Presented at "Short Course V on Conceptual Modelling of Geothermal Systems",
organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, February 24 - March 2, 2013.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

RESISTIVITY METHODS USED IN EL SALVADOR GEOTHERMAL EXPLORATION

Pedro Santos
LaGeo S.A. de C.V.
15 Av. Sur, Colonia Utila,
Santa Tecla, La Libertad
EL SALVADOR
psantos@lageo.com.sv

ABSTRACT

The resistivity methods have been used in the exploration of the geothermal fields in El Salvador since the 60's. The DC resistivity techniques such as Schlumberger, Misse a la masse, Dipolo dipole and Head on were applied for decades, despite the limited penetration capacity, they have contributed in delineating the major geothermal areas as well as defining drilling target.

The natural source method such as MT combined with artificial source technique such TDEM have demonstrated to be a powerful tool to estimate the size and the thickness of the producer reservoir. The joint analysis of these techniques allows mapping of the resistivity distribution from the very shallow level up to several kilometres depth.

While geothermal systems are usually associated with low resistivity at shallower levels, the high-temperature geothermal reservoir itself has a resistive signature, due to lower porosity and resistive alteration minerals (epidote, quartz, chlorite). The upflow zone is located where the conductive-resistive interface attains its highest elevation. Conductive anomalies within the reservoirs may represent large fractured zones to be used in defining drilling targets.

1. INTRODUCTION

A geothermal system generally causes inhomogeneity in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), elastic properties influencing the propagation velocity of elastic waves (seismic survey), density (gravity survey) and magnetic susceptibility (magnetic survey). Most of these methods can provide valuable information on the shape, size, and depth of the deep geological structures constituting a geothermal reservoir, and sometimes of the heat source. (Manzella, 1995).

The parameter of electrical resistivity gives information on temperature and alteration of the rocks with depth, which are major parameters for understanding the geothermal systems. The correlation

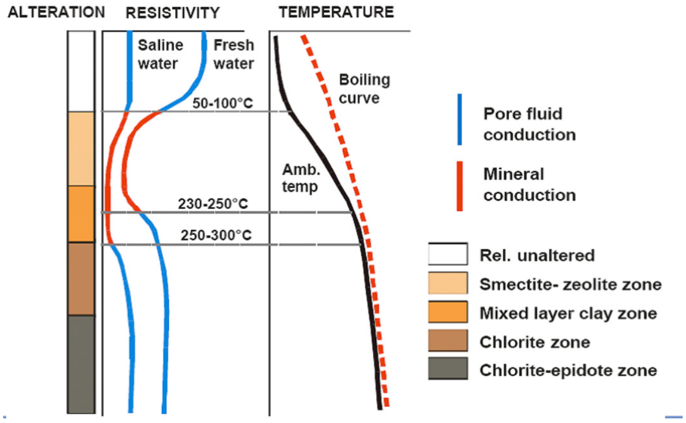

FIGURE 1: Resistivity of rocks and its association with alteration and temperature (Árnason et al., 2000)

between the resistivity parameters and alteration, lithology, temperature, porosity, water saturation etc. is shown in Figure 1.

The typical structure of a high-temperature geothermal system is presented schematically in Figure 2. The resistivity of the smectite zone is primarily determined by the type and intensity of alteration, modified by the degree of saturation and actual temperature, and is generally between 1 and 10 ohm-m. The amount of illite increases with temperature, forming the mixed-layer clay (illite-smectite) at 180°C. Above this temperature, the smectite content continues to decrease, and pure illite commonly appears at greater than 220°C with other high-temperature alteration minerals (chlorite, epidote, etc) in the propylitic alteration assemblage, with typical resistivity lying between 10 and 60 ohm m (Errol et al, 2000).

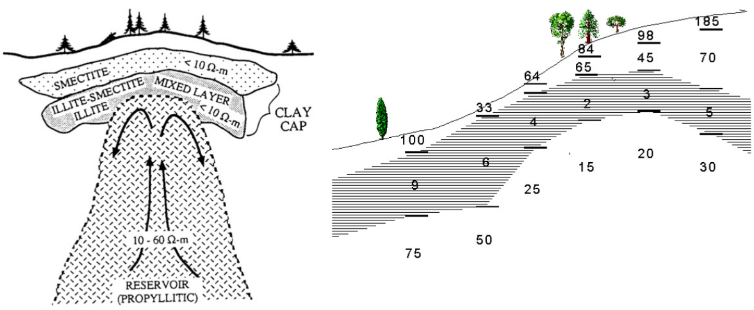

FIGURE 2: Typical structure of a high-temperature geothermal system (Errol et al, 2000)

While geothermal systems are usually associated with low resistivity at shallower levels, the high-temperature geothermal reservoir itself has a resistive signature, due to lower porosity (lithostatic load) and resistive alteration minerals (epidote, quartz, chlorite). The upflow is located where the conductive-resistive interface attains its highest elevation. Conductive anomalies within the reservoirs can represent large fractured zones to be used in defining drilling targets.

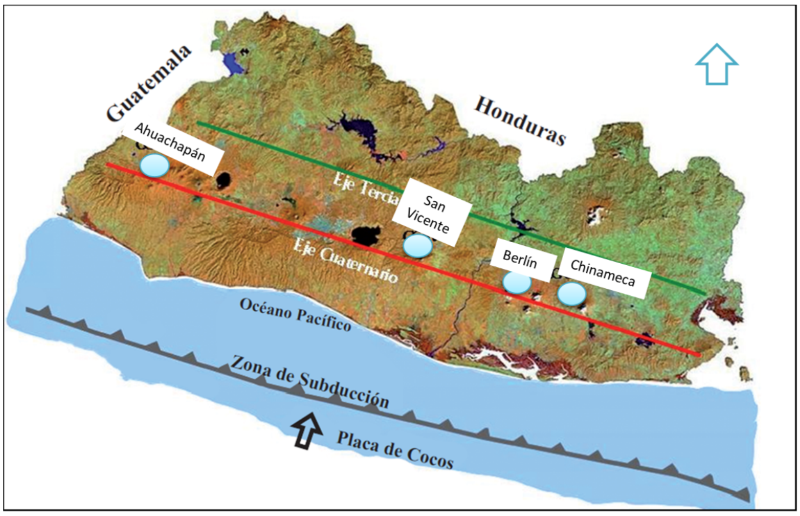

FIGURE 3: Location of the high temperature geothermal field in El Salvador

High temperatures geothermal fields in El Salvador are located at the northern flank of the active volcanic chain, from the Quaternary age as shown in Figure 3.A brief review of the geophysical methods applied in the different geothermal areas of El Salvador is shown in Table 1. Important contributions in the knowledge and characterization of the different geothermal systems in El Salvador have been provided through the implementation of these techniques.

