COMBINATION OF EM AND DC MEASUREMENTS FOR UPPER CRUSTAL STUDIES

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Abstract. Joint use of electrical and electromagnetic techniques is found to be useful for better understanding of the subsurface electrical resistivity structure. Detection of thin buried layers (conductive or resistive), which may be difficult to identify by a single method alone, could possibly be identified by a combination of methods. Further, distortion or error in the observed data could be corrected, as both methods depend on the same physical parameter, namely electrical conductivity. Although these methods have been known for the last several decades, joint interpretation of data sets is increasingly being used in recent years, especially for complex geological problems. This review covers the main results of the combination of these methods, giving more emphasis to case histories.

Keywords: electric, electromagnetic, joint study

1. Introduction

Subsurface models of the earth obtained from a combination of two or more geophysical methods are likely to be more reliable than models obtained from any single method. Modeling different data sets by combination or integration is increasingly being used in recent years so as to allow for more confidence in the derived models and to reduce the ambiguity in interpretation. The subject of ambiguity of interpretation in geophysics is comprehensively dealt with in a classic paper by Roy (1962). Due to the inherent ambiguities in geophysical methods, an integrated approach involving two or more techniques is recommended (Sill et al., 1977; Bahr, 1983; Stanica and Stanica, 1993; Wang et al., 1993; Oldenburg et al., 1994; Hering et al., 1995; etc.). Similar to other geophysical methods, electrical (E) and electromagnetic (EM) methods also suffer from ambiguity in interpretation due to the phenomena of the 'principle of equivalence', especially for thin middle layer problems (Patra and Mallick, 1980; Zhdanov and Keller, 1994).

As both methods depend on the same physical property, namely the electrical conductivity, conductivity variation with depth should be reflected in the measurements of both methods at least with varying response in different ways. For example, let us consider two simple models (1 and 2) of three layers each with a conductive middle layer (Figure 1). The thickness of the middle layer is 1 km for model-1 and 2 km for model-2. Both MT and DC responses are computed for these models and the relative deviation is plotted. As can be seen from the

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figure, the maximum relative deviation in apparent resistivity curve in DC is about 10%, whereas it is about 50% in MT. This is due to the problem of equivalence in DC as explained in more detail in a later section. In this case, the detectability of the middle layer is easier using MT than using DC. Similarly, one can have models in which the DC apparent resistivity can show a large deviation compared to MT, especially for resistive middle layers. Therefore, to detect a middle layer in certain cases can be a problem when applying a single method alone. Thus, joint use of both methods in principle should give better estimates of the subsurface parameters. The aim is also to get more information from the use of two methods. Apart from the general benefit of obtaining more confidence in the derived model, joint use of E and EM methods has added advantages – tackling the equivalence problem, correction of data sets and constraining the part of the model (shallow or deep) of one method with the results from the other. In the present study the advantages of using the combination of E and EM methods are presented, giving more emphasis to case studies.

2. Electrical and Electromagnetic (E and EM) Methods

The theory and principles of E and EM techniques are well known to the EM induction community and are well covered in monographs such as the ones edited by Nabighian (1987, 1991) and also in various text books such as Patra and Mallick (1980), Parasnis (1986), Zhdanov and Keller (1994), etc. One can have any number of ways of conducting the field survey in E and EM methods. Given a choice, both methods have a variety of ways. For example, DC electrical resistivity sounding surveys can be carried out using various types of electrode configuration – Wenner, Schlumberger, dipole–dipole, pole–dipole, two electrode, square array, etc. Similarly, electromagnetic surveys can be carried out using different techniques such as TDEM (time domain electromagnetic), FDEM (frequency domain electromagnetic), TEM (transient electromagnetic), LOTEM (long offset transient electromagnetic), CSEM (controlled source electromagnetic), AMT (audio magnetotelluric), telluric (T), MT (magnetotelluric), CSAMT (controlled source audio magnetotelluric), etc. The sensitivity of these techniques can be studied quantitatively by calculating the Frechet derivatives (Zhdanov and Keller, 1994). For a three-layered earth – a resistive layer sandwiched between two conductive layers – Keller (1992) compared the Frechet derivative curves (Figure 2) of MT sounding, DC electrical sounding and TDEM sounding methods. By comparison one can see that the greatest amplitude is provided by TDEM methods, being about twice as large as those for the DC as well as MT sounding methods, but its form depends on the ratio of source-receiver separation to depth of perturbation. Discussing various aspects of these methods and their limitations, Keller stressed the need for multiple field observations in complex geological situations. He concluded that major

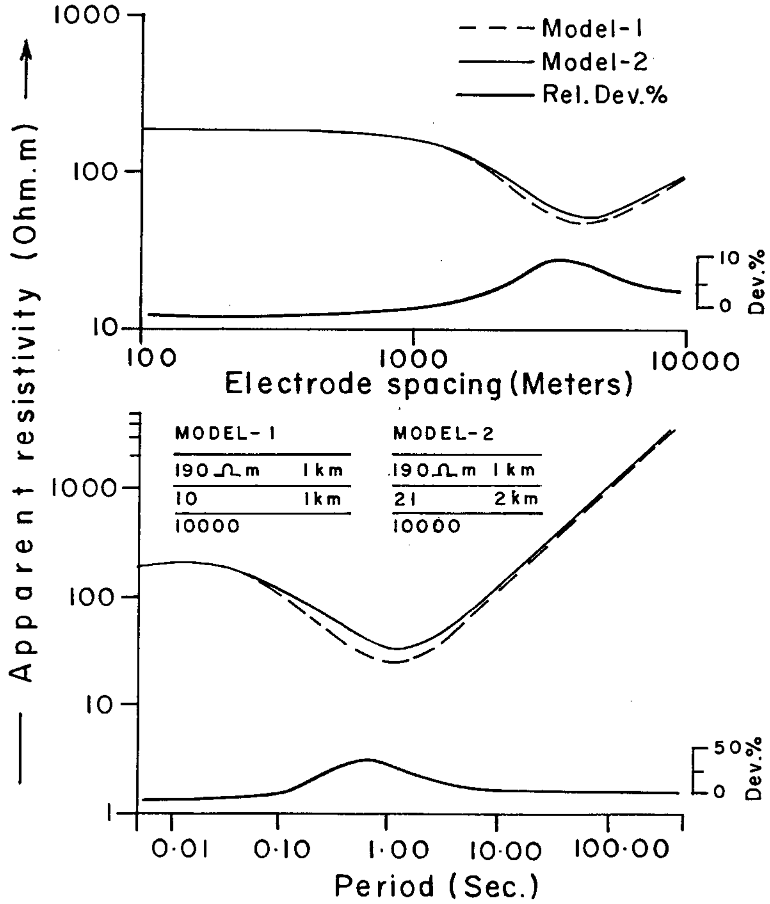

Figure 1. DC and MT apparent resistivity curves for two models and their relative deviation with respect to Model 1. Due to an equivalence problem, there is a small deviation in DC (top) and for the same model there is a large deviation for MT (bottom).

effort is necessary in designing the data acquisition methods such that the expected targets can be mapped efficiently.

