A REVIEW OF ENVIRONMENTAL APPLICATIONS OF QUASI-STATIONARY ELECTROMAGNETIC TECHNIQUES

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Abstract. Electromagnetic (EM) techniques are the most commonly used geophysical methods in mineral exploration. However, the use of EM measurements for environmental and engineering applications like the detection of contaminant plumes or the exploration of waste sites is relatively new.

The reason for the success of the application of EM methods to environmental problems lies in the variation of conductivity caused by different geometry of pore fluids and clay contents in rocks, and by the presence of organic and inorganic contaminants.

Many EM methods/instruments used for mapping near surface geology exist and nowadays they play a central role in environmental geophysics. In general, these methods can be classified in two blocks: EM methods using a plane wave source of excitation and EM methods using a controlled source like a magnetic dipole or a loop source. The Very Low Frequency (VLF, VLF-R) and Radiomagnetotelluric (RMT) methods are chosen as representative methods for plane wave techniques, while horizontal loop EM methods operating in low induction numbers (EM31, EM34) and Transient Electromagnetic methods (TEM) are chosen as representatives of magnetic dipole or loop source techniques. Basic principles, advantages and disadvantages of each technique as well as their connection to specific environmental problems will be discussed.

Different successful applications of these methods are reported in the literature. However, this review will focus on three major subjects: waste site exploration, detection of contaminated earth layers, and groundwater exploration. Case histories are presented illustrating the suitability of EM methods for solving such problems.

Keywords: conductivity, conductivity models, electromagnetics, environmental applications

1. Introduction

In the last decade there has been a tremendous resurgence of interest in the use of EM techniques for environmental applications due to their improved spatial resolution and low costs.

In Figure 1 the frequency ranges of some EM methods are summarized. Usually Controlled Source Audiomagnetotellurics (CSAMT) and Horizontal Loop EM (HLEM) systems operate below 10 kHz, but 'Stratagem' system (Geometrics) can observe transfer functions up to 70 kHz. The conventional VLF has a limited frequency range (10 kHz–30 kHz). RMT (10 kHz–1 MHz) is between VLF and conventional Georadar, but there still remains a gap (1–10 MHz). Plane waves

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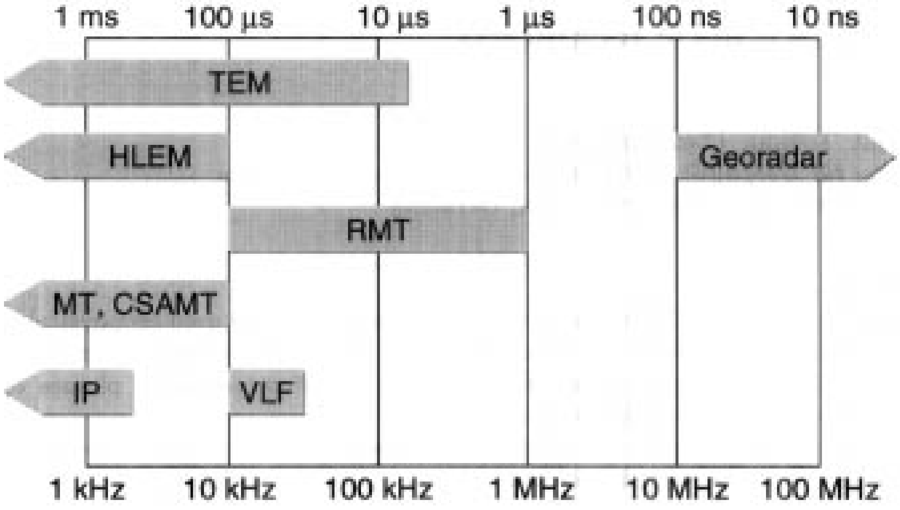


Figure 1. Frequency and time range of some EM-techniques.

in the 1–100 MHz frequency band are available from existing radio transmitters or can easily be generated by using controlled sources, but displacement currents cannot be neglected in this frequency range. Theoretical aspects and solutions for this case have been presented by Kaufman and Keller (1983), Zhdanov and Keller (1994) and recently by Song et al. (1997). Unfortunately, there is no instrument available to cover the whole frequency range.

The transient EM (also known as time domain EM) instruments measure the decay of eddy current in the time range of 5 μs to 100 ms depending on the type of instrument. This corresponds to an investigation depth between several meters to several hundred meters depending on the conductivity of the earth.

Traditionally all EM methods are divided into high frequency, quasi-stationary, and stationary groups (Zhdanov and Keller, 1994). Frequency ranges determine the fundamental physics which governs EM field propagation. A high frequency field (e.g., Georadar or Ground Penetrating Radar) is wave-like and a quasi-stationary field is diffusion-like (e.g., Magnetotellurics). This paper especially deals with the methods based on quasi-stationary fields. Stationary fields could also be included in Figure 1 and can be classified as special cases of an electromagnetic field at zero frequency. In this case, the magnetic field decouples from the electric field (Zhdanov and Keller, 1994). Related techniques are: potential magnetic method, Direct Current (DC) and Induced Polarization (IP) methods. They are also used for environmental applications, but this is beyond the scope of this paper.

On the other hand, EM induction methods used in environmental geophysics can also be classified into two groups (e.g., McNeill, 1990), and this classification is chosen in this paper. One group uses a plane wave source; the corresponding techniques are Magnetotellurics (MT), Audiomagnetotellurics (AMT), Very Low

Frequency (VLF, VLF-R), Radiomagnetotellurics (RMT) and Controlled Source Audiomagnetotellurics (CSAMT) in the far field zone. The other group uses magnetic dipole or loop source. Horizontal Loop EM (HLEM), Ground Conductivity Meter (which is a special type of HLEM system operating in low induction numbers), and the Transient EM (TEM) methods are the corresponding techniques for this group.

A large number of instruments developed especially by using magnetic dipole or loop source (e.g., MaxMin, Genie, etc.) exists. Instead of describing all the EM methods/instruments used in environmental geophysics, we will focus in the following (Sections 2 and 3) on two techniques (VLF, RMT) representing the EM plane wave source and on two techniques (EM34, TEM) representing magnetic dipole or loop source. Airborne measurements will not be discussed, nor will Ground Penetration Radar (GPR). Inductive EM techniques will be considered at relatively low frequencies where displacement currents can be ignored.

All EM methods used in environmental geophysics observe the conductivity distribution in the subsurface. Conductivity, besides viscosity, represents the physical parameter with the highest dynamic range in the nature. For the materials in the earth, it varies from 10^{-18} S/m (diamond) to 10^{7} S/m (copper), i.e., by 25 orders of magnitude (Weidelt, 1997). There is also a large variation of conductivity observed on waste deposits (0.01–1 S/m).

In general, a discrimination between two types of contaminants is made, namely between organic and inorganic contaminants. When in contact with groundwater or wet soil, inorganic chemicals usually dissolve easily into ions, increasing the number of totally dissolved material within the rock's pore fluid, and thus the bulk conductivity increases. The effect of organic contaminants on ground resistivities is rather complex and subject of present investigations. In general, the resistivity of rock should increase when high resistive oil occupies the place of the pore fluid, but observations in the laboratory showed a decrease of resistivity at a frequency of 1 Hz right after oil contamination on samples of sand and till (Vanhala, 1997). An explanation for this may be that oil detaches ions from the surfaces of rock particles so that the number of total dissolved solids within the electrolyte increases. It could also be possible that the hydrocarbons are cracked into ions by biochemical processes.

The application of EM methods and other near surface (0–200 m) geophysical techniques for the solution of problems in archaeology, engineering science, groundwater exploration, detection of contaminant plumes, and buried unknown waste sites has three distinguishing characteristics not shared with regional geophysics (Butler et al., 1997):

(a) very high resolution surveys;
(b) public health and safety concerns;
(c) near real time validation.

This calls for new efficient instruments, methods of data collection and interpretation procedures (Christensen and Sørensen, 1995; McNeill, 1990). However,

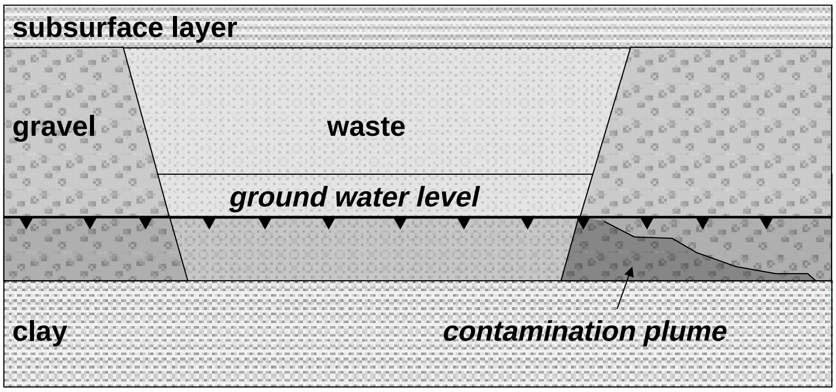


Figure 2. A common waste site situation.

today's EM methods used in environmental geophysics constitute in general a new context for an old subject. They rely mainly on principles and methods known and practised for decades, but they address problems and issues that are for better or worse a product of our times.

Nowadays, buried waste deposits represent one of the important and actual environmental problems. A schematic common waste site situation in Europe is illustrated in Figure 2. During the last 50 years, small gravel pits have been filled with household refuse, building debris and a different kind of potentially dangerous industrial waste. They were often filled up in an uncontrolled manner with little or no documentation. These waste sites may impose a huge risk for the environment and can be the main source for groundwater contamination.

Waste sites, especially in Europe, constitute a serious problem. There exists a large number of old waste sites (approx. 90000 in Germany). Unfortunately, only 5% of them have been explored by geophysical methods. Commonly, shallow boreholes covering the survey area have been used for monitoring, but such an approach is very expensive. Besides, it is possible to obtain detailed information about the extent of such waste sites in a faster and more effective way with the help of geophysical methods, in particular by the application of EM-methods, as shown in the case histories in chapter 2.1 and 3.1.

New waste sites are at present more carefully designed, especially in the industrialized countries: A clay layer at their base functions as a geological barrier and the deposed waste material is much better controlled than prior. Hence, there is a demand to study them.

In general, the conductivity of such waste sites is much higher compared with the surrounding host. Therefore, EM techniques are very suitable for the exploration of waste sites. Case histories were recently reported about the detection of their lateral and vertical extent (e.g., Berktold et al., 1992; Tezkan et al., 1996; Zacher et al., 1996a; Pellerin and Alumbaugh, 1997).

A more difficult geophysical problem is the detection of possible contaminant plumes emanating from waste sites where also a conductivity anomaly is expected (Ben Miloud, 1986; Greenhouse et al., 1989).

In addition to the detection of contaminant plumes, the exploration of cavities and tunnels, and the detection of hydrocarbon contaminated soil constitutes a very important field of environmental application of EM methods (Walraevens et al., 1997; Recher et al., 1998).

Such hydrocarbon contaminations may occur at military airports, refineries, and industrial complexes where a large number of buried pipes and cables disturb the EM response. The effect of such pipes should be considered when interpreting the EM data by conductivity models quantitatively (Recher et al., 1998).

