.
3. Gold exploration. AEM results have been used to interpret fault structures.
4. Groundwater exploration. AEM survey work was conducted to study the transgression boundary between seawater and fresh water.

Unfortunately, final maps from this work have not yet been released and cannot be shown here.

GEOSURVEY INTERNATIONAL LTD., NAIROBI, KENYA

The Geosurvey Tridem IV system is the most recent and includes a number of improvements over the earlier systems. In terms of EM noise reduction, of note are:

A. The addition of temperature monitors. The principal cause of drift in wing-tip AEM systems is the relative movement of coils as the airframe contracts or expands with changing temperature. Temperature monitors, when properly located, provide information which can correct the in-phase readings. Such techniques may be used to significantly reduce drift.

B. The addition of accelerometers. Aircraft accelerations distort the airframe and result in changes in relative coil

Figure 14.2. Geosurvey aircraft with Tridem coil pod at extreme end of the wing. Nose stinger contains the magnetometer sensor.

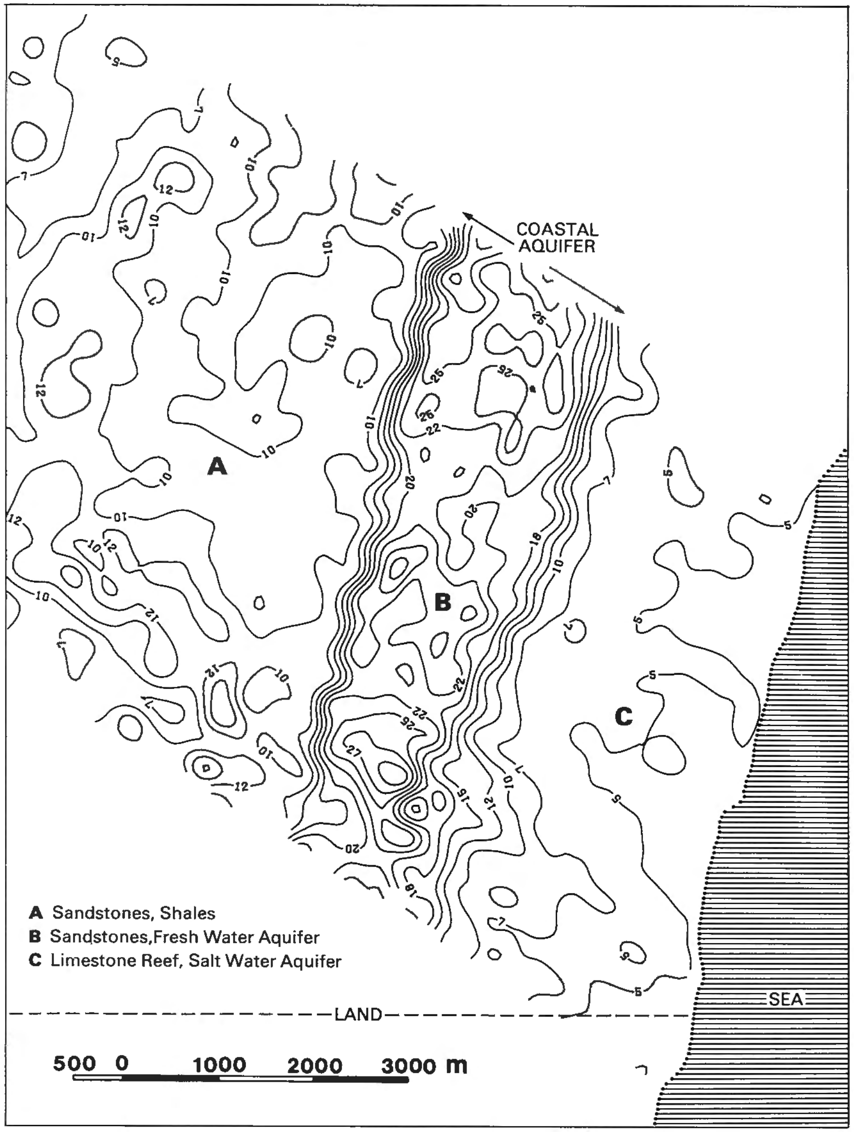

Figure 14.3. Contoured apparent resistivity map over a portion of the Tiwi aquifer near Mombasa, Kenya. Survey flown and compiled by Geosurvey International Ltd. of Nairobi.

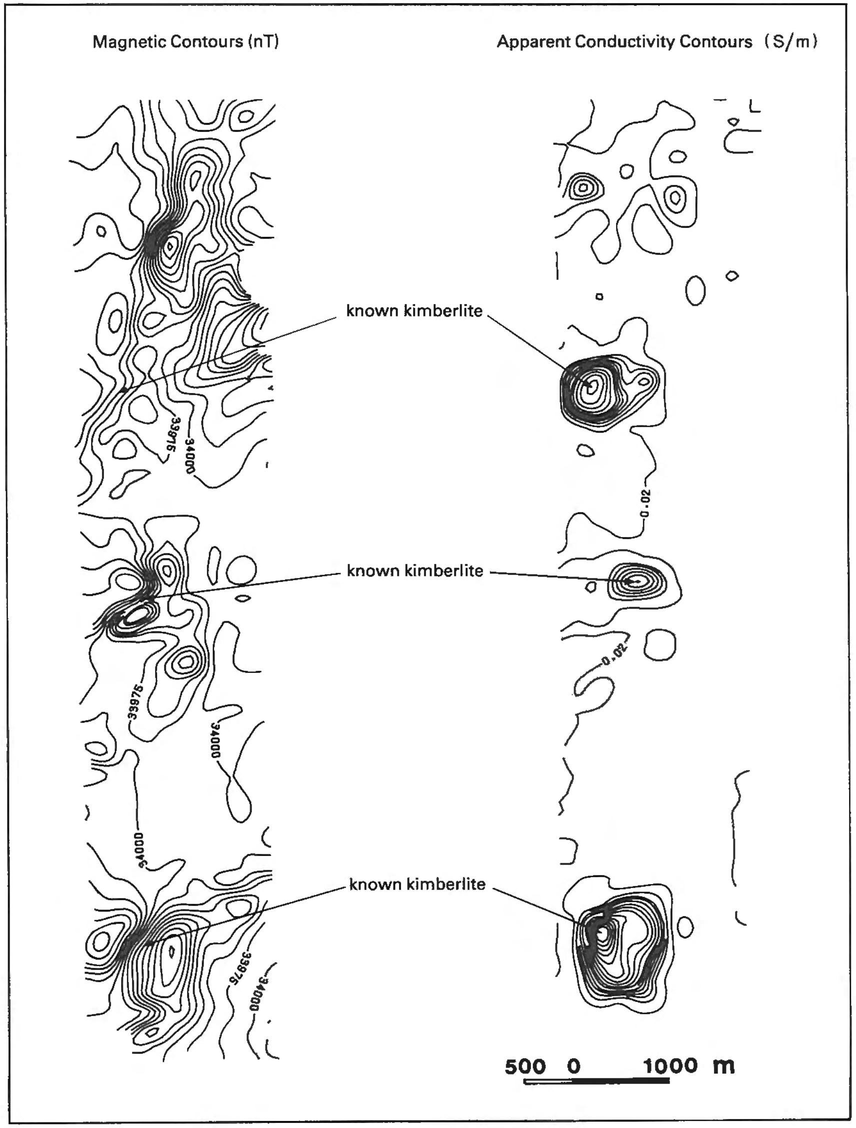

Figure 14.4. AEM/magnetic data over 3 known kimberlite pipes in Eastern Africa. The magnetic contour interval is 25 nT, the conductivity contour interval 0.02 S/m.

separation and/or orientation. Accelerometer information can be used to eliminate noise caused by such distortions.

The aircraft installation is shown in Figure 14.2. In addition to the Tridem EM system, it includes a multi-channel spectrometer with both upward and downward looking crystals, and a high sensitivity magnetometer. Navigation is Doppler controlled.

The system has been flown over a number of areas. Results of a survey flown to map a fresh water aquifer are shown in Figure 14.3. The aquifer is bordered by a saltwater aquifer and the Indian Ocean on one side and by shales, on the other. The survey of some 450 line km was flown with a line spacing of 250 m. The inphase and quadrature Tridem data were inverted to give apparent resistivity and depth of burial. The model used is the same one as the "pseudo-layer" model of Fraser (1978). Apparent resistivities derived from the data obtained at 520 Hz are presented in Figure 14.3. The contour interval is 2.5 Ωm. The freshwater aquifer shows up as a resistivity high of more than 20 Ωm, the land area bordering the sea has an apparent resistivity of some 5 Ωm, and sandstones and shales west of the aquifer have apparent resistivities of 10 to 12 Ωm.

An important application of AEM surveying is prospecting for kimberlites. These igneous ultramafic rocks, which are the source formation for diamonds, weather deeply (Palacky, 1986). The highly conductive "yellow ground" formed at their top can be detected by an EM system and such techniques have become increasingly used in diamond prospecting both from the air and on the ground. Typical resistivity of the "yellow ground" ranges from 3 to 10 Ω-m. Like most ultramafic rocks, kimberlites are usually magnetic, but cases have been described of economic pipes without magnetic association (Macnae, 1979). As long as conductive clays have not been removed, AEM systems provide a more reliable kimberlite mapping tool than magnetics. Figure 14.4 shows geophysical responses of three kimberlite pipes in eastern Africa. The AEM magnetic survey was flown with the Tridem IV system. While strong AEM anomalies are associated with each of the known pipes, one of them does not have an associated magnetic anomaly. The conductivity contour lines have an interval of 0.02 S/m.

CONCLUSIONS

The Tridem is the most popular close-coupled fixed-wing AEM system in use today. Emphasis has been put on installed systems which are operationally simple and capable of producing low noise inphase and quadrature data at three frequencies. The system has been used in a number of countries in programs to map resistivity changes over large areas. The use of temperature and accelerometers to reduce noise is expected to become standard. Methods to routinely produce geologically useful resistivity maps at a reasonable cost are advancing in parallel.

ACKNOWLEDGMENT

Thanks are due to Geosurveys International Ltd. of Nairobi, Kenya, for supplying examples of Tridem AEM surveys.

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- 15 -

Groundwater prospecting by multifrequency airborne electromagnetic techniques

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Sengpiel, Klaus-Peter, Groundwater prospecting by multifrequency airborne electromagnetic techniques; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 131-138, 1986.

Abstract

Under favourable conditions, airborne electromagnetic (AEM) surveys even with one operating frequency can yield useful results for groundwater prospecting. In general, however, a more detailed section of the resistivity distribution is desired. This can be achieved by measurements with a multifrequency EM system, and by an appropriate inversion of the survey data into ground parameters.

Large quantities of multifrequency EM data and their inversion into parameters of ground with an unknown number of layers can be handled efficiently using a newly developed algorithm. Results of its application to several hydrogeological models with up to five layers are presented and discussed. The models are mainly related to the problem of determining the freshwater/saltwater interface. Based on the encouraging results a large helicopter EM survey (10 000 line km) is scheduled for 1986-87 in Pakistan.

Résumé

Dans des conditions favorables, les levés électromagnétiques aériens (ÉMA), même réalisés sur une seule fréquence, peuvent apporter des résultats utiles dans le domaine de la prospection des eaux souterraines. Mais en général, une coupe plus détaillée de la répartition de la résistivité est souhaitable. On peut l'obtenir en faisant des mesures avec un système ÉM à plusieurs fréquences et en inversant d'une manière appropriée les données du levé pour obtenir des paramètres au sol.

Un algorithme récemment mis au point permet de traiter efficacement de grandes quantités de données ÉM obtenues sur plusieurs fréquences et de les inverser pour obtenir les paramètres au sol, relativement à une quantité inconnue de couches. L'étude examine les résultats de cette technique appliquée à plusieurs modèles hydrogéologiques comportant jusqu'à cinq couches. Les modèles portent principalement sur la détermination de l'interface entre l'eau douce et l'eau salée. Par suite des résultats encourageants obtenus, un vaste levé ÉM héliporté (10 000 km linéaires) est prévu pour 1986-1987 au Pakistan.

INTRODUCTION

To apply AEM techniques to groundwater prospecting means to face competition of a successful standard technique, ground dc resistivity sounding, which yields a detailed picture of the ground resistivity distribution. Obtaining results of comparable quality by AEM would require a multifrequency measuring system and inversion of EM survey data into multilayer parameters.

Neither requirement is met by the available three-frequency systems and currently performed data inversion with a two-layer model. These shortcomings of the AEM techniques are partly balanced by the speed (100 km/h) and the sampling density (one measurement per 15 m) of an airborne survey. Furthermore, for EM data acquired with systems with small transmitter-receiver separations, the results of interpretation using the layered model should be less affected by lateral changes of resistivity than the results of dc soundings with electrode distances of several hundred metres. In groundwater applications, the two methods supplement rather than replace each other.

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GROUNDWATER SURVEY ON SPIEKEROOG

Bundesanstalt für Geowissenschaffen und Rohstoffe (BGR) selected the sandy island of Spiekeroog, several kilometres off the North German coast, for a test survey with the Dighem II system (Fraser, 1979). At that time (1978), both transmitters generated EM fields close to 900 Hz. In the northern part of the island, there is an elongated freshwater lens, recharged by rain, with a depth from several metres below the land surface to about 50 m. This lens is surrounded by a saltwater-bearing sandy environment. Typical resistivities are 1-1.5 Ωm for saltwater-saturated layers and 100-150 Ωm for freshwater-filled sands. The values are known from 26 ground dc resistivity soundings and the geological situation was checked by a few drillholes. The depth contours of the bottom of the freshwater lens as inferred from the dc soundings are shown in Figure 15.1.

The results of the AEM survey are presented in Figures 15.2 and 15.3. The line spacing was 100 m and the total flown was 40 line km. The interpretation of the measured secondary magnetic field was based on the homogeneous half-space model. If the ground is not homogeneous, the interpretated parameters are referred to as "apparent resistivity" and "apparent depth" of equivalent half-space (for further explanation see Sengpiel and Meiser, 1981). The contours of apparent

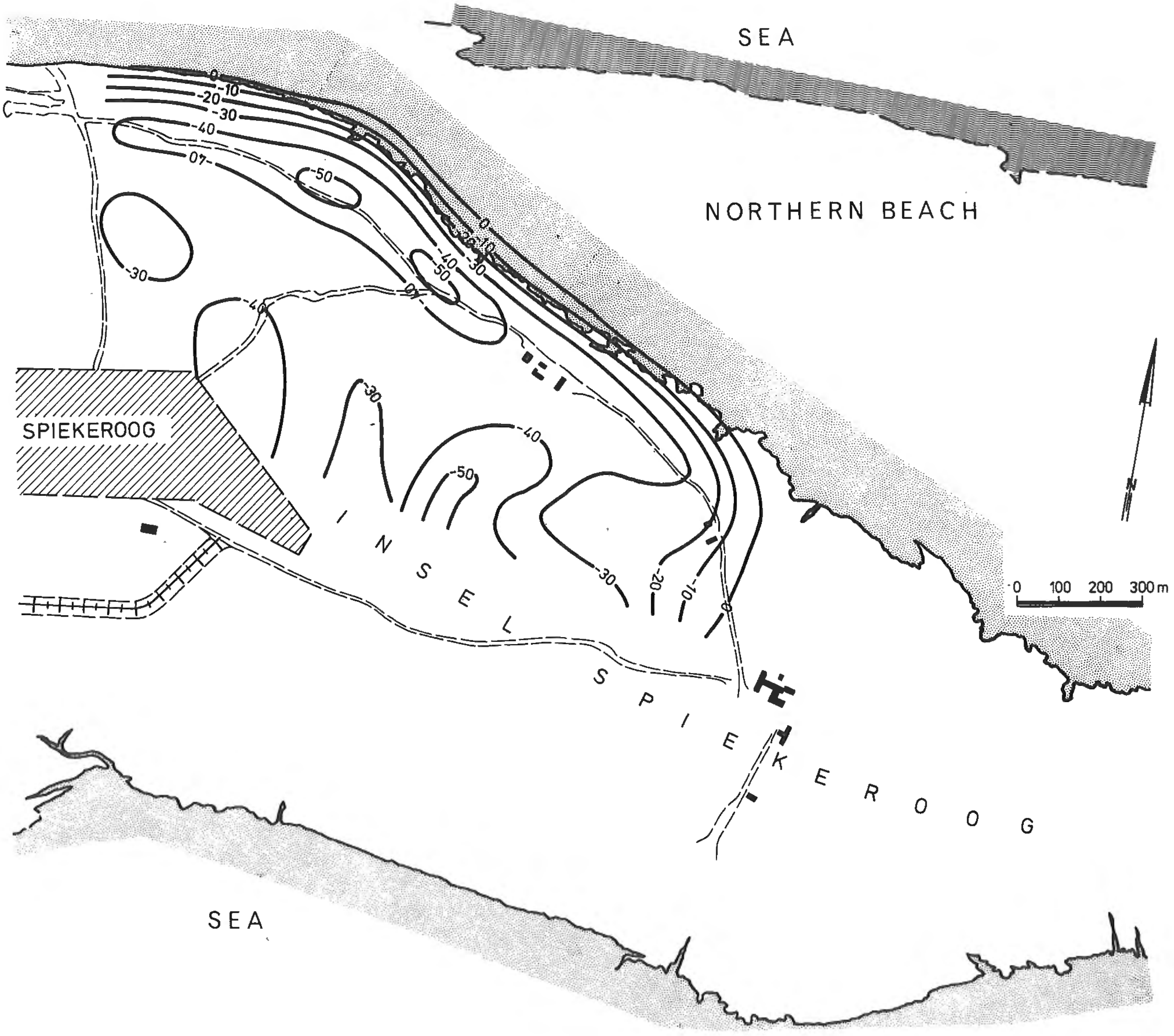

Figure 15.1. Depth contours (m) of the bottom of a freshwater lens as inferred from 26 dc resistivity soundings on the Island of Spiekeroog.

resistivity (Fig. 15.2), especially the belt of somewhat higher resistivities, follow the outlines of the freshwater lens.

Without additional information it is difficult to interpret the distribution of apparent resistivity in terms of the freshwater lens. Compared with apparent resistivity, the apparent depth contours (Fig. 15.3) are certainly more informative: they show approximately the depth to the surface of a conducting half-space, i.e. the saltwater zone, which is depressed by the overflowing freshwater lens. The Spiekeroog case history and the technique used in interpretation of Dighem II data was described by Sengpiel (1983).

INVERSION ALGORITHM

In the described case the results of mapping apparent depth and resistivity with only one frequency were useful. The method, however, is not adequate for more complicated layering, especially when a conductive upper layer is present, which can render the apparent depth values too small or even negative. This was our experience from surveys in coastal areas. A new impulse to tackle the problem came from the author's development of a fast inversion algorithm which yields approximate resistivity/depth distribution from multifrequency AEM survey data obtained with dipole sources

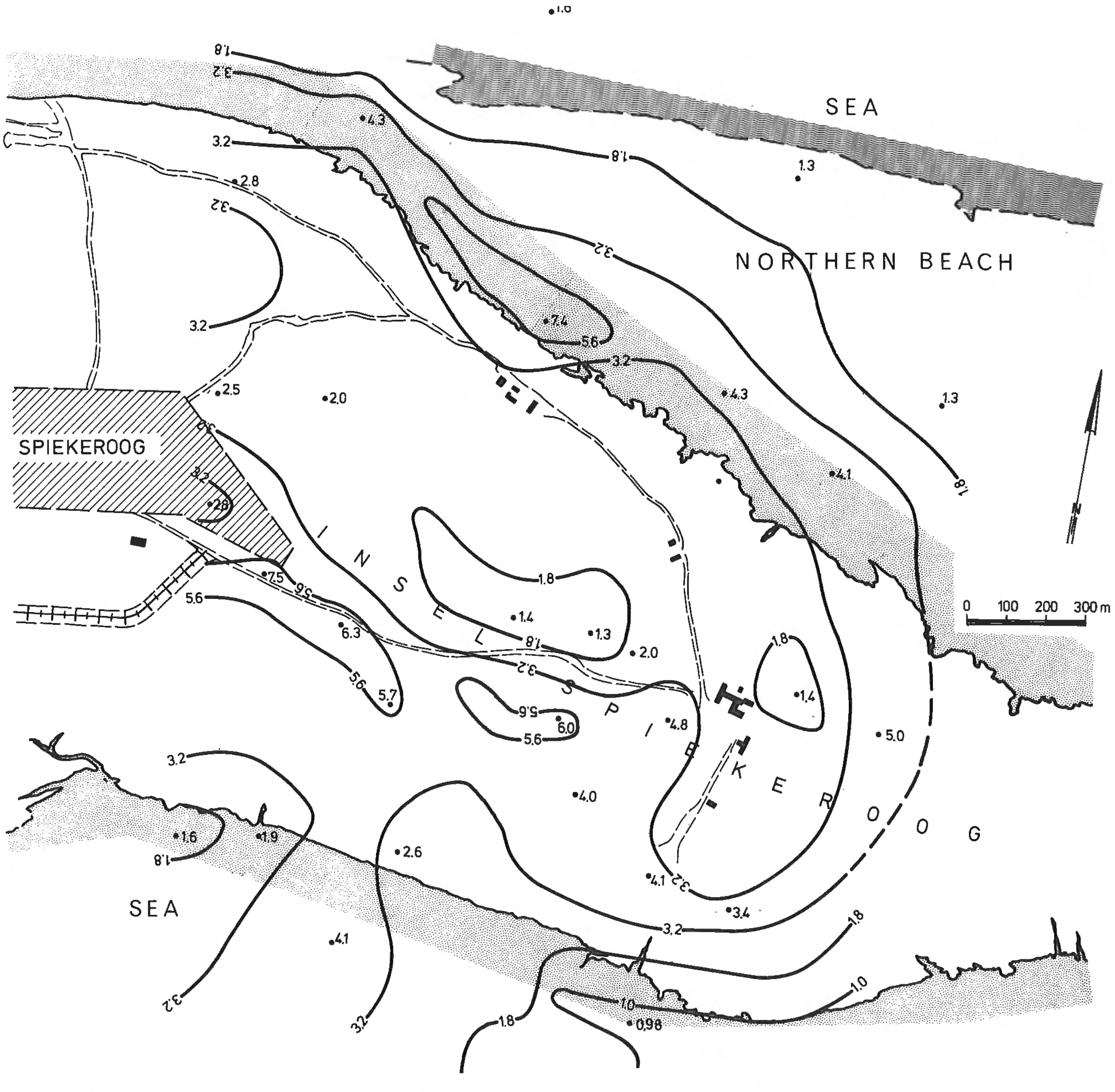

Figure 15.2. Apparent resistivity contours (Ωm) around the freshwater lens obtained from a HEM survey with one operating frequency (900 Hz), Spiekeroog.

(Sengpiel 1984). Instead of apparent depth of the equivalent half-space a new parameter called the "central depth" z* is calculated from the secondary magnetic field for each frequency. Under certain conditions z* is the depth of the "centre of gravity" of the induced current system and ρ* is the ambient resistivity at that depth. The following examples of model calculations will give the reader an insight into its capabilities for groundwater prospecting. BGR will apply this algorithm to data from a pilot project in Pakistan, in 1986, where an AEM survey will be carried out to prospect for freshwater aquifers in a saline desert environment.

Let us start with a simple two-layer case (Fig. 15.4) where resistivities are $\rho_1 = 500\ \Omega$m, $\rho_2 = 1\ \Omega$m, the thickness d_1 of the top-layer varies between 10 and 100 m. For each of the five frequencies indicated in the figure we obtain a depth value z*, and an apparent resistivity ρ* or ρ_a, which is representative of the resistivity within a certain volume around the central depth z*.

The figure may be viewed as a resistivity section along a flight line. Resistivities ρ_a are roughly contoured with two lines per decade. The interface of the two layers is clearly indicated by the maximum gradient of resistivity versus depth andcoincides closely with the 10 Ωm contour. Figure 15.4 also shows that a broad range of frequencies is necessary to explore the ground within a limited depth range.

Figure 15.5 gives some details of ρ_a (z*) for a two-layer case with $d_1 = 30$, 60, and 100 m. Now, the function

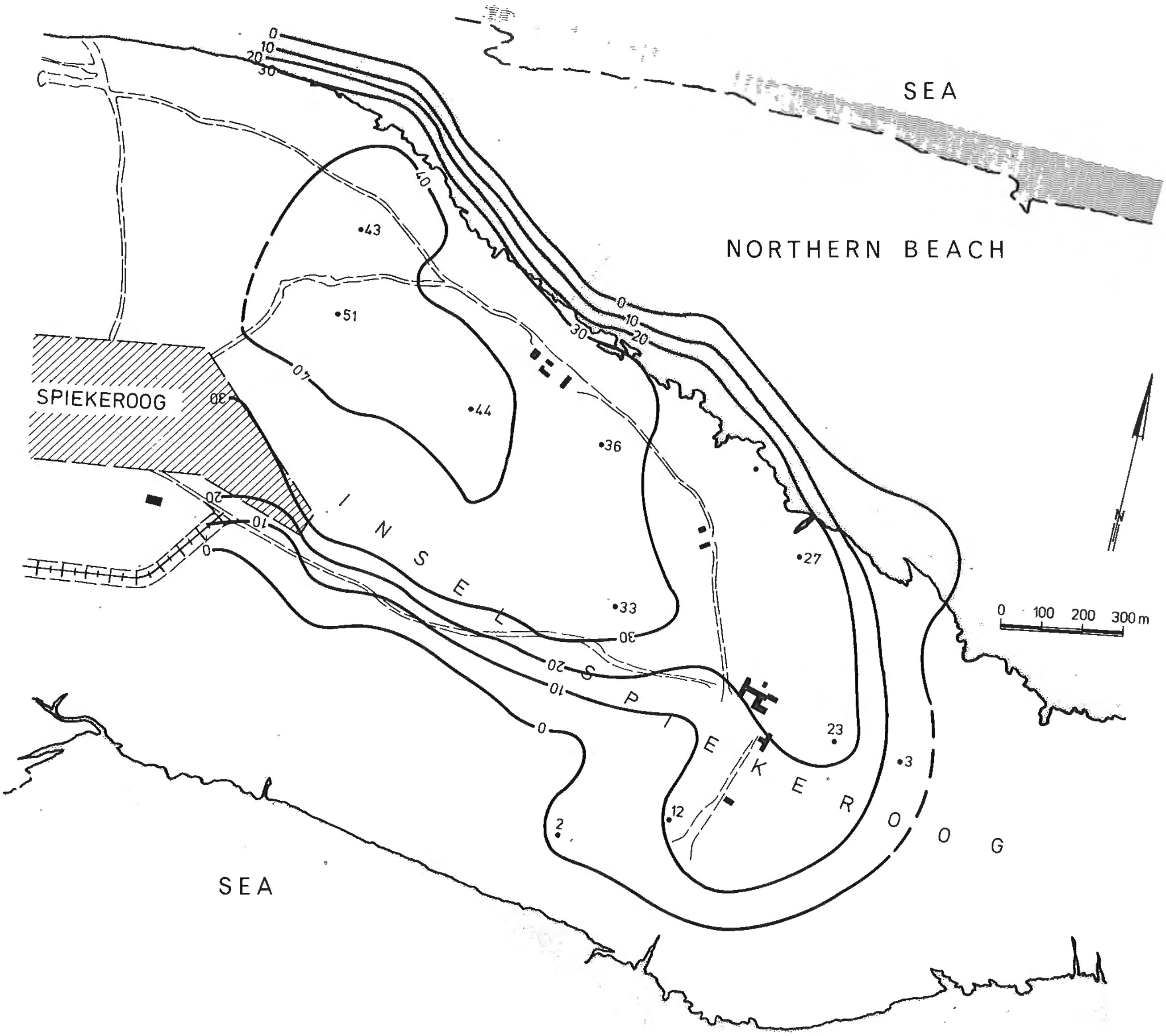

Figure 15.3. Map of apparent depth to the conductive layer (saltwater) obtained from HEM data. The contours indicate the extent and thickness of the freshwater lens, Spiekeroog.

$\rho_a = f(z^*)$ is shown for 12 frequencies. Note that the strongest gradient of ρ_a occurs for $z^* \approx d_1$, where ρ_a is about 10 Ωm for all three values of d_1. Such calculations should be done before commencing a survey to establish the most suitable frequencies for a given situation.

Unknown parameters for a two-layer case may, of course, be ascertained also by other methods. Nevertheless, there remains the risk that the application of a two-layer inversion may not be appropriate when the actual layering is more complicated.

The ρ^* (z^*) method does not require previous knowledge of the number of significant layers. Moreover, it gives a clear indication of that number. This can be seen from the calculated results for the four-layer cases of Figure 15.6, where $\rho_1 = 50$, $\rho_2 = \rho_4 = 1000$, and $\rho_3 = 1$ Ωm. The thickness d_1 of the cover layer is heldconstant at 10 m, while the depth of a

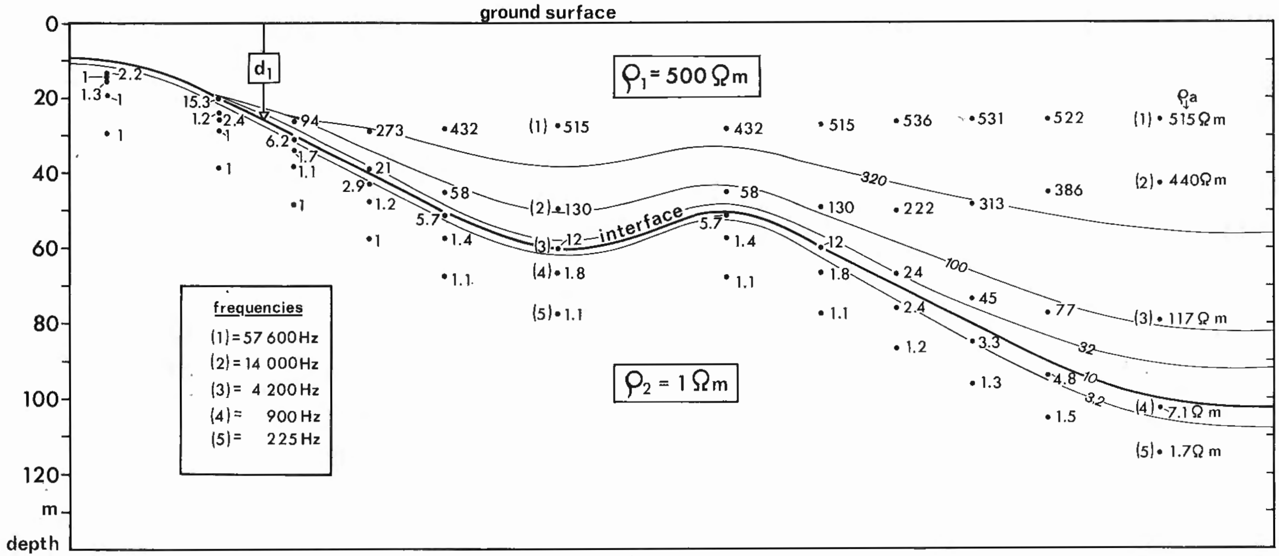

Figure 15.4. Calculated apparent resistivities and central depths (•) for two-layer cases with different d_1.