TABLE 1: Geophysical methods applied in the different geothermal areas in El Salvador

	DC RESISTIVITY METHODS					ELECTROMAGNETIC		SEISMIC METHODS			
AREA	SEV	DIPOLO-DIPOLO	CALICATAS	MISE ALA MASSE	HEAD ON	MT/TDEM	MAGNETIC	PASSIVE SEISMIC	SEISMIC TOMOG	GRAVITY	HEAT FLOW
AHUACHAPAN	●	●	●	●	●	●	●	●		●	
CHIPILAPA	●	●	●	●	●	●	●	●		●	
CUYANAUSUL	●		●			●	●			●	
BERLIN	●	●	●	●	●	●	●	●	●	●	
COATEPEQUE	●	●								●	
SAN VICENTE	●				●	●				●	
CHINAMECA	●				●	●				●	
OBRAJUELO	●									●	●
CHILANGUERA	●		●				●			●	
CONCHAGUA	●		●		●		●			●	
PENETRATION	>1Km	>.5Km	>.3Km	>1Km	>.3Km	<5Km	>.3 Km	<5Km	<2Km	<2Km	>.1Km

2. RESISTIVITY METHODS USED FOR THE GEOTHERMAL EXPLORATION IN EL SALVADOR

Electrical methods include many different types of measurements and varying setups or configurations for the different types. The most important types used in El Salvador are:

- Direct Current (DC) Resistivity Methods such as Shlumberger, Dipole Dipole, Mise a la Masse and Head on profile.
- Artificial Source Electromagnetic methods such Time Domain Electromagnetic Method (TDEM), Control Source Audio magnetic Method (CSAMT).
- Natural source Resistivity Electromagnetic Methods such as Magnetotellúric (MT), Audio Magnetotelluric Method (AMT) and the Self Potential.

This paper will present the resistivity method applied in El Salvador, its principles and main results.

3. DIRECT CURRENT (DC) RESISTIVITY METHOD

The resistivity measurement is normally undertaken by injecting into the ground a known current (I) through the two current electrodes (A, B), and measuring the resulting voltage difference (V) at two potential electrodes (M, N). From the current and voltage values, an apparent resistivity (ρα) value is calculated as follows.

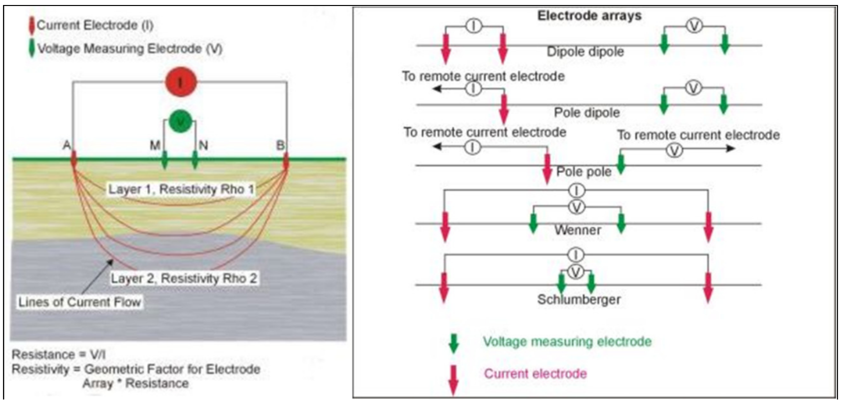

FIGURE 5: Basic principle of DC Resistivity methods and different electrodes arrays (www.cflhd.gov/resources)

ρa= kV/I, where k is a geometric factor which depends on the electrodes array.

Several electrode arrays are used to measure resistivity, and most of them are illustrated in Figure 5.

DC resistivity methods can be divided into various subcategories depending on the geometrical arrangement of electrodes. The most common used in El Salvador are:

1. Schlumberger
2. Head on profile resistivity sounding
3. Dipole dipole profile sounding
4. Mise a la Masse

3.1 DC Schlumberger resistivity sounding

In this method, the two potential and two current electrodes are placed along a straight line. The array is symmetrical around the midpoint O (Figure 6). As the distance between the current electrodes is increased, as a consequence, the prospecting depth is increased too. For each electrode separation, a value of apparent resistivity is calculated. This value is plotted in on a graph known as the field curve.

$$\rho_{BC} = [\Delta V_{BC}\ \pi\ (S^2 - P^2)]/[IP]$$

where S= Distance between AB electrodes
P= Distance between MN electrodes

The field data are inverted into 1D layer resistivity model by using commercial software. In this process, one initial guess model is used for running the software, after finish a defined numbers of iteration, the final model is generated and accepted if a good fitting between the measured and calculated curves is achieved (Figure 6)

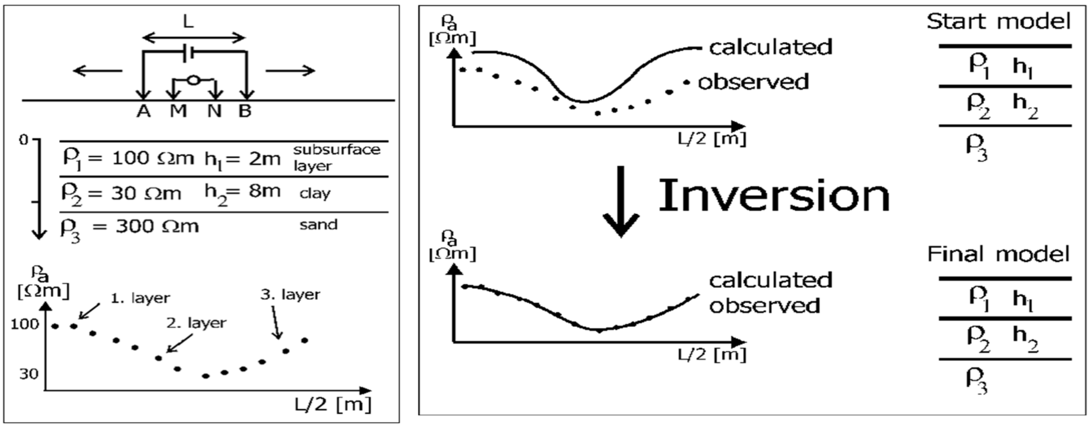

FIGURE 6: Schlumberger array and data process
(modified from www.fhwa.dot.gov/)

More than 120 SEV have been done at the Berlin Geothermal Field in El Salvador, located in the eastern part of the country. The geothermal area was delineated by a low resistivity anomaly (1D resistivity map) while the top of the producer reservoir was associated with uplifted resistive anomaly body at the southern part of the field (Figure 7).

