Day 3

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

03 Geothermal reserve estimation and unconventional geothermal systems

04 Oil and gas well conversions, future trends

Recap of Day 2

- Multiphase flow in geothermal reservoirs requires consideration of relative permeability, where the presence of one phase (e.g., water) reduces the flow of another (e.g., steam).
- Reinjection of fluids is critical for maintaining reservoir pressure and avoiding thermal/chemical pollution, but poor reinjection design can harm reservoir performance.
- Tracer tests are widely used to understand flow paths and storage in geothermal reservoirs. Tracers help predict chemical and thermal breakthrough by analyzing return curves and concentration changes over time.
- Thermal breakthrough lags behind chemical breakthrough due to slower heat transport.
- Power generation in geothermal systems involves vapor-dominated, liquid-dominated, or binary cycles.
- Geothermal power plants generally have lower efficiency than conventional thermal plants, with a typical upper limit around 21%.

Clarifications and Some Information

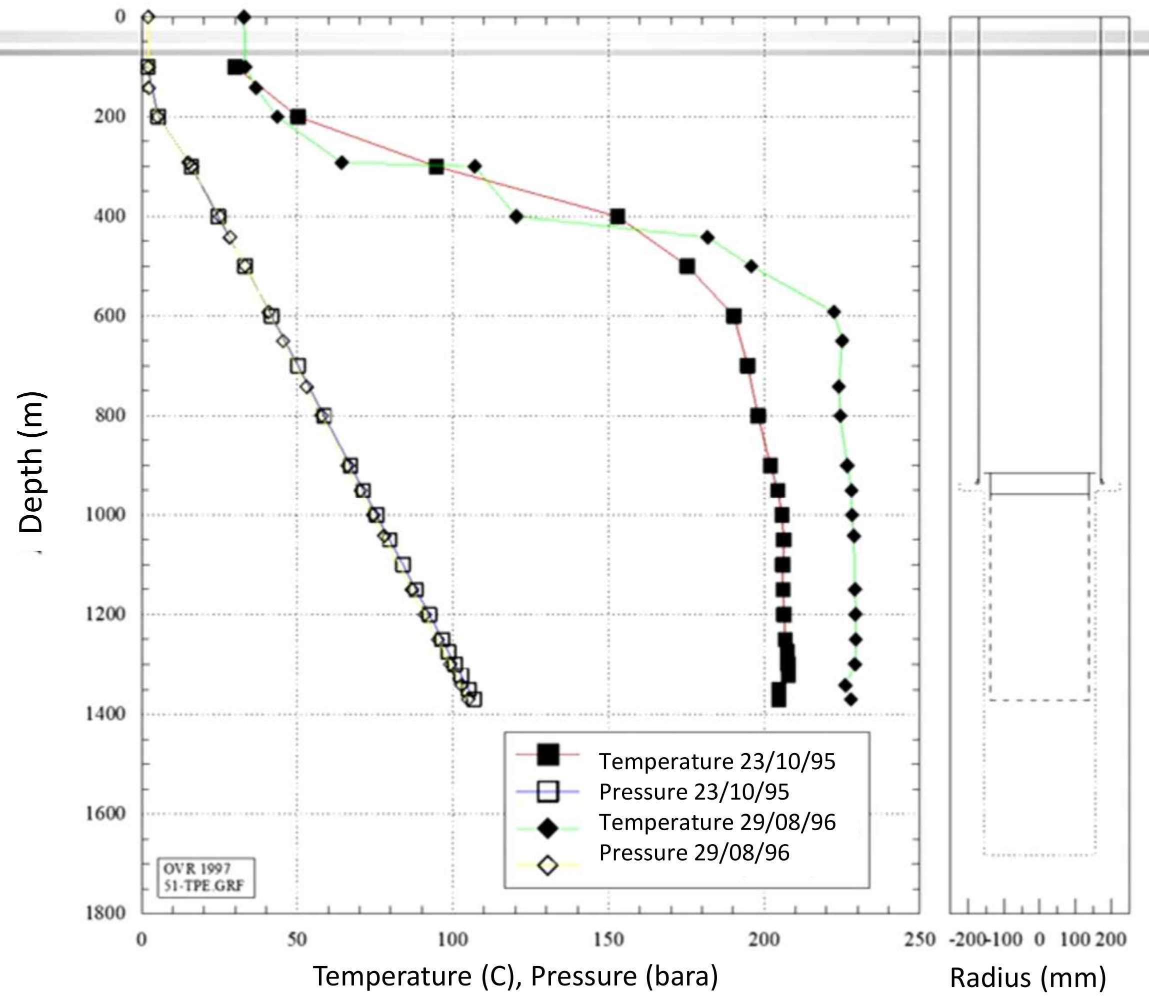
- Thermal breakthrough is independent of the injected fluid temperature.
- The Day 2 Excel sheet has been modified to account for when t_c is calculated and when t_c is known (like from tracer tests).
- Day 3 Excel Sheet provides information about your project. Each participant will present their solutions on Day 4 (3 minutes each).
- There will also be a Kahoot Quiz on Day 4 to wrap up the course.

Introduction to Your Project

- You have been supplied with information about a saturated liquid-dominated geothermal site. Based on what you have learned from the course, evaluate the feasibility of geothermal development. Provide sound technical justifications.

- Step 1: Estimate Reservoir Temperature and Pressure
- Step 2: Determine the enthalpy
- Step 3: Choose a type of power plant
- Step 4: Evaluate the size of the resource or recoverable reserves
- Step 5: Estimate the plant capacity

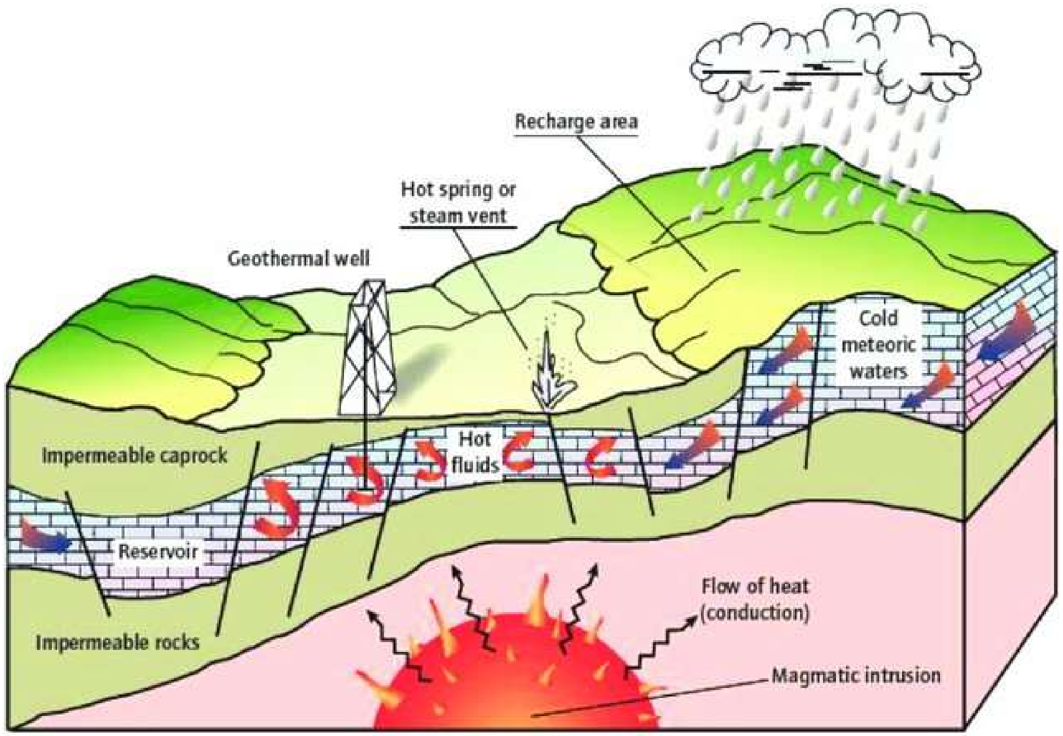
Temperature and Pressure Log



Additional Information

- Steam quality = 20%
- Reservoir of porosity = 10%.
- Rock specific gravity is 2.65.
- Rock heat capacity is 1.0 kJ/kg-°C.
- Volume=10.8 km^3
- T_o= 25 °C

- Load or capacity factor is 95%
- Recovery factor is 25%
- Estimated project life of 30 years.



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(New) Field Development Process for Geothermal Energy

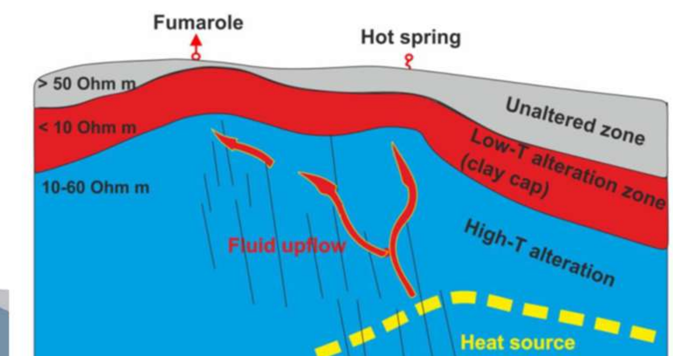
Exploration → Conceptual model ⇄ Exploration drilling → Reservoir modeling & simulation ⇄ Production & injection drilling → Reservoir management

Conceptual model → Well design → Exploration drilling

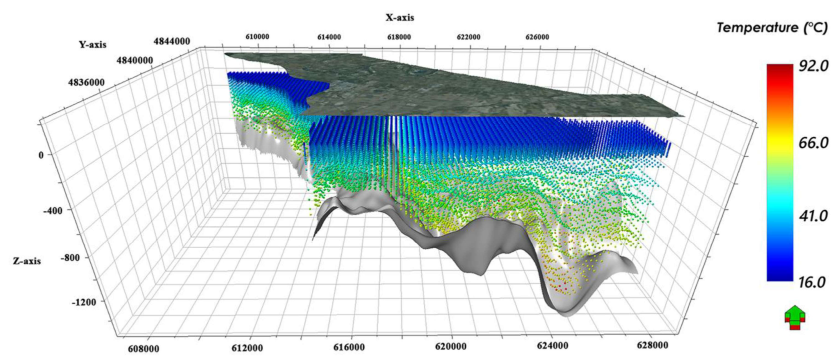
Conceptual model → Reservoir modeling & simulation

Reservoir modeling & simulation → Well design & completion → Production & injection drilling

Reservoir management → Abandonment (and/or conversion)



Source: TellusExplora



Source: Sbrana A et al., 2018

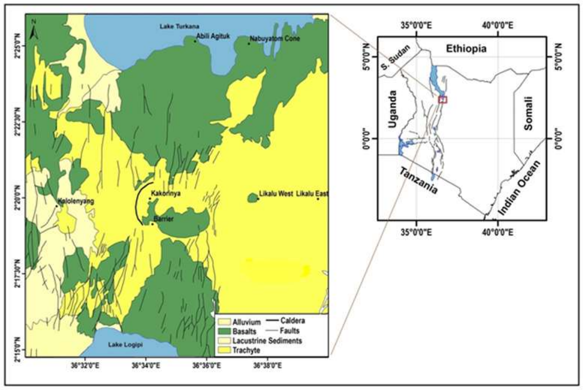
Geothermal Resource Identification (1)

1.Geological Surveys:

1. Conduct detailed geological mapping of the area to identify potential geothermal reservoirs.
2. Study the types and properties of rocks, fault lines, and fractures that may indicate the presence of geothermal fluids.

2.Geophysical Surveys:

1. **Gravity and Magnetic Surveys**: Measure variations in the Earth's gravitational and magnetic fields to identify subsurface structures and anomalies.
2. **Seismic Surveys**: Use seismic waves to map subsurface rock formations and identify potential reservoirs.
3. **Electrical Resistivity Surveys**: Measure the electrical properties of rocks to identify zones of high fluid content or altered mineralogy.



Geothermal Resource Identification (2)

1.Geochemical Analysis:

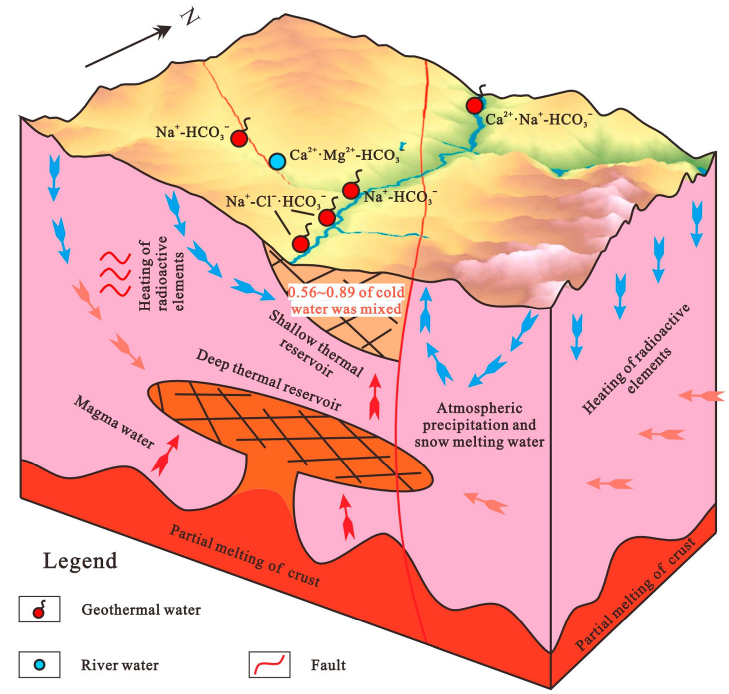
1. **Fluid Sampling and Analysis**: Collect samples of water or gas from wells or surface features to analyze for temperature, chemical composition, isotopic ratios, and dissolved gases (e.g., H2S, CO2).
2. **Gas Emission Studies**: Study the type and concentration of gases emitted from the ground, which can indicate the presence of geothermal reservoirs.