EM methods have also become much more common for groundwater explorations (Fitterman and Stewart, 1986; Buselli et al., 1990; McNeill, 1990; Goldstein et al., 1990; Turberg et al., 1994; Meju et al., 1988). This fact is due to the ability of EM methods to distinguish between hydrological formations, because conductivity is often strongly correlated with porosity and hydraulic conductance. Due to pollution and intensive use of the uppermost aquifer, more interest is now given to deeper lying aquifers and many electromagnetic surveys investigate buried valleys (Christensen and Sørensen, 1995).

Impressive case histories demonstrate the use of EM techniques for the detection of fresh water–salt water boundaries (Sandberg, 1987; Goldman et al., 1991). EM measurements with DC resistivity measurements show good results for the investigation of aquifers, especially in semi-arid areas (Meju et al., 1998). Excellent reviews about electromagnetic methods for near surface applications were given by McNeill (1990) and Frischknecht et al., (1991).

The review of David C. Nobes, given in 1994 during the ‘12th workshop on electromagnetic induction in the earth’ in Brest, gives a detailed overview on electrical and electromagnetic methods and their environmental applications (Nobes, 1996).

A quick look in the proceedings of the annual conferences of the environmental and engineering society (EEGS), after the review of Nobes (1994), show the increased number of EM applications on environmental problems and the related theoretical and instrumental improvements in the USA and Europe.

EM measurements by car and by a towed system are now possible (Sørensen, 1996; Stiefelhagen, 1998) and satisfy the very important requirement in environmental geophysics of quickly covering a large area. In environmental studies, EM data were often interpreted qualitatively. Empirical methods are used as anomaly detectors, where only the location of anomaly is resolved, but the parameters of the section such as shape, depth of the bodies, etc. are not determined. An important trend during the last years is the quantitative interpretation of observed data by conductivity models (Tezkan et al., 1996; Beamish, 1998; Ogilvy et al., 1998; Kaikkonen and Sharma, 1998). Rigorous inversion methods, 1-D, 2-D and in some cases even 3-D (Alumbough and Morrison, 1995; Zhdanov and Keller, 1994; Nabighian, 1991; Smith and Booker, 1991; Lines, 1989; Constable et al., 1987), are used for quantitive interpretation. The migration technique for the quantitative interpretation of EM data should also be mentioned at this place (Zhdanov et al., 1995a, b).

2. EM methods using a plane-wave source of excitation

The well-known techniques belonging to this category are: MT, AMT, VLF, VLF-R, RMT and CSAMT in the far field zone. In the case of MT and AMT, electromagnetic fields of natural sources behave like plane waves at the surface of the earth with a small amount of energy propagating vertically downward into earth (Vozoff, 1991). Due to their large penetration depth, these methods are normally not used in environmental geophysical exploration; only the AMT method is used for groundwater prospecting (Weidelt, 1997; Meju et al., 1998).

VLF, VLF-R and RMT methods use the carrier waves from high-powered civilian and military transmitters operating in a frequency range between 10 kHz and 1 MHz (Figure 3). At a great distance from such transmitters (vertical electric dipole), local electromagnetic fields can be viewed as being those of a plane wave (McNeill and Labson, 1991). The electromagnetic field consists of a horizontal magnetic field perpendicular to the direction of propagation and a horizontal electric field in the direction of propagation. The presence of a large discrete conductor or any anomalous conductivity structure in the earth will modify the anomalous magnetic and electric fields observed. The ratio of the orthogonal horizontal components $\left|E_x/H_y\right|$ is related to an average resistivity of the subsurface for the observed frequency. The phase difference between E_x and H_y also contains information of the conductivity structure.

The RMT method is an extension of VLF-frequencies (10–30 kHz) to higher frequencies up to 1 MHz (Müller, 1983; Lagabrielle, 1986; Turberg et al., 1994). The principle of this method is demonstrated schematically in Figure 3. At a large distance from the transmitters the magnetic field is measured by a coil and compared with the electric component measured between two grounded electrodes spaced up to 20 m apart. The electrodes are placed perpendicular to the magnetic field (e.g., in the direction of the transmitter). From the ratio of amplitudes of the horizontal electric and magnetic field components apparent resistivity values are derived using the Cagniard formula of magnetotellurics as shown in Figure 3 (Cagniard, 1953). Furthermore – since the source transmitter is operating at a single, well established frequency – it is possible to measure accurately the phase angle between electric and magnetic field components.

Due to the large number of transmitters (especially in Europe) it is easily possible to cover the entire frequency range with selected frequency pairs. In an ideal

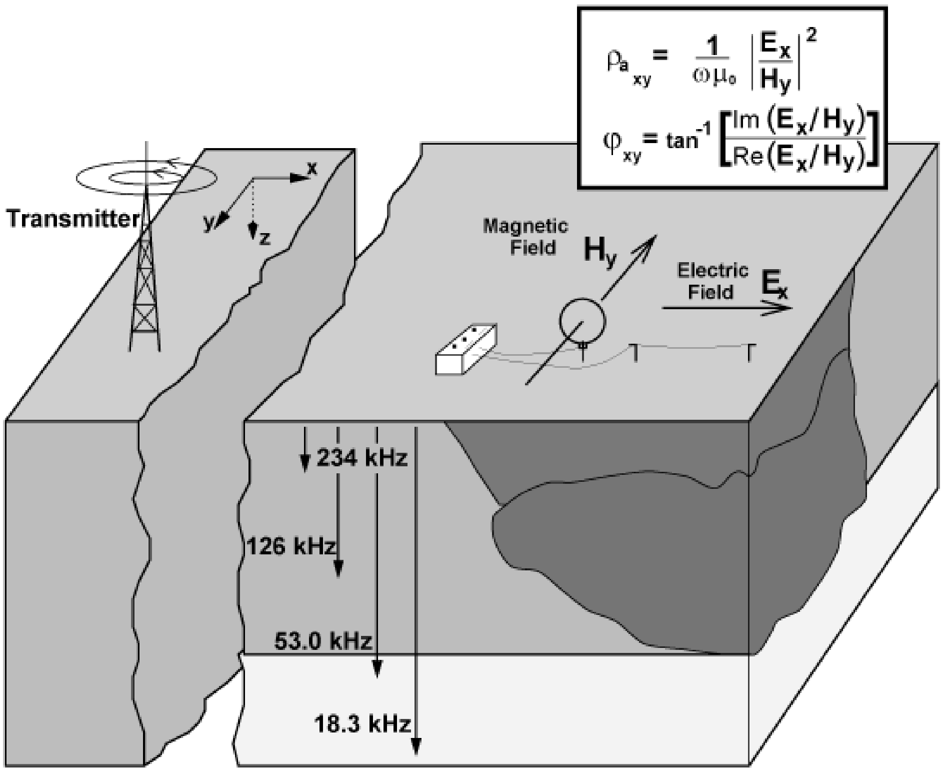


Figure 3. Schematic diagram for illustrating a RMT field setup over a hazardous waste site.

case, each pair should have similar frequencies with one transmitter direction parallel (E-polarization) and one perpendicular (B-polarization) to the general strike given by geological or anthropological structures. Assuming a two-dimensional resistivity distribution in the survey area, the data can be associated to the E- and B-polarization (Tezkan et al., 1996; Zacher et al., 1996a). With this assumption the E- and B-polarization data can be inverted jointly using 2D inversion techniques (e.g., Madden and Mackie, 1989; Smith and Booker, 1991). Model calculations show that displacement currents can be neglected under normal conditions up to $1MHz$ and the plane wave approximation is valid for VLF and RMT data (Zacher, 1992; Schröder, 1994) so that the well-tested magnetotelluric interpretation software can be used.

In practice, however, the strike direction is often unknown. In these situations the same procedure is applied (i.e., perpendicular transmitters pairs with similar frequencies are chosen) and the data are interpreted by 2D conductivity models which can be biased by 3D effects.

VLF-R data are normally presented along profiles or as contour maps of resistivity and phase. In general, no sounding information is available and interpretation is carried out mostly qualitatively. However, in some cases the data can also be interpreted in terms of a 1D and 2D conductivity model (Ogilvy et al., 1997; Beamish, 1998). VLF-resistivity can be considered as an alternative for terrain conductivity methods (Section 3) in many environmental and engineering surveys. Regular VLF (e.g., the measurement of the transfer functions for the local vertical magnetic field) is normally used to locate large mineralized zones, but can also be useful in delineating lateral inhomogeneties of conductivity (e.g., shear zones and overburden troughs).

VLF and RMT instruments are light-weight and easy to use. This is one important reason for their wide use in environmental applications. Using the RMT instrument developed by the Hydrogeological Institute of the University of Neuchâtel (Müller, 1983), scalar measurements (i.e., apparent resistivity and phase observations from one transmitter direction) in the frequency range between 1 kHz and 300 kHz can be carried out in a relatively short time (about 2 minutes are necessary to measure apparent resistivity and phase values for 4 frequencies at one station).

Hollier-Larousse et al. (1994) have also developed a RMT-system (10 kHz–1 MHz), but only apparent resistivities (no phase information) for selected frequencies are measured. Several impressive applications of their technique on engineering problems have been reported (e.g., Dupis and Choquier, 1996).

There is no instrument available which is suitable for carrying out tensor measurements for frequencies above 70 kHz. The Stratagem system of Geonics allows tensor measurements up to 70 kHz. VLF and RMT systems can only carry out scalar measurements.

The development of an instrument operating in a broad frequency range from several Hz to 100 MHz will be a task for the future.

2.1. CASE HISTORIES

Many VLF and RMT surveys have been widely and successfully conducted for a range of different purposes in the last few years, mainly for groundwater exploration (e.g., Turberg et al., 1994; Hollier-Larousse et al., 1994; Schwinn and Tezkan, 1997), for archaeological purposes (Zacher et al., 1996b; Baum, 1998), and recently for waste disposal exploration (Tezkan et al., 1996; Zacher et al., 1996a).

Due to the availability of only one frequency, VLF measurements are interpreted mostly qualitatively and it is difficult to derive depth information from the VLF data. For many applications in environmental geophysics this procedure is sufficient (e.g., detection of lateral borders of a waste site).

2.2. VLF-R-SURVEY

Figure 4 demonstrates a representative example of a VLF-R survey for the location of a contaminant plume moving away from a municipal landfill. The contaminated unit is a sand layer, typically 10 m thick, overlying crystalline bedrock (Ben Mil-

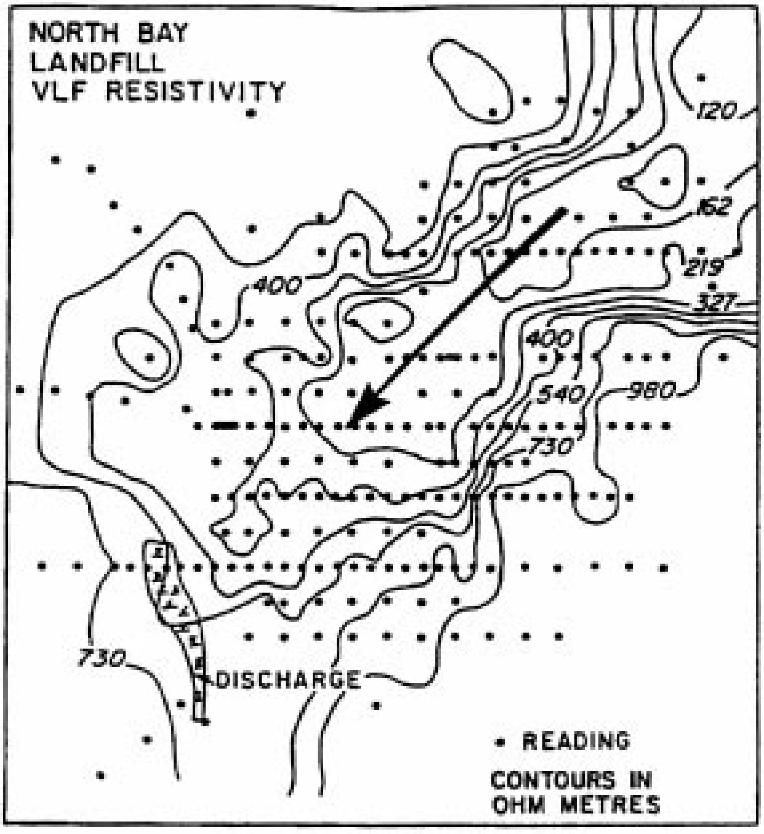


Figure 4. Apparent resistivity contours over contaminant plumes near North Bay, Ontario (Ben Miloud, 1986). Contaminated groundwater emanates from a landfill source at upper right and moves towards discharge points in a swamp.

oud, 1986). The direction of a contaminant plume is interpreted from the shape of isolines derived from the observed apparent resistivity.