By applying this technique, it is possible to get a picture of the subsurface resistive distribution of the most of geothermal areas of El Salvador.

3.2 Head-on profile resistivity method

Head-on profiling resistivity method designed for detecting narrow conductive zones in a resistive background, which could be associated with faults, dykes or fractures. The method uses a half-Schlumberger electrode layout, where a third current electrode C is additionally placed at an infinite distance and perpendicular to the Schlumberger array (Figure 8). The infinite distance must be at least four times the AB separation distance.

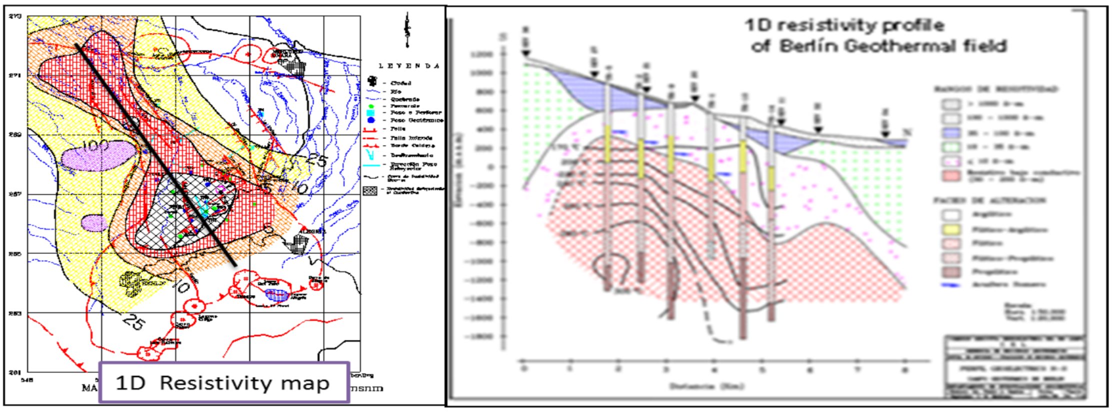

FIGURE 7: Schlumberger resistivity results in different geothermal area

The potential difference between the dipoles AB, BC y AC is measured and the corresponding resistivity values are calculated by using the next formulas:

$$\rho_{AC} = [\Delta V_{AC}\, \pi\, (S^2 - P^2)]/[IP]$$
$$\rho_{AB} = [\Delta V_{AB}\, \pi\, (S^2 - P^2)]/[2IP]$$
$$\rho_{BC} = [\Delta V_{BC}\, \pi\, (S^2 - P^2)]/[IP]$$

where S= Distance between AB electrodes
P= Distance between MN electrodes

The resistivity along the profile is plotted as a function of deploy center ("O"). In the same graph, the differences ρ_{AC}- ρ_{AB} , ρ_{BC}- ρ_{AB} and ρ_{AB} are plotted. The estimate location the fault is the point the curves ρ_{AC}- ρ_{AB} and ρ_{BC}- ρ_{AB} are intercepted (Hersir and Bjornsson, 1991).

The profile is set perpendicular to the supposed system of fault trend. The electrode C is kept fixed, while the half-Schlumberger electrode layout is moved along the profile, across the conductive structure. The evidence of the faults is suggested by a cross in the apparent resistivity curves.
The penetration depth is similar to that obtained with a full Schlumberger electrode array with the same maximum AB/2 value. This means that investigation will be restricted to the shallow resistive surface layer.

This method has been implemented with successful results in different geothermal areas in El Salvador such as San Vicente, Ahuachapán, Chinameca and Berlin.

In 2010, a resistivity survey using the head on profile was carried out at the southern part of San Vicente Geothermal field. As a result, a possible permeable area toward the south of the SV-1 well was inferred, which was confirmed by the last drilled geothermal well (Figure 8).

3.3 Dipole-dipole, 2D resistivity profile

Profiling with 2D DC-resistivity methods is conducted by making measurements along a surface profile using different offsets. The data are inverted to create a model of resistivity along a section of the subsurface that can be used to detect and define individual fracture zones.

The dipole-dipole array has better horizontal resolution but poorer depth of penetration, compared to the Schlumberger array.

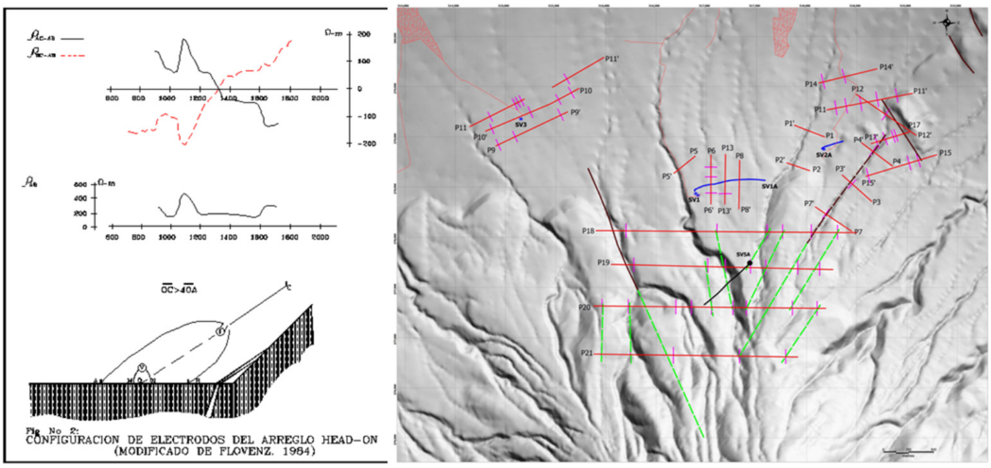

FIGURE 8: Head on profile array and head-on (Flovenz, 1984) and the obtained results in San Vicente geothermal area

The equipment used in this method is the same as that used for DC resistivity soundings, but more current injection capacity is required.