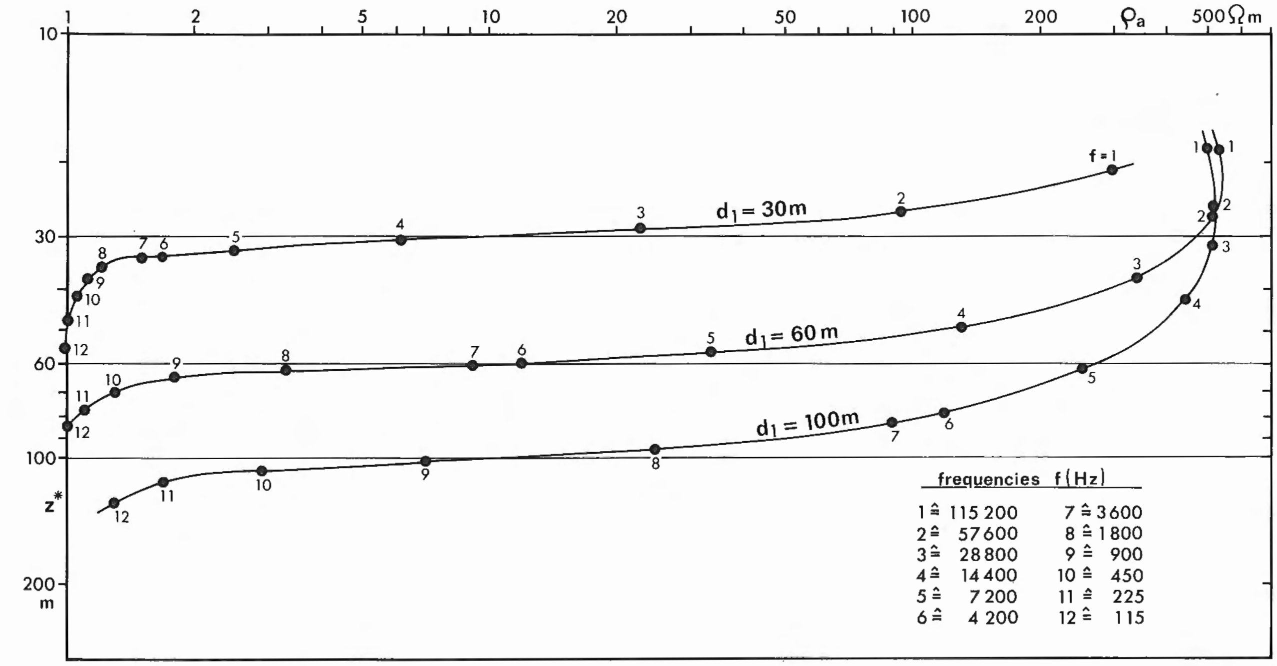

Figure 15.5. ρ_a as a function of central depth z^* resulting from a new inversion algorithm for two-layer cases where resistivities are $\rho_1 = 500$ Ωm, $\rho_2 = 1$ Ωm, and thicknesses of the top layer $d_1 = 30$, 60, or 100 m.

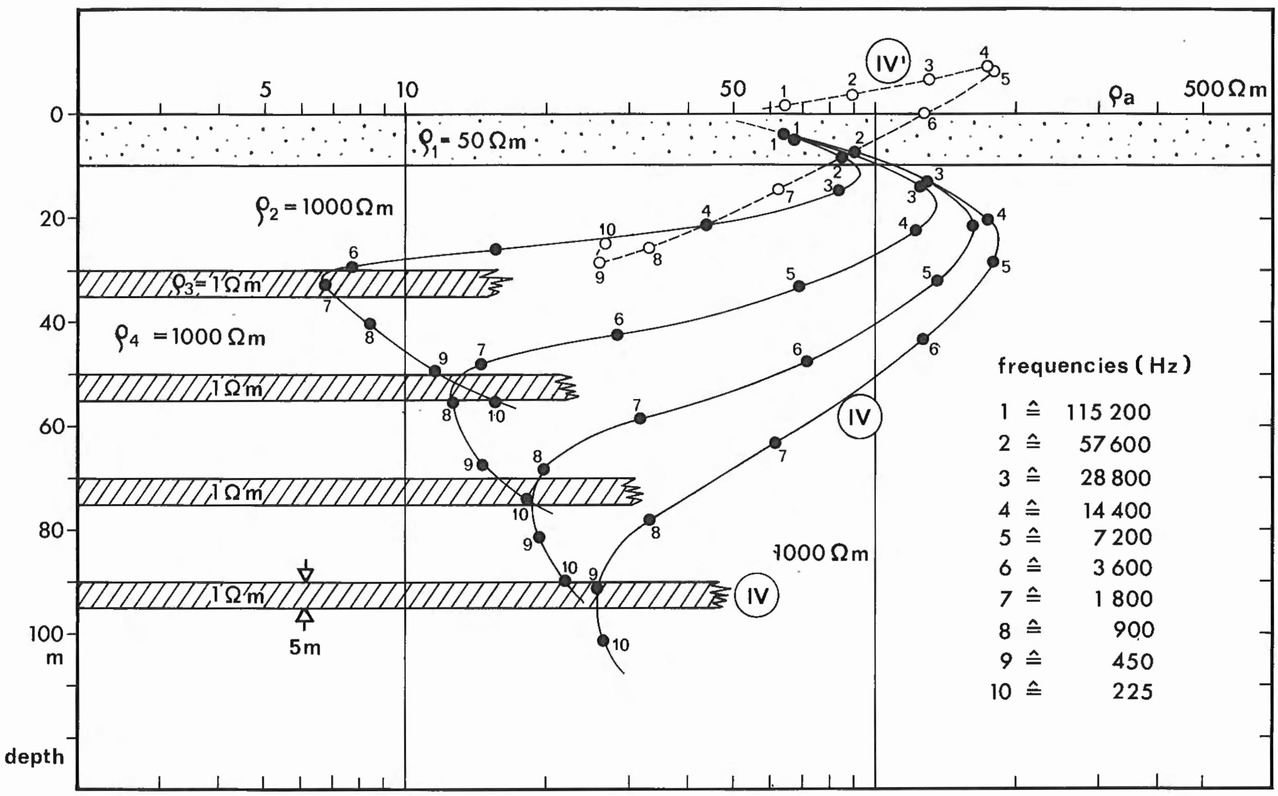

Figure 15.6. A four-layer case with an intermediate conductive layer ($\rho_3 = 1\ \Omega$m) at varying depth: 30, 50, 70, or 90 m. Four solid curves show the $\rho^*(z^*)$ function. The curve IV′ gives the results $\rho_a(d_a)$ for the case IV, where ρ_a and d_a are conventional apparent resistivity and depth, respectively.

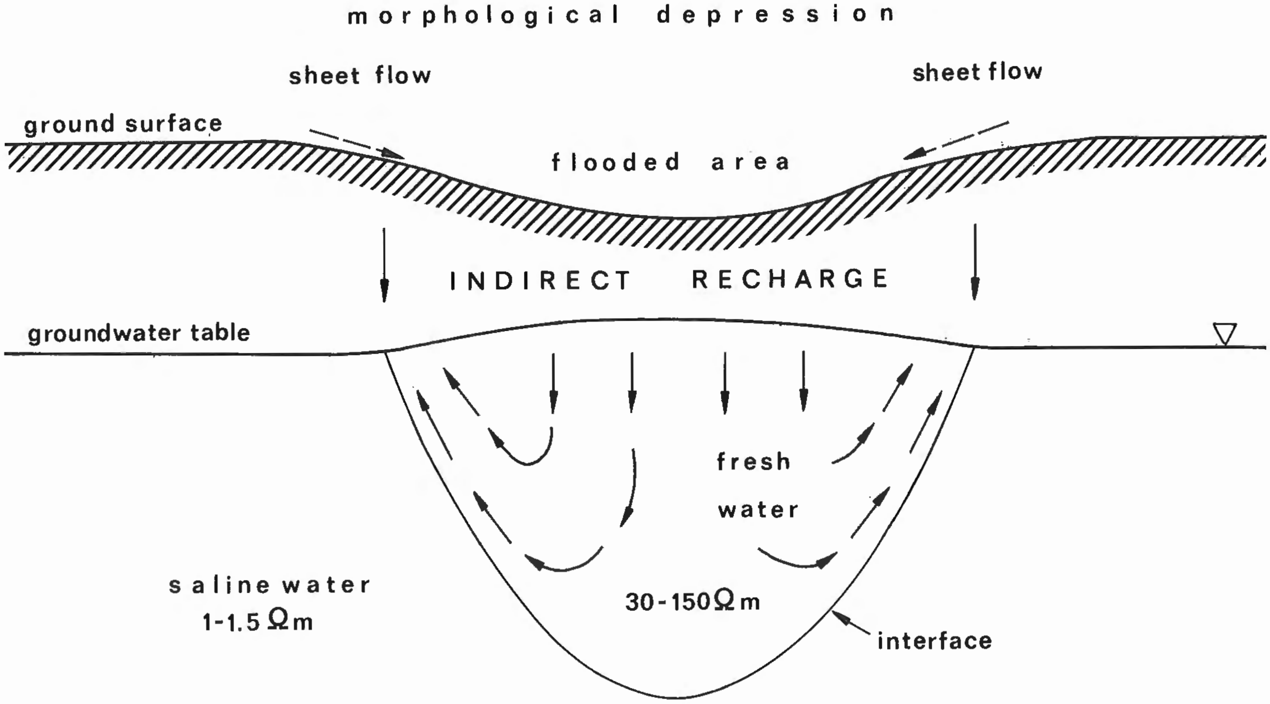

Figure 15.7. Freshwater lens below a morphological depression.

thin, intermediate conducting layer ($d_3 = 5$ m) is varied as indicated ($z_3 = 30, 50, 70$, and 90 m). Ten frequencies were used to show how ρ_a varies with depth z*. A four-layer case $\rho_1 < \rho_2 > \rho_3 < \rho_4$ can be derived from each of the ρ_a (z*)-curves. The most important fact is that the minimum of ρ_a as a function of z* occurs at the true depth of the intermediate conductor. This enables us, for instance, to map the true depth of a conducting layer using z* at the minimum of ρ_a at each sampling point.

PAKISTAN PILOT STUDY

To assess the feasibility of groundwater prospecting by AEM in desert areas in Pakistan, we have applied the central depth algorithm to the actual resistivity distribution which was obtained at 25 field sites by ground dc soundings (Bender and Sengpiel, 1984). The three selected survey areas are rather flat. In general the groundwater is saline, but some freshwater aquifers are known. They originate from rainwater by the so-called indirect recharge. A typical situation is presented in Figure 15.7. Below the groundwater table the resistivity is 1-2 Ωm in the saline zone and 16-150 Ωm in the freshwater lens. There may be considerable changes of resistivity in the top-layer. The following two examples relate to sites around and above the described freshwater lens.

In the upper part of Figure 15.8 there is an apparent resistivity sounding curve obtained with a Schlumberger array (electrode spacing AB/2) at a site with saline groundwater. The calculated layer model is shown as a bar at the bottom of the figure. Indicated are resistivities of the five layers and depths of the interfaces (to be read on the AB/2, z* axis). This five-layer model was the input for a calculation of the ρ*(z*) values shown in the diagram. In the vicinity of the

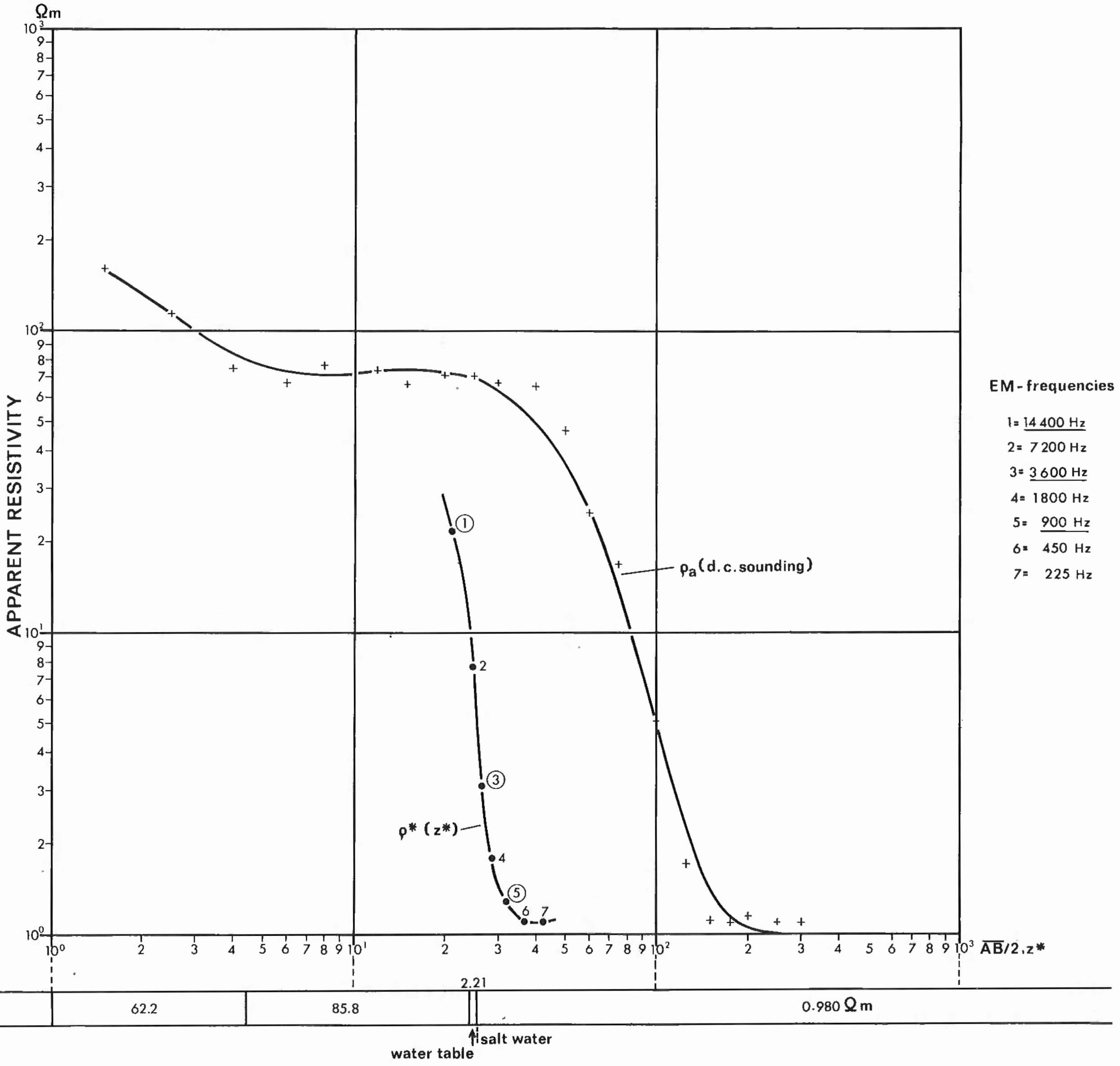

Figure 15.8. Apparent resistivity data from a Schlumberger sounding in Pakistan, model curve (diagram), and layer parameters (lower bar). The ρ*(z*) values are calculated for the geoelectric model and seven frequencies.

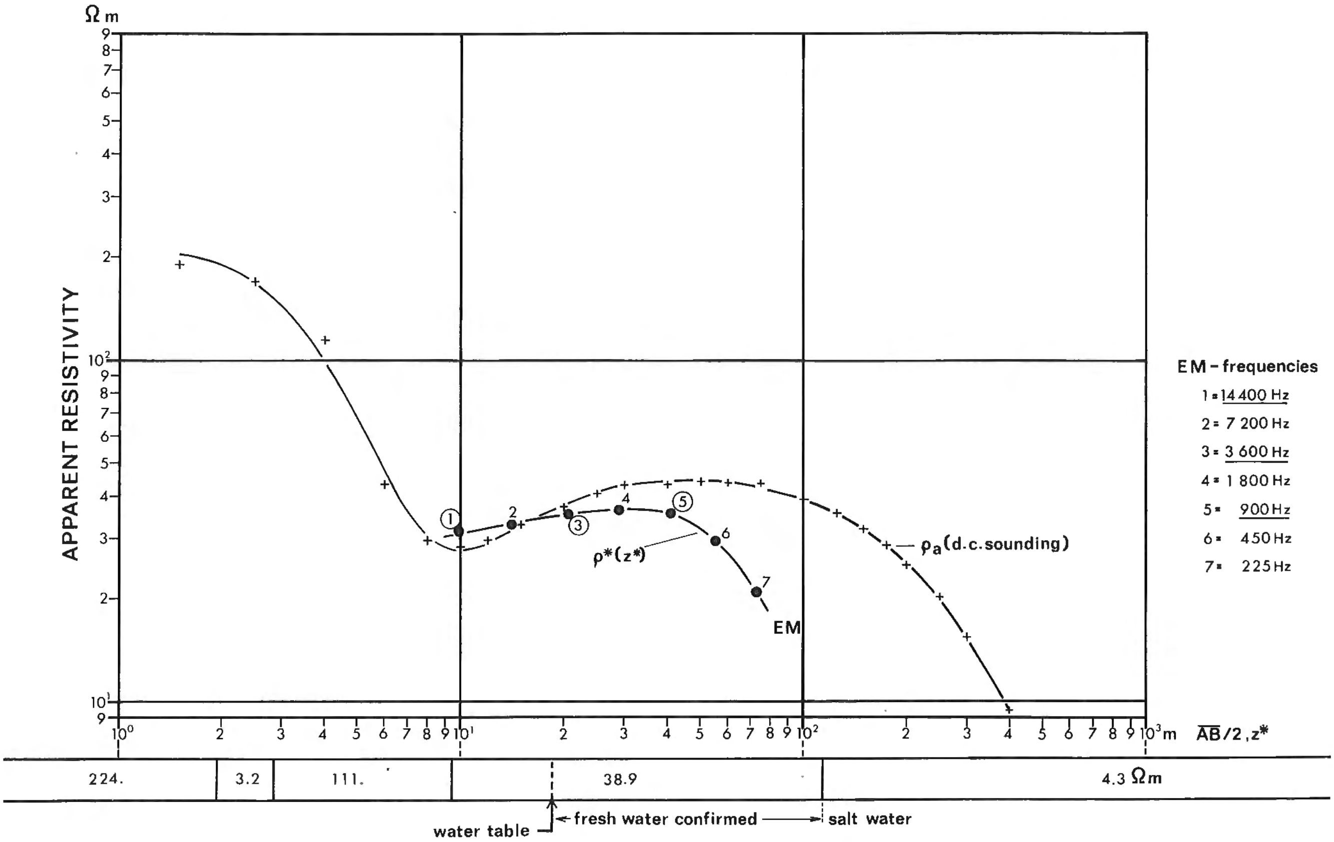

Figure 15.9. Results of a Schlumberger sounding in Pakistan and theoretical ρ*(z*) values for an AEM sounding with 7 frequencies. Compare with Figure 15.8, where no freshwater aquifer was found.

water table (at 22 m) there is a dramatic drop of ρ* from 21 to 1.1 Ωm, fully accomplished within few metres. The results suggest that there is little chance of finding freshwater below the water table at that place.

More promising are the results shown in Figure 15.9. The results of the Schlumberger sounding can be interpreted as a five-layer situation with a thin intercalation of highly conducting material between 2 and 3 m and a substratum of 4.3 Ωm at 104 m depth. A broad zone of medium resistivity extends from 10 to 104 m depth. No change of resistivity was observed at the depth of the water table (here at 18 m, as found by drilling). These conditions are also met by the ρ*(z*) results for the frequency range of 14 400 to 900 Hz. For lower frequencies, i.e. for z* approaching the depth of the conducting substratum (which contains saline water), ρ* starts to decrease. At this site, a freshwater body was found by drilling. It extends from 18 to 104 m depth in silty and fine grained sand.

CONCLUSIONS

Surveys with helicopter EM systems in coastal areas have shown that the technique is effective in mapping freshwater/saltwater interface. Satisfactory results were obtained after interpretation of one-frequency AEM data. However, to obtain a detailed resistivity section, which is necessary in complex hydrogeological environments, AEM surveys have to be conducted at various frequencies. In preparation for a pilot AEM survey in a desert area in Pakistan, which will be carried out in 1986-87, a computer algorithm was developed for interpretation of multifrequency AEM data. Although the algorithm does not yield true resistivities of a multilayer ground, it gives a correct image of the resistivity change with depth and of the approximate interface depth. Tests have indicated that the ρ*(z*) method is faster and more robust than a rigorous multilayer inversion. The details of the technique will be published after successful testing on survey data.

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- 16 -

Airborne electromagnetic mapping of geothermal systems in the Basin and Range and Cascade provinces, U.S.A.

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Hoover, D.B. and Pierce H.A., Airborne electromagnetic mapping of geothermal systems in the basin and range and cascade provinces, U.S.A.; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 139-143, 1986.

Abstract

Tests of INPUT® and Dighem II airborne electromagnetic (AEM) systems were flown in the Basin and Range and High Cascade physiographic provinces of western United States to evaluate their effectiveness for reconnaissance geothermal exploration. The airborne work resulted from extensive ground EM surveys which showed that deep-penetration AEM methods should be effective in many geothermal areas.

Results of the INPUT survey at Steamboat Springs, Nevada, show excellent correlation with a variety of ground electrical surveys. Dighem resistivity maps obtained at Lassen National Park, California, identified four principal areas of near-surface thermal features. These features correlate closely with results from audio-magnetotelluric measurements in the region. The Medicine Lake, California, geothermal area was flown prior to acquisition of ground electrical data and showed three areas of low resistivity. Subsequent ground work has confirmed the presence of the three low resistivity areas and no others. The results, we feel, demonstrate the utility of AEM mapping techniques for geothermal exploration.

Résumé

On a réalisé des essais avec les systèmes électromagnétiques aéroportés (ÉMA) INPUT® et Dighem II dans les provinces physiographiques Basin and Range et High Cascade, dans l'Ouest des États-Unis, pour évaluer leur efficacité dans le domaine de la prospection géothermique de reconnaissance. Les travaux aéroportés étaient consécutifs à des levés ÉM étendus effectués au sol et ils ont montré que les méthodes ÉMA à pénétration profonde pourraient être efficaces dans un grand nombre de zones géothermiques.

Les résultats du levé réalisé avec le système INPUT à Steamboat Springs, Nevada, montrent une excellente corrélation avec divers levés électriques au sol. Des cartes de résistivité établies avec le système Dighem au parc national Lassen, en Californie, ont permis de déterminer quatre secteurs principaux de phénomènes thermiques près de la surface. Cettes déterminations présentent une étroite corrélation avec les résultats de mesures audio-magnéto-telluriques faites dans la région. Dans la zone géothermique de Medicine Lake, Californie, on a fait un levé aérien avant l'acquisition de données électriques au sol qui a révélé trois zones de faible résistivité. Les travaux ultérieurs au sol ont confirmé l'existence de ces trois zones et le manque d'autres zones de faible résistivité. Ces résultats démontrent, à notre avis, le potentiel de l'utilisation des techniques de cartographie ÉMA pour la prospection géothermique.

INTRODUCTION

The U.S. Geological Survey has recently conducted tests of deep-looking airborne electromagnetic (AEM) systems in order to evaluate their effectiveness for geothermal exploration. Fixed-wing INPUT and helicopterborne Dighem II systems were used in the High Cascade and Basin and Range physiographic provinces, where the Geological Survey had conducted extensive ground geophysical surveys. To our knowledge, AEM techniques had not been used in prior geothermal work because the principal targets were generally considered to be too deep for detection. However, based on

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our ground EM studies, we predicted that the present deep-penetration AEM methods would be useful in many geothermal areas.

Most hydrothermal systems leak to the surface, often along faults as evidenced by fumaroles, hot springs, geysers, sinter, etc. These leaks also tend to be self-sealing with time. The process of sealing causes the leaking portion to migrate along weak structures. Within the more than fifty Known Geothermal Resource Areas (KGRAs) investigated by Hoover et al. (1978) in western USA, low resistivities are generally associated with known areas of shallow thermal manifestations. These resistivity lows, at depths less than 100 m, often extend along fault trends for considerable distance and show no evidence of surface thermal features. We assume these areas of low resistivity are related to the presence of hot, saline thermal waters and associated alteration, or to fossil hydrothermal systems. Audio-magnetotelluric (AMT) soundings in the KGRAs have shown that the shallow zones of low resistivity were connected in many cases at depth to deeper and broader low-resistivity zones which could represent the geothermal targets. AEM techniques which can identify such shallow leakage zones can become a useful reconnaissance tool for selecting areas where deeper penetrating ground geophysical methods can be applied.

A total of 1282 line km of INPUT surveys was flown at Long Valley, CA, Surprise Valley, CA, Steamboat Hills, NV, Wabaska, NV, and Raft River, ID, in late 1979 (Christopherson et al., 1980 a,b). As the results of these surveys were very encouraging, a second test with 1325 line km flown was conducted in the High Cascades using a Dighem II system (Christopherson and Hoover, 1981; Fraser, 1983). The Dighem II system was used in the Cascades because of rugged topography. The areas surveyed were Lassen, CA, Medicine Lake, CA, Mt. Hood, OR, and Mt. St. Helens, WA. The area of Surprise Valley, CA, surveyed previously with INPUT, was reflown. Flight line spacing for each area was nominally 400 m. Magnetic data were also recorded during both surveys.

RESULTS OF INPUT AEM SURVEYS

Because earth resistivities are very low in most of the Basin and Range areas flown with the INPUT system (about 20 Ωm) it was necessary to reduce the normal system gain in order to keep signals from saturating. Typically, channels 1 to 5 were operated at 25% of normal, channel 6 was operated at either 50% or 100% of normal. Palacky (1975) discusses the interpretation of INPUT data in areas of conductive overburden. The area of Surprise Valley has particularly conductive surficial material due to the presence of saline lake deposits.

The best correspondence between ground and airborne electrical data was observed in the Surprise Valley, Wabuska, and Steamboat Hills surveys. No clear patterns could be established in data from the Raft River area. We believe this reflects the lack of significant leakage of hydrothermal fluids to the surface and the information is consistent with other data from the area. At Long Valley, areas of extensive surface alteration as well as many of the hot springs were identified. Thermal springs at Hot Creek Ranch and Whitmore Hot Springs, however, showed no significant anomalies, although ground electrical data suggested that deep conductors were present.

Figure 16.1 shows nested profiles of the channel 6 data from Steamboat Hills, NV. Because of abundance of ground data this area will be used for comparisons. The principal hot springs are located just west of Highway 395. They are aligned along a north-trending fault zone (not shown on the map) on which several shallow geothermal wells are located. A strong AEM response was observed in the springs area, although some anomalies are related to local cultural features. To the west, a strong conductor with a north strike can be correlated with a fault. Its presence was also inferred from ground electrical data, and we believe the feature forms the east side of a small graben. The inferred bounding faults are shown in Figure 16.1. This AEM anomaly correlates directly with the most significant conductive anomaly, which was defined by ground methods — telluric J mapping and 2 telluric traverses at 30 s periods, and AMT soundings in a frequency range of 7.5 to 20 kHz (Hoover et al., 1978). A large, 200 mV self-potential anomaly was also observed along the trend. A production steam well has been drilled near the southern end of this structure.

RESULTS OF DIGHEM AEM SURVEYS

In the Cascades Province, the near surface resistivities are high over outcropping volcanic rocks. At Medicine Lake, resistivities have been measured exceeding 100 000 Ωm (A. Zohdy, personal communication, 1985). The Dighem system was flown with a coaxial coil pair operating at 3600 Hz and a coplanar pair at 900 Hz. Details of the survey were described by Fraser (1983). At the time of flying we had extensive ground geophysical data from Lassen and limited data from Mt. Hood. No electrical data, however, were available from Medicine Lake so that this area served as a true test of the method for focusing of follow-up exploration.

At Lassen, four principal regions of low resistivity (less than 30 Ωm) were identified in the Dighem resistivity maps (Fig. 16.2). At the Bumpass Hell thermal area (within the National Park) resistivities were determined under 10 Ωm. The conductive areas are surrounded by materials having surficial resistivity in excess of 1000 Ωm. Three of the four regions have known surface thermal features. The HEM resistivity map clearly defines structural trends associated with the thermal features and shows that thermal waters are, or have been, more pervasive than previously thought. A good correlation was found between HEM and AMT results in identifying thermal features not only in areas where they were known, but also in a previously untested area (Hoover et al., 1978).

Figure 16.3 shows the resistivity map of Medicine Lake obtained at 900 Hz. Three areas were identified where resistivities are less than 32 Ωm, while the regional background is over 1000 Ωm. The easternmost low is associated with a fumarole known as the Hot Spot which is the only known surface thermal manifestation in the region. The Hot Spot is

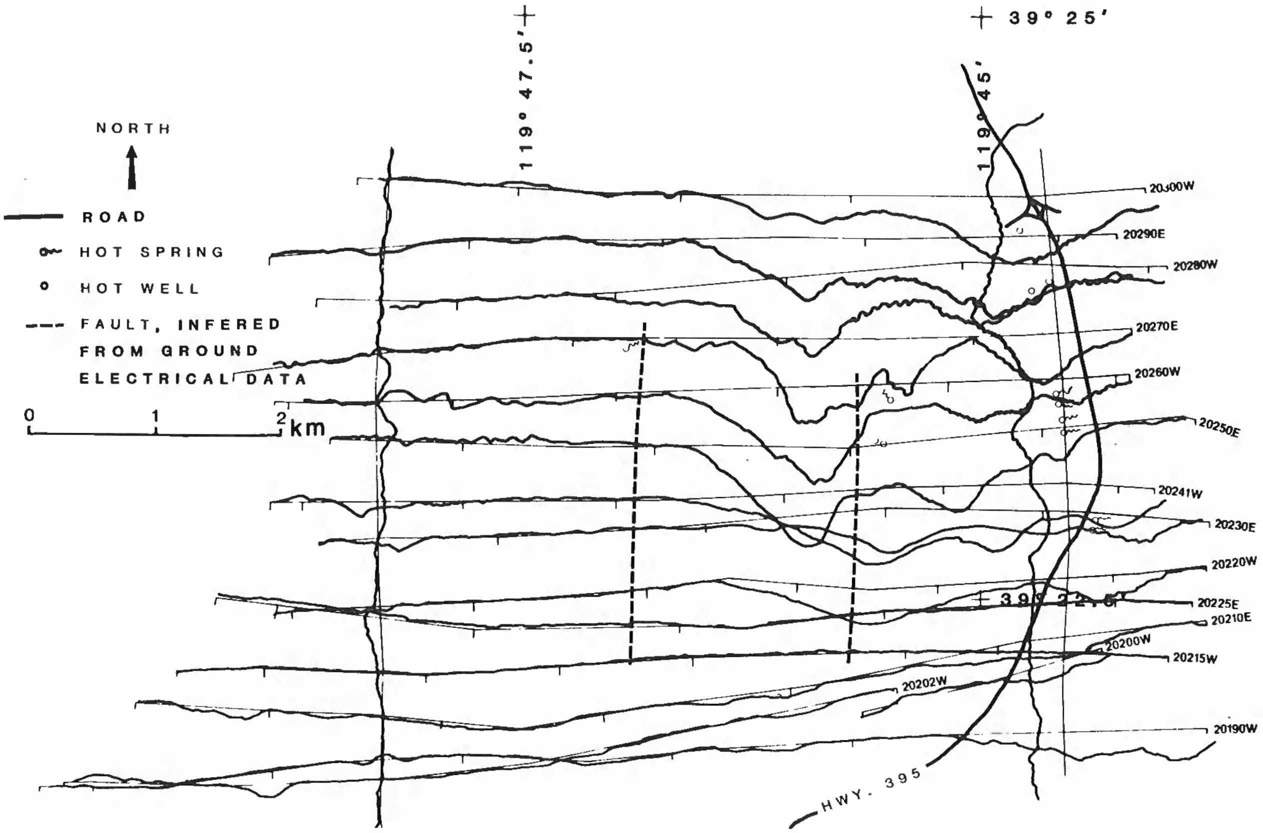

Figure 16.1. Nested channel 6 INPUT profiles across Steamboat Springs, Nevada, geothermal area. AEM data on each profile are referenced to the flight path location.