Other VLF surveys (Kampmeier, 1992; Berktold et al., 1992; Ogilvy et al., 1998) also show the effectiveness of this method for waste disposal explorations.

2.3. RMT-SURVEYS

However, by using the RMT technique which has an extended frequency range including the VLF frequencies, the data can be interpreted quantitatively by conductivity models and depth information can be derived. The RMT technique is relatively new compared to conventional VLF methods. Thus, more emphasis is given on this application in the following. Figures 5–8 demonstrate a successful application of this technique to waste site exploration (Zacher et al., 1996a). Commonly, waste site exploration is carried out by geotechnical methods. Geophysical methods (especially EM techniques) are barely known, particularly in the state

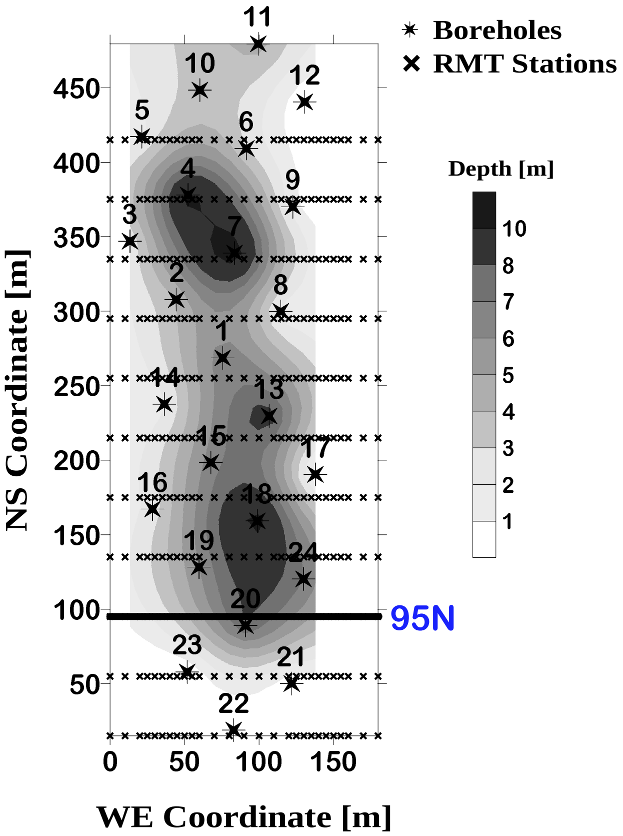


Figure 5. Lower boundary derived from drillings of a waste site near Cologne.

departments for environmental studies. To derive the vertical and lateral extend of a waste site which is located very close to Cologne/Germany, a company had drilled 24 boreholes on a 50 × 50 m grid.

Figure 5 shows the lower boundary of waste material derived from these boreholes. The waste deposit has dimensions of approximately 80 × 300 m. The thickness of the waste is decreasing rapidly towards its boundaries. The bright areas indicate the undisturbed geology, whereas the dark areas show the largest thickness in the middle of the waste deposit.

Three pairs of frequencies from radio transmitters perpendicular to each other have been used for RMT measurements in this area and apparent resistivity and phase data were collected on 11 profiles (Figure 5) (Zacher et al., 1996a). The RMT measurements were made to interpolate between the drilling locations in order to determine the boundaries more accurately than it was possible with the coarse drilling grid. The measurements and the interpretation were done without taking into account the information from the boreholes in Figure 5. The main aim

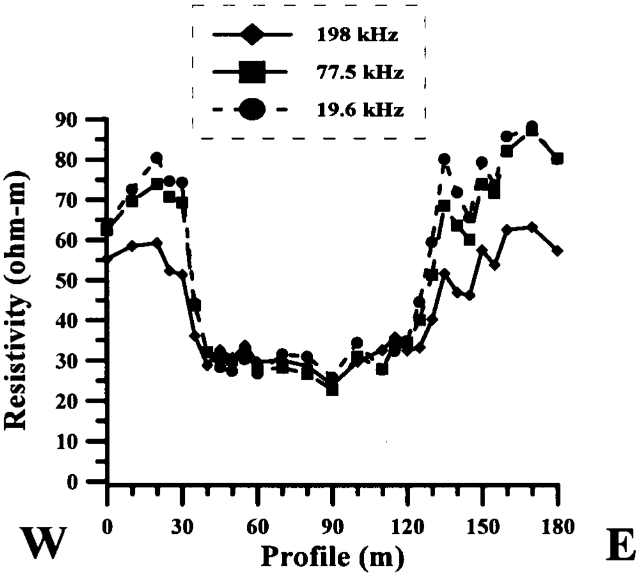


Figure 6. Apparent resistivity data of profile 95N for 3 frequencies at the Cologne waste site. The lateral boundaries at profile meter 30 and 130 coincide with the drilling results in Figure 5. The transmitters are located in E–W direction.

of the survey was also to test the efficiency of RMT in an area well studied by geotechnical methods.

Apparent resistivities on profile 95N (close to borehole 20 in Figure 5) are shown in Figure 6 for the frequencies 195, 77.5 and 19.6 kHz as a representat-

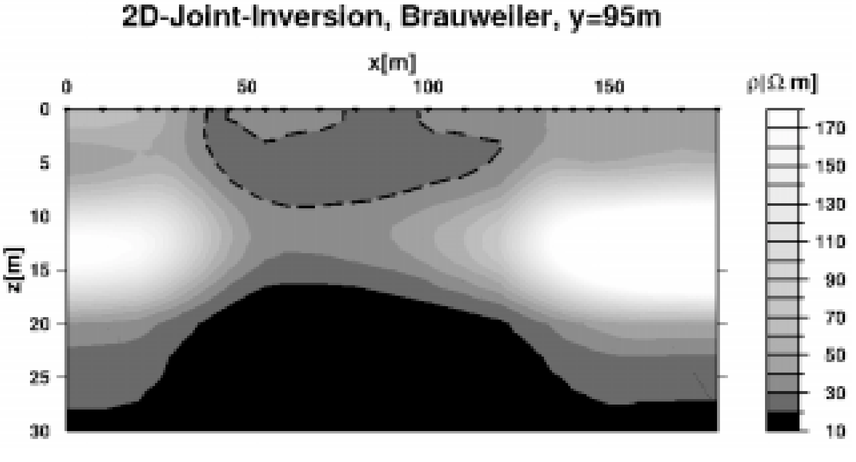

2D-Joint-Inversion, Brauweiler, y=95m

Figure 7. 2D inversion result for profile 95N at the Cologne waste site which is characterized by low resistivities (< 30 Ω m) between profile meter 30 and 120. The deeper low resistive structure indicates the clay layer.

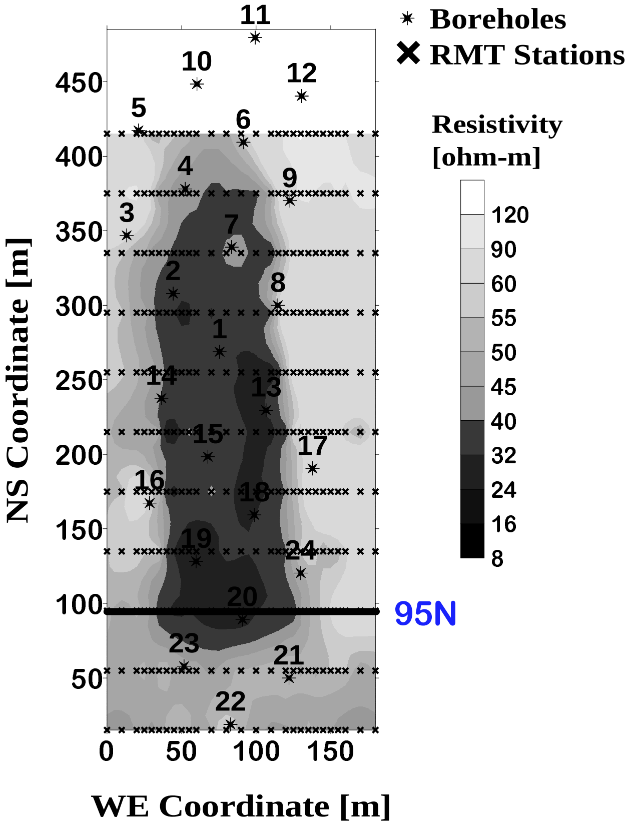


Figure 8. Resistivity distribution of the survey area at a 3 m depth at the Cologne waste site.

ive example. The lateral boundaries are characterized by strongly decreasing and increasing apparent resistivities at profile 30 and 130 m for all frequencies coinciding with the drilling results in Figure 5. The RMT data are interpreted by a 2D inversion technique (Mackie et al., 1994, Rodi and Mackie, 1999). Figure 7 shows for instance the 2D resistivity model for profile 95N. As expected from the field data shown in Figure 6 the lateral borders of the waste site are well resolved and additional depth information can be derived. The drilling point 20 was very close to this profile (Figure 5) and indicates the bottom of the waste site to be 7 m deep, which corresponds with the RMT modeling in Figure 7. Due to the smoothness parameter used in the 2D inversion algorithm (Smith and Booker, 1991; Mackie et al., 1994, Rodi and Mackie, 1999) the vertical transition from one layer to another is not very sharp in 2D RMT-conductivity models. Similar 2D inversions have been carried out for all RMT profiles and the results correspond with the drilling results. A quasi 3D resistivity distribution beneath the survey area has been derived from these inversions. Figure 8 presents a slice through this data set for a depth of 3 m. The lateral boundaries of the waste deposit have been determined more accurately

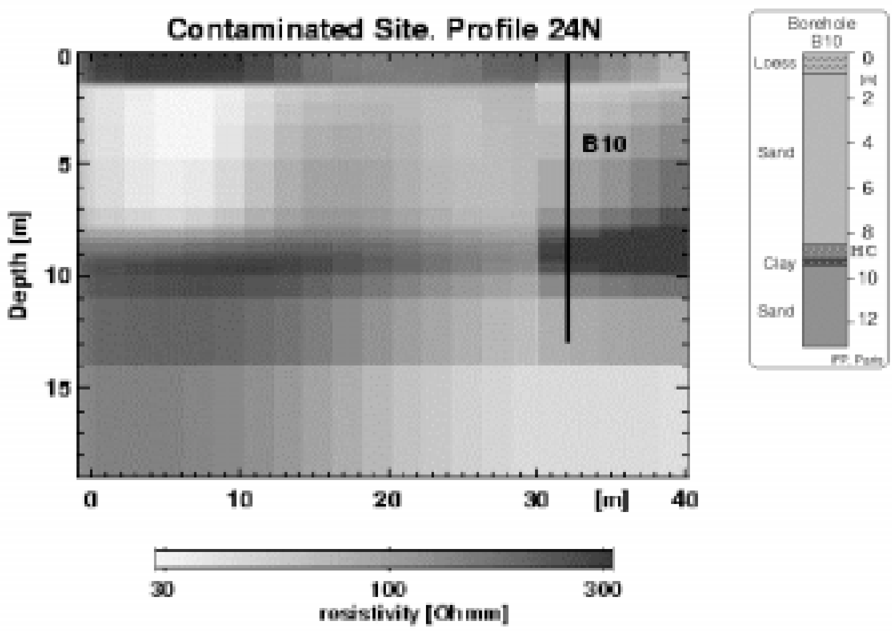


Figure 9. A 2D conductivity model derived from RMT data observed on a profile at a contaminated site near the International Airport Strasbourg (Recher et al., 1998). The resistive layer at 9 m depth may be interpreted as a contaminated zone in the sandy layer.

than by the drilling results. The results demonstrated in Figure 8 can be regarded as a final step for RMT-interpretation.