The dipole dipole survey is conducted with the electrodes arranged in a linear array. The first pole is used to inject the current while the others poles are used to measure the induced potential. The process is repeated by injecting in the second pole and so on as is shown in Figure 9. The resistivity is calculated as follows:

$\rho a = \pi n(n+1)(n+2)aV/I$

where n is the ratio of the distance between the C1-P1 electrodes to the C1-C2 dipole spacing

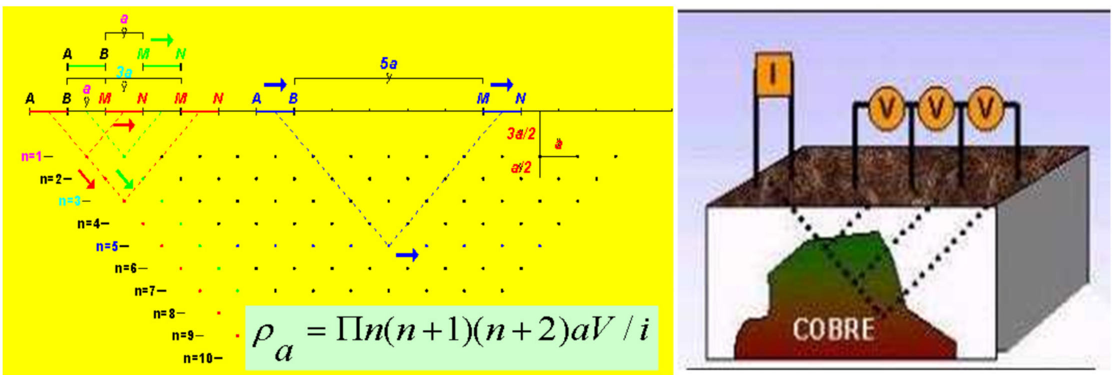

FIGURE 9: Dipole dipole array applied in the geothermal exploration (www.geofisica.cl)

This technique has been successfully applied in Ahuachapán and Berlin geothermal fields. Lateral resistive discontinuity suggested the presence of faults or fractures in Ahuachapan geothermal field, as shown in Figure 10.

3.4 Mise a la mase Method

Mise-a-la-masse or “Charged body potential” is a resistivity method where a DC current is injected into the ground using the well casing as electrode; the other current electrode is set at theoretically at “infinity’, which means at least three times the depth of the well. The potential field caused by this signal at ground surface is measured by a roving dipole, setting in radial lines, and usually separated 45 degrees from each other (Figure 11). The apparent resistivity at each point is calculated from the

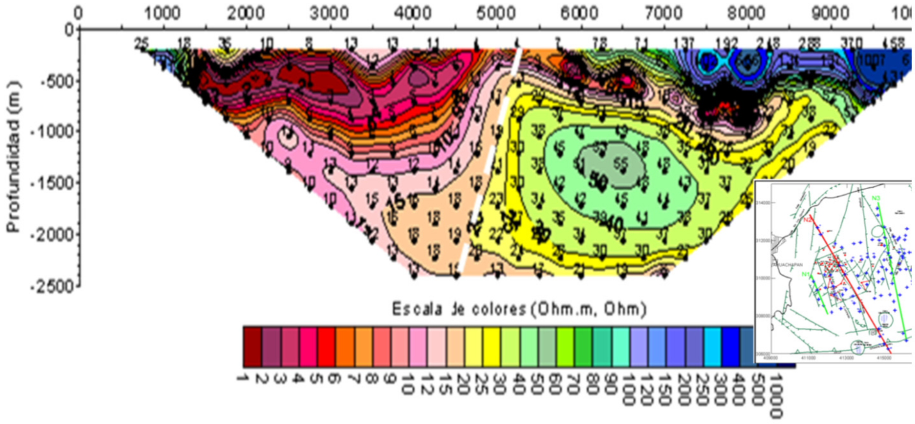

FIGURE 10: 2D modeling of dipole dipole profile in Ahuachapán geothermal field, inferred fault shown in dotted lines

measured potential difference, the current and the distance from the well. This parameter is defined by:

$$\rho a = 4\Pi XV/I,$$

where x is the distance between the current and the potential electrode.

By the use of the Misanaly software, the well casing effect is removed and the residual apparent resistivity map is elaborated.

The lateral resistivity discontinuities as well as the strong gradient curves observed in the residual resistivity anomaly map are correlated to the permeable fractures as is shown in Figure 12.

This method was implemented in 1996 and has been applied in most of the geothermal wells of Ahuachapán and Berlin geothermal fields. The results were considerable for defining geothermal target for production wells at both geothermal fields.

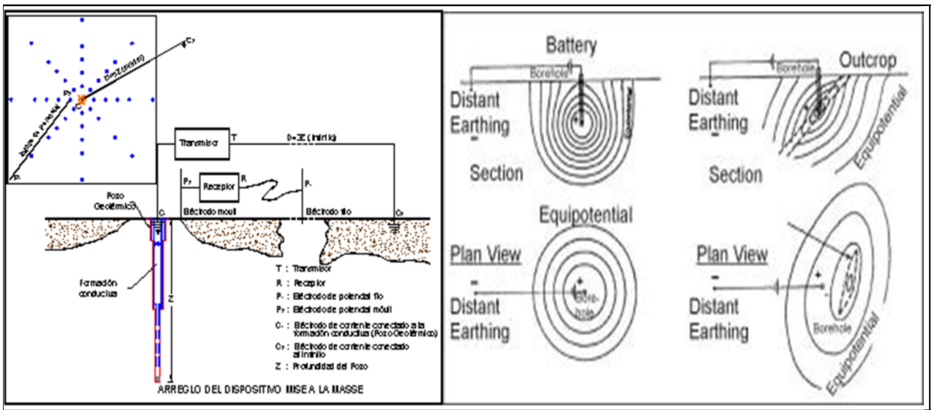

FIGURE 11: Mise a la Masse DC resistivity method array and anomaly example

4. ARTIFICIAL SOURCE ELECTROMAGNETIC METHODS

In these methods, an artificial source is used to generate the electromagnetic (EM) field and the most used in geothermal exploration are the Control Source Audio Magnetotelluric Method (CSAMT) and de Time Domain Electromagnetic Method (TDEM).

