Overview of Geophysical Methods Used in Geothermal Exploration

Lúdvík S. Georgsson
Director UNU-GTP

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Surface Exploration

- The objective is to **obtain information** about the properties of the geothermal system **prior to drilling**

- Successful surface exploration **reduces the cost at later stages** in the development and thus saves a lot of money in the end

- Geothermal surface exploration is a **multidisciplinary task**

- Exploration **strategy depends on many factors**, including geological settings and temperature in the system
Surface Exploration Can Provide Information on

- **Temperature** in the geothermal reservoir
- **Permeability** (fractures) of the reservoir
- **Areal extent** of the thermal anomaly
- **Depth to useful temperatures**
- **Location of the up-flow zone**
- **Chemical composition** of fluid
Components of Geothermal Surface Exploration

- Geological mapping
- Geophysical exploration
- Geochemical exploration
- Environmental impact
Measuring Earth’s Physical Properties

- Geophysical exploration of geothermal resources deals with measurements on the physical properties of the earth.
- Emphasis is on parameters sensitive to temperature and fluid content of the rocks.
- Aim is to delineate a geothermal resource, outline a production field, locate aquifers and site wells or estimate the properties of the system.
- Ultimately the information is intended to be used for economic exploitation of the resource.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reservoir</strong></td>
<td><strong>Measured</strong></td>
</tr>
<tr>
<td>• Temperature</td>
<td>• Temperature (°C)</td>
</tr>
<tr>
<td>• Porosity</td>
<td>• Electrical resistivity (Ωm)</td>
</tr>
<tr>
<td>• Permeability</td>
<td>• Magnetization (Vs/m²)</td>
</tr>
<tr>
<td>• Chemical content of fluid</td>
<td>• Density (kg/m³)</td>
</tr>
<tr>
<td>(salinity)</td>
<td>• Seismic velocity (km/s)</td>
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<tr>
<td>• (Pressure)</td>
<td>• Seismic activity</td>
</tr>
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<td></td>
<td>• Thermal conductivity (W/mK)</td>
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<td></td>
<td>• Streaming potential (V)</td>
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Methods

Direct
- Thermal methods
- Electrical methods
- SP

Structural / indirect
- Magnetics
- Gravity
- Seismic methods
- Seismicity
Approach

Combine methods
• No method universally applicable
• Different for low-temperature and high-temperature systems
• Choose carefully
• Usually two or more methods give better results
• Different approach may suit different countries
• Important to be ready to improvise or try new methods

Integrated surveys
• Geophysical exploration does not stand alone, needs to be integrated with geology and geochemistry?

Success of a survey
• Success is best measured by time, effort and money the survey may have saved
Thermal Methods

• Direct measurements

  of temperature and heat. No method correlates better with the properties of the geothermal system

• Heat exchange

  *Conduction* – atomic vibrations, important for transfer of heat in the earth's crust

  *Convection* – transfers heat with motion of mass, natural circulation of hot water

  *Radiation* – not in geothermal
Application

Thermal distribution at the surface
- Detailed mapping (GPS)
- Soil temperature measurement
- Airborne IR survey

Temperature in 20-100 m gradient wells
- Used to delineate regional or local gradient anomalies

Heat flow surveys for regional assessment
- Thermal conductivity measurements, gradient survey, possibly with terrain corrections
Reykjanes Field - 2004
Soil Temperature at 15 cm depth
Stykkishólmur Gradient Map
Electrical / Resistivity Methods

- **Most important** in geothermal exploration
- Electrical current is induced into the earth - signals that are generated are monitored at the surface - many varying methods

- **DC methods**, current injected into earth through electrodes at the surface - the signal measured is the electrical field generated at the surface.

- **MT**, current is induced by the time variations in earth's magnetic field - the signal measured is the electromagnetic field at the surface.

- **TEM**, current induced by a time varying magnetic field from a controlled source - the monitored signal is the decaying magnetic field at surface.
Resistivity

Ohm’s law

\[ E = \rho \ j \]

- \( E \) is electrical field strength (V/m)
- \( j \) is current density (A/m\(^2\))
- \( \rho \) is electrical resistivity (\( \Omega \)m - ohmm) - material constant

For a unit cube/bar, resistivity is defined as

\[ \rho = \frac{V}{I} \]

The reciprocal of resistivity is conductivity - \( \sigma \)

Most rocks are resistive, conduction is through water in pores and at water-rock contacts.
Resistivity of Water Saturated 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 - saturation - steam content
- Pressure

Electric conduction is mainly through interconnected water-filled pores
DC Methods: Sounding – Profiling

**Sounding** - centre fixed, electrode spacing varied used for mapping resistivity changes with depth

**Profiling** - electrode distances fixed, whole array moved in profile line - for mapping lateral changes

Many methods - different electrode arrays
- **Schlumberger sounding**, widely used and a key method for decades
- **Dipole sounding or profiling**, various arrays
- **Wenner**, not much used today
- **Head-on profiling**, for locating fractures
Borgarfjördur & Hvalfjördur