A successful RMT application for the location of a kerosene contaminated area near the airport of Strasbourg, France, is reported by Recher et al. (1998). Figure 9 shows the 2D inversion result of the RMT data measured on the contaminated site where the effect of buried pipes beneath the survey area is taken into account (Recher, 1998). Unfortunately, a large number of buried pipes exist in such contaminated areas and their response can bias the result of a 2D RMT-inversion. Their location and depth should be known accurately, so that they can be considered in the RMT inversion process. The result of this 2D inversion was compared with the borehole results. A resistive layer has been found in the sandy layer which may correspond to the contaminated soil near the water table as indicated with ‘HC’ in the borehole plot of Figure 9. The thin clay layer cannot be detected by 2D RMT-inversion.

To verify that electromagnetic methods are appropriate for environmental investigations, especially for waste sites, the Idaho National Laboratory Cold Test Pit has been constructed to simulate hazardous waste occurrences (Pellerin and Alumbaugh, 1997). Variable cap materials were 1–2 m thick and the bottom of the waste site is approximately at 8 m depth (Pellerin et al., 1997, Zhdanov et al., 1995)). Four profiles over the boxes and drum cells have been defined (Figure 10),

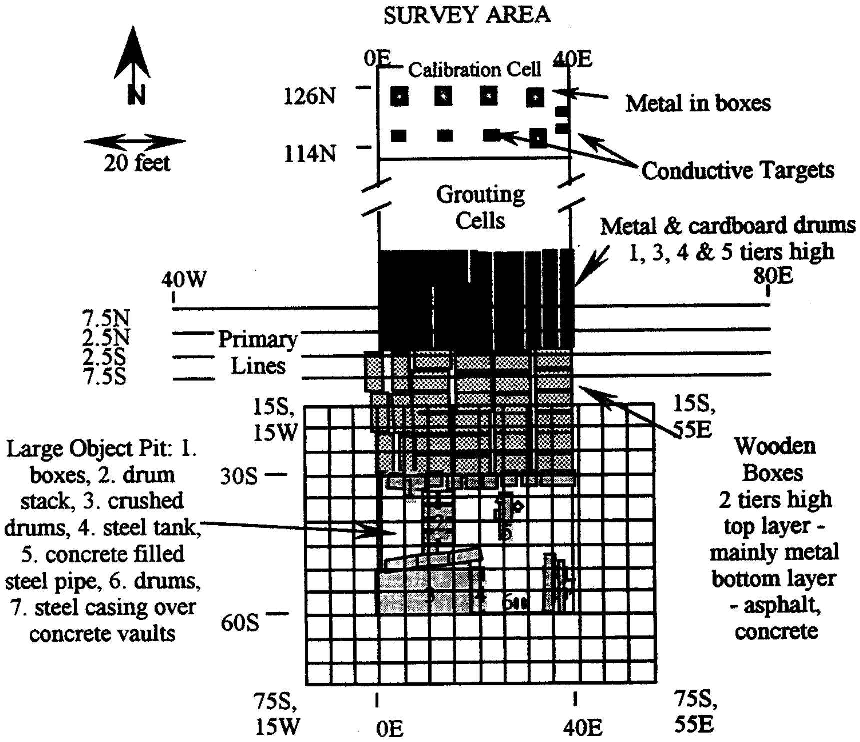
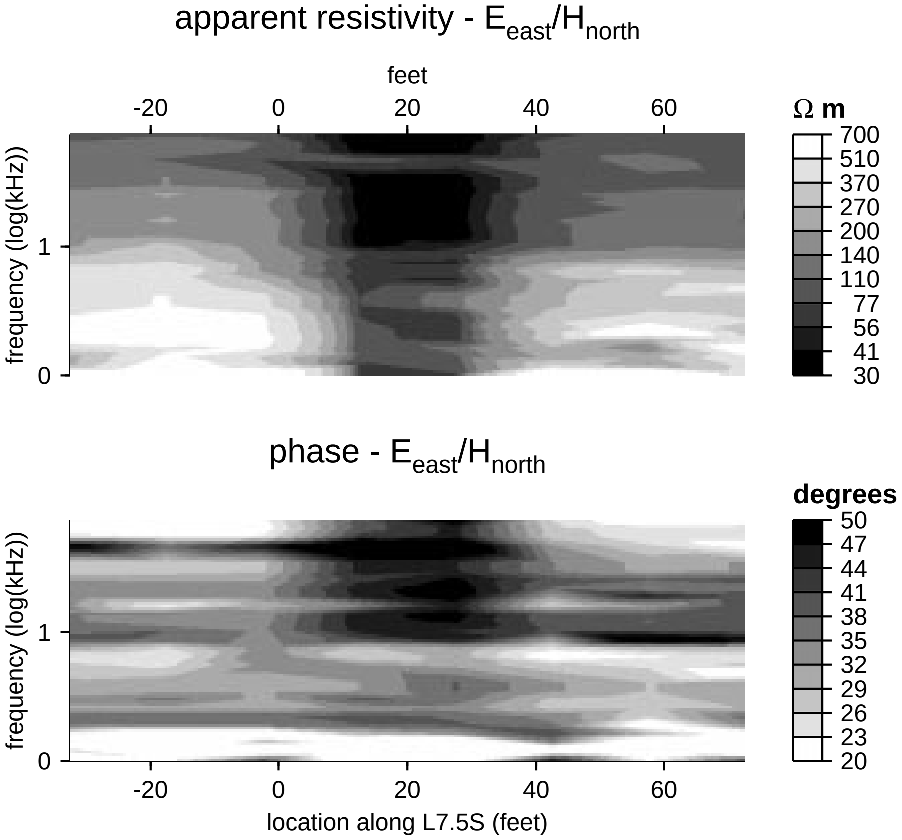


Figure 10. Survey layout at the Idaho National Engineering Laboratory Cold Test Pit (Pellerin and Alumbaugh, 1997).

and 11 different EM methods were applied. The successful results are summarized by Pellerin and Alumbaugh (1997). Especially, the plane wave methods (RMT and CSAMT in the far field zone) show excellent results due to the highly developed interpretation techniques. Figures 11–13 present the results of these methods for the profile 7.5S (Figure 10). The CSAMT method was represented by the Stratagem system. Data were collected from 0.8 to 72 kHz. In Figure 11, apparent resistivity and phase data are presented as pseudo sections for the B-polarization case (the E-field is perpendicular to the strike direction which is N–S) and profile data are shown in Figure 12. The waste is clearly seen as a strong conductive anomaly in the apparent resistivity data. The existence of the bedrock is clearly detected by the phase values (phases below 10 kHz are less than 45°).

Four transmitters in a frequency range of 10–200 kHz located perpendicular to the strike direction of the survey area (i.e., E–W) were selected and RMT data of high quality were obtained (Tezkan et al., 1997). Apparent resistivity and phase data show the lateral borders of the waste site by strongly decreasing apparent resistivities and significantly varying phase values. The result of the 2D inversion



apparent resistivity - E_{east}/H_{north}

phase - E_{east}/H_{north}

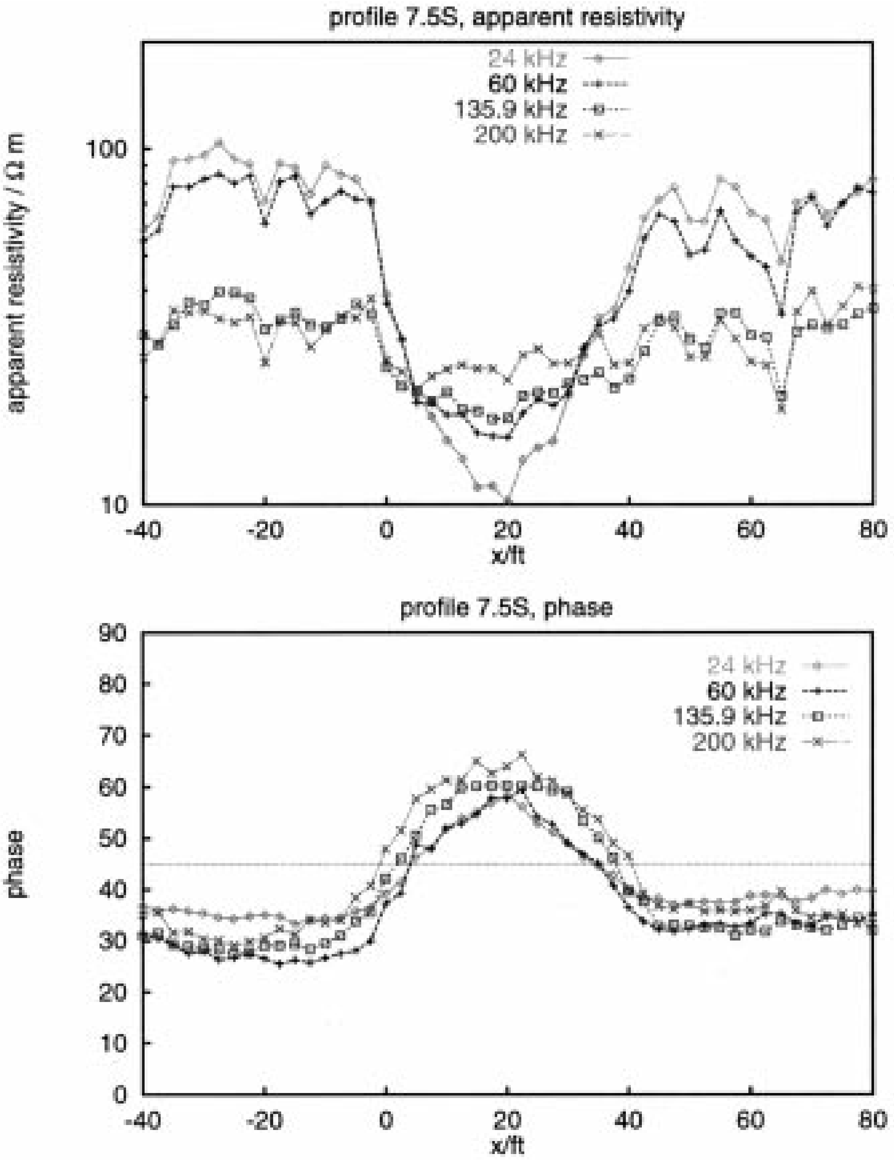
Figure 11. Resistivity and phase pseudosections for profile 7.5S at the Idaho National Engineering Laboratory Cold Test Pit (B-polarization mode) (modified after Pellerin and Alumbaugh, 1997).

of the data set is shown in Figure 13, where the highly conductive waste is clearly resolved beneath the poorly conducting top layer.