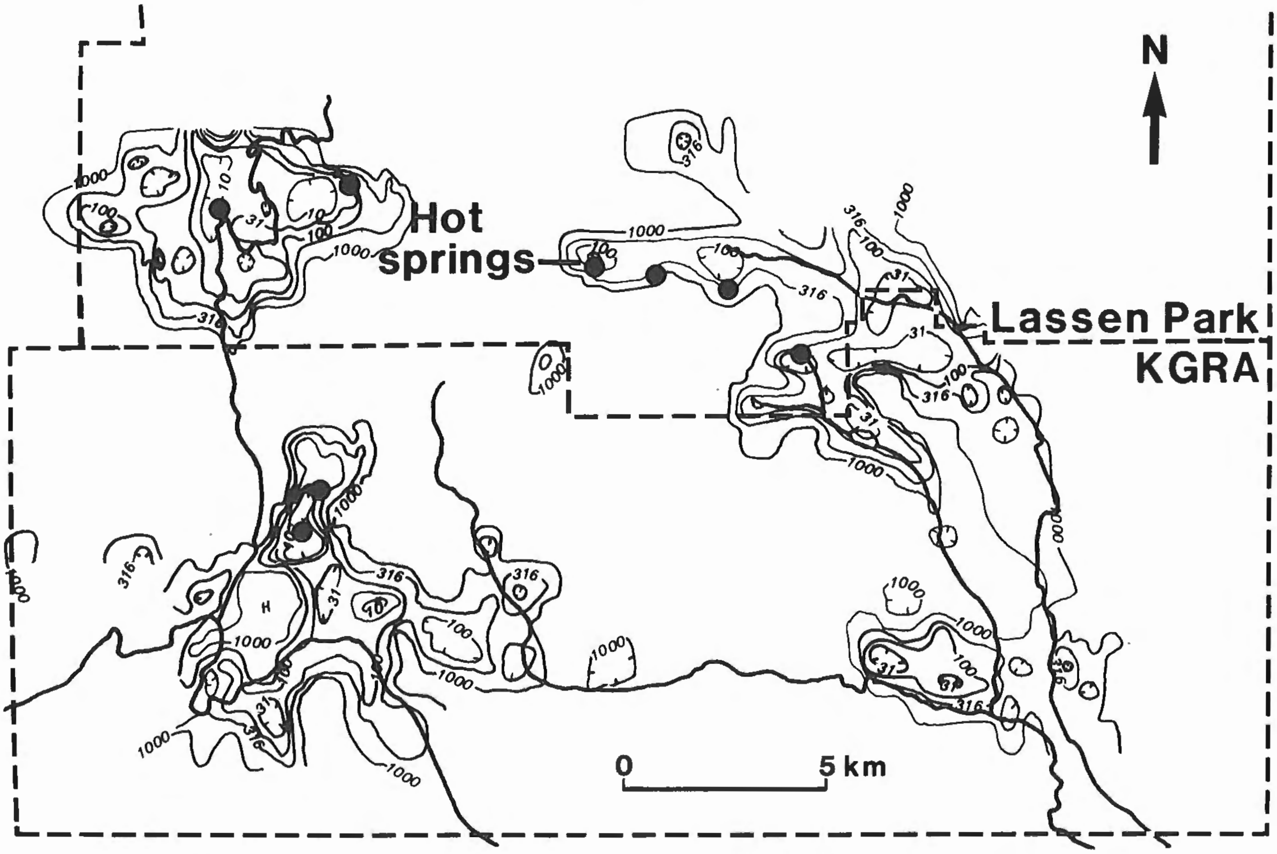

Figure 16.2. Dighem II resistivity map at 900 Hz of Lassen National Park, California. Only areas with resistivities smaller than 1000 Ωm are contoured.

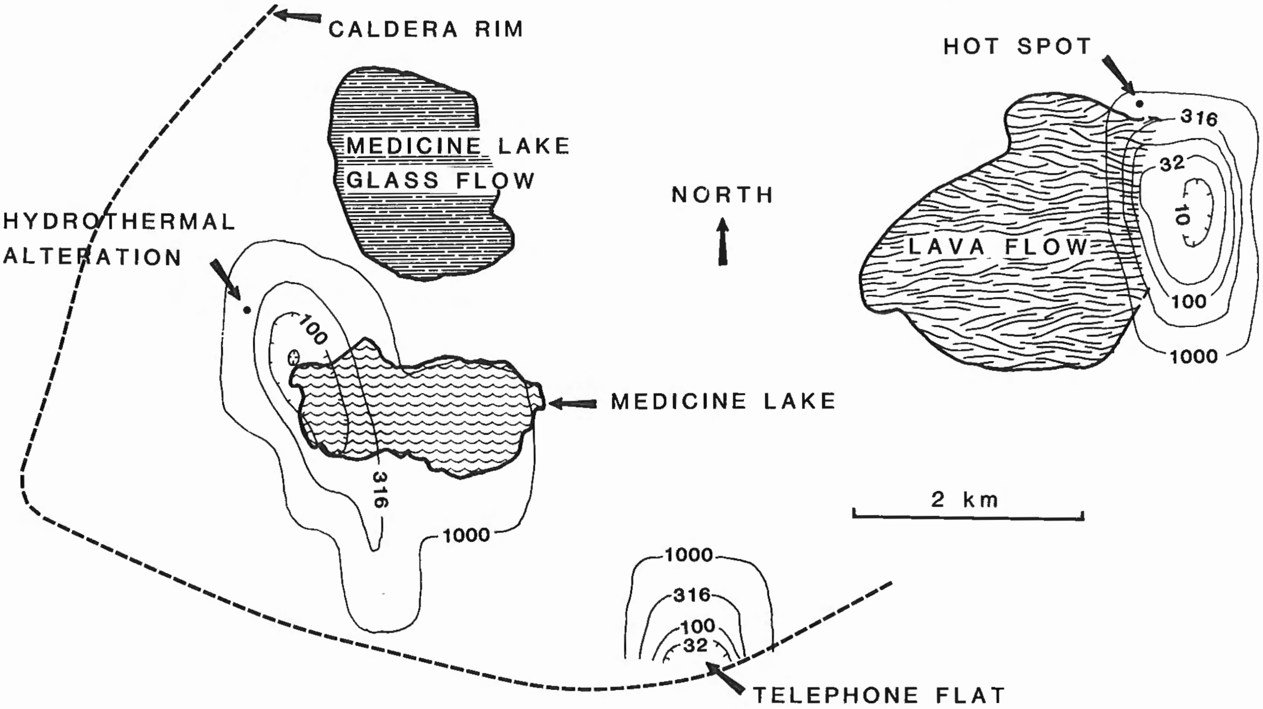

Figure 16.3. Dighem II resistivity map at 900 Hz of Medicine Lake, California. Only areas with resistivities smaller than 1000 Ωm are contoured.

offset significantly from the major anomaly of low resistivity. Within the Medicine Lake Caldera, on the western edge of Medicine Lake, another low resistivity area trends north-northwest. No thermal springs are known in this area, but subsequent to this survey, a small area of hydrothermal alteration has been mapped. The third anomalous area was identified on only one flight line, in the area of Telephone Flat, where no thermal manifestations have been known. Extensive follow-up surveys using Schlumberger VES and time-domain EM soundings have been carried out at Medicine Lake (Zohdy and Bisdorf, 1982). This work has identified extensive deep conductors which narrow toward the surface and coincide at shallow depth with the HEM results. The surface leakage in this region appears to be fault controlled.

CONCLUSIONS

The results from both INPUT and Dighem surveys in the western United States clearly show the utility of AEM methods for reconnaissance surveying of potential geothermal areas. Such surveys can identify regions where hydrothermal systems have leaked hot saline fluids to within the upper 100 m of the surface. A better outline could be obtained of the aerial extent of shallow alteration and the presence of thermal fluids than from the previously used surface geological mapping. AEM surveying provides an efficient means of focusing additional ground exploration effort because many of the near-surface conductive areas are directly related to hydrothermal systems at depth.

The AEM surveys reported here were all concerned with exploration for active hydrothermal systems. Their application is obvious and straightforward to exploration for fossil hydrothermal systems as well. Such systems are receiving increasing exploration interest today because of their direct genetic relationship to disseminated gold deposits.

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- 17 -

Airborne resistivity surveying applied to nuclear power plant site investigation in France

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Deletie, P. and Lakshmanan, J., Airborne resistivity surveying applied to nuclear power plant site investigation in France; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 145-152, 1986.

Abstract

In 1981, Compagnie de Prospection Géophysique Française (CPGF) was asked by Électricité de France (ÉDF) to study the feasibility of using airborne geophysics for site investigations for nuclear power plants. It was necessary to investigate soil properties of the first 100 m, mostly in horizontally stratified environments. Mathematical modelling showed that airborne EM surveys could give appropriate answers in at least 70 % of the geological situations of interest to ÉDF.

Test flying with the Dighem system was carried out in 1982. CPGF acted as supervisor on behalf of ÉDF. Seven sites were flown in different areas of central and southeastern France, totaling 2 000 line km. The flight line spacing was 100 or 200 m. At some of the sites, large amounts of ground geophysical and drilling data were available. At Sennecey, in the Saône Valley, correlation with 50 drill holes showed that HEM surveys could outline resistive limestones beneath a layer of conductive clays and marls which was up to 100 m thick.

Résumé

En 1981, la Compagnie de Prospection Géophysique Française (CPGF) a été chargée par Électricité de France (ÉDF) de réaliser une étude de faisabilité sur l'application des méthodes géophysiques aéroportées à l'étude des fondations de centrales nucléaires. Il était demandé de prospecter les 100 premiers mètres de terrain, dans des milieux horizontalement stratifiés. Un modèle mathématique montra que l'électromagnétisme héliporté pouvait donner des réponses significatives dans 70 % des situations géologiques définies par ÉDF.

En 1982, des vols d'essai furent réalisés avec le système Dighem, CPGF ayant un rôle de conseil d'ÉDF. Sept sites furent étudiés dans différentes régions du Sud-Est et du Centre de la France, avec 2 000 km de vols. L'écartement entre lignes était de 100 ou de 200 m. Pour quelques uns de ces sites, d'importantes quantités de données (géophysique et sondages) étaient disponibles. A Sennecey, dans la vallée de la Saône, une corrélation avec 50 forages mécaniques a montré que les prospections électromagnétiques héliportées pouvaient suivre le toit des calcaires résistants, sous une couverture d'argile conductrice pouvant atteindre 100 m d'épaisseur.

INTRODUCTION

In December 1980, the French State Power Board (Électricité de France), decided to investigate the possibility of preliminary site investigation of nuclear power plant sites by airborne geophysics. Obviously, it is advantageous to cover a large area without entering private properties. In follow-up, the most favourable zones are surveyed in detail by more conventional means. Électricité de France (ÉDF) made a catalogue of the main geological features found in those parts of France where nuclear power plants were to be constructed.

A feasibility contract was awarded to Compagnie de Prospection Géophysique Française (CPGF) in order to appraise all available airborne geophysical techniques. This study included:

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[1] Électricité de France, 18 rue de Tilsitt, 75017 – Paris, France

[2] Compagnie de Prospection Géophysique Française, 77 avenue Victor Hugo, 92500 – Rueil-Malmaison, France

1) The development of a mathematical model corresponding to the selected technique, and checking of its applicability.
2) Enquiries among users, universities, contractors and constructors.
3) Assistance to ÉDF in calling for tenders among selected contractors.

It was soon realized that helicopter electromagnetic (HEM) surveying was the most appropriate technique. After a call for tenders, Dighem Ltd. of Toronto, Canada, was selected to carry out, under CPGF's supervision, test flights over 7 selected areas (Fig. 17.1). These sites were already well surveyed by ground geophysics and drilling. 2000 line km were flown between February and March 1982.

GEOLOGICAL SITE CONDITIONS

The geological conditions at the nuclear power plant sites in France are sketched on Figure 17.2. The illustration corresponds to the following test sites:

(a) Alluvium on Tertiary marls: Verdun-sur-le-Doubs, St. Pourçain.

(b) Alluvium on Tertiary marls, with dipping Jurassic limestone at depth: Sennecey, Soyons.

(c) Alluvium on variable Tertiary bedrock (clays and sandstones): Limons.

(d) Karstic limestone: Civaux.

(e) Alluvium on faulted sedimentary structures: Arras-sur-Rhône

(f) Additionally buried river channels exist at Soyons, Limons, St. Pourçain (not shown in Fig. 17.2).

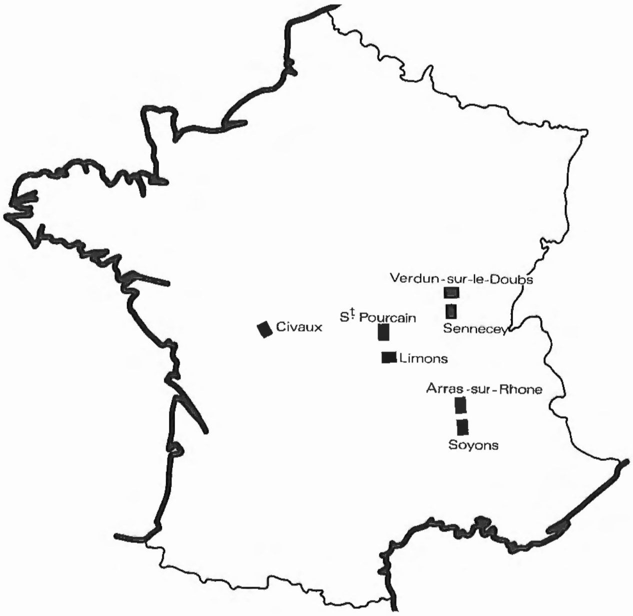

Figure 17.1. Locations of sites investigated by CPGF for nuclear power plants in France.

The probable ranges of resistivities are as follows:

Alluvium	clay and top soil	: 7 to 30 Ωm
	sand and gravel	: 200 to 1,000 Ωm
Tertiary marls and clays		: 10 to 30 Ωm
Tertiary sandstone		: 100 to 300 Ωm
Jurassic limestone		: 200 to 800 Ωm

POSSIBLE GEOPHYSICAL TECHNIQUES

In specifying the requirements for geophysical techniques, the depth of investigation had to exceed 100 m. Several methods were assessed during a preliminary investigation.

Airborne gravity was not found accurate enough. Anomalies of less than 5 mgals and 3 km wide (corresponding to a horst over 200 m high) are not detectable. Results of airborne magnetic surveys have been frequently used to calculate overburden depth elsewhere, but in the sedimentary areas selected by EDF the susceptibility contrast was not sufficient. A magnetometer was included aboard the survey helicopter and the results confirmed the initial skeptical assessment of the technique.

Airborne VLF has been mainly used in delineating vertical faults and conductors in resistive environment. Such situations do not exist at the investigated sites. Nevertheless, a VLF receiver was fitted on the helicopter. The field results confirmed that this method is not suitable for the mapping task.

Time-domain INPUT is probably the most extensively used airborne mapping tool. However, at the time of the enquiry (1980-1981), aids for quantitative interpretation of horizontally stratified media were not commercially available. Interpretation of frequency-domain EM data could supply resistivity and depth maps in horizontally stratified cases even at that time. After a detailed study, questionnaires were sent to 29 institutions, such as geological surveys, universities, contractors and manufacturers in 10 countries. The results confirmed their interest in helicopter EM surveying, but showed that 99 % of previous surveys had been applied to mining exploration.

MATHEMATICAL MODEL

In order to predict the HEM response at the given geological sites, and particularly to evaluate depth of penetration, computer software was developed for a CDC 7600 computer. It is based on the program written by Sinha and Collett (1973). The survey parameters were defined as follows:

Flight altitude	: 30 m
Bird length	: 9 m
Frequencies	: 375, 900, 3600 and 8000 Hz (on all 3 coil configurations)

Coil configurations : vertical coplanar
horizontal coplanar
vertical coaxial

For interpretation, the following model was suggested: horizontally stratified media with 4 layers. Typical thicknesses (t) and resistivities (ρ) are:

First layer (clay): $t = 0$, 3, or 6 m, $\rho_1 = 10\ \Omega\mathrm{m}$

Second layer (sand and gravel): $t = 20$, 17, or 14 m, $\rho_2 = 400\ \Omega\mathrm{m}$

Third layer (Tertiary clay and sandstone): $t = 0$ to infinite, $\rho_3 = 0.2$ to $400\ \Omega\mathrm{m}$

Fourth layer (Jurassic limestone or granite): $\rho_4 = 1000\ \Omega\mathrm{m}$

These cases are summarized schematically in Figure 17.3. The main problem was whether the resistive fourth layer basement could be located under a thick conductive third layer.

Figure 17.4 shows the inphase response for one of the cases which was described in greater detail by Lakshmanan and Bichara (1981). For a frequency of 900 Hz, the maximum response of 130 ppm corresponds to an infinitely thick third layer. When the basement (fourth layer) is moved up to a depth of 100 m, the total response is reduced to 123 ppm, i.e. 95 % of the maximum response. This depth of 100 m can be considered to be the "depth of penetration" for 900 Hz in this particular case, i.e., depth up to which the resistive fourth layer can be located. The algorithm is used separately for each frequency. However, a way to combine results acquired at different frequencies is to compute the ratio of two apparent resistivities, or their logarithmic difference.

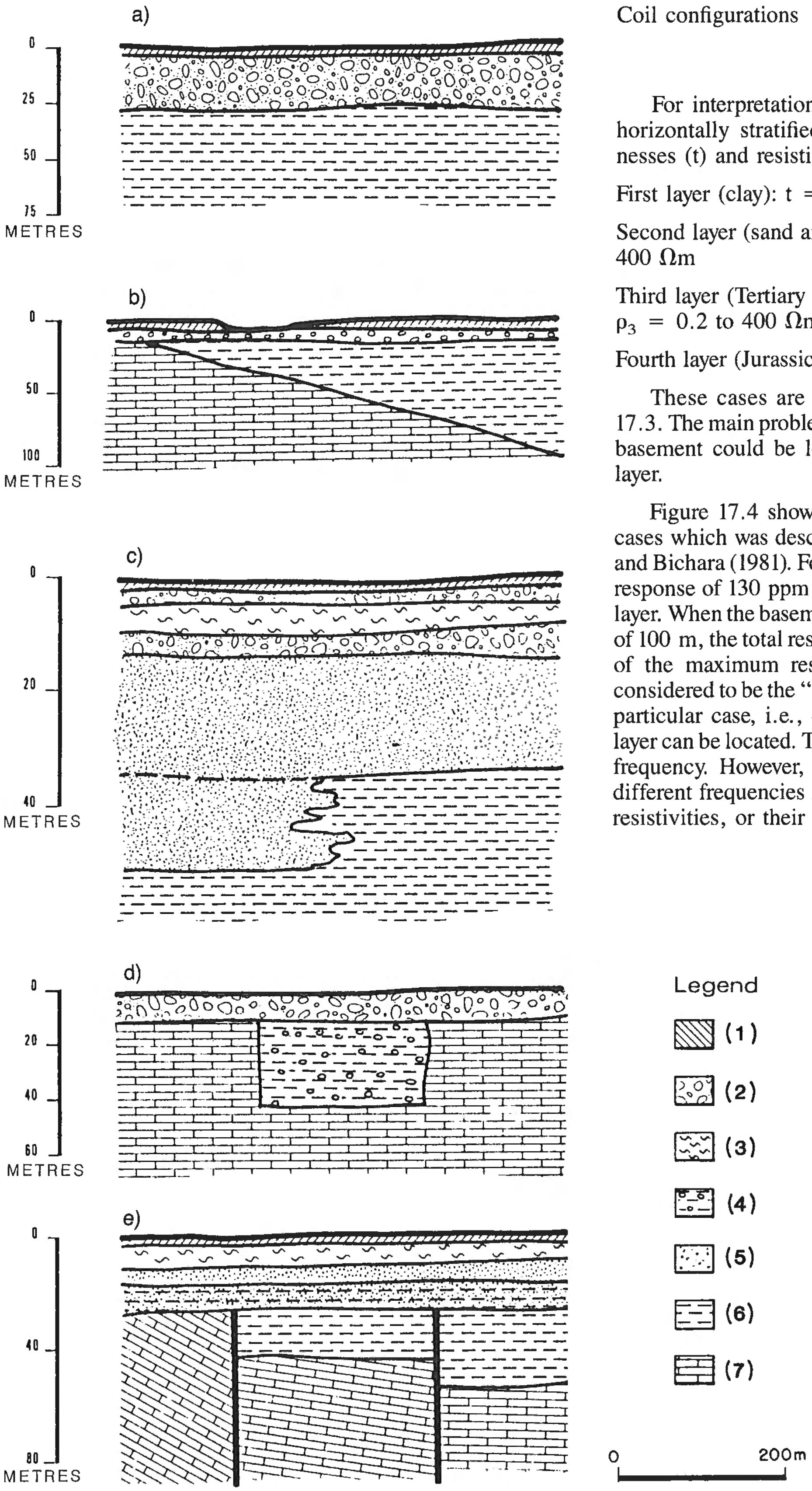

Figure 17.2. Typical geological situations (see text for their location and description). Geological units: (1) Top-soil and clay, (2) Quaternary sand and gravel, (3) Quaternary clay, (4) Karstic clay, (5) Tertiary sands, (6) Tertiary clay, (7) Jurassic limestone.

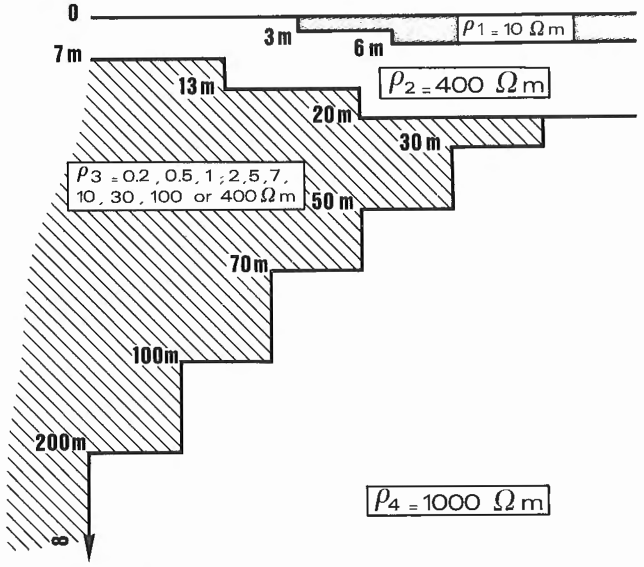

Figure 17.3. Sketch of geological parameters used in mathematical modelling. The situations should be considered as columns.

FIELD TESTS

The system used (Dighem) had two coplanar coils operating at 900 and 3600 Hz. They were placed in a 9 m long bird, which was towed by a helicopter. In addition, VLF and magnetic data were recorded, but did not generally give significant results in the sedimentary basins studied. Resistivity processing was done, for each frequency, with the infinite half-space algorithm (Fraser, 1978). This supposes an infinitely resistive first layer overlaying an infinitely thick conductor.

The algorithm first takes into account inphase and quadrature response and neglects bird's height. It then computes the conductor resistivity and its depth below the bird. In a second step, the actual bird elevation above the ground is subtracted from the computed depth. If the difference is positive, it is equal to the apparent thickness of the first layer, supposed to be infinitely resistive. If one ends up with a negative thickness, the first layer is in fact conductive. In all cases, the computed second layer resistivity is quite stable, and is not much affected by variations in first layer resistivity (Fraser, 1986).

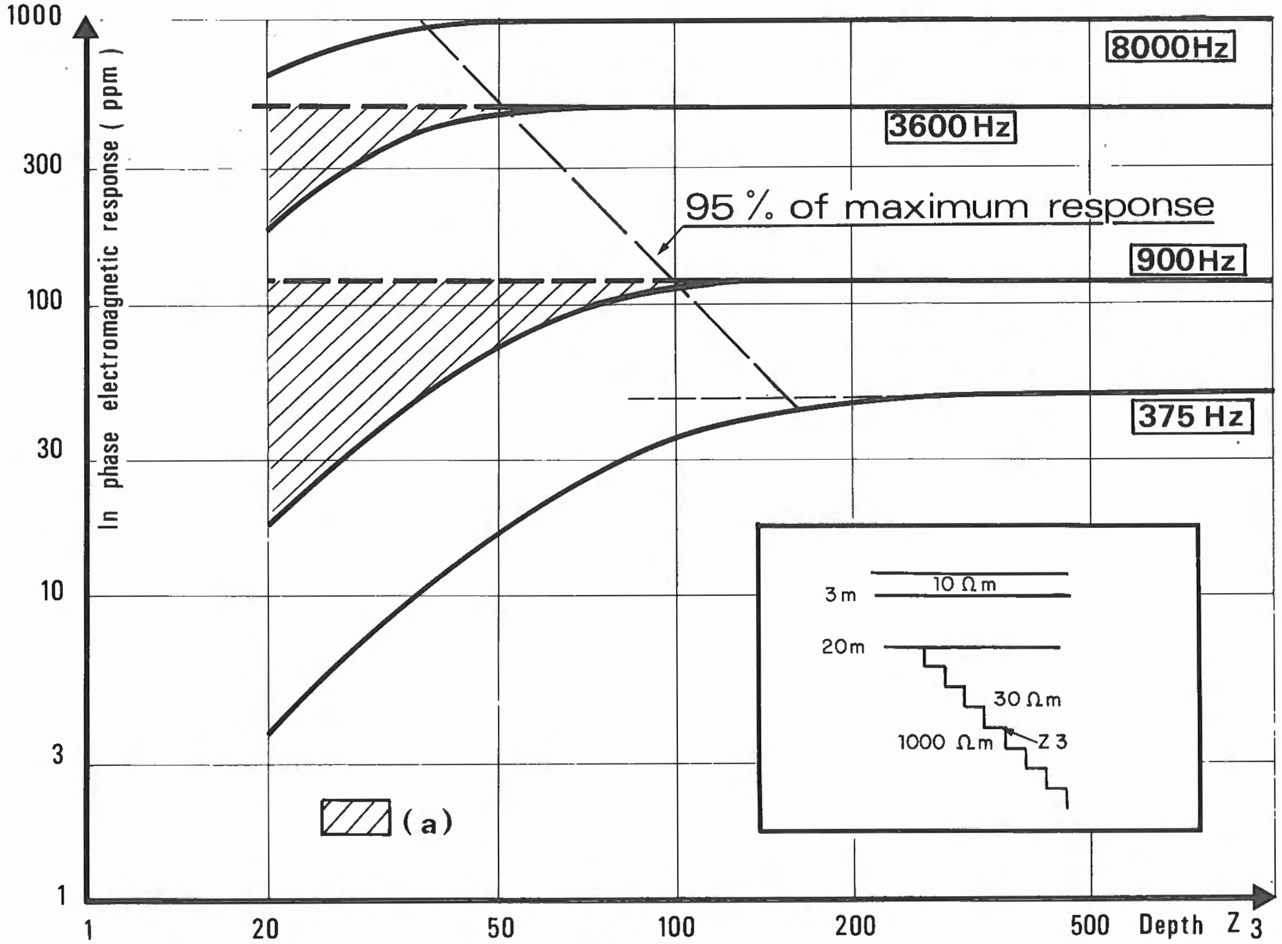

Figure 17.4. Inphase EM response for 4 frequencies as a function of depth. Resistivities and thicknesses are sketched.

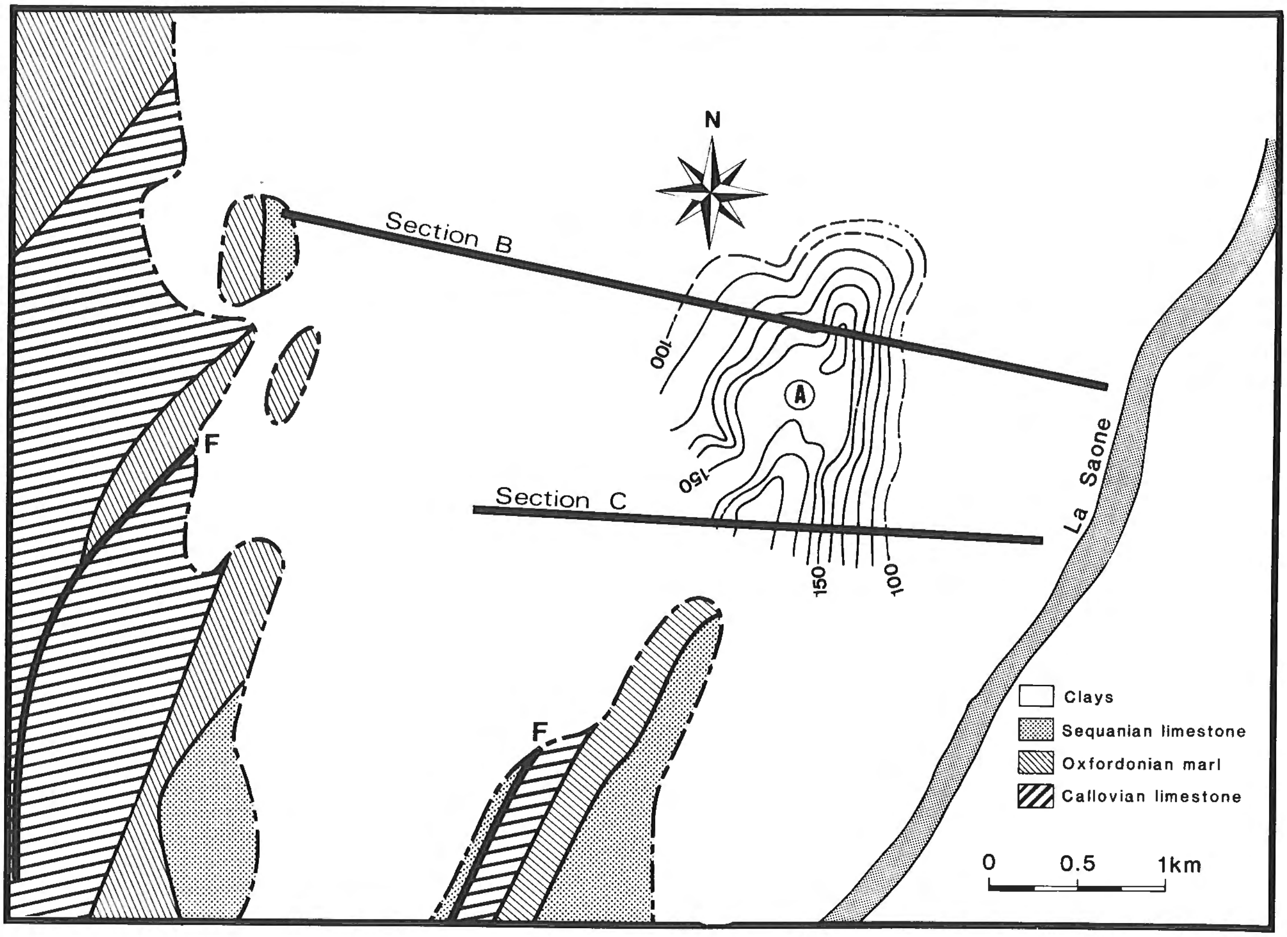

Figure 17.5. Geological map of the Sennecey test site. Letters indicate the following: S: Sequanian limestone, O: Oxfordian marl, C: Callovian limestone, F: Fault, A: Main horst. Contours indicate the elevation of the limestone horst above sea level. The mean elevation of the area is 200 m.

The Sennecey site is described here in greater detail. Figure 17.5 shows the geological map, and Figure 17.6 the east-west sections. The site is located in the Saône River valley, where Quaternary sands and gravels, 8-15 m thick, overlie thick Tertiary marl. At the western limit of the Tertiary basin lie Burgundy hills, which are formed by outcropping Jurassic limestone and marl. Under Tertiary marl, folded Jurassic formations plunge towards the east. South of the test area, a limestone horst (A) outcrops. In the test area, over 50 drillholes were used to trace the topography of the limestone below the Tertiary marl (Fig. 17.5). The average ground elevation is around 200 m. The limestone horst (A) plunges gently north of its outcrop.

Figure 17.7 shows Schlumberger apparent resistivities for a separation of $\frac{AB}{2}$ = 200 m. The contour map was plotted from over 100 resistivity soundings. The highest apparent resistivities were observed above the top of the horst (A), and confirmed its plunge towards the north. Apparent resistivity computed from HEM data (frequency 900 Hz) is shown in Figure 17.8. Four elongated resistive zones have been detected corresponding to limestone ridges. They are separated by conductive zones, which are due either to Oxfordian marl, or thick Tertiary marl. The easternmost ridge corresponds to the main horst "A". The extent of horst A is clearly shown when geological map (Fig. 17.5) and HEM resistivity map (Fig. 17.8) are compared.

