KMS Technologies – KJT Enterprises Inc.

Chapter 1
Introduction

from

Strack, K.-M., 1992, ***Exploration with deep transient electromagnetic:*** Elsevier, 373 pp.

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A significant amount of research in electromagnetic geophysics has been done around the globe because electromagnetic techniques offer a unique way of determining the resistivity at depth from the surface. The resistivity can be correlated with different pore fluids and porosity and thus aid the geological interpretation.

The intention of this book is to give the novice a comprehensive practical review of the subject as well as bringing him to the present state-of-the-art of the technique as it is used in the exploration environment. The expert should be able to use this book to design his own depth sounding system and carry out field measurements.

To demonstrate the usefulness of deep transient electromagnetics, case histories are included in most chapters. These case histories originate from many different parts of the world as shown in figure 1.1.

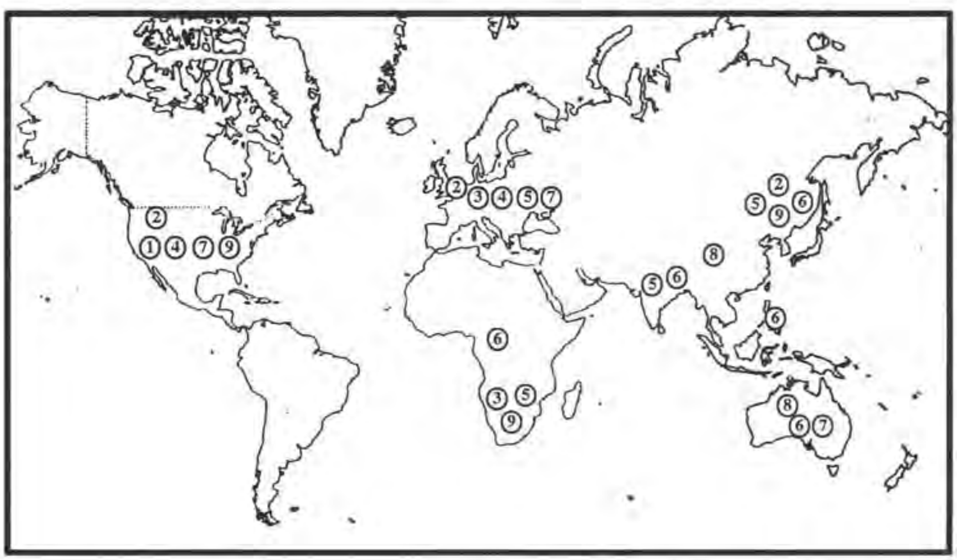

Fig. 1.1: Location of the case histories shown in this book. The numbers represent the chapters where the case histories can be found.

The concept of the text follows the general background on how resistivities can be related to real geology and where the uncertainties lie in the resistivity determination.

From the basic physical background which starts with Maxwell's equations, the reader will be guided as to how to convert the field data to apparent resistivities. The latter give a representation of the changes in resistivity with time/depth. When acquiring real field data, one must overcome a significant signal–to–noise problem. This can be achieved using data processing techniques as described in chapter 3. The results of the data processing are smooth apparent resistivity curves as theoretically required. They can be interpreted using a class of inversion methods and in some selected cases even 3–D numerical modeling.

Before describing the deep transient electromagnetic sounding method, the framework in exploration geophysics is given. Further, the interpreter must understand the limitation of electrical resistivity determination.

THE ROLE OF ELECTROMAGNETIC METHODS IN EXPLORATION

In search for new energy resources, exploration methods alternative to reflection seismics have become increasingly important. The increase in *nonseismic methods* on the world scene is mainly due to the fact that new oil fields are now being found in environments where the quality of the seismic data is not adequate. During the years 1983 – 1987 seven giant oil fields have been found. Three of them (Brazil, Colombia, North Yemen) are in areas where electromagnetic techniques have the potential to delineate new targets. Many different techniques are being applied to either improve the seismic data or to solve the exploration problem by tackling it from a different angle. Since the oil industry predominantly uses seismic methods, the techniques are sometimes called *nonseismic methods*. *Nonseismic methods* can be classified into five categories:

- *Gravity* – Land, marine, helicopter, airborne, and borehole gravity respond to density contrasts of the geologic structure. Gravity methods are well established in the exploration industry. They are cost–effective and their general use for specific exploration problems is well understood.
- *Magnetics* – Land, marine, airborne magnetic measurements are a standard tool for the exploration industry, since the methods respond to susceptibility contrasts. Their use is similarly well understood as it is for gravity. In oil exploration magnetic techniques are slightly less used, in mineral exploration they are more frequently used than gravity.
- *Electromagnetics* – Electromagnetic (EM) methods show in general less ambiguity than the above mentioned potential field techniques. However, they are a lot more difficult to understand than most geophysical techniques. This is mainly due to the different behavior of the electromagnetic induced currents for different techniques. Land, airborne and borehole measurements are available to

the explorationist. Borehole measurements are routinely done in most exploration wells. Airborne electromagnetics (AEM) is a routine technique for mineral and groundwater exploration (Palacky, 1983). Oil exploration has not used the technique as much as it could, which is mainly due to the limited depth of investigation. Land techniques, although frequently used around the world, are still exotic and only the past decade has seen some more routine applications of magnetotellurics. There is an increased need for EM techniques, but the instrumentation and integration with other geophysical techniques will take time. Many techniques are presently being evaluated; among them the most promising are the transient EM technique because of its simplicity in operation and similarity in data processing techniques to the seismic method. This method has also the advantage of having the highest coupling of all EM techniques of the measured signal to the resistivity structure of the subsurface. For these reasons we have chosen the transient electromagnetic technique as our research emphasis.

- *DC-resistivity* – In rare instances direct current (DC) resistivity methods are used for hydrocarbon exploration. This is mainly, because the methods integrate over a very large volume using large current electrode spacings when the depth penetration of 3 – 4 km is required. Resulting from this large volume of integration is the lack of detailed resolution. Thus, if DC-resistivity is applied for oil exploration, it is only being used for large scale reconnaissance. The DC-resistivity technique employed is mostly a mapping technique, the dipole-dipole mapping.