2.Hydrological Studies:

1. To understand the recharge and flow regime. This is normally achieved by detailed mapping of groundwater (water rest level), cold springs, lake levels and groundwater level and ultimately developing a potentiometric map.

3.Temperature Gradient Surveys:

1. Measure the change in temperature with depth in boreholes to estimate the geothermal gradient and identify potential reservoir depths.



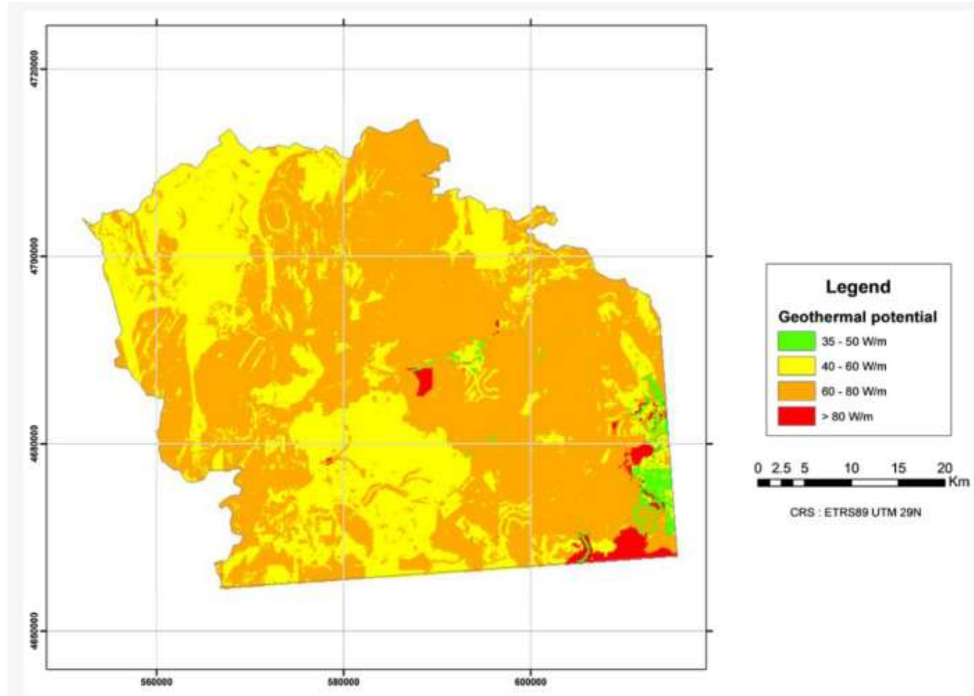
Geothermal Resource Identification (3)

1. Remote Sensing:

1. Use satellite or aerial imagery to detect surface features indicative of geothermal activity, such as hot springs, fumaroles, or altered mineralogy.

2. Exploratory Drilling:

1. Drill test wells to confirm the presence of a geothermal reservoir, determine the temperature and flow rate of the fluids, and assess the permeability of the rock formations.



Geothermal Resource Identification (4)

1.Hydrogeochemical Modeling:

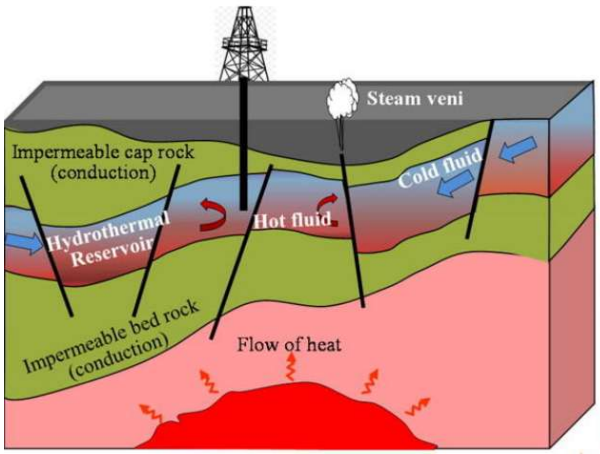
1. Use computer models to simulate the movement and interaction of fluids in the subsurface, helping to predict the behavior of geothermal reservoirs.

2.Data Integration and Analysis:

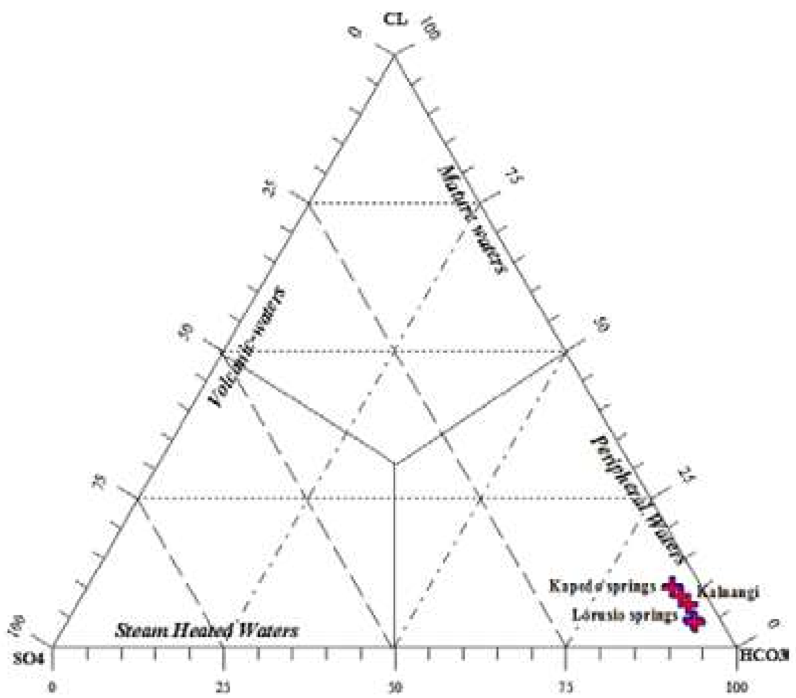
1. Combine and analyze data from various sources, including geological, geophysical, and geochemical surveys, to create a comprehensive understanding of the geothermal resource.

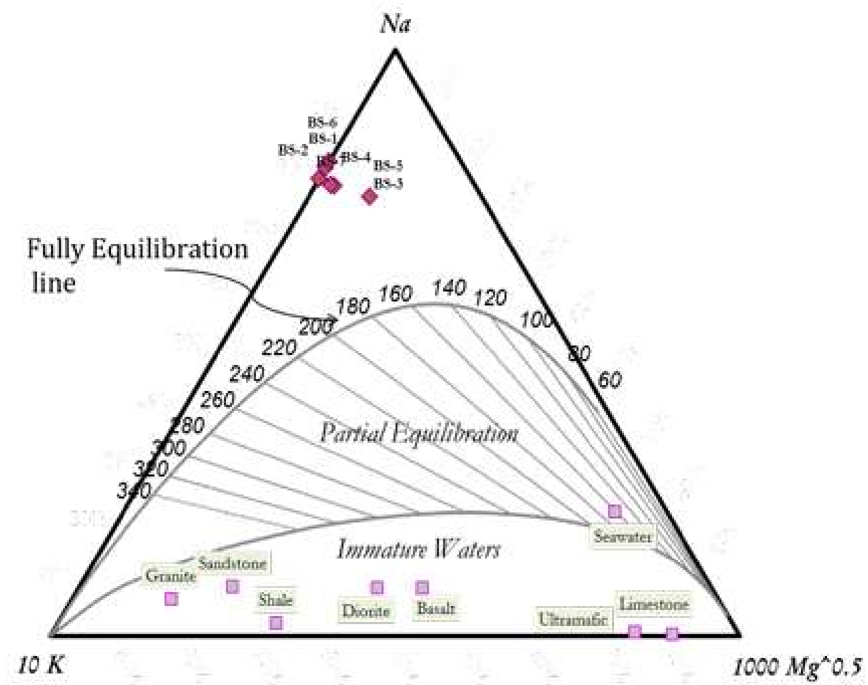
3.Geological and Geophysical Modeling:

1. Construct three-dimensional models of the subsurface based on collected data to visualize and better understand the geometry and characteristics of the geothermal reservoir.



Geothermal Resource Characterization – Ternary Diagrams

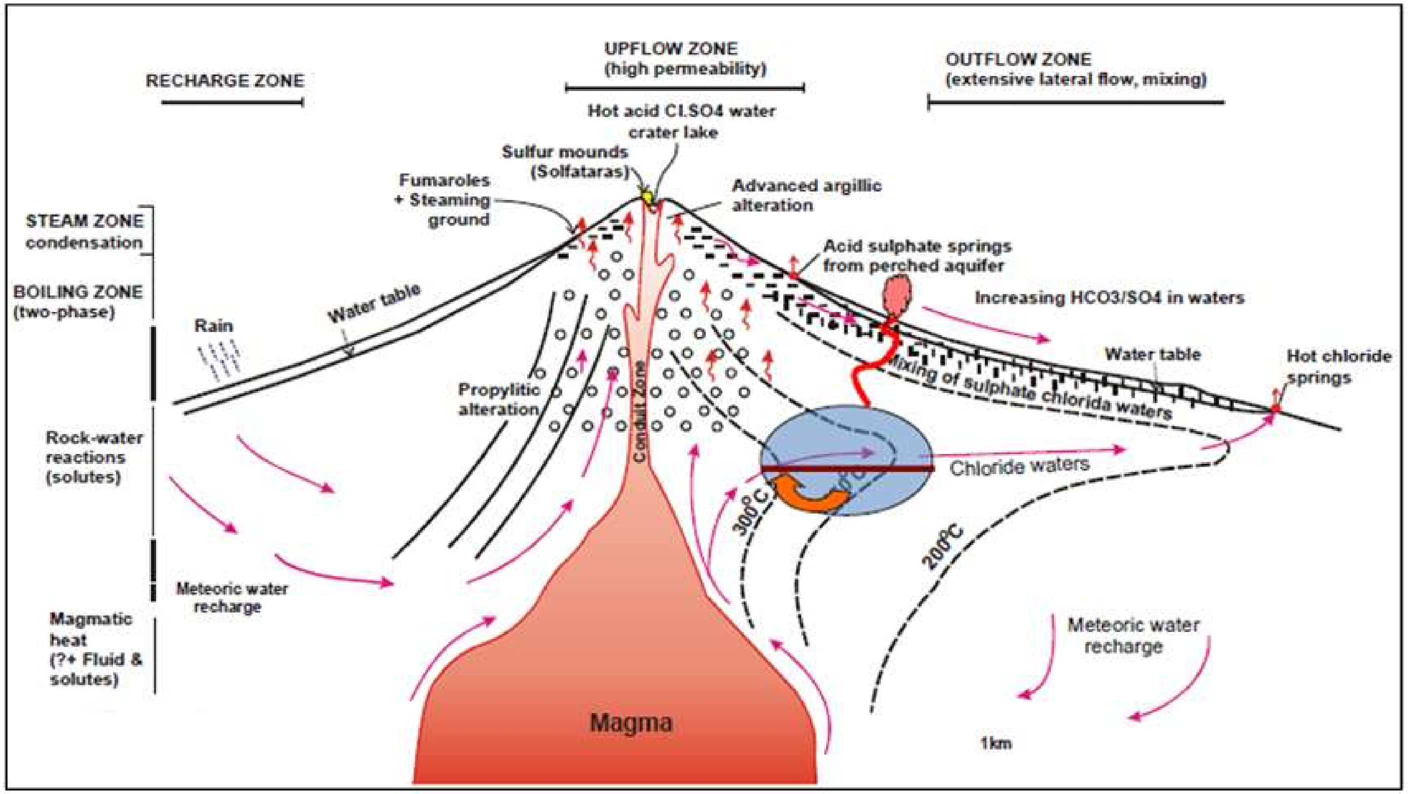




Conceptual Model

- A conceptual model is a descriptive or qualitative model incorporating, and unifying, the essential physical features of the systems in question.

- Information is derived from various disciplines.

