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RESISTIVITY METHODS - DC AND TEM WITH EXAMPLES AND COMPARISON FROM THE REYKJANES PENINSULA AND ÖXARFJÖRDUR, ICELAND

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ABSTRACT

Resistivity methods have for a long time been proven as the most successful method in geothermal exploration, due to the resistivity of rocks in geothermal environment being chiefly controlled by parameters that correlate to the geothermal activity. The most important method for measuring the resistivity in the uppermost kilometre was for a long time the DC resistivity method, especially with the Schlumberger configuration. It was in the 1990's replaced by the TEM method, more specifically the central loop TEM sounding method, as the routine method for the exploring the uppermost kilometre. Description is given of both methods and their differences discussed. Then examples are taken from two geothermal areas in Iceland, the outer Reykjanes Peninsula and the Öxarfjördur area, where surveys using both methods have been done. The results are discussed and conclusions drawn that confirm the advantage of TEM over the DC method.

1. INTRODUCTION

Resistivity methods have been used in geothermal research since the 1940s and since the 1960s they have been the most important geophysical methods in the surface exploration of geothermal areas, and as such key methods in delineating geothermal resources and production fields. The parameter of interest is the electrical resistivity which in geothermal areas gives information on temperature and alteration of the rocks with depth which are major parameters for the understanding of the geothermal systems.

The main principle is that electrical current is induced into the earth which generates an electromagnetic signal that is monitored at the surface. There are many different methods and varying setups or configurations for the different methods. The most important methods are:

DC methods, where current is injected into the earth through electrodes at the surface generating an electric field at the surface. The electrical field is measured. Based on that and the geometry of the set-up, the electrical resistivity of the rock structures below is calculated. The DC methods can be grouped into several types and in addition there can be different geometrical configurations.

TEM methods, where current is induced by a time varying magnetic field from a controlled source , thus secondary magnetic field is created that consequently creates secondary currents in the earth. The monitored signal is the voltage induced at surface in a receiver coil due to the decaying secondary magnetic field. Here there are also different possibilities in the set-up.

MT or Natural-source electromagnetics, where the current is induced by the time variations in earth's natural magnetic field, and the signal measured is the electromagnetic field at the surface.

Distinction is made between **soundings**, which are used for mapping resistivity changes with depth, and **profiling** where the whole array is moved along profile lines for mapping lateral changes of the resistivity.

In this paper the DC and TEM methods are presented with emphasis on the Schlumberger method (DC) and the Central loop TEM method. The basis is the experience gained in Iceland through the years in using these methods, with DC methods having been used in geothermal exploration from its infancy in the late 1940s and TEM from the late 1980s. For further information see e.g. Hersir and Björnsson (1991), Árnason and Flóvenz (1992) and Keary and Brooks (1992).

2. RESISTIVITY OF ROCKS

Electrical resistivity of rocks in geothermal surroundings is a parameter which reflects the properties and history of the geothermal system. Thus, a good knowledge on the resistivity is very valuable for the understanding of the geothermal system. This relates to the fact that **the resistivity of rocks is chiefly controlled by parameters that correlate to the geothermal activity**, such as:

- Porosity and pore structure, where distinction is made between:
    - Intergranular porosity such as in sedimentary rocks;
    - Fracture porosity, relating to tension, fracturing or cooling of igneous rocks;
    - Vugular porosity which relates to dissolving of material (limestone) or gas content (in volcanic magma).
- Alteration of the rocks – often related to as water-rock interaction;
- Salinity of the fluid in the pores;
- Temperature;
- Amount of water, saturation or steam content; and
- (Pressure)

The four first, namely fracture porosity, alteration, salinity of the fluid, and temperature, are the most important ones. That also explains why the resistivity is so important in geothermal exploration, especially in volcanic surroundings, and the important role of resistivity soundings. Further discussion on resistivity of rocks and its correlation to the properties of geothermal systems will not be given here, but the reader is referred to Árnason et al. (2000) for further information.

3. DC METHODS – SCHLUMBERGER SOUNDING

The important relationship behind DC resistivity methods is the **Ohm's law:**

$$\vec{E} = \rho \vec{j}$$

where $\vec{E}$ is electrical field strength (V/m);
$\vec{j}$ is current density (A/m^2); and
ρ is electrical resistivity (Ωm), which is a material constant.

For a homogenous earth and a single current source (Figure 1), the relevant equation for the electrical potential *V*, at a distance *r* from the current source *I,* becomes:

$$V_r = \rho I / 2\pi r, \quad \text{or} \quad \rho = 2\pi r V_r / I$$

This is the key equation to calculate the resistivity for all the different DC configurations.

Most configurations rely on **two pairs of electrodes** – one pair for current transmission and the other for measuring the potential difference. The most common DC methods are:

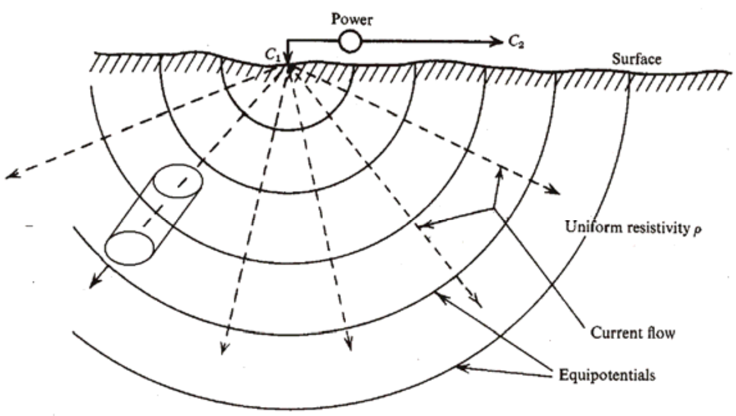
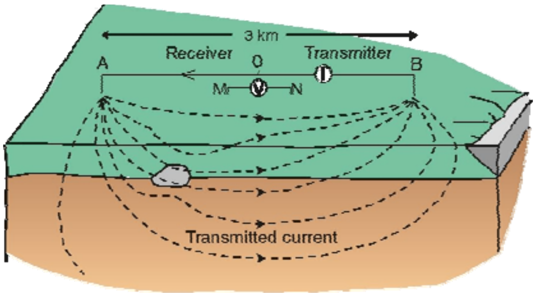


FIGURE 1: Current distribution around a single current electrode in the earth (Keary and Brooks, 1992)

- **Schlumberger sounding,** which has been widely used and is the most popular one (Figure 2). The electrodes are on a line, and the set up is mirrored around the centre. The pair of potential electrodes is kept close to the centre, while the pair of current electrodes is gradually moved away from the centre, for the current to probe deeper into the earth. The distance between the current electrodes is increased in near-logarithmic steps until the scheduled maximum length of the current arm has been reached. Conventional soundings may have a maximum current arm AB/2 of approximately 1.5 km;
- **Dipole sounding or profiling**; here various arrays exis; many used quite much in the 1970s into the 1980s;
- **Wenner sounding**, not much used today, but quite similar to Schlumberger. The electrodes are on a line but the same distance is always kept between all of them.
- **Head-on profiling,** a successful method for locating near-surface vertical fractures or faults. It is really a variety of the Schlumberger method with a third current electrode located far away at a right angle to the profile line.