- *Induced polarization* – During the past three decades induced polarization methods have been applied for oil exploration. In some cases the technique was successful (Oehler and Sternberg, 1984) and in others not. A serious drawback of the method has been that many different cultural effects (such as pipelines etc.) can produce induced polarization responses similar to subsurface mineralization. The interest in the technique has faded during the past years even though not completely disappeared.

Among the large variety of exploration problems are some which are particularly suited for electromagnetic techniques. In the following, those applications have been selected for which case histories can be found literature. Among them are:

- *permafrost* – velocity and thickness variations in permafrost layers can cause false structural interpretation of anticlines or synclines if based on seismic alone. In order to obtain reliable static corrections, transient electromagnetic techniques have been applied (Rozenberg et al, 1985).

- *oil-water contact* – many hydrocarbon producing fields contain highly saline connate water or brine, which is underneath or at the edge of the hydrocarbon deposit. The seismic velocities do not always change very much between the oil and brine saturated reservoirs, whereas the electrical conductivity changes greatly. Transient electromagnetic methods have been successfully applied to this type of exploration/production problem in the USSR and USA (Spies, 1983; Earth Technology Corporation, 1985).

- *volcanic cover* – exhibits scattering of the seismic waves, especially at high frequencies. Also, very large impedance contrasts cause reverberation of the seismic waves. Many different *nonseismic techniques* have been applied to the volcanic exploration problem. Among them are gravity, magnetics and electromagnetics (Prieto et al, 1985; Keller et al, 1984).

- *overthrusting, diapirism* – causes scattering in the seismic waves. Many different *nonseismic* techniques have been applied to this problem including surface gravity, borehole gravity, and electromagnetics. The results are encouraging but not conclusive.

- *deeply weathered overburden* – causes in some instances severe problems with the static corrections in reflection seismics. Almost all *nonseismic* geophysical techniques have been applied to this problem which is encountered in many different varieties (Christopherson, 1990).

- *extreme topography in connection with any of the above* – again causes problems with the seismic static corrections. *Nonseismic* methods can be used effectively as reconnaissance tools in this case, since they integrate over a larger volume.

- *mapping of porosity variations* – in areas where good seismic data exist, but porosity variation can not be defined from the seismic, electromagnetic methods can sometimes be very helpful. Even if porosity variations are interpreted from the seismic data (i.e. using shear wave; Robertson, 1987), electromagnetic techniques can give complementary information. For instance, once a well log and seismic data are available, one can fix the structure for the inversion from the seismic interpretation, use the well log for deriving a calibration curve for resistivity and porosity (or sand–to–shale ratio) and then invert the data for resistivities. These can then be converted to porosity maps to help the explorationist interpret the geology (Strack et al, 1989b). This will probably be the most important future application, since approximately 40 % of the world oil reserves are located in carbonates, where seismic methods do not yield enough information to interpret porosities.

- *deep crustal studies* – in order to investigate the earth crust, deep seismic profiles are being measured around the world. In many instances a low velocity zone appears within the upper 10 kilometers of the section. Sometimes this low velocity zone can be correlated with a low resistivity anomaly

(Strack et al, 1990; De Beer et al, 1991). Long Offset Transient ElectroMagnetics (LOTEM) can be effective in that particular depth range in defining the resistivity structure.

- *massive sulphide mineralization* – most base metals occur in nature as sulphide minerals which are electrically conductive, particularly when massive. Direct exploration for base metal sulphide ores has been the main impetus for the development of electromagnetic techniques, including TEM.

HISTORICAL DEVELOPMENT OF LOTEM

Before starting with the main topic, the *deep transient electromagnetic method*, the history of transient EM methods is given and categorized as needed for the context of this book. A detailed description of the theoretical background can be found in a recent monograph by Kaufman and Keller (1983). The beginning of direct current (DC) geoelectric measurement was marked by the early work of Wenner (1912) and Schlumberger (1922), whereas the alternating current applications are documented by a German patent (322040, 1913, assigned to K. Schilowsky) and an American patent (U.S. patent 1211197, assigned to H. Conklin). The first depth soundings were conducted by L. W. Blau (U.S. patent 1911137, 1933) who used an electric dipole as transmitter. Through the grounded wire he injected a pulse into the subsurface and measured the electric field changes.

For mining applications Wait (1951a, b) published the basic theory for a transient prospecting method followed by a patent (Wait, 1956; US patent 2735980) assigned to Newmont Mining Corp. (Nabighian and Macnae, 1991). Newmont subsequently developed and successfully applied several systems (Dolan, 1970). The first airborne TEM system (INPUT) was developed by Barringer in 1958 (Barringer, 1962). In the same year, research started in the Soviet Union at the Moscow Institute of Geological Prospecting where their first transient EM field system MPPO-1 was developed. In 1968 a Soviet patent of the MPPO system appeared in Australia (Australian patent 415022 assigned to Vsesojuzny Nauchno-Issledovatelsky Institut Metodikii Tekhniki Razvedki), which was at that time a promising frontier for transient electromagnetic technique because TEM could penetrate through the Australian conductive overburden. In 1973, Lazenby and Wondergem (US patent 3737768) patented an "Apparatus for remote detection of conducting bodies utilizing electromagnetic waveforms exhibiting abrupt discontinuities." The Canadian transient EM systems were mainly directed towards the search for ore bodies. In Australia, Buselli from the CSIRO developed the first computerized transient EM system and patented in 1981 (US patent 4247821) his SIROTEM development with emphasis on the noise compensation of the system. Most transient EM related patents between 1960 and 1980 were directed towards mineral exploration. Rocroi patented 1985 the Transiel system (US patent 4535293 and related French patents 1979, 7917766 and 1980, 8003159) of CGG which was mainly used for measurements of the induced polarization. Interpretation was stated in his patent application to be only qualitative. Since the system was adopted to seismic contractor needs, several similarities to seismics can already be seen in their patent application which covers a tremendous range of applications and hardware configuration. Presently, only a new generation of field hardware using new concepts would be patentable.