The lowest RMT frequency is limited to 10 kHz. If the target has a high conductivity, the bottom of it cannot always be determined. A combination of the Stratagem and RMT system (0.1–1 MHz) would be ideal for many environmental applications and groundwater exploration.

2.4. CAR-BORNE MEASUREMENTS

Although VLF and RMT techniques are relatively fast, even faster methods and techniques are necessary in environmental geophysics in order to survey a large area in a relatively short time. One of the newest developments in this area is a VLF instrument which allows the acquisition of data with the help of an antenna mounted behind a car. Figure 14 shows this instrument, developed at the Hydrogeological Institute of the University of Neuchâtel (Stiefelhagen, 1998).


profile 7.5S, apparent resistivity

profile 7.5S, phase

Figure 12. Apparent resistivity and phase of profile 7.5S at the Idaho National Engineering Laboratory Cold Test Pit (Tezkan et al., 1997).

The orientation of the magnetic coils is controlled automatically by another horizontal coil which is perpendicular to the primary field and adjustments coil orientation are continually made to keep it always in the direction of signal minimum.

The velocity of the car during the measurements is about 20 km/h. Components that are recorded continuously are ‘in phase’ and ‘out of phase’ of the transfer

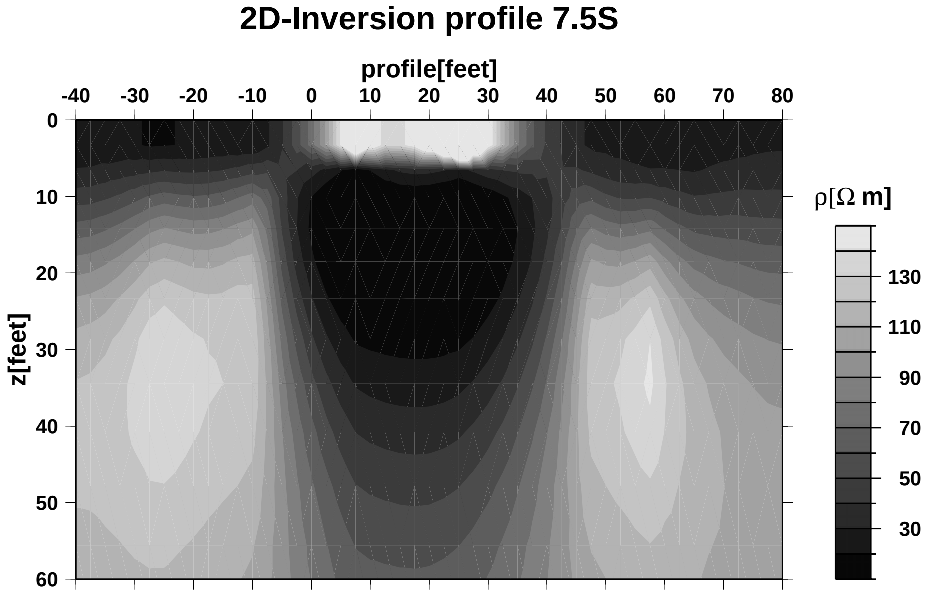


Figure 13. A 2D conductivity model obtained from the RMT profile along 7.5S at the Idaho National Engineering Laboratory Cold Test Pit (Tezkan et al., 1997).

function. Stiefelhagen (1998) applied this technique successfully to engineering problems (landslide, cavity detection) in Switzerland and for ground water investigation in Niger. Figure 15 demonstrates the out of phase measurements in Niger carried out with a car-borne VLF-instrument. Borehole locations are successfully derived from these measurements with the help of additional Slingram measurements, which are not shown here. In Figure 15 the locations of suggested boreholes according to these measurements are marked and the obtained ground water amount is indicated. The dry drilling was positioned at an extreme value of the VLF and Slingram data and the productive drilling was positioned in between to such extreme values. The quality of the data suffered from the ruggedness of the terrain and the errors of GPS measurements. A first statistical analysis of the data confirms, for example, the experiences of Palacky et al., 1981 about the geological situation of wide areas in Africa where productive drilling should be done in between extrema of corresponding VLF and Slingram data.

3. EM methods employing a magnetic dipole or loop source

The adaptions of horizontal loop EM methods are probably the most used geophysical techniques for contaminated site investigations. In these techniques the transmitter creates a time varying primary magnetic field (H_p) which induces currents in the subsurface. These in turn create a secondary magnetic field (H_s) which

Figure 14. Car with automatically oriented antenna fixed behind for car-borne VLF measurements (Stiefelhagen, 1998).

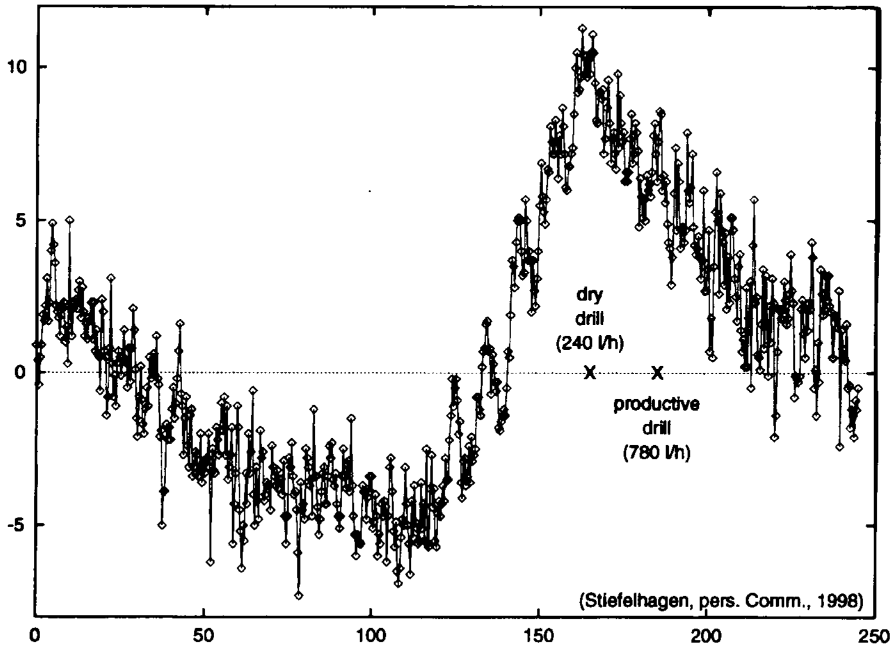


Figure 15. VLF data (out of phase component) on a profile for groundwater exploration in Niger. The frequency used was 18.3 kHz. Borehole locations are also marked (Stiefelhagen, 1998).

is measured by the receiver. The ‘Slingram’ method measures the ‘in phase’ and ‘quadrature phase’ components of the vertical magnetic field at several frequencies and is very effective in mapping faults and shear zones for groundwater prospecting. The Slingram method does not directly obtain the apparent conductivity. For low induction numbers, however, the ratio of the secondary (H_s) to the primary field (H_p) is proportional to the frequency, square of intercoil spacing (r) and terrain conductivity (σ) (McNeill, 1980). A fixed combination of coil distance and frequency can be used if the response parameter (Spies and Frischknecht, 1991)

$$Q = r\sqrt{\frac{\sigma\mu\omega}{2}} \tag{1}$$

is smaller than 1 for a wide range of conductivity (μ = permeability and ω = angular frequency). This is true if r is much smaller than the skin depth. For ground conductivities above 100 mS/m however, this condition is not valid and the readings will be erroneous. As shown by McNeil (1980), for low induction numbers the ratio of the secondary to the primary magnetic field is directly proportional to terrain conductivity. By measuring the quadrature component of H_s/H_p (in phase is assumed as negligibly small), the apparent conductivity can be obtained:

$$\sigma_a = \frac{4}{\mu_0\omega r^2}\left(\frac{H_s}{H_p}\right). \tag{2}$$

These are the basic conditions for the design of the Geonics EM31 and 34-3 systems, two of the most frequently used instruments in environmental geophysics, operating at discrete frequencies between 0.4 and 10 kHz. These instruments are usually used for lateral profiling. However, several combinations of horizontal and vertical modes and coil spacings can be used to perform vertical soundings.

The advantage of these systems lies in the fact that large areas can be surveyed rapidly and inexpensively, whereas their major disadvantage is that they give limited information about the variation of conductivity with depth (McNeil, 1990).

The EM31, which consists of two coplanar coils (intercoil spacing is 3.7 m) mounted on a rigid boom, can be operated by one person. The approximate depth of exploration is about 6 m.

The EM34-3 uses two circular coils, connected by cables to the electronics. Intercoil separations of 10, 20 and 40 m are allowed. The approximate depth of exploration varies between 6 and 30 m. The EM31 and EM34-3 instruments can be used in both horizontal and vertical dipole mode.

Figure 16 describes the vertical penetration and resolution of these systems in horizontal and vertical coil axis modes. The sensitivity falls off quickly at depths below one coil spacing. The vertical coil configuration penetrates a little deeper but is less sensitive to surface materials.