It is known that E and EM methods are sensitive in different ways to the same earth situation, as discussed in greater detail by many (see, e.g., Vozoff and Jupp, 1975; Verma and Mallick, 1979; Gromez-Trevino and Edwards, 1983; Keller, 1992) and also in the next section of the present study. Fitterman and Stewart (1986), while discussing the various situations in groundwater exploration, showed that electrical methods are suited to resolving resistive layers, while the EM methods are best suited to detecting conductive layers. Many have reported that joint use of E and EM methods is relatively more advantageous than the use of a single method alone in various geological situations, such as for mineral, geothermal, and environmental studies, as described in later sections.

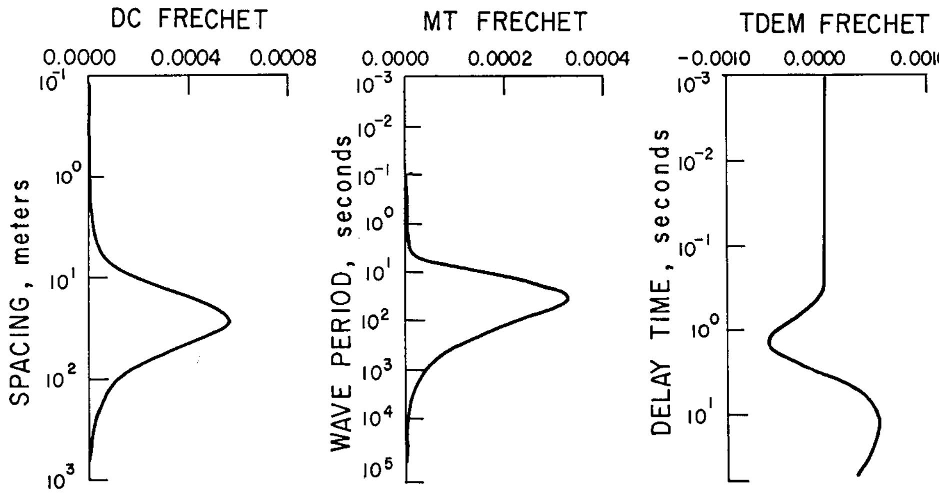

Figure 2. Frechet derivative curves for DC, MT and TDEM sounding methods. The shape and amplitude of the curves are similar for DC and MT with depth of burial, whereas TDEM curves are different (from Keller, 1992).

Application of E and EM techniques for environmental applications has been well reviewed recently by Nobes (1996), with a good number of references which describe the use of these methods from historical times to recent years. Similarly Spies (1996) has reviewed EM borehole measurements. A search in the database of literature up to February 1998 for combined studies of E and EM techniques has provided fewer than 100 research papers which for the most part belong to the 1970's and onwards. This shows that although both methods have been well known for the last several decades, a need for their joint use has arisen in recent years, especially after the development of joint techniques (Vozoff and Jupp, 1975; Sill et al., 1977; Oldenburg, 1978).

3. Detection of Thin Middle Layer and Joint Inversion Study

Detection of a thin middle layer poses a problem for both E and EM methods. This is mainly due to the equivalence problem in DC resistivity methods and the relatively lower sensitivity of EM methods to resistive layers. The problem of the principle of equivalence and detectability of middle layers in both methods has been dealt with by various researchers (Flathe, 1955, 1963; van Dam, 1976; Verma and Mallick, 1979; Rakesh Kumar et al., 1981; Dorn, 1985; Fitterman and Stewart, 1986; Fitterman et al., 1988; van Overmeeren, 1989; Hoerdt et al., 1990; Simms and Morgan, 1992; Verma and Sharma, 1993; etc.) and a few are briefly described here. Discussing the inherent ambiguities in DC resistivity and magnetotelluric methods, and their response to conductive and resistive layers (Figure 3), joint inversion of both the data sets was proposed by Vozoff and Jupp (1975), especially to resolve thin resistive layers and the usefulness of the method is shown with field examples in the 1-D environment. They also resolved the anisotropy in layered media using joint inversion (Jupp and Vozoff, 1977). Sasaki (1989) developed a 2-D joint inversion algorithm for MT and dipole-dipole resistivity data and demonstrated its usefulness with CSAMT, dipole–dipole data from the Roosevelt Hot Spring geothermal resources area in Utah. The Backus–Gilbert inverse theory was used by Oldenburg (1978), assuming a gradual change in conductivity with depth, and joint inversion has been carried out for magnetotelluric and DC resistivity sounding data sets. It is observed that the two methods are complementary to one another and provide increased resolution on the derived subsurface parameters. Mundrey (1978) studied the thin layer problem in both electrical (Schlumberger sounding) and in magnetotelluric methods. Model curves for the resistive and conductive middle layer have been prepared and compared. It is observed that the equivalence parameter is different for both methods. For example, in the case of a resistive middle layer, ρ_2 and t_2 as the resistivity and thickness respectively, transverse resistance $\rho_2 t_2$ in DC sounding and $\rho_2 t_2^2$ in MT sounding are the equivalence parameters. He stressed the need for use of joint inversion as suggested earlier by Vozoff and Jupp (1975). Recently, Monteiro Santos et al. (1997) have demonstrated the usefulness of joint inversion with AMT and DC (Schlumberger) data for a complex conductive graben structure in northern Portugal.

As mentioned above, many examples are available in the literature on the success of joint inversion to locate targets, which would have been difficult or impossible from a single method. A few of these examples are discussed below. The applicability of joint inversion was demonstrated by Gomez-Trevino and Edwards (1983) who, in considering the data sets from long grounded wire EM and Schlumberger electrical sounding, successfully predicted the dipping nature of the beds in the Ontario sedimentary basin. CSAMT, MT and LOTEM data sets near the Munsterland borehole in north west Germany have been subjected to joint inversion (Hördt, 1989). CSAMT and MT data sets are combined to form a single data set. The results of joint inversion showed better correspondence with borehole data than the results from individual methods as can be seen in Figure 4. Similarly, detection of buried high resistivity of the Great Limestone in Northern England was demonstrated by applying joint inversion of magnetotelluric and deep resistivity sounding data from Rookhope (Harinarayana, 1993). Verma and Sharma (1993) demonstrated the use of joint inversion of DC resistivity with various electrode arrays and multi-frequency EM data with a rectangular loop system for conductive and resistive layer problems. The relative advantage in each case is discussed. Joint inversion can locate a very thin (thickness to depth ratio is 1 : 20) conductive middle layer which would not be possible using individual methods. By comparison, it is observed that joint inversion of EM and dipole array electrical sounding data give better resolution with a faster rate of convergence as compared to other arrays such as Wenner, Schlumberger and two-electrodes. It may be noted that for a meaningful