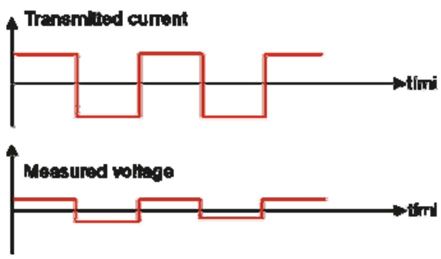


FIGURE 2: The principles behind the Schlumberger configuration and the associated current distribution in the earth

Necessary **equipment** for DC soundings is a good current transmitter able to transmit at least 0.5-1 A, a sensitive voltage receiver, wires on reels, electrodes, and a power source. Using (car) batteries as a source for the current transmitter, the equipment is not very bulky, and usually possible to carry on foot for measurements in areas where access by car is not possible. Good DC equipment is marketed by many companies selling geophysical instruments.

The earth is not homogeneous so what we are looking at is a sort of average resistivity of the earth below the measuring site within a certain depth range. This "average" resistivity is usually referred to as **apparent resistivity, ρ_a.** In the case of Schlumberger soundings, the relationship for apparent resistivity can easily be derived from the equation above and is given as:

$$\rho_a = \Delta V/I \times (S^2 - P^2)\pi/2P$$

where S = AB/2 and P = MN/2.

Apparent resistivity is plotted as a function of AB/2 on a bilogarithmic scale with increasing electrode separation (Figure 3). The curve does reflect the true image of the resistivity distribution in the earth below, as can be inferred from the 1D interpretation shown with it.

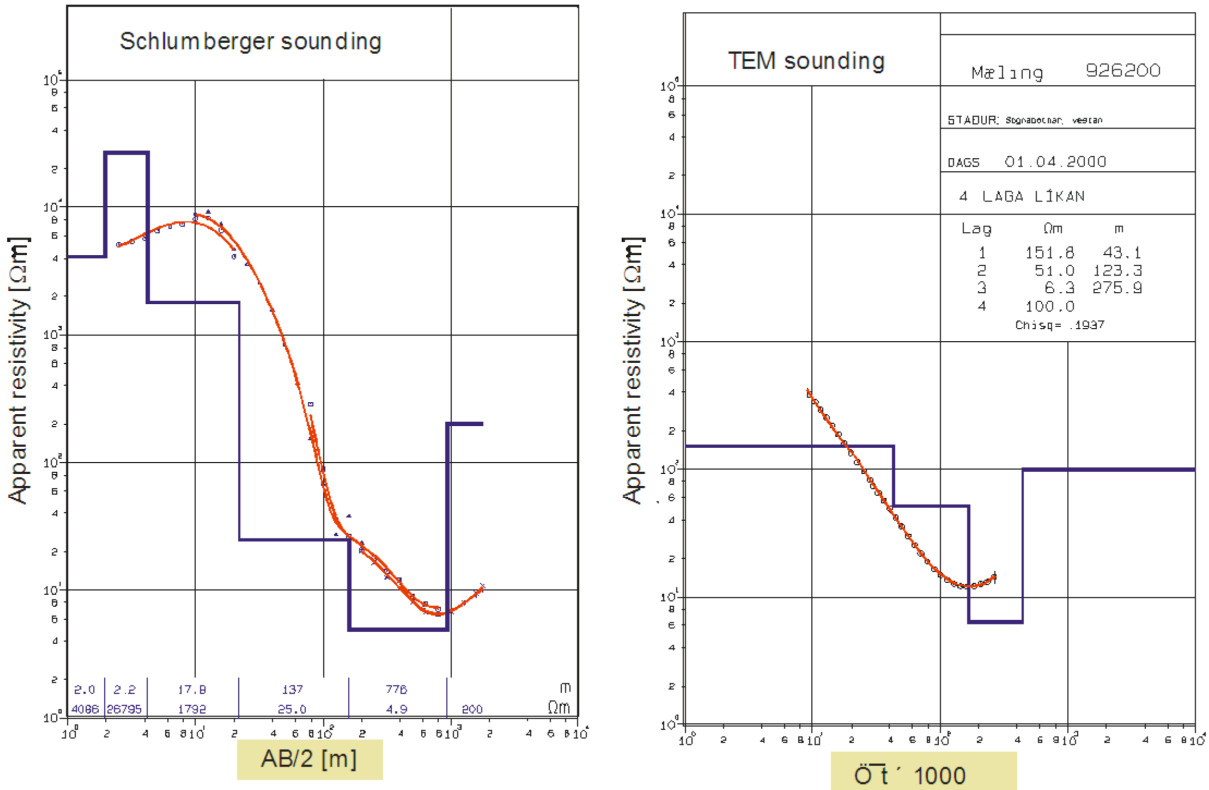


FIGURE 3: Curves showing a typical Schlumberger sounding (left) and a TEM sounding (right) and 1D models for their interpretation

Schlumberger soundings are usually extended to a maximum current arm, AB/2, of 1-2 km, but much longer current arms have been used. But in practice, much longer wire distances can be difficult to control. For the depth penetration of the sounding, a rule of thumb says that it reaches down to about 1/3 of the distance AB, the actual resistivity structure may, however, influence this significantly, usually to a lower value. In principle, the distance between the potential electrodes MN, should be small and fixed, but in practice it needs to be enlarged a few times to increase the measured signal. It is, however, important for it to be kept at all times within 20% of that of the distance between the current electrodes. Due to this increase in MN, the sounding curve consists of a few segments that usually, if local anomalies can be avoided, are well tied together (Figure 3).

For effective measurements, a minimum number of persons in a **field crew** is four, one for extending each current arm, and two for the potential electrodes and measuring equipment. Under good conditions they might be expected to make about 2 soundings per day, and even 3 may be reached under optimal conditions. To this number, extra crew members can be added according to the necessities of the actual project, conditions or routine, such as for cutting down vegetation along the profile, carrying equipment, security etc.

4. THE TEM METHOD

The TEM method uses a magnetic field to induce currents in the earth. In the central loop TEM sounding method (referred to as TEM only from now on), constant magnetic field is built up by transmitting current through a big loop. The current is abruptly turned off. The decaying magnetic field induces secondary currents and a secondary magnetic field, decaying with time. This decay rate of the secondary field is monitored by measuring the voltage induced in a receiver coil (or a small loop) in the centre of the transmitting loop. Current distribution and the decay rate, recorded as a function of time, depend on the resistivity distribution of the earth, and can be interpreted in terms of the subsurface resistivity structures. Other methods may be based on a grounded dipole to create the primary magnetic field. The TEM method is a fairly recent addition to the resistivity methods used in geothermal exploration, developed in the late 1980s.

