Selected examples of induction studies in continental regions, including AMT prospection, for natural resources

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Abstract : *This paper is an attempt at reviewing relatively recent electromagnetic techniques and/or surveys for the detection of natural resources. It is divided into main categories such as the application to mining, hydrogeology, geothermal studies, propecting for oil, and geological mapping. In each case, we separate ground methods from airborne techniques, and again subdivide these into either plane wave or « other » methods.*

Key words : Electromagnetic prospecting - Natural resources.

Résumé : **Exemples choisis de prospections électromagnétiques, y compris l'audio-MT, pour la détection de ressources naturelles en régions continentales.** *Cet exposé passe en revue les techniques électromagnétiques relativement récentes ainsi que quelques exemples de leur application à la détection de ressources naturelles. Il est divisé en chapitres selon l'application de ces méthodes à la recherche minière, l'hydrogéologie, les études géothermiques, la prospection pétrolière et la cartographie géologique. Dans chaque chapitre, les méthodes « au sol » sont considérées séparément des méthodes « aéroportées », en distinguant d'autre part les méthodes utilisant les « ondes planes » des « autres méthodes ».*

Mots-clés : Prospection électromagnétique - Ressources naturelles.

INTRODUCTION

The subject of this review is quite large and the reader will often be referred to excellent papers already in the litterature. Note however that bore-hole techniques will not be considered here.

Among the excellent papers the tutorial of PALACKY (1983) takes a preferential place. Dealing with « Research, Applications aud Publications in Electrical and Electromagnetic Methods », it constitutes a review by itself. Electromagnetic (EM) techniques are widely used in surveys and have led to numerous papers, but PALACKY regrets the lack of papers dealing with instrumentation, techniques, case histories and physical properties of rocks. Figure 1 shows that among electrical and electromagnetic (EM) methods, magnetotelluric (MT) and EM methods have made the best progress in expenditure. For PALACKY, all these methods are more versatile than any other geophysical technique since they can be applied to crustal studies, oil, coal, iron ore, base metals, graphite, salt, kimberlite, geothermal energy, ground-water research, water pollution studies, karst cave exploration, engineering studies (including nuclear waste disposal), mine construction, landslide investigation, uranium exploration, and archaeology.

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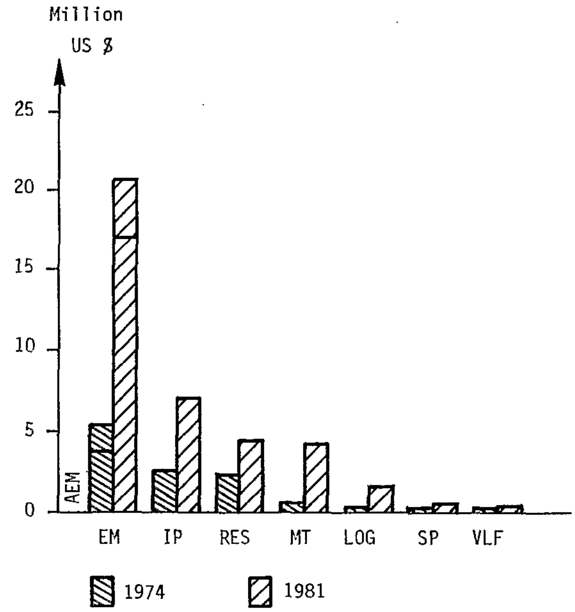

Fig. 1. — Expenditures on electromagnetic (EM) ; induced polarization (IP), resistivity (RES), magnetotelluric (MT), electrical well-logging (LOG), self-potential (SP), and VLF methods in 1974 and 1981 (From PALACKY, 1983).

Mineral exploration was certainly the most important application of both electrical an EM methods up to the early seventies, but now the spectrum of applications has considerably enlarged (e.g. Audio-Magneto-Telluric (AMT) methods for civil engineering, radio MT, archaeology, etc.).

The theme of this review being applied geophysical research, the structure of the paper will follow the main applications of EM methods : namely mining, hydrogeology, geothermal studies, oil, and geological mapping. Since it is necessary to consider the great variety of electromagnetic and inductive methods, a distinction between the two main approaches will occasionally be introduced when needed.

Previous reviews were organized around a main theme, stressing this or that aspect of the methods. For instance, fixed or moving sources, uniform or non uniform fields, frequency or time domain, one or several components, or nature of the source field. In this review, we simply separate source fields into plane waves or « others ». In the first group, we consider the telluric and magneto-telluric (MT), as well as VLF (Very Low Frequency) and AF-MAG (Audio Frequency Magnetic) methods. As a rule, these methods have a common characteristic which distinguishes them from the others : they are based on the utilization of natural phenomenons and consequently they have only receivers and no transmitters (but note the recent development of controlled source audio magneto-telluric (CSAMT). In the second group, the methods are classified according to the means used to create the source fields : long cable, large loop, small loop or dipole. Every method presents advantages and disadvantages, thus giving a wide range of applications. Obviously, long grounded cables will not be frequently used in highly resistive environment and light dipoles would be preferable for rapid reconnaissance of a target. Heavier techniques are justified for the extension of already exploited deposits or for the more precise localization of targets already defined by other geophysical techniques.

Within the controlled source methods, a distinction must be introduced between time domain and frequency domain methods. Frequency domain methods are characterized by the emission of variable frequency sine waves, while time domain techniques rely on the emission of transient pulses with variable shapes and repetition rates. Note that time domain methods may have better resolution than frequency domain ones.

From a theoretical point of view, airborne methods are not very different from ground-base methods. Except for AF-MAG and VLF, they do not use plane wave sources. Most of them are based on dipolar harmonic sources (at one or several frequencies) but some use transient sources. Variants are very numerous depending on the type of aircraft used : fixed wing planes or helicopters with a bird or another form of receiver. Obviously the designs of the mechanical and electrical elements of the equipment are of paramount importance for industrial use. More can be found on the subject in the review of PELTONIEMI (1982) who critically compares various airborne electromagnetic methods.

MINING

Because mining research is the most common target of applied electromagnetism, this section will be the largest of the review.

Ground techniques

PLANE WAVE METHODS

PHILIPS and RICHARDS (1975) have very systematically studied the effectiveness of VLF for detecting a mineralized fault. This method utilizes the signal produced by powerful transmitters (e.g. that of Rugby, Maine, Moscow, Le Blanc) used for communication with submarines. The signal contains both electric and magnetic components, but since the magnetic components carry the bulk of the signal energy, and offer advantages from a practical point of view, they are used more often than electric components. The two

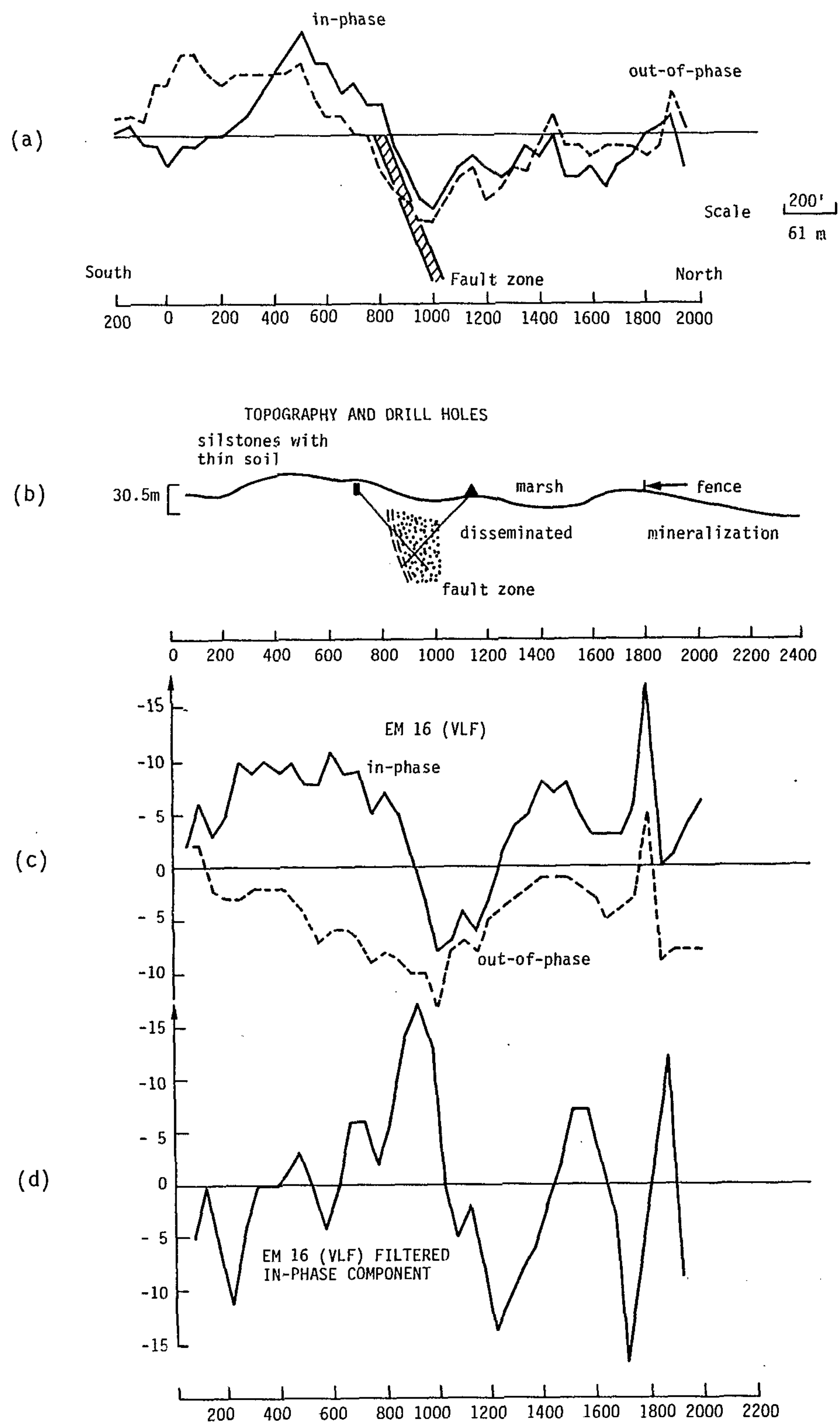

Fig. 2. — VLF electromagnetic effects on a mineralized fault zone, Glogfawr Mine, Cardiganshire (From PHILIPS and RICHARDS, 1975).

