TEMPERATURE GRADIENT WELLS

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Sustainable Development Goals Short Course II
on Exploration and Development of Geothermal Resources
Geothermal gradient is the rate of increasing temperature with respect to increasing depth in Earth’s interior (°C/km). It is a very useful tool for geothermal research. Away from tectonic plate boundaries, it is about 25-30°C per km of depth in most of the planet (25-30°C/km). Earth’s internal heat comes largely from heat produced through radioactive decay. The major heat-producing isotopes in Earth are K-40, U-238, U-235 and Th-232. At the centre of the planet, the temperature is about 5400°C (similar to the sun’s surface) and the pressure about 3.6 million atm (360 GPa).
Non-radiogenic heat generation

• Comes mainly from the primordial heat of the Earth. The heat from Earth's formation that has been trapped in the planet. The planet was much, much hotter in the “old days”
• Chemical reactions
• Alteration processes
• Thermodynamics not well known
• Earthquaked, could be important in some areas
As the human population continues to grow, so does energy use and the correlating environmental impacts that are consistent with global primary sources of energy, namely fossil fuel and wood. This, of course, results in greenhouse gas emission so it is of critical importance to find sources of energy that are renewable and have reduced greenhouse gas emissions. One of these sources is geothermal, whether low-medium or high temperature. It can be used directly or for generating electrical power. Using geothermal resources requires no fuel.
Because much of Earth’s heat is provided by radioactive decay, it is believed that early in Earth’s history, before isotopes with short half-lives had been depleted, that Earth's heat production must have been much higher. Heat production may have been twice that of present-day at approximately 3 billion years ago, resulting in higher temperature gradients within the Earth, larger rates of mantle convection and plate tectonics.
As such, the geothermal gradient is getting lower and lower as time passes. Also remember that Earth was itself much hotter billions of years ago.
Heat transfer within Earth

• By conduction through solid material. Heat spontaneously flows from a hotter to a colder body.

• By convection or advection, i.e. by moving masses (water, magma) within Earth. Mantle convection, hydrothermal convection.

• By thermal radiation, but it is very low unless at very high temperatures.

Heat transfer mechanisms within the Earth, along with the % amount of heat flow in each layer.
RADIOACTIVE HEAT GENERATION IN THE CRUST

**In continental crust:**
2-3 µW/m³
Crustal thickness 30-60 km
*Radioactive heat generation accounts for a significant part of the continental heat flow*
Heat source; Radioactive U, Th and K isotopes

**In oceanic crust:**
Basalt: 0.5 µW/m³
Crustal thickness: ~10 km
*Radioactive heat generation is negligible in the oceanic crust*
*Most of the heat flow comes from the hot underlying mantle and the cooling plate*

Radioactive heat generation can be calculated from well logging using natural gamma emission:

\[ H = 0.0145 \times (\text{API units} - 5.0) \text{ µW/m}^3 \]
Some Concepts that may Affect the Geothermal Gradient

- Porosity: Volume ratio of pores in rocks
- Temperature gradient, heat increase with depth $\frac{dt}{dz}$ ($^\circ$C/km)
- Heat flow, $Q = k \cdot \frac{dT}{dz}$
- Thermal conductivity, $k = 1 - 4$ W/m°C
- Heat production in $\mu W/m^3$:
  - Basalt 0,5
  - Continental crust 3,0
  - Sediments 1,0
HEAT FLOW

The relation between heat flow and temperature gradient in steady state flow is given by:

\[ Q = \kappa \cdot \frac{\Delta T}{\Delta Z} \]

where:

- \( Q \) = heat flow (W/m²)
- \( T \) = temperature (°C)
- \( Z \) = depth (m)
- \( \kappa \) = thermal conductivity (W/m°C)

In rocks the value of \( \kappa \) is usually 1.5 - 4. In Icelandic basalt \( \kappa \) varies between 1.6 - 2.0 W/m°C, i.e. it is almost constant. Therefore temperature gradient can practically be used instead of heat flow. Temperature gradient in Iceland is 40-170°C/km
Heat flow decreases away from the axial rift zone. The high heat flow (> 200 mW/m²) reflects roughly the axial (volcanic) rift zones (Hjartarson 2015).
Heat Flow and Temperature Gradient

If we have steady state conductive heat flow through the upper crust and heat production is negligible the heat equation gives:

\[ T = T_0 + \alpha \cdot (z - z_0) \]

where \( \alpha \) is constant and denotes the temperature gradient.
THE BACKGROUND TEMPERATURE GRADIENT

- Reflects the conductive heat flow through the upper crust, mainly based on shallow geothermal drill holes (<1.5 km)
EXAMPLE: FINDING GRADIENT FROM WELL LOGS

- Finding the geothermal gradient from a temperature log.