A novel concept of "logarithmic resistivity difference" D, was first tested during this survey. D is defined as 34.74 $[\ln \rho_{3600} - \ln \rho_{900}]$. When D is negative, a conductor overlies a resistor. This map (Fig. 17.9) clearly shows the limestone horst extension towards the north (A), where D is negative ($\rho_{900} > \rho_{3600}$ Hz).

Analyzing the depth of penetration reached by various techniques, one comes to the conclusion that HEM at 3600 Hz penetrates 70 m of conductive marls (10 Ωm). At the frequency of 900 Hz the penetration increases to 120 m. Schlumberger resistivity soundings with AB/2 = 200 m had a penetration of 150 m. Surficial high-resistivity lenses degrade the accuracy of the soundings, but have practically no influence on HEM measurements. The field results confirm the mathematical model, which had shown that a resistive basement could generally be located below 100 m of conductive (10 Ωm) overburden.

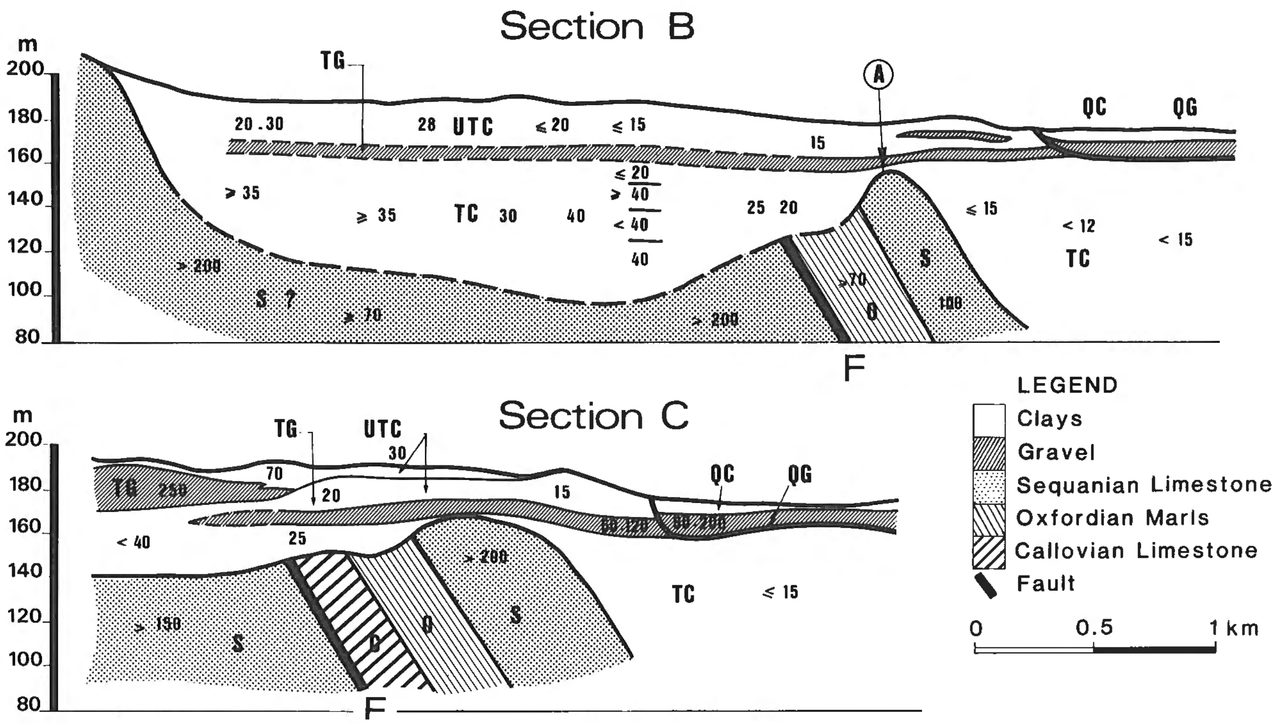

Figure 17.6. Sections at the Sennecey test site. Letters indicate: QC: Quaternary clay, QG: Quaternary gravel, UTC: Upper Tertiary clay, TG: Tertiary gravel, TC: Tertiary clay, S: Sequanian limestone, O: Oxfordian marl, C: Callovian limestone, A: Main horst, F: Fault. Numbers give resisitivites (in Ωm) interpreted from Schlumberger soundings.

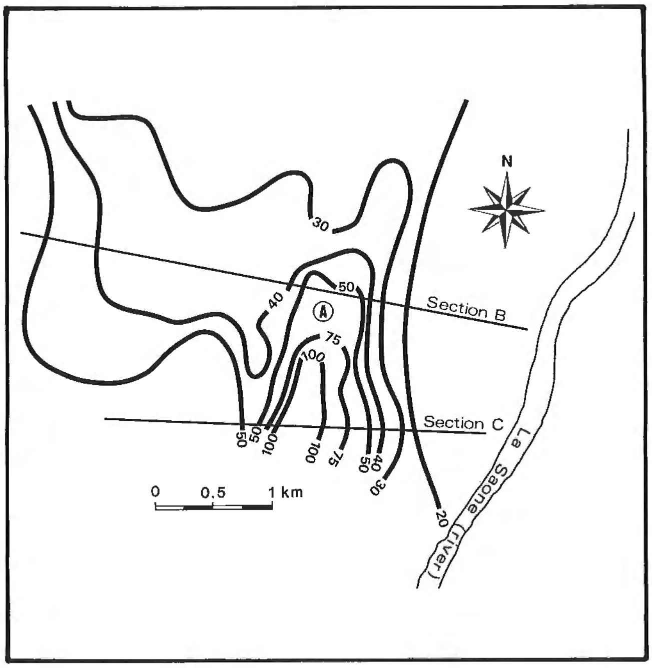

Figure 17.7. Contour map of apparent resistivities obtained along traverses B and C from Schlumberger soundings (AB/2 = 200 m). The area shown is the same as in Figure 17.5.

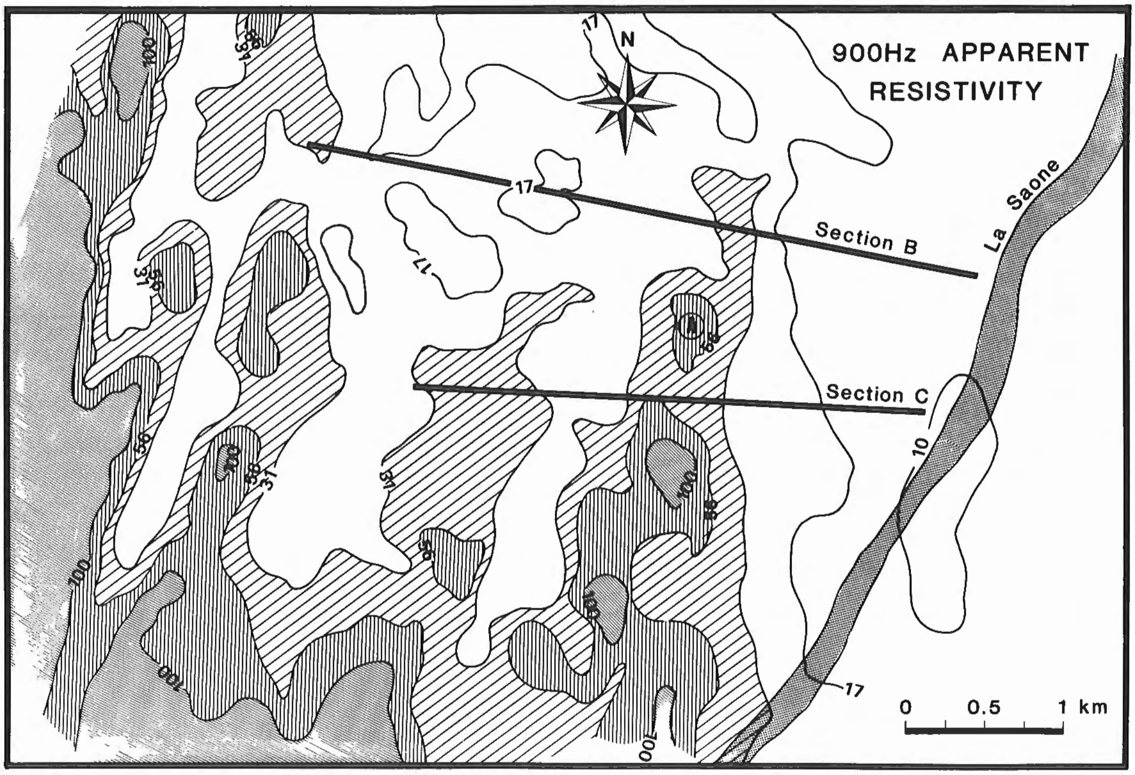

Figure 17.8. Contour map of apparent resistivities computed from HEM data at 900 Hz. The area shown is the same as in Figure 17.5.

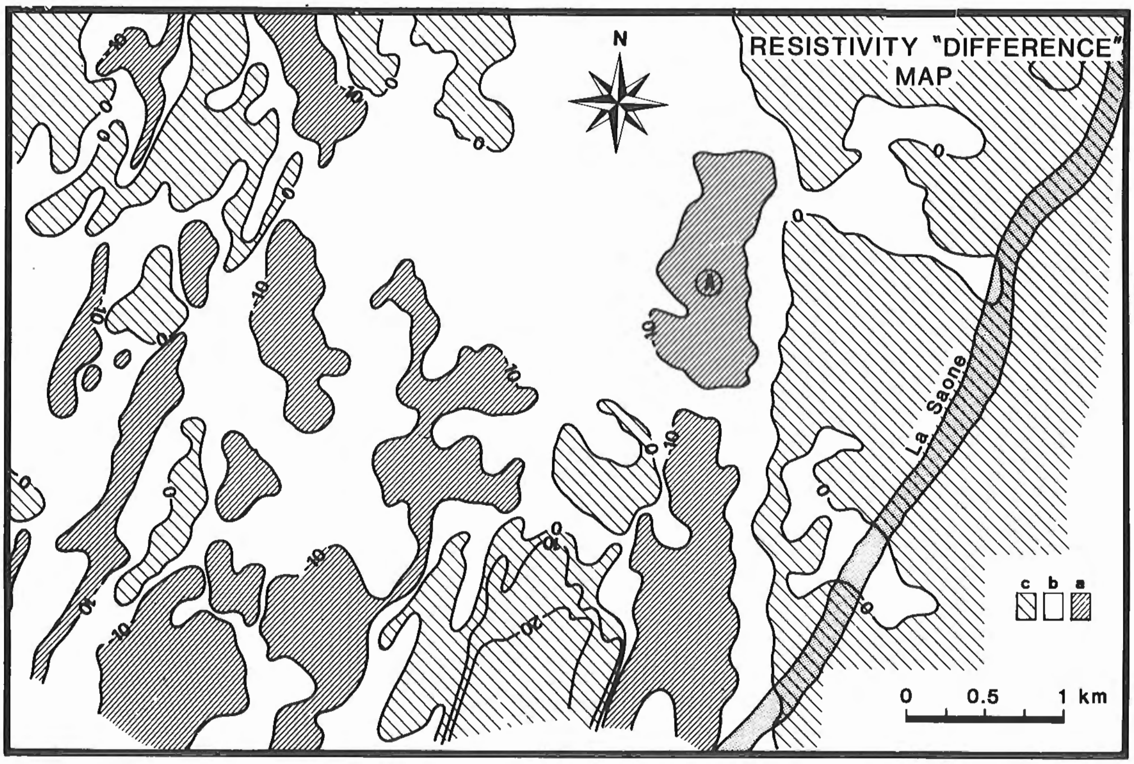

Figure 17.9. Map of HEM resistivity "difference" (for definition see text). Three situations can be distinguished: a–conductor over resistor, b–homogeneous medium, c–resistor over conductor. The area shown is the same as in Figure 17.5.

CONCLUSIONS

The seven selected sites constitute about 75 % of the possible nuclear sites in France. Satisfactory results were obtained at horizontally stratified sedimentary sites, dipping sedimentary sites, over lateral facies variations and buried river channels. At Sennecey, a penetration through 100 m of conductive clays was proved. Less satisfactory results were obtained over karsts at Civaux. Coastal sites were not tested.

EDF's conclusion was that low-cost continuous coverage could be achieved by using helicopter EM surveys. Progress in interpretation techniques seem necessary to increase the efficiency of the quantitative data analysis.

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Airborne electromagnetic methods in the concept assessment phase of the Canadian Nuclear Fuel Waste Management Program

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Soonawala, N.M. and Hayles, J.G., Airborne electromagnetic methods in the concept assessment phase of the Canadian Nuclear Fuel Waste Management Program; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 153-158, 1986.

Abstract

Airborne EM methods have been widely applied in the Canadian Nuclear Fuel Waste Management Program, the objectives being the development of techniques for the detection of fracture zones in bedrock and the characterization of overburden. Major linears in the Whiteshell and Atikokan Research areas have been adequately mapped by helicopter-borne VLF and Dighem systems. Follow-up, consisting of detailed ground surveys and drilling has confirmed that the major airborne VLF anomalies correspond to significant fracture zones in the bedrock. Numerical modelling shows that if a fracture zone is overlain by conductive overburden, the latter can contribute significantly to the resultant anomaly.

Résumé

Le programme canadien de gestion des déchets de combustibles nucléaires fait un large usage des méthodes de levés ÉM aériens. L'objectif de ce programme est d'élaborer des techniques pour la détection de zones de fracture dans la roche en place et l'établissement des caractéristiques du mort-terrain. On a cartographié adéquatement des linéaments majeurs dans les zones de recherche Whiteshell et Atikokan à l'aide de systèmes héliportés à VLF et Dighem. Le suivi, qui a consisté à effectuer des levés détaillés au sol et des forages, a confirmé que les grandes anomalies détectées aux cours des levés VLF correspondent à des zones de fractures importantes dans la roche en place. Les modèles obtenus par ordinateur montrent que si une zone de fracture est recouverte par un conducteur superficiel, ce dernier peut sensiblement contribuer à l'anomalie détectée.

INTRODUCTION

Since the mid 1970s, Atomic Energy of Canada Ltd. (AECL) has been implementing a major research and development program, the Nuclear Fuel Waste Management Program (NFWMP), aimed at developing methodologies for the safe and permanent disposal of nuclear fuel wastes arising from nuclear generating stations. Since the concept being currently examined is that of the burial of nuclear fuel waste about one kilometre below surface in plutonic rock, the geosciences play a major role in the research program (Scott, 1979). An overview of the role of geophysics in this program has been provided by Soonawala (1984).

Amongst the methodologies being developed are those for geotechnical reconnaissance of relatively large areas of up to several hundred square kilometres, and thus airborne geophysical methods are expected to play a significant role in this phase of the research activities. Several research areas have been established in the Precambrian Sheild for the purposes of field testing the concepts being developed in the NFWMP, and all of these have been surveyed with helicopter electromagnetic (HEM) systems, which in most cases have been followed-up by ground geophysical surveys and drilling. Some results of such surveys at the Whiteshell and Atikokan research areas are presented in this paper. Both research areas were surveyed with the Dighem system (Fraser,

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[1] Whiteshell Nuclear Research Establishment, Pinawa, Manitoba R0E 1L0

1979) with a VLF (15 to 30 kHz) sensor also being a part of the HEM package.

The geological features that are of interest in the NFWMP and on which information can be provided by the HEM and VLF techniques are the following: low-resistivity zones that coincide with the surface expression of vertical-trending fractures in the bedrock, the depth of overburden, and the type (and hence the resistivity) of overburden. All granitic plutons studied so far have been found to contain large regional linears, several kilometres long, which can be mapped by several methods including geological mapping, air photo analysis, aeromagnetics, and HEM. Drillhole data strongly suggest that some of these features are structural discontinuities that can have depths in excess of 1 km. Since structural discontinuities can be major groundwater pathways, it is important to identify major linears and determine whether they are related to potential pathways. The success of the EM methods in detecting linears is probably due to the fact that the bedrock is preferentially eroded in their vicinity, and the resulting valleys are filled with wet, highly conductive overburden such as clay.

Information provided by the EM methods on the depth and the nature of overburden helps hydrogeological modelling, the planning of shallow drilling, and the interpretation of several types of geophysical surveys.

The effects of conductive overburden on the VLF field and the relative magnitudes of anomalies caused by bedrock conductors and overburden, can be clearly seen in Figure 18.1 which shows the results obtained from a numerical model developed by T.R. Madden of the Massachusetts Institute of Technology (A.K. Sinha, personal communication, 1985). A modelled bedrock conductor (Fig. 18.1A) is assumed to have a resistivity of 500 Ωm and a width of 12.5 m, values that are typical of many of the fractures that have been drilled in the NFWMP. Host rock is assumed to have a resistivity of 10 000 Ωm. Figure 18.1B shows a 3 m thick layer of overburden of resistivity 30 Ωm. It can be noted that it produces an anomaly much larger than the fracture zone. The combined effect of these two conductive features is shown in Figure 18.1C. It is obvious that for the situation described here the contribution of the bedrock conductor is very small and could possibly remain unrecognized. Though this analysis has been done for a ground VLF survey, it can be expected that the results for a low altitude helicopter-borne VLF survey would be similar.

WHITESHELL RESEARCH AREA

The Whiteshell Research Area is located on the Lac du Bonnet batholith in southeastern Manitoba, which is a member of the Winnipeg River batholithic belt in the English River Subprovince of the Superior Province of the Precambrian Shield (Beakhouse, 1977). Extensive geoscience investigations to provide data for groundwater modelling and to verify its results have been carried out there. Figure 18.2 shows the conductor axes interpreted from a helicopter-borne VLF survey implemented over a 40 km^2 area. The Dighem II system was also operated from the same aircraft at a frequency of about 3600 Hz. Lines spaced 100 m apart were flown by a turbine helicopter at a nominal air speed of 130 km/h. The EM bird was at an average height of 53 m. A Herz Totem 1A VLF sensor (Herz, 1986) was deployed at an average altitude of 58 m, and the station NAA (Cutler, Maine, 17.8 kHz) was used for the primary north-south survey direction. Conductor axes, interpreted from a ground VLF-EM survey at 100 m line spacing over a 4 km^2 area, within the larger area covered by the HEM survey, are shown in Figure 18.3, along with highly resistive zones (greater than 10 000 Ωm) mapped by a gradient-configuration resistivity survey. As can be expected, the airborne survey map does not show the same degree of detail as the ground VLF survey map, but

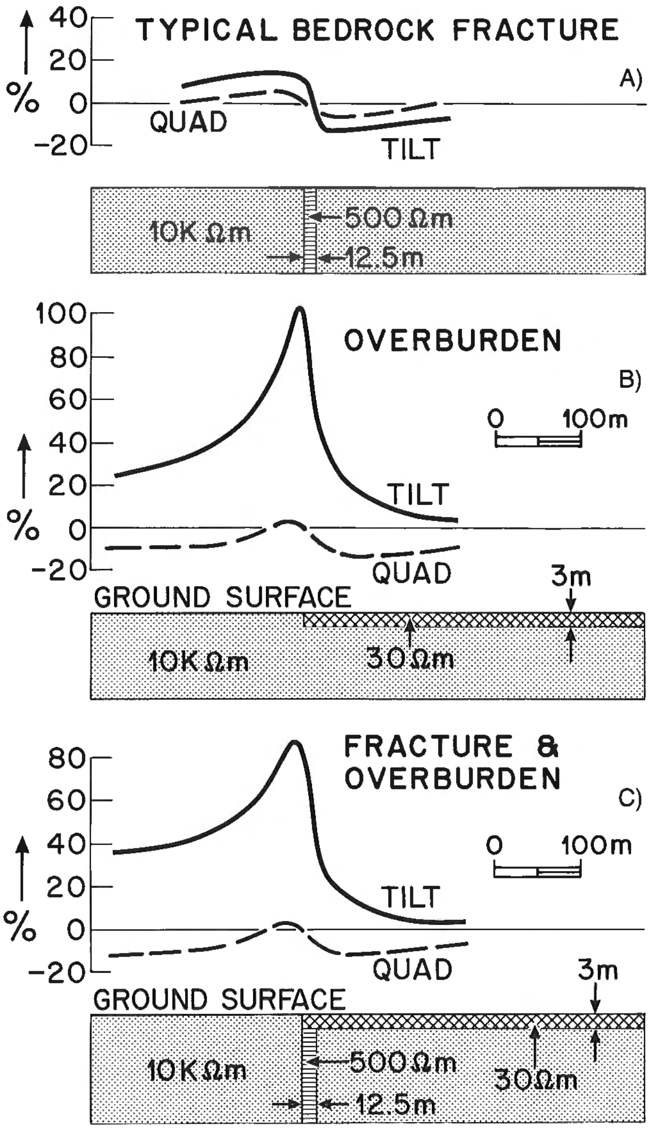


Figure 18.1. VLF tilt angle and quadrature responses due to: A) bedrock conductor alone; B) a layer of conductive overburden, and C) a combination of the two.

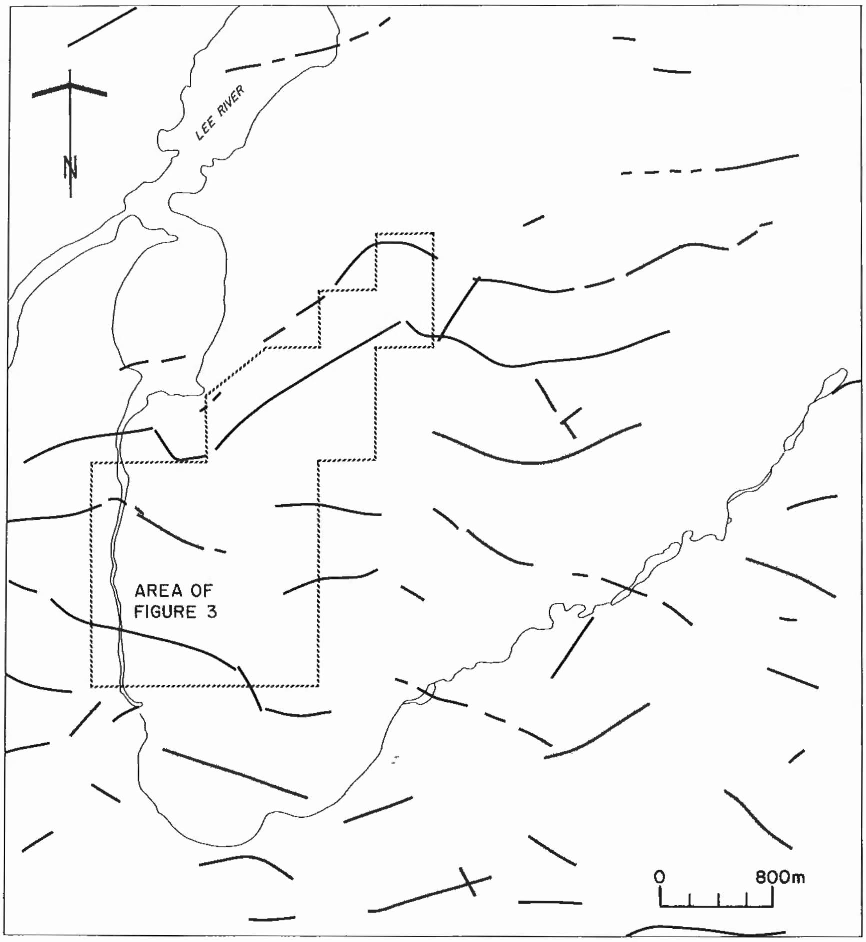


Figure 18.2. Airborne VLF conductor axes over a part of the Whiteshell Research Area. The NAA transmitter was used for north-south flight lines.

the more prominent conductors, e.g., AA′ and BB′, were adequately mapped by the airborne system. As discussed earlier in relation to the models shown in Figure 18.1, it is likely that these anomalies are caused by conductive overburden, which in turn can be related to bedrock features.

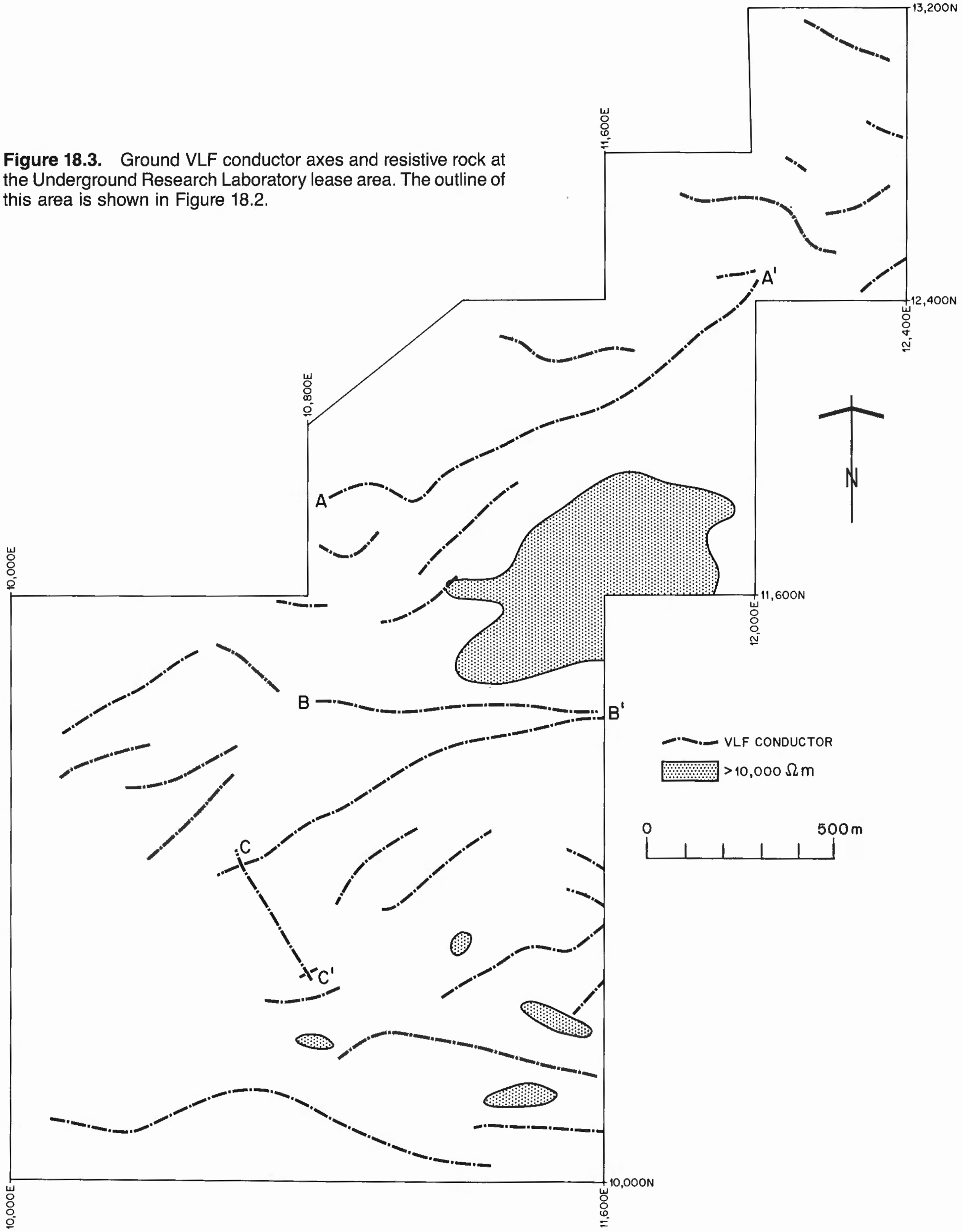
Figure 18.4 is a cross-section showing subsurface fractures in that area, interpreted from extensive drilling data by Davison (personal communication, 1983). This section is approximately at right angles to the strike direction of AA′. It is evident that the intersection of the moderately dipping fracture zone 3 with the surface corresponds to AA′. Geological examination of core has shown that this fracture zone is entirely within the Lac du Bonnet granite and consists of highly weathered material up to 10 m wide. At places, the consistency of the weathered material is similar to that of clay.

ATIKOKAN RESEARCH AREA

The Atikokan Research Area is centred around the granite Eye-Dashwa Lakes pluton, about 25 km northwest of Atikokan in northwestern Ontario. It lies within the Superior Structural Province of the Precambrian Shield (Stone, 1984). At this research area a helicopter-borne EM survey was carried out using equipment and survey parameters similar to those used at the Whiteshell Research Area. As a result, a prominent VLF conductor has been located that extends through Eye and Dashwa lakes and is open-ended at either end (Fig. 18.5). Its location has been confirmed by detailed VLF and magnetic surveys on the ground between the two lakes and on the ice on Dashwa Lake. Figure 18.6 shows conductors AA′ to PP′ that have been interpreted on the basis of VLF surveys carried out in two orthogonal directions and for which transmitters NAA, NSS and a local transmitter were used. Conductors AA′ and HH′ clearly correspond to the airborne conductor shown in Figure 18.5. A prominent fracture zone corresponding to this conductor has also been located by drilling, at a downhole length of about 150 m in borehole ATK-8 whose trace is shown in Figure 18.6.

A two-layer model developed by Dighem Ltd. was also used to calculate the overburden characteristics in that area, using data from the Dighem III system at 900 and 7200 Hz. One pair of co-axial coils and two pairs of coplanar coils were used. The former operated at 900 Hz, whereas the latter two pairs were operated at either frequency. A two-layer inversion routine was employed, in which the input parameters are the in-phase and quadrature components at 900 and 7200 Hz

Figure 18.3. Ground VLF conductor axes and resistive rock at the Underground Research Laboratory lease area. The outline of this area is shown in Figure 18.2.



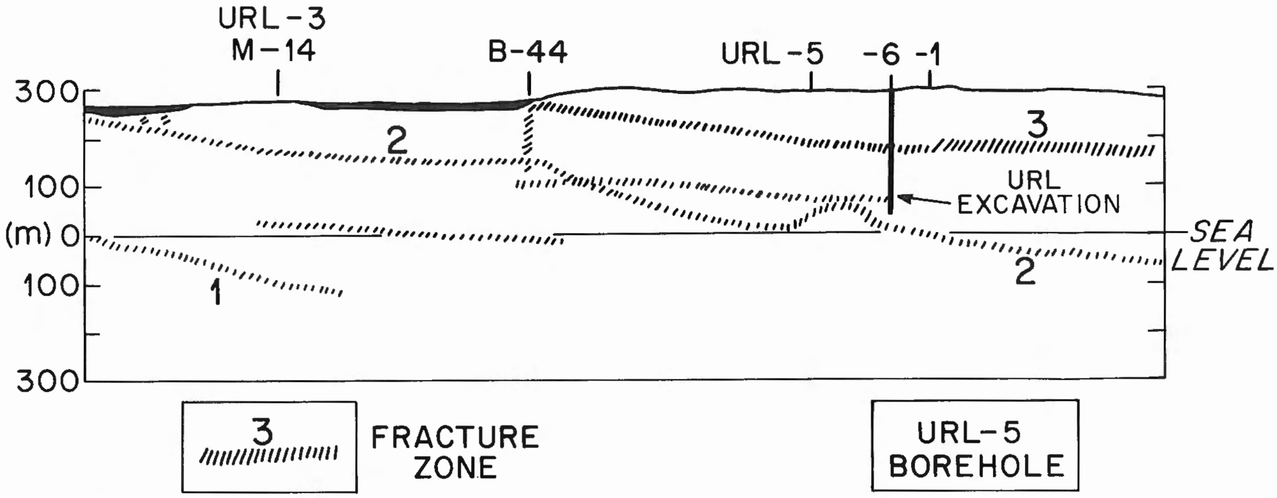


Figure 18.4. A cross-section through the Underground Research Laboratory lease area. Locations of URL-, M- and B-series of boreholes are indicated.

