Geophysics for Geothermal Exploration

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Agenda

- Basic concept of Geophysics: Review
- Geophysical signatures of a geothermal system
- Geophysical methods for geothermal exploration
- Examples
- Discussion, Q/A
Basic concepts of Geophysics

- Major task of geophysics is to make quantitative statements about the interior of the earth (model) from observation (data)

- Data $\leftrightarrow$ subsurface physical property

- Geophysical methods:
  - gravity, magnetics, geo-electrics, electromagnetics, seismics, ...

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Basic concepts of Geophysics

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data processing $\rightarrow$ subsurface model
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field data
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```
measurement
```
```
signal / Earth’s Response (observed parameters)
```
```
interpretation
```
```
Basic concepts of Geophysics

Measurements over the Earth are data.

Inversion estimates Earth models based upon data and prior knowledge.
Elements of a geothermal system

- Heat source (magmatic)
- Reservoir
- Cap rock
- Recharge system

Role of Geophysics

- Role of geophysics is to identify each element of a geothermal system
  - geometry
  - lithology
  - conceptual model
Role of Geophysics

- Exploration of a geothermal system is a multi-disciplinary approach
  - Geology and Geochemistry
  - Geophysics
  - Drilling and Reservoir Engineering

Geophysical signatures

- Gravity and magnetics
  - gross-structure of a geothermal system
    (caldera / rim structure, pull-apart basin or shear zone, etc.)
  - heat source (magmatic intrusion)

- Geo-electrical
  - cap rock
  - reservoir zone
Geophysical signatures

- **Self-Potential**
  - fluid movement (up-flow, in-flow)
  - fracture zone
  - fluid movement (production, reinjection process)
  - monitoring - reservoir management

- **Micro-seismic**
  - fracture zone
  - reservoir changes

Geophysical Techniques Geothermal Exploration

- **Standard:** MT, T-MT, TDEM, Gravity
- **Legacy:** Dipole-Dipole, Tensor Dipole-Bipole
- **Special:** VES, AMT, CSAMT, SP, HEM
  - Aeromagnetics, Precision Ground Magnetics
- **Research:** Reflection / Refraction Seismic
  - Special Applications
- **Development:** Microgravity, Microearthquake, Subsidence
- **Proprietary:** E-Scan, E-Map
- **Unreviewed:** Aquatrack
- **Suspect:** Seismic Noise, Low Res Ground Magnetics
  - Plausible methods with weak technical support

(Cumming Geoscience)
Geophysical Survey Design

- Problem / site specific
- Exploration strategy
  - start with “inexpensive” or conventional methods to cover vast area (reconnaissance)
  - delineate anomalous zone
  - follow-up with specialized method for detailed targeting

Geophysical Survey Design

- Development strategy
  - start from a specific area to a larger area, to explore possibilities from existing (known) information
Typical Geophysical Surveys

- Reconnaissance
  - Gravity (and magnetic)
  - Geo-electrical Resistivity Sounding and Mapping

- Advanced
  - Magnetotellurics (MT), Time Domain EM (TDEM)
  - Micro-Seismics
Figure 2: Alteration mineralogy with increasing temperature in basaltic country rock. In the temperature range 100°C to 180°C smectite becomes the dominant alteration product and generally forms a smectite/bentonite clay cap (source: Geological Survey of Iceland ISOR).

Alteration – Resistivity

<table>
<thead>
<tr>
<th>RELATIVE PERCENTAGE OF SMECTITE</th>
<th>1-D TDEM RESISTIVITY MODEL</th>
</tr>
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<tbody>
<tr>
<td>SURFACE</td>
<td></td>
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<tr>
<td>TRACING MINOR</td>
<td>MAJOR</td>
</tr>
<tr>
<td>T.D. 918'</td>
<td></td>
</tr>
<tr>
<td>500 FEET</td>
<td></td>
</tr>
<tr>
<td>15 OHM-M</td>
<td></td>
</tr>
<tr>
<td>9 OHM-M</td>
<td></td>
</tr>
</tbody>
</table>
Electromagnetic Induction

- Transmitter generates time varying EM field
  -↓-
  - induces Eddy currents in the conductor (Earth)
  -↓-
  - generate secondary magnetic field
  -↓-
  - electric and magnetic fields are sensed at the receiver
natural electromagnetic field

Magnetotellurics (MT)
1-D MT smooth modeling
2-D and 3-D interpretation of MT data in the Bajawa geothermal field Flores, Indonesia (Uchida et al., 2002)
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The Karaha-Telaga Bodas Geothermal System, Indonesia (Raharjo et al., 2002)

- North-trending high follows ridge axis
- Circular gravity high near Telaga Bodas
- 2-D modelling
The Karaha-Telaga Bodas Geothermal System, Indonesia (Raharjo et al., 2002)
Repeat SP measurements at the Sumikawa geothermal field, Japan (Matsushima et al., WGC 2000)

Using surface SP to monitor underground fluid flow - an example from a HDR stimulation (Darnet et al., EAGE 64th Conference, 2002)
SP monitoring during the hydraulic fracturing using the TG-2 well (Kawakami & Takasugi, EAGE 56th Conference, 1994)

Field set-up of Fluid Flow Tomography, i.e. SP monitoring integrated with mise-à-la-masse (MAM) measurement

Reservoir monitoring by a 4-D electrical technique (Ushijima et al., The Leading Edge, vol. 18 no. 12, 1999)
Hot dry rock (HDR) hydraulic fracturing experiment, Ogachi Electric Power Industry, Akita Prefecture, Japan

Figure 4. Observed SP distributions during water injection operations.

Figure 6. Current source distribution determined by 3-D inversion of SP data with AE hypocenters during the second stage fracturing operations.