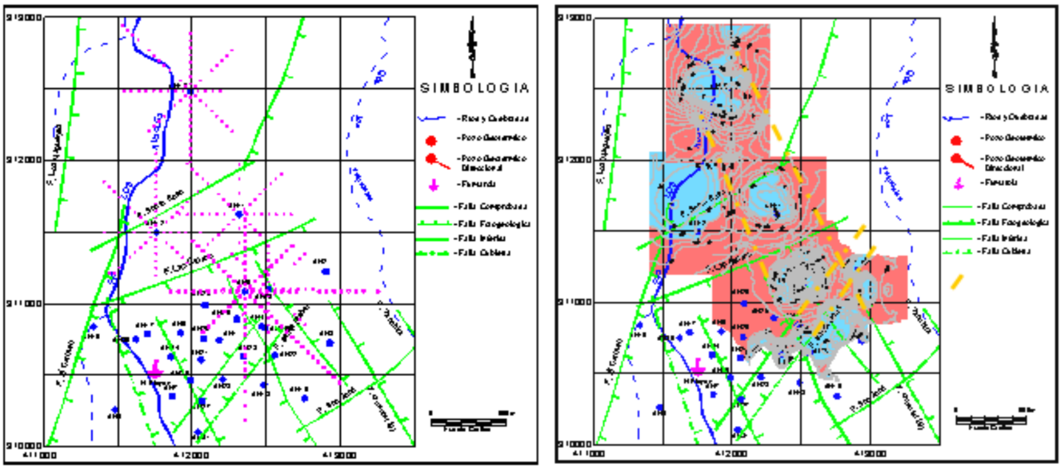

FIGURE 12: Mise a la masse results in Ahuachapán geothermal field, conductive fracture has been defined

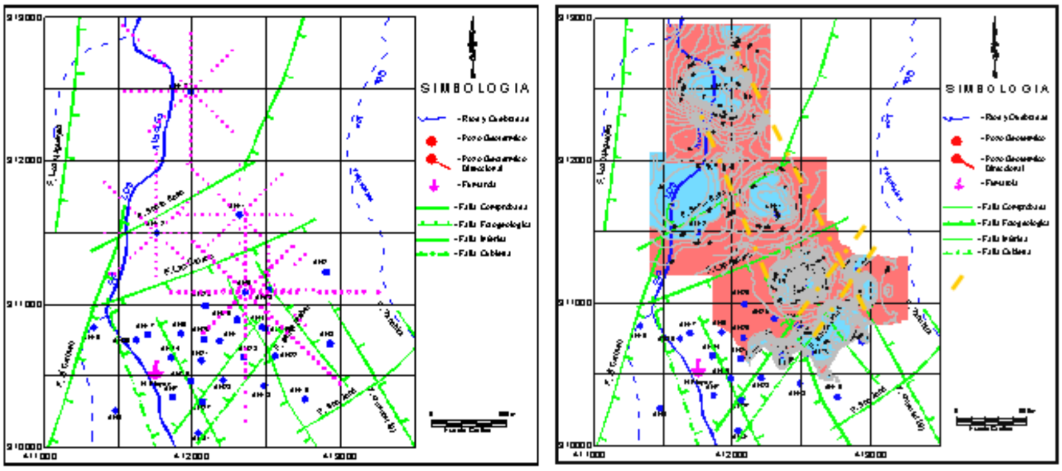

FIGURE 12: Mise a la masse results in Ahuachapán geothermal field, conductive fracture has been defined

4.1 Control source audio magnetotelluric method (CSAMT)

The CSAMT method involves transmitting a controlled signal at a series of frequencies (0.167 to 1024 Hz) into the ground from one location (transmitter site), and measuring the received electric and magnetic fields in the area of interest (receiver site). The ratio of orthogonal, horizontal electric and magnetic field magnitudes (e.g. Ex and Hy) are used to calculate the resistivity structure of the earth (Figure 13) given by the equation

$$\rho_a = \frac{0.2}{f}\left|\frac{E}{H}\right|^2$$

where, ρ_a: apparent resistivity in Ohm-m
f : Frequency in Hz
E : Electric field magnitude in mV/km
H : Magnetic field magnitude in nT

Equivalent depth of investigation, $D= 356\sqrt{f}$ *(D in meters)*

Lateral resolution is mainly controlled by the station spacing. The received signal strength is proportional to the length of the station spacing, so if the station size is cut in half, the signal strength is also reduced in half. The station spacing is usually between 10 to 200 m.

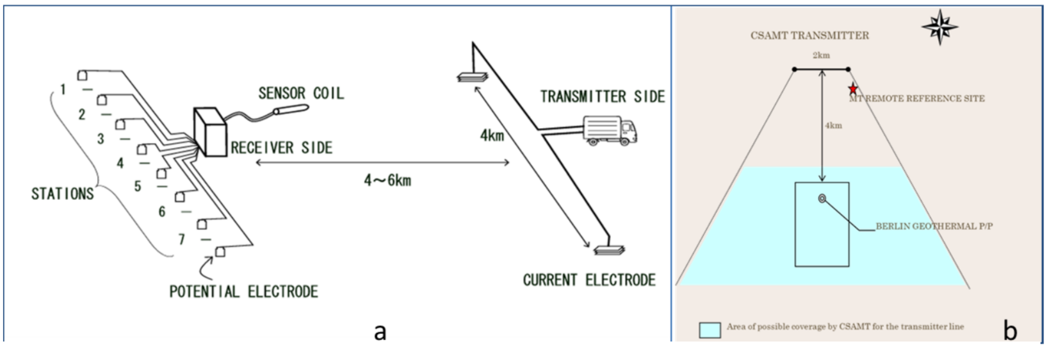

FIGURE 13: a) General layout for CSMAT and b) Survey configuration in Berlin geothermal field (West Jec, 2001)

In 2001, West Jec (Japan) carried out a CSAMT resistivity survey in Berlin Geothermal field. The data was collected by Phoenix Geophysics Company. A total of 86 station distributed every 300 m along 11 profiles covering an area of 10 km^2 were measured. As a result, several resistivity maps were created, one of them is shown in Figure 14.

