Resistivity methods
DC and TEM

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Resistivity methods

- **Most important** in geothermal exploration since the 1960s.
- **Key methods** in delineating geothermal areas and drilling fields.
- Electrical current is induced into the earth – generated electromagnetic signals are monitored at the surface - many varying arrays and setups.
- **DC methods**, current injected into earth through electrodes at the surface generating an electric field at the surface. The electrical field is measured and electrical resistivity of the structures below is calculated from these two variables and the geometry - many different types with different geometrical setups.
- **TEM**, current 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 decay secondary magnetic field.
Resistivity of water bearing rocks

Controlled by:

- Porosity and pore structure
  - Intergranular – sediments
  - Joints-fissures - tension, cooling - igneous rocks
  - Vugular – dissolved material, gas - volcanics, limestone
- Alteration (water-rock interaction)
- Salinity of the water
- Temperature
- Amount of water – pressure

Variables that directly correlate to the geothermal activity
Methods discussed

- Schlumberger resistivity sounding
- Central loop Transient ElectroMagnetic method
- Head-on resistivity profiling
DC - Theory

• Ohm’s law

\[ E = \rho j \]

- \( E \) is electrical field strength (V/m)
- \( j \) is current density (A/m²)
- \( \rho \) is electrical resistivity (\( \Omega \)-m) - material constant

For a homogenous earth and a single current source, the relevant equation, for the electrical potential at a distance \( r \) from the source becomes:

\[ V_r = \frac{\rho I}{2\pi r} \]

Key equation 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 earth is not homogeneous so what we are looking at is a sort of average resistivity of the earth below within a certain depth range, usually referred to as apparent resistivity, $\rho_a$.

**Sounding** – by increasing distance between the electrodes the electricity probes deeper - thus we get knowledge of resistivity changes with depth.

**Profiling** – by moving the whole array horizontally, we get a horizontal profile showing how the resistivity changes along the profile.
DC – Different types of arrays

Schlumberger array: Symmetrical array with two outer current electrodes and two inner potential electrodes on a line.

Dipole arrays: Each pair of electrodes moved in a special way depending on the specific array.

Wenner array: Symmetrical array, similar to Schlumberger but with the same distance between all electrodes.

Head-on profiling: Schlumberger array with a third current electrode located at “infinity” at a right angle to the profile line. Current sent alternately between all sets of electrodes.

Schlumberger sounding has been the most common and successful DC method
\[ a = \frac{\Delta V}{I} \times (S^2 - P^2) \pi/2P \]

with

\[ S = \frac{AB}{2} \]
\[ P = \frac{MN}{2} \]
Schlumberger resistivity sounding - Presentation

Apparent resistivity plotted as a function of AB/2 on a logarithmic scale with increasing electrode separation. The sounding reflects the true image of the resistivity distribution in the earth below. Manual 1D interpretation possible and the key before the time of the computers but done by inversion programs.
TEM method

Makes use of a magnetic field to induce currents in the earth.

In the central loop TEM sounding method, 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 decay rate recorded as a function of time depend on the resistivity structure of the earth, and can be interpreted in terms of subsurface resistivity structure.
TEM configuration

\(\rho_a\) a function of several variables:
- Measured voltage
- Time elapsed from turn off
- Area of loops/coils
- Number of windings in loops/coils
- Magnetic permeability

For homogeneous half-space, apparent resistivity \(\rho_a\), is expressed in terms of induced voltage at late times after the source current is turned off is given by

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

For a layered earth the expression is much more complicated
Apparent resistivity is plotted as a function of time since current was turned off.

Resembles the Schlumberger sounding graphically, however, it does not reflect the image of the true resistivity compared to Schlumberger sounding.

1D interpretation by 1D inversion programs, manual interpretation impossible.
**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

- **1D** interpretation - layered earth. Inversion available for all methods
- **2D** interpretation - resistivity constant in one direction. Forward interpretation used for long time, but inversion now available for DC and MT methods
- **3D** interpretation - resistivity varies in all directions.
  - Inversion available for DC
  - Forward modelling is available for TEM and MT and inversion is within reach
Forward - Inversion

- **Solution to the forward problem**
  - Algorithm to calculate response of a given model

- **Inversion algorithm**
  - Improve the model based on the difference between the measured data and the response of the model
1D interpretation

• Each sounding is interpreted independently
• Resistivity varies only with depth, but not in horizontal directions
• It is normally assumed that the earth is layered and each layer is homogeneous and isotropic
• 3D models are often compiled from 1D models of individual soundings.
Interpretation using Occam inversion improves resolution even further.

“Continuously” changing resistivity instead of few specific layers.

Together with improved instruments, this can also give additional details in the geothermal interpretation.
2D Interpretation

- Measurements must be on a profile and are interpreted together.
- Resistivity can vary with depth and along the profile but not in (strike) direction perpendicular to the profile.
2D resistivity grid
3D interpretation

- Good and regular coverage is needed and all soundings are interpreted together
- Resistivity can vary in all three directions
General advantages of TEM

• In TEM no current has to be injected into the earth and it has shorter wires - important in deserts, lava fields and cold areas – thus data collection is possible on snow and ice, or bare rock.

• In TEM distortions due to local inhomogeneities are small – TEM is much more 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.