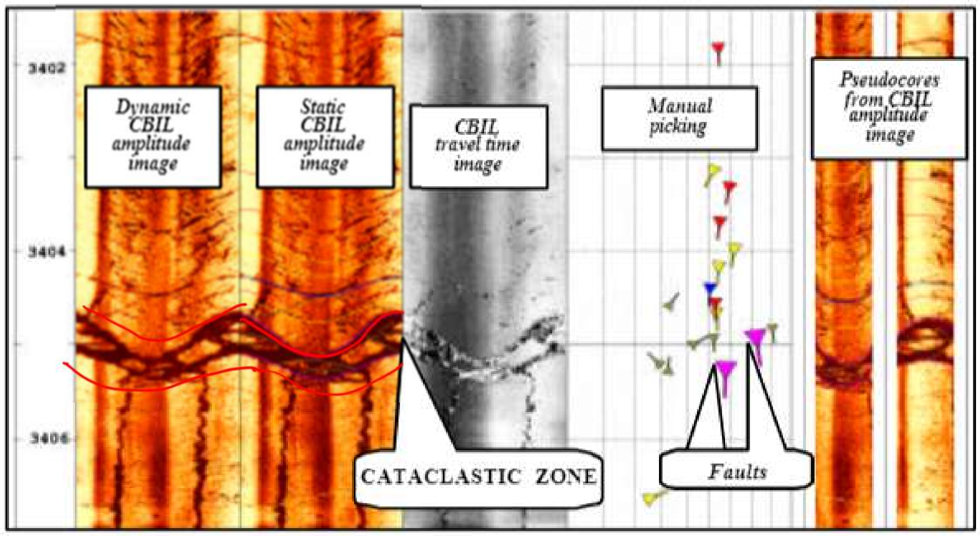


Geothermal Well Logging

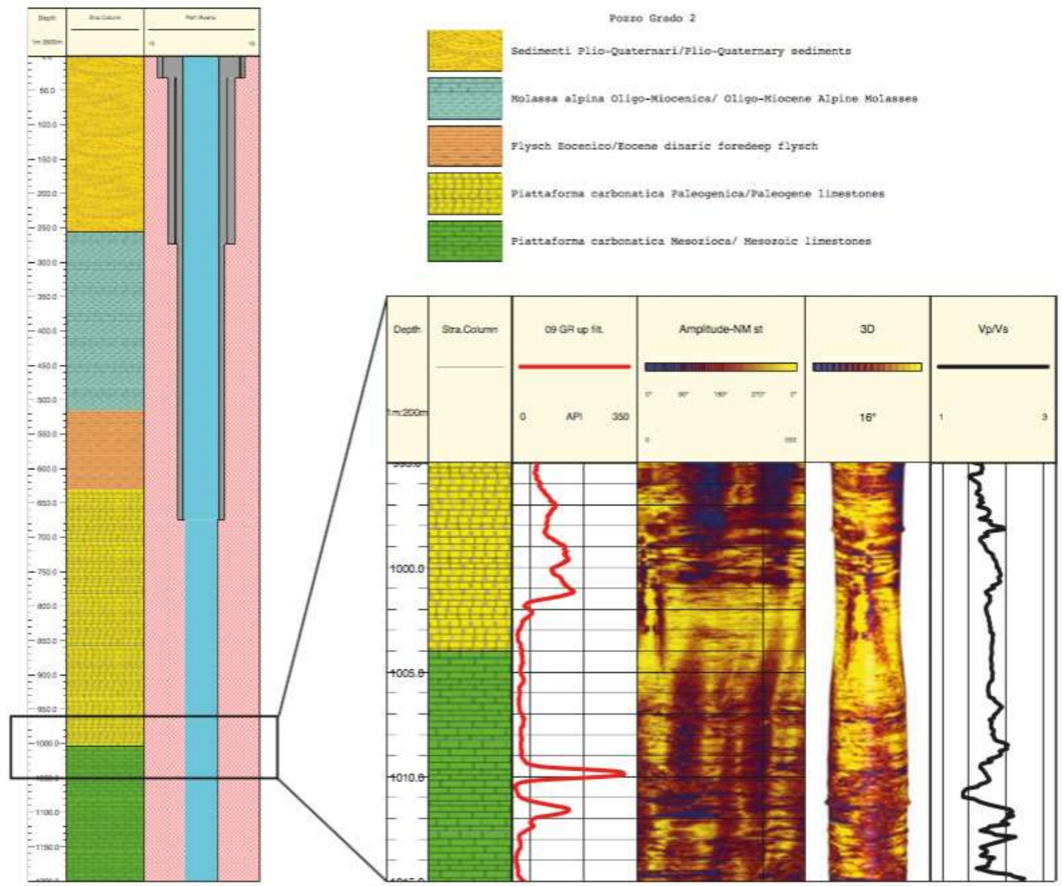
Logging items	Main functions
Natural gamma ray	Classification of lithologies; stratigraphic correlation; calculation of the shale content; division of aquifers
Spontaneous potential	Classification of lithologies; division of aquifers; determination of formation water resistivity; identification of formation salinity; calculation of the shale content
Resistivity	Determination of the apparent resistivity parameters of rock formations; classification of lithologic profiles; determination of aquifers
Acoustic slowness	Determination of reservoir porosity; stratigraphic division
Well temperature	Determination of geothermal gradients; identification of outlet water temperature and the location of water stop section
Caliper	Evaluation of borehole changes; assistance in determining lithologies

Geothermal Well Logging

Feed zone



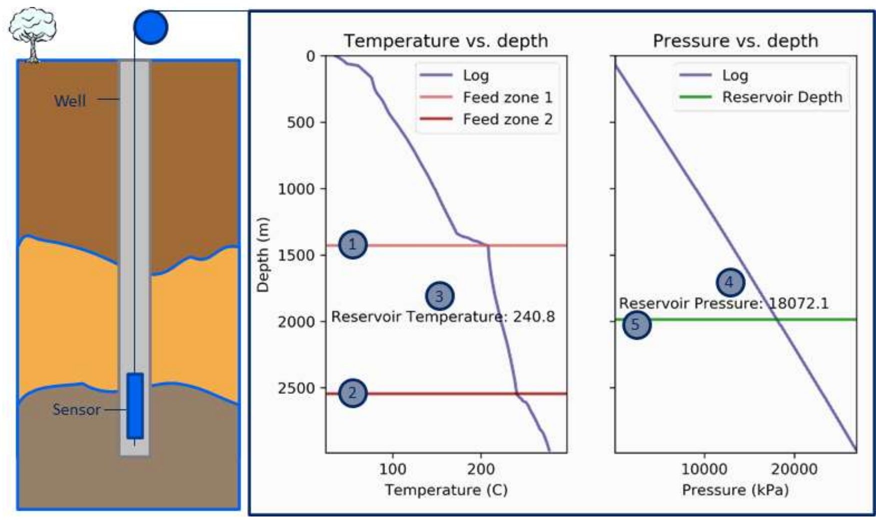
•DOI: 10.13140/2.1.1332.7362



https://www.waterstones-srl.it/en/well-logging-for-the-geothermal-reservoir-characterization/

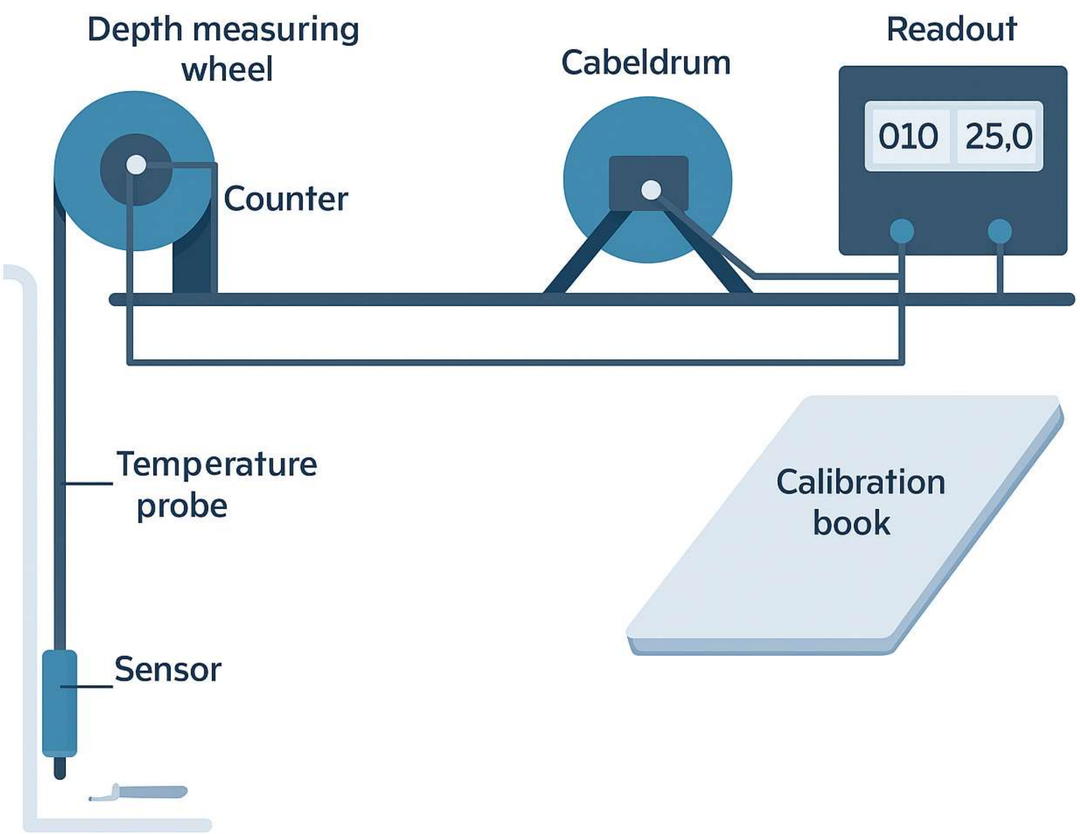
Geothermal Well Logs

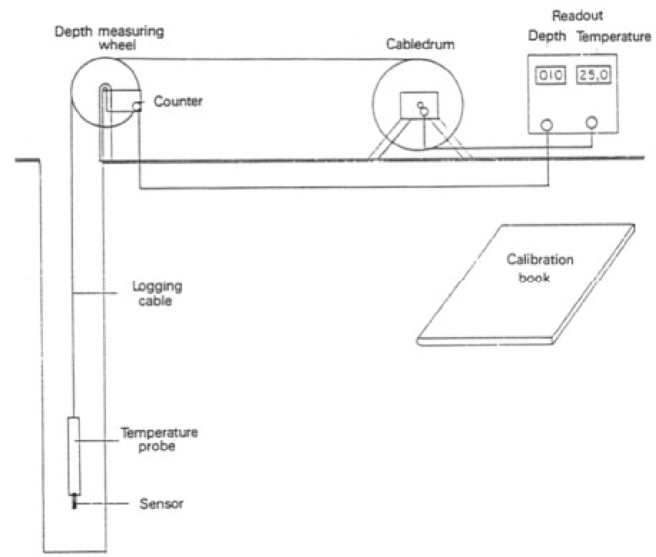
- Geothermal temperature and pressure logs: -
- the most important well logs in geothermal exploration and development
- used at early stages to determine formation temperature and pressure
- used later in the life of a field for reservoir management



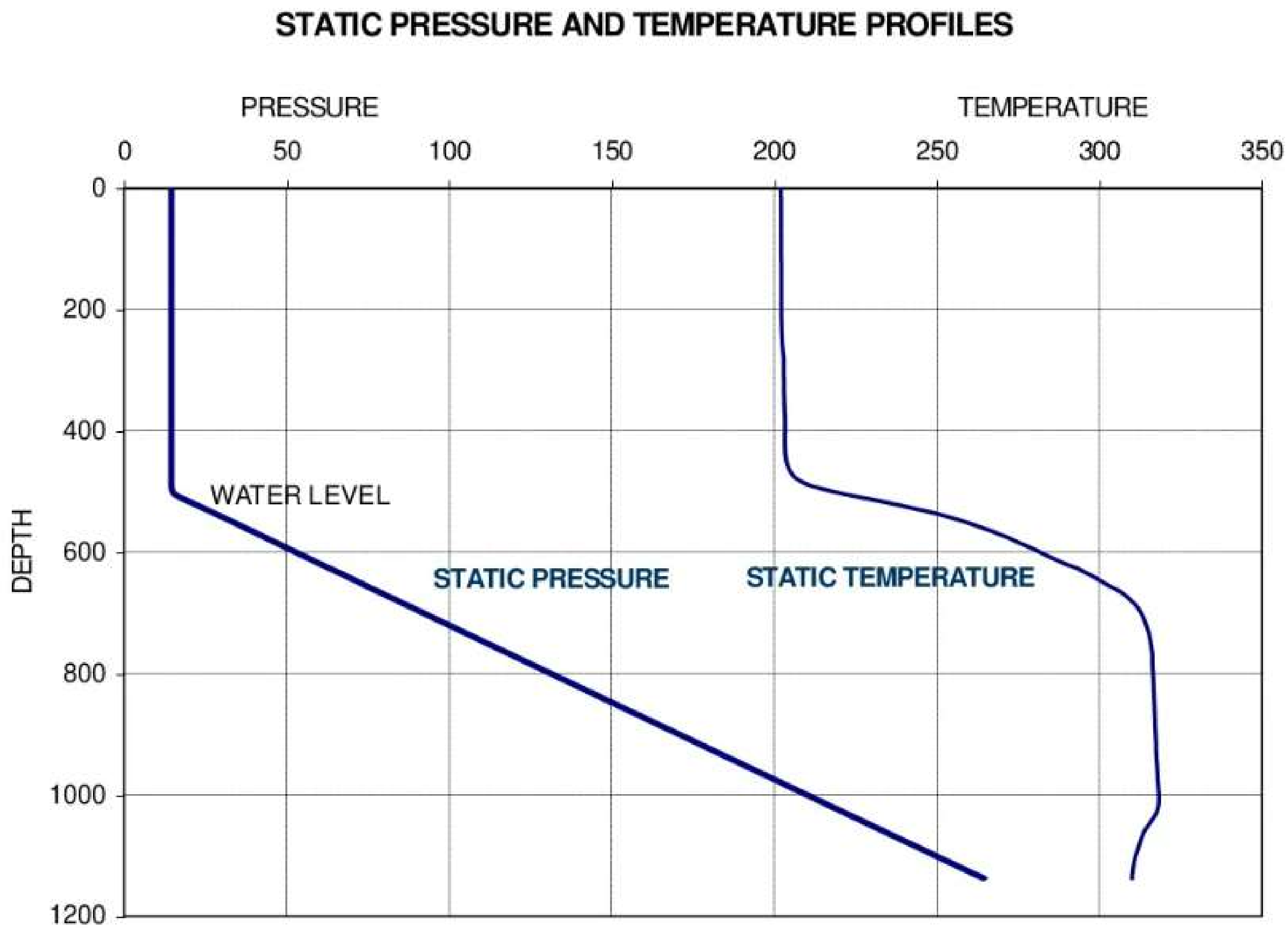
•Logging is carried out during phases in drilling, during heating-up after drilling, and during flow tests.