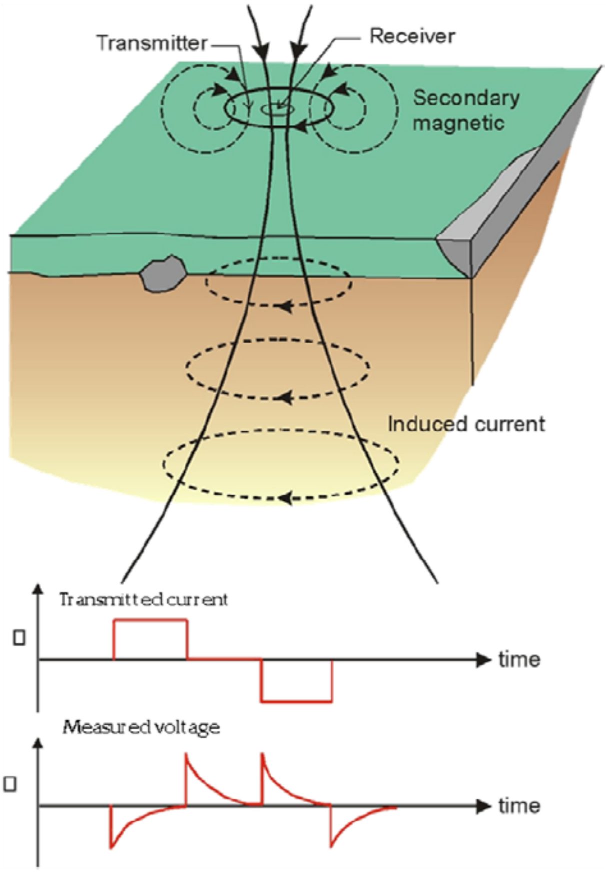


FIGURE 4: The principles behind TEM soundings and the expected magnetic and current distribution in the earth

Figure 4 shows the actual lay-out for a TEM sounding. When the current in the big loop is turned off and the primary magnetic field decays, secondary currents are induced that gradually migrate to deeper levels. The secondary induced magnetic field is monitored by the receiver loop and a receiver in the centre of the survey. Readings are done from the turn-off at fixed intervals during the decay of the secondary magnetic field as it approaches zero, the last ones reaching the deepest structures.

The measured resistivity in the subsurface is, similarly to the Schlumberger soundings, expressed as **apparent resistivity ρ_a,** 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, ρ_a, expressed in terms of induced voltage $V(t, r)$ at late times after the source current is turned off, is given by:

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

where A_r, A_s = The area of the receiver loop and the transmitter loop, respectively (m^2);
n_r, n_s = The number of windings in the receiver loop and the transmitter loop, respectively;
I_o = The current sent through the transmitter loop (A);
t = Time elapsed from the turn off (s);
μ_o = Magnetic permeability (H/m).

For a layered earth the expression is much more complicated. See Árnason (1989) for further information and details.

Apparent resistivity is plotted as a function of time after the current was turned off (Figure 3). The graph resembles the Schlumberger sounding graphically. However, it does not reflect the image of the true resistivity as the Schlumberger sounding.

TEM **equipment** is sophisticated and relatively expensive, at least compared to DC equipment. Besides the receiver including a datalogger, a transmitter is required connected to a good electric generator able to generate high currents (the order of 10 A) and thus a strong magnetic field through the transmitting loop. The heavy generator makes it difficult to do measurements by carrying the equipment on foot. In addition, a measuring coil and wires for the loops are needed, the current wires need to be able to carry heavy current. Finally, a field computer is necessary to make preliminary interpretations at the end of a day's work for data quality assessment.

A minimum of three **field crew** members is needed for making TEM soundings and only two if the soundings are carried out on snow-covered earth by the help of snow scooters. They may be able to carry out 4-5 soundings in a day if they are well trained and the conditions are good.

In practice, the big transmitting loop is usually a square with a side of 150-300 m. With good conventional TEM equipment and a transmitter loop 300×300 m, with TEM it is possible to study resistivity structures down to depth levels of approx. 1 km.

5. INTERPRETATION

Apparent resistivity does not show the true resistivity structure of the earth and needs to be interpreted in terms of the actual resistivity distribution. The procedures are similar whether we are considering Schlumberger soundings or TEM soundings. In the interpretation, reference is usually made to the restrictions in the geometry of the resistivity structures:

- **1D** interpretation means that the resistivity distribution is assumed to resemble a horizontally layered earth, where the horizontal layers are assumed to stretch at least well outside the boundaries of the sounding.
- **2D** interpretation means that the resistivity distribution is assumed to be constant in one direction, which usually agrees with the direction of the main structures or the geological strike in the area. Soundings are made along a profile line which should be perpendicular to the strike line. Good data density is required along the profile line, with not more than 1-2 km between soundings. 2D interpretation also allows building into the interpretation variations in the terrain and thus necessary terrain corrections.
- **3D** interpretation allows the resistivity to vary in all directions. For a meaningful 3D interpretation a high data density is requested with a good spread of the different soundings, preferably in a net or close to that.

In the beginning, manual 1D interpretation of Schlumberger soundings was the state of the art, done with the help of master curves that were published in large volumes, but here computers took over in the late 1970s. We distinguish between forward and inverse modelling.

Forward modelling is really the first step in the inversion process. When the data has been plotted on a graph, a model is suggested to fit the resistivity distribution presented in the sounding. The forward algorithm simulates the response of the earth to the measuring equipment by calculating the response of the model to be compared to the actual data. The data and the response are compared and improvements suggested to the model to improve the interpretation. Thus, the interpreter can continue to improve his model until a satisfactory agreement is reached.

Inversion algorithms take care of the improvement of the model, and produce a "best" solution. This they do by improving the model, first by calculating the difference between the measured data and the response of the model, then suggesting improvements, recalculating the response based on the improved model and thus continuing until a satisfactory agreement has been reached. These calculations (Figure 5) are based on iterative procedures and some conditions built into the actual program, such as how many layers a sounding may have, how good the agreement needs to be, etc.

Usually good 1D interpretation of soundings is the starting model for a more complicated interpretation. The programs for interpretation can both be complicated and computer demanding. Programs for 3D interpretation require both very sophisticated software and high capacity computers, and a good and evenly distributed data coverage.