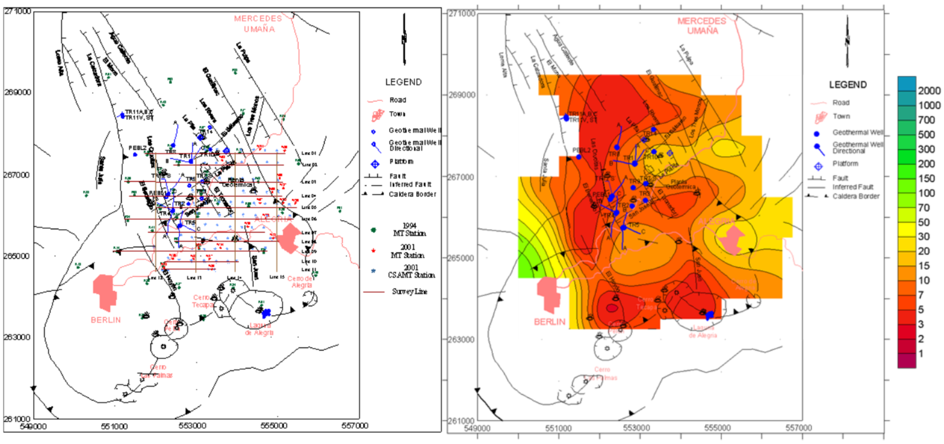

FIGURE 14: CSAMT survey at Berlin Geothermal field, measured points and resistivity map at 500 depths (West Jec, 2001)

4.2 Time domain electromagnetic method (TDEM)

In this method, a constant magnetic field is built up by transmitting current **I** through a big loop (grounded dipole). Then the current is abruptly turned off. A secondary field is thus induced, decaying with time. This decay rate is monitored by measuring the voltage induced in a receiver coil in the center of the loop on the surface. Current distribution and decay rate recorded as a function of time, depending on the resistivity structure below the measuring site. The signal can also be based on a grounded dipole to create the primary magnetic field (Figure 15).

The measured resistivity in the subsurface is similar to the Schlumberger soundings, expressed as apparent resistivity ρa, and is an expression for the "average resistivity" of the structures below the centre of the sounding. It is a function of several variables, including measured voltage; time elapsed from turn off; area of loops/coils; number of windings in loops/coils and magnetic permeability. For a homogeneous half-space, apparent resistivity, ρa, expressed in terms of induced voltage $V(t, r)$ at a later period after the source current is turned off, which is given by:

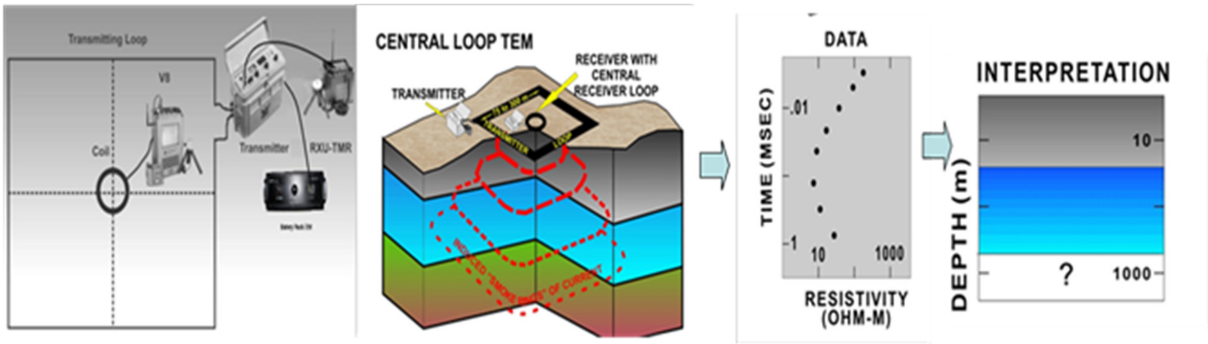

FIGURE 15: TEDM field layout, processing and interpretation process (modified from Cumming and Mackie, 2010)

$$\rho_a = \frac{\mu_0}{4\pi}\left[\frac{2\mu_0 A_r n_r A_s n_s I_0}{5t^{5/2}V(t,r)}\right]^{2/3}$$

where *Ar, As* = area of the receiver loop and the transmitter loop, respectively (m^2);
nr, ns = number of windings in the receiver loop and the transmitter loop, respectively;
Io = current sent through the transmitter loop (A);
T = time elapsed from the turn off (s);
μo = magnetic permeability (H/m).

This technique had been implemented in the geothermal exploration since 2004 in El Salvador. Figure 16 shows the results of the 120 TDEM sounding carried out in Ahuachapán Geothermal field. The resistivity map at 100 m depth as well as the resistivity profile shows the main alteration area, and a possible shallow aquifer.

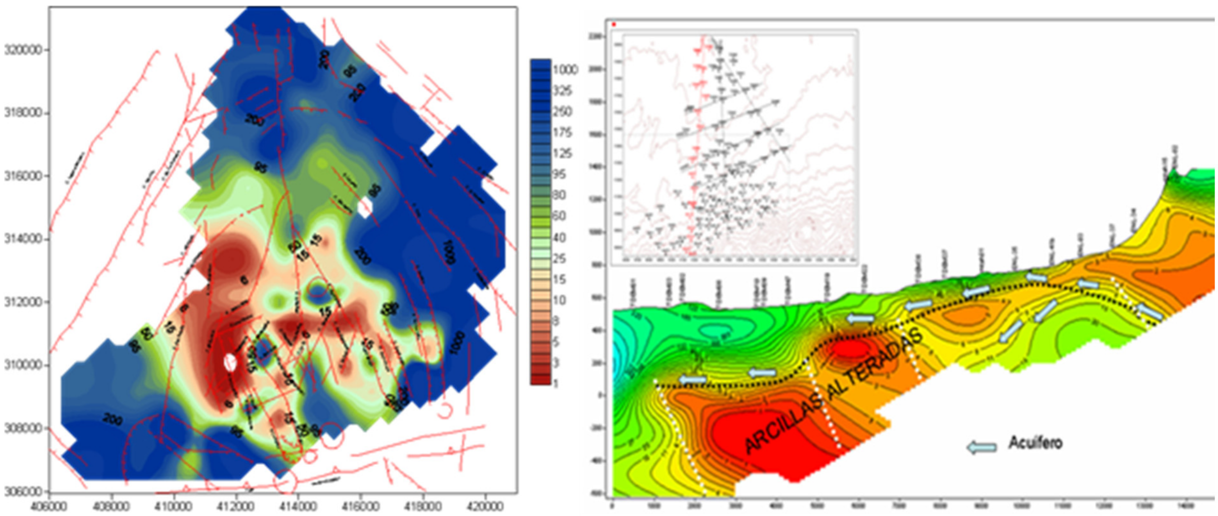

FIGURE 16: TDEM Resistivity map at 100 m depth and profile from Ahuachapán geothermal field

5. THE NATURAL SOURCE METHODS

The most common methods are the Magnetotelluric Method (MT) and self potential. In El Salvador, only the MT technique has been implemented in the exploration of the different geothermal fields.