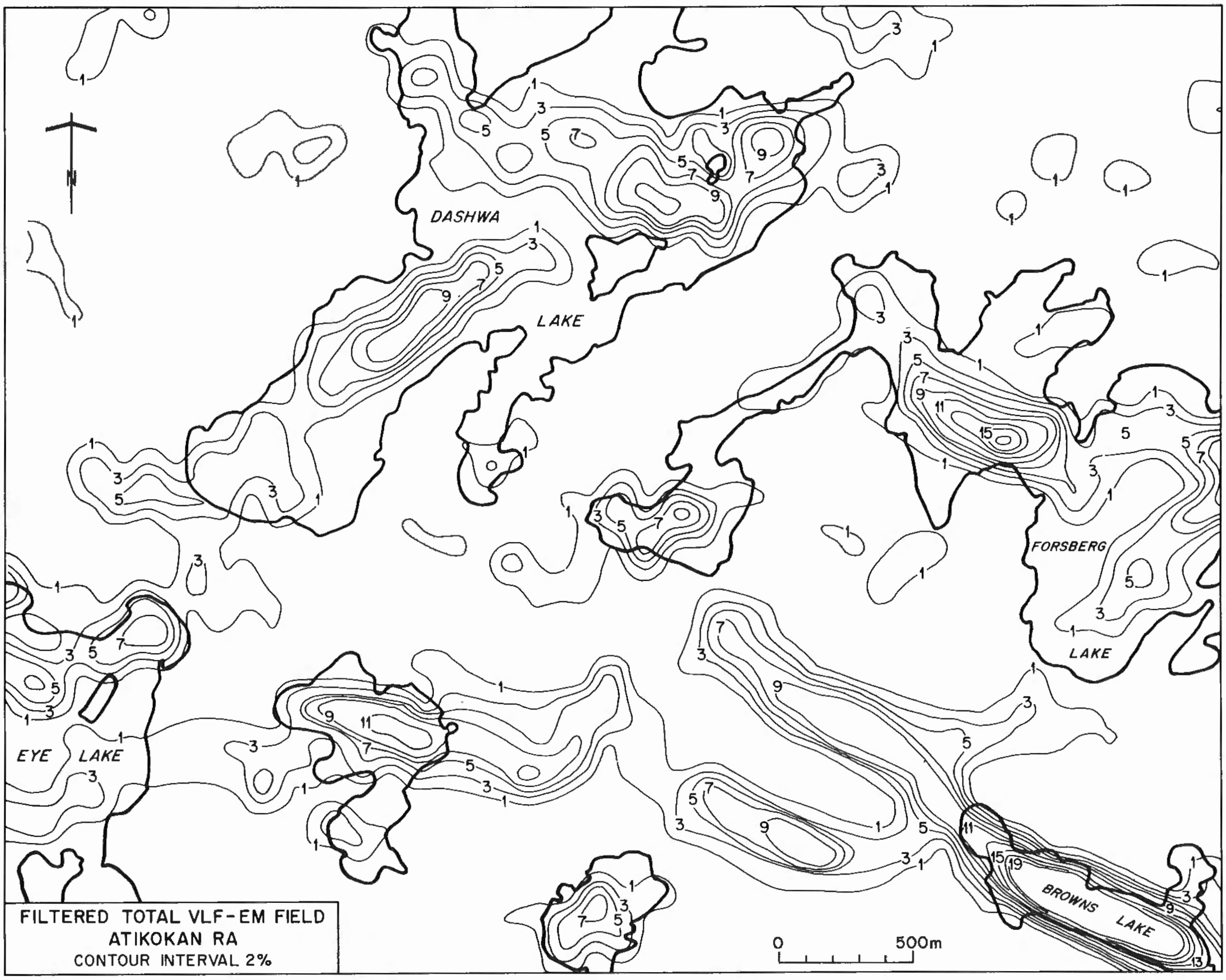


Figure 18.5. Airborne VLF conductors over a part of the Atikokan Research Area. The flight lines were north-south and NAA transmitter was used.

from the two sets of coplanar coils; and the output parameters are the resistivities of the upper and the lower layer and the thickness of the former. Results of the modelling were not entirely satisfactory, probably because in the rugged topography of the Precambrian Shield, the two-layer model is not very realistic and the lower frequency (900 Hz) was too low to energize any material other than the most conductive lake bottom sediments.

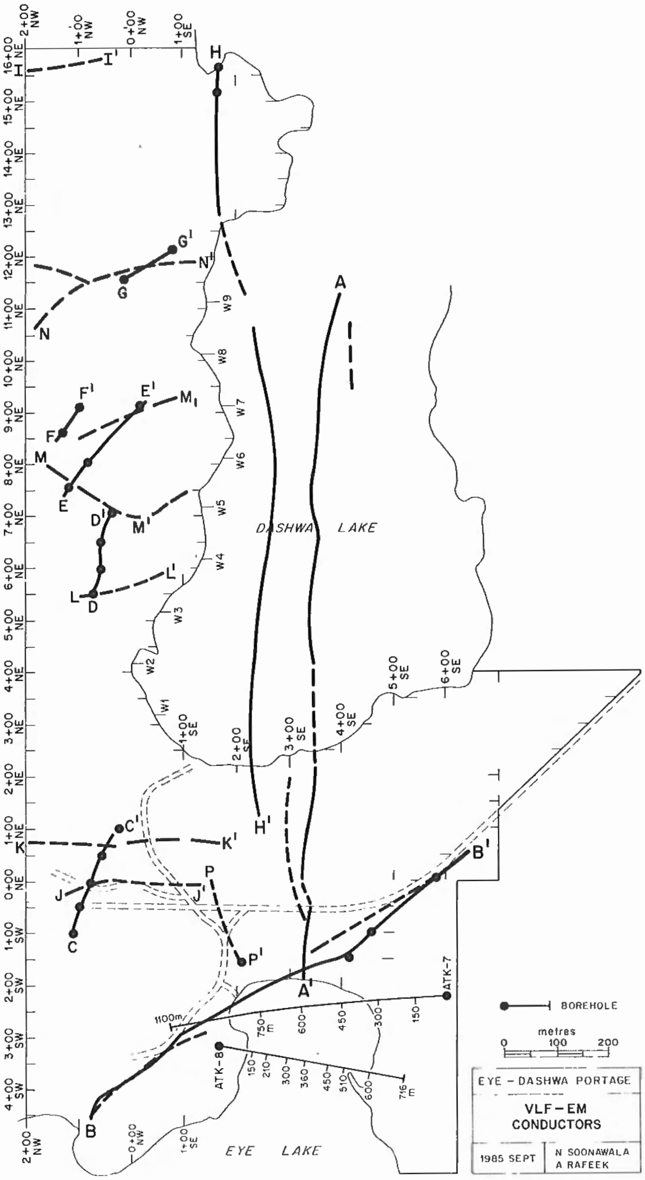


Figure 18.6. Ground VLF conductors in the Eye-Dashwa lakes region of the Atikokan Research Area.

CONCLUSIONS

Helicopter-borne EM and VLF methods have been useful in mapping linear conductors, which are significant features in the context of the Canadian Nuclear Fuel Waste Management Program and usually correspond to fracture zones in the bedrock. Most of these are prominent regional features which can also be observed on aerial photographs. Much success has not been achieved so far in the characterization of surficial material, but the prospects are good once more suitable frequency ranges and more realistic interpretation models become available.

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- 19 -

Systematic airborne electromagnetic surveys in Finland: an overview

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Abstract

The development and application of airborne electromagnetic (AEM) methods in Finland are briefly described. Most of the AEM surveys have been carried out by the Geological Survey of Finland, which has been involved in the development and the use of the technique since the early 1950s. Several different methods have been applied until today. Special attention is focused in this paper on the rigid-coil AEM systems used for low-elevation surveys since 1972. Such surveys, for both exploration and geological mapping, are conducted in Finland in an attempt to replace geophysical ground surveys over extensive areas. On account of the mutual correlation of survey data and the costs involved, aeromagnetic, AEM, and airborne gamma-ray surveys are undertaken simultaneously. The amount of AEM surveys currently flown is about 60 000 line km per year.

Numerical and scale modelling studies have been used to assess the performance of the different AEM systems. Computer programs have been developed by the Geological Survey and by industry that permit the inphase and quadrature data to be transformed into apparent conductivity, conductance, and depth values with one-layer, two-layer and half-plane conductor models.

Further developments for AEM survey methods in Finland include the addition of a new VLF resistivity mapping technique, and the improvements in the data processing and interpretation methods. The importance of airborne geophysical surveys for geological mapping in Finland is evidenced by the fact that since 1982, no such mapping projects have been started without the map area being first surveyed with airborne geophysics.

Résumé

L'étude décrit la mise au point et l'application des méthodes de levés électromagnétiques aériens (ÉMA) en Finlande. La plupart des levés ÉMA ont été réalisés par la Commission géologique de Finlande, qui élabore et utilise des techniques de ce genre depuis le début des années 1950. Plusieurs méthodes ont été appliquées jusqu'ici. La présente étude accorde une attention particulière aux systèmes ÉMA à bobines rigides utilisés pour les levés d'altitude de vol faible depuis 1972. En Finlande, on effectue des levés de ce type tant pour la prospection minérale que pour la cartographie géologique, afin de remplacer les levés géophysiques au sol sur de vastes étendues. Afin de porter la corrélation réciproque des données des levés et la rentabilité des travaux, les levés magnétiques, ÉMA et radiométriques aériens sont entrepris simultanément. Le rendement annuel des levés ÉMA est proche de 60 000 km linéaires.

On a réalisé des études numériques et sur modèles à l'échelle pour évaluer le rendement des différents systèmes ÉMA. La Commission géologique et l'industrie ont élaboré des programmes informatiques qui permettent de transformer des données en phase et en quadrature en valeurs de conductivité apparente, de conductance et de profondeur avec des modèles à une couche, deux couches et à demi-plan vertical.

Les perfectionnements qu'on prévoit apporter aux méthodes de levés ÉMA en Finlande porteront notamment sur une nouvelle technique de cartographie par VLF et sur l'amélioration des méthodes de traitement des données et d'interprétation. On peut juger l'importance que revêtent les levés géophysiques aériens pour la cartographie géologique en Finlande, si l'on considère que depuis 1982, aucun projet de cartographie géologique n'a été entrepris dans ce pays sans que la zone à cartographier ait d'abord fait l'objet de levés géophysiques à l'aide de systèmes aéroportés.

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INTRODUCTION

This study deals with the application (past, present, and future) of airborne electromagnetic (AEM) methods in Finland. The Geological Survey of Finland has been engaged in the development and use of AEM methods since the early 1950s, and has carried out the majority of the measurements. However, larger exploration companies in Finland have also carried out quite extensive AEM surveys, either with their own systems or with those of contractors. As several AEM methods have been applied during the past thirty years, the developments in Finland reflect world wide trends in AEM techniques.

An important step in the execution of any airborne geophysical survey is the selection of methods. Multiple techniques flown simultaneously lower the survey cost and permit better correlation between data sets. Aeromagnetic, AEM, and airborne gamma-ray systems should, when possible, be included. A longterm, country-wide mapping program allows two major applications, direct prospecting and geological mapping of conductive formations and favourable horizons. The use of the results of the combined surveys to exploration and geological mapping requires that survey data of various methods are presented systematically and with sufficient uniformity, and in a form readily available to all end-users. This is particularly important for present-day detailed surveys, since they are conducted to maximize detail, in an attempt to replace geophysical ground surveys over extensive areas.

The importance of airborne geophysical results for geological mapping in Finland is evidenced by the fact that, since 1982, no new geological mapping at a scale of 1 : 100 000 or greater has been started without the area first having been surveyed with airborne geophysics. This allows direct savings in the cost of fieldwork and improves substantially the accuracy of the final geological maps.

AEM SURVEYS IN FINLAND

Most airborne geophysical measurements in Finland have been undertaken by the Geological Survey of Finland. Mapping started in 1951 with aeromagnetics using a flux-gate magnetometer. In 1954, measurements with a towed-coil AEM system constructed at the Survey were introduced, and in 1956 an airborne gamma-ray scintillometer was added to the equipment. These early (high-elevation) surveys were undertaken at a flight height of 150 m, a line spacing of 400 m, and an average survey speed of 260 km/h. The AEM equipment, a predecessor of the widely used dual-frequency system (Paterson, 1961), was installed in a Lockheed Lodestar aircraft. The System operated at a frequency of 400 Hz and had a coil separation of 150-250 m.

High-elevation airborne surveys were terminated in 1972, when the general aeromagnetic mapping of the whole country was completed. In the same year, more detailed (low elevation) surveys were started at a nominal flight elevation of 30 m, a line spacing of 125-200 m, and a survey speed of 170-200 km/h. The survey equipment, which included two proton precession magnetometers, an AEM rigid-coil system (frequency 3220 Hz, coil separation 25 m), and a gamma-ray spectrometer, was installed in a Douglas DC-3 aircraft (Peltoniemi, 1982). Since 1980, the present equipment, which consists of a three-magnetometer gradiometer, a wing-tip AEM rigid-coil system (frequency 3113 Hz, coil separation 21.4 m), and a gamma-ray spectrometer, has been fitted in a DHC-6 Twin Otter aircraft (Vironmäki et al., 1982).

In the 1960s and 1970s, the national airborne geophysical mapping program of the Geological Survey was not able to meet alone all the survey requirements of Finnish mining companies. Consequently, both Outokumpu Oy Exploration and Rautaruukki Oy Exploration have performed extensive AEM surveys.

Outokumpu Oy Exploration started systematic AEM surveys in 1960 with the rotary field method (Ketola et al., 1971). The company used the system in a two-aircraft version. The distance between the two aircraft (the coil separation) was 220-260 m, the frequency was 880 Hz, the flight elevation 60-100 m, and the line spacing 250 m.

Rautaruukki Oy exploration undertook AEM surveys from 1966 onwards with a wing-tip AEM system installed in a Cessna 185 aircraft. The coil separation of the vertical coplanar coil system was 11 m, and the frequency 1920 Hz. The surveys were flown at a nominal elevation of 30 m, and with a line spacing of 200 m.

Finnprospecting Ky, and later Suomen Malmi Oy, performed AEM contract surveys for Finnish mining companies from the early 1970s until 1979. The system was installed in a Pilatus Turbo Porter aircraft and included AEM, aeromagnetic and gamma-ray spectrometric equipment. The coil separation of the wing-tip AEM system was 16.4 m and the frequency 3600 Hz.

Geoinstruments Ky, a Finnish manufacturer of geophysical survey intruments, has been actively involved in the design and construction of AEM systems. The company has recently exported two rigid coil AEM systems to Sweden.

To date, AEM surveys in Finland have covered almost 1.9 million line km, which is a large amount considering the size of the country (337 000 km^2). The breakdown of the total coverage is given in Table 19.1. The amount of AEM surveys currently flown is about 60 000 line km per year.

Finland has been virtually self-sufficient in its AEM surveying programs. Only a few test flights were undertaken with foreign equipment. Rotary-field test surveys from AB Elektrisk Malmletning, Sweden, were ordered by Outokumpu Oy in 1959 before the company acquired its own system. In 1964, Otanmäki Oy performed a test survey with a rigid-coil wing-tip system developed by Boliden Ab, Sweden. In 1961 the same system had been used in a test survey at the Pyhäsalmi sulphide ore deposit. In 1965, Barringer Research Ltd. of Canada collaborated with Otanmäki Oy in experiments with the time-domain system over the Gulf of Bothmia near the town of Raahe, and in the following year

Table 19.1 AEM surveys flown in Finland in 1954-1985.

Organization and type of survey	Distance (line km)
Geological Survey of Finland	
high elevation surveys	800 000
low elevation surveys	676 000
Outokumpu Oy Exploration	
rotary field surveys	173 000
low elevation surveys	58 000
Rautaruukki Oy Exploration	
low elevation surveys	166 000
Total	1 873 000

with both Otanmäki Oy and Outokumpu Oy on various prospects in NW Finland.

PROCESSING AND INTERPRETATION OF AEM DATA

In Finland, both stacked-profile and contour maps of inphase and quadrature components are produced from the AEM survey results. The basic processing of AEM data involves the removal of noise originating from non-geological sources, and the correction of temporal drift in the zero levels of the recorded signals. Visual interpretation and the use of stacked profile maps are not hindered by small errors in the zero levels or drift corrections. However, for compilation of contour maps, the zero levels must be correct within a narrow error range.

The maps (example of stacked-profile maps is given in Fig. 19.1) are produced at a scale of 1 : 20 000 in accordance with the Finnish topographic map division. The stacked-profile maps have a linear scale for anomalies with a scale coefficient of 400 ppm/cm or, in areas with large anomalies, 1000 ppm/cm. It is worth noting that the data on the stacked-profile maps have not been submitted to any additional filtering except that due to the time constant of the detector (0.3 s) and spherics removal. This preserves the original resolution of the data and allows the recognition of small, short-wavelength anomalies.

To produce AEM contour maps of inphase and quadrature components the data are interpolated onto a rectangular grid, one element measuring 50 × 200 m^2. Hence the data matrix of a standard-sized map sheet of 10 × 10 km^2 has about 11 000 data points. Contours are generated from the gridded data by a commercial software package. The contours are plotted on a progressive scale, and the maps have three colours to highlight high and low amplitude anomalies (red and blue respectively, with black used for average values).

The most common usage of AEM results has been in visual interpretation, using also information from lithology and Quaternary geology of the study area. Geometric characteristics of anomalies such as their shape and extent are used to distinguish conductor types. Where quantitative rather than visual interpretation is called for, well-defined anomalies can be interpreted using characteristic anomaly parameters or curve-fitting methods. The application of these methods, an example of which is given in Figure 19.2, requires a suite of AEM responses to a variety of idealized conductor models by both numerical modelling and scale model measurements. The Geological Survey of Finland has recently devoted considerable efforts to AEM modelling problems (Peltoniemi, 1982; Poikonen, 1985).

A more sophisticated method for interpreting AEM data is to perform direct transformation of survey data into model parameters that include both the geometry and the physical properties of the conductors. An effective approach is to fix the geometry of the inversion model and to determine conductivity of the conductor with the aid of a computerized data bank. Computer software was developed at the Geological Survey in 1978-81 for interpreting vertical coaxial (DC-3 system) data (Peltoniemi, 1982). The software has recently been extended and now allows vertical coplanar (Twin Otter wing-tip system) data to be transformed as well. Models have been implemented for a conductive half-space and a conductive overburden. Figures 19.3-19.5 give examples of results obtained with both models. Figure 19.3 also shows a comparison of results from different ground surveys. A total of 46 000 line km of AEM survey data has been processed so far using the software developed by the Geological Survey. The results show that, with proper choice of dimensions for the AEM systems, the transformation of single-frequency AEM data is feasible and gives useful results. One should add that conductivity conditions in Finland (thin glacial overburden and highly resistive bedrock) are less complex than most parts of the world.

FUTURE DEVELOPMENTS

A major AEM project underway at the Geological Survey of Finland is the development of an airborne VLF survey system. The existing AEM wing-tip system can map resistivity values 3000 Ωm or smaller. The addition of a VLF resistivity mapping technique to the current set of methods operational in the Twin Otter installation will permit higher resistivity values to be measured. It will thus extend the range of geological mapping and engineering applications and turn the AEM method into a truly wide-band resistivity mapping technique (Poikonen, 1985). The first two steps in the project are to select optimum parameters of measurement, and to monitor and select VLF-band transmitters suitable for airborne surveys in Finland; these two phases have already been completed. The third phase, which comprises the design and construction of the VLF detector and signal processing unit, is currently in progress.

Rapid developments in computer hardware technology have made feasible a truly interactive mode of processing and interpretation of AEM data. Using a graphic-display terminal or work station the geophysicist can select the desired operations from a menu on the terminal screen which displays simultaneously all the data within a selected window in the same way as the data will appear on the final map. Windowing

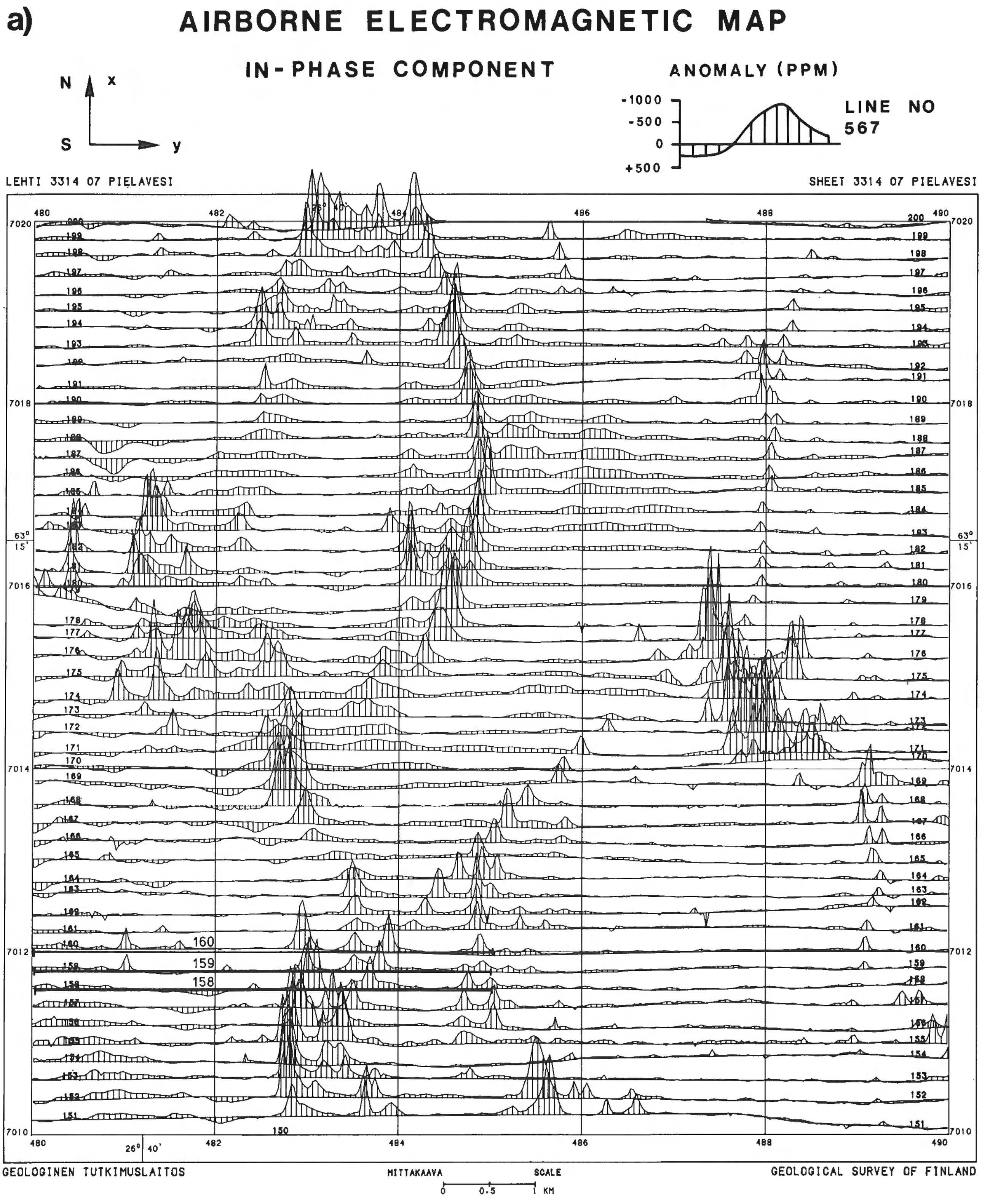
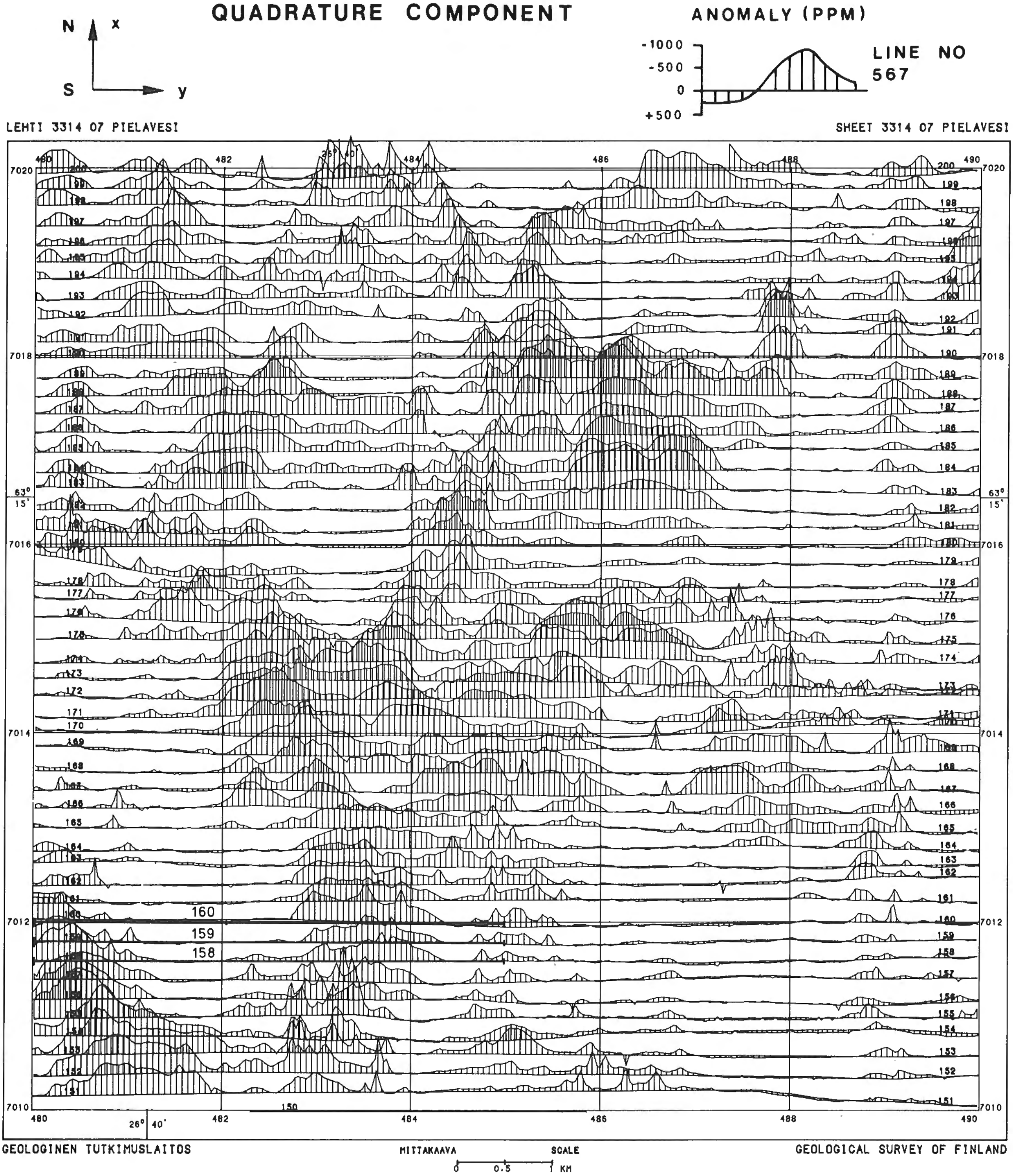


Figure 19.1. AEM anomaly map of the Pielavesi area, central Finland. Vertical coaxial (DC-3) system. The Säviä Cu-Zn deposit is traversed by survey lines 158, 159 and 160 in the SW corner of the map area. a) In-phase component. b) Quadrature component (from Peltoniemi 1982).

b)

AIRBORNE ELECTROMAGNETIC MAP

QUADRATURE COMPONENT



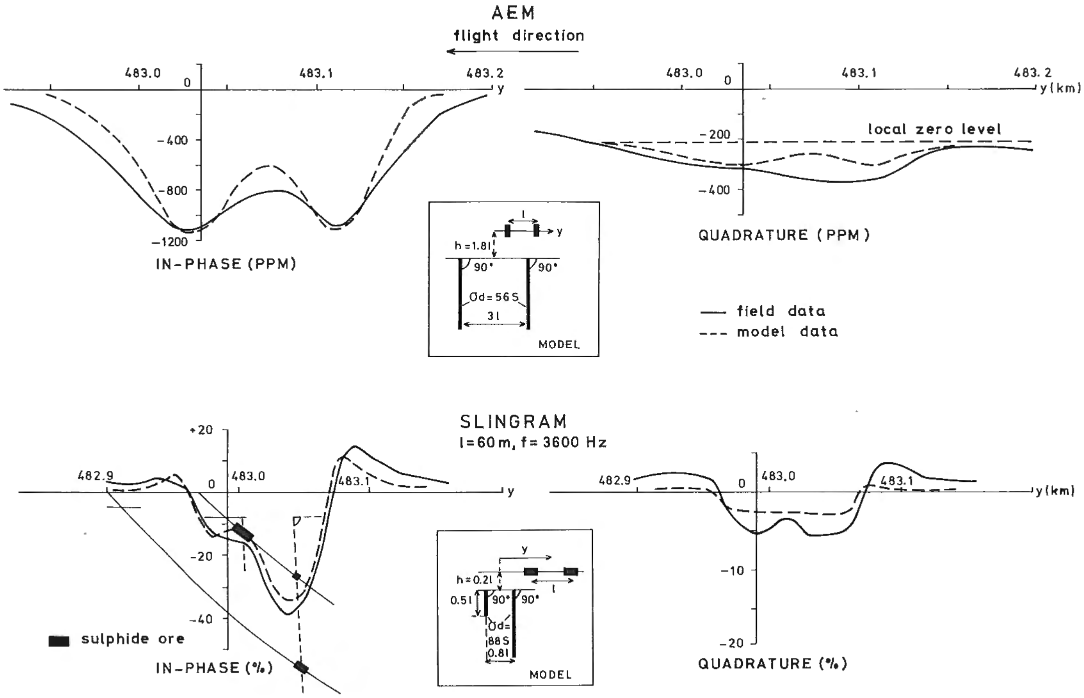


Figure 19.2. Example of interpretation: vertical coaxial (DC-3) AEM results from the Säviä deposit, survey line 158 (cf. Figure 19.1). Interpretation of horizontal-loop EM data is also given (after Peltoniemi, 1982).

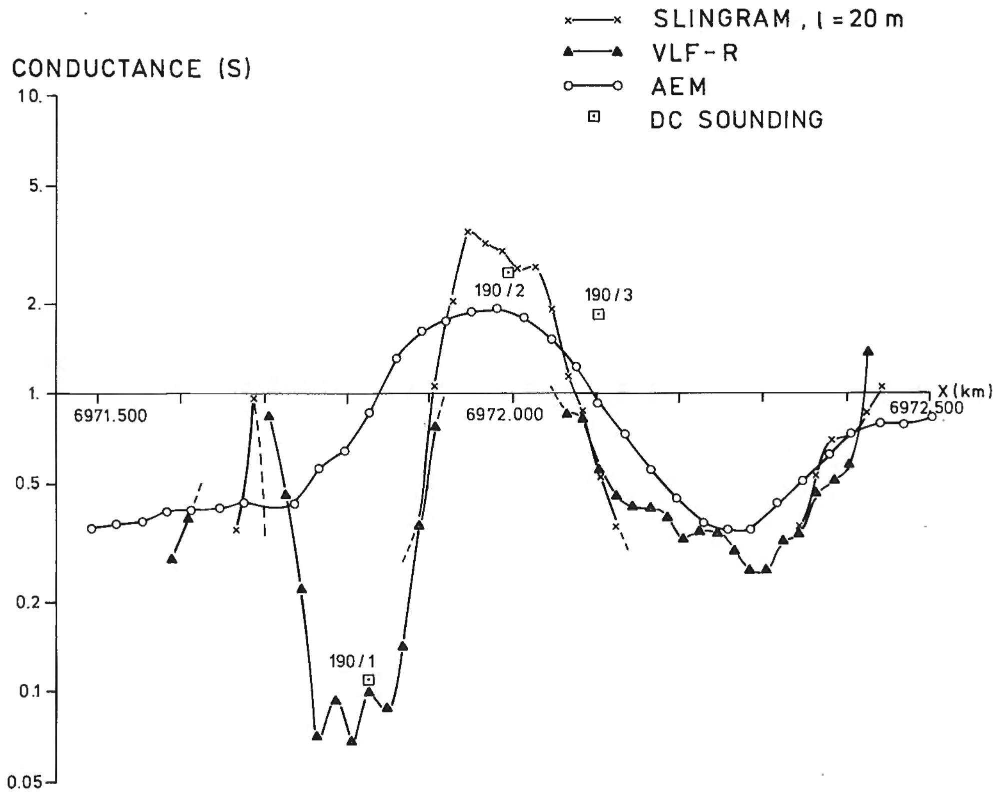


Figure 19.3. Values of apparent conductance (in S) of conductive overburden, calculated from the results of different electrical and EM data. Seinäjoki area (line 190), western Finland (from Peltoniemi, 1982).

