RESISTIVITY OF ROCKS

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Sustainable Development Goals Short Course IV
on Exploration and Development of Geothermal Resources
Why do we care about resistivity?

It tells us something about the reservoir-conditions in the Earth, without drilling.

Direct relationship between temperature and resistivity.

In high-temperature areas of volcanic origin alteration minerals dominate the resistivity structure.
What is resistivity?

**Electrical resistivity** and its inverse, electrical conductivity, is a fundamental property of a material that quantifies how strongly it resists or conducts electrical current.

**Units**
Resistivity: Ωm (ohm meter)
Conductivity: S/m (siemens per meter)
Ohm’s law and resistivity

Ohm’s law:

\[ U = R \times I \]

- \( U \) potential difference \([V]\)
- \( R \) resistance \([\Omega]\)
- \( I \) current \([A=C/s]\)

Electric field:

\[ E = \frac{U}{L} = \frac{dU}{dx} \quad [V/m] \]

Current density:

\[ J = \frac{I}{S} \quad [A/m^2] \]

\[ E \times L = R \times S \times J \]

\[ \Rightarrow E = \frac{R \times S}{L} \times J \]

\[ E = \rho \times J \quad \text{(Ohm’s law)} \]

Resistivity:

\[ \rho = \frac{R \times S}{L} \quad [\Omega m] \]
Ohm’s law and resistivity

Conductance:
\[ S = \frac{1}{R} \quad [\Omega^{-1} = S] \]

Conductivity:
\[ \sigma = \frac{1}{\rho} \quad [S/m] \]

\[ J = \sigma \times E \quad \text{(Ohm’s law)} \]

R and S depend on size and shape
\( \rho \) and \( \sigma \) are intrinsic properties independent of size and shape.

**Serial resistors**
\[ R = R_1 + R_2 \]
\[ 1/R = 1/R_1 + 1/R_2 \]

**Parallel resistors**
\[ S = S_1 + S_2 \]
Archie’s law

From the oil industry and works well for sandstone saturated with relatively saline water

\[ \rho = \rho_w a \phi^{-n} \]

\( \rho \)  bulk resistivity, \( \rho_w \)  pore fluid resistivity, \( \phi \)  fractional porosity, \( 0 < \phi < 1 \)

\( a \) and \( n \) are empirical factors \( (a \sim 1, n \sim 2) \)

Conductivity \( \sigma_w \)  increases (resistivity decreases) with increasing temperature and salinity

\( \sigma_w = 1/ \rho_w = 1/\rho_{w0}^* (1 + 0.023(T - 23)) \) \ for \( T < 200^\circ C \)

\( \sigma_w = k^\ast C \) \ for moderate salinities \( C \)
Resistivity of electrolytes

As a function of **temperature**

As a function of **salinity**
OLD ASSUMPTIONS

- Archie’s law approximately valid
- Pore fluid conduction dominates
- Concentration of dissolved ions increases with temperature
- The resistivity of electrolytes decreases with temperature

Conclusion

The higher the temperature, the lower the resistivity!

But!!!!
Contradicting evidence
A PUZZLE

- Data show very low resistivity at a certain depth range in the geothermal systems.

- At greater depth and at higher temperatures the resistivity increases considerably again.

- What is the explanation of this?

- What is controlling the resistivity?

- How can we distinguish between resistive cold rocks and resistive hot rocks?
Nesjavellir

The diagram shows a cross-sectional view of the geothermal area at Nesjavellir, with various geological layers and temperature gradients indicated. The area is characterized by a range of resistivity values and temperature conditions.

Key features include:
- **Temperature °C**
- **Resistivity**
  - > 25 Ωm
  - 10 - 25 Ωm
  - 2 - 10 Ωm low resistivity cap
  - High resistivity core
- **Alteration**
  - Unaltered rocks
  - Smectite - zeolite zone
  - Mixed layered clay zone
  - Chlorite zone
  - Chlorite-epidote zone

The diagram is annotated with depth markers and geological boundaries, providing a detailed view of the subsurface geology at Nesjavellir.
Four contributions:

1. Conduction in the rock matrix (normally negligible)
2. Conduction by dissolved ions in the pore fluid (Archie’s law)
3. Conduction by adsorbed ions on the pore surface
4. Conduction in alteration minerals
Which conduction mechanism dominates depends on salinity of the pore fluid, the amount and type of alteration minerals.
Conduction mechanisms

Resistivity as a function of pore fluid resistivity; $\phi_f$ is the fracture porosity.
Conduction mechanisms

Resistivity as a function of temperature
The role of alteration

The solution of the puzzle

- In the high-temperature geothermal systems water-rock interaction produces alteration (secondary) minerals.

- The type of minerals formed depends on the chemical composition of the host-rocks and pore fluid and temperature.