coils of the EM 16 instrument used by PHILIPS and RICHARDS (1975) allow both in-phase and out-of-phase measurements. Illustrating the nature of these measurements, we consider a survey located in an area east of Glogfawr Mine, Cardiganshire (fig. 2a). In-phase measurements show a peak (10 %) at station 500 N, then decrease to the North to reach a negative peak (7 %) at station 1 000 N, and return to low negative values. This figure is characteristic of in-phase measurements in traverses across a conductor. In this exemple, the presence of a steep northward dipping fault near station 800 N is known from the geology. If we refer to figure 2b, it can be seen that station 850 N is directly above the conductor : here the secondary field is horizontal and parallel to the primary field, thus the in-phase amplitude is zero (the so-called « in phase cross-over point »). The out-of-phase amplitudes vary approximately as S. sin φ sin α/H and are thus very weak in the region of the in-phase cross-over point (since α is close to zero).

Interpretation of VLF data can be very difficult because of the numerous causes of secondary fields at shallow depths. Using a simple filter, it is easy to transform cross-overs and inflection points into peaks (either maxima or minima) and to remove regional gradients. These filtered data are easier to interprete on a map and are more easily correlated with other results (e.g. geophysical or geochemical data) than the original information. Figure 2 also compares the performances of other methods along a particular line (1 000 E), chosen here because it is almost perpendicular to the direction of the transmitter. For the VLF data (fig. 2c), the significant feature is the cross-over point of the in-phase profile at 900 N. The out-of-phase data differ significantly from the in-phase data. They very probably indicate the presence of sulfide mineralization on the fault since they are sensitive to changes in conductivity. Note that at the north-end of the filtered in-phase profile (fig. 2d), a sharp anomaly is due to the fence indicated on the sketched geological section (fig. 2b). Following PHILIPS and RICHARDS (1975) the main advantages of the VLF method are thus :

— its low cost,
— the survey work can be undertaken by a single operator,
— it has a certain success in detecting mineralized faults.

However, the method has disadvantages such its easy contamination by anomalies caused by fences, metallic pipes, as well as its relative poor penetration depth (due to the high frequencies it uses) with may be a very severe draw-back in regions of highly conductive overburden. For comparison of performances, we can mention that IP (Induced Polarization) is very effective in detecting disseminated mineralization, but that it needs a crew of at least three. In this exemple, geochemical exploration was not very effective because of the cover of glacial drift alluvium and peat bog in such old mining areas, and because of the contamination of surface soils.

AMT is another method which has been used in mining investigations, for instance by STRANGWAY and KOZIAR (1979) who give a case history of the Cavendish Geophysical Test Range. This area, which includes two well-known main conductors is often used for test surveys. As the structural directions are known to be approximately N-S and E-W, scalar evaluations of AMT apparent resistivity (ρ_a) were made along these axes. The data are presented in terms of the classical sounding diagrams and pseudosections, as well as in therms of residual plots given by ρ_a at individual sites normalized by the mean apparent resistivity along the total line (at given frequencies). North-south and east-west plots were produced by plotting the ratio of ρ_a in these two directions. The residual plots emphasize the lateral geological variations (fig. 3a and b) which are very important in mining exploration. The authors concluded that the north-south, or TE, mode gave the best diagnostics signatures over the two main conducting zones. Other detailed features were found to be in full agreement with previous measurements using different EM techniques (grounded electric dipole source, time domain EM, ...).

In Finland (ADAM *et al.*, 1982) AMT is commoly used for mining investigations, as well as for larger investigations (e.g. the ELAS project). AMT is a useful guide in the choice of MT sites, and in the interpretation at great depths. Unfortunately, the equipment records scalar data and the measurements must be undertaken in four directions at 45° to approximate tensorial data. This procedure only gives true tensorial information if the source field remains stationary during the measurements (wich is not often the case).

OTHER METHODS

Other techniques (i.e. those for which the source field is not a plane wave) have made significant advance over the last two decades, perhaps because they avoid the problem mentioned by PRESTON (1975). Indeed, PRESTON stated that electromagnetic methods were not very effective in tropical and subtropical regions whereas they were often successful in northern regions. It is now well known that this is due to a great difference in the nature of the ground surface and subsurface. In the first case the weathering zone may be more than 30 m deep whilst in the other one it is very thin or inexistant. A mining research is directed towards finding conductive ore bodies, it is obviously more efficient in regions where these bodies are not embedded in a thick and conductive weathered zone.

According to WARD (1982), weathered rocks are characterized by low and irregular density, high porosity and fluid permeability, and good electrical conductivity due to the high salt concentration. They also show low electrical polarization due to the complete oxidation of pyrites, pyrrhotite, etc. They contain many sources of spontaneous potential and are less magnetic than unweathered rocks due to a lower magnetite content.

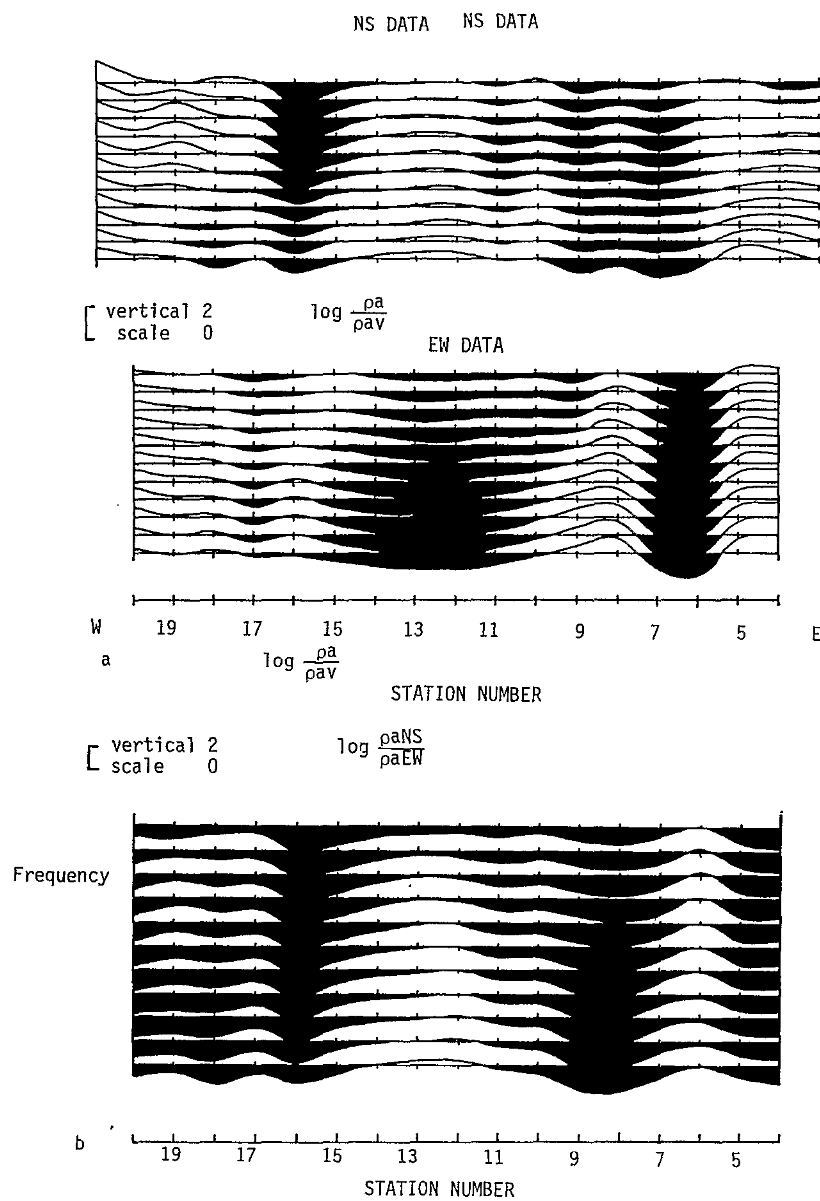

Fig. 3. — a) Residual plots at each station of the ratio of ρ_a on ρ averaged on the entire line at each frequency in Audio M-T (lower frequencies at the bottom). b) Ratio of orthogonal resistivities from dipole data on the same line (From STRANGWAY and KOZIAR, 1979).

SLINGRAM is a horizontal small loop electromagnetic method operating at two frequencies (880 and 2 460 Hz). SEABORNE *et al.* (1979) established that their Slingram anomalies were more affected by the shallowness of the conductor than by its high conductance. This is an important result, as Slingram has often been used for prospecting massive mineralizations. The authors also underlined the role played by the conductive overburden, and the risk of misinterpreting anomalies due to conducting features if fault controlled modification of the observed anomalies is ignored.

TURAM is a fixed source method consisting of a long grounded cable and of two receivers (loops) displaced on profiles normal to the source. Large errors can occur in regions of high overburden conductivity due to misorientation of the coils as there is a large horizontal field component, and anomalies can be large enough to create a field intensity near zero or in a reverse sense. In these case the Turam ratios of secondary to primary fields may pass from zero to infinity either in a positive or negative sense.