To date, not much has changed from the original field techniques. The improvements – apart from the hardware and acquisition side – have mainly been made in understanding the physics and how to transform the observation to information which helps the geologist. The problem with the EM methods in early days was the misconception that the signals measured were caused by reflections of the electromagnetic waves. As expected, the method gained a lot of interest in oil exploration. It was not until the theory was fully understood (Yost, 1952; Yost et al, 1952; Orsinger and Van Nostrand, 1954) that everybody realized that the signals measured on the earth surface were not caused by reflections. It happened several times between early days and the present that inexperienced companies offered similar techniques to the oil industry, without properly understanding the physics behind the method. This caused a tremendous distrust by the oil industry of any electrical method. Only today, with the thorough research done on electromagnetics (and magnetotellurics in particular) and the increase in computer power available to the geophysicist, can we see a complete new generation of cost-effective exploration techniques evolving, although the distrust in its practical application still exists.

In the past decades, most electromagnetic methods were understood and applied in academia before the oil industry accepted them. In *magnetotellurics (MT)* only very recently was the large amount of work done around the world reviewed by K. Vozoff (1972; 1991). The MT method is now well established in industry, about 20 years after the initial efforts by Geoscience Inc. applying the technique in the United States. *Transient electromagnetics* has not come that far yet, since for oil exploration neither enough case histories nor a complete understanding of the theory has been, to date, accomplished. There have been several review papers on mining applications where transient electromagnetics has been accepted for many years as the most effective EM technique (see special transient EM issue in Geophysics 49(7); Macnae and Spies, 1989). The growing interest in controlled source electromagnetic techniques (Nekut and Spies, 1989) leads to an increase in controlled source EM instruments. Almost every manufacturer of EM instruments has or is preparing a deep TEM system.

The principal difference between a time domain and a frequency domain system lies in the signals for time domain systems which are measured in the absence of the source signal. For frequency domain systems the primary signal is always present. Thus, time domain signals are easier to measure and interpret. Figure 1.2 shows the two basic modes of both domains. In the figure the frequency domain primary field is for practical reasons a square wave. At the receiver site the primary field and the superimposed secondary field is measured. For the time domain setup no secondary field is being generated after the current switching, and the secondary signal is recorded in the absence of the primary field.

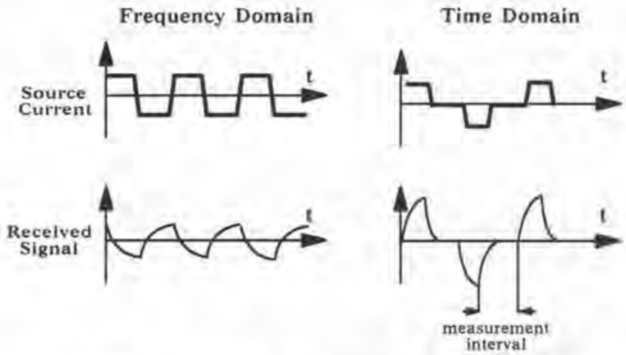

Fig. 1.2: Signal and source waveforms in frequency and time domain systems (after Nekut and Spies, 1989)

Among the *transient electromagnetic techniques* are two which have been the most promising during the past years: the UTEM (University of Toronto EM) system and the LOTEM (Long Offset Transient EM) system. The UTEM system is being used primarily by Lamontagne Geophysics Ltd. in Canada and around the world. From the system concept and the interpretation scheme it is probably the most advanced and the most versatile system in the world. Its only drawback for oil exploration as can be seen today, is the limited depth range in conductive environment and that UTEM can only resolve conductive targets due to the use of an inductive source. Thus, the UTEM system is primarily applied to mineral exploration. The LOTEM system is the deeper penetrating system of the two. Because of the different terminologies among *transient EM systems*, the name LOTEM was invented in Australia by Vozoff and Strack to distinguish between the shallow systems like SIROTEM and EM37 (by Geonics) and the deeper ones. *LOTEM means that the distance between transmitter and receiver is approximately equal to or greater than the exploration depth.* LOTEM measurements require also a tradeoff between the practical field aspects and the theory. The theory would like to have the receiver as close as possible to the transmitter to avoid uncertainties due to lateral inhomogeneities, whereas the practical constraints (selection of the optimum time window) such as power line noise restrict the method to a minimum offset in order to obtain signal frequencies undistorted by power line noise or analog filters used in the system.

The roots of *transient electromagnetics* for deep exploration as discussed here are in the Soviet Union (Kraev, 1937; Tikhonov, 1946; Vanyan, 1967). Although Vanyan's monograph (1967) gives the impression that *transient electromagnetics* is a routine exploration tool, not many case histories have reached the western world. Keller did most of the pioneering work with the method at the Colorado School of Mines and his geothermal exploration company Group Seven Inc. (see Keller et al, 1984 for a historic summary of these efforts). Offsprings from CSM were Geopacific Resources Inc., Group Seven Inc. and from Group Seven Inc. and CSM, Integrated Geosciences Inc.. Geopacific Resources Inc. conducted the first transient electromagnetic measurements in Asia (unpublished). Further measurements were done by CSM in Iceland (Tulinius, 1980) and Latin America (unpublished). Integrated Geosciences Inc. has mainly applied the method in the USA and recently in Turkey and Northern Ireland. Mostly unknown are some tests done by Elf Aquitaine in France and the Middle East during the early 1980s (unpublished).

Figure 1.3 shows the historical tree of the active LOTEM work in the western hemisphere. At the different institutions the hardware systems consisted of either modified commercial or special purpose systems. According to my terminology, DEMS I (**D**igital **E**lectro**M**agnetic **S**ystem) was designed, built and used in a production mode at