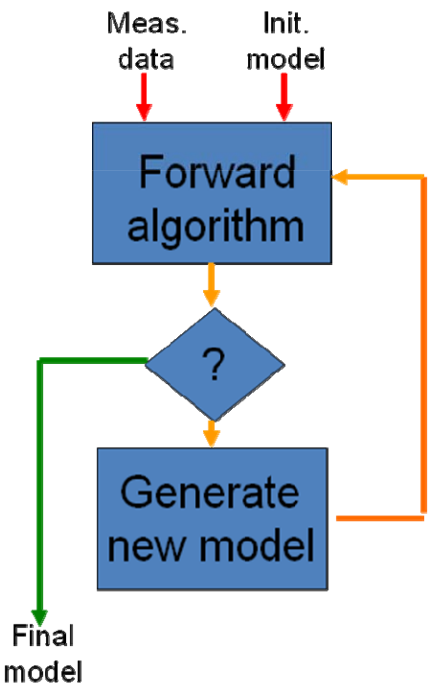


FIGURE 5: Flow diagram showing how a forward model is used as a starting model for the inversion (Árnason, pers. comm.)

Inversion programs have been available for 1D interpretation of Schlumberger and TEM soundings for decades. Interpretation using Occam inversion improves the resolution even further by assuming „continuously" changing resistivity instead of a few specific layers. 2D forward interpretation programs have also been available for Schlumberger soundings for a long time, while inversion algorithms are now also available. With a 3D signal source 2D has no real meaning for TEM. For 3D interpretation, forward modelling is available for both Schlumberger and TEM soundings. Inversion is now also available for DC soundings and is within reach for TEM, even though it is more of academic interest than practical due to the extra computer demanding calculations (K. Árnason, personal comm.).

The interpreted resistivity data is usually presented in resistivity contour maps and cross-sections. The contour maps show the resistivity distribution at specific depth levels, usually compared to sea level, while the cross-sections show the resistivity changes with depth along a profile line.

6. COMPARISON OF SCHLUMBERGER AND TEM SOUNDINGS

6.1 Advantages and disadvantages

The TEM method has many advantages over the Schlumberger DC sounding method. They relate to several facts, such as the method of transmitting the signal, and the simplicity of the field work. The main advantages are:

- In TEM, no current has to be injected into the earth and shorter wires (though heavier) are used. This is important in areas where the contact resistivity in the surface is very high and thus current transmission difficult, such as in deserts, lava fields and cold areas, making data collection even possible on snow and ice, or bare rock.
- In TEM, distortions due to local inhomogeneities are small, due to the signal (the downward migrating currents) being more downward focussed
- Similarly, TEM is much less sensitive to lateral resistivity variations than DC methods. Thus, 1-D interpretation is much better justified.
- In DC-soundings the monitored signal is low when surveying over low-resistivity structures like in geothermal areas, but strong in TEM-soundings, increasing depth penetration in target areas.

- Finally, TEM needs less manpower, both in the field and for interpretation; and measurements are considerably faster to carry out. Thus it is more cost effective, or allows collection of data in higher density, and consequently giving a more detailed model of the geothermal system.

In the following two subsections examples are taken from two geothermal fields in Iceland and the results of Schlumberger and TEM soundings compared. There are not many geothermal fields where "state of the art" surveys (for its time) have been carried out with both Schlumberger soundings and TEM soundings, and drilling been done to test the results, but this has been done on the outer Reykjanes Peninsula, SW-Iceland and in the Öxarfjördur area, NE-Iceland.

6.2 Results from the outer Reykjanes Peninsula, SW-Iceland

Figure 6 shows the Reykjanes Peninsula in SW-Iceland, the active volcanic fissure swarms and the high-temperature geothermal systems found on the outer part of the Peninsula. They are (from west) the Reykjanes field, where a new 100 MWe power plant went on-line in late 2006, Eldvörp and Svartsengi where the Svartsengi power plant is located producing now 76 MWe (December 2007) and 150 MWth. A by-product of the latter is the famous Blue Lagoon. The area is flat and mainly covered with Holocene lavas with occasional low hyaloclastite mountains dating from the glacial period breaking through the flatness. The elevation is mainly at 10-40 m a.s.l.

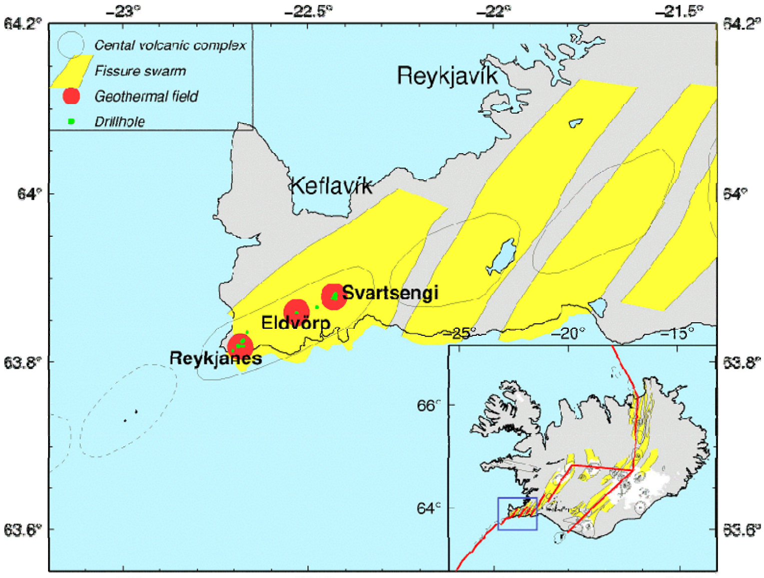


FIGURE 6: The volcanic systems and high-temperature areas on the outer Reykjanes Peninsula, SW-Iceland (H. Eysteinsson, pers. comm.)

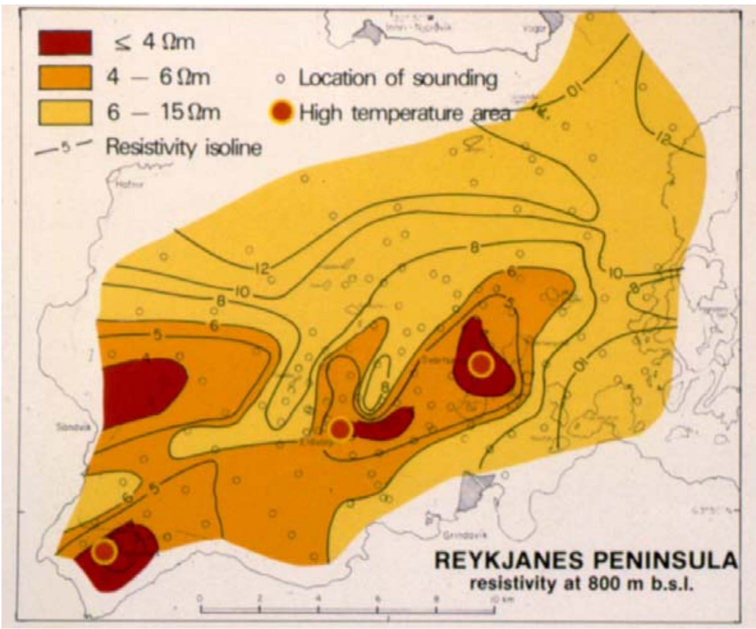


FIGURE 7: DC resistivity map of the outer Reykjanes Peninsula at 800 m b.s.l. (Georgsson, 1984)