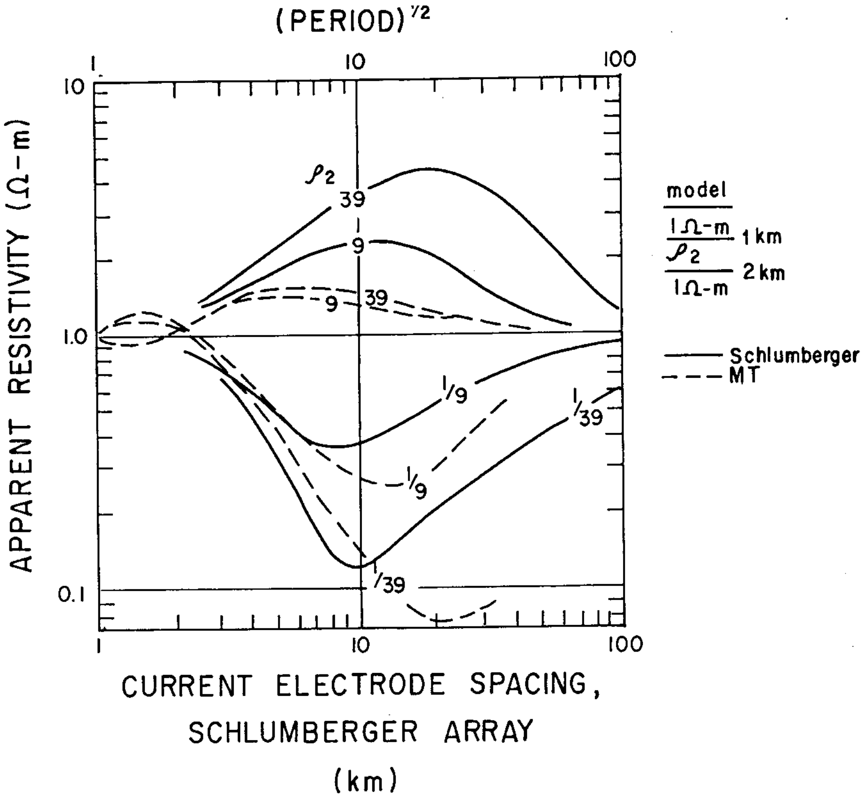

Figure 3. Comparison of the responses of the DC resistivity and MT methods for a 3-layer model. The responses for a resistive and conductive middle layer are different for both methods. MT apparent resistivity curve is more sensitive to a conductive layer than a resistive layer (from Vozoff and Jupp, 1975).

joint inversion (between E and EM or between two EM systems), the datasets should preferably have a large overlap depth of investigation. When there is little overlap, joint interpretation can be carried out by considering the results obtained from one method as a constraint on the other.

4. Correction of Data Sets

In EM methods, the measured electric field is distorted due to the galvanic type boundary charges built up on near-surface inhomogeneities. Such a distortion is called a static shift effect on the data and some procedures are suggested to correct the data (e.g., Jones, 1988; Jiracek, 1990; Beamish and Travassos, 1992; Kawakami et al., 1997; etc.). A combination of two methods – two EM systems or DC and EM – can be used for correction of the data sets. Various examples are available to correct MT data sets from TEM data sets (e.g., Sternberg et al., 1988; Pellerin

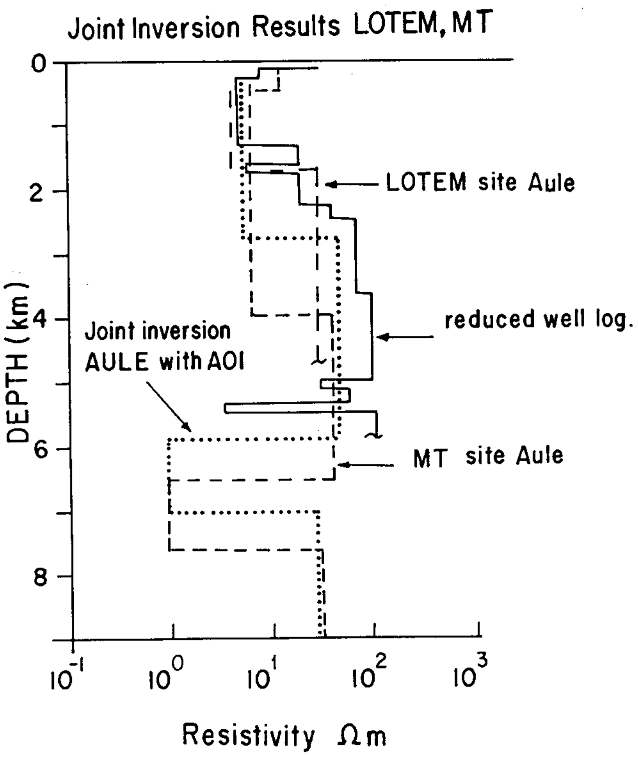

Figure 4. The results obtained from individual and joint inversion of MT and LOTEM datasets from NW Germany are compared with borehole laterolog (reduced) data. Joint inversion result are close to the bore hole data, (from Strack, 1992; originally from Hördt, 1989).

and Hohmann, 1990). DC electrical sounding data are also used to correct MT sounding data (Romo et al., 1997; Harinarayana et al., 1998) before applying joint inversion.

Pellerin and Hohmann (1990) reviewed the various procedures for static shift correction methods. They used TEM data near an MT station for static correction of MT data. Firstly, a subsurface model is derived from the TEM data and the MT response is computed for such a model. Then the observed MT data are shifted to match the MT computed data. Field data from Long Valley, California are shown with such a correction. Meju (1996) applied joint inversion to TEM and MT data sets from Northern Ireland. Without making corrections to the MT apparent resistivity data, TEM apparent resistivity data are considered in the high frequency range and MT phase data in both high and low frequency ranges. Meju demonstrated that these data sets can be modeled using joint inversion and the results are comparable with a subsurface section near a known sulphide deposit (Figure 5).