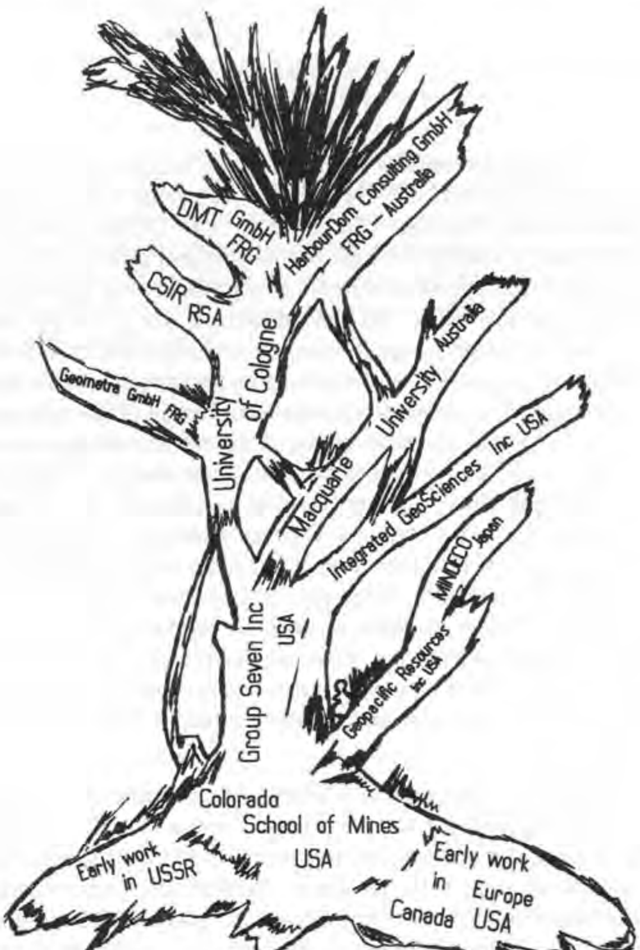

Fig. 1.3: Historical tree of the different organizations involved in deep transient electromagnetics.

Group Seven Inc. DEMS I consisted of off–the–shelf components mounted on a truck. The hardware was powered by a 12V DC to 110V AC converter. Integrated GeoSciences Inc. used DEMS II, which was an improved version of the developments at CSM and Geopacific Inc.. DEMS II was a special purpose battery powered portable acquisition system. Subsequently, 1983, DEMS III, an improved combination of DEMS I and II was built in Australia. DEMS III was a modified full scale computer with all standard power supplies replaced by ruggedized field versions such that it completely operated on DC without DC to AC converter. The initial work in Australia (Strack, 1984) was continued by Vozoff (Vozoff et al, 1985), who used for the first time a general purpose EM system (Zonge's GDP 12 general purpose receiver) for *deep transient electromagnetics*. In 1985, the German Ministry for Research and Technology (BMFT) and the European Community granted the University of Cologne the support for the development of the new generation of equipment, called DEMS IV. DEMS IV is a portable system, completely battery powered and containing a computer with more power and a removable hard disk for data transfer. DEMS IV was the first system which acquired and kept all individual ("raw") records for prestack processing. DEMS IV was manufactured by Metronix GmbH under the University of Cologne's supervision for the LOTEM demonstration project in China and India.

During 1988 and 1989 the DEMS IV system was successfully used for six months without major breakdown in China and India. During the same year DEMS IV was successfully combined with a Zonge transmitter for deep crustal research in South Africa. The South African research group at the CSIR is presently developing a special purpose system for ultra deep crustal studies.

The latest generation of deep transient EM equipment follows a new acquisition principle: using remote units which acquire the data independently, thus (in principal) not limiting the number of channels. This generation is called DEMS V. The development is based on the SEAMEX (patent pending) seismic system of WBK (now DMT) of Bochum, Germany. The patent for the new system (called TEAMEX) has been applied for by WBK–DMT. The received data is acquired with instantaneous floating point amplifiers and stored in the remote unit. The data is then sent unmultiplexed in digital form to the central unit via a two wire telemetry. Several new generations of LOTEM hardware are on the drawing board with the most promising coming from seismic industry.

ELECTRICAL CONDUCTIVITY / RESISTIVITY IN EXPLORATION

Exploration geophysicists dealing with electromagnetic data are facing the problem that they must assume the electrical properties of rocks to be given or measured correctly. Already this assumption in itself is very restrictive, since significant uncertainties are associated with the resistivities of rocks. In this section only some of the key problems of electrical resistivity necessary for the interpretation of LOTEM data are addressed. Excellent reviews of the subject can be found in Keller (1988) and Palacky

With these data and the conditions in the target area, it is relatively easy to select an optimum survey layout. This should be done as final step to give input to the logistics operator for the survey design: optimum transmitter–receiver offset, optimum time window, required accuracy for the data. The latter always results in a tradeoff: the longer you stay at one receiver site the better your averaged signal becomes, but also the costs per station increase. The feasibility study can put limits on the required accuracy and therefore help in both, time–planning and in cost estimation.

You may refine the presurvey feasibility study even more, if you have more data available. If noise measurements from the survey area and the system response of your system exists, you may actually want to calculate synthetic, noisy, raw field data and simulate the whole interpretation process. The more time you spend on the feasibility study the more time you will save during the data acquisition and interpretation phase.

In the next section artificial noise is added to the data and the resolution is investigated under production conditions by looking at the inversion results.

RESOLVING A DEEP CARBONATE UNIT

A difficult target for EM techniques is the determination of resistivity and thickness of thick resistive units at a depth of 4 to 6 km. For production and exploration problems this is however very important because accurate porosity predictions can save money spent on dry wells. To simulate this situation we have selected a case history simulating an exploration situation in China (Baxian Depression). The objective of the feasibility study was to find the optimum survey strategy under the following conditions:

- The LOTEM measurements are carried out in a production mode along a profile.
- Two wells at either end of the profile and a good seismic section are available.
- The interpretation is restricted to one–dimensional modeling to maintain production and constrain the effort in interpretation.
- Archie's formula applies to the carbonates embedded in clastic sediments.

The color figures for this feasibility study are given in Appendix 7. Figure A.7.2 (top) shows an electrical section with three layers which has an additional fourth layer embedded between 4 and 6 km depth. The section without the additional layer represents the overall structure of the Baxian Depression according to Chen Leshou et al's (1988) interpretation of magnetotelluric data (table 6.3). The Baxian Depression is part of the Bohai Gulf Basin which has a great variety of different oil and gas pool

The integration of the above concepts starts already in the field. When carrying out field measurements, the observer should notice changes in physical properties or the environment. Production of reliable data can only be increased when effective quality control is done on a continual basis. In particular, the success of a method strongly depends on a field crew and the amount of quality control done in the field. During the interpretation phase, the knowledge of possible combinations of the physical parameters such as possible resistivity variations associated with porosity variations is extremely important. This knowledge is usually the key factor when separating unreasonable subsurface images from the realistic ones. The geophysicist is usually responsible for the integration of theory and model realization. He/she will in most instances provide the interpretation tools such as numerical and analog modeling. These tools can only be effectively applied when the range of possible resistivities and their meaning is understood. During this interaction the geophysicist will in most instances be responsible for the transfer of his knowledge of processing theory and methods to the other members of the interpretation team. This will enable them to come up with the most reasonable interpretation in accordance with the field data. Avoiding this interaction most likely will produce biased interpretation results.