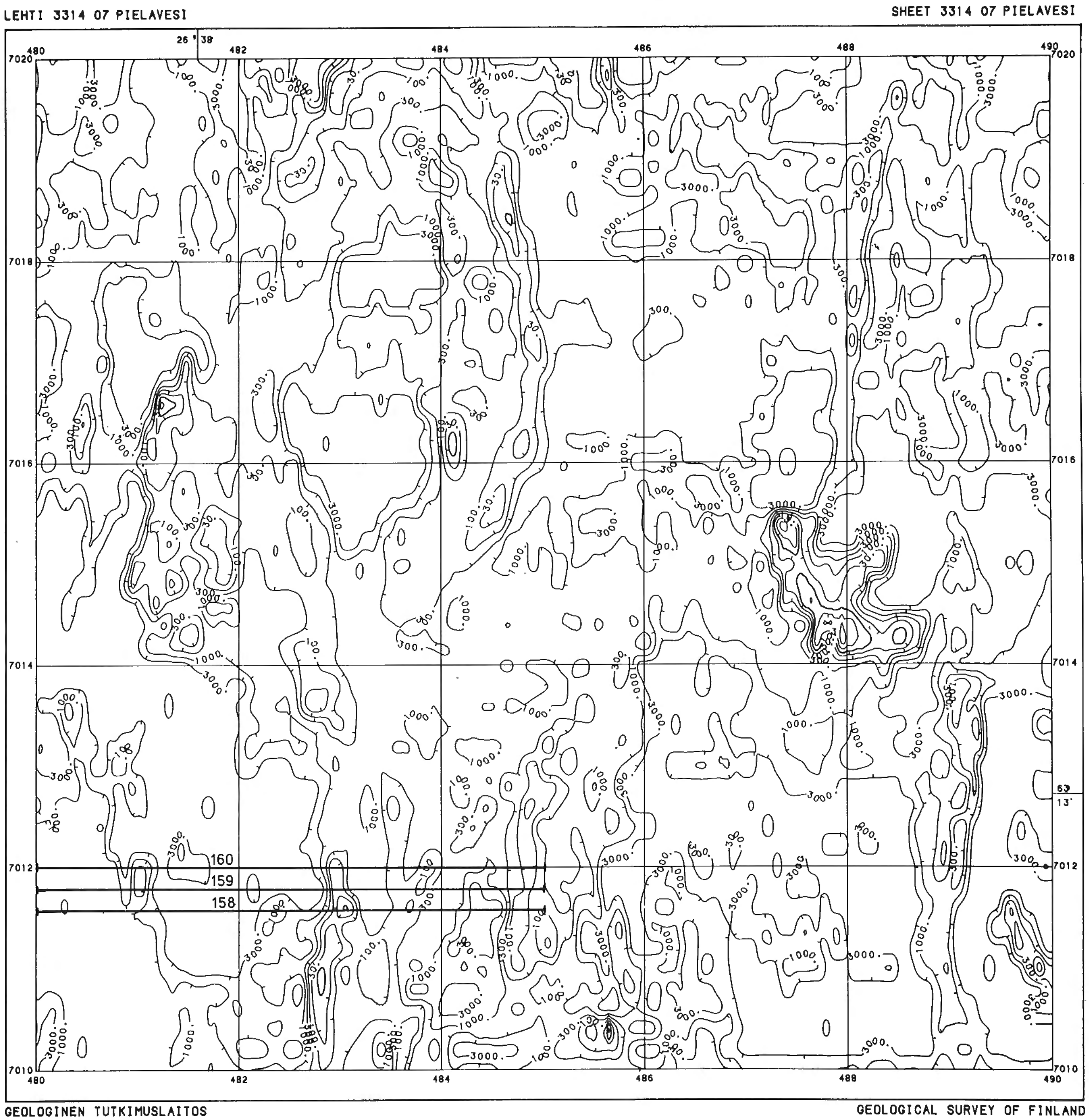


Figure 19.4. Apparent resistivity map compiled from AEM data (cf. Fig. 19.1) assuming a conductive half-space model. Pielavesi area, central Finland. Contours (in Ωm) 3000, 1000, 300, 100, etc. (after Peltoniemi, 1982).

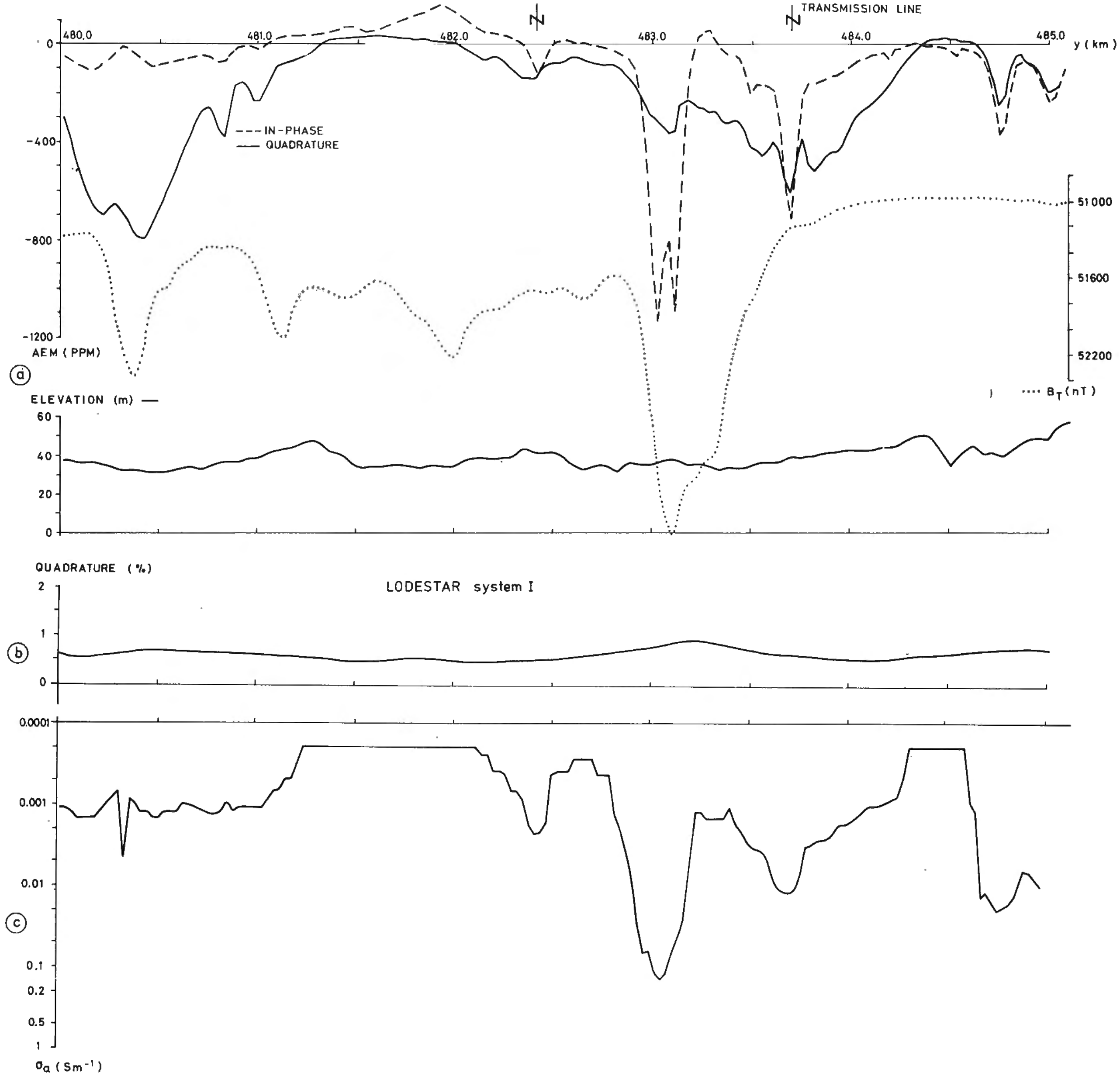


Figure 19.5. Survey line Pielavesi 158, results of various geophysical methods. a) DC-3 airborne geophysical survey: AEM, magnetic and flight elevation data. b) High-elevation AEM (Lockheed Lodestar system) data. c) Values of apparent conductivity σ_a calculated from AEM (DC-3) survey data (assuming half-space model). Cf. Figures 19.1, 19.2 and 19.4. (from Peltoniemi, 1982).

and zooming operations allow the user to achieve the required level of accuracy in the corrections. Software of this nature has been developed by Geoinstruments Ky. All operations for basic processing are interactive, and the half-space, overburden and half-plane models have been incorporated into the transformation module of the software. The current version of the software can process AEM data from a four-channel system. Geoinstruments Ky and the Helsinki University of Technology are currently working on a joint project to incorporate more input channels and new conductor models.

The goal and longterm plan of the airborne geophysical mapping program in Finland is to cover the whole country with detailed low-elevation surveys. With the present capacity and survey specifications it will take another fifteen years and a million line km before the program is completed.

ACKNOWLEDGMENTS

I thank my colleagues at the Geological Survey of Finland, especially Jouko Vironmäki, Jukka Multala and Ari Poikonen, for information about recent developments in, and future plans for, the AEM survey technique at the Geological Survey. Thanks are also due to the Helsinki University of Technology and Geoinstruments Ky, Finland, for assistance received in the course of this study.

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- 20 -

La couverture en levé électromagnétique aéroporté de la province de Québec

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Lefebvre, D.L., Dion, D.J. et Keating, P., La couverture en levé électromagnétique aéroporté de la province de Québec; in Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 000-000, 1986.

Résumé

La couverture en levé électromagnétique aéroporté du Québec a débuté en 1969 avec un levé INPUT® en Abitibi. Depuis lors, quelques 111 700 km² de territoire ont été couverts en Abitibi, dans la fosse du Labrador, en Gaspésie et en Estrie. L'espacement des lignes de vol est de 200 m avec une hauteur de vol de 120 m pour l'INPUT et de 40 m pour les levés héliportés. Les données électromagnétique et magnétiques sont publiées à l'échelle de 1:20 000. Depuis 1974, les données sont enregistrées digitalement; des traitements sont appliqués aux données numériques pour produire des cartes en couleur de gradient vertical et de champ total magnétique. Une banque de données électromagnétiques et magnétiques est en voie de réalisation. Nous cherchons à réaliser des interprétations intégrant la géologie, la géophysique, la géochimie et la télédétection. Les efforts sont centrés sur un service optimum à offrir aux compagnies d'exploration minière au Québec.

Abstract

Airborne electromagnetic coverage of Québec started in 1969 with an INPUT® survey in Abitibi. Since then, some 111 700 km² have been flown in Abitibi, Labrador Trough, Gaspé and Eastern Townships. The maximum line spacing has been 200 m, and the flight height 120 m for INPUT surveys and 40 m for helicopter-borne surveys. The electromagnetic and magnetic data are published at the scale 1:20 000. Since 1974 data have been recorded digitaly; data processing techniques have been used to produce colour maps of the total magnetic field and calculated vertical gradient. A data bank containing all magnetic and electromagnetic results is presently being established. An attempt is made to integrate interpretation of geological, geophysical, geochemical and remote sensing data. Our goal is to be of assistance to mining exploration companies in Québec.

INTRODUCTION

La couverture en levé électromagnétique aéroporté du Québec a débuté en 1969 avec un premier levé INPUT dans la région de Rouyn-Noranda. Le ministère des Richesses naturelles, ainsi appelé à cette époque, était principalement intéressé au développement du potentiel minier de son territoire le plus prometteur, l'Abitibi. En plus de cette région, il était aussi nécessaire de développer d'autres zones au potentiel élevé (la Gaspésie, l'Estrie, la fosse du Labrador). Le ministère de l'Énergie et des Ressources (MÉR), selon sa présente appellation, est à l'écoute des compagnies d'exploration pour réellement saisir leurs besoins et mieux y répondre. La couverture ÉM aéroporté totalise, à ce jour, 111 700 km² pour un dépense totale de 14,7 millions de dollars (tableau 20.1). Les levés INPUT et les levés ÉM héliportés ont été choisis en raison de leur pertinence vis-à-vis l'exploration des métaux de base. Les cartes du champ magnétique et des anomalies ÉM produites par le ministère ont toujours été bien reçues par les compagnies privées d'exploration. A preuve, il suffit de voir la véritable course au jalonnement déclenchée par chaque publication des levés ÉM du Ministère.

Les cartes du champ magnétique et des anomalies ÉM ont surtout été utilisées par les géologues dans les régions où la

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Tableau 20.1 Couverture électromagnétique aéroportée du Québec (1969-1985)

Région	Superficie couverte (km^2)	Coûts (000 $ CDN)
Abitibi	83 000	9 456
Côte Nord et fosse du Labrador	10 945	2 606
Sud du Québec	3 875	755
Gaspésie	13 900	1 850
Total	111 720	14 667

couverture en affleurements est déficiente et l'information géologique réduite. La géophysique y a permis une interprétation géologique plus assurée sur de plus grandes étendues.

En rétrospective, on peut affirmer que ces levés avaient trois buts principaux:

a) la détection directe des dépôts de sulfures massifs;

b) une meilleure connaissance géologique à travers les marqueurs géophysiques relevés;

c) une incitation des compagnies d'exploration à réaliser des travaux de détail.

Le tableau 20.2 montre les travaux géophysiques de ÉM aéroporté effectués dans quatre régions du Québec.

CARACTÉRISTIQUES DES LEVÉS ÉLECTROMAGNÉTIQUES

Tous les levés aéroportés effectués pour le gouvernement du Québec ont des spécifications communes, soit, un espacement majeur des lignes de vol de 200 m, une hauteur de vol de 120 m pour les levés INPUT et de 40 m pour les levés héliportés. Les spécifications instrumentales sont spécifiques aux différents systèmes utilisés.

Les six premiers levés INPUT ont été effectués avec un système de type Mk-V alors que tous les suivants le furent avec un système de type Mk-VI. Les levés furent compilés sur des photomosaïques non contrôlées à l'échelle de un demi-mille au pouce (1/31 680), et 1/20 000 après l'introduction du système d'unité SI. Plus récemment, on a commencé à compiler les levés sur des fonds topographiques à l'échelle du 1/20 000. Ceci fut possible grâce à la publication de cartes topographiques 1/20 000 de haute qualité en Abitibi. Il s'en suit que les anomalies ÉM, les cartes aéromagnétiques et géologiques peuvent facilement être comparées et combinées; ceci est dû à l'absence totale de distortion.

Depuis 1974, tous les levés sont enregistrés digitalement en cours de vol. On pourrait donc, en théorie, retraiter ces données, si nécessaire. Par exemple, nous produisons actuellement des cartes aéromagnétiques et de gradient magnétique vertical calculé à partir de ces données. Il est aussi prévu de produire des cartes de conductivité pour quelques régions spécifiques.

La plupart des levés héliportés ont été effectués en Gaspésie, une région à topographie accentuée. Trois l'ont été en Abitibi, un dans la fosse du Labrador et deux dans l'Estrie. On trouvera au tableau 20.2 une liste des différents systèmes utilisés. Mentionnons qu'une carte de conductivité avait été publiée pour le levé de Dalquier (DP-793, 1980).

Tous ces levés ont été faits pour aider et favoriser l'exploration minière. Aucun de ces levés n'a été fait dans le but de produire des cartes de conductivité. Nous croyons cependant qu'une partie des données peut être retraitée et utilisée pour produire des cartes de conductivité. Par contre, tous les levés se sont montrés très utiles en terme de cartographie géologique. Dans plusieurs régions, la géologie a été réinterprétée par les géologues résidents à l'aide des cartes magnétiques et d'anomalies ÉM.

ORIENTATIONS FUTURES

Étant donné les résultats intéressants des levés et les commentaires encourageants de l'industrie minière, le MÉR va définitivement poursuivre ces levés régionaux de ÉM aéroporté. La couverture de l'Abitibi, du Sud du Québec et de la fosse du Labrador sera étendue (Figure 20.1). Ces levés utiliseront la meilleure technologie disponible; la présentation des résultats sera rehaussée pour tenir compte de tous les paramètres enregistrés. Nous avons aussi à nous assurer que les compagnies d'exploration peuvent utiliser et comprendre les cartes produites à partir de nouveaux systèmes d'acquisition. Nous voulons insister sur l'utilisation du meilleur système de positionnement pour nos levés. Avec une meilleure localisation, nous pouvons calculer des cartes de dérivées magnétiques plus précises et mieux représenter les transformations des données originales.

Tout en portant notre regard vers l'avenir, nous avons aussi à bien reconsidérer la masse des données acquises dans le passé. Nous avons déjà commencé la vérification des rubans magnétiques contenant les données de nos vieux levés. Des cartes du gradient magnétique vertical ont été calculées pour l'Abitibi. Avec cette banque de données magnétiques et ÉM, nous voulons tenter de rehausser ces vieilles données et retenir l'attention de nos clients que sont les compagnies d'exploration. Actuellement, les compagnies attachent une importance particulière à une approche intégrée d'interprétation combinant la géologie, le magnétisme, la gravité, l'ÉM, la géochimie, la télédétection. Si nous arrivons à identifier plus précisément des zones de fort potentiel minéral, nous aurons réussi et pleinement justifié l'emphase accordée aux levés aéroportés.

CONCLUSION

Voici nos principales visées pour être d'un réel service à l'industrie minière:

- utiliser les meilleurs systèmes opérationnels pour effectuer les levés aéroportés;
- utiliser les meilleures techniques de rehaussement et d'interprétation des données brutes.
- trouver le meilleure façon de présenter les données finales;
- interpréter les données géophysiques en concurrence avec les autres données géoscientifiques.

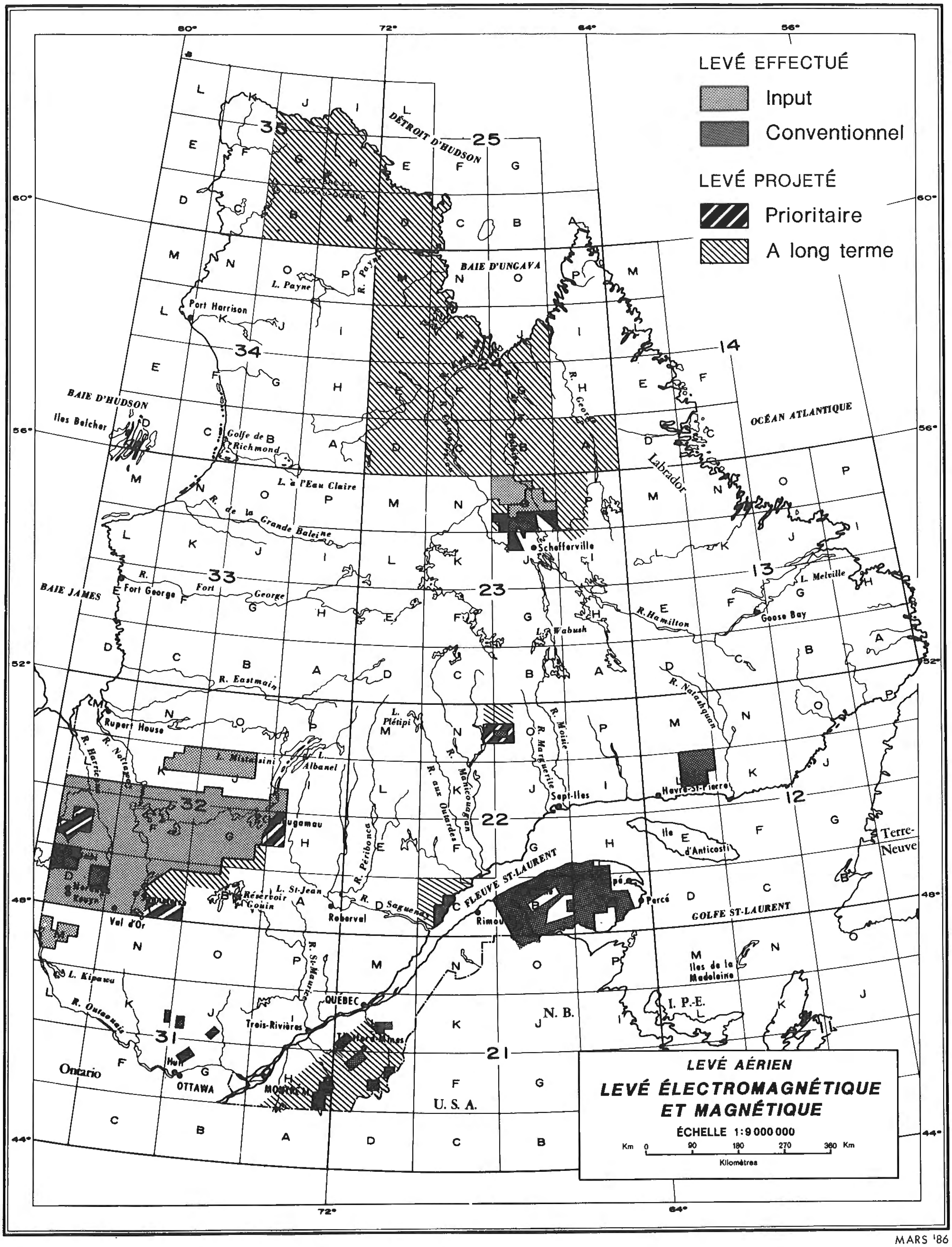

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Figure 20.1. Couverture en lévé électromagnétique aéroporté au Québec.

Tableau 20.2 Détails de la couverture électromagnétique aéroportée du Québec.

TYPE DE LEVÉS	LOCALISATION	ANNÉE DU CONTRAT	COÛTS (000 $ CDN)	SUPERFICIE COUVERTE (km^2)	KILOMÉTRAGE	FORMAT DES DONNÉES A = analogique D = digital	PRESENTATION DES DONNÉES M = fond mosaïque T = fond topographique
INPUT MKV	Rouyn	1968	64,4	1 326	6 564	MAG: D EM: A	MAG: T EM: M
INPUT MKV	Val-d'Or	1969	79,9	1 729	7 889	MAG: D EM: A	MAG: T EM: M
INPUT MKV	Malartic	1970	80,0	1 510	7 567	MAG: D EM: A	MAG: T EM: M
INPUT MKV	Amos	1971	225	4 576	22 781	MAG: D EM: A	MAG: T EM: M
INPUT MKV	Chibougamau	1971	79,8	1 534	7 799	MAG: D EM: A	MAG: T EM: M
INPUT MKV	Normétal	1972	219,2	3 750	18 676	MAG: D EM: A	MAG: T EM: M
INPUT MKVI	Senneterre	1972	70	1 135	5 699	MAG: D EM: A	MAG: T EM: M
INPUT MKVI	Bartouille	1973	100	1 615	8 090	MAG: D EM: A	MAG: T EM: M
INPUT MKVI	Riv. Turgeon	1973	100	1 575	7 890	MAG: D EM: A	MAG: T EM: M
INPUT MKVI	Belleterre/ Ville-Marie	1974	150	2 235	11 180	MAG: D EM: D	EM: M
INPUT MKVI	Joutel/Poirier	1974	190	2 830	14 162	MAG: D EM D	MAG: T EM: M
INPUT MKVI	La Dauversière	1974	100	1 490	7 453	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Opemiska	1976	149,3	1 835	9 175	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Matagami	1976	200,7	2 467	12 337	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Cogny/Chaste	1977	236,4	2 370	11 850	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Waconichi	1977	271,6	2 720	13 613	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Comtois / Cavelier	1978	486,3	4 470	22 350	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Riv. Chibougamau	1978	331,1	3 045	15 224	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Desmaraisville	1979	248,6	2 050	10 250	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Brouillan-Manthet	1979	395,3	3 260	16 300	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Lac Doda	1979	433,3	3 280	16 400	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Riv. Broadback	1979	466	3 530	17 640	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Marin-Barrin	1980	315	2 310	11 540	MAG: D EM: D	MAG: M EM: M
INPUT MKVI	Lac au Goéland	1981	772,8	5 090	25 460	MAG: D EM: D	MAG: T EM: T
INPUT MKVI	Lac Madeleine	1981	362,5	2 220	11 092	MAG: D EM: D	MAG: T EM: T
INPUT MKVI	Lac Grasset	1982	641,8	3 930	19 640	MAG: D EM: D	MAG: T EM: T
INPUT MKVI	Haüy, Lemoyne McKenzie	1983	45,2	250	1 250	MAG: D EM: D	MAG: T EM: T
INPUT MKVI	Troïlus-Frotet	1983	628,7	3 480	17 400	MAG: D EM D	MAG: T EM: T
INPUT MKVI	Quénonisca	1983	808,6	4 480	22 380	MAG: D EM: D	MAG: T EM: T
INPUT MKVI	Wetetnagami	1983	539,1	2 980	14 920	MAG: D EM: D	MAG: T EM: T
EM-33	Malartic	1978	243,2	1 565	7 825	D	M
EM-33	Lac Abitibi	1978	340,6	1 785	8 925	D	M
EM-33	Dalquier	1978	80	570	2 860	D	M
		TOTAL	9 456	82 292	414 960		

Tableau 20.2 (cont.)

FOSSE DU LABRADOR ET COTE NORD

TYPE DE LEVÉS	LOCALISATION	ANNÉE DU CONTRAT	COÛTS (000 $ CDN)	SUPERFICIE COUVERTE (km^2)	KILOMÉTRAGE	FORMAT DES DONNÉES A = analogique D = digital	PRESENTATION DES DONNÉES M = fond mosaïque T = fond topo-graphique
INPUT MKVI	Nord de Schefferville	1983	625	2 970	14 836	MAG: D EM: D	MAG: T EM: T
REXHEM III	Johan-Beetz	1983	993,6	4 230	21 140	MAG: D EM: D	MAG: T EM: T
REXHEM III	Fosse du Labrador	1983	540,5	2 040	10 198	MAG: D EM: D	MAG: T EM: T
REXHEM III	S.E. Fosse	1983	270,0	945	4 737	MAG: D EM: D	MAG: T EM: T
REXHEM III	Grandes-Bergeronnes	1985	130,0	560	2 800	MAG: D EM: D	MAG: T EM: T
EM-33-II	Hart-Jaune	1981	47,2	200	1 000	MAG: D EM: D	MAG: T EM: T
		TOTAL	2 606	10 945	54 725		

SUD DU QUEBEC

REXHEM III	Estrie	1983	260	1 115	5 580	MAG: D EM: D	MAG: T EM: T
REXHEM III	Estrie	1983	270,2	1 150	5 750	MAG: D EM: D	MAG: T EM: T
REXHEM III	Gatineau	1982	225,0	1 610	8 046	MAG: D EM: D	MAG: T EM: T
		TOTAL	755	3 875	19 375		

GASPESIE

GAR-X LTEE	Matapédia	1971	131,3	2 150	10 750	A	M
DIGHEM	Matane	1971	198,7	1 570	7 850	A	A
DIGHEM	Ste-Anne-des-Monts	1972	156	1 200	6 000	A	M
DIGHEM	Mont Auclair	1973	12	100	500	A	M
GAR-X LTEE	Mont Louis	1973	68	635	3 175	A	M
LHEM-250	Murdochville	1973	185	1 690	8 450	A	M
DIGHEM	Riv. Madeleine	1973	118	850	4 250	A	M
DIGHEM	Newport	1973	60	460	2 300	A	M
LH.EM-250	Restigouche	1974	300	1 380	6 900	A	M
EM-33	Mont Alexandre	1978	95	600	3 000	D	T
EM-33	Deville Clappertone	1978	132	800	4 000	D	T
EM-33	Dunière	1979	259	1 660	8 300	D	T
EM-33	Carleton	1979	136,5	822	4 110	D	T
		TOTAL	1 850	13 900	69 500		
		GRAND TOTAL	**14 667**	**111 712**	**558 560**		

INPUT MARK V et VI est une marque de commerce de Barringer Research Ltd/Questor Ltd.

REXHEM III est un système Geotech III volé par LES RELEVÉS GÉOPHYSIQUES INC.

EM-33 est un système de Geonics Ltd volé par LES RELEVÉS GÉOPHYSIQUES INC.

Appendix I*

A BIBLIOGRAPHY OF AIRBORNE ELECTROMAGNETIC METHODS: INSTRUMENTATION, INTERPRETATION, AND CASE HISTORIES

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Geological Survey of Canada

Abstract

This bibliography contains articles written about airborne electromagnetic methods. Included are all papers published on the subject in the following journals: Geophysics, Geophysical Prospecting, Geoexploration, Exploration Geophysics (formerly the Bulletin of the Australian Society of Exploration Geophysicists), Canadian Journal of Earth Sciences, Canadian Mining Journal, and Bulletin of the Canadian Institute of Mining and Metallurgy. Further, articles on the subject that were published in the following monographs: Mining Geophysics (Society of Exploration Geophysicists), Advances in Geophysics (Academic Press), Methods and Case Histories in Mining Geophysics (Proceedings of the 6th Commonwealth Mining and Metallurgical Congress), Mining and Groundwater Geophysics/1967 (Geological Survey of Canada), Geophysics and Geochemistry in the Search for Metallic Ores (Geological Survey of Canada), Applied Geophysics in Tropical Regions (Brazilian Geophysical Society), Expanded Abstracts of the Annual Meetings of the Society of Exploration Geophysicists (1982-1985), Exploration Technology Development Program of the Board of Industrial Leadership and Development (Ontario Geological Survey). In addition, articles published in other journals and books were included, but the search was not systematic. No company, government, or university research reports were considered. The bibliography is complete until December 1985.

The bilbiography is divided into two sections, Review Articles and Textbooks, and Technical Papers. The first section provides the reader with a selection of articles that permit an introduction to the subject. The more recent reviews are obviously more pertinent, but the older ones will be of interest to a scholar studying the history of the technique. All papers are included only once, either in the first or the second section.

Updates on airborne EM instrumentation can be found in P.J. Hood's review article "Mineral exploration: trends and developments", which is published annually in the January issue of the Canadian Mining Journal. Society of Exploration Geophysicists compiles annually statistics on geophysical activities in the world (published in The Leading Edge). The data are furnished by contractors and are reasonably complete for North America.

Résumé

La bibliographie renferme des articles qui portent sur des méthodes électromagnétiques aériennes. On y trouve tous les articles publiés sur le sujet dans les revues scientifiques suivantes: Geophysics, Geophysical Prospecting, Geoexploration, Exploration Geophysics (autrefois le Bulletin of the Australian Society of Exploration Geophysicists), le Journal canadien des sciences de la Terre, Canadian Mining Journal et le Bulletin of the Canadian Institute of Mining and Metallurgy. On y trouve en outre certains articles parus dans les monographies suivantes: Mining Geophysics (Society of Exploration Geophysicists), Advances in Geophysics (Academic Press), Methods and Case Histories in Mining Geophysics (Proceedings of the 6th Commonwealth Mining and Metallurgical Congress), Mining and Groundwater Geophysics/1967 (Commission géologique du Canada), Geophysics and Geochemistry in the Search for Metallic Ore (Commission géologique du Canada), Applied Geophysics in Tropical Regions (Brazilian Geophysical Society), Expanded Abstracts of the Annual Meetings of the Society of Exploration Geophysicists (1982-1985), Exploration Technology Development Program of the Board of Industrial Leadership and Development (Commission géologique de l'Ontario). De plus, certains articles publiés dans d'autres revues scientifiques et livres ont été inclus, mais la recherche ne s'est pas faite de façon systématique. Aucun rapport de

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**In* Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 175-180, 1986.