The DC survey on the outer Reykjanes Peninsula (Figure 7) was done in the mid 1970s and early 1980s (Georgsson, 1984). The target area was covered with around 150 Schlumberger soundings with maximum current arms around 1500 m. It could prove quite difficult to get satisfactory data for the last few data points in some of the soundings, so the actual maximum current arm was in the range 800-1560 m. With very rough lava fields covering parts of the area, the terrain can be difficult to traverse, so carrying the equipment on foot was the only option in some locations.

The geohydrological situation is also quite unusual. The whole of the outer part of the peninsula has saline groundwater, with seawater having penetrated through it. Floating on the seawater, like ice on water, is a lens of freshwater, usually with a thickness of 40-50 m. With the actual density contrasts (approx. 1:35) it gives an elevation of the ground water table at 1-1.5 m. Above that the rocks consist of dry lavas. The salinity of the groundwater means that the regional resistivity in the area is quite low, about 10 Ωm.

Figure 7 shows a resistivity map of the area at 800 m b.s.l. based on the Schlumberger soundings. It shows a low-resistivity zone along the target area with a resistivity below 8 Ωm, and anomalies of extra low resistivity, 2-4 Ωm, outlining the active high-temperature fields. Of interest is an additional low-resistivity anomaly 2-3 km to the north of the Reykjanes field, indicating existence of possible new field there.

Figure 8 shows a NW-SE trending resistivity cross-section through the Svartsengi field, and illuminates very well both the special resistivity distribution in the area with its horizontal layers that relate to the geohydrological situation, and the low-resistivity anomaly associated with the Svartsengi high-temperature field. It also explains why 1D interpretation is believed to be adequate for the Schlumberger soundings.

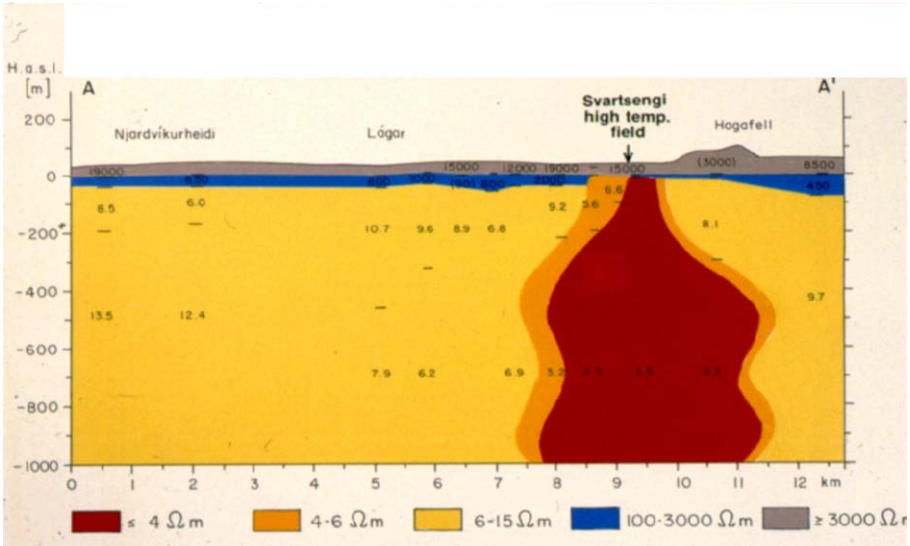


FIGURE 8: DC resistivity cross-section trending NW-SE through the Svartsengi geothermal field, Reykjanes Peninsula (Georgsson, 1984)

The TEM survey dates from the mid 1990s (Karlsdóttir, 1997). Figure 9 shows the elevation of the top of the high-resistivity layer seen in TEM measurements in the area. Even though this is a very different way of presenting the data, the same anomalies are seen associated with the high-temperature activity and even the fourth anomalous area is seen. The difference is that here high resistivity below low resistivity is being shown, which could not be established with certainty in the Schlumberger soundings even though its presence was suspected. A high-resistivity core is something that characterizes high-temperature fields in Iceland, and is associated with changes in alteration mineralogy with depth and temperatures, from smectites and mixed-layer clays to chlorite and epidote, which happens above 240-250°C (Árnason et al., 2000).

In Figure 10 there is a WSW-ENE trending resistivity cross-section along the active high-temperature fields based on TEM data. It shows the existence of the high-resistivity core overlain by a low-resistivity cap. Furthermore, it shows well the close connection between the Eldvörp and Svartsengi fields.