PODDAR (1981) conducted a survey over the sulfide deposit of the Mailaram copper belt in India. He used a six frequency Turam system in the range 84 to 2 688 Hz. Interpretation was carried out using a thin sheet model to represent the finite heterogeneous resistivity of the ground and by substracting this effect from the observed response. The Turam method was showed to be a better tool than Slingram as it has a better depth of investigation. This kind of interpretation is a first step in the right direction, but the inability to model the Turam response, either numerically or physically, in a conducting environment was emphasized. To counteract the difficulty, LILE *et al.* (1982) proposed to model Turam responses with a finite element 2-D algorithm. A case history is given from Moskogaissa in northern Norway (fig. 4) and it is shown that the amount of conductive current is considerably larger when one of the cable electrodes is grounded in the ore horizon. Also, when a conductor is shallow, it is detected by the inductive current concentrations whereas when the conductor is deep it is detected by the gathered (or conductive) current.

Another transient electromagnetic (TEM) system is discussed by OGILVY (1983) who present the SIROTEM equipment used in coincident, or common loop, mode. A single turn large loop serves as both moving source and receiver. The results confirm the advantages of this system if prospecting for large, deep-seated ore deposits owing to a rapid multispectral excitation when the signature of buried targets may be masked by less conductive overburden.

A new method was proposed by HALL (1983) who uses a source equivalent to a 2 horizontal electric dipole (HED) ring source with a phase difference of $\pi/2$ between the dipoles. E and H fields couple strongly with steeply dipping conductive targets regardless of their strike direction. Analogue modelling studies were made with both conductive or inductive targets (graphitic target insulated or not). By discriminating between the two types of responses, it is found that, at the inductive limit of response, current gathering provides the major portion of the anomaly and the individual conductive and inductive optimizations combine in such a manner as to improve the net optimizing ability.

Airborne techniques

PLANE WAVE METHODS

In airborne EM, plane wave sources are rarely used. ARCONE (1978, 1979) presented some interesting work based on VLF airborne prospecting. He measured the electric field Ex and Ez components in the nose of an aircraft. By measuring quadrature and in-phase components, he defined wavetilt, surface impedance, and resistivity. It was shown that the phase of the wavetilt is an important factor for distinguishing high resistivity in regions of near surface crystalline bedrock, a value smaller than 45° corresponding, as in the MT method,

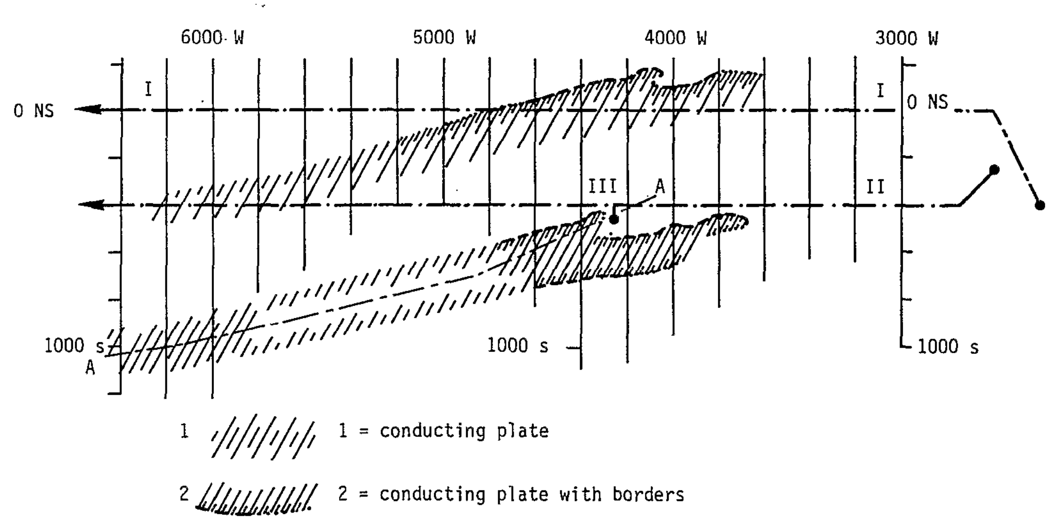

Fig 4. — Turam measurements in Moskogaissa using the cable layouts, I, II and III (From LILLE *et al.*, 1982).

to an increase of apparent resistivity (which, itself, may be due to a decrease in weathering). The method was tested at a flight altitude of 150 m in a mountainous area of predominantly slate and igneous rocks in northern Maine. The results were controlled and verified by a ground survey. In the second paper, ARCONE (1979) studied the effects of survey altitude, anomalous size and average ground resistivity upon airborne values. Il was found that an altitude of more than 75 m was responsible for large attenuation of some ground anomalies. Topography has an important effect on Ez.

OTHER METHODS

These methods are very largely used in mining geophysics and we will only mention some recent applications.

A massive sulfide ore body in Brazil was detected by PALACKY and SENA (1979) from EM and magnetic surveys. Their paper is very interesting since case histories describing airborne and ground EM measurements in tropical regions are rarely published. In

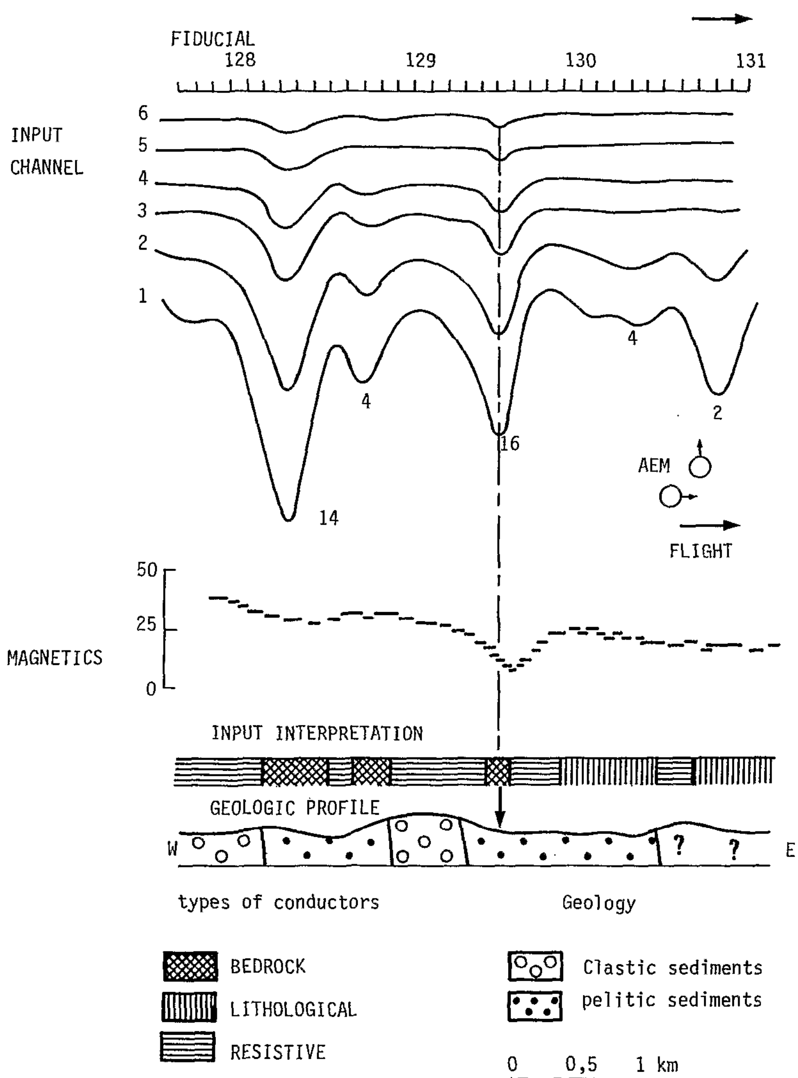

Fig. 5. — Airborne time domain Input and magnetic data over a target in tropical terrains (conductance estimates written near anomaly peaks). The anomaly of 16 mhos was investigated on the ground and drilled (From PALACKY and SENA, 1979).

such regions the conductive overburden (derived from the underlying rocks), varies considerably over small areas and its effects are hardly distinguishable from those due to bedrock conductors. Standard techniques were found to be only partially satisfactory, and a new scheme of target selection was developed, based on statistical analysis of conductance in a given lithologic unit. Massive sulfides were found in the Itapicuru greenstone belt as a result of a carefully conducted EM survey.

The airborne survey was performed with a towed bird, time domain INPUT (Induced Pulsed Transient) system and the EM ground surveys by a horizonal-loop multifrequency system (Apex Max-Min II). On the ground, frequencies and coil separation were selected from the airborne anomaly characteristics, and only those attributed to bedrock conductors were investigated with ground EM. The depth of the conductor (fig. 5) was estimated at 5 m and its conductance at 10 S. But magnetic anomalies were found to have other sources, so additional geophysical measurements were performed (gravity, IP). It was found that the magnetic anomaly was probably associated with the thickness of volcanic sequences and that the EM, gravity and IP anomalies were caused by a layer of metatuffs. A drill hole intersects metatuffs with bands of massive pyrite and minor pyrrhotite. This was an important technical success even if it was without economic significance. It is interesting to note that, according to the authors, the multifrequency horizonal-loop EM is more efficient in tropical terrains than any vertical-loop EM, shootback EM, or TURAM. They also stated that no extra low-frequency methods are required to penetrate the conductive overburden in Brazil as the lower end of the standard frequency range (200-500 Hz) yields all the information necessary to locate exploration drill holes.

An airborne Input survey is described in a paper by REED (1981). The survey led to the discovery of two zinc - copper - silver mineral deposits in close proximity in the northern part of the greenstone belt west of Matagami, Quebec. While an earlier airborne EM survey detected the zones in 1958, they remained untouched until the Input survey of 1971. The Input system is a time-domain EM system using a half sine current pulse in the transmitter, and six successive measurements of the transient voltage produced in the receiver coil by eddy currents in the ground.