Temperature and Pressure Logging Tools



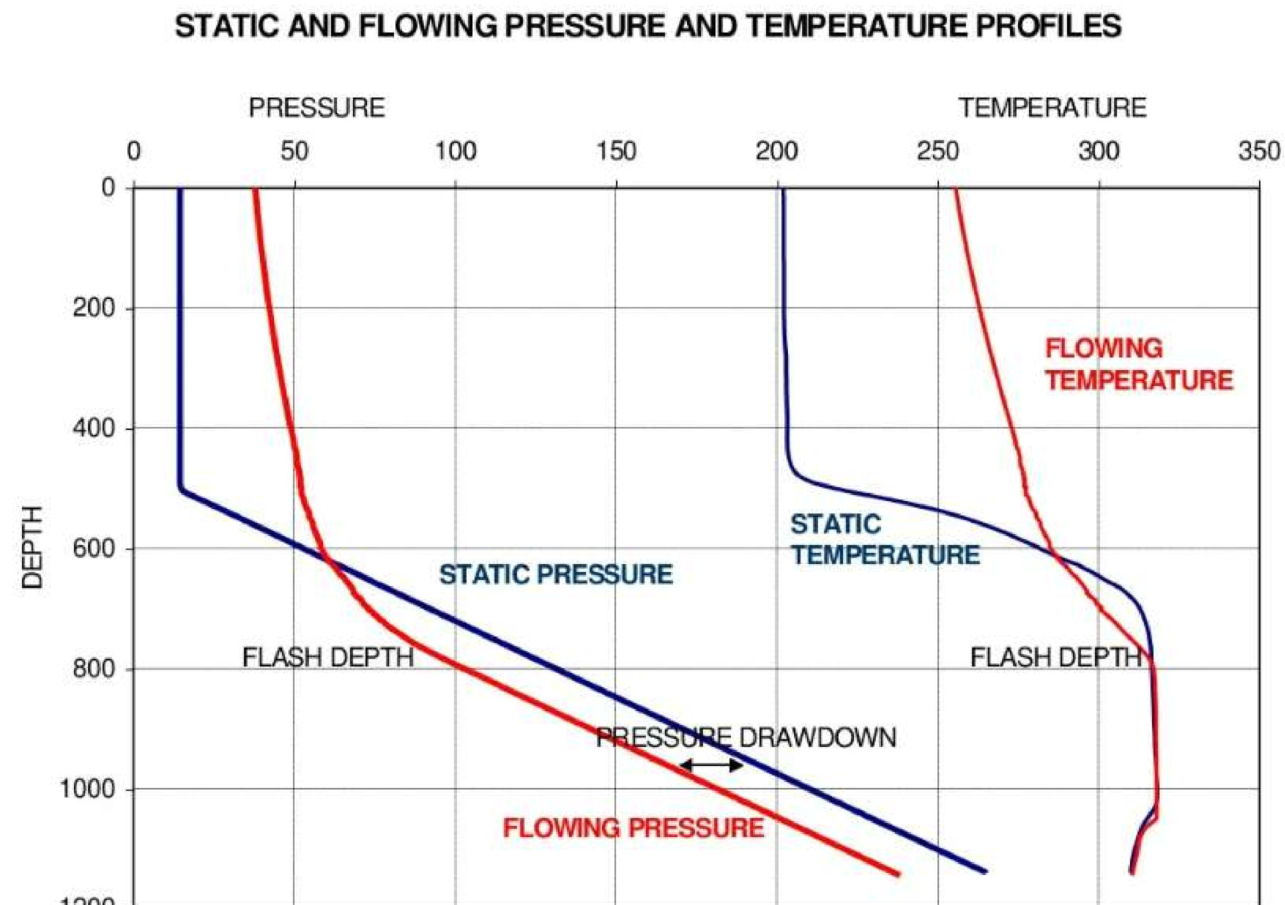


Temperature and Pressure Logging Plots



https://www.slideshare.net/hzharraz/well-logging

Temperature and Pressure Logging Plots



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Stored Heat Estimate

- The simplest assessment of a reservoir is the "stored heat" method. Similar to the volumetric and mass-in-place methods.

$$Q_{tot} = V\rho_r C_r (T_r - T_o)$$
$$Q_{tot} = Ah\rho_r C_r (T_r - T_o)$$

- If we consider that the reservoir has pores

$$Q_{tot} = Ah(T_r - T_o) \times [(1 - ø)\rho_r C_r + ø\rho_f C_f]$$

- where T_o is the reject temperature or local air temperature, or a cut-off temperature when the project will not be economical.

Reserves / Power Plant Capacity

- It is usual to express the reserves in MWe^{-yr} or as MWe for a set period of time, say 30 years.

$$MW = \eta r \int \rho_r C_r (T - T_o)\, \mathrm{d}V / (L_F \times 30 \times 8760)$$

$$MW = \eta r \int \rho_r C_r (T - T_o)\, \mathrm{d}V / (L_F \times 2.628 \times 10^5)$$

- Where L_F is the load or capacity factor, η is the plant efficiency, and r is the recovery factor around 25%.

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Steam Reservoir Performance

- Material-balance equations provide a relationship between original fluids in place, cumulative fluid production, and average reservoir pressure. For many gas reservoirs, a simple material-balance equation can be derived on the basis of the following assumptions:
  - Gas-filled pore volume is constant
  - Gas dissolved in water or liberated from the rock is negligible
  - Reservoir temperature is uniform and constant

- With these assumptions, the real-gas law can be used to derive an expression to determine the mass of resource in place.

Steam Reservoir Performance

- A reservoir changes from condition 1 (p_1, V_1, T_1) to a later condition 2 (p_2, V_2, T_2).
- The gas behavior is described by the Real Gas Law:

$$p_1 V_1 = z_1 nR T_1 \text{ and } p_2 V_2 = z_2 nR T_2$$

- For constant temperature:

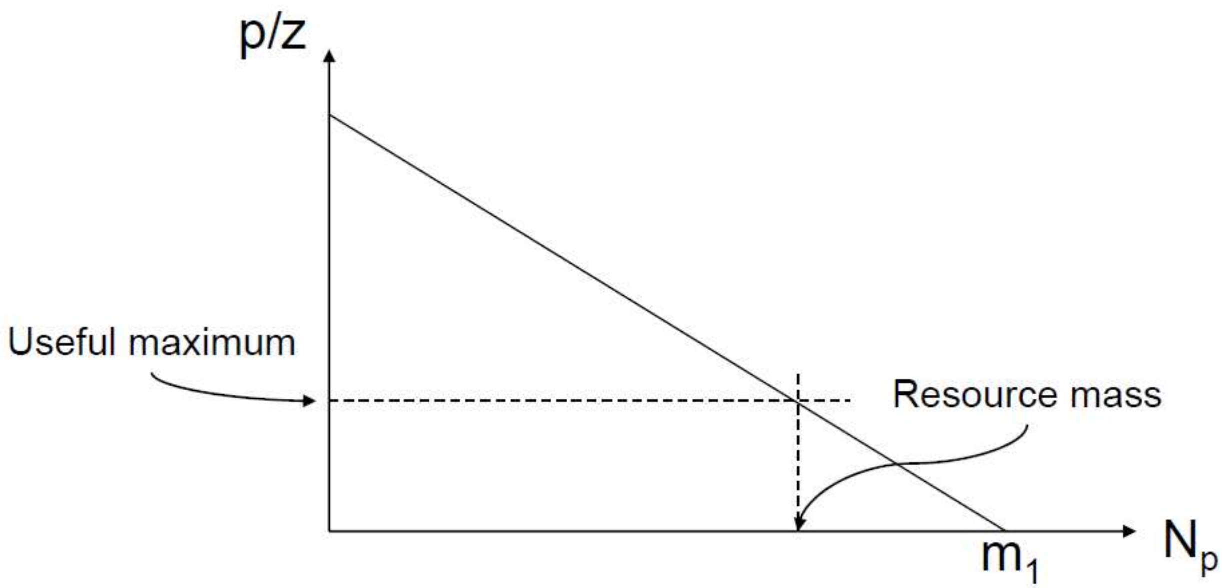
$$\frac{p_1}{\rho_1 z_1} = \frac{p_2}{\rho_2 z_2} \quad or \quad \frac{p_2}{z_2} = \frac{p_1}{z_1}\left(\frac{\rho_2}{\rho_1}\right)$$

- For a fixed reservoir volume

$$\frac{p_2}{z_2} = \frac{p_1}{z_1}\left(\frac{m_2}{m_1}\right)$$

Steam Reservoir Performance

- But $$m_2 = m_1 - N_p$$
- Therefore: $$\frac{p_2}{z_2} = \frac{p_1}{z_1}\left(1 - \frac{N_p}{m_1}\right)$$



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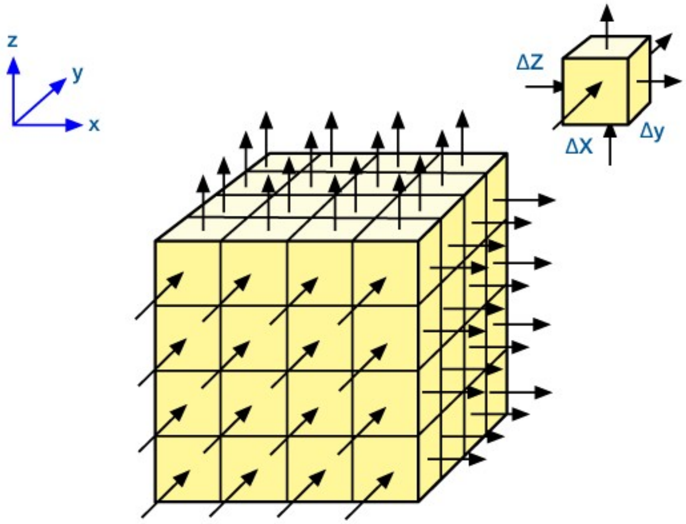
Reservoir Simulation

- What is Reservoir Simulation
- A **numerical reservoir simulation** model is a grid block model of a reservoir where each of the blocks represents a local part of the reservoir. Within a grid block, the properties are uniform (porosity, permeability, Kr, etc.) although they may change with time as the reservoir process progresses.
- Blocks are generally connected to neighboring blocks so fluid (and heat) may flow in a block-to-block manner. The model incorporates data on the reservoir fluids, their rock data, and their distribution is space. Sub models represent and model the wells.

