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Transient Electromagnetic Resistivity Survey at the Geysir Geothermal Field South Iceland

Yohannes Demissie

Hydrogeology, Engineering Geology and Geothermal Studies Department, P.O.Box 8512, Addis Ababa, Ethiopia

gelogy@telecom.net.et

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ABSTRACT

A central loop Transient Electromagnetic TEM Resistivity Survey was conducted at the Geysir high temperature geothermal area as part the project of the author. The area is situated 110 km away from Reykjavik and lies in a shallow valley elongated north-south. Geologically it is surrounded by three volcanic domes made-up of rhyolites, hyloclastites and inter-glacial basaltic lava that obtain heat from an intrusive body. As a result of this survey a high resistivity temperature field is revealed beneath Geysir. The resistivity of the earth reflects the thermal alteration of the rock. High resistivity at the surface reflects fresh lava and low resistivity reflects water saturated rocks situated below the water table.

The high temperature field is characterized by a low resistivity cap underlain by high resistivity without confirmed evidence. This resistivity reflects the thermal alteration of the rock dependent on temperature. Hence, provided there is equilibrium between alteration and temperature, the resistivity measurements indicate temperature. The benefit of central loop TEM sounding method over the conventional DC method is clearly stated.

INTRODUCTION

The geophysical methods are broadly divided into two; active and passive. A passive geophysical method is the study of the earth's surface by using the natural fields of the earth. The natural field methods consist of gravity, magnetic, electrical and electromagnetic methods (Keary, P., and Brooks, M., 1992). Active geophysical methods involve generation of an artificial electrical or electromagnetic fields that may be used analogously to natural fields. The natural field methods provide information at greater depths of the earth than artificial source methods.

In geothermal exploration the task of geophysics is related to detection and delineation of geothermal resources, local exploitable reservoirs and sitting of drill holes through which hot fluids at depth can be extracted (Hersir and Björnsson, 1991). The most common geophysical methods in geothermal exploration are: electrical resistivity methods, (DC or AC resistivity methods), magnetic survey, SP survey and geophysical logging. In geothermal prospect the required information includes low resistivity bodies, dikes, faults, irregular shaped bodies and volcanic plugs.

In DC resistivity measurements, Schlumberger array is the most preferable configuration for improved vertical resolution at depths of up to about two km but for greater depth resolution magnetotelloric method is the best. It is very common to apply integrated geophysical methods rather than one single method in geothermal exploration. The choice of the geophysical method during the exploration of a geothermal field depends on the objective and the cost of the survey. It should be noted that there is no single method or combination of different methods that can be called optimum in all cases. The most suitable method may vary for different geothermal fields. In Iceland the thermal method, electrical resistivity and transient electromagnetic (TEM) methods and passive seismic stand out among the others in the study of geothermal reservoirs

The main reason for using resistivity methods in Iceland is that resistivity is more dependent on important reservoir parameters like temperature, porosity and fluid salinity than any other physical parameters that can be measured from the surface. It is also a cost-efficient prospecting method. The central loop transient electromagnetic sounding method has also several advantages over conventional DC sounding methods. The most important one is that, transmitter couples inductively to the earth and no current has to be injected into the ground (Árnason, 1989).

Central loop transient electromagnetic (TEM) survey was conducted at Geysir geothermal field and the surrounding areas as part of the project of the author of this report. The field trip was organized by the United Nations University, Geothermal training Program, ISOR, and Iceland Geosurvey. The duration of the field was August 6 to 14, 2003 and the main purpose of the field trip was to provide a basic knowledge of a geophysical survey of geothermal fields. A total of 9 stations were studied during the field season. Comparison of the results of the present TEM resistivity survey and the previously studied DC survey is included in this report. A 1-D inversion program for central loop transient electromagnetic soundings was used for an interpretation of the data. This report is a summary of the final project of the author at the end of the six months training which is provided by the United Nation University (UNU).