- The amount of alteration depends on time, permeability and the chemical composition and texture of the rocks.

- Some of the alteration minerals are highly conductive others are less conductive or resistive.
The role of alteration

Alteration mineralogy at different temperatures

- **50°C**
  - Thermal Alteration starts
  - Smectite
  - Zeolites
  - Dominant

- **100°C**
  - Thermal Alteration prominent
  - Smectite
  - Zeolites disappear

- **200°C**
  - Smectite
  - Zeolites disappear

- **230°C**
  - S - Ch
  - Mixed layered clay

- **250°C**
  - Chlorite
  - Epidote
  - Dominant
The role of alteration

CONDUCTIVITY OF ALTERATION MINERALS

- **Smectite**
  - Conductive
  - Mobile cations

- **Chlorite**
  - Conductive

- **Brucite**
  - Resistive
The role of alteration

Nesjavellir

The diagram shows the distribution of temperature and resistivity in the Nesjavellir geothermal area. It highlights different zones of alteration:

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

The temperature is indicated in °C, and the resistivity is shown in Ωm. The diagram includes wells labeled as NJ-11, NG-7, and NG-10, with depth measurements in meters.
The role of alteration (cont.)

Asal-Rift
Djibouti

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Temperature (°C)</th>
<th>Resistivity (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-26</td>
<td>&gt; 200</td>
<td>&gt; 260</td>
</tr>
<tr>
<td>26-100</td>
<td>150-200</td>
<td>26-200</td>
</tr>
<tr>
<td>100-250</td>
<td>100-150</td>
<td>23.0</td>
</tr>
<tr>
<td>250-400</td>
<td></td>
<td>1.5-23.0</td>
</tr>
<tr>
<td>400-1300</td>
<td></td>
<td>2.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Alteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smectite - zeolite zone</td>
</tr>
<tr>
<td>Mixed layered clay zone</td>
</tr>
<tr>
<td>Chlorite zone</td>
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<tr>
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<table>
<thead>
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<th>Temperature</th>
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<tr>
<td>100°C</td>
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</table>
The role of alteration

- Field and laboratory data show that the general resistivity structure is controlled by the degree and type of alteration.

- In unaltered rocks the conductivity is mainly in the pore fluid.

- In altered rocks the conductivity is dominated by mineral and/or surface conduction, except for cases of extremely saline pore fluid.

- Details depend on types of minerals and porosity
  \( \rho = b \phi - m \); with different \( b \)
The general resistivity structure

Resistivity Structure summarised

- **Alteration**:
  - Saline water
  - Fresh water

- **Resistivity**:
  - 50-100°C
  - 230-250°C
  - 250-300°C

- **Temperature**:
  - Boiling curve
  - Amb. temp

- **Conduction Types**:
  - Pore fluid conduction
  - Mineral conduction
  - Surface and pore fluid conduction

- **Material Zones**:
  - Rel. unaltered
  - Smeectite- zeolite zone
  - Mixed layer clay zone
  - Chlorite zone
  - Chlorite-epidote zone
Is the resistivity a thermometer?

- If the host rocks are relatively homogenous and alteration mineralogy is in equilibrium with temperature YES.

- If the rocks are very inhomogeneous (inter-bedded sediments) or alteration not in equilibrium with temperature NO.

- If the system cools down, the alteration remains.

- The resistivlty is a sort of maximum thermometer.
An example of cooling
SUMMARY

- Electrical conduction in rocks is a complex phenomenon
- Different conduction mechanisms contribute:
  - Rock matrix conduction (negligible)
  - Pore fluid conduction
  - Alteration mineral conduction
  - Surface conduction
- When one conduction mechanism dominates:
  \[ \rho = k\phi - m \]
  
  k decreases with temperature
SUMMARY (CONT.)

- Pore fluid conduction dominates in unaltered rocks.
- When alteration minerals are present, mineral and/or surface conduction dominate, except in the case of extremely saline fluids.
- Different alteration minerals have different conductivities.
- Different minerals formed at different temperatures.
- If equilibrium between temperature and alteration then the resistivity structure reflects the temperature.
- If cooling has occurred, the resistivity is a maximum thermometer.
Conduction mechanisms

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Conduction mechanisms – solution to the puzzle

Which conduction mechanism dominates depends on salinity of the pore fluid, the amount and type of alteration minerals.
The general resistivity structure

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- **Pore fluid conduction**
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- **Relative unaltered**
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The role of alteration

Nesjavellir

The diagram illustrates the role of alteration in geothermal resources, focusing on the Nesjavellir site. It shows the relationship between temperature, resistivity, and alteration zones, including:

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

Key features include:

- Temperature in °C
- Resistivity in Ωm
- Depth in meters

The diagram highlights different zones and their resistivity characteristics, aiding in the exploration and development of geothermal resources.