Reservoir Simulation

- Why Reservoir Simulation for Geothermal Reservoirs
- 1.Generating the potential of field
- 2.Appropriate production well spacing
- 3.Decline rate of wells
- 4.Enthalpy and chemical changes with time
- 5.Effect of reinjection on well performance
- 6.Effect of reinjection of reservoir behavior
- 7.Location of reinjection wells



Fundamental Equations

$$\varphi \rho_f c_f \frac{\partial T}{\partial t} + (1-\varphi)\rho_r c_r \frac{\partial T}{\partial t} + \nabla \cdot \left(\varphi \rho_f c_f \boldsymbol{u} T\right) - \nabla \cdot \Big((1-\varphi) k_r \nabla \mathrm{T} + \varphi k_f \nabla \mathrm{T}\Big) = source/sink$$

Heat stored / accumulated in fluid	Heat stored/accumulated in rock	Heat flow by fluid convection	Heat flow by conduction in rock	Heat flow by conduction in fluid	Energy balance

φ: porosity (-)
ρ: density (kg/m^3)
c: specific heat capacity (J/(kgK))
T: temperature (K)
u: Darcy velocity (m/s)
k: heat conductivity (W/(mK))
$_r$: rock
$_f$: fluid

$$\nabla \cdot \left(\frac{\rho}{\mu} \mathbf{k} \cdot \nabla p\right) + R = \frac{\partial}{\partial t}(\phi \rho).$$

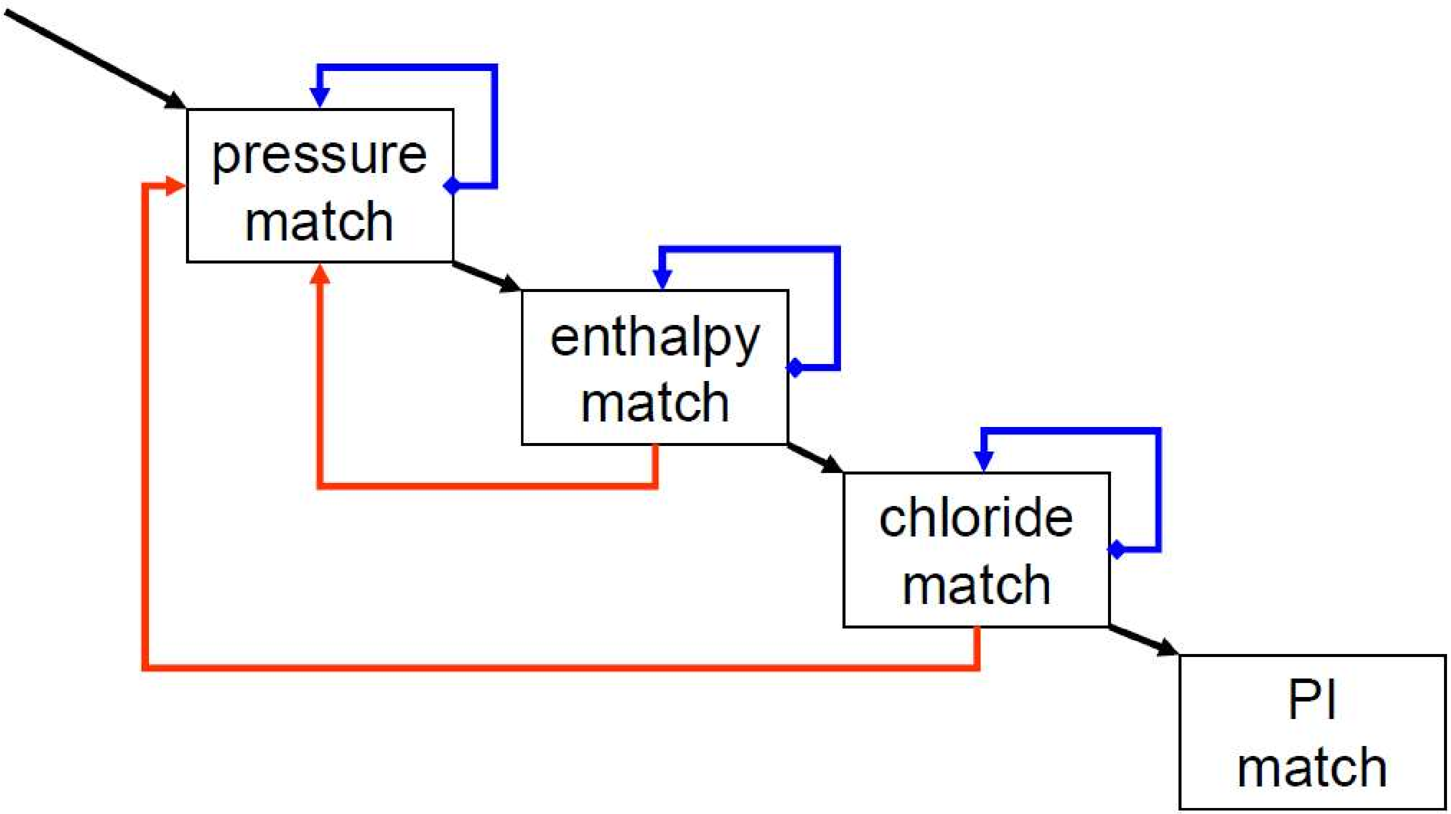
Mass flow term	Source/ sink	Fluid accumulated	Mass balance

These equations are solved with initial and boundary conditions, and constitutive equations

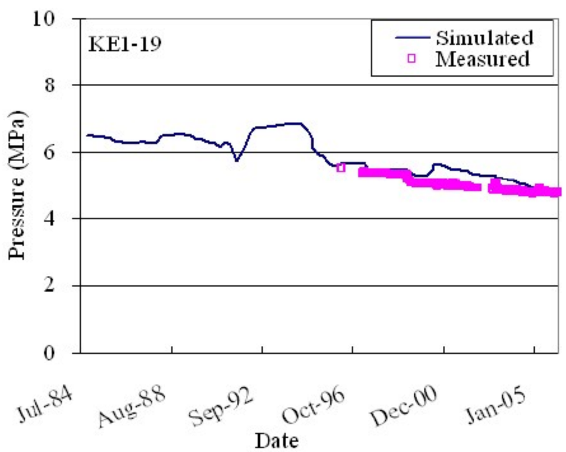
Modeling Steps

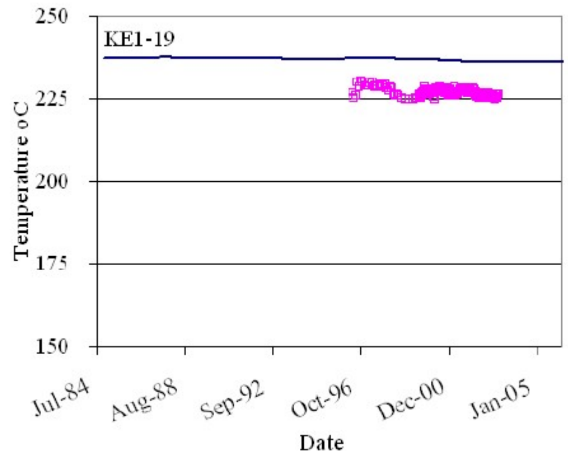
1. Natural state modeling:
   - Reproducing the measured pressure, temperature and enthalpies prior to development.
2. History matching:
   - Matching the changes of pressure, temperature, enthalpy and chemistry during production.
3. Exploitation modeling:
   - Forecasting the future performance of the reservoir.

Modeling Steps – History Matching

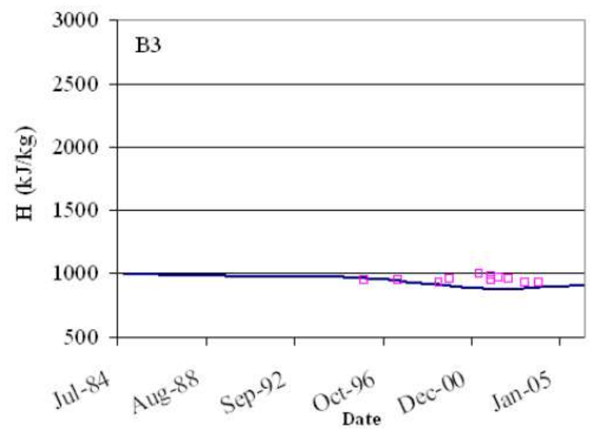


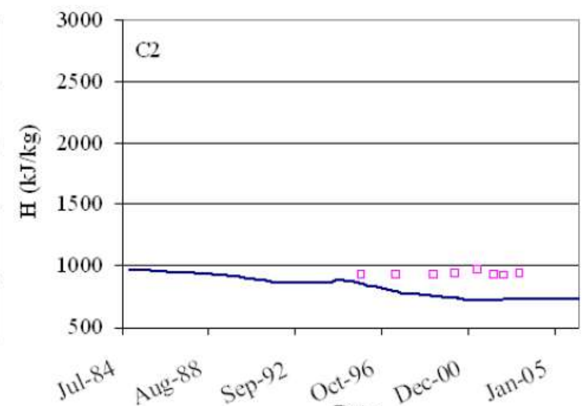
History Matching





- Enthalpy Match





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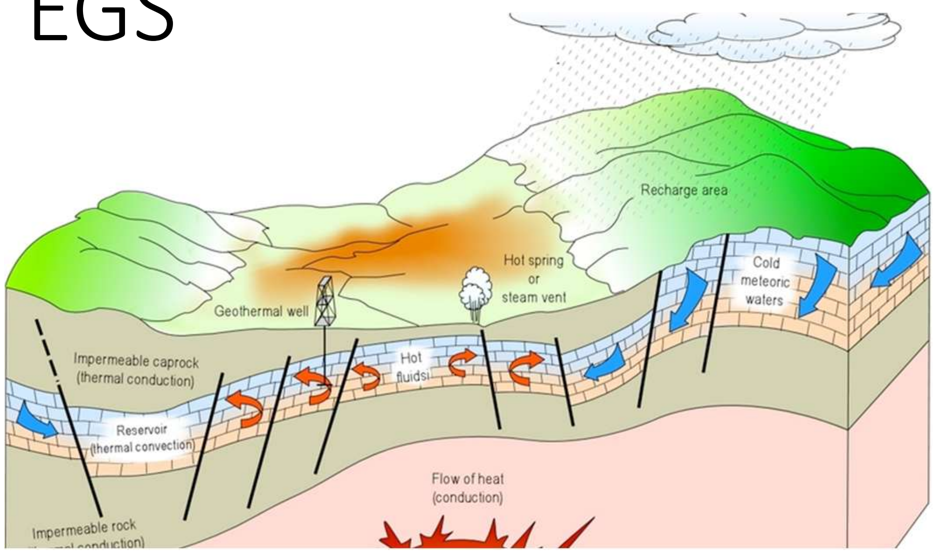
Conventional vs. EGS

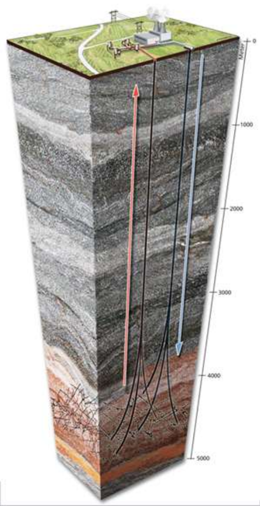
Conventional hydrothermal requires:

- Fluid in place
- High geothermal gradient (>150 W/m^2 at reservoir <3000m depth)
- High permeability
- Cap rock



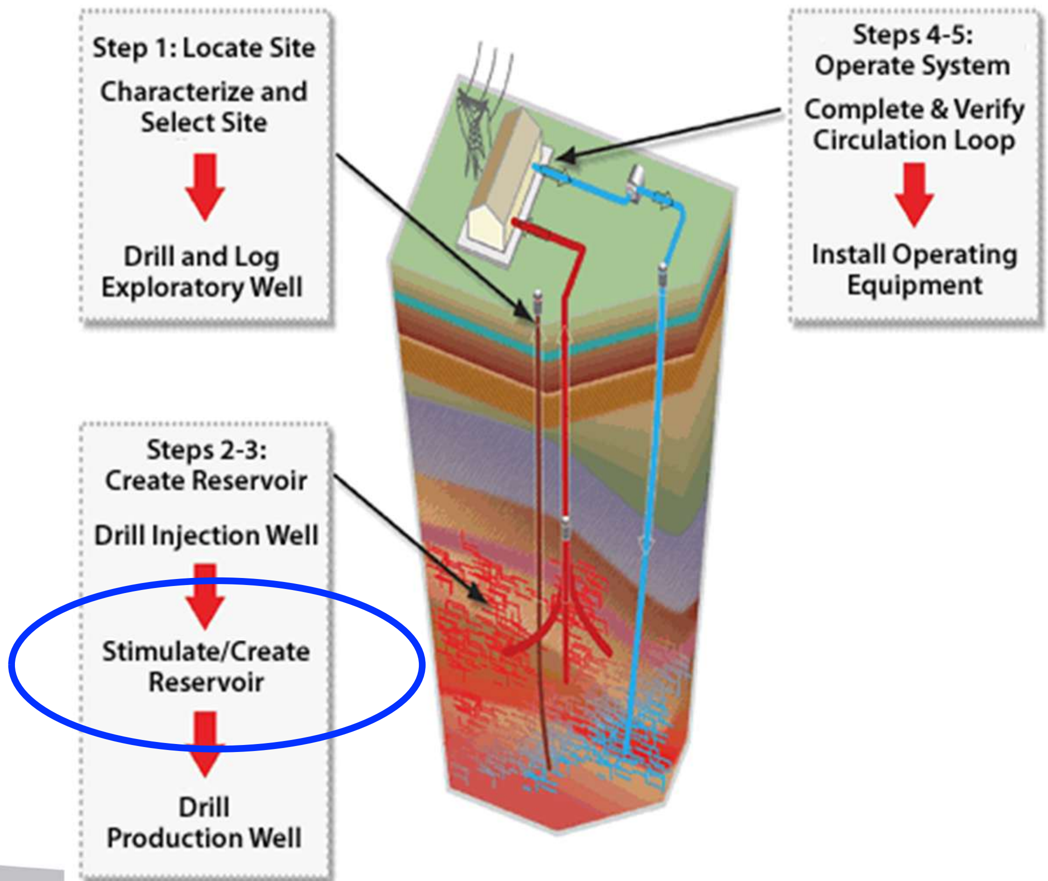
Enhanced Geothermal Systems Technology:

- Produce energy from resources that are otherwise not economical due to lack of fluid and/or permeability
- EGS rocks are hot, and may have natural fractures