Figure 1.5 shows the resistivity range for consolidated and unconsolidated sediments. Knowing the rock type does not suffice, since the ranges are very large. Additional information about the petrophysical behavior of the rocks and their in situ conditions is needed to narrow down these ranges and to obtain reliable estimates of the resistivities. For example, coal which may vary in resistivity over five and a half decades can puzzle the interpreter. Wet, "dirty" coal is conductive and dry, clean coal resistive. The interpreter must consider all dependencies of assumed resistivity in order to obtain reliable information.

The resistivity of a rock with respect to its components is not easily expressed in terms of a formula. The best review of the subject is given in one of the Schlumberger manuals (Schlumberger, 1987). For clean compacted sand Archie (1942) derived an empirical formula:

$$\rho = \rho_w \frac{a}{\phi^m} \frac{1}{S^n}, \qquad (1.1)$$

where ρ is the resistivity of the formation, ρ_w is the resistivity of the pore fluid, a is an empirically determinated constant, ϕ is the porosity of the formation, and S is the fraction of the pore volume occupied by formation water, m and n are empirical constants. Unless found different, n is recommended by Schlumberger (1987) as n = 2. The exponent m is also called cementation factor. For sands the formation factor F = a / ϕ^m is

$$F = \frac{0.62}{\Phi^{2.15}} \quad \text{(Humble formation factor)} \qquad (1.2)$$

and for compacted formations $F = 1 / \Phi^2$ (Archie formation factor). When the formation becomes shaly, the above relation no longer applies and further corrections need to be applied. An example is given in one of the Schlumberger manuals (Schlumberger, 1987):

$$\rho = \frac{F\ \rho_w}{S^2\ (1 - V_x)} + \frac{C\ V_x}{\rho_x} \quad , \tag{1.3}$$

where ρ_x is the resistivity of the shale or clay, V_x its volume and C a term related to the water saturation. Table 1.1 shows possible values for the constants for the determination of the formation factor constants for different rock types.

Table 1.1: Different constants to be substituted in Archie's formula when lithology of a rock is known (after Keller, 1988).

DESCRIPTION OF ROCK	a	m
Weakly-cemented detrital rocks, such as sand, sandstone, and some limestones, with a porosity range from 25 to 45 %, usually Tertiary in age	0.88	1.37
Moderately well cemented sedimentary rocks, including sandstones and limestones, with a porosity range from 18 to 35 %, usually Mesozoic age	0.62	1.72
Well-cemented sedimentary rocks with a porosity range from 5% to 25%, usually Paleozoic in age	0.62	1.95
Highly porous volcanic rocks, such as tuff, Aa and Pahoehoe, with porosity in the range from 10% to 80%	3.5	1.44
Rocks with less than 4% porosity, including dense igneous rocks and metamorphosed sedimentary rocks	1.4	1.58

From the above table, even the determination of a simple parameter such as the rock resistivity can be difficult under static conditions due to the composition of rocks. The determination of the rock resistivity becomes even more difficult in situ when the behavior of rocks changes with temperature and depth, salinity and porosity. Figure 1.6 shows the change in resistivity versus temperature for different salt concentrations of the pore fluid. All factors need to be considered when deriving a reliable estimate for a particular formation at a particular depth.

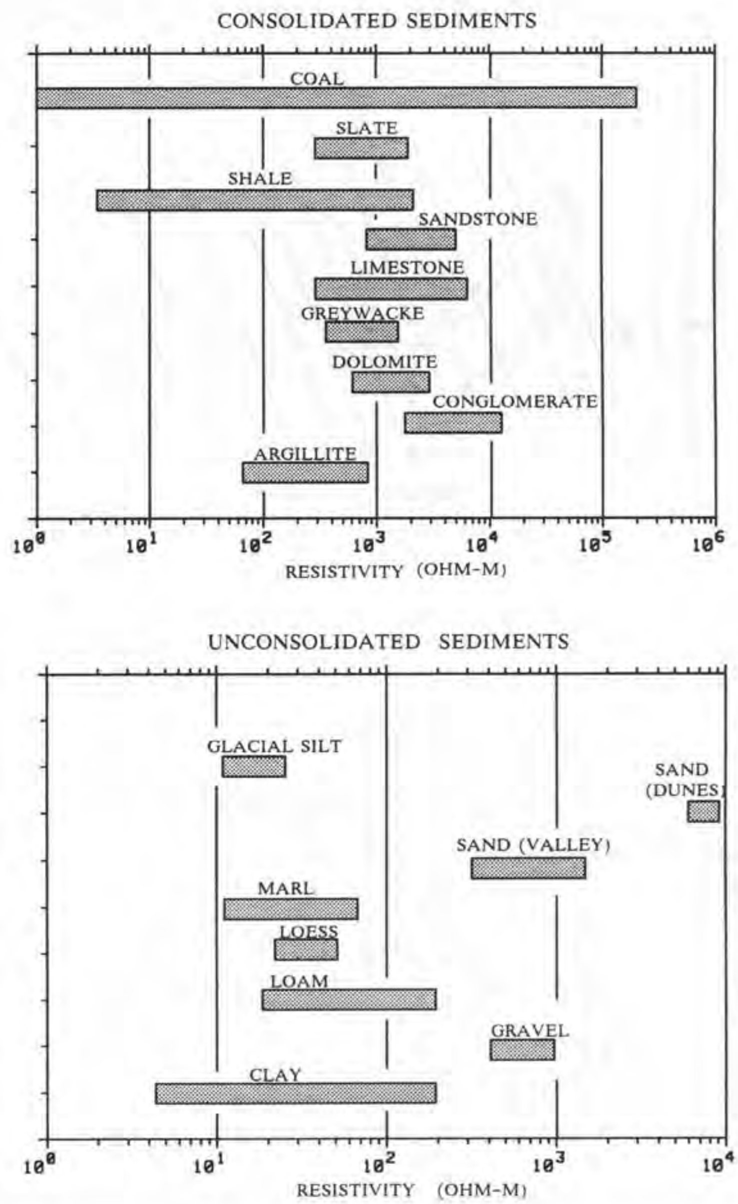

Fig. 1.5: Ranges of resistivity for consolidated and unconsolidated sedimentary rocks (modified after Angenheister, 1982).