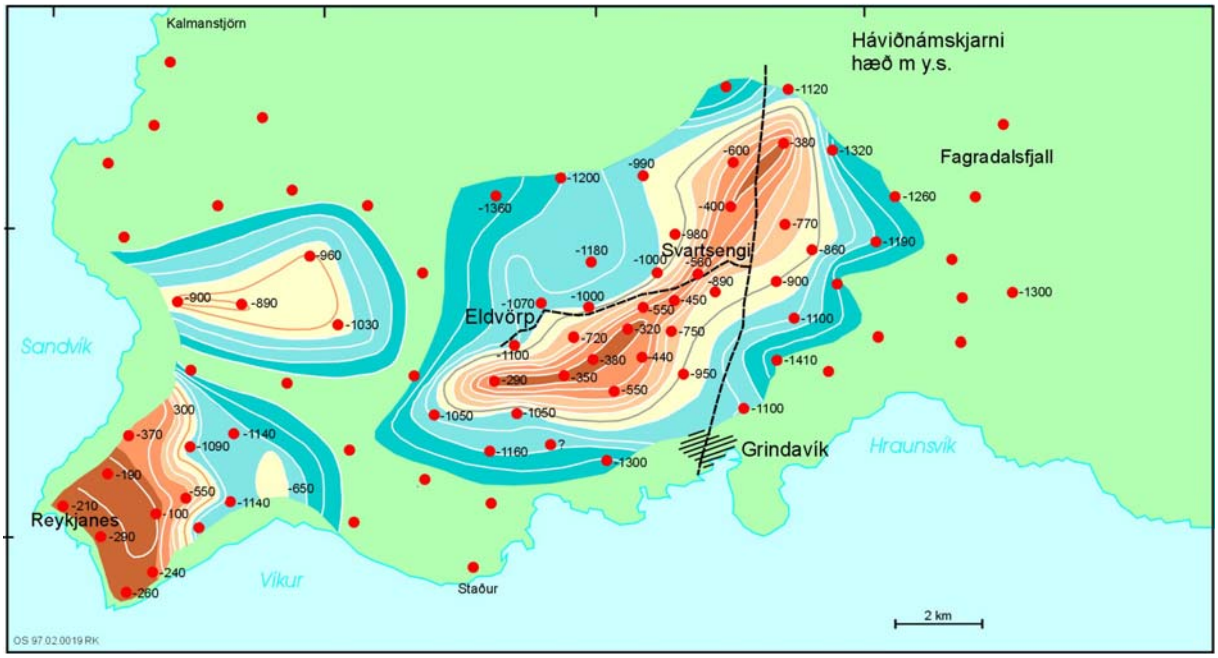


FIGURE 9: TEM resistivity map of the outer Reykjanes Peninsula
showing the elevation of the high-resistivity anomaly in m a.s.l. (Karlsdóttir, 1997)

Comparing the results of the two surveys, we can conclude the following:

- There is considerably better depth penetration in the TEM soundings;
- The large picture is similar in outlining the active geothermal systems and a possible new system;
- At deeper levels there is much better resolution in TEM with new details in the resistivity structures not seen with certainty in the Schlumberger soundings;
- TEM shows clearly high resistivity inside the geothermal systems, despite the very saline groundwater, something that was suspected but not confirmed from the Schlumberger soundings;
- TEM also shows different layers in the low-resistivity layer;
- The Schlumberger soundings give a better resolution of the uppermost 100-200 m, especially the water table or the fresh water lens floating on the seawater.

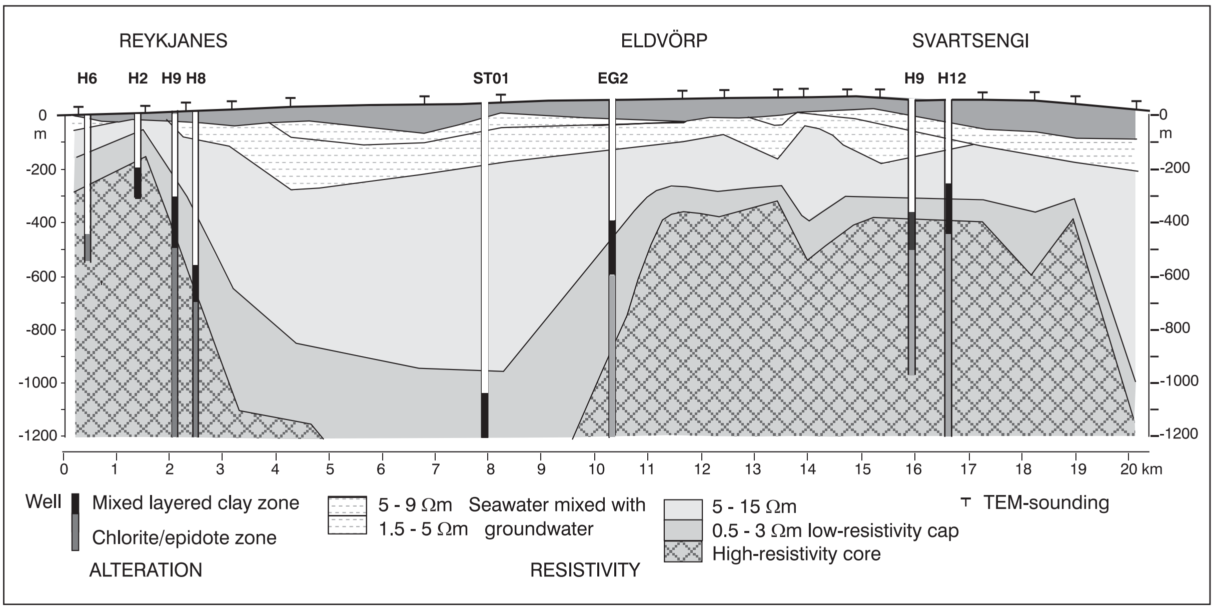


FIGURE 10: TEM resistivity cross-section trending ESE-WNW, along the
outer Reykjanes Peninsula through the geothermal fields (Karlsdóttir, 1997)

6.3 Results from the Öxarfjördur area, NE-Iceland

The Öxarfjördur bay and associated lowlands in NE-Iceland is chiefly a N-S trending, 25 km wide, downfaulted trough filled with sediments. The region is dominated by the delta of the Jökulsá-river, one of the major glacial rivers of Iceland which carries a lot of sediments with it, and three active N-S trending fissure swarms which are parts of active volcanic systems further inland. The thickness of the sediments reaches 500-1000 m at the coast in the central part of the area. The geothermal activity is mainly confined within the active fissure swarms with the main manifestations associated with the Krafla fissure swarm (Figure 11). Geothermal activity and active volcanic systems in sedimentary stratigraphy is unique for Iceland.

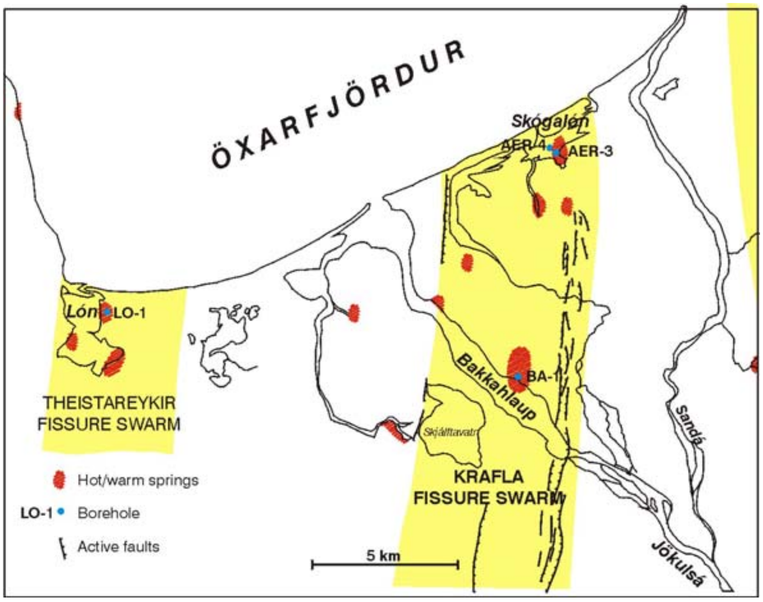


FIGURE 11: Geothermal and tectonic map of the Öxarfjördur area, NE-Iceland (Georgsson et al., 2000)

The **Krafla central volcano** is located about 50 km from the coast, but its fissure swarm stretches well into the Öxarfjördur bay. During 1975-1984 there was intense volcanic activity and rifting associated with the Krafla volcano and its fissure swarm, usually referred to as the Krafla fires. This included several distinct rifting episodes associated with magmatic intrusions (and/or surface eruptions), 3-4 of which were recorded in the Öxarfjördur area, without the lava reaching the surface there, but associated with large surface deformation and faulting along the fissure swarm (Björnsson, 1985).