Recent progress in fast switching circuits also allows time domain EM (or transient EM: TEM) systems to be used for hydrogeological and environmental studies

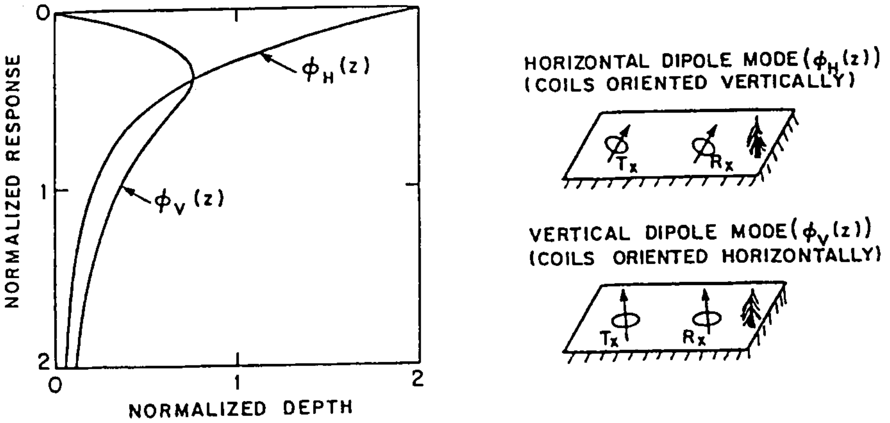


Figure 16. Terrain conductivity response as a function of depth for vertical and horizontal dipole models of the GEONICS EM-31 and EM-34. The horizontal axis is depth-normalized by the coil spacing and the vertical axis gives relative response (McNeill, 1980)

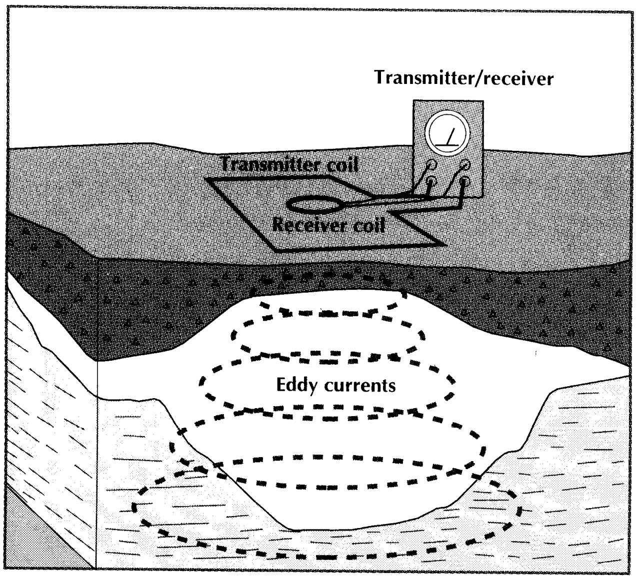


Figure 17. Diagrammatic representation of the transient electromagnetic method (Sørensen, 1996).

(Nobes, 1994). One possible field setup is shown in Figure 17. It demonstrates the smoke ring concept and interpretation method published by Eaton and Hohman (1989) The induced eddy currents will travel down quickly through electrically poorly conducting layers like sand and gravel, whereas they will be decelerated in good conductors, such as clay. By interpreting the decay of the measured magnetic field (transient) it is possible to determine the resistivity distribution in the subsurface below the measured area (Christensen and Sørensen, 1995).

TEM methods are commonly used for mineral exploration and groundwater prospecting. However, recent improvements in electronics allow faster transmitter turn-off times and therefore shallower soundings for environmental applications (Mauldin-Mayerle et al., 1998; Fainberg et al., 1998). Faster electronics also allow the acquisition of all three magnetic field components simultaneously, increasing the amount of information available for interpretation and modeling (Mauldin-Mayerle et al., 1998).

A new development in this area is the ‘Pulled Array Transient Electromagnetic Method’ (PATEM) (Sørensen, 1997), where a transmitter and a receiver coil system are towed with a speed of approximately 2 km/h along the profile lines while measuring. The transmitter system is optimized to transmit high currents with short turn off times in small coils of the order 2.5 × 2.5 m. The receiver coil system consists of a suspended horizontal coil with parallel amplifier channels with progressively increasing gain. With this method, the cost of the TEM field work is drastically reduced. The comparison of PATEM data with conventional PROTEM 47 data show an excellent agreement. (Sørensen, 1997).

For environmental (Tezkan et al., 1996; Greinwald et al., 1997) and groundwater studies (Fitterman and Stewart, 1986; Meju et al., 1998) Slingram mode and central loop mode are usually used. TEM data are less affected by lateral inhomogeneties in the earth and can also be interpreted by means of 2D and 3D conductivity models (Helwig, 1994). For many shallow environmental targets the minimum exploration depth obtainable from TEM data may be too large. In this case, a combination of TEM with DC resistivity or with RMT measurements is recommended. In the case of horizontal stratified earth the interpretation of the data can be carried out by 1D joint interpretation techniques (e.g., Harinarayana, 1998).

3.1. CASE HISTORIES

There exists a large number of case histories for the use of horizontal loop EM methods for environmental applications (see proceedings of EEGS, 95, 96, 97), mainly the exploration of lateral variations of waste sites (e.g., De Iaco et al., 1998) and the mapping of the extent of groundwater contamination by waste deposits (e.g., Walraevens et al., 1997). The results of these EM surveys can directly guide the placement of sampling and monitoring wells. Successful application of EM34 measurements are also reported for mapping lateral variations of conductivity beneath a planned deposit (Kolodziey, 1997) and for the investigation of a strand zone (Gourry and Watremez, 1998). EM31 measurements have often been applied to detect buried drums, tanks and pipelines by virtue of their high contrast in electrical properties. In the following section, two typical EM34 applications are demonstrated.

3.2. EM34-SURVEYS

The first case history is taken from Walraevens et al. (1997) and reports EM34 measurements on two waste sites in Belgium. The aim of this study is the investigation of groundwater pollution mainly caused by the presence of waste disposal sites. Figure 18 shows contours of the observed apparent conductivity for a coil spacing of 10 m in horizontal dipole mode. The unpolluted area shows a terrain conductivity mostly below 20 mS/m. The position of the triangular waste deposit is clearly expressed by a high conductivity peak. The position of the rectangular waste disposal does not correspond to a peak in the apparent terrain conductivity. However, a high conductivity anomaly was also detected outside the waste site. The contamination plume has migrated with the groundwater towards the southwest and is now concentrated along a lane bordered by a brook which is draining groundwater flow (Walraevens et al., 1997). The responses for three coil separations used during the measurements along the lane (see Figure 18) have been compared with each other in Figure 19. The anomaly is evident for all coil spacings, indicating that the pollution occurs in the lower and upper aquifer in this region. The presence of pollution has been confirmed by well loggings.

The next EM34 case study demonstrated in Figure 20 depicts the contamination emanating from a municipal landfill in Brazil (Greenhouse *et al.*, 1989). EM34 measurements were carried out at each marked point. The contours define a high conductivity plume which clearly originates from the landfill and intersects a well at a farmhouse 200 m away (Greenhouse et al., 1989).

In general, it is not easy to interpret the observed conductivity anomaly outside the waste as a contamination plume. The same anomaly can also, for example, be interpreted as clay lenses. Therefore, non-EM methods (e.g., seismics) are sometimes able to help in solving the problem (Lindler et al., 1993). In the case histories discussed in this paper the conductivity anomalies were confirmed by contaminated drilling samples.

3.3. TEM-SURVEY

In addition to the detection of polluted areas at relatively large depths and the delineation of the bottom of deep waste deposits, the TEM method has proved to be very efficient in mapping the depth of good conducting tertiary clays forming the sides and the bottom of the aquifer.

Nowadays, groundwater prospecting emphasizes the investigation of deeper-lying aquifers, because the uppermost aquifer is often affected by pollution, especially in the industrial countries. Sometimes deeper aquifers are composed of quaternary sand and gravel formations in tertiary valleys in the clays. Many hydrogeophysical investigations are carried out to look for such buried valleys which are invisible from the surface (Christensen and Sørensen, 1995).

Many more TEM case histories have been published, especially for groundwater contamination (e.g., Fitterman and Stewart, 1986; Goldman et al., 1991).

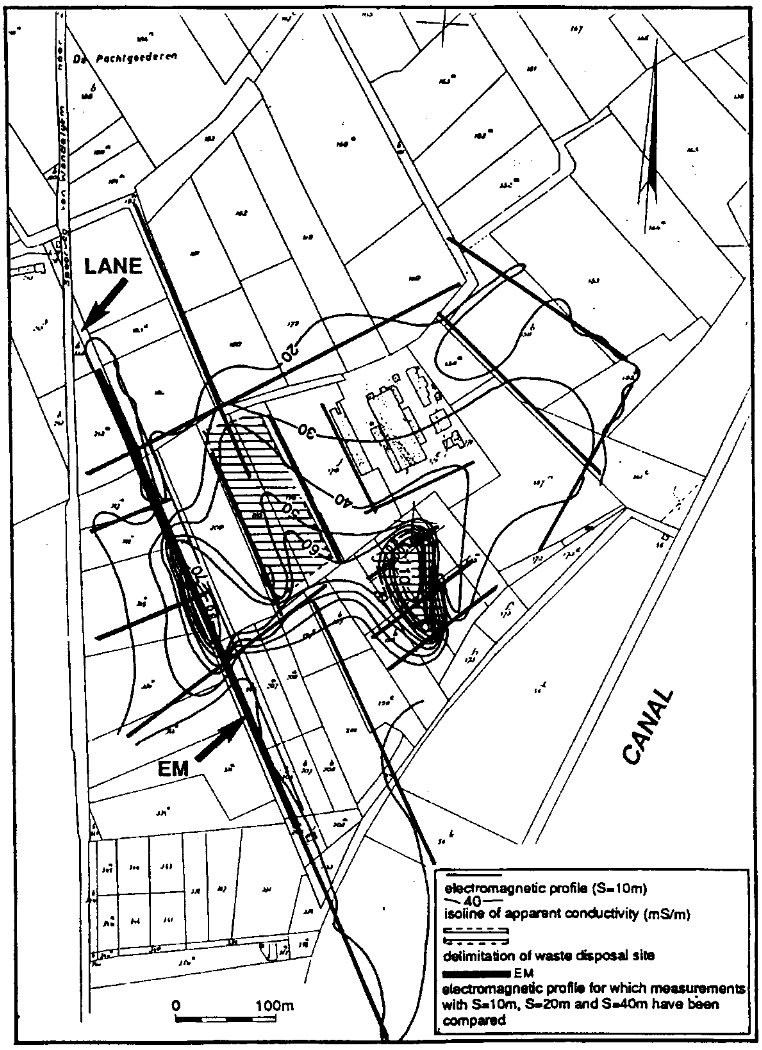


Figure 18. Contours of apparent conductivity for EM34 measurements with an intercoil spacing of 10 m at two waste sites in Belgium (Walraevens et al., 1997).

In recent years, TEM has been introduced in connection with the mapping of larger structural formations and has provided extremely good results in Denmark (Christensen and Sørensen, 1995), so that these EM methods are well known and accepted by local and regional authorities. The map in Figure 21 shows the depth to a well conductive tertiary clay layer derived from 1D-interpretations of 1500 TEM soundings (Sørensen, 1996). The high data density produces a detailed and coherent map of interconnections between the pre-quaternary valleys. Such a map is crucial for the interpretation of the aquifers in this area.

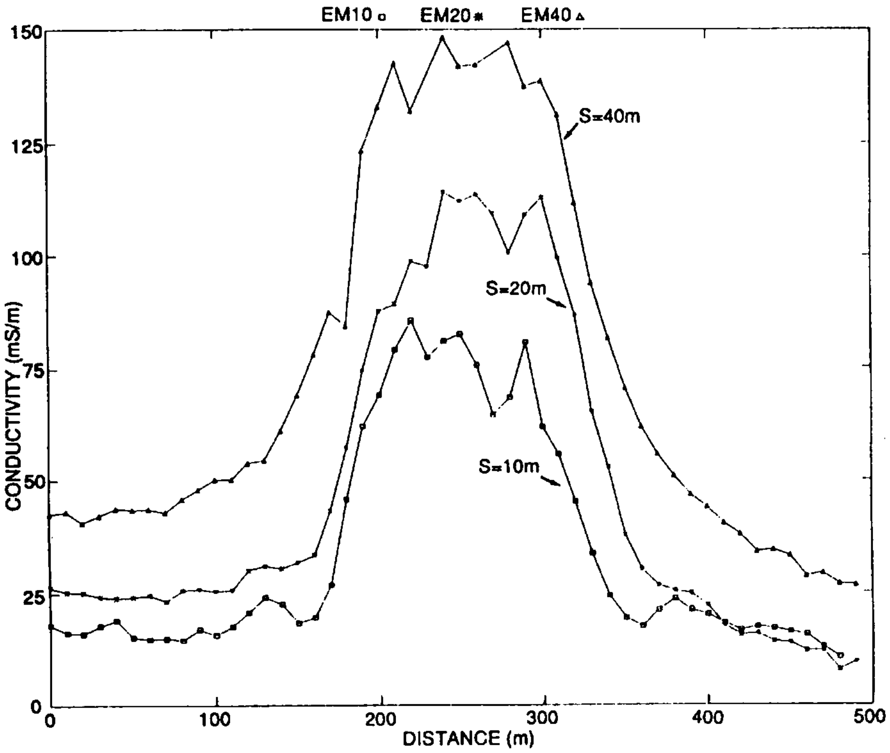


Figure 19. EM34 measurements with intercoil spacing of 10, 20 and 40 m along the lane indicated in Figure 19.