5.1 The magnetotelluric method (MT)

The magnetotelluric (MT) method is a passive surface measurement of the earth's natural electrical (**E**) field and magnetic (**H**) field in orthogonal directions. It can be shown that the relationship between the horizontal orthogonal magnetic and electric fields depend on the subsurface resistivity structure. It is therefore used to determine the conductivity of the earth, ranging from a few tens of meters to several hundreds of kilometers. MT generally refers to recording of 10 kHz to 1000 s (0.001 Hz).

During field surveys (Figure 17), the magnetic fields are measured in the X (Hx), Y (Hy) and Z (Hz) directions and the induced electric fields are also measured in the X (Ex) and Y (Ey) directions forming 5 components. These measurements are taken over at different frequencies or time periods.

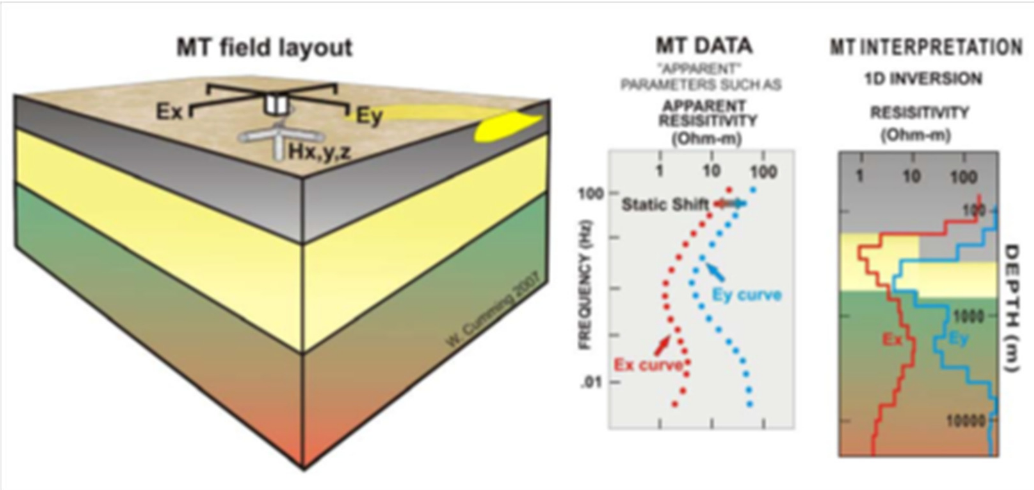

FIGURE17: MT field layout, processing and interpretation process (Cumming and Mackie,2010)

The resulting data is Fourier transformed and apparent resistivities in the two directions ρ_{xy} and ρ_{yx}, as well as the prospection depth calculated as a function of frequency (δ) and is shown in the next equation.

$$\rho_{xy} = \frac{1}{5f}\left|\frac{E_x}{H_y}\right|^2 \quad \rho_{yx} = \frac{1}{5f}\left|\frac{E_y}{H_x}\right|^2 \quad \delta = 355\sqrt{\frac{\rho}{f}}$$

In order to correct the low resolution of MT for higher frequency at the shallow levels; measurements of TDEM (Time Domain Electromagnetic Method) are done at the same MT location, because TDEM is able to resolve the shallow layers while MT would provide the deeper information. This technique was implemented in Berlin since 1994, more than 125 MT had been measured.

The 3D analysis interpretation of the MT data suggests that the geothermal propylitic reservoir is associated with an uplifted resistive body with a thin conductive cover, as is shown Figure 18.

Based on the results of geothermal wells drilled by ENEL at the southern part of the production zone, the MT model was adjusted to the well data, mainly to the temperature and mineralogy alteration. In this adjusted model, the producing reservoir corresponds to an uplifted resistive layer at depth, with resistivity values ranging form 40 to 90 ohm-m inside the resistive basement; at higher values, an inversion in the temperature curve is observed (Figure19).