The surface geothermal activity in the Öxarfjördur area must be considered rather meagre. With the temperatures around 40-80°C, consisting of unimpressive pools or warm ground in the sandy lowlands. The largest areas are in the central part of the Krafla fissure swarm at the banks of Bakkahlaup (the main outlet of Jökulsá), about 8 km from the coastline; and at the coast at Skógalón. During the Krafla fires surface geothermal activity increased considerably in the area, e.g. both Skógalón and Bakkahlaup reaching close to boiling temperatures. The surface activity is now declining again.

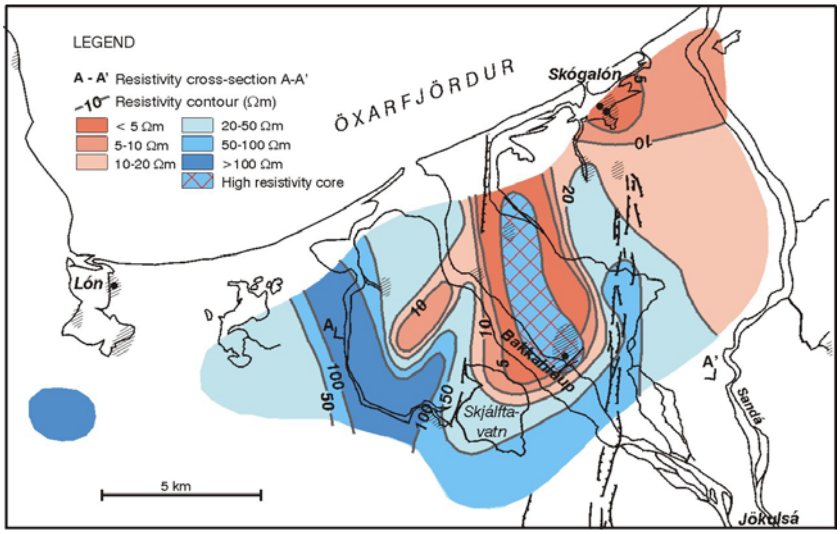


FIGURE 12: DC resistivity map of the Öxarfjördur area at 500 m b.s.l. (Georgsson et al., 2000)

The DC resistivity survey in the Öxarfjördur area (Georgsson et al., 2000) included about 60 Schlumberger soundings dating mainly from the mid 1980s, when three main profile lines were measured intended for 2D forward interpretation. Figure 12 shows a DC resistivity map of the Öxarfjördur area at 500 m b.s.l. It shows two main resistivity anomalies, the most important one in the central part of the Krafla fissure swarm associated with the Bakkahlaup geothermal field with resistivity of 1-5 Ωm, and a high-resistivity core below. Another low-resistivity area is associated with the Skógalón field. The Bakkahlaup resistivity anomaly shows typical characteristics of an anomaly associated with high-temperature geothermal activity in Iceland. This is even more evident in the DC resistivity cross-section trending W-E seen in the upper part of Figure 13.

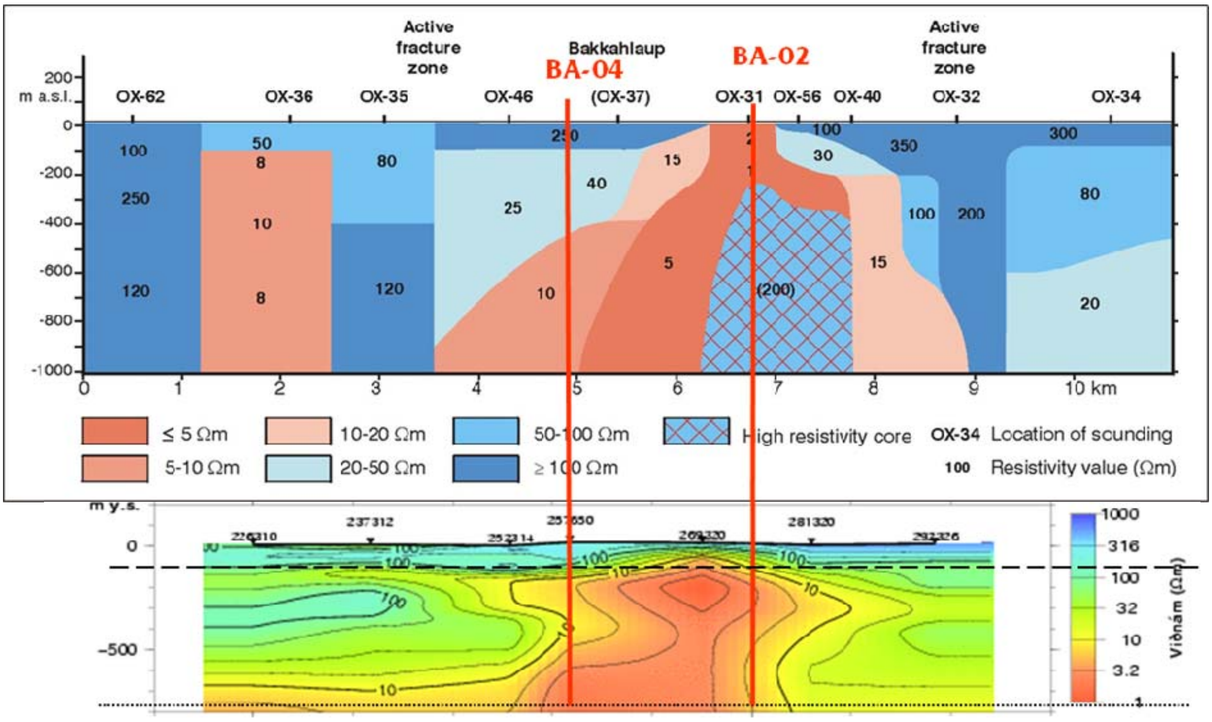


FIGURE 13: DC (above) and TEM (below) resistivity cross-section trending W-E through the Bakkahlaup geothermal field, Öxarfjördur, NE-Iceland (Georgsson et al., 2000; Karlsdóttir and Flóvenz, 2005)

Based on the results of the resistivity survey a deep exploration well, BA-02, was drilled in 1999. It is located centrally in the southern part of the anomaly seen in Figure 12, just north of the geothermal upflow and was drilled down to 1962 m in 1999. The result of the well was quite disappointing with the temperature reaching only 170-180°C at about 500 m, but cooling down below that. Another deep exploration well, BA-03, was drilled late in the year 2000 down to 700 m. It was located about 2 km north of BA-02. The results were even more disappointing. The well had many good aquifers, but none of them seemed to have temperatures above 100°C. It was a good low-temperature well with no indications of the high-temperature activity that was the target for the drilling actvity. The wells confirmed the existence of the thick sediments, being more than 500 m in the Bakkahlaup area, growing thicker towards the coast.