• TEM needs much less manpower, both in the field and for interpretation and measurements are faster – thus very importantly it is more cost effective, or allows much higher data density.
Reykjanes Peninsula – Where the N-Atlantic ridge enters Iceland
Reykjanes peninsula
Terrain extremely difficult – rough lava
Regional resistivity very low due to saline groundwater (sea water infiltration)
Current output in DC measurements very low due to the surface conditions
DC therefore difficult to measure to full lengths (depth)
Reykjanes Peninsula – Schlumberger r 1D resistivity map at 400 m b.l.s.
Reykjanes Peninsula – Schlumberger 1D resistivity map at 800 m b.l.s.
Reykjanes Peninsula – Schlumberger 1D resistivity cross-section
TEM soundings at Reykjanes Peninsula

LEGEND
- ⚫ TEM measurements in 1997
- ○ TEM measurements in 1991 & 1996
Reykjanes Peninsula – Surface of low resistivity
Reykjanes Peninsula – Surface of high-resistivity body
Reykjanes - Comparison DC-TEM

- Better depth penetration in TEM soundings
- The large picture similar in outlining the active geothermal systems and a possible new system
- Much better resolution in TEM at deeper levels with new details not seen with certainty in the DC- soundings
  - High resistivity inside the geothermal systems, despite the very saline groundwater – suspected but not confirmed from DC
  - Different layers in the low-resistivity coat
- Schlumberger soundings give a better picture of the uppermost 200-300 m, especially the fresh water lens floating on the seawater
Öxarfjördur - Location

- Öxarfjördur is chiefly a N-S trending, 25 km wide, downfaulted trough filled by sediments
- Region dominated by the delta of Jökulsá river and three active N-S trending fissure swarms
- Geothermal activity and active volcanic systems in sedimentary stratigraphy is unique for Iceland, with 500-1000 m of sediments
Öxarfjördur – Geology & geothermal

Krafla central volcano ~50 km from the coast - its fissure swarm stretches into the Öxarfjördur bay.

Intense volcanic activity and rifting was in 1975-1984.

Distinct rifting episodes associated with magmatic intrusions - 3-4 of which were recorded in the Öxarfjördur area.

Meagre surface geothermal activity.

Geothermal activity increased during Krafla fires, but is now declining.
The Öxarfjördur delta
Öxarfjördur – Schlumberger resistivity map at 500 m b.s.l.
Öxarfjördur - Schlumberger 2D resistivity cross-section A-A’
Öxarfjördur – Old model of the Bakkahlaup geothermal system
Resistivity cross-section A-A’
Resistivity cross-section B-B'
Öxarfjördur – TEM anomalies

TEM shows 4 main low-resistivity anomalies, and 2 smaller ones. The Bakkahlaup anomaly, A, is comparatively small and a high-resistivity body is not found below it, nor elsewhere.

Other anomalies are typical for low-temperature surroundings with saline ground water, some correlating quite well with surface geothermal activity. The upflow is probably mainly associated with N-S trending fissures.
Öxarfjördur – New model of the Bakkahlaup geothermal system
Öxarfjördur – Comparison DC-TEM

• Schlumberger soundings outlined one large low-resistivity anomaly with a high-resistivity body below which is typical for Icelandic high-temperature fields, and other smaller low-resistivity anomalies, in sedimentary surroundings.

• Drilling of two deep exploration wells in the main anomaly at Bakkahlaup did not confirm the existence of a large high-temperature area, but indicated that the resource was more limited and the temperatures probably not much exceeding 200°C.

• Drilling also confirmed the existence of the thick sediments reaching about 500 m at Bakkahlaup and up to 1000 m at the coast.

• The combination of sediments and varying salinity of the ground water may have influenced this difference.
Öxarfjördur – Comparison DC-TEM

• TEM measurements show a much more detailed picture
• At deeper levels the resistivity distribution is complicated and quite different from the one based on Schlumberger soundings
• The main low-resistivity area or upflow zone appears to be quite limited, as indicated by the drilling, and no confirmed high-resistivity body can be seen at deeper levels
• Several other low-resistivity areas are seen, some agreeing quite well with the older maps
• The upflow is probably mainly through fissures, trending N-S
• With no high-resistivity body, temperatures ought to be lower than in conventional high-temperature fields, as seen from wells
• Drilling of the third exploration well in 2005 has further strengthened the model based on the results of the TEM
• The central part of the Bakkahlaup area is below the glacial river
HEAD-ON PROFILING

- Developed in China to map near-vertical structures
- Schlumberger configuration with an extra current electrode C placed at infinity. AMNB moved stepwise along a profile perpendicular to vertical structure, new measurements for each step.
- Current I is injected into earth between all three pairs but the potential always measured between M and N, giving three data sets and three different resistivities.
- Resistivities are plotted as a function of movement usually $\rho_{AC} - \rho_{AB}$, $\rho_{BC} - \rho_{AB}$ and $\rho_{AB}$
- Depth penetration is controlled by AB, profile usually measured for two current arms
- Using 2-D interpretation the method is strong in locating permeable near-vertical structures – inversion is now available
Head-on configuration

\[ oC \Rightarrow AB \]
Theoretical head-on curves for a low-resistivity vertical structure
Calculated model curves for head-on compared with actual data curves.
Urridavatn –
A successful head-on survey
Main conclusions

• TEM has many advantages over DC
  - in requiring less manpower and thus in cost effectiveness
  - in its low sensitivity to local inhomogeneities
  - in no current transmission into ground
  - in strong signal associated with low resistivity (geothermal)
  - in easy computer interpretation, usually 1D is enough
  - in improved resolution of the resistivity distribution thus giving improved information on the geothermal system

• DC soundings have advantages
  - in their simpler and more robust equipment
  - in the transparency of the data giving confidence in results
  - showing near surface layers better


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Thank you for the attention

Uxahver around 1860
(by Carl Baagoe)