2. CENTRAL LOOP TRANSIENT ELECTROMAGNETIC (TEM) RESISTIVITY SURVEY AT THE GEYSIR GEOTHERMAL FIELD

2.1 Location and accessibility

The great Geysir geothermal field is located in the southern part of Iceland, about 110 km away from Reykjavik, the capital of Iceland. The Geysir is a special kind of a hot spring, which from time to time expels a column of water above the ground. The temperature of the erupting water is usually close to boiling or near 100°C.

Historically the Geysir was the property of an individual who gave it to the people in 1953. In 1953 a special group, The Geysir committee, was put in charge of the area and the following year the area was fenced off. The fence kept the livestock out and since then the vegetation has recovered much. In 1960 some shrubs were planted and now some 125 species of higher plants and 20 species of moss are found inside the fenced area. Even if the roads from Reykjavik to Geysir were accessible, the area is highly restricted due to the risk of stepping on altered ground and incurring injuries.

2.2 Instruments

TEM resistivity survey was conducted by using the instrument called Protem 67, 20 gate model from the Geonics Ltd. The main components of the equipment are a generator and a current transmitter, box, receiver and transmitter loops and a computer. During the current-off portions of the current wave form the receiver measures the time derivative of the vertical component of the magnetic field using both small coil with an effective area of 100m, and a flexible loop with an effective area of 5613m. The transmitter loop was a single turn square loop with 300m side length.

The maximum transmitted current is usually in the range of 20-40 A, and the transient signal is recorded in the time interval of 0.087-70 ms at 20 logarithmically spaced channels after it is turned off. Both the transmitter and the receiver timing are controlled by synchronized high-precision crystal clocks. The induced voltage is measured by the receiver each time after the transmitter is turned off. Data were recorded for two transmitter frequencies. At high frequency, the repetition rate of transmitted current signal is 25 Hz, with 10 ms current-off segments. At low frequency, the repetition rate is 2.5 Hz, with current-off segments of 100ms. Repeated transients are stacked and stored in the computer memory of the receiver and later downloaded to a PC computer.

2.3 Results of the TEM-survey

An example of TEM sounding and its interpretation is given in Figure 1 that shows TEM station 28316. The interpretation of the sounding assumes five layers. Two layers of relatively high resistivity reach down to almost 200 m depth reflecting un-altered rocks close to the surface Below 200m depth there is a layer of moderate resistivity (30 ohm-m), the decrease in the resistivity most likely due to increased low- temperature alteration and temperature. At approximately 325 m depth, a thick (574m) low resistivity layer of 6.5ohm-m is seen. This is the low resistivity defining the high temperature field below a little rise in the resistivity with depth is indicated though still within 10 ohm-m.

Results of TEM soundings survey at the Geysir geothermal field reveals the sequence of the resistivity distribution of the rock formation at depth. The resistivity in the upper most 100-400m is generally quite high, ranging between 200 and 3000 ohm-m except within the thermally altered surface area where it is lower. As has been discussed previously, the high resistivity is correlated with fresh basalt and un-altered rhyolitic rocks near Laugarfjall. Thermal alteration is minimal in these rocks. Below that, the resisitivity is generally low to very low, and to some level it obviously influenced by the high temperature geothermal activity, with resistivity on the order of 1-10 ohm-m.

2.3 The resistivity structure of the Geysir area

The characteristic resistivity structure of a high temperature field in Iceland is low resistivity cap underlain by a high resistivity core. The low resistivity is defined by resistivity value in the range of 1-10 ohm-m in fresh water system. The high resistivity core has resistivity at least an order of magnitude higher than that of the low resistivity cap. The outer margin of the low resistivity cap delineated the high temperature field within a crust not influenced by high-temperature alteration.