In the Ahuachapan Chipilapa geothermal area, El Salvador, Romo et al. (1997) have shown that MT data can be corrected for static shift effects using the models

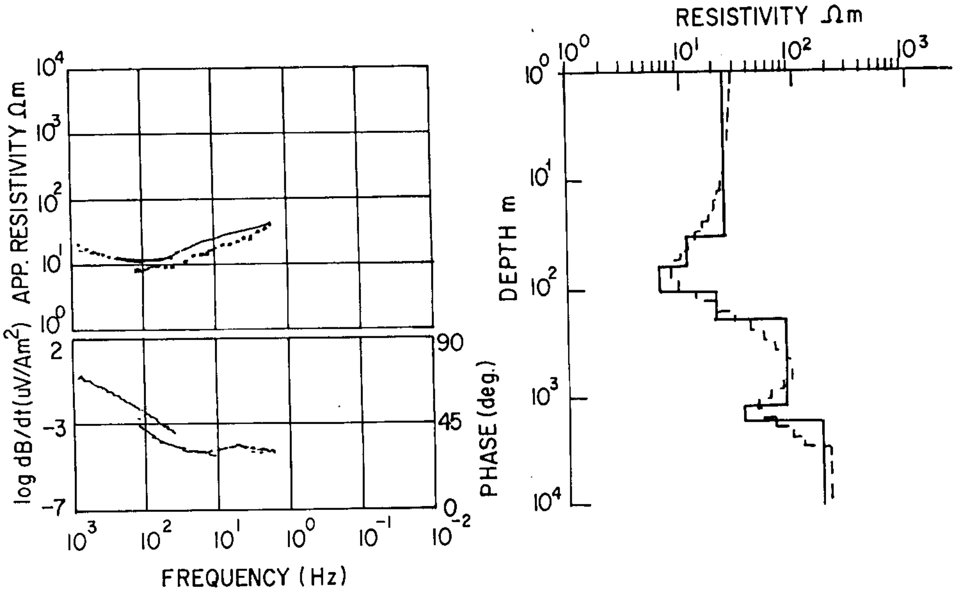

Figure 5. TEM and MT data from Ireland near a known sulphide deposit. The data have been subjected to joint inversion without static shift correction considering TEM data in the high frequency range (1000–50 Hz) and MT phase data. Good fit to phase data and misfit to MT apparent resistivity data can be seen. The two models shown on the right side of the figure are derived assuming initial half space (broken line) and sparsely parameterized model (solid line) (from Meju, 1996).

obtained from DC electrical sounding data. The observed MT apparent resistivity data are statically shifted to the computed MT response at 0.02 s. After such a correction to the data sets, meaningful subsurface models could be obtained. Harinarayana et al. (1998) used deep resistivity sounding (DRS) data (AB/2 = 10 km) to correct the MT data sets for static shift effects. The MT response is computed for the models obtained from DRS data and the observed MT apparent resistivity data are shifted to match the computed data considering the high frequency (100–10 Hz) range, where both the datasets have good overlap of depth of investigation. Without such correction, good fit could not be achieved with joint inversion. The results obtained from individual methods and joint inversion after the correction of the MT data set are compared with deep (3.5 km) boreholes (at Lodhika, Gujarat) litholog data (Figure 6). As can be seen from the figure, that joint inversion result is close to the borehole litholog.

5. Exploration Problems: Case Studies

Companies and organizations involved in mineral exploration problems in the upper crust routinely use various geophysical methods to detect the ore bodies. Since large numbers of ore bodies, pollutants, geothermal areas and sediments are known

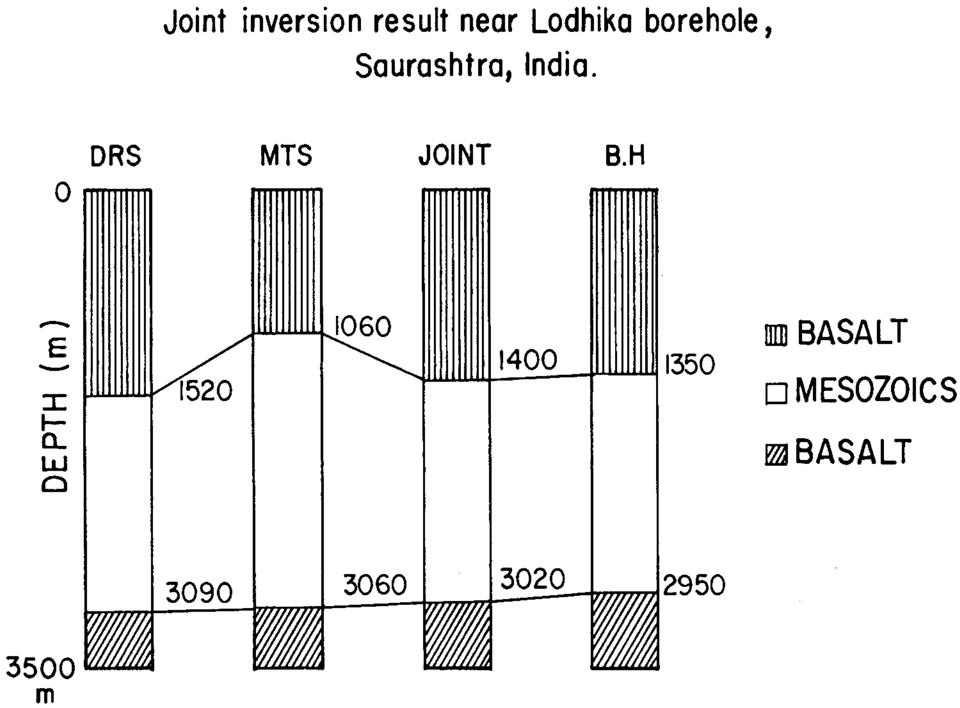

Figure 6. Models derived from deep resistivity sounding (DRS), MT (uncorrected) and from joint inversion of MT (corrected) and DRS data sets (Harinarayana et al., 1998). Results are compared with the deep borehole lithology.

to be the sources of high conducting zones, the EM and a combination of E and EM methods play an important role in these areas. There are many examples in the literature of joint use of E and EM methods for these problems and only a few of them are presented here. These examples are chosen as they are characteristic and closely related to the topic and well illustrated in the literature.

5.1. Mineral and Hydrocarbon Exploration Studies

Application of induced polarization (IP) and resistivity datasets have been discussed by Pelton et al. (1978) in the application of 2-D simultaneous inversion using Ridge regression techniques. After testing the algorithm on simple numerical models, the technique is tested on field data from four different mineralized zones. They are from: Brenda Porphery copper deposit, near Peachland, British Columbia; copper prospect near Mendoza, Argentina; a lead-zinc deposit near Pine Point, North West Territories, Canada; a massive sulphide deposit near Ladysmith, Wisconsin; the Iso-copper fields near Noranda, Quebec; and the Poseidon nickel sulphide deposit near Windarra in western Australia. The subsurface sections obtained from 2-D simultaneous inversion of both data sets are compared