FRASER (1979) used a multicoil airborne (helicopter) electromagnetic system, which consisted of a 9 m bird towed 30 m below the helicopter, the small size of which improves resolution for small bodies e.g. : discovery of the New Insco copper and of the Montcalm copper-nickel ore bodies. The recorded data include the basic recorded data, the EM difference, a channel of resistivity, and a channel of conductance (but not the nature of the conductor !). Its most important application is to metallic mineral prospecting but it can be used for sand and gravel detection with two, well separated fequencies. Their system was called DIGHEM II, and it largely overcomes the limitations of the earlier multicoil I system. The two orthogonal transmitters and three orthogonal receivers coils yield six EM configurations and the system can be flown in two survey modes. Either the whaletail mode is used, i.e. the plane of the coil has the orientation of a whale's tail (horizontal), or the fish-tail mode is used, i.e. the coil is vertical with its horizontal axis perpendicular to the bird axis (as in a fish tail).

The whaletail mode of flying provides the ability to determine the geometry of the conductor (fig. 6) since

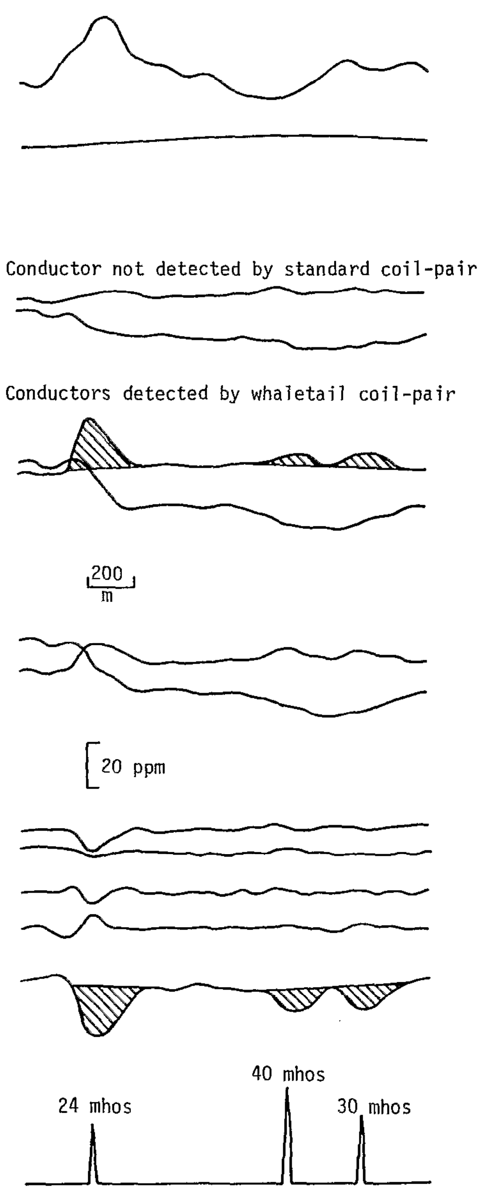

Fig. 6. — Conductors detected in the whaletail mode when the flight line is parallel to their strike (From FRASER, 1979).

the data are essentially independant of flight direction. The ratio of anomaly amplitudes between whaletail and standard coils yields information on the shape of conductors. This mode is useful in areas where bedrocks conductors are abundant, and where the differenciation of thick and thin targets could be of major economic interest. The fishtail mode provides excellent coupling to conductor of any attitude, but it is less used than the whaletail mode because the latter provides more useful data.

The difference functions, obtained by combining received signals from the standard and coplanar coils, yield anomalies which are essentially free of the response of a conductive overburden or of the negative in-phase response of magnetite which are both considered as geological noise. Digital filtering sometimes degrades the resolution of conductors (e.g. 60 m rather than 40 m for analog records), but this is balanced by the fact that noise reduction permits a depth of exploration in excess of 100 m. Detailed Input information shows that the conductors associated with the discovery have only moderate conductance values. A system of grading, favoring highly conductive responses, would have rejected the anomalies. They were, however, selected on the basis of their comparatively large amplitude, their isolation from other conductors and their proximity to known favorable geology.

FRASER (1981) described an application of Dighem II to magnetite mapping. In a first paper (FRASER, 1979) magnetite was considered to be geological noise and thus it is interesting to see how the equipment can be useful for that purpose. In fact, a new EM parameter was added which provided an estimate of the magnetite content of near surface rocks. The mapping method used horizontal, coplanar, in-phase data and only bedrock features were mapped provided that the overburden did not contain magnetite. The method is sensitive to 0.25 % magnetite by weight when the sensor is towed 30 m above a magnetic half-space. It is a complementary method to magnetometer mapping an is not influenced by remanent magnetism of magnetic latitude. Being far less sensitive than magnetometer mapping it is more able to resolve closely spaced magnetite zones, to differentiate between various rock types and to define rock contacts.

In his paper, MACNAE (1979) discussed geophysical techniques for the search of kimberlite pipes, a major

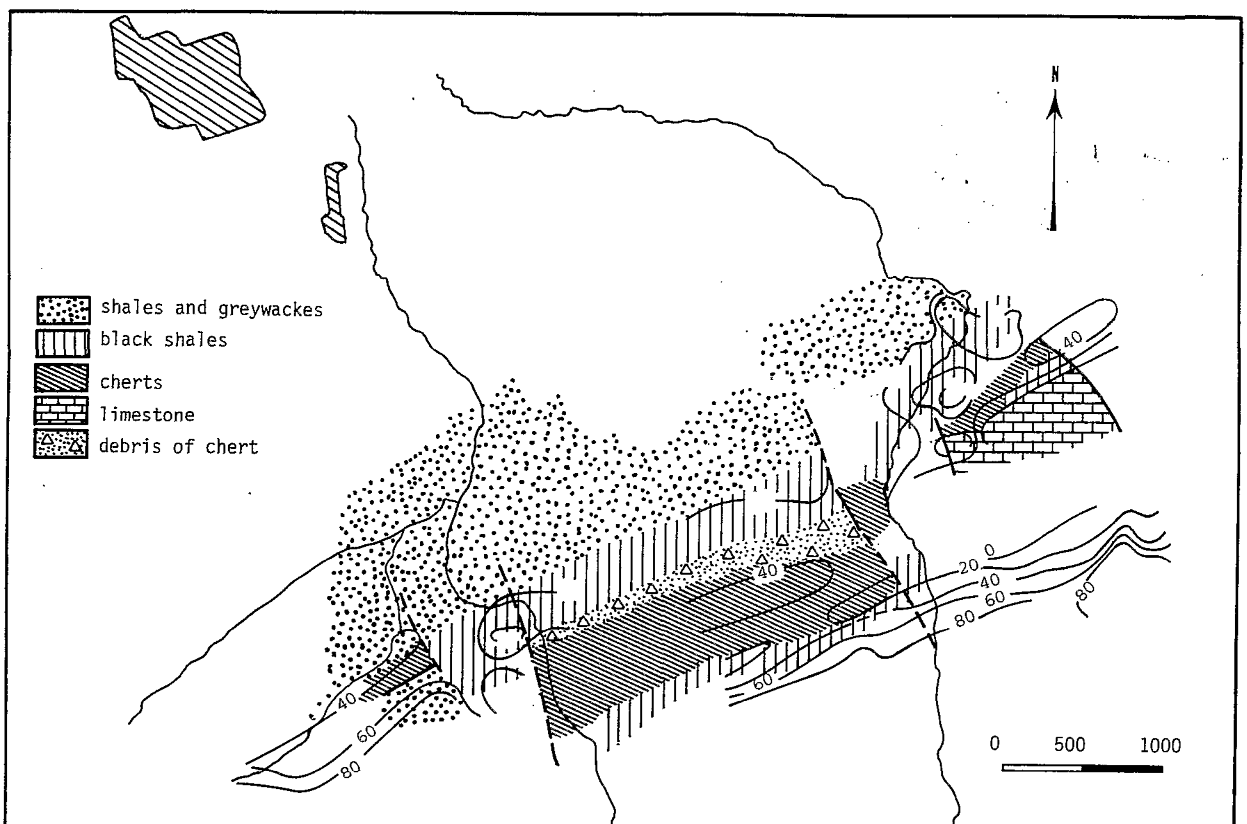

Fig. 7. — Contours and extreme values of the apparent depth in meters with Dighem II, Geologic sketch (From SENGPIEL, 1983).

source of diamonds. In one large survey in South Africa, airborne EM has proved to be very effective in detecting the presence of weathered clays or epiclastic kimberlite contained within the pipes. All pipes discovered during this survey had unmistakable EM signatures, while five out of eight had very small magnetic anomalies which were not likely to have been selected as potential targets on the basis of magnetic data alone. He concluded that in areas where deep weathering is expected an EM survey is essential in combination with a magnetic survey if reconnaissance is to be based on airborne geophysical techniques.

With Dighem II, SENGPIEL (1983) considered the behaviour of parameters ρ_a (apparent resistivity) and d_r (apparent depth) above various conductivity models, and at various flight altitudes, for both theoretical examples and several field applications. ρ_a and d_r are good approximations of the true ρ and d of an extended, buried conductor only when the shielding effect of the cover is small. Moreover, a depth value has meaning only whitin the lateral boundaries of a target conductor. *A method is described to locate these* lateral boundaries and to select acceptable depth and resistivity values by means of the « area of d_r confidence » which is derived from the horizontal gradient of log ρ_a and the maxima of d_r (fig. 7). The results of the resistivity and depth mapping are presented over known sulfide ore bodies, and they show that reliable data can be obtained on the depth, dip and extent of a conductor, as well as on the approximative resistivity of the conductor and of the host rock.