Figure 2 shows cross-section AB through the Geysir high temperature field from the TEM survey. The location is along the line A-B oriented NE-SW. It shows the characteristics of a geothermal field with very low resistivity, 1-10 ohm-m, in the vicinity of geothermal area, but without a certain sign of high - resistivity core down to at least 800 m depth. Low resistivity of 5-10 ohm-m, is found at the outskirts and at upper levels, but underlain by resistivity of < 5 ohm-m. Three soundings 324338,330341, and 340347 shows a similar character with a body of high resistivity found between low-resistivity layers. These features could have various explanations. One is dense intrusion with less porosity than the surrounding rocks, but that cannot be verified as there are no drill holes in the area. Being only seen in the soundings on this cross-section there is no knowledge of the extent of this high – resistivity body. This could even be explained by a 3-D effect, but verifying that would require more soundings and computer software not within the task of this report. Outside the reservoir delineated by the low resistivity, the cross-section shows a resisitivity structure of unaltered rock at upper levels, and slightly altered rocks at deeper levels.

The resistivity structure of most high temperature fields reflects the thermal alteration. The low-resistivity cap within the resistivity < 10 ohm-m in fresh water systems corresponds to the smectite-zeolite zone. The resistivity increases in the mixed layered clay zone due to increasing chlorite and decreasing smectite. The high resistivity core corresponds to the chlorite-epidote zone. Provided there is equilibrium between alteration and temperature, the resistivity structure relates directly to temperature.

In the Geysir area, no high resistivity core is seen, or it is found at deeper levels than seen by the TEM soundings presented here. Chemical evidence states that the Geysir area is definitely a high- temperature system with a temperature of 220-240 °C (Pasvanoglu, 1998). The resistivity structure seen in cross-section A-B (figure 11) and in other soundings of the TEM – survey at the Geysir field presented here seem to indicate that the temperatures in excess of 220-230 °C are not reached in the uppermost kilometre.