- Solution:
  - \( \frac{\Delta T}{\Delta Z} = \frac{T_2 - T_1}{D_2 - D_1} = \frac{23.6 - 5.5}{70 - 0} = 0.258 \, ^{\circ}C/m \)
  - or \( x \times 1000 = 258 ^{\circ}C/km \)

The result implies that at 1 km depth the temperature of the rocks in the well are about 260°C.
MEASUREMENTS

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TEMPERATURE GRADIENT MAP OF ICELAND

Compiled by Olafur G. Flovenz
and Kristján Saemundsson
Factors Affecting Temperature Gradient:

- Thermal Conductivity
- Climatic Changes
- Heat Generation
- Intra-hole Fluid Movement
- Ground Water Flow
- Erosion/Sedimentation
- Topographic Effects
- Environmental Changes
CLIMATIC CHANGES – PALEOCLIMATE

- Seasonal variation
- Long period variations like the little ice-age
THE EFFECT OF CLIMATE COOLING

Environmental changes can give similar effects:

• Deforestation
• Asphalt on streets
HIGH RATE OF SEDIMENTATION REDUCES THE TEMPERATURE GRADIENT
RAPID EROSION LEADS TO HIGH TEMPERATURE GRADIENTS
Fluid flow affects temperature gradients.

Fluid flow within a borehole affects the estimation of temperature gradient.

Sometimes it can be difficult to see if there is internal flow within a borehole.
FLOW OF GROUND WATER

Hydrostatically driven groundwater flow disturbs the background temperature gradient if the permeability is higher than $10^{-15} \text{ m}^2$. 

2) GROUND WATER FLOW

- THE SEA
- HOLE
- MOUNTAIN

Hydrostatically driven groundwater flow can disturb the temp. field if unless the permeability is very low ($10^{-15} \text{ m}^2$)
Heat flow is higher in valleys than in mountains due to deviations from vertical heat flow.
HEAT FLOW IN GEOTHERMAL EXPLORATION

Geothermal systems at depth create anomalies in the near surface temperature gradient that can be mapped.

- Cover the exploration area with shallow boreholes with suitable spacing
- Log the temperature and calculate the gradient
- Make appropriate corrections to the gradient
- Measure thermal conductivity vs. depth is necessary
- Calculate the heat flow and make heat flow maps
- Draw conclusions from the map (Practical project at a later date)
HEAT FLOW IN GEOTHERMAL EXPLORATION

• Note: If variations in thermal conductivity of the rock is small, temperature gradient maps can be used instead of heat flow maps.

• Boreholes for heat flow measurements
  • Drill into un-fractured, impermeable rock, avoid abnormal places
  • Drill 50-100 m into the layer where heat transfer can be assumed to be purely conductive.

• The regional geothermal gradient must be known as a basis for recognizing thermal anomalies. The greater the difference the better prospects.
TEMPERATURE GRADIENT WELLS IN LOW TEMPERATURE AREAS

- The method has proved most useful in areas where the geothermal system is confined to a fracture of local extent.
- In Iceland many exploitable geothermal systems have been discovered by this method where no surface manifestations were seen.
- Fracture controlled geothermal systems can develop anywhere, also in areas of low geothermal gradients including continental settings with an average geothermal gradient.
ANALYSIS OF HEAT FLOW ANOMALIES

• **Consider**
  
  • The amplitude of the anomaly compared to regional background values
  • Size of the anomaly
    • Linear anomalies indicate underlying fractures
    • Narrow anomaly has shallow origin – broad anomaly deep

![Diagram showing heat flow anomalies with considerations](image-url)
Geothermal Distribution in Iceland

Black dots reflect low-medium temperature areas

Snæfellnes Peninsula

Hengill
Nesjavellir
Hellisheiði

Reykjanese
Svartsengi

High temperature field
Low temperature field

Krafla
Peistareykir

Light-brown delineates the location of the rift-zones

Centre of Mantle Plume

Bedrock
- < 0.8 M. years
- 0.8 - 3.3 M. years
- 3.3 - 15 M. years
Snæfellsnes Peninsula W-Iceland

Skýringar
- Laugar
- Grígar
- Gosreinn
- Húlín jæðhóttakerfi
- Sprunguskróður

Hot pool
Cranes
Volcanic zone
Hidden geothermal systems
Fissure swarm
Case Examples of how Useful Geothermal Gradient Wells can be

- Several shallow wells drilled into a potential low-temp. geothermal area in W-Iceland to find the centre of geothermal upwelling (area of main permeability).
- A production borehole was drilled vertically into the peak of the anomaly.
- Outcome: 20 l/s of 85°C hot water.
- Fracture intersected at 810 m depth.
- Reinjection borehole was drilled 1500 m to the NW intersecting the same fracture at 400 m depth.
- Similar yield and water temperature.
- Interference between two boreholes from a pressurization test occurred within less than 5 minutes.
THERMAL GRADIENT MAP OF REYKJAVÍK AREA

LEGEND
- Boreholes
- Thermal gradient isolines in °C/km
- Aquiclude
Coal vs. Geothermal

In the 1930s geothermal energy for space heating replaced coal in Reykjavik. This completely changed the air quality in the city. This can clearly be seen in the pre- and post geothermal photographs.
In low temperature areas the geothermal gradient method is usually used to outline the distribution of an anomaly, its size and shape, with the purpose of siting a hot water borehole. In high temperature fields the method may be applied to estimate the thermal output. It can, for example, be used to record changes in surface activity over a period of time following the initiation of steam production.
Diffuse Degassing Measurements may work similar to Geothermal Gradient

Gas anomaly detected as gas flux through soil or gas concentrations in soil
He and CO$_2$ concentrations in soil may outline the same anomalies.
Soil gas map of CO2 gas survey carried out in Olkaria Domes field. Station numbers are demarcated by the plus signs in the map and the red line to the south shows the preferred E-W alignment of CO2 anomalies (Munyiri, 2016).