In their paper, VILLEGAS-GARCIA and WEST (1983) proposed a new improvement in detection of EM overburden anomalies. They undertook an analogue modelling study to investigate the EM response of non-uniform conductive overburden layers with an horizontal loop technique. They report several characteristics of the response that will help to differentiate between the EM response of non uniform overburden layers and the response of bedrock mineralized conductors. *To recognize these characteristics, survey data at* several frequencies and coil separations are required. The response of ramp-like, ridge-like and valley-like inhomogeneities in the overburden can be mistaken as being caused by bedrock conductors. For the ramp and ridge inhomogeneities, the migration of the negative peak anomaly observed in profiles surveyed, at different coil separations, was one of its more diagnostic characteristics. Prominent positive shoulders as well as an abnormal distance between crossovers of a given detected field anomaly might be the first indication of the presence of a valley-like inhomogeneity underneath the overburden.

HYDROGEOLOGY

Induction methods are not as widely applied in search for water as they are in mining research. We shall *summarize here three recent papers based on plane* wave methods, and a fourth one discussing the application of other methods in general.

Ground techniques

PLANE WAVE METHODS

Recently, FISCHER *et al.* (1983) published a paper on VLF surveys of two-dimensional stuctures. If the electric field is measured as well as the magnetic field, the interpretation can be much more detailed than when only magnetic components are recorded. The case of a vertical conducting dyke was studied, and surprising results are shown in figures 8a and 8b. In fact, what is important here is the high degree of anisotropy over the dyke itself. It clearly shows that interpretation requires at least two radio-transmitters, one being *approximately in the strike direction and the other* almost aligned with the profile. The finite separation of the electrodes (5-10 meters) is another problem, especially in the H-polarization since the electrodes may span a geological structure and give an average field measurement.

An example is given of a karstified vertical strike-slip fault. The usefulness of phase measurement is demonstrated as it requires the introduction of a higly conducting base, the phase being above 45°. It is emphazised that in a 2-layer case, even with only one frequency analyzed, the phase difference between E and H indicates the electrical nature of the second layer : a value above 45° indicates a conductive basement, a value below 45° a resistive one.

This study is important by showing that a VLF ground survey is a quick and powerful tool for the investigation of geological features within about 100 m of the surface.

Another type of set up was proposed by GUINEAU (1975) and DUPIS (1978) based on the exploitation of radio waves. It will be described in more detail in the last section.

For water research, ROBIN (1984) made extensive use of this equipment in order to obtain resistivity maps (fig. 9) which were very usefull in characterizing underground water flow in karstifield limestones. Data processing is similar to that for MT, but problems may arise from the direction of the incident waves when they are not parallel to the strike.

VOZOFF *et al.* (1982) attempted water exploration by AMT in Australia. Perhaps more than anywere else, the problems are numerous and delicate. In western New South Wales, sources of water found to be in very thick post Permian clastics with rapid lateral variation of facies between coarse or fine gravels, sands and clays over a few hundred meters.

The conclusion of these authors was that joint interpretation of AMT and DC resistivity was far better than either one on its own for quantitative interpretation.

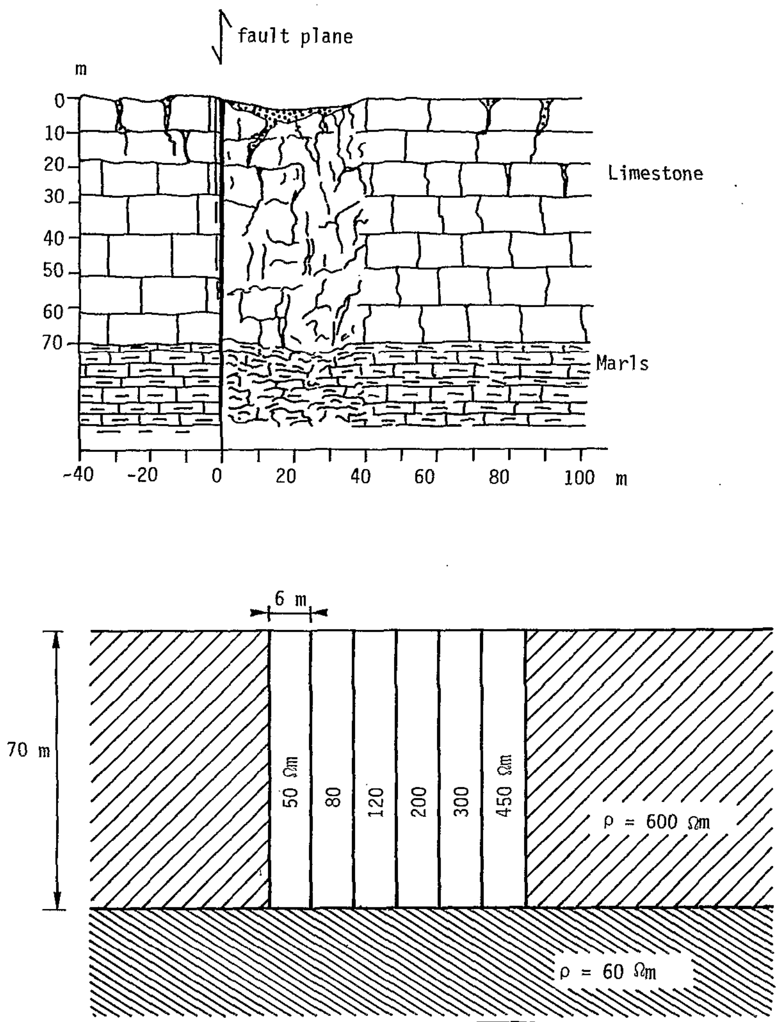

Fig. 8. — a) Geological sketch of a strike-slip fault. b) 2-D model of the strike-slip fault used to compute the theoretical VLF response (From FISCHER *et al.*, 1983).

OTHER METHODS

Ground water problems are treated by KOEFOED and BIEWINGA (1976) with electromagnetic frequency sounding. They found the method attractive because a change in penetration depth is obtained by changing the frequency, instead of displacing current electrodes, and because in arid areas it is very difficult to inject the current into the ground when the surface layer is very resistive.

For practical reasons only horizontal transmitting coils were used (horizontal or perpendicular).

The horizontal coil system was finally selected and in 85 % of the cases response curves were obtained which permitted a good interpretation in terms of 2- to 4- layered earth.

GEOTHERMAL STUDIES

In this section only a few recent papers are discussed since many reviews have already been published (e.g. BERKTOLD, 1983 ; HERMANCE, 1983 ; HERMANCE *et al.*, 1976, 1980, 1984) on electromagnetic and magnetotelluric investigations for geothermal research. The papers mentionned here emphazise the research of very deep structures in volcanic regions, and propose 2-D and 3-D models to explain particular experimental results.

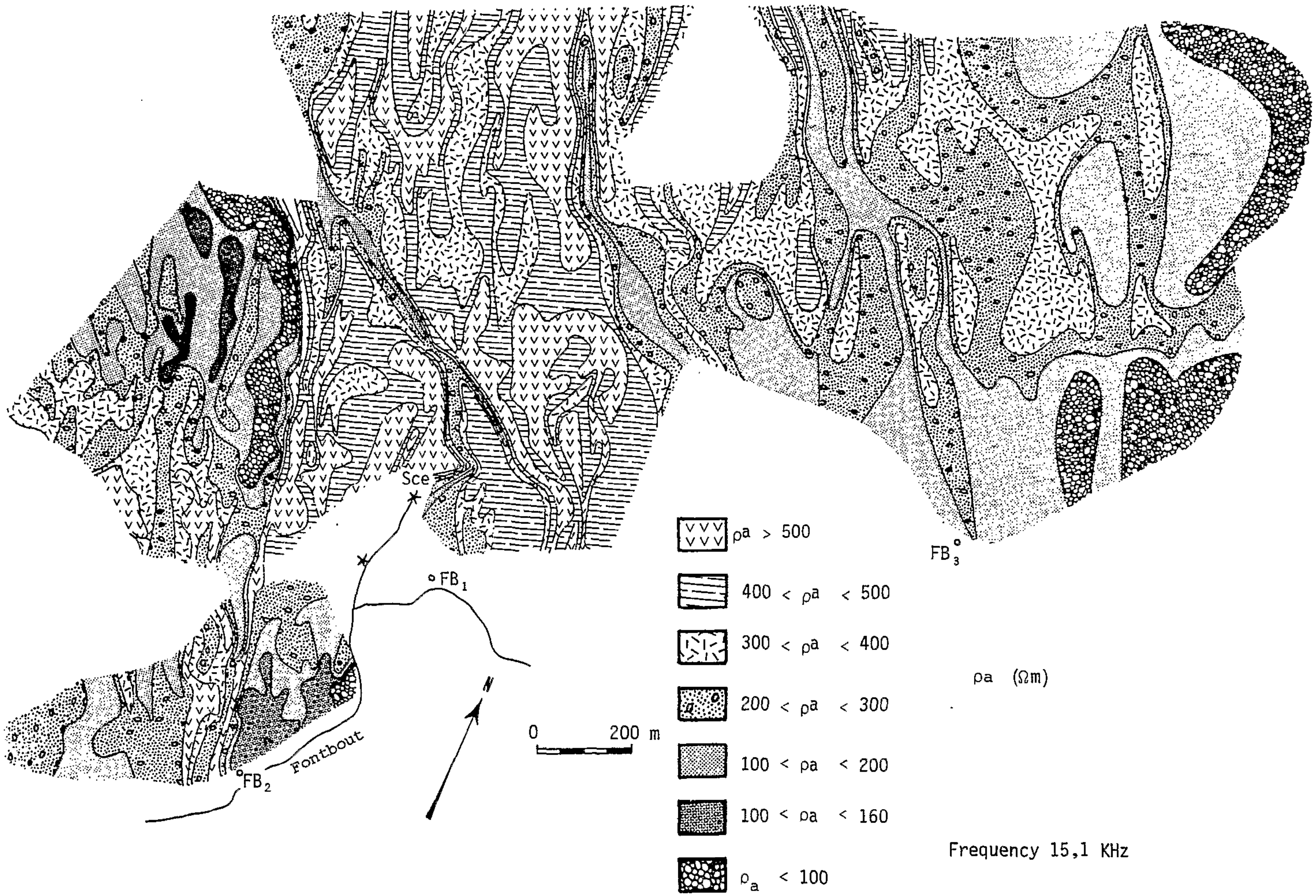

Fig. 9 — Radio MT resistivity map for water detection One can observe : on the left hand : a relatively conductive area limited by a fault (N 170°) and a narrow conductive area leading to a spring (Sce) and to a drilling (FB1). On the right hand : a conductive anomaly (NW-SE) to the south of which was drilled the productive FB3 (From ROBIN, 1984).