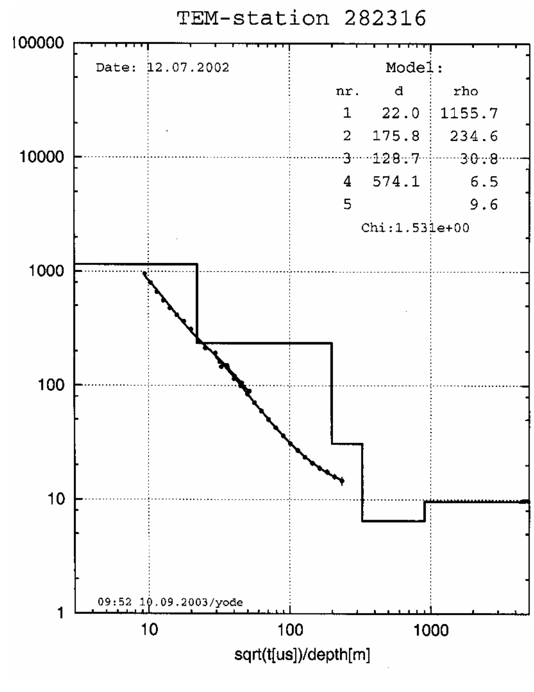

FIGURE 1: TEM sounding curve for station 282316

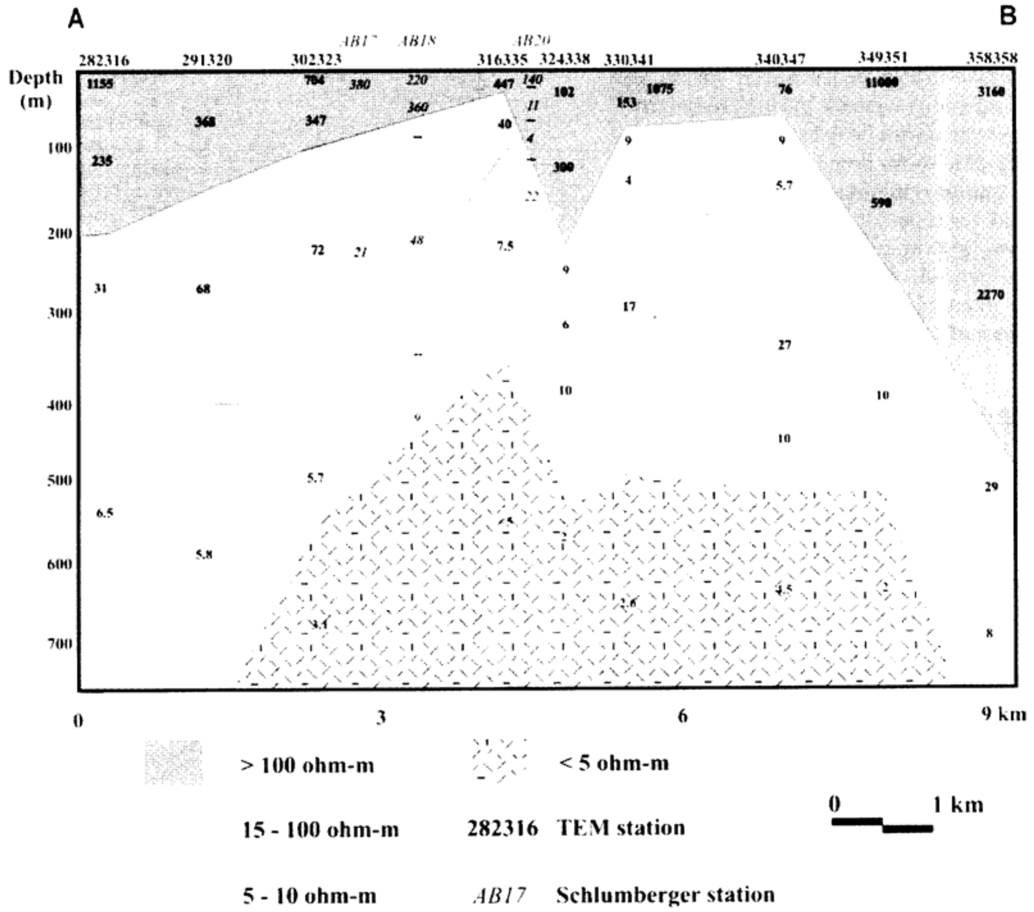

Figure 2: TEM cross-section A-B

2.4 Relationship between a temperature log and the resistivity structure

One of the most important aspect of the TEM resistivity survey at the Geysir geothermal field is, that it is helpful to locate the site of the reservoir and it's resistivity in general and the relationship between resistivity and temperature of that reservoir in particular. The temperature and hence the thermal alteration increases with depth. Due to water rock interaction and chemical transport by geothermal fluids, the primary minerals in the host rock matrix are transformed, or altered into different minerals. The alteration process and the resulting type of alteration minerals are dependent on the type of primary minerals, chemical composition of the geothermal fluid and temperature. The intensity of alteration is furthermore dependent on the temperature, but also on time and texture of the host rocks. The geothermal fluids can be divided into two relatively homogenous type, i.e. low salinity or fresh water and saline fluids. Due to this homogeneity, the stability and formation of alteration minerals is mainly dependent on temperature (Árnason et al., 2000).

In the Geysir geothermal field, the TEM survey reveals the sequence of the temperature distribution of the rock formation at depth. Provided there is equilibrium below thermal alteration and temperature at present. As it has been discussed partly in the previous chapters, the low temperature 50-100 °C is correlated with fresh basalts, post glacial lava and un-altered rhyolitic rocks. The resistivity characteristic of this region is very high which is ranging between 220-3155 Ohm-m. This is a region where thermal alteration of rocks and minerals will be started but not come into existence. The temperature at the surface shows that the drill hole is artesian yielding 5l/sec of 70°C water Hence, at 300 meter depth, the temperature log map is correlated with all resistivity maps of TEM soundings and also the same with DC sounding curve.

When we transfer to the second horizon, the resistivity starts to decline from high value (> 220 Ohm-m) into low value (10-100 Ohm-m). In this region it is clearly observed how the resistivity of a rock is affected by the intensity of alteration in that region. The transformation from high resistivity to low resistivity is resulted from degree of alteration in the rocks at depth below 300 meter. In the high resistivity zone there was only a circulation of cold water and hence, no alteration is seen temperature gradient was also very small. In contrary, in the low resistivity zone there is an increase in intensity of alteration and smectite-zeolite zone is formed. In the well log this region is located by a high temperature gradient (>200°C/km) at a depth below 300 meter.