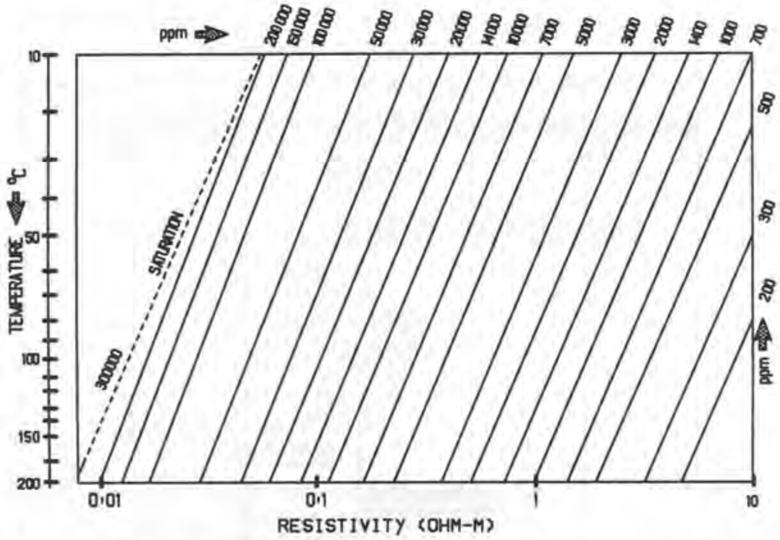

Fig.1.6: Resistivity versus temperature / depth of the pore fluid for different salt concentrations (after Schlumberger, 1987).

In combination with the above we must consider the dependence of the resistivity on the age of the rock. Figure 1.7 shows this dependence for various rock types, based on a statistical evaluation.

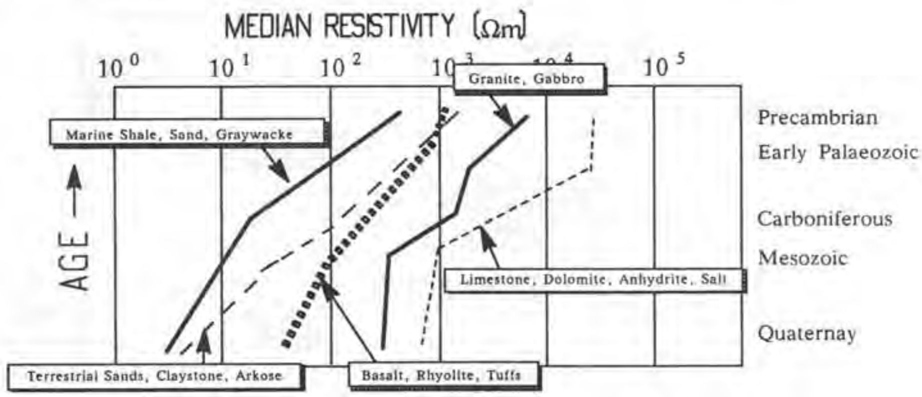

Fig.1.7: Dependency of the resistivity versus geologic age (after Vozoff 1989 pers. comm.).

Another very important factor usually neglected is the electrical anisotropy of rocks. We speak of anisotropy when the resistivity of a rock is different in longitudinal (horizontal) and transverse (vertical) direction. Strictly speaking, we are using anisotropy in a two-dimensional sense, i.e. the difference between resistivity measured in vertical and horizontal direction (assuming no horizontal anisotropy). For most sedimentary areas this is valid because of the slow sedimentation process which deposits sediments in a layer-cake. Figure 1.8 illustrates this anisotropy with a block model. Here a cyclic deposition process has been assumed which causes a cyclic change in resistivities from ρ_1 to ρ_2. When deriving the theory for anisotropic cases the scalar resistivity must be replaced by a tensor which quickly increases the number of possible solutions to a problem.

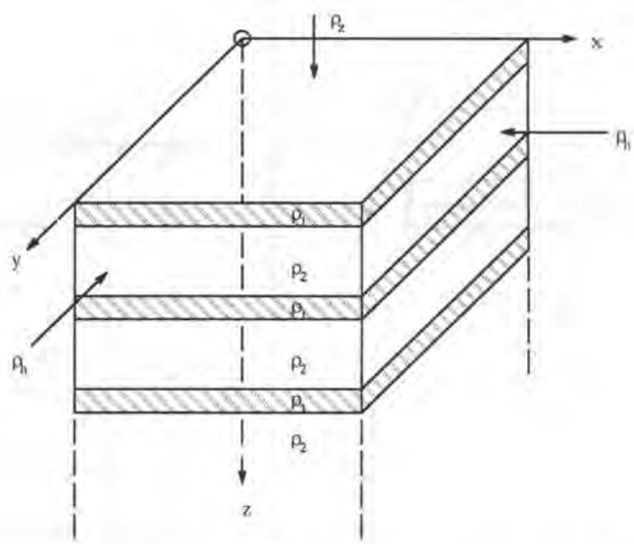

Fig. 1.8: Resistivity anisotropy as a result of horizontal bedding during cyclic deposition.

Since the problem of anisotropy is more complex than can be considered here, only simple examples are discussed. How can we observe anisotropy in the data with the LOTEM method? We must find means to measure the vertical current flow and display it. In addition to horizontal induction current flow the LOTEM method generates vertical currents with the grounded wire transmitter (see next chapter). When considering the magnetic component of the receiver, we will predominantly see the effect of horizontal induction or in the sense of this chapter longitudinal resistivities. The electric receiver signal contains also information about vertical current flow or the transverse resistivity of the subsurface. In figure 1.9 this effect is used to demonstrate how electrical anisotropy influences the signal measured with deep transient electromagnetics. The top and bottom graphs compare a half space with an average resistivity of 10 Ohm–m (typical value for sediments) with the same basic geologic model plus two thin (each 50 m thick) resistive layers at great depth (2000 m and 2250 m respectively). It can be shown in figure 1.8 that this model represents an anisotropic situation. For the magnetic field derivative (top), measured with an induction loop magnetometer, the anisotropy can not be seen which is due to the nature of the magnetic field measurements which only sense horizontal current flows. The two curves do not differ from each other. For the electric fields the anisotropy becomes visible which is expressed by the difference between the half-space response and the anisotropic model response from approximately 0.5 s on.