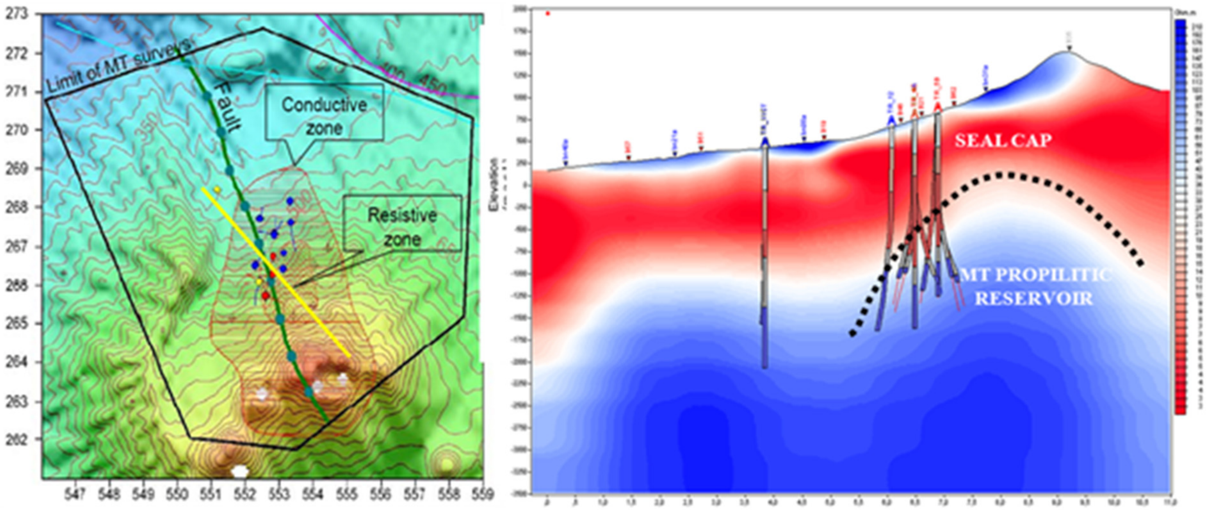

FIGURE 18: MT resistivity model of Berlin based on the 3D analysis data

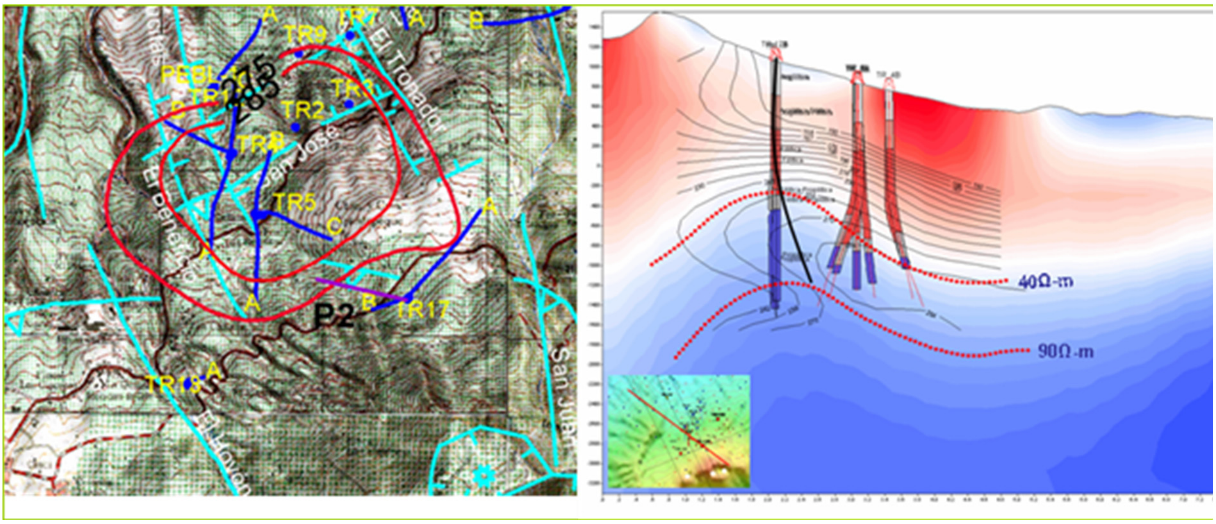

FIGURE 19: MT adjusted model based on the results of the drilled wells in the southern part of the production zone

6. CONCLUSIONS

The resistivity methods have been used in the exploration of the geothermal fields in El Salvador since the sixties; they have made an important contribution in the identification and characterization of the geothermal active system in the country.

The parameter of electrical resistivity gives information on temperature and alteration of the rocks with depth, which are major parameters for the understanding of the geothermal systems. Good correlation between the resistivity parameters and alteration, lithology, temperature, porosity, water saturation is observed.

The DC resistivity techniques such as Schlumberger, Misse a la masse, Dipole-dipole and head on were applied for decades, despite of the limited penetration capacity, they have contributed in delineating the major geothermal systems as well as defining drilling targets.

The natural source method (MT) combined with artificial source technique (TDEM) have demonstrated to be a powerful tool for estimating the size and the thickness of the producing reservoir;

the joint analysis of these techniques allows mapping the resistivity distribution from the very shallow level up to several kilometres depth.

The 3D analysis interpretation of the MT data suggests that the geothermal propylitic reservoir of Berlin is associated with an uplifted resistive body with a thin conductive cover. Based on the results of geothermal wells drilled by ENEL at the southern part of the production zone, the MT model was adjusted to the well data, mainly with the temperature and mineralogy alteration. In this adjusted model, the producing reservoir corresponds to an uplifted resistive layer at depth, with resistivity values ranging from 40 to 90 ohm-m inside the resistive basement; at higher values, an inversion in the temperature curve is observed.

REFERENCES

Anderson E. and Usher G., 2000: Bulls-Eye! - simple resistivity imaging to reliably locate the geothermal reservoir. *Proceedings of the World Geothermal Congress 2000,* Kyushu-Tohoku, Japan.

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., and Gudlaugsson, S.Th., 2000: The resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan,* 923-928.

Bromley, C. Khosrawi K. and Taebil B., 2000: Geophysical exploration of Sabalan geothermal prospects in Iran. *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan*.

Cumming, W., and R. Mackie, 2010: Resistivity imaging of geothermal resources using 1D, 2D and 3D MT inversion and TDEM static shift correction illustrated by a Glass Mountain case history. *Proceedings of the World Geothermal Congress 2010, Bali, Indonesia.*

Flóvenz, Ó.G.; 1984: Application of the head-on resistivity profiling method in geothermal exploration. *Geothermal Resources Council, Transactions, 8.*

Georgsson, L.S., and Karlsdóttir R., 2008: Resistivity methods - DC and TEM with examples and comparison from the Reykjanes peninsula and Öxarfjördur, Iceland. *Presented at Short Course III on Exploration for Geothermal Resources, organized by UNU-GTP and KenGen, Naivasha, Kenya,*15 pp.

Hersir G.P. and Bjornsson A.; 1991: *Geophysical exploration for geothermal resources, principles and application*. Geothermal Training Programme, Report 15, Iceland.

Manzella, A., 1995: *Geophysical methods in geothermal exploration*. Italian National Research Council.

Osiensky, I.L., and Donaldson, P.R., 1994: A modified Mìse-a-la-Masse method for contaminant plume delineation. *Ground water, 32-3*, 448-457.

Santos, P., 1995: 1D and 2D Interpretation of Schlumberger sounding of Berlin geothermal field. Report 11 in: *Geothermal training in Iceland 1995.* UNU-GTP, Iceland, 269-302.

WestJEC, 2001: *CSAMT and MT resistivity survey at Berlin geothermal field*. CEL, internal report

Zonge, K.L., 1992: Broad band electromagnetic systems. In: Van Blaricom, R. (ed.), *Practical geophysics II for the exploration geologist*. Northwest Mining Association, 439-523.

www.cflhd.gov/resources - The central federal lands highway division, webpage.

www.geofisica.cl - Geophysical topics, webpage.

www.fhwa.dot.gov/ - The federal highway administration, webpage.