As it has been shown in the cross-section map figure 2 and data from the temperature log, low resistivity formation is started from 250-300 metre depth, which is the possible depth of the cap rock. The resistivity of this cap-rock is < 10 Ohm-m where the estimated boundary of reservoir is situated. Figures 2 and borehole data are correlated with each other by having low resitivity zone in the cross-section and high temperature gradient in well log data. The high resistivity zone in the DC sounding is in good agreement with temperature log.

3. ADVANTAGE OF TEM METHOD OVER CONVENTIONAL DC METHOD

In the following section, various advantages of TEM sounding method over a conventional DC resistivity method is summarised.

- The transmitter couples inductively to the earth and no current has to be injected into the ground. In the places where the surface is dry and resistive, it is most important method.

- The monitored signal is decaying magnetic field not the electric field which makes the TEM measurement much less dependent on local resistivity conditions at the receiver site. Distortion due to local resistivity inhomogenities at the receiver site can be a sever problem in DC measurements.

- With respect to DC method, TEM is less sensitive to lateral resitivity.

- In DC-sounding the monitored signal is low when subsurface resistivity is low, as in geothermal areas, whereas in TEM soundings the situation is reverse, the lower the resistivity the stronger the signal.

- Central-loop TEM is more downward focused than the DC-soundings. To increase depth of penetration in DC measurements, one needs to increase the electrode spacing and this evolves a large volume of rocks that could affect the monitored electric field significantly. This makes one-dimensional inversion better justified in the interpretation of central-loop TEM sounding than in DC-sounding.

- Performing a TEM-sounding takes less manpower than performing a DC-schlumberger sounding.

- With the instruments used in this survey, the DC-soundings have a better resolution in the upper most 50-100 meters where as the TEM-soundings have a better resolution at depth.

CONCLUSION

A total of 9 stations were interpreted from TEM resistivity survey conducted at and in the vicinity of the Geysir geothermal field. Results of a previous DC resistivity survey and data from well ND-1 at Nedridalur are also used for comparison. The data interpretation of the TEM survey was done by one-dimensional inversion program CLTINV. The interpreted data are presented in the form of cross-section and data curves and models. Based on the results of TEM measurements at the Geysir geothermal field, the reveals sequence of resistivity distribution of the rock formation in the uppermost kilometer. The resistivity in the uppermost 100 – 400 m is quite high ranging between 200 and 300 ohm-m. This high resistivity close to the surface is correlated with fresh basalt and un-altered rhyolitic rocks. Thermal alteration is minimal in the in the rocks. Below that, the resistivity is low, and at some level it is obviously influenced by the high temperature geothermal activity, indicated by 1-10 ohm-m The lowest values are found close to the Geysir area.

The resistivity cross-section of the Geysir high temperature geothermal field shows characteristic of a geothermal system with very low resistivity at depth, 1-5 ohm-m, around the Geysir area, but without conformed evidence of evidence of high resistivity in the central part of the geothermal system. Provided there is equilibrium between thermal alteration of the rock and present temperature, the resistivity survey might indicate temperature as high as 200-220 °C in the uppermost kilometer of the geothermal system, but not exceeding that, as there is no sign of high resistivity core. Chemical evidence indicates temperatures of 220=240 °C in the geothermal system, agreeing fairly with the resistivity.

The well ND -1 about 2 km southwest of the Geysir fields, is located close to TEM station 302323 and shows that the temperature gradient is very high, or about 220 °C /km. This indicates that below 350-400 m depth (temperature above 70 °C), the smectite – zeolite zone has been reached. This alteration zone is associated with quite low resistivity, here < 10 ohm-m. The well penetrates the outskirts of the geothermal system that results in this high thermal gradient.

TEM soundings are more effective in the survey of geothermal fields than the conventional DC method. There may be various reasons for this conclusion; the main one is that TEM has more depth penetration than DC method and a better resolution.

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