Regional Mapping of Resistivity

Resistivity at 500 m b.s.l.
Faxaflói

Geothermal systems and flow channels

Regional Mapping of Resistivity

Borgarfjördur & Hvalfjördur

Flow Pattern of geothermal water

LEGEND:
- Orange circle: Geothermal field
- Orange arrow: Flow of geothermal water
- Light blue area: Extinct central volcano
- Black dashed line: Active fracture zone

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Resistivity and Alteration

Unaltered rocks
Smectite - zeolite zone
Mixed layered clay zone
Chlorite zone
Chlorite-epidote zone

High resistivity core
2 - 10 Ωm low resistivity cap
10 - 25 Ωm
> 25 Ωm

ND-11
NG-7
NG-10
Controlled-source electromagnetics – TEM

In TEM, constant magnetic field is built up by transmitting current $I$ through a big loop (grounded dipole), and then $I$ is abruptly turned off. A secondary field is induced, decaying with time. This decay rate is monitored by measuring the voltage induced in a receiver coil in the centre of the loop. Current distribution and decay rate recorded as a function of time depend on the resistivity structure below.
Hengill

TEM Resistivity Map at 600 m b.s.l.
TEM – 3D interpretation

- Good and regular coverage is needed and all soundings are interpreted together
- Resistivity can vary in all three directions
Natural-source Electromagnetics MT

Natural EM field used as an energy source.

Low frequencies, 0.0001 - 10 Hz are used for deep crustal investigations, higher freq., 10 - 1000 Hz, for the upper crust.

Frequency range $10^{-4}$ Hz to 10 kHz.
MT - Strengths & Weaknesses

• MT is a powerful method to probe deep resistivity structures
• Data collection is simple and the equipment portable
• Sensitive to cultural noise (power lines etc.)
• Probes a large volume of rocks and is therefore sensitive to 3D resistivity variations
• Consequently detailed interpretation is difficult (2D or even 3D interpretation may be needed)
• Good to use in combination with TEM to enhance general depth penetration
• MT combined with TEM is now State of Art for resistivity measurements in high-temperature geothermal fields
Menengai, Kenya - MT Cross-section
Structural Methods

Reflect the structure of the rock – not the temperature

**Magnetic methods** are used in geothermal exploration often together with gravity and refraction in mapping geological structures - based on varying magnetisation in rocks

**Gravity surveys** are widely used in geothermal exploration to detect geological formations with different densities, and are as such a typical structural method

**Active seismic methods** detect sound velocity distribution and anomalies in the earth and attenuation

**Passive seismic methods** detect seismic activity in the earth
Magnetic Method

• Two kinds of magnetisation
  ✓ Induced magnetisation $M_i$ - same direction as the ambient earth's field;
  ✓ Permanent magnetisation $M_p$, in igneous rocks it often predominates; it depends upon their properties and history

• Magnetic anomaly is a local disturbance caused by local change in magnetisation; characterised by the direction and magnitude of the effective magnetisation and the shape, position, properties and history of the anomalous body

• Measurements aim mainly at finding location and depth estimate of hidden intrusives or tracing buried dykes and faults, or areas of reduced magnetization due to thermal activity

• Procedures - On ground, regular measurements in profiles or grid, in aeromagnetic surveys, e.g. 100 m above ground and with 100 m between lines
Ásgardur – Magnetic Map

Measured at 2.5 m elevation
Ásgardur - 3D Magnetic Map
Chinameca, El Salvador

Magnetic Map & Structures
Gravity & Density
Gravity Measurements

- **Gravity** measurements are based on **density contrasts** of rocks in the earth which lead to different gravitational force – usually measured in mGal or $10^{-3}$ m²/s
- Gravity usually shown as **Bouguer anomaly** (after corrections):
  \[ g_B = g_M + C_{FA} - C_B + C_T - g_N \]
- **Density** depends on rock composition & porosity, ~2-3 g/cm³
- **Important applications**
  - Basement depth variation (sedimentary area)
  - Intrusive rocks (possible heat source)
  - Fault or dyke systems etc.
  - Alteration, cementation due to thermal effects
  - Monitoring mass extraction with production
Miravalles
Costa Rica
Bouguer Gravity Map
Svartsengi

Mean gravity change
1975-1999
Elastic Waves – Seismic Methods

- Elastic waves - different velocity in different rock types
- Refracted and reflected at discontinuities in formation

- Two types of elastic body waves:
  - P-waves, wave movement in the travel direction
  - S-waves material movement perpendicular to wave direction

- Seismic methods use this for info. on the geothermal system

- Two types of measurements
- Active methods – not used routinely in geothermal – expensive. Info. on density, porosity and texture; fluid-filled zones & temp. Include seismic refraction and seismic reflection
- Passive methods - seismic activity. Info. on active faults and permeable zones (shear wave splitting), S-wave shadow can indicate partial melt, brittle – ductile transition in the rocks informs on temp.
Olkaria
Event distribution
Reykjanes Peninsula – Seismic Zone
Integrated Results – the Key to Understanding

Ásgardur geothermal model
Conceptual Model of Olkaria, Kenya
Selected References


Thank you for the attention!