OVERVIEW OF GEOPHYSICAL METHODS USED IN GEOTHERMAL EXPLORATION

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Source of Heat - Magma?
Porosity and Fracture permeability
Fluid Circulation – Thermal fluids and Recharge
How deep is the hydrothermal reservoir (base of cap)
GEOPHYSICAL METHODS

➢ To detect and delineate geothermal resources

➢ Location of exploitable reservoirs and the sitting of drillholes through which hot fluids at depth can be detected

➢ Estimate properties of the system (temperature, permeability, heat sources etc.)

➢ Geophysics together with geology, geochemistry, temp measurement will contribute to the conceptual model
WHY GEOPHYSICS

Investigate the physical chemical properties of the rocks

*What we measure*
- ✓ Density
- ✓ Magnetic susceptibility
- ✓ Acoustic wave velocity
- ✓ Electrical resistivity

*What we want*
- ✓ Temperature
- ✓ Permeability and porosity
- ✓ Fluid content/Medium (heat transfer)
The goal is to develop a conceptual model for geothermal system. Data can be processed through inversion or forward modelling. Geophysical information can be presented as:
- Anomaly maps
- 2D cross-sections
- 3D blocks

A = B + C

Question: If A = 10 what is B and C?
SURFACE GEOPHYSICAL EXPLORATION METHODS

Potential Field Methods

✓ Gravity Methods
✓ Magnetic Methods

Resistivity Methods

✓ Direct Current Methods (DC)
✓ Transient Electromagnetic Methods (TEM)
✓ Magnetotelluric Methods (MT)
✓ Spontaneous Potential (SP)
✓ etc

Seismic Methods

✓ Passive Seismic (Earthquake )
✓ Active Seismic (Refraction, Reflection)
Data processing can be done singly or together

Data processed to describe the subsurface geology

All geophysical data must be constrained to make geologic sense

For geothermal exploration the data should show

- Where is the fractured reservoir
- Where is the cap rock
- Where is the heat for the system
- How if fluid flow
Gravity method

Gravity Method is guided by the Newton's Law of attraction between two bodies

\[ F = \frac{GM_1 M_2}{r^2} \]

*where*  
\( G \) (universal gravitational constant) = 6.673 \( \times \) 10\(^{-11}\) m\(^3\) kg\(^{-1}\) s\(^{-2}\)

\( M_1 \) and \( M_2 \) are the two masses in kg, and  
\( r \) is the distance between the point masses, in metres.

Magnetic Method

Considers the Earth Magnetic field

Geothermal exploration takes advantage of the alteration caused by the interaction of thermal fluids with the volcanic rocks

Although not widely used in geothermal exploration
GRAVITY METHODS

Gravity Meter and Global Positioning System

Magnetometer
Gravity Data Analysis

Bouguer Gravity (500 Mgal)

Regional

Residual

Bouguer Anomaly

Distance

Bouguer Anomaly

A- Smooth contour lines.
B- Parallel.
C- Space between lines are equal
D- Large magnitude (495 Mgal)

A- Complex contour lines.
B- Irregular.
C- Space between lines are not equal
D- Small magnitude (5 Mgal)
Gravity Data Analysis

Profile

Bouger Anomaly

Residual

Regional

Distance

Map

Example:

1. Ore body

Residual

Regional

16
Gravity Data Analysis

Gravity plot along the Kenya rift
Gravity Data Analysis

- Gravity model along the rift valley
- High anomalies associated with rift volcanoes
- Heavy rocks may imply the heat source for the geothermal system
Gravity data Analysis

Map of geological features in the East African Rift System, including Menengai Caldera, Lomoro volcano, and surrounding volcanic activity. The map highlights various geological units such as post-caldera trachytes, syn-caldera ignimbrites, welded tuff, and Pleistocene/Pliocene Miocene lavas. The map also shows the location of Lake Nakuru and Lake Victoria, and important cities like Nairobi and Addis Ababa.
Band pass filtered gravity data
Gravity Data Processing

3D density Model from gravity data

The density was allowed to vary from 2.4g/cc to 3g/cc
Gravity Data Analysis

Coso geothermal field
Gravity Data Analysis

Coso geothermal field

Hydrothermal reservoir

Detachment Fault

Dikes and sills

Brittle-ductile transition zone

-15000m

0.3 0.2 0.1 0 0.1 0.2 0.3

q/cc

10km
Magnetic Methods

- Magnetic data interpretation can be complicated
- Not common in geothermal exploration although it is easy and cheap reconnaissance tool.
Investigate for:

- Fluid distribution - liquid/vapor \((\text{liquids-low resistivity, Vapor-high resistivity})\)
- Hydrothermal alteration and mineral distribution \((\text{High and low resistivity})\)
- Lithology and geological structures/tectonic features \((\text{resistivity gradients})\)
- Regions with magmatic material \((\text{low resistivity})\)
RESISTIVITY METHODS

Direct Current (DC) Methods

Magnetotelluric (MT) Method

Transient Electromagnetic (TEM)
DC Resistivity

Vertical Electrical Sounding (VES)

DC resistivity is good for very shallow crustal analysis.
The penetration depth is only 1/3 of the distance between A and B.
Time domain Electromagnetic

- Current is artificially induced in the ground by time varying magnetic field from controlled source into a loop laid on the ground.
- The monitored signal is the decaying magnetic field at surface with a receiver at the center of the loop.
Magnetotelluric (MT)

- High frequencies (short periods) probe shallow depths.
- Low frequencies (long periods) probe deep.
- The resistivity is resolved by the ratio of orthogonal electric and magnetic fields to give impedance tensor.

\[ \rho_a = \frac{1}{\omega \mu} \left| \frac{E}{H} \right|^2 \quad ; \quad \theta_a = \arg \left( \frac{E}{H} \right) \]
MT and TEM Equipment deployment

Field crew at work
Quality assurance is key in data collection
- In MT good site selection
- Ensure good electrode contact with the ground
- Management of Static shift on MT data
Resistivity Interpretation for High Temperature geothermal system

Resistivity Structure summarised

**ALTERATION**
- Saline water
- Fresh water
- Pore fluid conduction
- Mixed layer clay zone
- Chlorite zone
- Chlorite-epidote zone
- Surface and pore fluid conduction
- Mineral conduction
- Amb. temp
- Boiling curve
- 50-100°C
- 230-250°C
- 250-300°C
Resistivity data analysis

- 1D, resistivity analysis
Resistivity data analysis

- 2D, resistivity analysis
Resistivity data analysis

- 1D, 2D and 3D resistivity analysis
SEISMIC METHODS

Wave propagation

Terms
- Travel time
- Arrival time
- Origin time
SEISMIC METHODS

Active Source Seismic Method

Prior Knowledge

Explosion – or energy source

Layer 1

B

B₁

B₂

Layer 2

direct wave

critical wave

refracted back up at the critical angle

critically refracted wave travels along the boundary at the faster speed.

top layer (slow)

30m 40m 50m 60m 70m 80m 90m 100m 110m

gapophones

boundary

lower layer (fast)
Passive Source Seismic

Seismometers

Fracture Zone

$h_1$, $V_1$

$h_2$, $V_2$

$h_3$, $V_3$

$h_4$, $V_4$

Surface lava rocks

Clay Cap

Host Rock

Heat Source
Picking of seismic phases and magnitude estimation

\[
M_c = 2\log[C] + 0.00325d - 0.97,
\]

\(d = \) epicentral distance [km],
\(C = \) duration earthquake coda [sec].
Why consider Seismic methods in geothermal exploration and development

- **Determine Presence of Heat Sources**
  - Seismicity Distribution With Depth
  - Mapping of Shear Wave Attenuating Bodies
  - Reflected Arrivals
  - Analysis of Poisson Ratios

- **Map Zones Of Reservoir Recharge**
  - Seismic Wave Spectral Analysis
  - Seismicity Patterns & Velocity Ratio Analysis

- **Evaluate Existing Reservoir Properties**
  - Analysis of P & S wave Seismic Velocity Ratios
  - Split shear Waves
Seismic Data Analysis

Seismic Ray Tracing
Seismic Data Analysis
Seismic Data Analysis

(a) A-A’ Southwest

(b) B-B’ Northwest

Vp/Vs

ÍSOR
ICELAND GEOSURVEY
Joint Interpretation Geophysical Data

Joint interpretation of micro-seismic data and resistivity

Resistivity and seismic event location - Menengai Kenya
Joint Interpretation Geophysical Data

Joint interpretation of micro-seismic events and gravity anomaly map

Gravity and seismic event location - Menengai - Kenya
Joint Interpretation Geophysical Data

Joint interpretation of resistivity and micro-seismic data

- Elevation in metres above Sea Level
- Distance in metres
Joint Interpretation Geophysical Data

Joint interpretation of gravity, microseismic and resistivity data
Information to input in the conceptual Model

- Depth to the heat source: - aseismic zone, deeper low resistivity zone and a denser material at depth
- The geothermal reservoir zone: - shallow intense seismic zone, fairly high resistivity (30-70ohm.m) and lower density areas
- The Clay cap: shallow low resistivity zone