EGS Development Sequence

- Fracture stimulation to enhance natural permeability
- Fluid circulation from injector to producer well(s)
- Create new fractures or slip preexisting fractures



https://www1.eere.energy.gov/geothermal/images/illustration_egssteps.gif

Creating the reservoir - Stimulation mechanisms

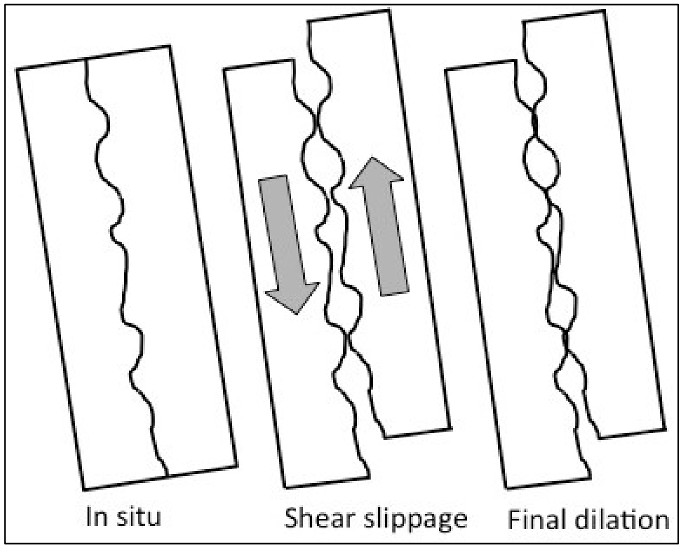
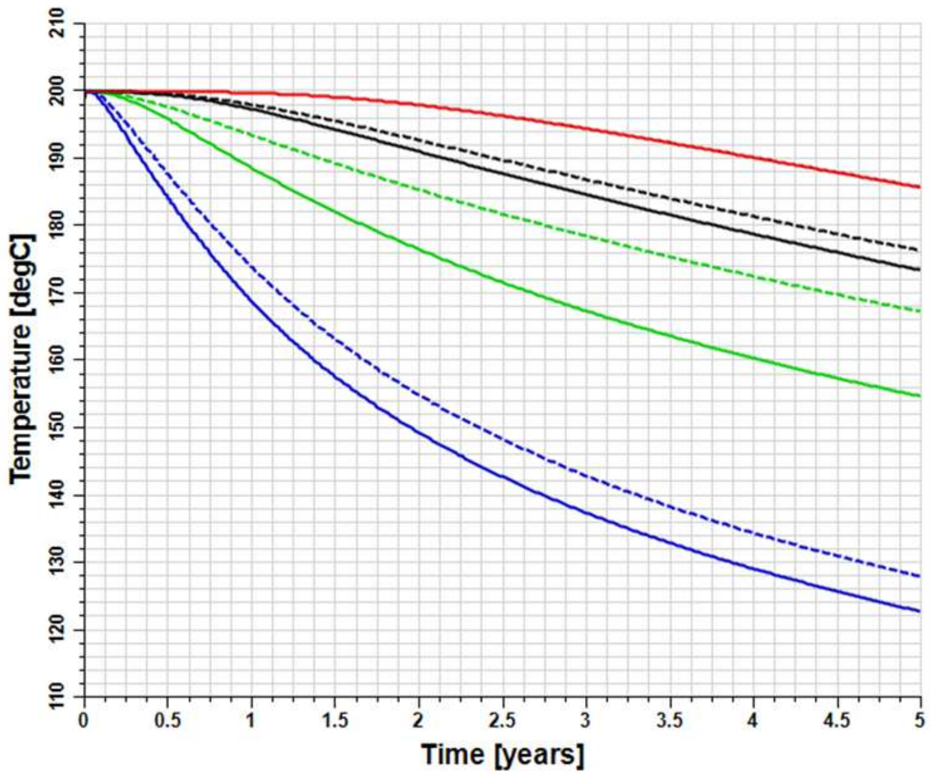


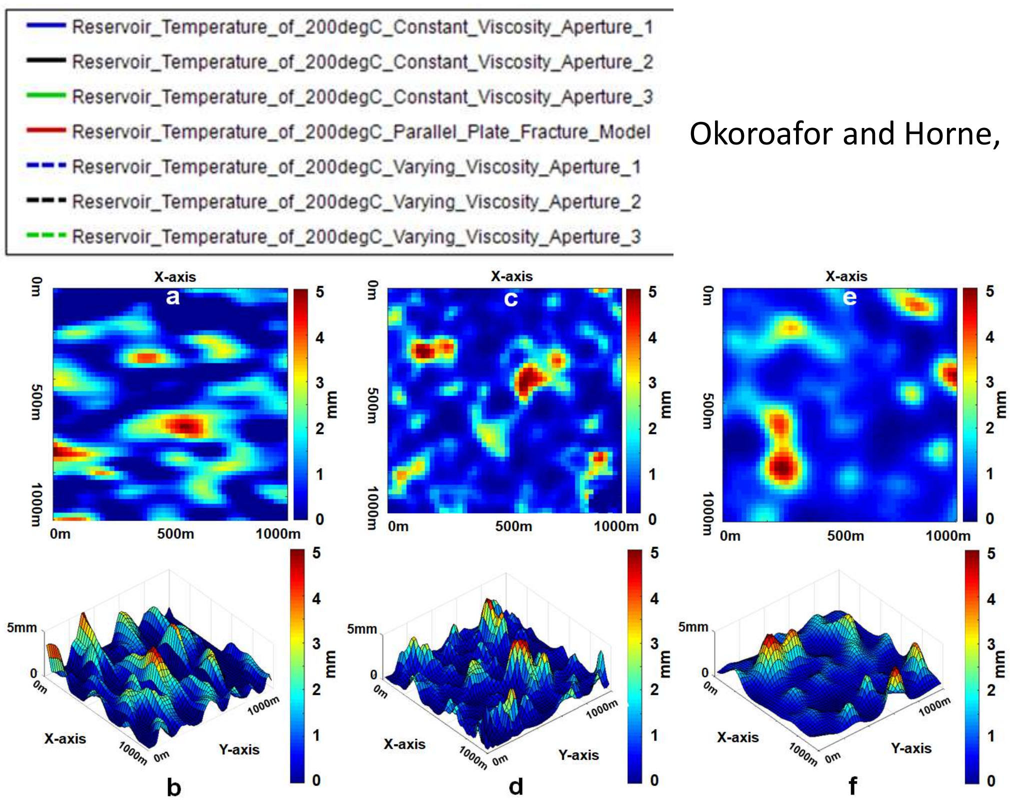
Figure: Hydroshearing

- Hydrofracking
  - high pressures – exceeds minimum principal stress
  - create new fractures
  - often combined with the use of proppants (particles) to retain fracture openings
- Hydroshearing – main EGS mech.
  - low pressures – lower than minimum principal stress
  - open existing fractures
  - openings retained by shear dilation and surface roughness

Thermal Drawdown Curves



Okoroafor and Horne, 2022



https://www.sciencedirect.com/science/article/abs/pii/S2451904922002451

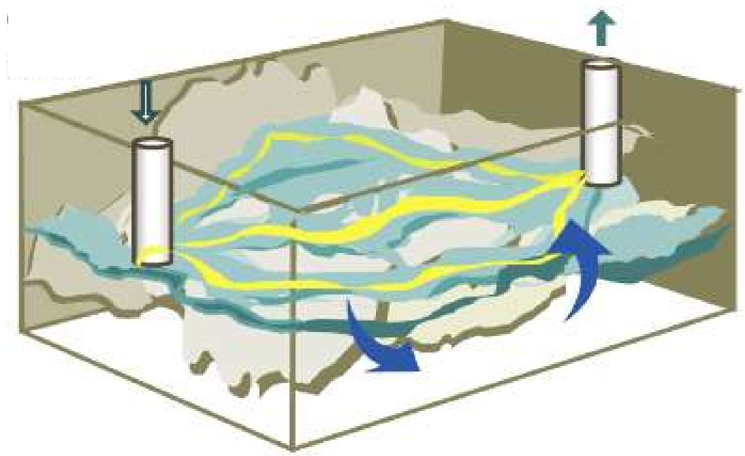
What kind of power plant would you recommend for EGS?

Simple EGS Model

$$q_A = \frac{T_{rock} - T_{inj}}{R_{well}}$$

$$q_B = \frac{2k_{\text{rock}} A_{\text{fracture}}}{b}(T_{\text{rock}} - T_f)$$

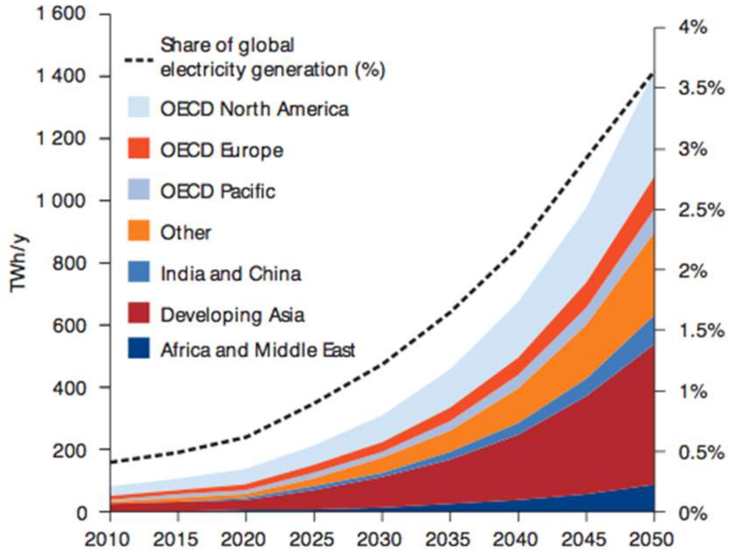
$$q_C = \dot{m} c_p (T_{prod} - T_{inj})$$



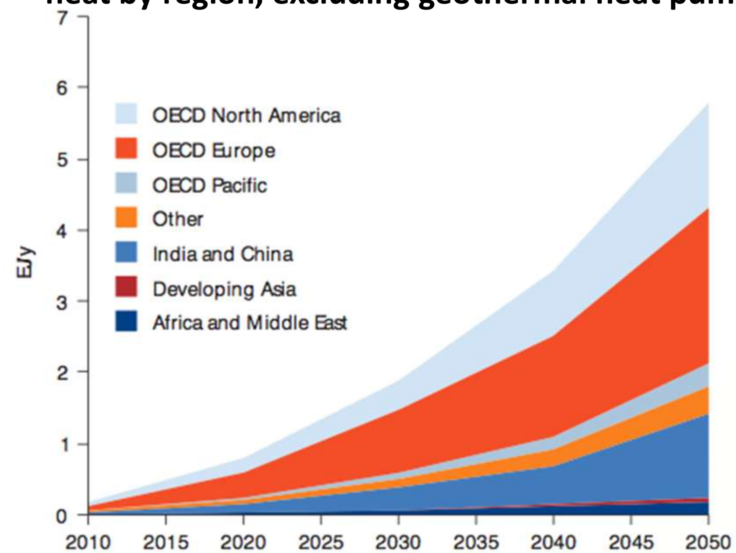
Future geothermal deployment

Source: IEA Technology Roadmap: Geothermal heat and power, 2011

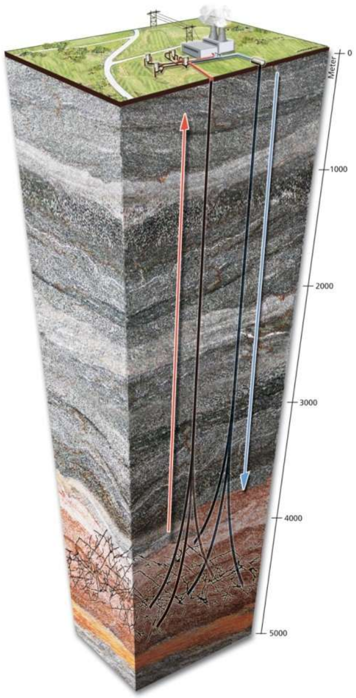
IEA Roadmap vision of geothermal power production by region



IEA Roadmap vision of direct use of geothermal heat by region, excluding geothermal heat pumps



- More than half of the projected increase from EGS resources
- Substantially more research, development, and demonstration are needed to ensure that EGS becomes commercially viable by 2030, but EGS could potentially provide base-load power from a large energy resource that is well-distributed globally.