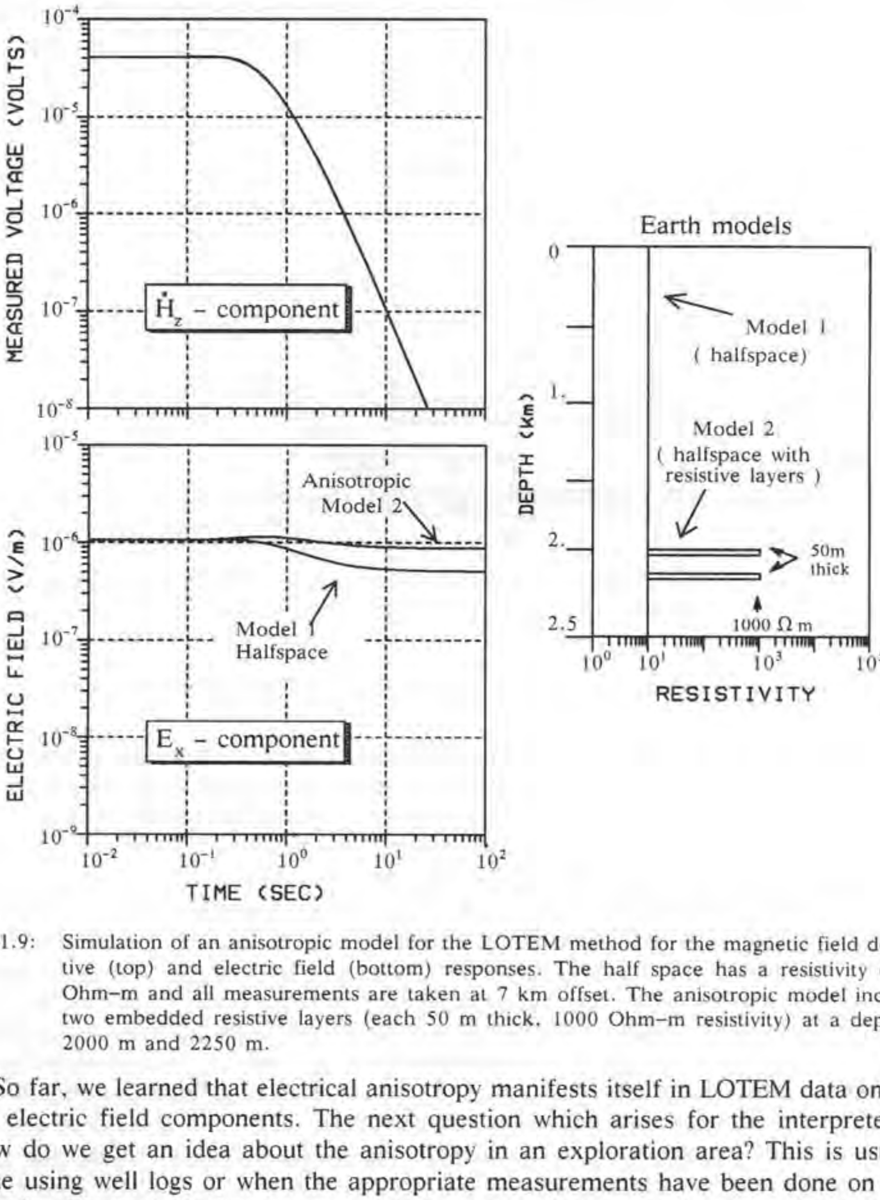

Fig.1.9: Simulation of an anisotropic model for the LOTEM method for the magnetic field derivative (top) and electric field (bottom) responses. The half space has a resistivity of 10 Ohm–m and all measurements are taken at 7 km offset. The anisotropic model includes two embedded resistive layers (each 50 m thick, 1000 Ohm–m resistivity) at a depth of 2000 m and 2250 m.

So far, we learned that electrical anisotropy manifests itself in LOTEM data only in the electric field components. The next question which arises for the interpreter is: How do we get an idea about the anisotropy in an exploration area? This is usually done using well logs or when the appropriate measurements have been done on core samples. Figure 1.10 shows an example for the longitudinal resistivities of two formations (from the Denver–Julesberg Basin) and the corresponding coefficient of anisotropy along the area (Keller, 1971). The anisotropy coefficient is the square root of the ratio of vertical and horizontal resistivity. The data was obtained from well log and core analysis. This type of information allows the interpreter to obtain a realistic first interpretation for an area, while at the same time drawing his attention to possible interpretation problems due to anisotropy. In figure 1.10 interpretation problems could be anticipated for data from range 50 to 54 where the coefficient of anisotropy rises. Using reliable interpretation input can save a significant amount of time and avoid problems due to possible misinterpretation.