4. Conclusions

As demonstrated, electromagnetic techniques can be applied successfully to environmental problems. They can, for example, delineate buried waste and characterize the surrounding geology. Some EM case histories of the detection of contaminant plumes give encouraging results. Sometimes a combination of different techniques (including DC resistivity) is necessary for a successful application.

The interpretation of the impedance methods (RMT, CSAMT) is highly developed. However, due to the limited frequency range of existing EM instruments used for shallow applications (e.g., VLF-R, RMT), it is sometimes difficult to get information beneath a highly conductive target. The development of an instrument operating from several Hz to 100 MHz is a future task. Many efforts were made to interpret the observed EM data by multidimensional conductivity models and to derive depth information. The successful interpretation of RMT data by 2D inversion techniques and 3D modeling of VLF data are the best examples of these. The TEM measurements for the mapping of aquifers in Denmark show particularly the acceptance of geophysics (EM techniques) by local and regional authorities and enable confidence to be placed in future investigations.

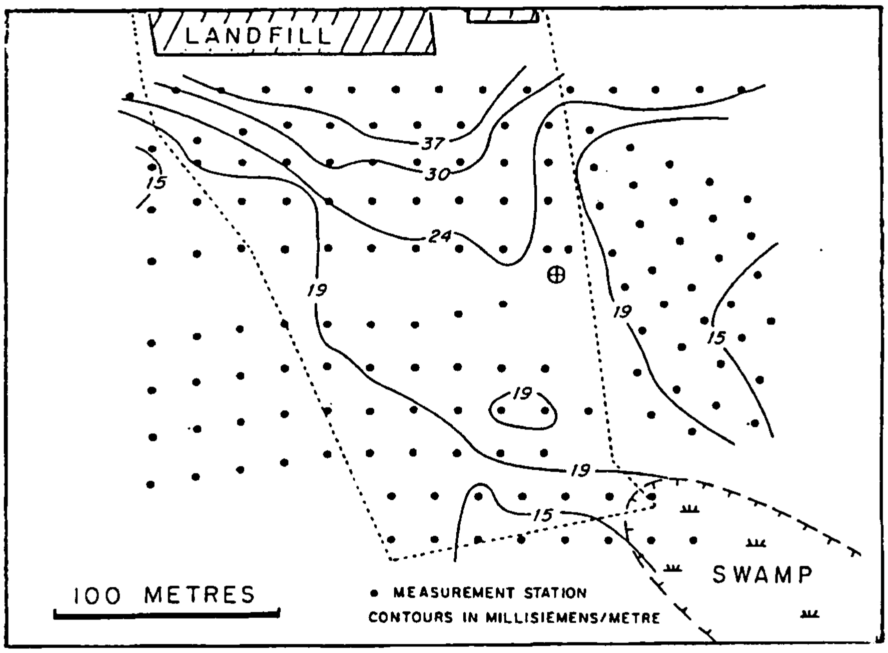


Figure 20. An EM34 survey near Novo Horizonte, Brazil. Leachate from a landfill at the top of the diagram moves towards discharge in a swamp at lower right, passing under a farmhouse and contaminating its well. Contours are in mS/m. (Greenhouse et al., 1989)

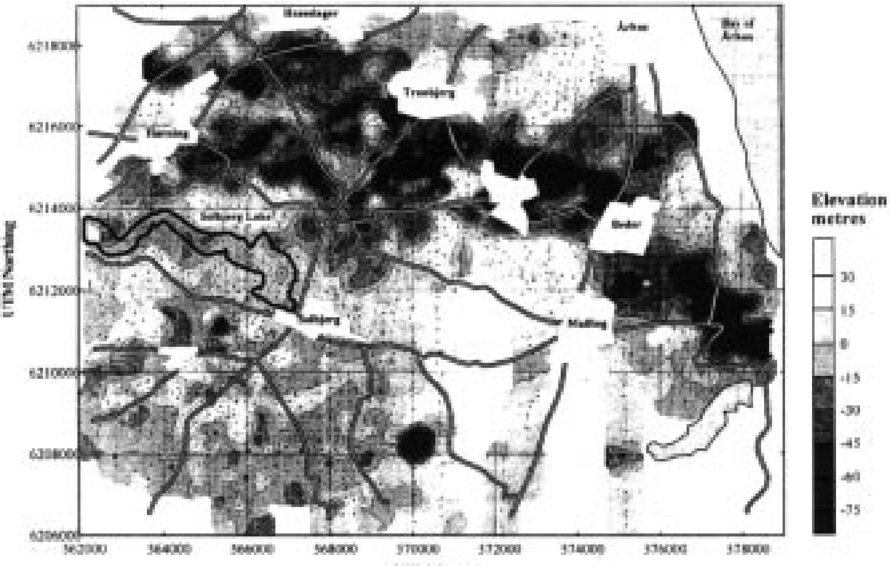


Figure 21. Elevation of a conductive tertiary clay layer based on interpretations of TEM soundings in the area of Århus, Denmark. The tertiary clay basement is relatively flat around Solbjerg and a deep pronounced valley cuts down into the basement at Beder and Tranbjerg (Sørensen, 1996).

New EM instruments developed in the last years allow the surveying of a large area in short time periods necessary in environmental applications. The VLF instrument developed at the University of Neuchâtel and the PATEM instrument developed in the University of Århus allow measurements by car and by a towed system respectively. There is also a clear tendency to build EM systems for quick measurements.

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References

Alumbaugh, D.L. and Morrison, H.F.: 1995, ‘Monitoring subsurface changes over time with crosswell electromagnetic tomography’, *Geophysical Prospecting* **43**(7), 873–902.

Baum, A.: 1998, Radiomagnetotellurische (RMT-) und Georadar-Messungen zur Erkundung der Reste einer durch Luftbild im Untergrund vermuteten römischen villa rustica im Worringer Bruch bei Köln, Diplomarbeit, Institut für Geophysik und Meteorologie, Universität zu Köln.

Beamish, D.: 1998, ‘Three-dimensional modelling of VLF data’, *Journal of Applied Geophysics* **39**(2), 63–76.

Ben Miloud, K.: 1986, Geophysical mapping of the subsurface at a landfill site near North Bay, Ontario, M.Sc. Prog., Dept. of Earth Sciences, The University of Waterloo, 68 pp.

Berktold, A., Schleicher, F., Strobl, P., Mathes, P., and Durlesser, H.: 1992, ‘Möglichkeiten und Grenzen des VLF-R Verfahrens im Ingenieur/Umweltbereich’, *Münchener Geophys. Mitteilungen* **6**, 65–88.

Buselli, G., Barber, C., Davis, G.B., and Salama, R.B.: 1990, ‘Detection of ground water contamination on near waste disposal sites with transient electromagnetic and electrical methods’, in S.H. Ward (ed.), *Geotechnical and Environmental Geophysics* **2**, 27–39.

Butler, D.K., Sjostrom, K.J., and Llopis, L.J.: 1997, ‘Selected short stories on novel applications of nearsurface geophysics’, *Leading Edge* **16**, 1593–1600.

Cagniard, L.: 1953, ‘Basic theory of the Magneto-Telluric Method of geophysical prospecting’, *Geophysics* **18**, 605–645.

Christensen, N.B. and Sørensen, K.: 1995, ‘New strategies for surface and borehole electromagnetic methods in hydrogeophysical investigations, extended abstract, proceedings’, *EEGS*, Torino, 356–359.

Constable, S.C., Parker R.L., and Constable, C.G.: 1987, ‘Occam’s inversion: A practical algorithm for generating smooth models from electromagnetic sounding data’, *Geophysics* **52**(3), 289–300.

De Iaco, R., Horstmeyer, H., Boerner, D.E., Lehmann, F., and Green, A.: 1998, ‘Georadar, electromagnetic and magnetic studies of a landfill and its host sediments, proceedings’, *EEGS*, Barcelona, 103–107.

Dupis, A. and Choquier, A.: 1996, ‘How electrostatic was introduced in subsurface geophysics, proceedings’, *EEGS*, Nantes, 125–128.

Eaton, P.A. and Hohmann, G.W.: 1989, ‘A rapid inversion technique for transient electromagnetic soundings, *Physics of the Earth and Planetary Interiors* **53**, 384–404.

Fainberg, E.B., Barsukov, P.O., and Khabensky, E.O.: 1998, ‘An application of modern TEM technology for environmental investigations, proceedings’, *EEGS*, Barcelona, 805–809.

Fitterman, D.V. and Stewart, M.T.: 1986, ‘Transient electromagnetic sounding for groundwater’, *Geophysics* **51**, 995–1005.

Frischknecht, F.C., Labson, V.F., Spies, B.R., and Anderson, W.L.: 1991, ‘Profiling methods using small sources’, in M.N. Nabighian (ed.), *Electromagnetic Methods in Applied Geophysics*, **2**, SEG, 105–270.

Goldman, M., Gilard, D., Ronen, A. and Melloul, A.: 1991, ‘Mapping of seawater intrusion into the coastal aquifer of Israel by the time domain electromagnetic method’, *Geoexploration* **28**, 153–174.

Goldstein, N.E., Benson, S.M., and Alumbaugh, D.: 1990, ‘Saline groundwater plume mapping with electromagnetics’, in H. Stanley Ward (ed.), *Geotechnical and Environmental Geophysics*, **2**, Society of Exploration Geophysicists, 17–25.

Gourry, J.C. and Watremez, P.: 1998, ‘Geophysical imagery of strand zone, proceedings’, *EEGS*, Barcelona, 155–159.

Greenhouse, J.P., Monier-Williams, M.E., Ellert, N., and Slaine, D.D.: 1989, ‘Geophysical methods in groundwater contamination studies’, in *Proceedings of Exploration 87*, Special Volume **3**, 666–677.

Greinwald, S., Illich, B., and Schaumann, G.: 1997, ‘Transientelektromagnetik’, in K. Knödel, H. Krummel, G. Lange (eds.), *Handbuch zur Erkundung des Untergrundes von Deponien und Altlasten*, Band **3**, Geophysik, Springer-Verlag, 305–326.

Harinarayana, T.: 1998, Combination of EM and DC measurements for upper crustal studies, review paper, proceedings, 14th workshop on electromagnetic induction in the earth, 193–214.