EGS – Future Use

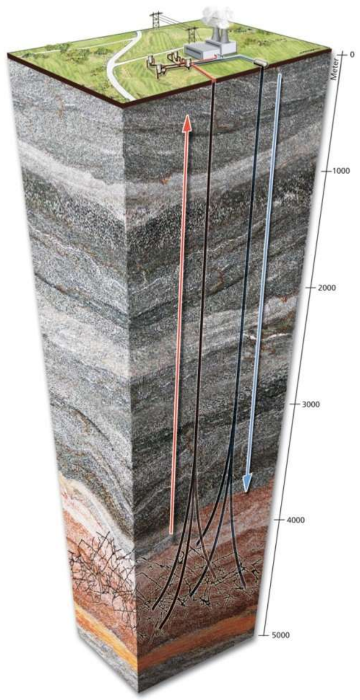
Drivers

- Climate change and negative impact of conventional power and heat production
- Energy independence and security
- Need of base-load power
- Limited land use

Barriers

- High up-front investment costs, lack of incentive schemes
- Resource development risk, water
- Limited awareness and information
- Health, safety and environmental issues (mainly induced seismicity)

EGS – Future Use

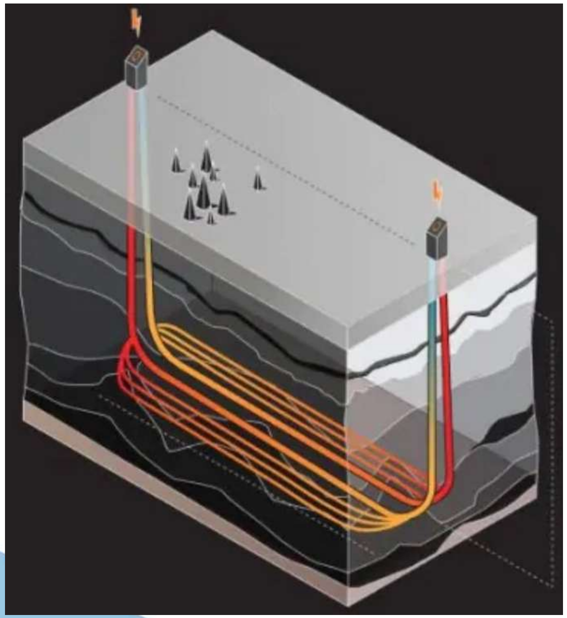


- Technological challenges
- Improved geological data and exploration methods
- Improved Enhanced Geothermal Systems technology
- Larger number of demonstration projects

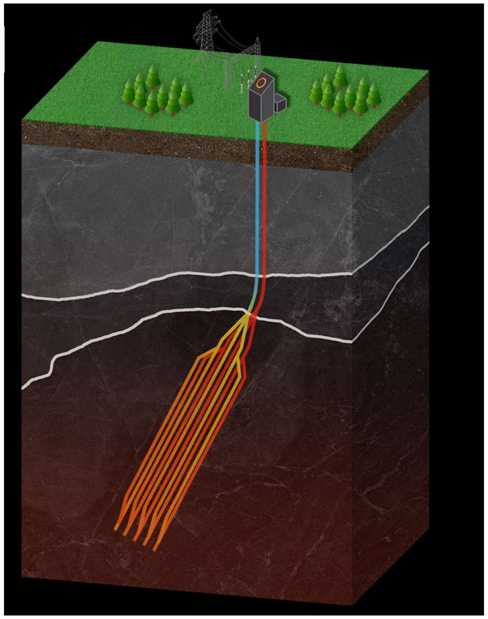
- Reservoir Challenges
- Flow rate
- Flow confined to a small number of fractures (GPK3, Soultz, France)
- Short circuiting (Hijiori, Japan)
- Poor injector/producer connection (GPK4, Soultz, France)
- Induced seismicity (Basel, Switzerland)

Advanced Geothermal Systems

U-loop designs

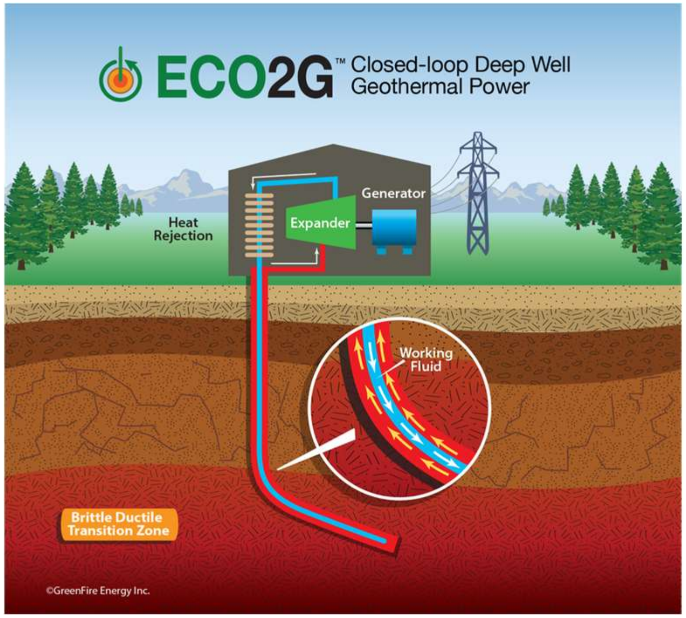


www.eavor.com



www.eavor.com

Co-axial designs



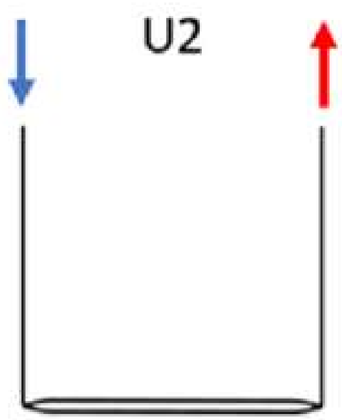
www.greenfireenergy.com

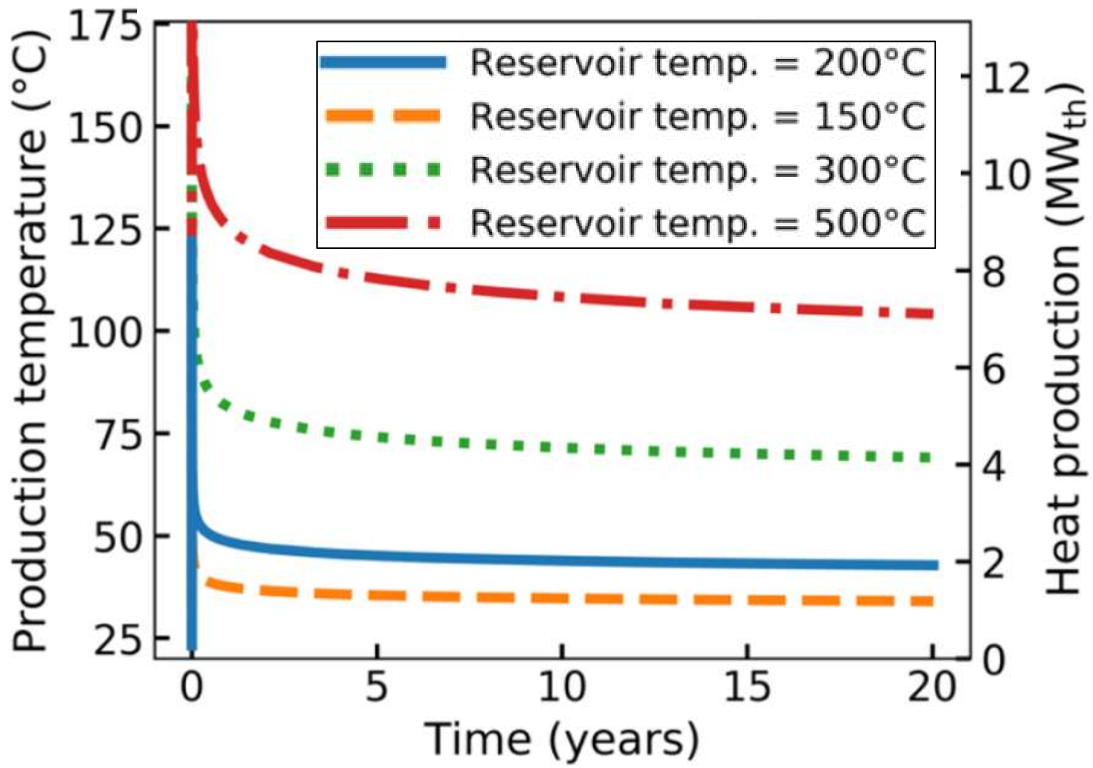
Often referred to as the Closed Loop Geothermal

Heat extraction characterized by rapid temperature decline

Configuration:

- U-loop with 2 laterals
- 2 km depth
- Laterals each 2 km long
- Water injected at 20 kg/s and 20°C

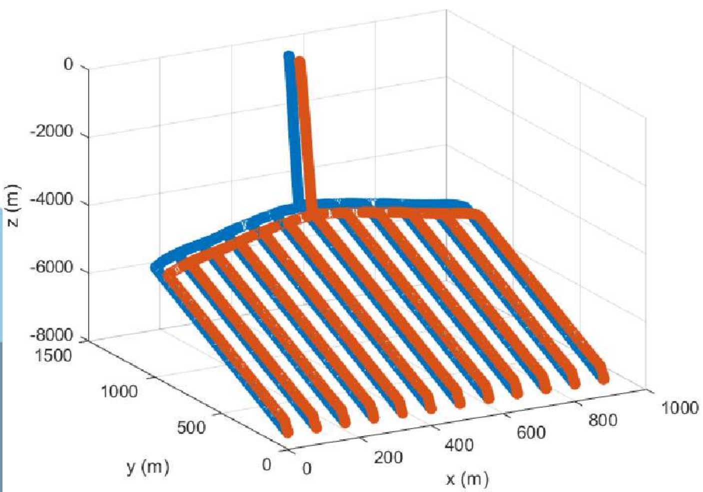


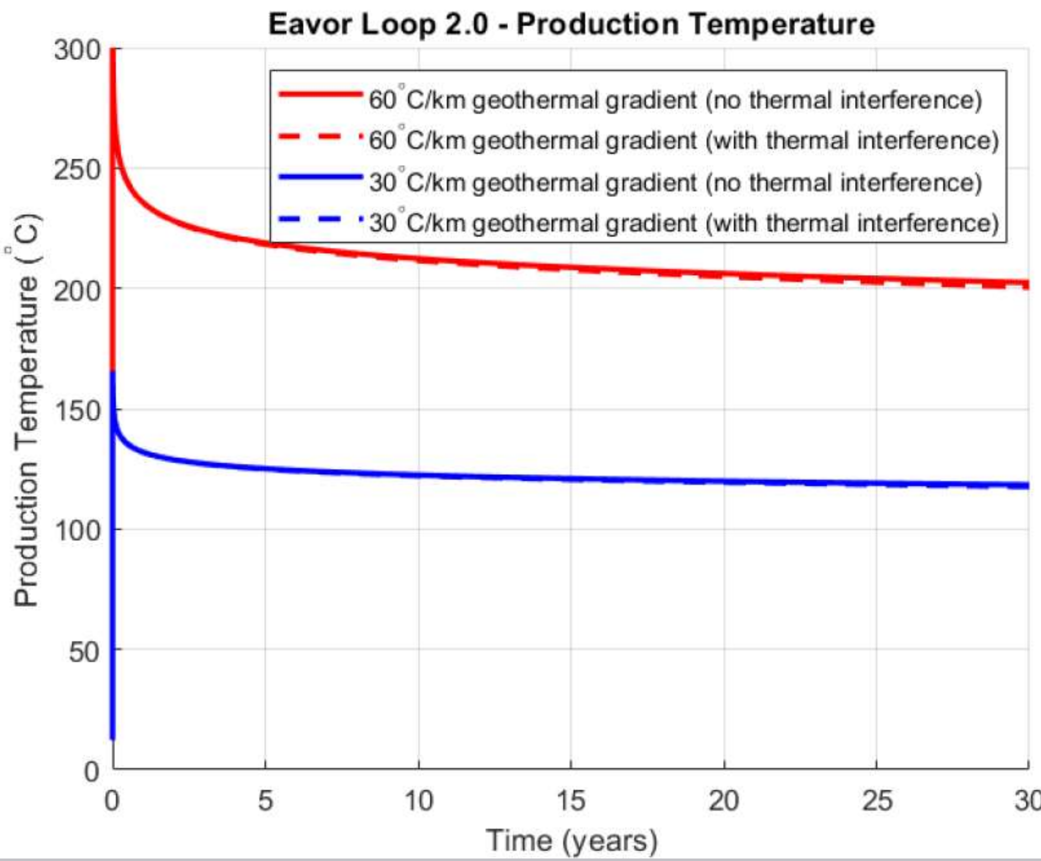


MW_e-scale systems require high temperatures and long laterals

Configuration:

- U-loop with 12 laterals
- 8 km depth
- Laterals each 6.5 km long
- Water injected at 80 kg/s and 60°C