Ground techniques

PLANE WAVE METHODS

BENDERITTER and GERARD (1984) describe a geothermal study of Reunion Island. Scalar AMT equipment was used over the whole island with a total of 535 soundings. In certain areas, the results were controlled by classical electrical methods as they suggested an unusual distribution of resistivities for lava flow. A correlation was found between decreasing resistivity and increasing hydrothermal alteration in areas where deep wells revealed high geothermal gradients. The conductive layers identified by AMT seem to correlate with thermal effects from an inferred hot-water reservoir. A general multi-layer model of Reunion Island (fig. 10) was proposed, some soundings showing an abnormally thin resistive surface layer are pointed out as being possible geothermal targets.

In the Travale - Radicondoli geothermal field, HUTTON *et al.* (1983) undertook AMT experiments with broadband tensor equipment. As the area was very unfavourable for natural measurements, automatic in-field analysis was used to ensure that good quality data were obtained. Owing to the importance of conducting coverformations (2 km and $\rho = 1\ \Omega m$) the period range was extended up to 10^4 s. The authors emphasized that the area tested was so restricted that they could not affirm that the conducting zones discovered in the basement were related to a thermal anomaly.

Controlled-source audiomagnetotellurics (CSAMT) in geothermal exploration was investigated by SANDBERG and HOFMANN (1982). In their opinion, CSAMT overcomes the main limitations of AMT, e.g. the low strength of natural signals and variations in the direction of the source field. Measurements were made with simple scalar equipment, and theoretical studies showed that the plane wave assumption is valid when the transmitter is more than five skin depths away in the co-linear configuration. It was found that CSAMT resolved details not shown by the dipole-dipole resistivity model. It is thus a high resolution method with efficient field procedure. It is an attractive tool for geothermal exploration since it is more cost effective than the dipole-dipole method. In the survey at the Roosevelt Hot Springs geothermal area in Utah it was, however, found that the technique had difficulty in detecting structures beneath a conductive overburden, and that the depth of investigation was considerably less than a skin depth in conductive areas.

OTHER METHODS

For geothermal research GOLDSTEIN (1982) used an EM 60 system from the Lawrence Berkeley Laboratory and the University of California. After an MT survey, three areas were investigated in more detail with this controlled source system. It was found that this system provides a more accurate measure of subsurface layering. However, problems were encountered in the

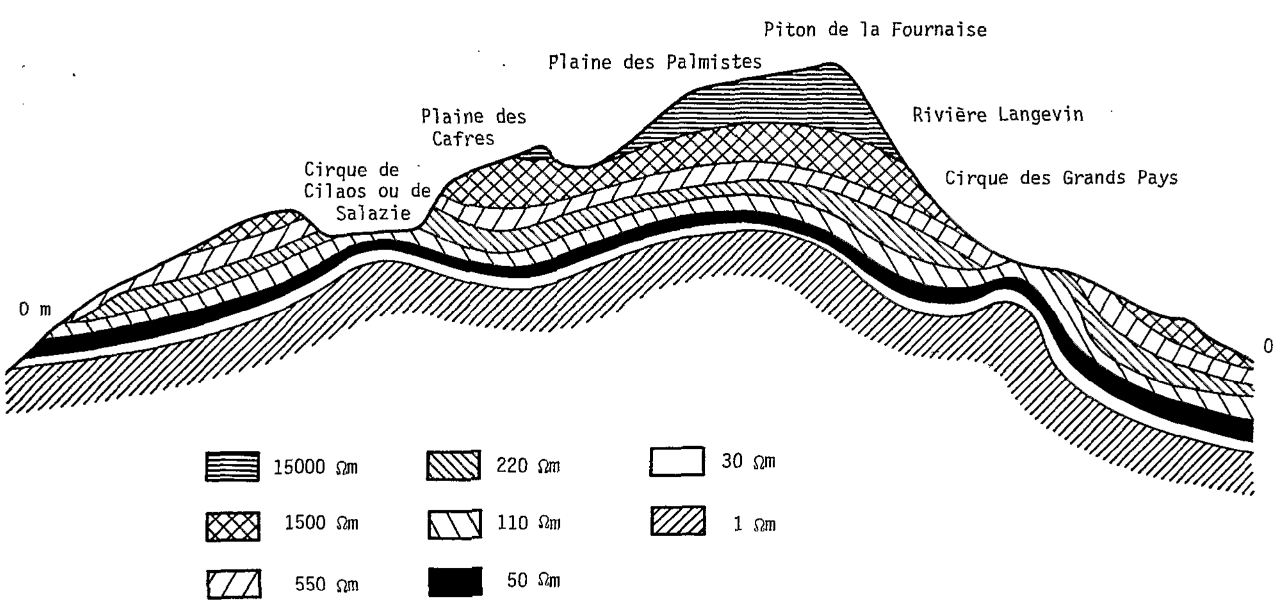

Fig. 10. — General resistive multi-layer model of Reunion Island from Audio MT (From BENDERITTER and GERARD, 1984).

correction of elevation differences between transmitter and receiver, a dipole moment inclined to the frame of measurement, and intervening terrain between transmitter and receiver. It was not possible to compensate for the latter point and in this case the results remained uninterpretable.

OIL RESEARCH

Ground techniques

PLANE WAVE METHODS

This section relies heavily on the monograph of ALPEROVITCH *et al.* (1982) translated by G.V. Keller, relating MT work to oil exploration in the USSR. As the references are very numerous, it gives us an overview of what is done with MT in this country. It also indicates applications of the method in regions with quite different geoelectric characteristics.

Three types of areas are essentially recognized. Areas where the conductive sediments lie directly on the resistive basement are the most suitable for MT methods. In other areas, the section above basement includes a highly resistive intermediate layer, which is a source of errors in interpretation. The least favourable situation is most probably that which includes a layer of moderate resistivity between the conductive formations and the bedrock.

The authors also present an important study of the distortion of MT curves. These distortions can be caused by the development of charge distributions on the surface of inhomogeneities (galvanic effect) or by the circulation of currents in inhomogeneous sections (induction effect).

In 2-D structures the type of distortion depends upon the direction of current flow. In TM, or $\rho\perp$ mode, current flows across the grain of the structure and galvanic effects appear primarily. These are characterized by a shift of the right-hand portion of the MT sounding curve along the resistivity axis (S - effect), the screening of structures above the basement (screening effect), and the occurence of depressions on the curve as a consequence of channeling of currents along the extent of a depression (the limit effect).

In TE, or $\rho\,/\!/$ mode, the current flows along the strike of the structure and induction effects are predominant. In such cases, they appear as weak minima and gradual transitions of the rising parts of the curves. Evidently, in 3-D structures MT curves are distorted by both galvanic and induction effects. There are concentrations of currents in depressions and reductions of currents in areas of uplift. Most often MT is used to obtain the relief of a highly resistive basement, if it is stratigraphically meaningful, covered by more conductives rocks.

The southeast part of the Siberian platform has been investigated with many geophysical methods : gravity, aeromagnetics, seismic refraction and seismic reflection. In general an analysis of MT soundings (carried out since 1958) has indicated that the most satisfactory information was provided by the effective curves (average curves of the principal sets of apparent resistivity values) obtained near block-faulted structures and in basins. For uplifts, the best way to minimize undesirable effects is to use the longitudinal curves obtained over the central parts of the uplifts or the transverse curves obtained near the edges of elongated uplifts.

All these types of curves were used in the central part of the Vilynis syncline. As an example in the south edge of the Vilynis syncline MT exploration provided results for the relief of the surface of resistant paleozoic formations in good agreement with gravity. They show low values of S (20-50 Siemens) corresponding to the Mekelin gravity maximum and high values of S (More than 200 Siemens) corresponding to the Sanan gravity minimum. The authors conclude that the surface of the resistant basement, and the steps in the basement surface in the Ƃotuobin arch are well recognized from MT data. MT also gave the first satisfactory determination of the thickness of the sedimentary section in the drowndropped areas of the Viliosk syncline.

In northern Sakalin gravity and seismic exploration had already been carried out. But MT sounding surveys were undertaken to assist in determining the thickness of the sedimentary sequence as seismic refraction has encountered unsatisfactory operating conditions.

The thickness of the sedimentary section was found to be between 1 and 10 km according to the different regions (uplifts in the Nish-Baikal synclinal zone and Baikal depression). A map showing the thickness of the Paleogene - Neogene section was prepared from MT data and is now used for comparative evaluation of the occurence of oil and gas in various parts and for the organization of operations.

This report shows also the aptitude of MT data for subdivising the sedimentary sequence, for identifying faults and for local structure recognition. It emphasizes the usefullness of combination with data from other methods in providing an unique interpretation of MT data.

In conclusion it can be said that the most effective method of MT exploration is MT sounding. MT profiling or telluric current surveys are less informative but more rapid. Introduction of digital recording equipment and field reduction of data on computer have helped to increase the information content of MT methods and to reduce their time requirements. Thus in a great number of regions some significant anomalies can be assumed to reflect the influence of oil and gas reservoirs. Furthermore, I should like to add that the use of audio magnetotellurics would improve the resolving power of MT surveying even in deep sedimentary basins.