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recherche provenant des sociétés privées, du gouvernement ou des universités n'a été retenu. La bibliographie est à jour jusqu'en décembre 1985.

La bibliographie est répartie en deux sections, les compte rendus et les ouvrages scolaires d'une part, et les études techniques d'autre part. La première section fournit aux lecteurs une sélection d'articles qui servent d'introduction au sujet. Les compte rendus les plus récents sont évidemment les plus pertinents, mais les plus anciens devraient quand même intéresser les universitaires qui étudient l'histoire des techniques. Toutes les études ne sont comprises qu'une seule fois, soit dans la première, soit dans la seconde section.

Les intéressés trouveront des mises à jour sur les appareils ÉM aéroportés dans la chronique annuelle de P.J. Hood intitulée "Mineral exploration: trends and developments", cette chronique paraît dans le numéro de janvier du Canadian Mining Journal. La Society of Exploration Geophysicists compile tous les ans des statistiques sur les activités géophysiques à travers le monde (celles-ci paraissent dans The Leading Edge). Les données sont fournies par des entrepreneurs et elles sont assez complètes pour l'Amérique du Nord.

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Appendix II*

PANEL DISCUSSION: AIRBORNE RESISTIVITY MAPPING AND ITS FUTURE

3 October 1985

Moderator: G.J. Palacky, Geological Survey of Canada, Ottawa, Ontario

Panel Members:

A.P. Annan, Chairman, A-Cubed Inc., Mississauga, Ontario

R.B. Barlow, Head, Geophysics and Geochemistry Section, Ontario Geological Survey, Toronto, Ontario

R. Bazinet, Associate Professor, École Polytechnique, Montréal, Québec

N.R. Paterson, President, Paterson, Grant & Watson Ltd., Toronto, Ontario

A.R. Rattew, Chairman, Geoterrex Ltd., Ottawa, Ontario

The moderator opened the meeting at 2 p.m., welcomed the participants, and introduced the panel members. There were about 120 people in the audience. The panel discussion and the Workshop were closed at 5 p.m. The edited transcript of the discussion was reviewed by the moderator. No significant statements were omitted or modified.

George Palacky: Today there will be three general topics for discussion, units and standards for airborne resistivity surveys, novel applications for airborne electromagnetic methods, and finally electromagnetic test sites and pilot study areas. The panel discussion will be run in the following way: first, the panel members will give their opinions on the selected topics, then other participants in the audience will be able to express theirs. I would like to remind everybody that this meeting is being recorded.

UNITS AND STANDARDS FOR AIRBORNE RESISTIVITY SURVEYS

George Palacky: First I would like to ask the panel members and the audience a question: shall we call this activity resistivity mapping or conductivity mapping? In my opinion, there are valid points in favour of conductivity. It seems logical that when looking for a conductor we would scan the data for high rather than low values. In presenting colour maps, high conductivity values should be represented by warm colours. Intuitively, one assumes that if something is very conductive, it is red rather than blue. Second, we should discuss what units should be routinely used in airborne electromagnetic surveys. My suggestion is millisiemens per metre. I would like to propose that the product of airborne electromagnetic surveys be not only a map or a set of maps but also an edited data set stored on tape or disc, which would be easy to use on a minicomputer or a personal computer. Having such data sets an individual geophysicist could do additional data processing best suited to a particular application. There is a significant difference between a data set resulting from flying along a flight line and an edited set gridded in the form of a map. After this brief introduction, I would like to solicit opinions from the panel members.

Peter Annan: Our company is involved in many activities besides airborne EM surveying. Conductivity has become the standard term which we use in EM and radar surveys. The only time we use resistivity is when we do galvanic resistivity soundings. I agree with the point made by George that intuitively we are looking for something positive rather than negative. The units we use are millisiemens per metre, which give simple numbers, in the right range for most geological materials, i.e. from 1 to 1000. There are extremes below that or sometimes above, but usually most values are in that range.

There are two other areas which are quite important. One is data storage, data handling, data presentation, or in short how people can get their hands on information. We have just started to look at testing a number of data processing algorithms and what we need are real survey data. To get that information at present, it is necessary to approach individuals who are involved in that particular survey, find out where the data are and figure out their format. The present situation is not simple and standards have to be established. The first level is to record raw information on a tape with a defined format. The second level is preprocessing, putting the data on a standard grid which allows generation of maps. There are pros and cons to that step. The pros are that it is easier to extract information which is already in the map form. The cons are that somebody has to do something to the data presumably involving interpolation or extrapolation which biases the information in a certain way. For applications such as conductivity mapping the information should be in a gridded form. The information is only useful when you look at it in a planned perspective and correlate the features from area to area. The absolute numbers that come out of an individual data point are usually meaningless, it is the trend that is the most important piece of information.

The biggest problem with multiparameter surveys is how to display the data. By definition we measure conductivity in x and y and also versus depth. How do we get that information onto a map? There are number of simple ways of doing it. In order to get the information out to the widest user market we have to make it simple. A conductivity-thickness map for the overburden and a bedrock conductivity map are about the minimum we can do. If somebody wants to have a depth map, then we can assume an average conductivity and get an apparent depth map. Maps like that can be used by people who have no idea about geophysics. We have to get to the consumer market, to the people who are going to use the information. They don't care whether it came from EM or somewhere else, but they want it in a form which is meaningful to them rather than to us.

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*In Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 181-192, 1986.

The second point I want to make is on standards. We have to come up with some way of standardizing the way we describe systems. We have heard over the last two days various descriptions of systems. What are the important parameters? One of the most important is the transmitter dipole moment. How do we quantify that? In time-domain systems people talk about peak moments and rms moments, but one of the pieces of information missing is the speed of switching. It is the rate of change of the moment which is the important parameter, not just the size of the moment. Of course, the description becomes simpler with a frequency-domain transmitter. Then when we know the rms moment and the frequency, the system is well defined. I think we have to standardize our terminology, so that people can understand what the numbers mean and how they can relate one system to the next. Another factor is how to look at the receiver sensitivities. There are some simple numbers, like the effective area of receiving coils, which should be standardized. Such measure would allow us to compare the performance of various systems. The geometry of a system is usually well defined, even though it can be variable in towed-bird systems. There are things which should be done to quantify the survey parameters. We cannot go back and tell what happened during the flight, therefore we have to put the information into the data base. Finally, we should quantify what noise levels mean. We talk about so many ppm of noise, but what does that mean? There are many kinds of noise in an EM system, like zero level drifts, but it is the fluctuation over time, which is really important. When we say peak-to-peak noise is acceptable over a certain time interval, little individual peaks, culture events or spherics are included, which are not really noise, because we can tell that they are extraneous items. To summarize, to introduce common standards for AEM surveys would be very useful.

Roger Barlow: Some of the geological problems that are important to us at the Ontario Geological Survey are related to overburden. We are doing extensive work in the Abitibi clay belt in order to descramble the Quaternary geology. We certainly need AEM systems that would collect more information at early delay times in the time domain, or over a large suite of frequencies in the frequency domain. Our work is very closely related to that of geochemists who need detailed Quaternary information on a regional and local scale. In EM we have to keep in full focus all geological problems, not only mineral exploration, and make sure that we collect the data well. The appropriate data presentation can be decided later in order to maximize the information contained in the data.

Robert Bazinet: Considering conductivity or resistivity units, it does not matter which unit is used, as long as everybody uses it and is consistent about it. Concerning standardization of the systems, I think it is a serious problem and it should be solved as soon as possible. In some cases problems appear when the recording format is not what it was supposed to be. It should not be too difficult for all contractors to agree on a certain standard. Most of the AEM systems use a computer in the plane and it is just a question of standardizing the way the data are recorded. In my opinion the users should set the standards because they are more numerous then contractors. The implementation is only a question of decision. It would be advantageous to store the data on a medium that is easy to use, such as a floppy disc. The tapes can hold vast quantities of data, but one needs special equipment to read them, and that may not always be available to the user. The question is what do you put on the tape or the disc. I think that we should store raw data. Pre-processing may help some users, but it may distort the information. No matter what kind of processing is done, it would not please everybody. We should have several levels of processing depending on the expertise of the client. Some prospectors are probably only interested in obtaining a conductivity map or an anomaly map, as they have been getting in the case of Input surveys.

Another point worth mentioning is the positioning standards. In my experience with Input maps, this has always been a serious problem. Some maps were excellent, some were really awful, and they could have come from the same contractor. At least the minimum positioning requirements should be established. The user may not want to be bothered knowing exactly about the positioning procedure, but he must be certain that a conductivity anomaly was plotted on the map in the right place.

Norman Paterson: I said my piece about conductance this morning and I don't have to repeat it. I have to get used to the word Siemens, the nice thing about mho was that you could put it in reverse and get ohm, but Siemens spelled backwards is a tricky thing. You could say Nemesis but that is not quite right. As far as the data formats are concerned, I don't see this as being a major problem. We have solved that problem very satisfactorily in other types of airborne geophysics. We get tapes from every contractor under the sun with magnetics and radiometrics which are more complicated than EM and they don't seem to be too difficult to read, even when they contain navigation information. The formats that are used in the industry now are standard. The GSC has come a long way to standardizing the file formats and when we get an archive tape from any of the six contractors, it is almost identical. I don't see the data presentation being a problem either, as far as some consistent measure is taken of time delays and frequencies and as long as the data are arranged in a logical file. I don't care whether the data are gridded or not because most of us regrid them in any case before processing.

However, the data presentation does bother me. Apparent resistivity and apparent conductivity are very nebulous terms and one needs an explanation on the map showing what interpretation models were used and a short note explaining some notations. I gave a lot of thought to this and I liked the idea of conductance maps. In most of the world the top layer has a measurable conductivity and a finite thickness and therefore one can produce a map of conductance. At least we have a result that is fairly standard and measurable by most systems. The problem is that this quantity is not the same at all frequencies and one has to stipulate the depth to the top of the conductive layer. One can use a thin sheet approximation at surface, but it is not quite as simple, and I would like to see more work in this direction. Of course, if you go over an outcrop, the conductance approximation map based on the thin sheet becomes meaningless; it applies only to areas of weathered rock or to glacial overburden areas. One may also consider producing half-space conductivity maps at a very high frequency, something in excess of 10 kHz. In this case one looks at the top few metres in overburden areas, but you are dealing with a quantity that you can understand. When one passes over an outcrop the response nosedives and the outcrop edges are well defined. If the frequency is high enough, one can see a difference between schists, gneisses, granites, and ultramafics. This is the kind of response a geologist can understand. I think the presentation is the major hang-up in conductivity mapping.

As far as noise is concerned, I don't consider this a particular problem. I don't care if people stayed with parts per million providing they stated how many ppm they get over a standard conductor. If you look at the paper I wrote in 1971 for the CIMM Bulletin I quoted everybody's noise levels for all systems relative to the response to a vertical half-plane of infinite conductivity at a normal flying height. If we have a standard, whether it is a vertical half-plane or a horizontal sheet, and the contractors quote noise levels over that standard conductor, then I think we have gone in the right direction. I am not worried about the system standards, that is up to the person who buys the survey to make sure that the contractor performs according to the specifications of these instruments. If that is done the maps will be satisfactory.

Art Rattew: International airborne geophysical contractors have always had to use different kinds of units according to what the customer wants. I noticed that most of the papers here were actually in ohm-metres and certainly many users in some of the new applications are ohm-metre people. I do agree in principle with what appears to be a consensus for conductivity measurements but I think that in general use one will have to be comfortable with both conductivity and resistivity for a long time to come. If Canada starts a systematic airborne resistivity mapping project, which I sincerely hope will happen, there will be a tremendous need for a much greater degree of standardization, not just in units, but in terms of what is being measured and how it is being presented. Obviously, two adjacent maps have to look similar and have to give identical information to the end user. One of the many benefits of the major program by the Canadian government would be to force us into a situation in which we would have a much better handle on what we are doing and how the different systems compare with each other.

Alex Becker, Professor, University of California, Berkeley U.S.A.: I found the panel to be rather modest in its requirements. I think that we could have been a little more specific, especially in the discussions that went on this morning and yesterday. We could have agreed on a number of things, including units. The millisiemens per metre seems to be a good unit because you get a nice number, between 1 and 1000.

The key point in AEM measurements is the geometry of the system. If you are making maps for a specific purpose, like prospecting for base metals, and you know the strike, you can fly with the directional system across the strike. This maximizes your return on the amount expended. However, if you are doing a general coverage survey, you must carry it out in such a way that you get the same number no matter in which direction you fly. We saw the first approximation to this on the Dighem maps that were flown in two directions. The second parameter that has to be specified is the bandwidth of the measurement, the range of conductivities you are going to cover to a certain depth. The third important thing is the presentation. The presentation that I found the most intriguing was by Don Hoover of the Schlumberger soundings results in one of the KGRA's (Known Geothermal Resource Areas). You can specify the resistivities every 10 or 20 metres between surface and the 150 metre depth corresponding to a given bandwidth. Then you use a certain technique to get those numbers and determine the presence of a conductive-layer and its position. We can probably make a very good shot at its conductivity-thickness product and, if things are favourable, we can probably also get its thickness. If you had a surficial map obtained at a high frequency and maps at two other levels, 50 and 100 metres, you would end up with 3 maps as radiometrics, which could then be combined, if you wished so. The last item you would want are the raw data.

Murray Telford, Professor Emeritus at McGill University, Montreal: This is really a trivial question and you have been over it before. The last time I read the Handbook of Physics, an update about 7 or 8 years old, the Siemens as a unit for conductance had an asterisk that said only accepted by so and so — and the mho was still hanging in there. Is there anybody who can tell me which one of these units is in right now.

George Palacky: The official SI unit is Siemens. Mho is not accepted as an SI unit.

Norman Paterson: I just want to make a quick reply to Alex about the desirability of producing pseudosections of apparent conductance. Of course, that is the ultimate objective. If we could do that I would be the first to say that should be the way to present our conductivity information, but how do you do it? I know that Dr. Sengpiel demonstrated that this morning, but we didn't have a chance to find out how he did it. He had some way of finding where the centres of the currents are for a given frequency, but I would like to know more about his algorithm. There is no simple way of ascribing a depth to a frequency, or for that matter, once you have done that, there is no way of determining what the conductivity is at that point without finding a solution for an n-layer system, which is very difficult.

Gordon West, Professor, University of Toronto: You mentioned your view, George, that you would like to see as the detailed product gridded data in a numerical, computer readable fashion. I think you are going to have to come up very quickly with the question as to whether you want full EM information, such as can be provided by some of the advanced systems, or whether in order to produce a standardized product you want a minimum geometrical information. If you want something that can be gridded without the heading information in it, then you are going to be limited entirely to vertical-axis closely spaced dipole systems. All the other information will automatically become useless if the heading information disappears from data recorded with other AEM systems. I really think that there are several stages of data recoding that have to be considered. There is the stage of raw data out of the aircraft, which in some systems are extremely raw, but in others are almost completely processed within the aircraft. Perhaps the user is not much interested in that product, but a contractor, who has to produce interpretations from it, might be. There is a question of fully processed output of a system which records all the information that the person who designed the system thinks can be obtained from that system. It is recorded directly as observed, meaning that a plane can fly the same track again and can get exactly the same data. That is a very fundamental stage and that kind of data should be archived somewhere. The next stage may be a digital data of format that is convenient for people to draw rescaled maps, so they can overlay a geophysical map on the pre-existing data, but that is a long way up. That is in the intepretation product stage.

I agree with the problem about the tape formats, but I think we should be very careful about this. The Australians are ahead of us; they have put a lot of thought and effort into trying to set standards for describing the information on computer tapes, thereby making them readable by many different systems. They have just published a complete standards description in a format that could pass the National Standards Organization. We should give serious thought to whether our objectives could be met by that general format. What we should not do is to sit down and decide, now we format in the following way, let's write that down and get everyone to do it the same way from here on. This kind of thinking about standards is how to standardize yourself into the grave.

There is a point about systems specification that most of us in Canada are quite negligent of. When surveys are carried out, a document should be written that specifies the system and its characteristics accurately, so that when raw data are transferred from one organization to another, the pertinent pieces of information are not lost, as often has been happening. I favour requiring accurate and understandable descriptions of systems, not necessarily beforehand, but post-survey specification.

System standardization is desirable, but one should keep in mind that the ultimate objective is to obtain interpretable data. It would be foolish to start a national program after having looked at a couple of exploration and engineering problems and to decide that the most appropriate system on the market is that one and that will become the standard. The overburden conductance problem was mentioned here and I am sure that in most of the areas of crystalline bedrock in Canada, and in many parts of the world indeed, a conductive overburden over a more resistive bedrock is an appropriate model, but one only has to fly in southern

Ontario near Toronto and it is the other way up, the Queenston shale is far more conductive than the tills that overlie it. You have to think of what is the ultimate product before deciding what AEM system you want to fly and what kind of maps would be useful.

George Palacky: I probably didn't make myself very clear on the idea of data processing. I did not suggest an alternative to the tape that is produced by the contractor during the flight. What I had in mind is an addition to that, an intermediate step between raw data and maps. With the advancement of multifrequency and wide-band system, which have several receivers, one may have something like 60 or 70 individual parameters at any point of the survey. It would become virtually impossible to produce and digest maps for three receiver components and a number of frequencies. However, this kind of data could very easily be stored on a floppy disc in a gridded form. The final user would produce a conductivity or any other map for the application he is interested in. The user may be a person working for a mining company, a utility, or a groundwater consultancy firm. He may be a layman in data processing compared with companies specialized in reprocessing of airborne geophysical data. Essentially, the product I am suggesting is an intermediate data set from which any individual could produce any number of maps or resistivity sections on his screen and plotter instead of going through a number of map sheets prepared by a contractor.

Doug Fraser, President, Dighem Surveys and Data Processing, Mississauga: I want to discuss the problem of units from a marketing perspective. Our company has been producing resistivity maps since 1975. When we first decided to contour values calculated from the raw AEM data, the difficult part was not how to do it, but to produce maps that people would accept as a result of their past intuition. It was apparent at that time that most geologists had never seen a conductivity map in Siemens per metre. However, resistivity surveys have been conducted in many parts of the world, where geophysics is extensively used in groundwater prospecting. Being in the service industry we have to meet the needs of the users. Therefore the ohm-metre has usually been the unit of choice. We can now routinely measure resistivity or conductivity over 4 decades. Our company has been trying to enter the geotechnical market, where the users are interested in complete resistivity distribution, and to develop the use of AEM for ice thickness determination and bathymetric mapping, but our major market remains prospecting for base metal deposits where the clients look for discrete conductivity anomalies. In our experience, the choice of units should depend on what the user wants and should not be postulated in advance.

Chris Vaughan, A-Cubed, Mississauga: There are too many systems measuring too many different parameters and carrying different groups of peripheral instruments to be able to set up a common standard. What might be done is that a standard header block be placed on every tape which should contain a minimum of information that we can agree upon, including the format in which the data are recorded as well as some of the geometrical information about the system. I had to process numerous foreign tapes of various formats and I found it often frustrating to figure out the proper format.

Markku Peltoniemi, Professor, Helsinki University of Technology, Finland: Concerning instrument standardization, I think we should address this problem from the end user's point of view. In that respect I fully agree with Dr. Paterson. His approach was in fact used in the figures I showed. The signal-to-noise ratio and the noise level over standard models are two important factors which help one to understand how the system behaves. You need not worry about how to specify the dipole moments. The signal-to-noise ratio is what gives a specific meaning to the data.

Robert Bazinet: Concerning data standardization, we should learn from the petroleum industry. The SEG (Society of Exploration Geophysicists) established data tape standards 10 years ago. I am not recommending the same standard because it is specific for IBM machines, but the idea of standardization is worth considering. The first block describes what is on the tape and all programs published by the SEG follow this convention. In my experience, often the problem is not that the format is unknown, but that the necessary format information is on the label, which may get lost after a few years. I agree with the statement made here that all system parameters should be specified and suggest that this information should be on the tape, also including the survey flight parameters. What medium for data storage would I like? Something, like a disc, containing raw data which I could use on my own computer. The problem at present is not with computers but with storage media. Floppy discs still do not have the sufficient capacity for large data sets produced in the course of modern surveys, but optical discs could be distributed at small cost and would be handier than rolls of maps. A program could be supplied to generate standard maps on the screen for unsophisticated users, others might want to do their own processing.

Robbert Bosschart, Consultant, Toronto: Regarding the signal-to-noise ratio, it sounds very simple, but I don't think it is. The signal may be simple enough in many respects but noise is not. Different systems have entirely different characteristics as far as noise rejection is concerned. I don't think we can specify that in simple terms.

Len Collett, Geological Survey of Canada, Ottawa: In the potential field measurements, such as magnetic surveys, figures of merit are used in assessing the equipment. I wonder if we could think about some kind of equivalent figure of merit for electromagnetic surveys.

Doug Hardwick, National Research Council, Ottawa: To continue on the recording format, most organizations have spent a tremendous amount of time and effort in building a data system and recording formats. There are several off-the-shelf recording systems in which the format and all the information needed to process the data are in a block header. Even changes made in flight are recorded in the header. That is the way we should go.

Last year a number of cheap data systems have come out that are PC and Apple compatible. A $2000-$3000 dollar hardware at the front end can be configured to do analogue-to-digital conversion at up to 50kHz data rates. One weakness with the present systems is that they are all hard-disc oriented, but some companies are coming out with streamers which can take floppy discs. Therefore some of the formatting problems might be solved in the near future in an inexpensive manner.

Bill Scott, Hardy Associates (1978), Calgary: On the question of units, when we measure inductively, we normally record the readings in millisiemens per metre. When we do DC resistivity soundings, we record the results in ohm-metres, and there is a good reason for doing this. If I were to do an inductive conductivity survey for somebody who is designing a grounding system, I would not hesitate to convert my conductivity units to resistivity. However, this assumes that I know the zero level of the inductive measuring system. If the conductivities are low, the signal is very close to the noise level of the zero level, and there can be gross errors generated by inverting conductivity to resistivity. If you do such a conversion you have the responsibility to point out to the end user what you have done to the data.

Peter Sengpiel, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany: On the representation of resistivity data, many people have shown here contour maps with drastic changes in colours from one contour interval to the next. Such presentation may be misleading to those who are used to geological maps, where colours represent rock units. We have come to the conclusion that it is necessary to standardize colours for different ranges of resistivity. I would ask contractors who produce colour maps to use smooth transitions between the contour values of resistivity.

Another comment: a resistivity map is a document, like a geological map, and one should be able to read it and understand it for many years after the survey. The map must have a legend describing the survey and the processing parameters. I have here a sample of coloured resistivity maps produced by the German Geological Survey, in which we have tried to incorporate the concepts I have been describing.

George Palacky: I would like to ask Peter Hood who is well known for his work on establishing standards for airborne magnetics whether he could tell us how difficult it was to achieve his goal.

Peter Hood, Geological Survey of Canada, Ottawa: The standards in magnetic surveys are tied to our contracts, which have been going on at the GSC since 1960. Len mentioned the figure of merit which gives an indication of the noise level one would expect under turbulent conditions for an aircraft. In order to establish the noise at the sampling frequency, we decided to go the 4th difference. The procedure which is described in the Exploration 77 volume is now accepted by most survey companies. However, if the noise has a frequency spectrum similar to the geological signal, then the 4th difference will remove the signal.

For calibration of aeromagnetic systems we have established a range at Bourget and we ask contractors to fly there. The test range is an easily identifiable crossroads near the Village of Bourget. In order to correct for diurnal variation the range is tied into the Blackburn Hamlet Observatory. The calibration data tell us whether the magnetometer in the aircraft gives a number which is close to what it should be in SI magnetic units. The Bourget test also gives the effect of the aircraft heading. We feel that it is better to do the calibration from the air using the actual flying configuration than to do it on the ground. However, in certain circumstances, for instance the survey in Zimbabwe, where we did not have a calibration range, the testing was done on the ground at the Blackburn Hamlet Observatory prior to shipping the magnetometer abroad.

George Palacky: I will briefly sum up the main points made during the first third of our discussion and add some of my own ideas. First, there was a desire expressed for standard description of airborne electromagnetic systems. One should define what is meant by noise level and one should express the dipole moment of a system in physical units. Some parameters may be rather difficult to establish by measuring the system performance on the ground. Therefore, it would be desirable to have calibration sites to allow comparison of the performance of various electromagnetic systems in the air. One should establish industry-wide standards for positioning. Formats of digital data tapes which are delivered to the client after the completion of the survey should be uniform. The tapes should contain a defined header label with the basic survey parameters. All these requirements essentially concern the contractors.

To the second point: what should be done with the recorded data and how the results should be presented. Because of the increasing amount of information that we obtained from advanced electromagnetic systems, we should produce, in my opinion, two sets of products: first, a conductivity map or a set of maps, preferably in colour, showing conductivity or conductance at various levels, and second, an edited data set stored on tape or disc. Opinions differed concerning the parameters to be measured and the units for maps. I suggested conductivity expressed in millisiemens per metre. There was a pertinent comment by Peter Sengpiel on smooth colouring of conductivity maps.

I would like to add a comment on data presentation. One could possibly merge two sets of information like conductivity and thickness by combining colouring and shading. Heavy and light shading could indicate the layer thickness, and colours the conductivity. The final user of the data, be it a geophysicist working for a mining company, a hydrogeologist in groundwater exploration, or an individual consultant, would probably welcome additional data sets which contain essentially the same information as a map, but in a form that can be manipulated more easily. To give an example, one may want to obtain a conductivity map at a certain depth, for instance 20 metres, or a depth contour map for a certain geological formation. Obviously, it would be wasteful to produce maps for each conceivable applications from the onset. One should make a greater use of conductivity sections, as mentioned by Alex Becker. All such data sets could be stored in a digital form and displayed on a screen by the user rather than publishing 10 or 20 sets of maps and sections for any given area. Obviously, one should also adopt the nationally accepted way of producing maps using the standard IMW map sheet numbering.

NOVEL APPLICATIONS FOR AIRBORNE EM METHODS AND SYSTEMATIC RESISTIVITY COVERAGE OF CANADA

George Palacky: As we have heard in the paper by Len Collett, the airborne electromagnetic method was developed in Canada, the USSR, and in the Nordic countries as a tool of prospecting for massive sulphides. It was a successful tool and perhaps this is why the method did not develop during the last 25 or 30 years in other directions as magnetics did. Few companies were prospecting for iron orebodies even those days and the people engaged in magnetic surveys immediately had to look to other markets, such as geological mapping. They improved the magnetic method to such a degree that it is now accepted as one of the standard geological mapping techniques. The same can be done for airborne electromagnetics. I tried to show in the paper I presented yesterday that airborne EM is an equally suitable technique of geological mapping, complementary to magnetics. It is more expensive but the results may often be more valuable. Electrical properties of clays formed in saprolite have a direct correlation with the standard lithological classification of igneous rocks. Magnetic maps are essentially a measure of magnetite content which is often unrelated to rock types. For instance, granites or volcanic rocks may be magnetic or nonmagnetic, but in normal conditions a saprolite formed over mafic volcanic rocks will be more conductive than one formed over granites. Gneisses will always produce a more resistive saprolite than schists or amphibolites.

During the Workshop a number of novel applications have been described. The most promising ones seem offshore shallow-water bathymetry, detection of salting and chemical contamination, geotechnical studies, groundwater prospecting, and geothermal exploration. It appears there are many potential new users. We should try to find out whether and how we can conduct general purpose airborne electromagnetic surveys in such a way that all users would find the results useful. I feel that the prime consideration should be the use of airborne electromagnetics in geological mapping. After all, the traditional prospecting for massive sulphides is nothing more than a specialized mapping of one particular commodity. If we carry out electromagnetic surveys in a systematic way, we conduct a complete inventory of natural resources. Now I will ask the panel members to give their opinion on novel applications for airborne EM and the desirability of systematic resistivity coverage of Canada.

Art Rattew: I would like to pursue from my own point of view the line of thought that George was developing here. It has been amazing to me that in the last two days so little has been said here about the terrible economic state in which the Canadian airborne EM industry finds itself at the present time. Norm Paterson alluded to it this morning at the beginning of his address and there was lots of talk about it in the corridor. I believe that even our Finnish friend, Dr. Peltoniemi, will agree with my assertion that Canada has dominated the airborne EM scene for the past 30 years. We heard from Len Collett yesterday that most of the early EM airborne systems were born here. During many years something over half of the world's EM flying has been done in Canada. This market, financed originally and mainly by the mining industry and more recently by the government, has been responsible for the numerous improvements in both fixed-wing and helicopter systems and has kept Canada in the forefront of the world's airborne EM technology, in terms of both the hardware and the data handling capability. Personally, I spent a large portion of my geophysical career exporting some of this Canadian airborne EM technology to other parts of the world: South America, Europe, the Middle East, Africa, and Australia. I have been proud to see that Canada is recognized everywhere as the world leader in airborne EM.

The papers given at this meeting have demonstrated the exciting new AEM equipment on the verge of entering the marketplace; systems that will permit a greater penetration, a better discrimination of conductors, and a wider range of applications. In fact, in addition to those that were mentioned before, Geoterrex has a new system called Geotem which is built around a digital receiver that Peter Annan and his people put together. The papers we have heard made it abundantly clear that software, data processing capabilities, and interpretational techniques are also progressing rapidly, as we adjust to new potential applications of airborne EM. It is obvious that we have here in Canada, in fact in this room, the potential to do everything that needs to be done in airborne EM to stay in the forefront of this specialized field well into the future. But is there a market in Canada, or anywhere in the world for that matter, to support this effort? Let us be very clear on the fact that base metal exploration has provided the incentive and the bulk of the financing to get us where we are today. Let us be equally clear on the fact that base metal exploration is critically ill, if not quite yet dead, worldwide, not just here in Canada. I haven't talked to a single mining person anywhere who foresees a fast turnaround in this situation. The recovery is going to take years not months. If there is a market for all of our new airborne EM technology, it is not in base metals.

Hopefully, the market for EM can be found in one or several of the various types of applications discussed during this meeting, things that we lump under the umbrella of airborne resistivity mapping. But how long can we wait? I am sure that the other airborne EM contractors have been doing the same as we have at Geoterrex, looking for new applications and new markets. In fact, it is obvious that we have all been doing this for quite a while as evidenced by the content of the papers we have had here during the last two days, but we contractors can also tell you that the number and size of contracts we get for the new applications is very small, nowhere near large enough to support an industry which grew in size to accommodate a buoyant base-metal exploration market, one that no longer exists. We are trying to find new markets, but to educate a new type of customers to use airborne EM to help solve their problems is a long, slow, painful exercise. In our experience, whether it be a water explorationist, coal geologist, or agriculturist who has salt problems someplace in Australia, it takes a long time and a lot of effort to get them to try something new.

We in the airborne EM industry in Canada have an immediate and serious problem. How do we justify maintaining the excellent and unique technology which we possess and how do we support the ongoing developments? Personally, I question strongly whether the Canadian airborne EM industry will even survive. Certainly not in its present form, unless something drastic happens soon. As my friends, who know me well here, will confirm, I am a free enterpriser all the way. Normally, my last thought is to turn to government for help, but it may be that the only short term move that is drastic enough to help is a major program within Canada to obtain a systematic resistivity coverage of this country. This move by Canada would also help our efforts to promote resistivity mapping in other parts of the world and to other types of users. One needs only see the effect internationally of Peter Hood's efforts with respect to the Canadian magnetic coverage and its publicity to realize the fact that other countries do look to Canada for leadership in geophysics. So finally, I have answered one of George's questions, I strongly support the systematic resistivity coverage of Canada. With George Palacky steering a Canadian resistivity mapping program, with his personal conviction on the subject and with his credibility and range of knowledge, I think such a program could be done very sensibly in Canada and the contractors could work together on it. Also George, like Peter, has excellent capabilities in publicity as well as geophysics and I think he would go a long way towards promoting and helping our business in other countries and other applications.