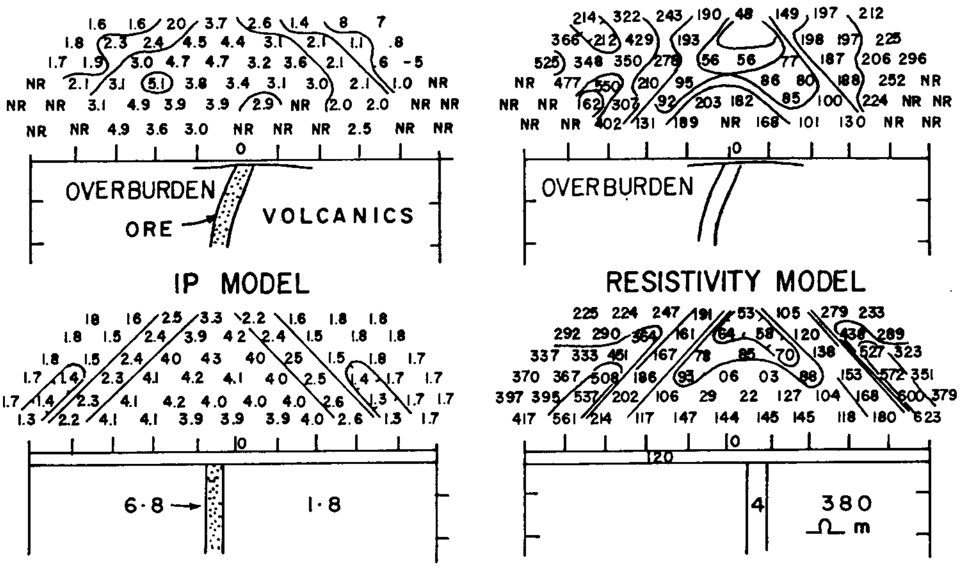

Figure 7. Observed (top) and computed (bottom) apparent polarizability and apparent resistivity data over the Flambean massive sulphide deposit, Wisconsin based on simultaneous inversion of IP (left) and resistivity (right) data sets (from Pelton et al., 1978).

and evaluated and its limitations are also discussed. In all these examples, it is shown that simultaneous inversion has helped greatly in locating the targets. As an example, the simultaneous inversion of IP and resistivity data for the Flambian massive sulphide deposit, Wisconsin are shown in Figure 7. The simultaneous inversion of both data sets have shown a good correlation with Turam results and helped to locate the mineralized targets.

Integrated geophysical studies including E and EM methods were being used in India by the mining companies and national organizations like the Geological Survey of India (GSI) and National Geophysical Research Institute (NGRI) to map mineralized zones. The Aladahalli schist belt area, Hassan district, Karnataka was proven to be a sulphide mineralized zone from integrated geophysical studies (Jayaram, 1982). There are no outcrops in the area, the lithology has been mapped from photogeological studies, and significant EM anomalies have been observed from airborne geophysical surveys. Subsequently, surface exploration over the anomalous zone with E, EM, IP and SP methods (Figure 8) identified the targets for mineralization, which were validated by drilling. About 3.9 million tonnes of ore is estimated to be in the area. As can be seen from the figure, the presence of a mineralized zone is indicated from IP, electrical resistivity methods, but clearly predicted by EM at 10E location on the profile with large anomaly. Thus, use of joint methods has helped in the location of the target. Gani-Kalava area located in the northwestern part of the Proterozoic Cuddapah basin is known to be a source of Chalcopyrite, Covellite, Chalcocite, etc. embedded in carbonaceous shales. Anomalous high conducting zones have been delineated using self-potential (SP), EM, IP and telluric methods. Individual methods have shown the conductive zones at different locations. Integrated interpretation of these methods has identified mineralized zones near N200-W500 and 0-W100 (Murthy et al., 1975; Sankernarayan et al., 1984; Harinarayana and Sarma, 1998a) which could be a difficult task for a single method as can be seen in Figure 9. Similarly, integrated geophysical studies including SP, E and EM have been carried out by GSI at Wajrakarur and Jonnagiri areas in Andhra Pradesh, Chitradurga area in Karnataka, Josiaralangalam areas in Tamil Nadu, etc., and detailed electrical resistivity profiling by NGRI in these areas has helped to understand the distribution of mineralized zones in more detail (Appa Rao and Roy, 1973; Appa Rao and Sarma, 1983). Appa Rao and Roy (1973) have compared various electrode configurations over conducting targets and have shown that a two-electrode configuration has a better resolution. Areas covered with volcanic rock pose serious problems for the conventional seismics, where E and EM methods are relatively successful. In order to detect and map the sediments buried below the volcanic rock area in the Saurashtra region, India, for hydrocarbon exploration, about 700 wide band MT stations (1 kHz–500 s) and 70 deep resistivity soundings (AB/2 = 10 km or more) were carried out and a joint inversion technique was applied. Figure 10 shows the compilation of MT studies in India along with a few DRS studies. Both methods are being used jointly in many cases. The results obtained from individual and joint inversion are compared with the Lodhika deep borehole (3.5 km), Saurashtra as described before (Figure 6) and observed that the joint inversion result was close to the borehole data.

A MT-VLF study was undertaken at La Fontaine du Canard, Corvol d'Embernard, Nievre in France by Guerin and Bendritter (1995). The data were corrected for verticalization of the electric field (similar to a reduction of the pole in magnetics) and interpreted in conjunction with DC resistivity profiling and depth soundings. This has resulted in more details on the subsurface structure being obtained. Raiche et al. (1985) have considered co-incident loop transmitter EM and DC electrical methods for the application of joint inversion algorithms. By jointly inverting the two data sets with linearized least squares inversion procedures, they observed that the error bounds on subsurface layered parameters have improved. The method has been tested with field data from South Australia. Tabbagh et al. (1991) have proposed a new concept for a VLF resistivity meter with a short (1 m) electric sensor coupled with a magnetic sensor. After correction of electric fields for horizontal deformation of the anomalies, it is demonstrated that the method works well even for medium and high resistivity targets. Iliceto et al. (1995) have considered 127 resistivity soundings and 3 MT soundings data near Balvedera Spinello Salt mine in southern Italy for joint study. By jointly interpreting the two datasets, they have obtained a conductive feature related to brine at 550 m, which was not resolved by the resistivity interpretation alone.