VOZOFF (1982) recalls that in petroleum exploration there was a discovery in the Columbia Plateau from MT owing to a geologically favourable situation due to basalt being the first layer. These conditions are also found in India (Traps) and in Brazil, and it is hoped that under the same conditions, the same success will occur everywhere.

STANLEY *et al.* (1985) discuss the results of regional MT surveys in Parana basin, Brazil. Basalts play an important role as they may be up to 2 km thick, are covered by a few hundred meters of cretaceous to holocene sediments and are underlain by 2 to 4 km paleozoic sediments. In fact sediments down to the Permian are more conductive than older units and MT does not identify the real geological bedrock. But a combined interpretation MT-aero-magnetic data helps to understand hydrocarbon migration and trapping mechanisms.

The main result of the survey is the selection of a sag area as regional target for the concentration of exploration efforts. The area is shown to be surrounded by dike systems on three sides with the open part pointing towards the deeper zone of the basin.

OTHER METHODS

GOMEZ-TREVINO and EDWARDS (1983) reported electromagnetic soundings in the sedimentary basin of Southern Ontario. They used an oscillating electric current flowing along grounded wire and a receiver (fluxgate or air-cored coil) for the vertical magnetic field, the frequency band being of 0.3 Hz to 5 kHz. The sounding were made in a region where the sedimentary environment was in the range and depth of interest for oil and gas exploration. Electrical and EM sounding were located to take advantage of the dipping nature of the sediments. Data were jointly inverted and the layered earth models containing the minimum number of layers were fitted to data. The intrinsic ambiguities of the models (S equivalence) of the deeper sections were resolved by a systematic, progressive site-to-site correlation of electrical units accross the basin. The overall electrical model of the region is consistent with the known geologic section.

GEOLOGICAL MAPPING

This section summarizes papers discussing general applications such as geological mapping or civil engineering problems.

Ground techniques

PLANE WAVE METHODS

SACIT SAYDAM (1981) considered the interpretation problem of tilt angle (α) and ellipticity (ε) measure-

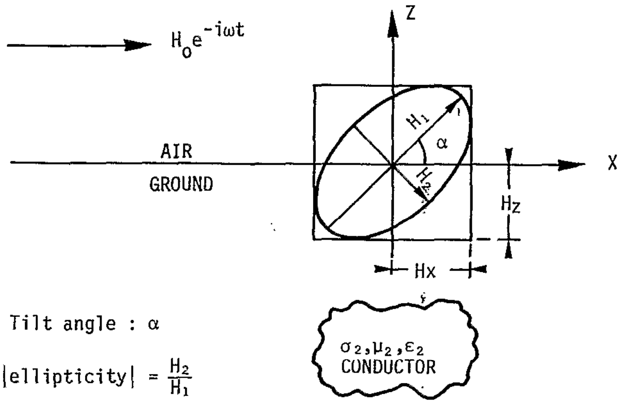

Fig. 11. — VLF electromagnetism : polarization ellipse in presence of a conductive inhomogeneity (From SACIT-SAYDAM, 1981).

ments in VLF. As expected, the frequency range of 17 to 25 kHz is so restricted that any frequency whithin it produces similar results to the overall response of the conductor (no frequency effects). A very simple rule of interpretation consists in taking half the distance between minimum and maximum locations (on tilt angle profiles). However, many authors showed that conductive overburden or host medium can considerably alter the response of conductors in a dipole field or in TURAM prospecting. The purpose is to interpret depth and conductance (conductivity - thickness product express in Siemens) of 2-D vertical sheet conductors embedded in a more or less conducting homogeneous medium from tilt angle and ellipticity measurements (fig. 11). It is believed that this kind of model closely approximates many geological situations : steeply dipping conductive beds, strata-bound sulfide deposits, steep faults, geological contacts, etc.

The modeling technique used is due to MADDEN and SWIFT (1969). It is shown that the « rule of thumb » previously used often leads to large errors in depth evaluation. An example of the five characteristics diagram is shown in figure 12. They are constructed by plotting peak-to-peak tilt angle (α max) versus peak-to-peak ellipticity (ε max), diagonal lines denote conductance $\sigma_2 t$ and depth D of the target. The examination of these diagrams shows interesting features. For instance, the tilt angle decreases at a faster rate than ellipticity as conductor depth increases. The rate of decrease of tilt angle and ellipticity with increasing conductor depth is greater with smaller host rock resistivities. A conductor can be detected at 20 m in a host rock of 50 Ωm and at more than 80 m in a 2 500 Ωm medium. The maximum change in magnitudes of tilt angle and ellipticity is observed for conductances of about 0.1 to 20 s and consequently highly conductive targets cannot be well resolved with these diagrams.

As the host rock resistivity is very important, it is necessary to have an idea of its value using other methods. However laboratory measurements as re-

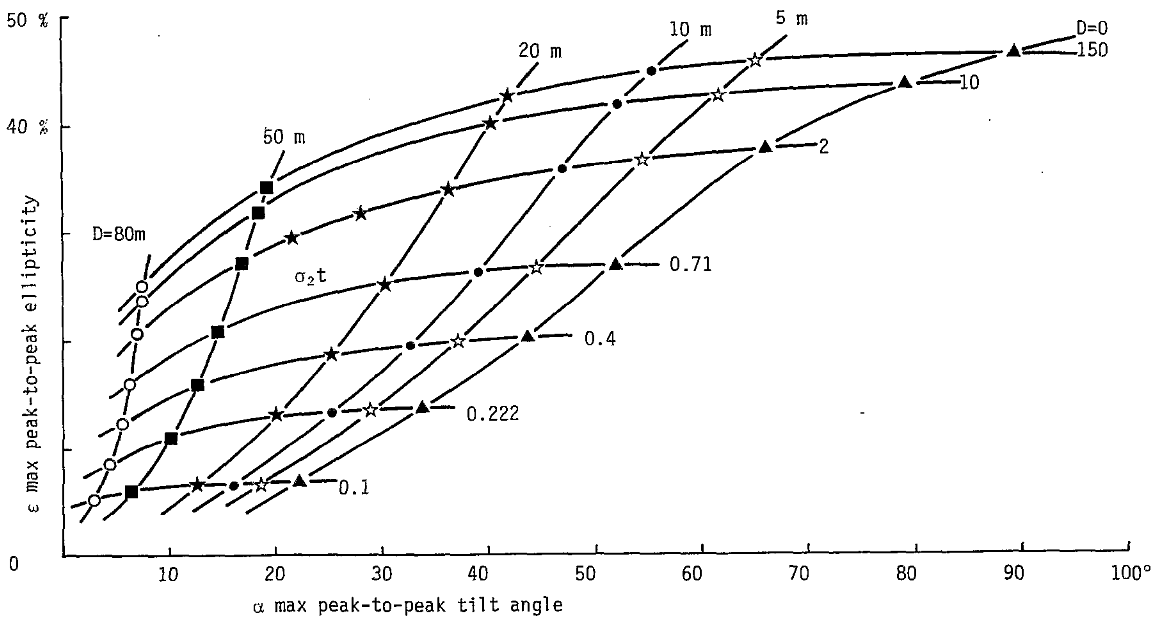

Fig. 12 — VLF electromagnetism : characteristic diagram for 2 500 Ωm host rock resistivity (From SACIT-SAYDAM, 1981).

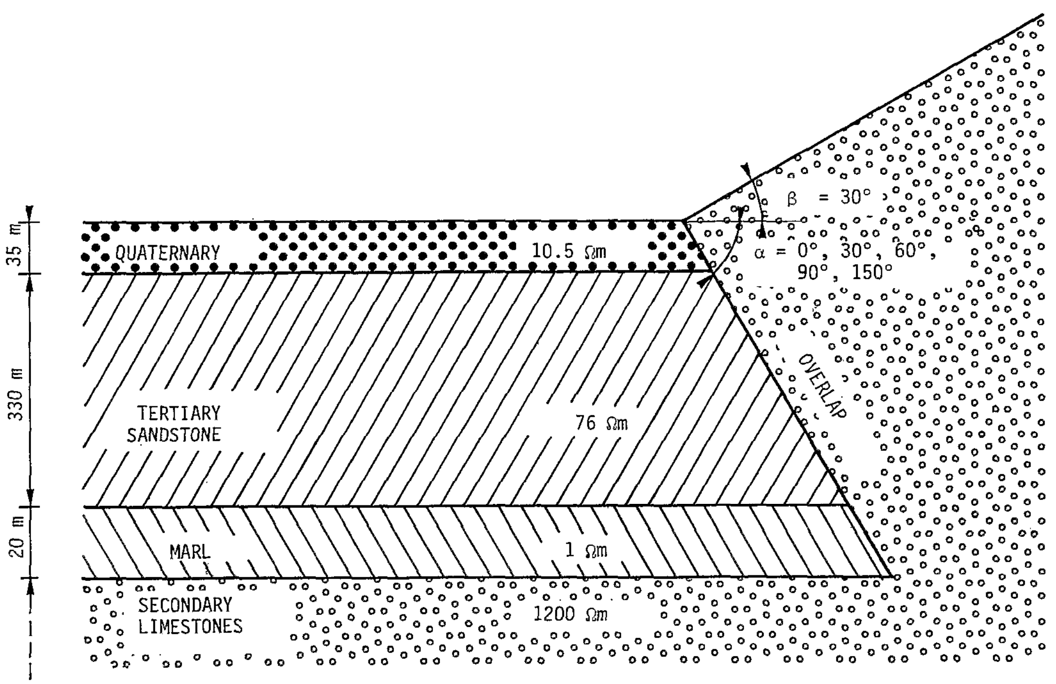

Fig. 13. — Audio MT : simplified 2D model used for numerical computation, the only variable parameter is the dip angle α (From SCHNEGG *et al.*, 1983).

commanded by various authors might appear as not an appropriate way to achieve this purpose ; it would be better to make more in-field measurements. Tilt angle is always attenuated in the presence of the overburden, whereas ellipticity is either enhanced or attenuated depending upon conductor depth and resistivity contrast between the overburden and the host rock. An example is given showing that this interpretation tool is very powerful — a target interpreted to be at 11 m was found at 9 m.