Norman Paterson: My perspective being that of a consultant, I am not as concerned as you are about keeping the planes flying, but I am concerned that we make every effort we can to solve what I regard as one of the most urgent problems the world has ever faced, namely the problem of desertification and the resulting starvation in some of the developing countries. I think this problem can be solved to a large extent by the application of airborne EM. As airborne EM technology has advanced over the past 5 to 10 years, this has been paralleled by an even greater advance in starvation in certain areas of the world, largely by the process started by overgrazing and aggravated by years of drought, with the result that groundwater is becoming the most precious commodity. Accelerated groundwater exploration is the only viable long term solution in those areas in Africa where over 50 million people are affected right now. We are sitting here in Canada with the technology, with the equipment, with the capability to find large buried reservoirs of water. Why aren't we doing it? We have to get off our chairs and start selling it. I have been selling it hard, and I know that other people in this room have been selling it hard, but you go to the World Bank, to CIDA, to UNDP, and you talk to those agencies, and they say 'Yes, but, you see we found that borehole resistivity works better', which of course illustrates that they haven't been listening to a single word that you have said. It is up to us to convince the agencies involved and the governments in general that we have a technology that can find groundwater. It was said this morning by Dr. Lakshmanan that groundwater is not always conductive. Of course, it is not always conductive, quite often it is resistive, quite often we can't find it, sometimes it is sandwiched between clay layers. However, in many cases, I would say 90% of the cases in sub-Saharan Africa, groundwater occurs either in saprolite, or in fissures in igneous rocks, or in water tables in sedimentary basins, all three of which can be found by airborne EM. I think we should be out there doing it.

Robert Bazinet: Concerning the correlation between resistivity values and rock types, in my opinion resistivity does not depend on the rock type but on porosity and water content. In the Canadian Shield most rock types are quite resistive if there is no water present. Geological mapping is certainly an interesting application for AEM, no matter what causes the resistivity contrast. In Quebec we use graphitic conductors as indicators of contacts between geological formations. That can be done on a much larger scale and even finer resistivity features can be used.

Considering new applications, there may be some about which we, geophysicists, don't even think and the potential customers don't know that we may have a solution for their problems. In civil engineering applications, only seismic techniques have been considered, but EM could certainly be applied in many situations. Gas companies have serious problems with their pipelines and carry out complex resistivity surveys in order to minimize corrosion. Perhaps they would be interested in having resistivity maps from airborne surveying for areas where they operate. There may be other companies interested, such as one building an aluminum plant in Quebec. Because of corrosion problems, resistivity of the ground is extremely important for the site selection. At present they electrically insulate reinforcing bars, but they would be willing to go quite far and spend money to achieve the best results possible. Considering the size of their operations the cost of the geophysical surveys would be quite small.

Roger Barlow: I have mixed feelings about a systematic coverage of Canada. It would be nice, if we could get across to other earth scientists the benefits of carrying it out, but how do you sell something like airborne resistivity surveys when we have so much detail in geological mapping across the country. It would be difficult to sell this concept even among technical people, because one has to decide on a unique way of trying to measure the resistivity using compatible standards, units, and systems. Some sort of a common denominator would be required for measurements across the whole country when using different types of systems. On the positive side, if you carry out systematic regional surveys, new ideas and problems appear, as we have seen in the case of aeromagnetics. New applications in earth science become feasible and new kinds of geological problems can be solved.

Across Canada there are large regions, such as the Abitibi clay belt, where resistivity mapping would be very useful in conjunction with mineral exploration. In the past five years there has been a tremendous increase in the amount of drilling of overburden to aid geochemical sampling of tills. The approach has been very effective in gold and base metal exploration. What is lacking in the opinion of Quaternary geologists and geochemists is more input from geophysics. Their problem is to outline bedrock topography which controls the composition of overburden and till distribution in the area, and EM surveys can contribute to solve it.

Electrical surveys could be useful in deep continental and marine basins, particularly deep soundings using either EM or MT equipment. We also have an indication that utility companies which are planning the location of power lines would like to know more about resistivities across the country. I think that groundwater is an important target, but I don't think we can sell the Canadian government on the idea of doing regional surveys for groundwater. However, we can use airborne systems to unravel the problems in Quaternary geology which would lead to understanding the distribution of aquifers. If we decide to do systematic surveys, we should think carefully about the areas of applicability instead of covering a great expanse of ground. We should try to make the surveys in such a way that they can spawn other developments, whether by solving problems directly or by providing a staging area for other types of work.

Peter Annan: I want to reiterate a couple of things that have been said and which I feel are extremely important: we have to identify new markets and we have to start with education. Those of us who are in the EM business must try to understand problems of other people, and find out how to present our product in a manner useful to them. To educate people takes years, not days or weeks, and what we need is to continue with efforts like the Workshop today. As a result of such meetings, particularly if they were widely advertised, people who would not have used the EM will start thinking about using it for their particular problems. Education is a slow and tedious process, but if we don't do it now, there isn't going to be a tomorrow.

Silvio Guedes, President, Prospec, Rio de Janeiro, Brazil: As an unbiased observer from Brazil, I would like to comment on the worries expressed by Art Rattew. This is perhaps my tenth trip to Canada, and whenever I come I always learn something, especially about airborne geophysics. However, this time I have been really worried about the general situation here. Ten years ago it wouldn't take me more than 3 or 4 days to visit all the geophysical contractors and manufacturers in Toronto. This time I stayed in Canada for 12 days and was not able to see them all. This surprises me because the market is at a low ebb. I look around and what do I see happening? There are many one-man companies, formed by people who worked for the companies I used to visit. All are producing wonderful instruments, but how long can they survive? Will the market grow to absorb all the intstruments they are making?

Len Collett: My observation is that we are really a cottage industry. My concern stems from the knowledge of proposals by geophysical companies that come to the government in search of financial aid. We believe in the entrepreneurial system, and we in the Federal Government and in some of the provincial governments, particularly Ontario, that provide research funding should not be required to make judgement on who gets aid money, if the proposal is technically sound. What really is worrying me now, is how far can we keep supporting all these companies.

Alex Becker, Professor, University of California, Berkeley, U.S.A.: We have seen here for two days a good cross-section of the applications of electromagnetics to the solution of geotechnical problems, geotechnical not only in the construction or the hydrological sense, but also in the sense of mineral exploration. Just as the governments of Canada, the United States, or Brazil had decided that an aeromagnetic map was a product which was of value to the country, now they should ask themselves whether electromagnetic maps are a valuable product. If yes, they should go ahead, but I do not think the plight of the industry should ever play a role in this decision.

Art Rattew: I do agree that one does not do a systematic coverage just to keep the survey industry alive. The reason and the point I was trying to emphasize is that the industry problem is short-term. I don't think we can survive another five years talking about the crisis and scrambling to find new markets because they are not big enough to sustain the kind of industry that Silvio sees when he comes here.

Arthur Darnley, Geological Survey of Canada, Ottawa: I was a little surprised at Roger Barlow's hesitancy about systematic airborne resistivity surveys. As I said in my opening remarks yesterday, I see no hope, no expectation, no reason for supposing that anything like 100% of Canada will ever be covered by systematic resistivity surveys, but if my arithmetic is correct 10% of Canada is equal to about three times the area of Finland so I think it is not too difficult to see some justification for 10% of Canada being surveyed using techniques such as have been described. With respect to the acceptance of the method by geologists; clearly, unlike Finland, we still have some way to go, and to some degree, we are all to blame for it. Maybe during the final stage of the discussion this afternoon, concerning the selection of test areas and demonstration sites, we can examine whether by applying a limited amount of seed money to some selected areas we might not be able to stimulate progress.

I have mentioned in my opening remarks the example of the GSC magnetic gradiometer, which a majority of the people here would now recognize as a highly successful development. There was at least a five-year period between its first flight, when a small group of insiders were convinced that it was a viable and valuable technique, and the accumulation of sufficient results to prove this to the satisfaction of the exploration community. During that period about 25 demonstration surveys were carried out in different parts of the country, to build up a ground swell of favourable opinion from industry and from provincial authorities. It took time for the gradiometer to be recognized as a technique that was useful and worth paying for. There is an undeniable problem in getting the acceptance of any new technique, particularly when there is a large dollar sign attached to it.

There is another point I have made about the level of geological knowledge that exists in parts of the country and whether it is therefore justifiable to do more work. What springs to my mind is the geology of the UK, which has been mapped at the scale of about 1:10 000; some parts of the country have been mapped at the scale of 1:2 500. Yet when systematic geochemical surveys were carried out in Britain they pointed to a number of geological features which were previously unrecognized, because they were invisible to the naked eye. New techniques provide new information. In my opinion we should consider the type of comprehensive airborne coverage that is being provided in Finland, 200 metre line spacing using a multisensor system, not just resistivity. Undoubtedly, we are going to reveal a lot of features that have not been visible to the naked eye. One should remember that in much of this country there is only 1% outcrop. What many people consider as an area with good outcrop has in reality about 5% outcrop. Any means that we can devise of seeing between those outcrops would be useful for recognizing discontinuities that are significant in many types of geoexploration. Very detailed knowledge is required in selected areas. However, this requirement is not something that can be easily generated from within government. The demand has to come from outside.

Norman Paterson: Arthur and I agree that the selling has to come from us and we look to your support so that we can say that the GSC agrees with us right down the line. However, there is one problem when you are trying to sell AEM for nonmetallic applications. The first question you are asked is where has it worked. You can say it will work, but you can't point to a large survey that has been flown for geotechnical purposes. As we saw yesterday and today, mostly there are 100 km here and 200 km there, but what we need desperately are good data over large, carefully chosen areas. Then we can take the results and show them to the politicians and people who are on the buying end of the scheme. What we need is some water to prime the pump. I hope it is not asking too much from the Canadian government to fly some surveys for nonmetallic purposes and to help us to get the demonstration material that we so badly need. In order to get things rolling, it should be done this year, not sometime in the future.

Ajit Sinha, Geological Survey of Canada, Ottawa: Obviously, we cannot make makeshift work to keep the industry busy. We have to create new applications for AEM where our expertise would be valuable to users. One such application is mapping permafrost, for which we have used ground EM methods. The oil industry is interested in knowing the permafrost thickness in their areas of exploration. We may need a few more frequencies to have a better chance of success, but such systems having 5 or 7 frequencies are now becoming available. We have to create a market for our product and this is the only way we are going to survive.

Roger Pemberton, Noranda Exploration, Toronto: With respect to airborne resistivity mapping in Canada, as George portrayed it in his initial paper, I see it principally as a geological mapping tool rather than a direct mineral exploration tool. If that is the case, then I am completely in agreement. We have been proud in Canada of the mapping programs by the GSC and the provincial governments. The mining industry has been supporting them and it would support one in resistivity mapping. Your geologists at the GSC are probably more attuned to using regional magnetics for mapping purposes than our in-house geologists. We are more interested in target identification and one could use resistivity for that. Unfortunately, resistivity mapping would have had to come at a different time, when we were looking for massive sulphide targets. At present, when 70% of our exploration programs are directed to precious metals, it is more difficult to justify the use of resistivity for mapping targets, such as the Destor-Porcupine fault or the Casa Berardi gold deposit. I have talked to Roger Barlow a few times this summer and I was really impressed with his interest in resistivity mapping. We are trying to understand how resistivity properties relate to overburden mapping and gold mineralization. I would like to see a program three times as big as Roger has had this summer. I don't know what the GSC is doing as far as orientation work goes, but the sooner they start the better. We at Noranda ask the contractors increasingly often to provide resistivity maps and we have been excited about their application. In certain geological environments we have been disappointed, but in others we have found them useful. It is going to be a few years before the mining business picks up again. The oil companies who were the big clients for airborne EM in recent years are now out of mineral exploration. We like the resistivity mapping approach, we are impressed with the progress in instrumentation and interpretation, and we will try to use it more.

Roger Barlow: I would like to return for a moment to Arthur Darnley's comments. I have tried hard to find a way that our governments could be helpful in getting resistivity mapping off the ground. It could be easily a Federal government initiative support strongly by the provinces, particularly Ontario. We have been in the business not quite as long as Quebec, but we have been supplying conductor maps that most users found useful. We didn't get into the airborne business from the point of view of doing geological mapping, but we found that airborne EM surveys were an ideal method to motivate exploration companies to carry out work in certain areas of the province. The approach had its economic as well as geological connotations.

Before one makes an investment in resistivity mapping, one has to think very carefully. The value of a government program is that government researchers would consider the scientific implications rather than just carrying out certain surveys. I am strongly behind the concept of resistivity mapping, but I am wondering whether we can sell it even to our own science community, because we are a very polarized group. First we have to learn the other person's problems and try to integrate our work with geologists on the national and provincial scale and with mining companies on the exploration scene.

Ken Robertson, Noranda Exploration, Bathurst, N.B.: The Canadian government has proposed building a half-billion dollar icebreaker to assert Canadian sovereignty in the Arctic. Perhaps we could approach the Canada Coast Guard or the Canadian Hydrographic Service to see whether they would be interested in putting an airborne EM system onboard some of the helicopters that are stationed permanently on the icebreakers. If such systems can determine the ice thickness ahead of the icebreakers, the coast guard would be pleased that their new flagship icebreaker would not get stuck in the high Arctic. The geophysical industry could help them to avoid a potential disaster and would get good publicity in return.

George Palacky: I would like to finish this part of the discussion with comments on Roger Barlow's words that I think are valid. The geophysical community, and particularly the electromagnetic group, are poor communicators. We have not been able to convince geologists that airborne electromagnetics is a useful tool of geological mapping. It is not enough to reach a consensus here. We have to sell this concept to the people who make decisions and also to our fellow geoscientists.

ELECTROMAGNETIC TEST SITES AND PILOT STUDY AREAS IN CANADA

George Palacky: As we have seen during the previous discussion, there is apparently a weak link between geology and geophysics, not only in actual communication between the two groups of geoscientists but often also between the concepts and terminology. We, geophysicists, know a lot about geophysical data and how to interpret them in terms of models, but such concepts are often abstract to geologists. Usually, we are less well informed about the real geological situations, for instance, how different types of massive sulphide deposits influence the selection criteria we use in interpretation of AEM surveys. In my opinion, more effort should go into conducting experiments not in a laboratory, but in the field, in a controlled geological environment. An outdoor laboratory is the concept of test sites and pilot areas. I will define the two. A test site is a fairly simple geological environment, for instance a well-defined conductor, which is used by instrument manufacturers for test new equipment, or by airborne contractors for calibration or performance evaluation of various systems. A pilot area is one, which is geologically very interesting; it may be complex, it may contain features which are not well understood from the geophysical point of view. For instance, in the Labrador Trough, there are thousands of anomalies due to iron-formations which have strong negative in-phase responses on helicopter EM data, about 250-300 ppm, which is more than one would expect from theoretical models. Maybe this could become a pilot area where we could learn more about certain geological environments and the EM responses they produce. In the Labrador Trough over 60 000 EM anomalies were identified in the course of one helicopter EM survey which had 10 000 line km. All anomalies have some geological meaning, but at the moment nobody would be able to explain satisfactorily more than 10 000 of them, even if he had sufficient time to examine them. Now I invite the panel members to express their opinion about establishing test sites and pilot areas in Canada.

Peter Annan: I would like to reiterate that there are two main objectives in setting up test sites and pilot areas, one is the technical evaluation of systems and the other is the applications development. The technical evaluation means knowing whether a system is working and at what level. For this you want a test site that is clean, simple, and well-defined, with lots of ground control. It is important that you can fly over the same place twice and know exactly where you flew.

In my opinion the pilot areas are even more important. In the last couple of days we have seen a number of case histories on applications of airborne EM, some of them novel. What we have to do now is to market the product and that means putting together case histories which demonstrate the performance of the systems. We have to choose applications for which there is a need, like groundwater or the salinity problem. Western Canada has had drought for the last couple of years and the farmers have experienced salinity problems as well. There is room in this country to do things which have global applications. We should try to set up pilot areas in such a way that we achieve two well-defined objectives: moving the technique ahead and marketing the concepts in the broader world market. There is no sense in picking a pilot area where we have no geological control. First we should do our homework, talk to people in the user community and find out what their problems are. Then we have to go out and look for sites that are meaningful to them, not sites that we think are meaningful to them.

Finally, there has to be some funding for test sites and pilot studies. I don't know where the money will come from, certainly not from contractors or system developers. Everyone is trying hard to develop new systems and to cultivate the market place, but these activities take time and money, and we would not have any funds to establish test sites.

Roger Barlow: The test range subject has been very dear to my heart for the last five years. When I put the Ontario program together I envisioned approximately five test ranges across the province in different geological environments. So far we have made good progress in one area and we are starting on another. We need more money to confirm the structure on the first test range at Night Hawk Lake near Timmins. This target is of the inductive type, not a particularly straightforward one, one that presents a challenge to EM techniques for the purposes of mapping it, not just simply detecting it. The target is not designed to calibrate equipment, for this we have to use a better defined body. My feeling was that we had enough mand-made structures that could serve this purpose and that we should look for something that had the physical properties of an exploration target, however, without being of economic interest.

One important consideration is the maintenance and protection of the test ranges and their grid system. The ranges should be designed as reserves or scientific parks. The importance of the test ranges lies in the possibility of using a variety of instruments over the same target, which is the only way to gain experience. The results at Night Hawk have been a real eye-opener to geophysicists who could see clearly how certain instruments respond in a controlled environment. The results showed us that we have to be careful in choosing the right instrument for a particular challenge.

So far, we haven't got very far in establishing the other four sites across Ontario. Some of these should be sounding experiments to assess the use of EM in layered environments. We are active in the Matheson area using shallow reflection seismics to investigate Quaternary geology. Seismics together with sonic drilling will help us to define the site and to understand how EM responds in this environment. As the work has progressed, we have encountered numerous problems, for instance physical properties of the local materials are still poorly understood. One of them is how to measure electrical properties once the unconsolidated material has been removed from the ground. We have tried to develop a suitable technique. We have discovered relaxation induced polarization (IP) phenomena in clays caused by varving or by differential water layers. All these problems need to be studied more so that we can understand the EM environment better.

Robert Bazinet: At the moment we are working on a test site in Quebec, at Waconichi near Chibougamau. The target is a structural conductor. The original idea was not to establish a test site, but to prove to geologists that they can extract useful information from airborne geophysical data. Ground truth was to be obtained by carrying out extensive geophysical surveys, geological mapping, and correlation of results. Last year we started drilling. So far we have spent $400 000, mostly financed by the Government of Quebec. The main problem we are facing is the disappearance of our grid lines, as one company will start logging in the area. We need to establish an accurate location of lines marked in the field by large bench marks to save our grid. For airborne work, the marks should be visible from the plane. An interim report on the site has been published this year, the rest will become available in May 1986.

Some difficulties in establishing a test site like ours are political. In order to get money, we had to stress the mineral potential of the area, and as a result one company has recently claimed half of our test site. From the work we have done I don't think they will find anything, but it is probably safer to establish a test site in a place that is in principle sterile. It should also be far from civilization, so that there is no danger of using the site for construction.

Norman Paterson: I would like to go back to Peter Annan's analysis of what are the reasons for having test sites. He mentioned that testing of instrumentation was one and testing of applications was the other. I don't think that instrument manufacturers really need a place in the field to test their instruments. Geology has the unfortunate way of being very complex. The best place to test an instrument is where the geology is extremely simple, otherwise you don't know whether it is the instrument that is giving you the aberrations or the geology. If I had to test an instrument, I would rather fly it over Lake Ontario to see what is the response of a half-space of a certain conductivity and to make certain that it matches my instrument's specifications. If you fly a new system over the Whistle deposit, you know that will find it anyway. I don't think that field test sites are worthwhile for instrument calibrations and testing. Their principal purpose should be research, for instance further developments in the mise-à-la-masse technique, galvanic energization, a new cross-coil EM system, single-receiver Turam. This activity is not instrument testing, it concerns methods and applications. To achieve useful results you need a well-known test site, with lots of drilling, which our present test sites don't have. We need more ground truth, there is no sense in testing a new application, when you don't know what is in the ground. Another reason for having test sites is education. Where would University of Toronto students learn how to use instruments, if we did not have Cavendish or Nighthawk?

Finally, I think the most important reason for having test sites is marketing. We are not going to sell AEM for groundwater unless we have some profiles over aquifers. I have sent letters to a number of airborne EM contractors asking them if they had time and a plane available to fly a test site in southern Ontario. The response has been good. Two of them have already flown it, and I have received the data. One contractor has flown a test line in Saskatchewan over the Humboldt area which has a buried river channel about 150 metres deep. The test flying has been done with our own money. We do not have to convince ourselves that the technique works, but we have to show it to the potential client.

Art Rattew: For our intended customers we need material about real geological targets, which we can find in this country. To organize and maintain test areas is costly, but it is the most important single element in attracting new clients. If the governments decide to carry out resistivity mapping, one would need various kinds of test ranges for checking individual systems to make sure that they meet the basic requirements and for achieving standardization of surveys flown with systems of different type.

George Palacky: At this point I would like to ask the panel members a question, which should clear some controversy on the subject. Should the governments be active in establishing test sites (by this I mean well defined sites for testing equipment), or should the governments concentrate on carrying out innovative studies in situations where the application of a certain technique may be novel? Several of my colleagues have mentioned a possible application of airborne electromagnetics to groundwater exploration and mapping of overburden. My question is as follows: To which program would give priority, to test sites or to pilot studies, or alternatively, would you like to see the government being involved in both activities?

Art Rattew: My interest would be in the pilot studies, where you would be able to put together case histories over situations, such as water exploration or other types of applications discussed here. Something that you could take to the potential clients. Obviously you need a good control and ground truth. Some input from people like ourselves would be required to define some of the situations that could have market potential. The first category, which is called test sites would be needed only for standardization if you have a major program underway. Then it would be essential; but if you don't have a program like that, I don't think it would be very important, whereas the pilot studies used in marketing really are important.

Norman Paterson: My answer is "Yes! Yes!" A very appropriate area for government support is both test sites and pilot studies. I would like to compliment the ETDF program of the Province of Ontario for including the test demonstration as one of the areas of their support. By encouraging this activity the contractors and consultants can go out to Night Hawk and try different techniques with government support. It would be foolish to expect calibrated and maintained test sites to spring out of nowhere. I think that is an initiative that the government has to take.

Robert Bazinet: I am in favour of both. Only the government can maintain test sites and reserve the land. Maybe the industry could contribute the funds necessary to establish the ground truth, but most financial support will have to come from the government. I think that there is also interest in pilot studies over potentially interesting targets to see how the various techniques work.

George Palacky: Robert, as a university professor, how important do you find test sites for training your students?

Robert Bazinet: We need sites for training students. I have been involved in organizing a field school for 10 years and we have changed places several times. One thing that we need is a secure access to sites. In one case, we were working in a field and a farmer shot at us. Another problem is orientation. Often roads which are on a map don't exist in reality, and vice versa. A good, well maintained site would be extremely useful to us. Recently, we approached mining companies and they gave us information on uneconomic targets which we can use for teaching purposes. As a test site we want a simple target, but with a good response to several techniques. In a field school you want to show your students a target where they can try not only EM, but also IP, magnetics, gravity and other methods.

Roger Barlow: I agree with both. Test sites would generate benefits internally in the government and even bigger ones on the outside. At test sites one could out set up experiments which are difficult to do in a laboratory. One should relate the test ranges to the problems of the day. If we feel that groundwater is an important future problem, then we should consider the possibility of making a groundwater test range. At the Night Hawk Test Range we have a wide range of geometries and physical properties. In addition to the rather complex inductive conductor, there is a diabase dyke which causes a gravity and magnetic anomaly. We have done various kinds of seismic, EM, IP, and other surveys on the property and have been able to investigate a wide range of different physical properties in situ.

Peter Annan: I think the establishment of pilot areas is by far the most important. It would be best handled by government auspices, which could set the standards for archiving information, drilling sites, etc. On the subject of technical evaluation sites I disagree with Norm. There are many steps necessary in testing an airborne EM system, and some problems are not going to show up immediately. If you have a simple, well-known site, then the information should be archived and the site should be documented so that contractors could evaluate their system performance there. There are different sites in Canada where contractors had tested their systems, but there is no central information that would describe the target location and their nature. What we want is a simple controlled target, we don't need conductors 500 feet deep.

Robbert Bosschart, Consultant, Toronto: As far as testing of airborne systems is concerned, I think a test site is rather inadequate. I would rather consider a test area because flying one line will not tell you very much about the performance of an airborne system. There is a test area in northeastern Ontario, west of Lake Abitibi, which Mel Best selected for experiments that were used by Shell Canada in testing a number of airborne systems. If you fly a 200 km survey, you can at least get some idea about the overall performance of an airborne system, about the noise levels under normal survey conditions. The overburden in that area varies from 50 to 300 feet, and there are many conductors and magnetic bodies. I think that is a more useful test of an airborne system than flying over one test target. I agree that single targets have their usefulness, but the overall performance of a system is what you really need in an evaluation.

George Palacky: The GSC and the Ontario Geological Survey have been trying to jointly develop a large test area (6 × 4 km) for airborne electromagnetic mapping near Val Gagne, east of Timmins. We have carried out a number of ground EM measurements, resistivity soundings, shallow reflection seismic surveys, and overburden drilling. Even at present when the work has not yet been completed, the geological and geophysical control at the Val Gagne test site is better than in the area used by Shell Canada 10 years ago.

Len Collett, Geological Survey of Canada, Ottawa: As far as the performance of airborne EM systems is concerned, I am wondering about taking the system high up, away from the influence of earth materials, and documenting the characteristics of the system going through different manoeuvres.

Robbert Bosschart, Consultant, Toronto: When testing an airborne system, you are not concerned about the signal in the system, you are only concerned about the noise. You do exactly what Len said; you test it out of range with the ground. There are many things, like the manoeuvre noise, rejection of spherics noise, effect of aircraft equipment, which you can check only outside the range of the ground.

Norman Paterson: All the people who develop airborne electromagnetic instruments go through the procedure that Len has described. Vaino Ronka knows better than anybody how essential is the testing at high altitude. There are other tests too, like flying and manoeuvering over a conductive half-space, but the results of these tests are seldom published. It would be most useful, if we could persuade the manufactuers to publish these results in some form, or to turn the data over to an agency, such as the GSC, for publication.

Vaino Ronka, Consultant, Burnaby, B.C.: I would like to recommend the establishment of a test site in B.C. mountains, which would have targets on the slope of a mountain.

Rolf Pedersen, Consultant, Ottawa: There are many successful examples in Canada of the use of airborne EM in mineral exploration, but there are some serious misses. Unfortunately, it only takes one miss and the whole geological community seems to know about it and EM is out. One mineral exploration operator I know believes in EM, drills all targets and comes up with discoveries. A geophysicist working for this company once gave a talk on the use of EM in Saudi Arabia, where his company has drilled a number of targets. At the end of the talk he asked if there were any questions. There weren't any and he said that is funny because we were looking for sphalerite which is not conductive.

There is one report written by a geologist in which the use of EM in the Iberian Pyrite Belt was rejected out of hand. This is something that should be countered in print; we need to sell our expertise to geologists, not to ourselves. There is another report from Australia, which was written by a geophysicist and published in Exploration Geophysics, about massive sulphides not responding to EM. The body has been drilled, the results are conclusive, but nobody explained why the sulphides are resistive. At a recent conference in Rabat on prospecting in desert terrains two papers mentioned the futility, not the utility, of EM, and all the geologists and managers making decisions were listening to that. And nobody stood up and tried to give a reasonable explanation from the geophysical point of view.

If you looking for water, all the tests carried out in Canada will not cut much ice overseas. They want to see the results of a test made in Spain, in Morocco or in Australia. I am sure the Brazilians would like to see the systems tested in an area where it rains a lot. It may rain a lot in B.C., but the geological and weathering conditions are not the same as in Brazil. These are the places where the contractors and consultants should go, if they want to develop new markets.

John Hayles, Atomic Energy of Canada, Ottawa: We are often faced with a situation that there is a steel casing in the hole, which does not allow us to carry out electrical logging of the overburden section or of the paleoweathered layer. It would be useful, if we could get an agreement with the diamond drilling community so that they would put in a perforated plastic pipe rather than steel casing in that section of the hole. In this case, we could do electrical logging and obtain in situ measurements that would be extremely useful in interpretation of EM anomalies caused by overburden or weathered layers.

George Palacky: As there are no further comments from the audience, I will summarize the last subject of the discussion. It seems that the panel members could not reach an unanimous agreement on whether it is desirable to develop test sites, which are simple geological targets suitable for testing by contractors and designers of airborne EM equipment. However, all panel members were in favour of systematic studies in pilot areas. These are sites about 5 × 5 km to 20 × 20 km where one could study, as in a field laboratory, geological conditions, geophysical parameters, and electrical and other physical properties of earth materials in situ. Such detailed geological and geophysical studies in controlled field environments would be best carried out by provincial or federal geological surveys. In my opinion, there would not be much point in collecting rock samples in the field and in measuring their resistivity in a laboratory. We have done that in the past and the results were not found relevant to real field situations. Electrical properties of materials, like water saturated clays and sands, which contribute significantly to EM responses in many places, can be measured meaningfully only in situ.

SUMMARY OF THE PANEL DISCUSSION

George Palacky: I will briefly sum up the discussion. On the first topic, units for resistivity mapping, we agreed that there is a need to use physical units in presenting results of airborne electromagnetic surveys. Unfortunately, we have not been able to reach a consensus, whether we should display the data as conductivity in millisiemens per metre, or as resistivity, in ohm-metres. The arguments for one or the other seemed trivial to most participants; some would not mind having it either way. However, if we start a systematic resistivity mapping program, it is essential to uniformly define the parameters and units of measurements. I have previously summarized the recommendations for the need to objectively specify the characteristics of airborne electromagnetic systems and also for the need to standardize the description and labelling of media used for information storage, such as format and headers on tapes and discs. I have also described the possibility of establishing an intermediate product, the edited data set, in addition to the raw data on tapes and to the contour maps which are presently produced by organizations carrying out airborne surveys. Such a data set, which could be conveniently stored on a floppy disc, would allow the final user to generate his own conductivity maps or sections, or to carry out quantitative interpretation of the data.

On the second topic, a major concern was expressed by the representative of geophysical contractors on the panel about the sad state of airborne contracting, which has been caused by the worldwide decline in mineral exploration activities. Most of those present here have agreed that governments should be more active in sponsoring systematic airborne electromagnetic surveys in addition to the existing programs of magnetic and radiometric coverage. One of the weakest points of our profession is communication. We often don't know how to effectively sell what we are doing to the potential users. Sometimes we don't communicate effectively even with our professional colleagues, the geologists. If we don't learn how to promote what we are doing, we cannot hope to convince the politicians that large systematic airborne electromagnetic surveys would be a worthwhile idea. At present it seems that there could be opposition to such an idea even within the geoscience community.

On the third topic, the test sites and pilot areas, it would be desirable to conduct carefully controlled geophysical studies over some types of geological targets, which in the past have been poorly defined from the geophysical standpoint, for example, glacial overburden, aquifers of hydrological interest, magnetite which often produces a complex electromagnetic response, weathered layers in regions where they constitute the major source of electromagnetic anomalies and their relation to the underlying lithology.

As far as recommendations are concerned, there was one underlying tone, a demand that governments should become more active in sponsoring systematic airborne electromagnetic surveys, in establishing test sites, and in developing new applications. It is a little awkward for me, a public servant, to formulate recommendations to myself and I will not try. They are obvious to all who attend this session. In conclusion, I believe that all of us, who work for the Geological Survey of Canada, have listened very carefully to what you, the members of the geophysical community, representing manufacturers, contractors, the mining industry and other users, have said here today and yesterday. We will try to do our best. We have been encouraged by the interest in airborne resistivity mapping. When we started the preparations for the Workshop, we expected about 70 people, but as you see today, 150 have registered. I hope that this was not the last meeting on the subject of airborne resistivity mapping. Thank you very much for your attention and for your attendance at the Workshop. (Applause).

Norman Paterson: I think that we should all show our gratitude to George Palacky for organizing this very successful meeting. (Applause).

Appendix III*

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*In Airborne Resistivity Mapping, ed. G.J. Palacky; Geological Survey of Canada, Paper 86-22, p. 193-195, 1986.

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