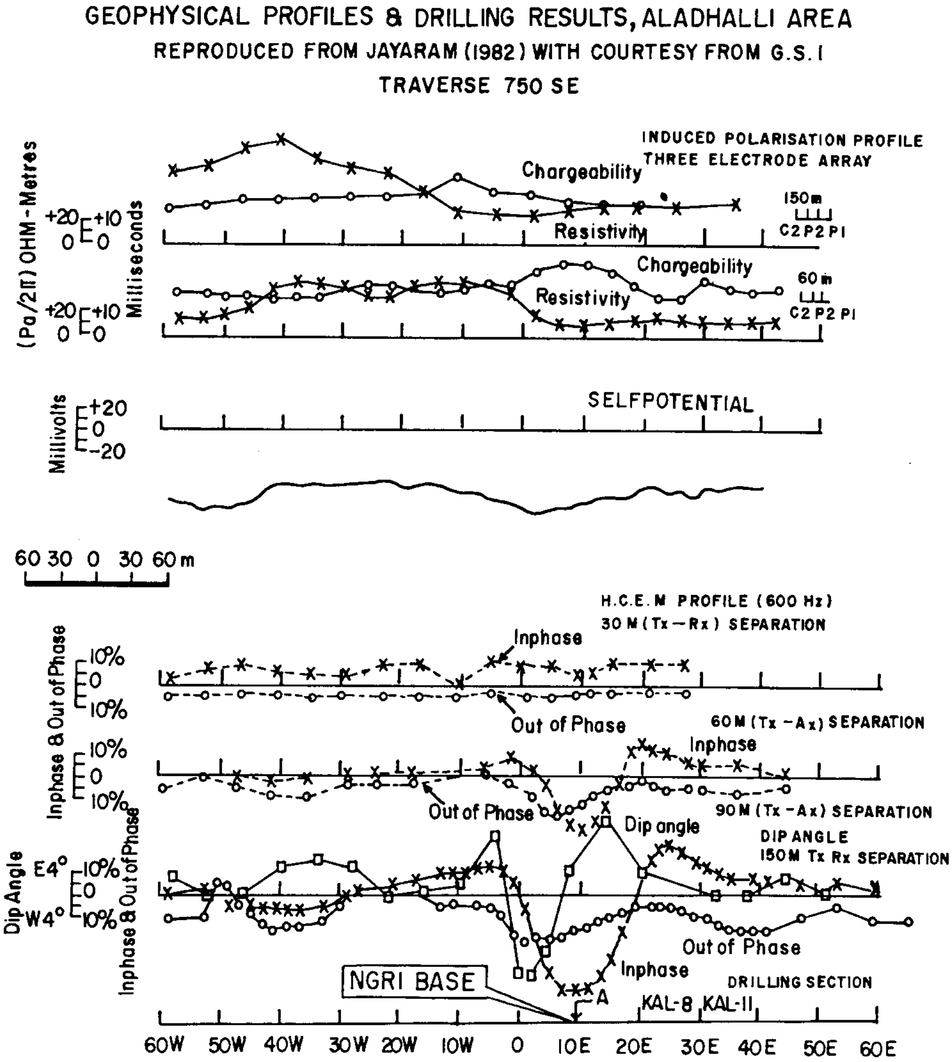

Figure 8. Various geophysical profiles – IP, SP, Resistivity, EM – near Aladahalli area, Karnataka, India. Mineralized zone (near 10E) is predicted from the integrated studies (from Jayaram, 1982, courtesy: G.S.I.).

5.2. GEOTHERMAL AREAS

Combined use of E and EM methods found application in geothermal areas as the structure is better resolved which could be difficult from a single method as described in the following examples. Tripp et al. (1978) carried out Schlumberger electrical resistivity soundings in the Roosevelt Hot Springs area, KGRA. 1-D and 2-D modeling of the data have indicated a conducting zone near the dome fault. However, they observed that 1-D parameters were poorly resolved. By the applic-

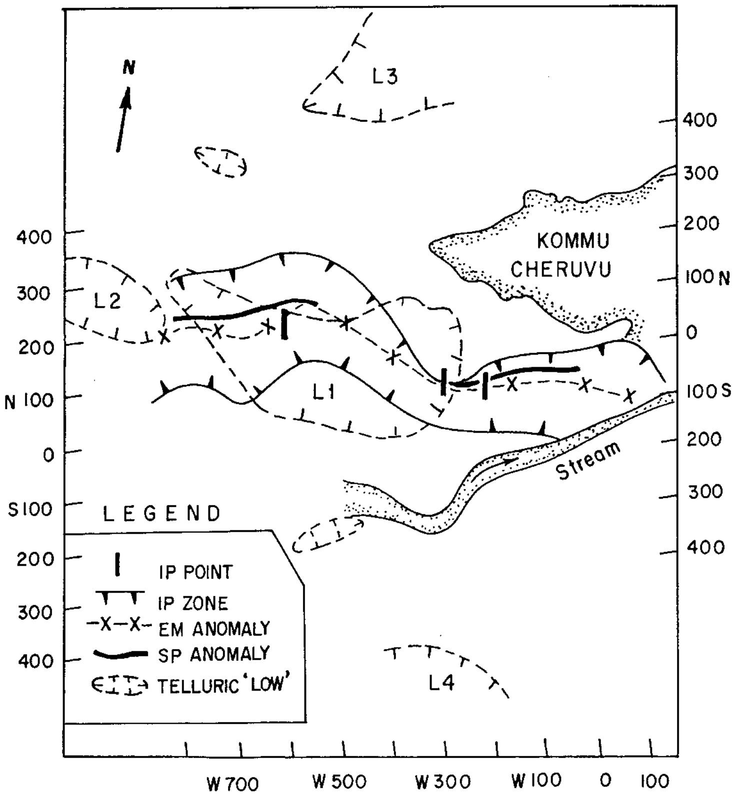

Figure 9. Integrated geophysical studies showing the anomalous conductive zones, near the Kalava area, Kurnool, India. Correlation of IP, SP, EM and telluric anomalous conductive zones interpreted as a deeper source of mineralization associated with carbonaceous shales. The numbers shown on the axis are distance in meters (from Harinarayana and Sarma, 1998a).

ation of joint inversion of Schlumberger and EM sounding data, the subsurface parameters are better resolved. Joint interpretation of telluric and narrow band magnetotelluric studies in the northern part of the Konkan geothermal area, India has yielded an anomalous conducting subsurface structure near the Sativili group of hot springs (Harinarayana, 1988; Harinarayana and Sarma, 1998b). Based on shallow DC resistivity soundings, which have indicated the presence of shallow acquifers, and telluric, magnetotelluric data a subsurface geoelectric model was proposed for the Konkan province, west coast of India (Figure 11). By the joint use of these methods anomalously high conducting structure both at shallow (from DC) and deeper (from telluric and MT) depths could be resolved.

Magnetotelluric and DC resistivity data at the Hatchobaru geothermal area, Japan, have been considered for modeling and joint inversion was applied by Ushijima et al. (1986). The depth estimates have been obtained with greater confidence as they are in close agreement with the drilling logs. Ushijima et al. observed that these results helped to locate the faulting and zone of fracturing which in turn

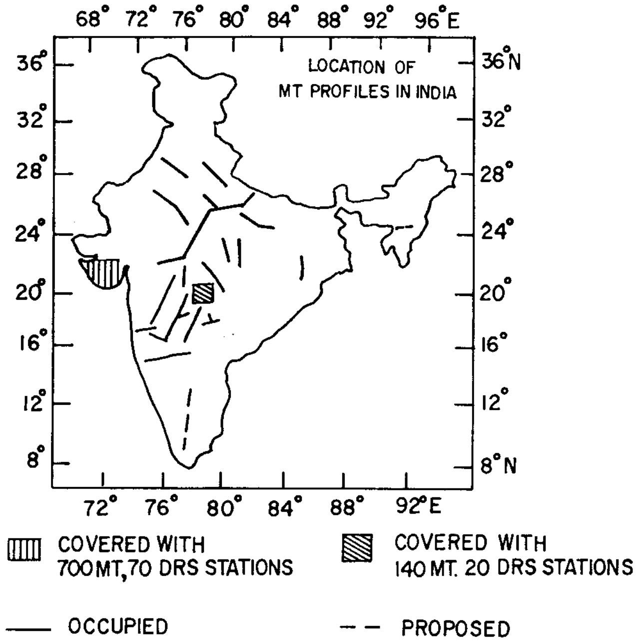

Figure 10. Compilation of location of wide band MT profiles by different organizations and institutions in India. The DRS stations are widely distributed in peninsular India and are not shown in the figure. Joint inversion applied to both the data sets near a deep bore hole in Saurashtra region is shown in Figure 6.