A revision of the conceptual model of the geothermal activity in the area was needed. For that purpose a TEM survey was carried out in 2003 and 2004 (Karlsdóttir and Flóvenz, 2005). Figure 14 shows TEM resistivity maps at 500 and 800 m depth b.s.l. The maps are somewhat similar, showing two main low-resistivity anomalies associated with the Bakkahlaup and Skógalón geothermal fields, and other smaller anomalies. The Bakkahlaup anomaly is comparatively small and higher resistivity beneath the low resistivity is not caused by high temperature alteration as anticipated earlier. The low resistivity in the uppermost 300-500 m is associated with warm saline water in sedimentary surroundings, not a typical low-resistivity cap of a high-temperature field.

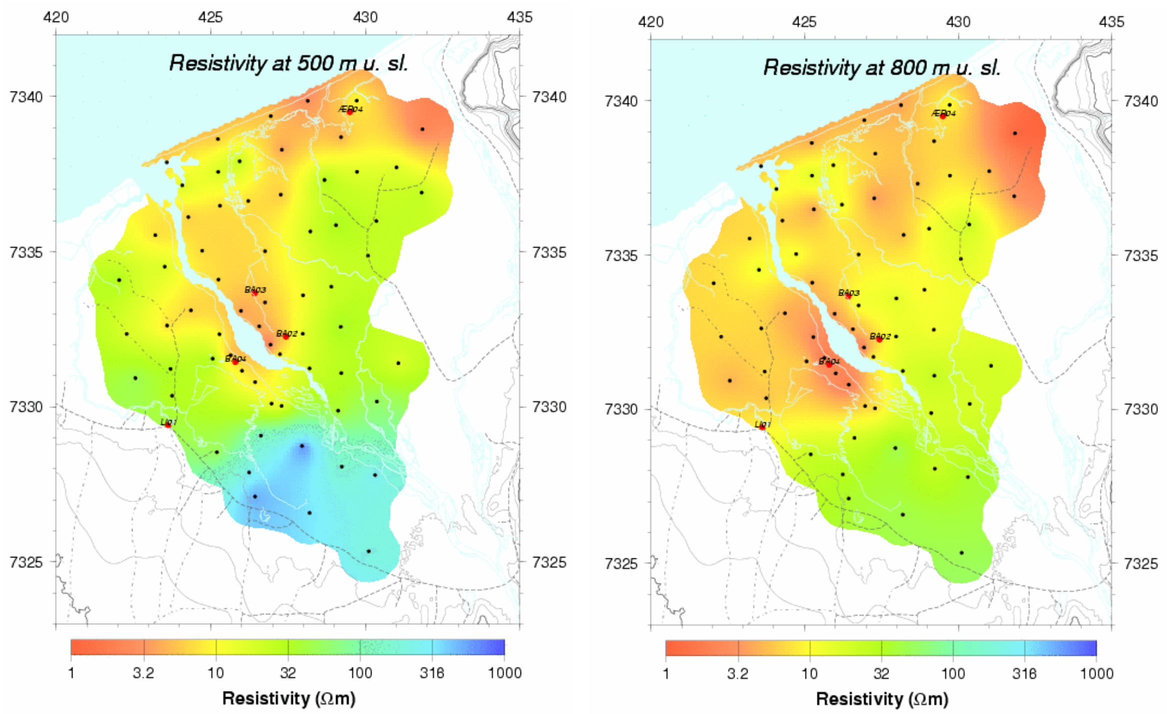


FIGURE 14: TEM resistivity maps of the Öxarfjördur area at 500 and 800 m b.s.l.
(Karlsdóttir and Flóvenz, 2005)

This is well illustrated in the TEM cross-section in the lower part of Figure 13, which is along a similar profile line as that shown above it based on the Schlumberger soundings. It shows a narrow upflow zone at depth and a low-resistivity layer interpreted as a discharge of geothermal water along a sedimentary layer at 100-200 m depth to the west but at 200-300 m depth towards east. Both wells cut through this sedimentary layer and show cooling beneath it. Well BA-02 is closer to the upflow and has less saline water, than well BA-03. From the upflow towards the shore in the north, the sedimentary layer is seen as a low-resistivity layer both because of the warm geothermal water as well as the seawater blending with it closer to the coast.

The TEM survey reveals fracture dominated geothermal fields with outflow along shallow sedimentary layers (Figure 14). The most prominent upflow zones are at Bakkahlaup and Skógalón. Contrary to the older model, the upflow zone of the Bakkahlaup geothermal field appears to be quite limited with its centre below Bakkahlaup river, and no confirmed high-resistivity body can be seen at deeper levels. This is in agreement with the results of the drilling of the exploration wells, and well BA-04 drilled in 2004 at the west bank of Bakkahlaup, further confirms this. The geothermal fields in the Öxarfjördur area are not characterized by high-temperature activity but their temperature may reach as high as 200°C. The lowering of the resistivity towards the coast is mainly due to seawater salinity.

The main reason for the difference in the two surveys with regards to the high resistivity may be influenced by several factors, such as the sedimentary surroundings and varying salinity of the ground water, combined with ambiguities in the data caused by compromises in the layout of DC soundings (location and directions of current arms) necessary due to the large glacial river cutting through the area of interest. The interpretation of the DC survey was relevant at the time, but the comparison of the two methods reveals that the DC method gives detailed picture of the uppermost 100-300 m, whereas the TEM method gives better resolution at depths down to 1000 m.

7. CONCLUSIONS

TEM soundings have many advantages over DC soundings, such as:

- in no current transmission into the ground;
- in its low sensitivity to local inhomogeneities;
- in a strong signal being associated with low resistivity (geothermal activity);
- in easy computer interpretation, usually 1D is enough;
- in faster data acquisition and requiring less manpower and thus in cost effectiveness;
- in improved resolution of the resistivity distribution thus giving improved information on the geothermal system.

DC soundings do also have some advantages:

- in their simpler and more robust equipment;
- in the transparency of the data giving confidence in results;
- in showing near surface features better.

Both methods are suited for exploration of geothermal systems. DC measurements are more suitable in low-temperature fields in revealing near surface features such as water bearing fractures in the uppermost 300 m. In high-temperature fields, with very low resistivity at the surface, the DC method will not "see" through the surface layers. The TEM method has the downward resolution in these surroundings and can be applied down to about 1000 m. For deeper exploration MT measurements are advised.

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