Electromagnetic investigations are used more and more frequently to solve problems other than those of natural resources. For instance, in the proceedings of the International Symposium on « Applied Geophysics in Tropical Regions », VOZOFF (1982) reviewed the « state of the art of magnetotelluric methods », from source field studies to interpretation and results. In Australia, AMT is used in combination with DC resistivity to improve quantitative interpretation of only one technique in sections of post-Permian clastics of different facies with rapid changes. The controlled source method (CSAMT) is also used to solve a great number of problems in civil engineering, mineral or geothermal exploration.

At the XVIIIth General Assembly of IUGG in Hamburg (1984), SCHNEGG and FISCHER proposed a new pulsed AMT technique. The equipment is mainly devoted to sounding in industrial areas. The source is located at more than three skin depths of the lowest frequency sampled. One hundred samples are staked and improve the signal to noise ratio by a factor of ten. As the method uses standard receiving equipment it is easy to compare its results to those of natural soundings. The correlation is very satisfactory.

SCHNEGG *et al.* (1983) briefly described a complete AMT equipment (five components, recording of digitized data, monitoring of resistivities in the field). An example is given of a very detailed study of a 2-D structure (fig. 13) and the finite difference technique yields a good solution with a reverse fault dipping at 30°.

YUNGUL (1977) made an exhaustive review of telluric and magnetotelluric methods, particularly in their applications to the study of sedimentary structures. It was stated that as telluric stations cost about a tenth of the price of MT stations, it is interesting to have a high density of telluric stations together with a few MT soundings at sites judiciously selected from the telluric data. The telluric method was considered as a lateral exploration tool, and MT as a vertical exploration tool yielding well-log type information. For instance, the search for small 3-D targets (salt domes, reefs, geothermal reservoirs, mining deposits) requires a great number of stations, and MT soundings alone would be very expensive and difficult to interpret.

In France, the Garchy group developped what was originally called VLF-MT but is now called radio MT as the frequency range is greater than that of VLF. The equipment is shown in figure 14. As in the MT method, there is a magnetic sensor (small loop) and a telluric one (capacitive electrodes are used, they are on rubber mats 3 m lenght, over each end of which is stuck in a thin sheet of brass). It is physically included within a « rug » which may be dragged over the ground by hand or by a small car. The great advantage of such a system is that continuous section diagrams of telluric or magnetic fields, or of the apparent resistivity, can be obtained. The spatial resolution is better than with point to point measurements. As has already been mentioned, this method has been used for water research (ROBIN, 1984), for geothermal investigations (DUPIS, 1978), for mining research (GUINEAU, 1975), and for archaeology.

An important development was undertaken in France by the highways department using the frequency range up to 1.5 MHz for civil engineering or waste disposal application (LAGABRIELLE *et al.*, 1983).

It also revealed itself to be a real instrument of geological mapping. It was called « the third tool of geologists » (after compass and hammer) by the first geologist to whom it was presented !

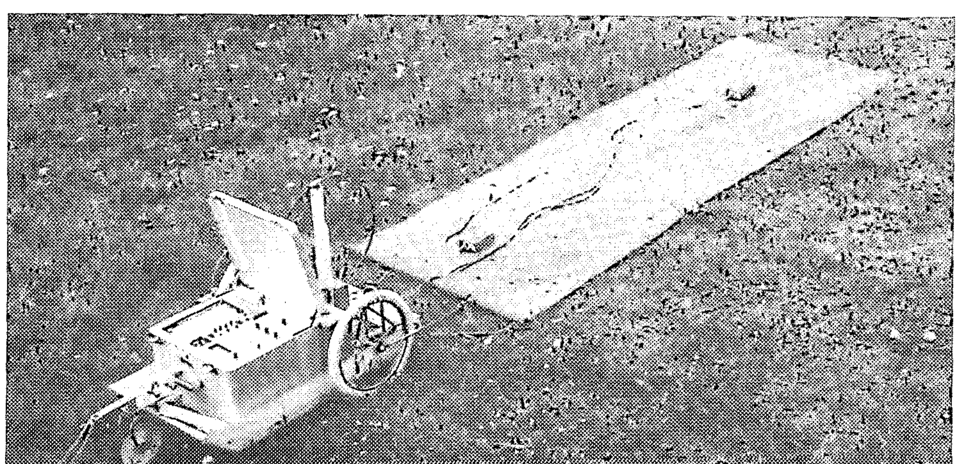

Fig. 14. — Radio MT equipment : the trolley with a strip chart recorder and data processing-magnetic sensor (loop), the rubber mat with two telluric preamplifiers.

OTHER METHODS

EM 60 was tested by WILT *et al.* (1983) in Nevada, and the authors exposed its strenghts and weaknesses. It is able to locate buried conductive bodies accurately but it had difficulties with 2-D and 3-D interpretation and with resistive bodies. On the other hand because of the spatial decay of the source field, 1-D interpretations seem to provide more useful results than MT can.

Airborne techniques

OTHER METHODS

Airborne techniques may also be used for geological mapping, although this is not usually done using plane wave methods. PELTONIEMI (1982) produced an important piece of work on airborne electromagnetism in Finland. Besides a summary of equipment many examples of geological surveying were given. These delt with traditionnal topics as well as with more original patterns like a volcanic sequence with black schist zones, with a differenciation of remanent magnetisation and with a detection of weakly magnetised but conducting formations in areas of poor outcrop. It also defined very strictly the parameters which, in turn, let the reader make his own mind about the different systems. These parameters are sensitivity, resolution, discrimination, lateral coverage and response function. Also the role of different elements (such as coil separation, flight elevation and coil configuration) was defined. A detection limit of an anomaly was defined as a signal Sd equal to four times the noise. PELTONIEMI (1982) emphasized the improvements due to rigid coils and shorter coil separation. He thought that these methods, for civil engineering in general, may be used firstly to discriminate soils from their surroundings by their resistivity (e.g. clay, gravel) and secondary to study, fracturation in bedrocks, permafrost thickness and geothermal areas.

CONCLUSION

It is clear that electromagnetic methods are continuously expanding their field of application from natural resources to archaeological or uppermantle structures. Why such an expansion ? The answer can certainly be found in the large progress which recently occurred in both technical and theoretical processes. In a less recent past, EM began to take the place of DC resistivity but this latter method was for a long time still superior by its quantitative aspect. With the development of plane wave methods (VLF, MT, AF-MAG) electromagnetism began its definitive growth, as quantitative interpretation was easier and more satisfying than with what have been called here « other methods ». Airborne methods play a predominant role essentially only in mining research as they allow great surface reconnaissance in a very short time, particularly in regions of difficult access. In this group plane wave methods do not take a preferential place but they are not negligible. The most important part is taken by the other methods ; improvements in mechanical and electrical mountings greatly improved the performances of some systems. Other considerations on the more theoretical aspects of instrument design have also led to better resolution of these methods. One can mention, for instance, the number of coils (transmitting and receiving), the coil separation (for penetration depth or higher resolution), the distance between the aircraft and the receiving coils, the spectrum of the system, the proved importance of quadrature systems, the number of recording channels, a realistic study of the line spacing, etc. From a practical point of view it seems that helicopter systems are much more often used now than fixed wing systems.

It is therefore on the ground that DC and EM methods still compete or supplement each others. VOZOFF (1982) showed that their reciprocal interest lies in their complementarity, at least for plane wave methods (here AMT). We also observe that over the last twenty years there has been a growth in importance of these « plane wave » methods, with the exception of telluric and AF-MAG methods. Overall, MT methods are still used to the largest extent. For instance, the application of AMT to geothermal studies was a good way of proving its efficiency. MT method plays a more important role since geophysicists broadened its frequency range. As a matter of fact, MT began with low periods and had problems when it came to comparing its results with those of seismic studies. With time, the improvements in sensors, field works, processing and interpretation reduced the gap with seismics so that in special cases (Columbia Plateau) MT provided better results than reflection. Now radio MT and AMT cover the full range of depths and allow the undertaking of any kind of prospecting. It must also be noted that high frequency results greatly improve the interpretation of deep exploration a fact which is not commonly used. A proof of the efficiency of MT has been recently brought up by ILKISIK and JONES (1984) in their statistical evaluation by the singular value decomposition technique. As a rule, plane wave methods do not require any transmitter and this is considered as a great logistic advantage. It is also a theoretical advantage as we may consider that the data are only representative of the ground under or near the sensors and not of the ground under the transmitter, the receiver and between the two as in « other methods ». Meanwhile the expansion of controlled source methods remove at least the logistic advantage and it was also shown that controlled sources do not overcome all problems and that there often remain difficulties with interference between artificial and natural sources and with source effects at lower frequencies. With uncontrolled but artificial sources, such as in VLF or radio MT, problems arise from reciprocal direction of strike and sources. The solution is to try to use two transmitters in orthogonal directions.

Is there any future for « other methods » on the ground, between airborne and ground plane wave ones ? The answer is not a priori evident and it would probably be negative if plane wave methods did not have any problems. But some difficulties always exist with signal, sensors, processing and interpretation producing important scattering in the results. On the other hand, the development of controlled source methods with transmitters capable of driving 100 amperes and more, is a real danger for these « other methods », since many improvements in equipments and processing are useful for « plane wave » methods as well for the others, and since interpretation is generally better with plane waves, the future of « other » techniques may be grim. The challenge then lies in the respective cost of either one solution or another and it is not always easy to analyse this important problem in natural resources research. Whatever happens EM methods must now be considered as an important alternative or supplement to seismic (another controlled source method) for geophysical investigations.

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