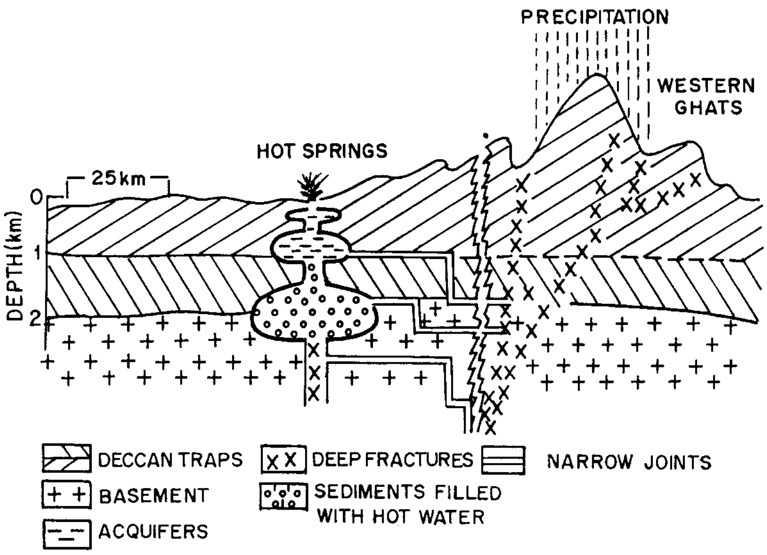

Figure 11. A schematic geological section is proposed based on shallow DC resistivity soundings, telluric and magnetotelluric data for Konkan geothermal province, west coast of India. DC resistivity soundings gave information on shallow acquifers and deep acquifers (1.5–2 km) is inferred from telluric and magnetotelluric studies (from Harinarayana and Sarma, 1998b).

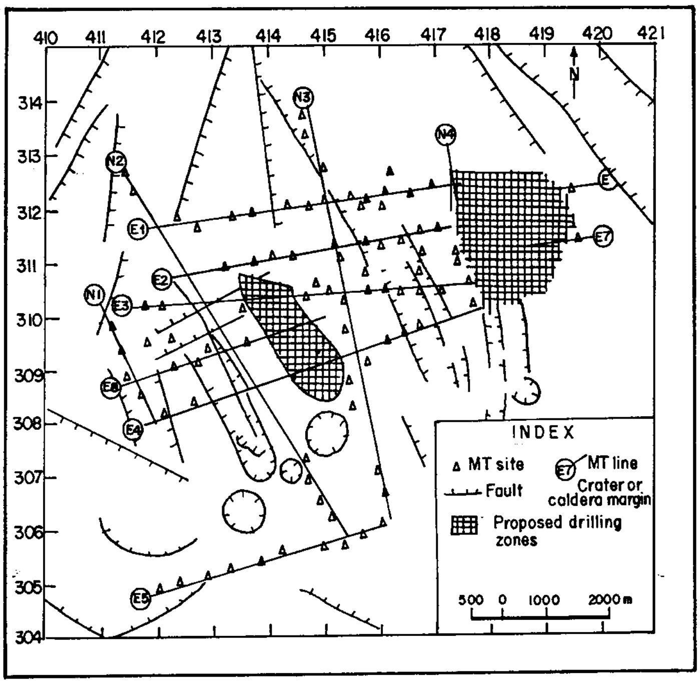

Figure 12. Proposed drilling zones for exploitable geothermal resources are shown by hatched lines, Chipilapa geothermal field, El Salvador. The inferences are drawn based on a combined interpretation of dipole–dipole resistivity and magnetotelluric data (from Romo et al., 1997).

show the areas with potential geothermal prospects. In Neopolitan geothermal area, Hunche et al. (1981) have jointly interpreted both MT (0.4–1000 s) and electrical resistivity sounding (AB/2= 3000 m or more) data sets. The shallow electrical section has been derived mainly from resistivity methods while the deep structure (4 km) was derived from MT and resistivity sounding methods. They observed a good agreement between these two geophysical methods and, when compared, the subsurface section is well correlated with that deduced from gravity data. Mogi et al. (1995) have used CSMT and long offset TDEM in two geothermal areas – the Kuju-Iwouyama and Waita area. A shallow subsurface section (1 km) was investigated from CSMT data and the deeper part from the TDEM data. Joint analysis of the two data sets has resulted in obtaining a relation between the sites of heat source and the geothermal reservoir. In the Chipilapa geothermal field, El Salvador Romo et al. (1997) have used Schlumberger and dipole-dipole resistivity data for correction of static effects and for constraining the shallow sections in 2-D MT models. The presence of a deep conductor overlain by shallow resistive layers seems to be a favorable zone in this area for exploitable geothermal zones. By jointly interpreting both data sets, favorable zones for geothermal resources are suggested in areas of deep conductor, detected mainly from MT data, overlain by a shallow resistive layer indicated from DC and MT data (Figure 12).

5.3. Environmental studies

Joint use of E and EM methods is also found to be effective for environmental studies, especially for groundwater problems (e.g., Davino et al., 1980; van Overmeeren, 1981; Van et al., 1987; Buselli et al., 1990; Brown et al., 1992). Location of groundwater in hard rock terrain is a difficult problem because of the nonuniformity of weathered and fractured zones. Great success has been achieved using both the EM and DC methods. For example, the hard rock terrain of Kano state, Nigeria was investigated for ground water by electromagnetic traversing (EMT) and DC electrical sounding (Beeson and Jones, 1988). Locations of high apparent conductivity observed from EMT data were investigated further by DC electrical sounding (Figure 13). Recommendations from the combined use of both data sets have yielded an 85% success rate for ground water site selection. Turberg and Barker (1996) have applied radio magnetotelluric (RMT) and electrical imaging surveys for hydrogeological investigation over two contrasting geological environments in the British East Midlands. One area comprises 6-m thick sand and gravel while in the other area the Triassic mudstones overlie the Precambrian rocks. Applying both methods and jointly interpreting the datasets yielded reliable estimates of subsurface parameters. Turberg and Barker observed RMT to be a fast covering geophysical tool for shallow targets and it is sensitive to the strike direction. Pham et al. (1994) applied DC electrical sounding and MT methods for ground water near Ho Chi Minh City, South Vietnam. The shallow resistivity structure was derived from electrical sounding data and the shallow parameters were used as a constraint and deeper structure derived from the MT data. With such a combination of interpretation of data sets, they could delineate the ground water contamination zone (Figure 14) effectively.