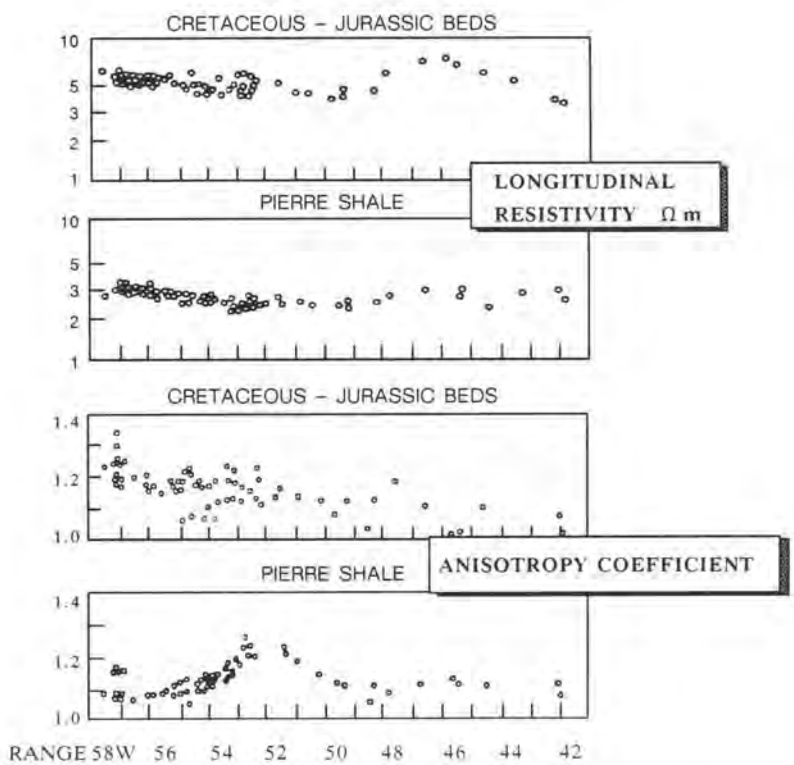

Fig. 1.10: Example of longitudinal resistivities (top) and electrical anisotropies (bottom) for two formations across an area in the Denver–Julesberg Basin, USA (after Keller, 1971).

In most cases an excellent resistivity interpretation across a profile (as in figure 1.10) does not exist. Then, one can use a well log to derive a basic electric model for the area. The finely resolved well log can then be reduced to a coarser blocked one as shown in figure 1.11. Here the blocking has been done by visual inspection. Also, the near surface conductor was not considered because the LOTEM system is not designed to resolve this shallow depth range. A description on how a more accurate blocking is done can be found in the chapter on presurvey feasibility studies. If even a single well log does not exist, the interpreter must rely completely on his/her judgement not forgetting all the inaccuracies and changes with the electrical resistivity.

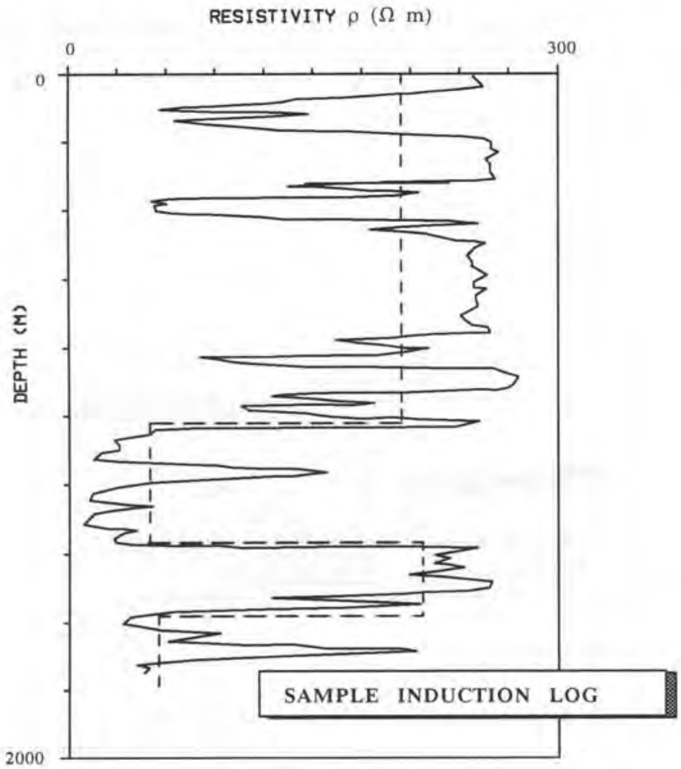

Fig.1.11: Example of an induction log as used for the definition of the interpretation model. The dashed line shows the interpreted starting model.

SUMMARY CHAPTER 1

Among electromagnetic techniques, magnetotellurics has become an acceptable tool for the exploration industry while transient electromagnetics is still in the evaluation phase. Transient electromagnetic methods can give very useful additional information for exploration problems associated with permafrost, oil-water contact, volcanic covers, overthrusting, diapirism, deeply weathered overburden, extreme topography in connection with any of the above, delineation of porosity variation, and deep crustal studies. In all cases transient electromagnetics can provide additional information which helps in clarifying and understanding of the exploration problem.

Historically, deep transient electromagnetics was introduced to the Western world by Keller at the Colorado School of Mines and Group Seven Inc. From there, the research activities spread out to Asia, Australia and subsequently to Germany and South Africa. Nowadays, several different research groups exist worldwide which are working on the advancement and in particular the industrial application of the technique.

When applying electromagnetic techniques to exploration problems, a thorough understanding of the basic assumptions such as resistivity estimates is very important. In particular, the reliability of these resistivity estimates must be evaluated by considering the individual components in the empirical formulae relating them to the rock resistivity. Even then, the range of resistivity variations given to us by the geology is rather large and forces the explorationist to continuously question his/her assumptions. Any additional information which can be obtained is extremely important to derive the best basic model which can then be related to the geophysical measurements. Even after finding the best geophysical model, the question of ambiguity caused by anisotropy must be eliminated by carrying out proper field measurements and evaluating the existence of and corrections for the anisotropy.

PROBLEMS CHAPTER 1

1. What is Archie's law or formula?
2. Which formula would you use to define the bulk resistivity of a sandstone with a sand–to–shale ratio of 50%?
3. How do we observe electrical anisotropy in LOTEM data?
4. Given a new exploration area, what information would you be looking for to evaluate whether you can apply LOTEM? Outline the strategy you would follow if one of the selected pieces of information is missing or non conclusive.
5. Calculate the rock resistivities for well–cemented sediments, highly porous volcanic rocks, and crystalline rocks for porosity values of 5, 10, 20, 30%.
6. Calculate resistivity as a function of depth for sandstones with 25% porosity and a salt concentration of 14 000 ppm. Use the standard geothermal gradient.
7. What are the main differences between a time domain and a frequency domain system?

KMS Technologies – KJT Enterprises Inc.
6420 Richmond Ave., Suite 610
Houston, Texas, 77057, USA
Tel: 713.532.8144

Please visit us
http://www.kmstechnologies.com