Helwig, S.L.: 1994, Auswertung transient elektromagnetischer Meßdaten aus dem Makhtesh Ramon, Israel unter Benutzung rotationssymmetrischer Modelle, Diplomarbeit, Institut für Geophysik und Meteorologie, Universität zu Köln.

Hollier-Larousse, R., Lagabrielle, R., and Levillain, J.P.: 1994, ‘Utilisation de la radiomagnétotellurique pour la reconnaissance en site aquatique’, *Journal of Applied Geophysics* **31**, 72–84.

Kaikkonen, D. and Sharma, S.P.: 1998, ‘2-D nonlinear joint inversion of VLF and VLF-R data using simulated annealing’, *Journal of Applied Geophysics* **39**(3), 155–176.

Kampmeier, U.: 1992, ‘VLF-R-Messungen auf Altlasten am Beispiel der rekultivierten Altlast “Am Hexenberg” in Köln–Ossendorf’, Diplomarbeit, Institut für Geophysik und Meteorologie, Universität zu Köln.

Kaufman, A.A. and Keller, G.V.: 1983, ‘Frequency and transient soundings’, *Methods in Geochemistry and Geophysics*, Bd. 16, Elsevier.

Kolodziey, A.W.: 1997, ‘EM38, EM31, EM34’, in K. Knödel, H. Krummel, G. Lange (eds.): *Handbuch zur Erkundung des Untergrundes von Deponien und Altlasten*, Band **3**, Geophysik, Springer-Verlag, 257–267.

Labson, V.F. and Becker, A.: 1987, ‘Natural-field and very low-frequency tipper profile interpretation of contacts’, *Geophysics*, **52**(12), 1697–1707.

Lagabrielle, R.: 1986, ‘Les bases de la radio-magnétotellurique, *Revue de l’industrie minérale, mines et carrières*, Oct.: 373–384.

Lindner, H., Lorenz, K., Seidemann, O., and Steiner, G.: 1993, Erkundung von Altstandorten, Hermsdorf/Türingen, *Ergebnisbericht*, Geophysik GGD (Leipzig) im Auftrag der Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

Lines, L.R. (ed.): 1988, 'Inversion of geophysical data', Society of Exploration Geophysicists.

Mackie, R.L., Smith, J.T., and Madden, T.R.: 1994, 'Three-dimensional electromagnetic models using finite difference equations: The magnetotelluric example', *Radio Science* **29**, 923–935.

Madden, R. and Mackie, R.: 1989, 'Three-dimensional magnetotelluric modeling and inversion', *Proceedings of the IEEE (77)*(2), 318–333.

Mauldin-Mayerle, C.M., Carlson, N.R., and Zonge, K.L.: 1998, 'Environmental applications of high resolution TEM methods, proceedings', *EEGS*, Barcelona, 829–833.

McNeill, J.D.: 1980, 'Electromagnetic terrain conductivity measurement at low induction numbers', Geonics. Ltd., *Technical Note TN-6*.

McNeill, J.D.: 1990, 'Use of electromagnetic methods for groundwater studies', in S.H. Ward (ed.), *Geotechnical and Environmental Geophysics*, **1**, Society of Exploration Geophysicists, 191–218.

McNeill, J.D. and Labson, V.F., 1991, 'Geological mapping using VLF radio fields', in M.N. Nabighian (ed.), *Electromagnetic Methods in Applied Geophysics*, **3**, SEG, 521–640.

Meju, M.A., Fontes, S.L., Oliviera, M.F.B., Lima, J.P.R., Ulugergerli, E.U., and Carrasquilla, A.: 1999, 'Regional aquifer mapping using combined VES-TEM-AMT/EMAP methods in the semiarid eastern margin of Parnaiba-Basin, Brazil', *Geophysics*, in print.

Müller, I.: 1983, 'Anisotropic properties of rocks detected with electromagnetic VLF (Very Low Frequency)', Int.-Symp. Field Measurements in Geomechanics, Zürich, Sept. 1983, Spec. Publ., 273–282.

Nabighian, M.N., (ed.): 1991, 'Electromagnetic methods in applied geophysics', 1: Theory, Society of Exploration Geophysicists.

Nobes, D.C.: 1994, 'Troubled waters: environmental applications of electrical and electromagnetic methods, extended abstract, 12th workshop on electromagnetic induction in the earth', Brest, 125–158.

Nobes, D.C.: 1996, 'Troubled waters: environmental applications of electrical and electromagnetic methods, *Surveys in Geophysics*, **17**, 393–454.

Ogilvy, R.D., Meldum, P.I., and Nissen, J.: 1997, 'Quantitative mapping of waste coal for deposits by EM conductivity and VLF resistivity surveys, extended abstract, proceedings', *EEGS*, Århus, 45–47.

Ogilvy, R.D., Beamish, D., Meldrum, P.I., and Mess, R.: 1998, 'Non-invasive geophysical mapping of chemical waste deposit and flow paths, extended abstract, proceedings', *EEGS*, Barcelona, 115–119.

Palacky, G.J., Ritsema, I.L., and De Jong, S.J.: 1981, 'Electromagnetic prospecting for groundwater in precambrian terrains in the Republic of Upper Volta', *Geophysical Prospecting* **29**, 932–955.

Pellerin, L. and Alumbaugh, D.L.: 1997, 'Tools for electromagnetic investigation of the shallow subsurface', *Leading Edge* **16**, 1631–1641.

Pellerin, L., Alumbaugh, D.L., and Pfeifer, C.M.: 1997, 'The electromagnetic integrated demonstration at the Idaho National Engineering Laboratory Cold Test Pit, proceedings', *SAGEEP*, Reno, 725–734.

Recher, S.: 1998, 'Untersuchung der Anwendbarkeit der Radiomagnetotellurik-Methode auf die Lokalisierung von kontaminiertem Boden, Diplomarbeit', Institut für Geophysik und Meteorologie, Universität zu Köln.

Recher, S., Tezkan, B., and Hördt, A.: 1998, 'Detection of hydrocarbon contaminated soil with radiomagnetotellurics, extended abstract, proceedings', *EEGS*, Barcelona, 57–61.

Rodi, W.L. and Mackie, R.L.: 1999, 'Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion', *Geophysics*, submitted.

Sandberg, S.K.: 1987, 'Transient electromagnetic data proceedings applied to a saltwater-intruded aquifer in central New Jersey, extended abstract', *SEG* **57**, 88–91.

Schröder, R.: 1994, ‘Gültigkeitsbereich der “Ebenen-Wellen-Theorie” unter Berücksichtigung der Verschiebungsströme bezogen auf die geoelektrischen Meßmethoden VLF-R, (LF-R), CSAMT und Short Wave Loop-Loop, Diplomarbeit’, Institut für Geophysik und Meteorologie, Universität zu Köln, 116 pp.

Schwinn, W. and Tezkan, B.: 1997, ‘1D joint inversion of radiomagnetotelluric (RMT) and transient electromagnetic (TEM) data; an application for groundwater prospection in Denmark, extended abstract, proceedings’, *EEGS*, Århus, 221–224.

Smith, J.T. and Booker, J.R.: 1991, ‘Rapid inversion of two and three dimensional magnetotelluric data, *Journal of Geophysical Research*, **96**, 3905–3922.

Song, Y., Morrison, H.F., and Lee, K.H.: 1997, ‘High frequency electromagnetic impedance for subsurface imaging, extended abstract, proceedings’, *SAGEEP*, Reno, 761–772.

Sørensen, K.I.: 1996, ‘The location of dense transient soundings in location of buried valley aquifers, proceedings’, *EEGS*, Nantes, 86–89.

Sørensen, K.I.: 1997, ‘The pulled array transient electromagnetic method, proceedings’, *EEGS*, Århus, 135–138.

Spies, B.R. and Frischknecht, F.C.: 1991, ‘Electromagnetic sounding’, in M.N. Nabighian (ed.), *Electromagnetic Methods in Applied Geophysics*, **2**, part A, SEG, 285–425.

Stiefelhagen, W.: 1998, ‘Radiofrequency electromagnetics (RF-EM): Kontinuierlich messendes Breitband VLF, erweitert auf hydrogeologische Problemstellungen’, Ph.D. thesis, University of Neuchâtel.

Tezkan, B., Goldman, M., Greinwald, S., Hördt, A., Müller, I., Neubauer, F.M., and Zacher, G.: 1996, ‘A joint application of radiomagnetotellurics and transient electromagnetics to the investigation of a waste deposit in Cologne (Germany)’, *Journal of Applied Geophysics* **34**, 199–212.

Tezkan, B., Dautel, S., and Pellerin, L.: 1997, ‘A radiomagnetotelluric survey at the Idaho National Engineering Laboratory Cold Test Pit, extended abstract, proceedings’, *EEGS*, Århus, 383–386.

Turberg, P., Müller, I., and Flury, F.: 1994, ‘Hydrogeological investigation of porous environments by radiomagnetotelluric-resistivity (RMT-R, 12–240 kHz), *Journal of Applied Geophysics* **31**, 133–143.

Vanhala, P.: 1997, ‘Mapping oil contaminated sand and till with the spectral induced polarization (SIP) method’, *Geophysical Prospecting* **45**, 303–326.

Vozoff, K.: 1991, ‘The magnetotelluric method’, in M.N. Nabighian (ed.), *Electromagnetic Methods in Applied Geophysics* **3**, SEG, 641–711.

Walraevens, K., Beeuwsaert, E., and De Breuck, W.: 1997, ‘Geophysical methods for prospecting industrial pollution; a case study, *European Journal of Environmental and Engineering Geophysics* **2**, 95–109.

Weidelt, P.: 1997, Grundlagen der Geoelektrik, in K. Knödel, H. Krümmel and G. Lange (eds.), *Handbuch zur Erkundung des Untergrundes von Deponien und Altlasten*, Band **3**, Geophysik, Springer-Verlag, 65–83.

Zacher, G.: 1992, ‘Hochfrequente Elektromagnetik auf Altlasten’, *DGG-Kolloquium ‘Elektromagnetische Tiefenforschung’ Borkheide*, G.F.Z. Potsdam, pp. 357–363.

Zacher, G., Tezkan, B., Neubauer, F.M., Hördt, A., and Müller, I.: 1996a, ‘Radiomagnetotellurics: a powerful tool for waste-site exploration’, *European Journal of Environmental and Engineering Geophysics* **1**, 139–159.

Zacher, G., Tezkan, B., Neubauer, F.M., and Zilkens, J.: 1996b, ‘Application of radiomagnetotellurics to archaeology – reconstruction of a monastery in volkenroda (Thuringia), extended abstract’, *EEGS*, Nantes, 212–215.

Zhdanov, M.S. and Keller, G.V.: 1994, *The Geoelectrical Methods in Geophysical Exploration*, Elsevier, Amsterdam, 873 pp.

Zhdanov, M.S., Traynin, P., and Portniaguine, O.: 1995a, ‘Resistivity imaging by time domain electromagnetic migration’, *Exploration Geophysics*, **26**, 173–178.

Zhdanov, M.S., Traynin, P., Portniaguine, O., and McLean, D.: 1995b, ‘Time domain electromagnetic migration in INEL RWMC Cold Test Pit characterization’, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, *SAGEEP 1995*, Orlando, 919–924.

Zhdanov, M.S. and Portniaguine, O.: 1997, ‘Time-domain electromagnetic migration in the solution of inverse problems, *Geophys. J. Int.* **131**, 293–309.