6. Conclusion

Although electrical and electromagnetic techniques have been used for the last several decades, the need for using joint inversion and joint interpretation techniques has increased during the last two decades. The combined use of electrical and electromagnetic techniques for mineral, geothermal, environmental problems – as illustrated by various case studies – provides more information on the subsurface parameters than any single method.

Several examples are presented showing the success of joint interpretations in various applications. For example, near Aladahalli schist belt area, Karnataka, India, DC resistivity data have indicated a low resistive area along a profile. Detailed EM profiling near the low resistivity area has identified the high conducting mineralized zone (Figure 8). Similarly, in geothermal exploration studies of Ahuachapan-Chipilapa field, El Salvador, a DC resistivity (Schlumberger and dipole-dipole) survey was carried out. The data have been used later for correction of static effects

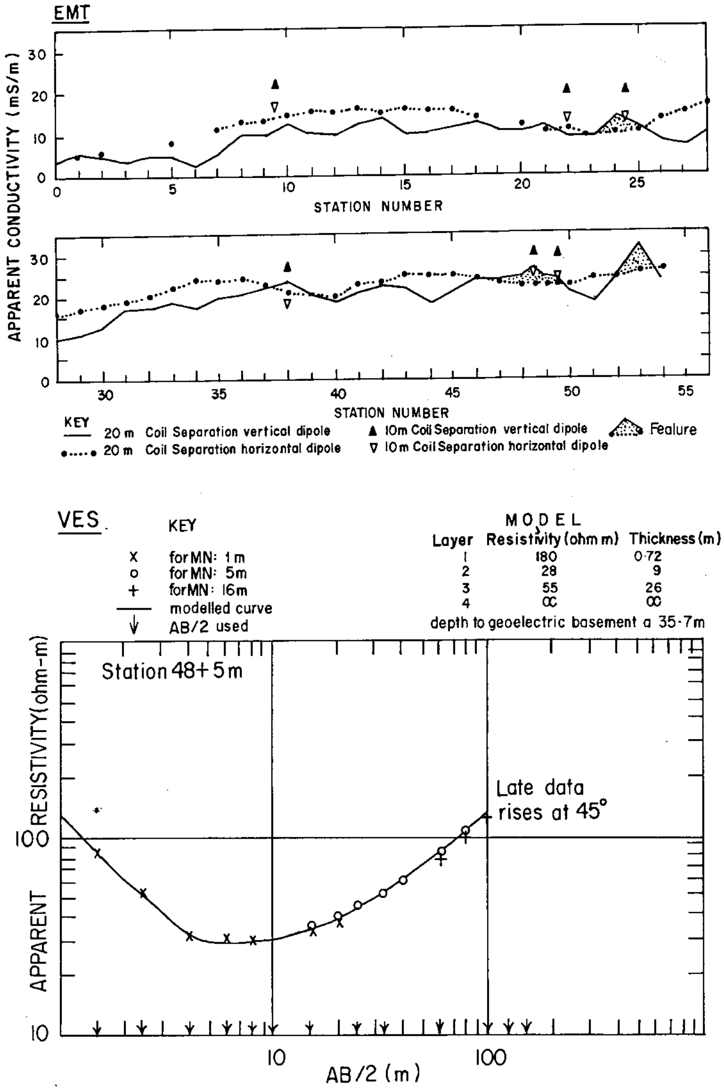

Figure 13. Apparent conductivity curves along a traverse with 20 m coil separation for EMT (electromagnetic traversing method). Near stations 48 and 53 high apparent conductivity can be seen (top). DC electrical sounding data near station 48 shows a H-type curve, indicating a thick conducting layer (estimated thickness = 35 m) in hard rock terrain (bottom). Drilling results showed a weathered and fractured pink granite and good groundwater potential is observed during a subsequent 3 hour pump test (from Beeson and Jones, 1988).

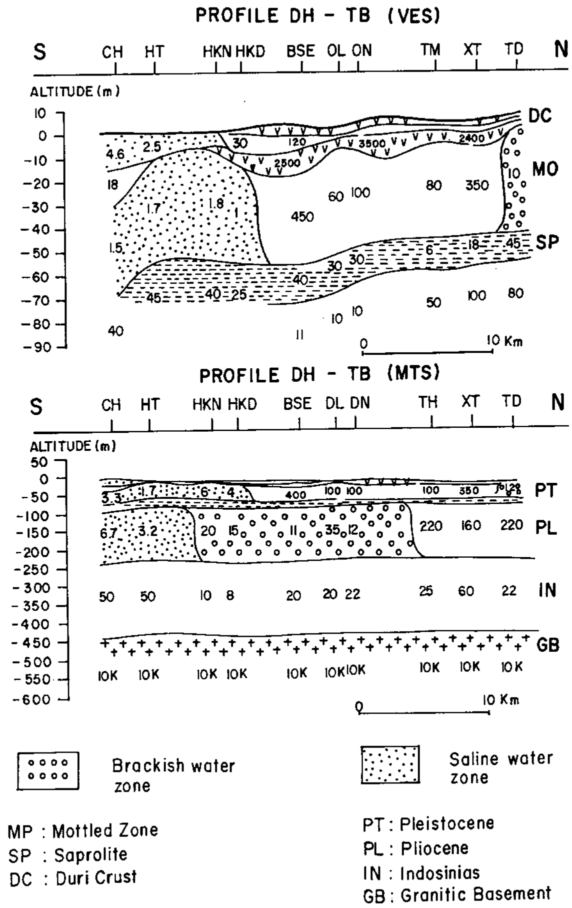

Figure 14. Near Ho Chi Minh City, Vietnam (top figure) derived from DC electrical sounding and from MT data (bottom figure). The sections are derived from simultaneous interpretation of both MT and DC data sets in an interactive mode with shallow section mainly from DC data and the deeper section both from MT and DC data (from Pham et al., 1994).

on MT data and also for constraining the models derived from MT. By combined interpretation of both the data sets, an exploitable geothermal reservoir is proposed (Figure 12). The location of groundwater in hard rock terrain is a difficult problem. Investigations by DC sounding at locations of high conductivity, indicated from EM profiling, showed a high yield of groundwater in Kano state, Nigeria (Figure 13).

Further, one can have more confidence in the derived parameters obtained from a joint study. In fact, in a more general sense, multiparameter surveys involving various geophysical methods – E, EM, seismics, gravity, magnetics etc. – are necessary to estimate the subsurface parameters with better resolution, especially in a complex geological environment.

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