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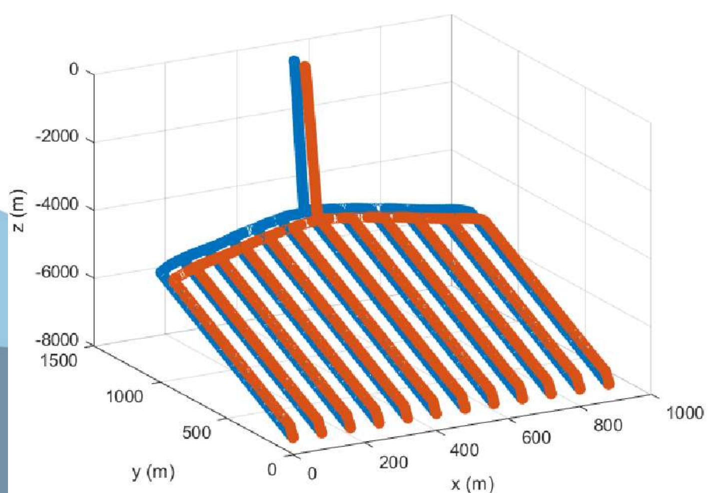
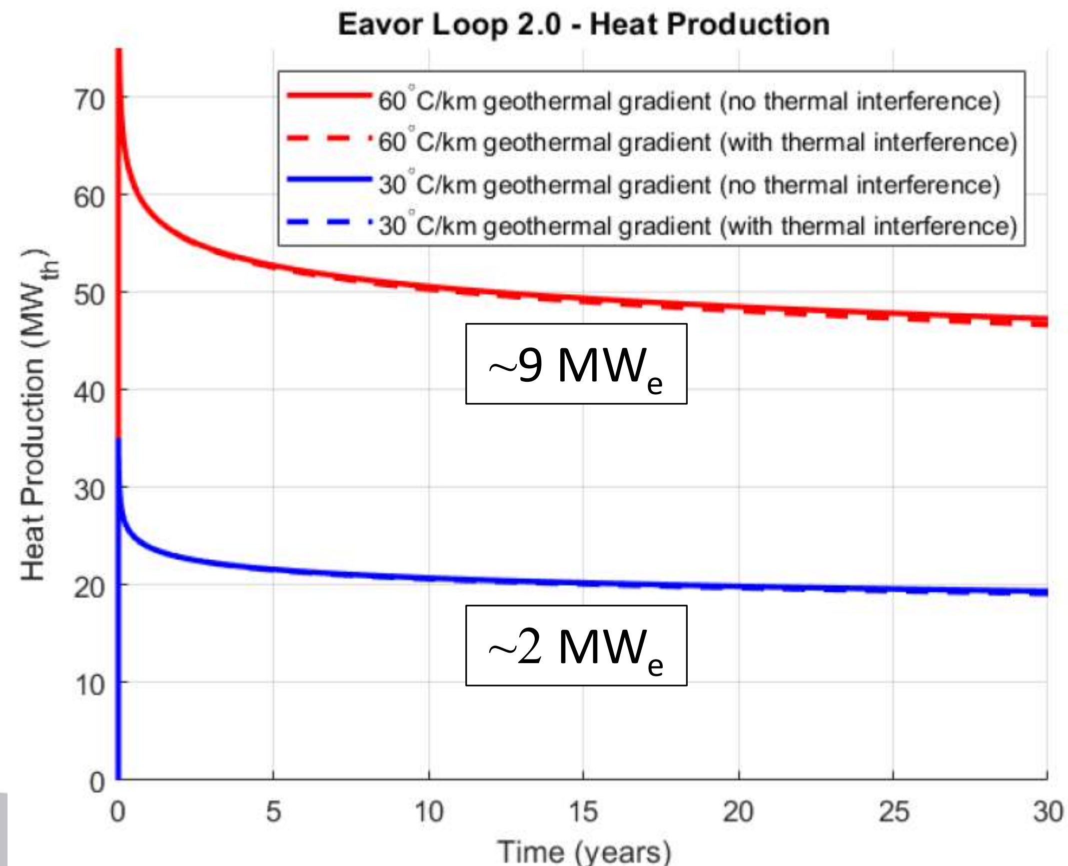
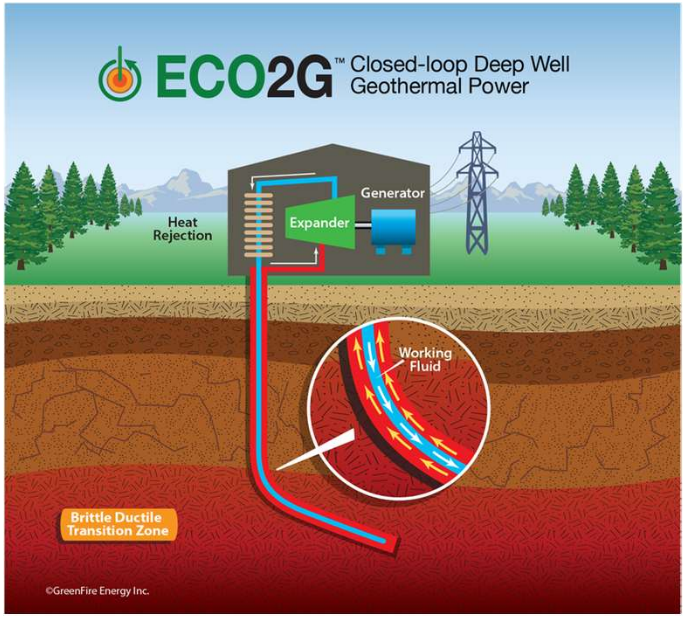




Simple Closed Loop Model

$$q_{coax} = \frac{T_{rock} - T_{in}}{R_{rock} + R_{cement} + R_{pipe}}$$

$$R = \frac{\ln(r_{outer}/r_{inner})}{2\pi k h}$$



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Total Thermal Resistance (casing + cement + rock):

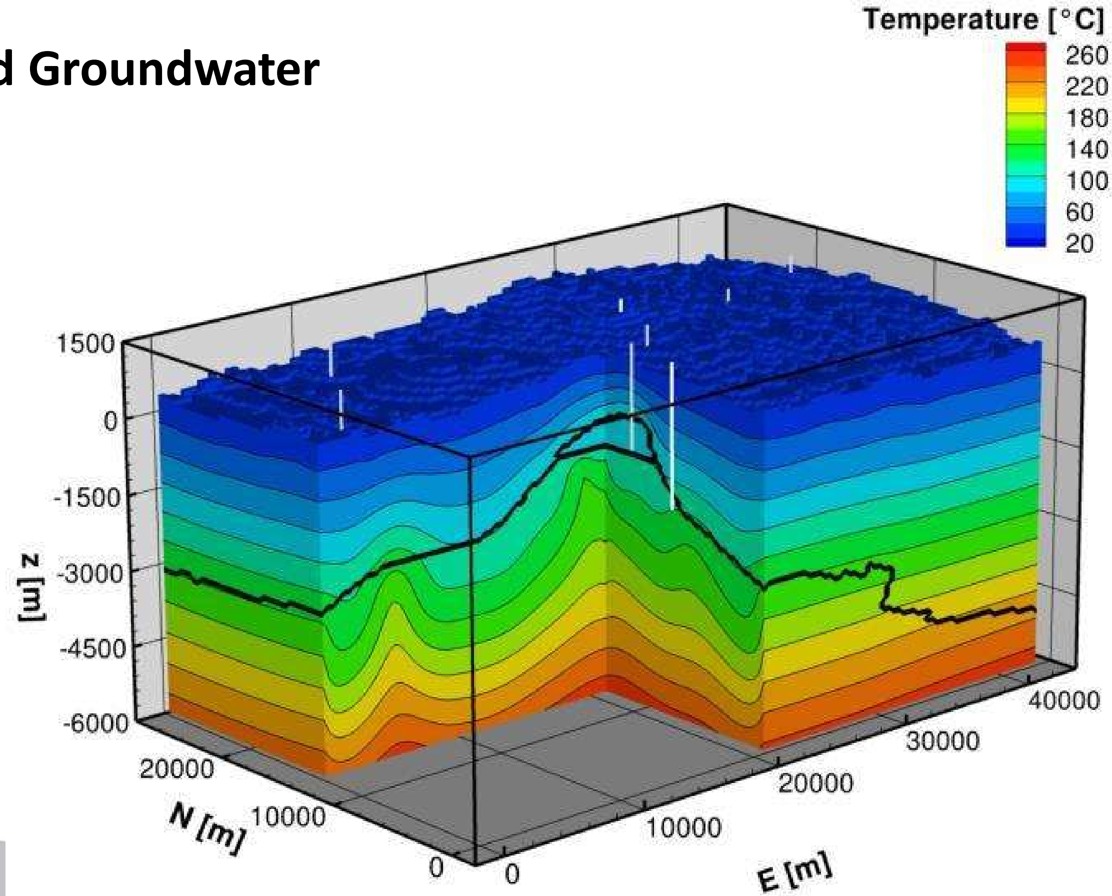
$$R_{total} = R_{casing} + R_{cement} + R_{rock} = \frac{\ln(r_2/r_1)}{2\pi k_{casing} h} + \frac{\ln(r_3/r_2)}{2\pi k_{cement} h} + \frac{\ln(r_4/r_3)}{2\pi k_{rock} h}$$

Simulation Models

Geothermal Software

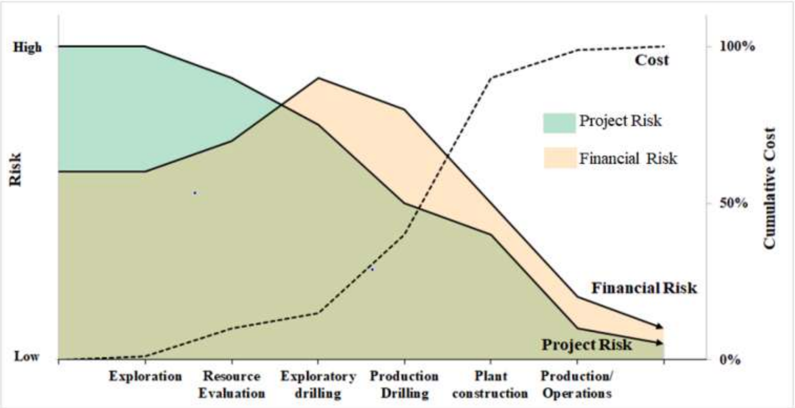
There are several specialized software packages available for geothermal resource engineering. These tools assist in tasks such as reservoir modeling, heat extraction simulation, and economic analysis. Here are some popular software options used in geothermal resource engineering:

1.TOUGH (Transport of Unsaturated Groundwater and Heat)
2.HOTSPOT
3.GEOPHIRES
4.COMSOL Multiphysics
5.FEFLOW
6.ModFlow
7.ResOpt
8.GRTensorII
9.WELLTRACE:
10.GeoModeller
•11.TETRAD
•12.ECLIPSE/PETREL/CMG
•13.LeapFrog
•14.ResFrac

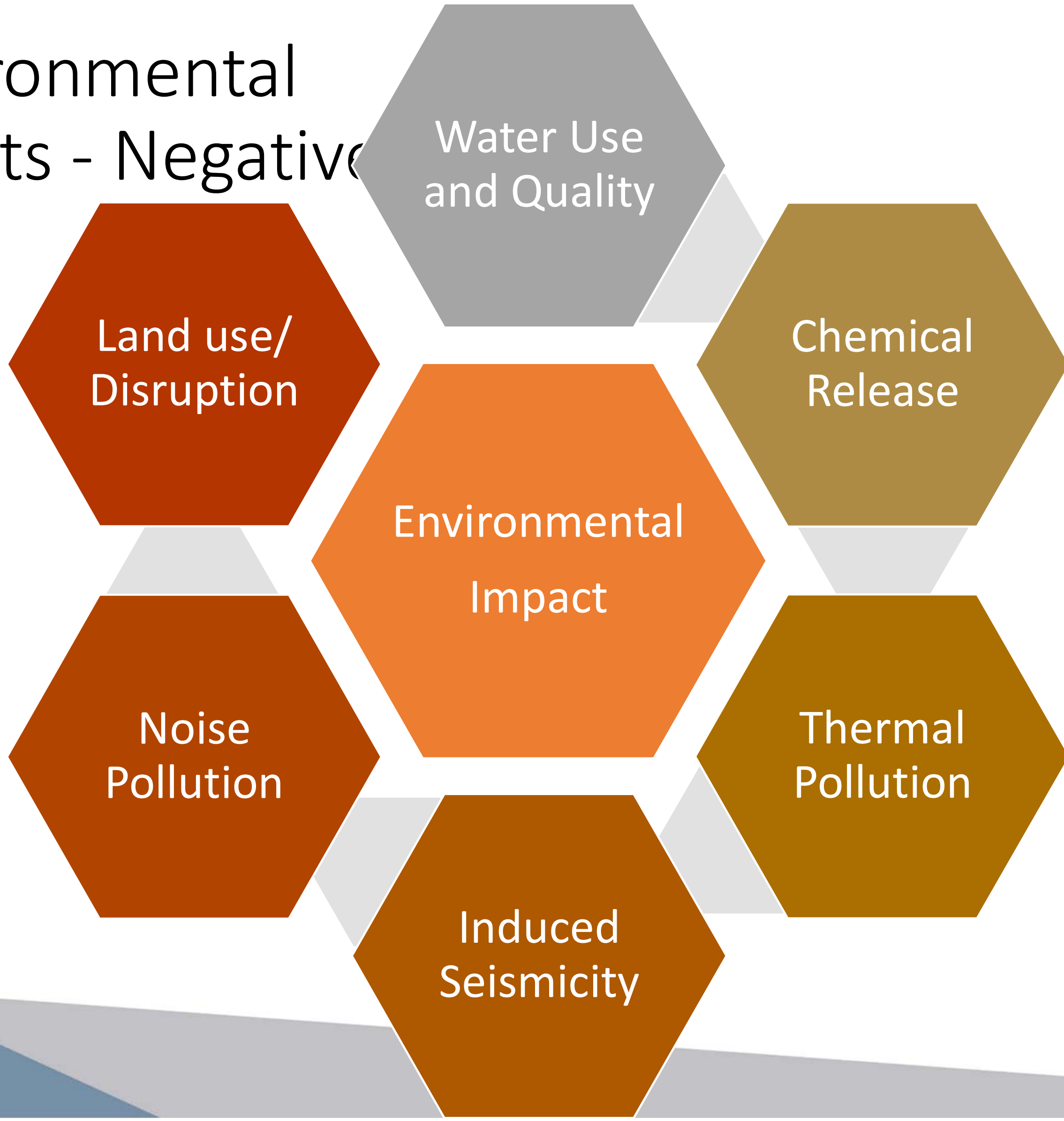


Risks Associated with Geothermal Energy Projects

- Resource Risks: Resource Uncertainty, depletion, and decline
- Environmental Risks: Subsurface Contamination, Geological Instability, Hydrogen Sulfide (H_2S) Emissions, Environmental Noise
- Operational risks: Drilling Risks, induced seismicity.
- Ancillary resource risk: Water resources and land use conflict
- Financial risks: Capital costs, Market Fluctuations.

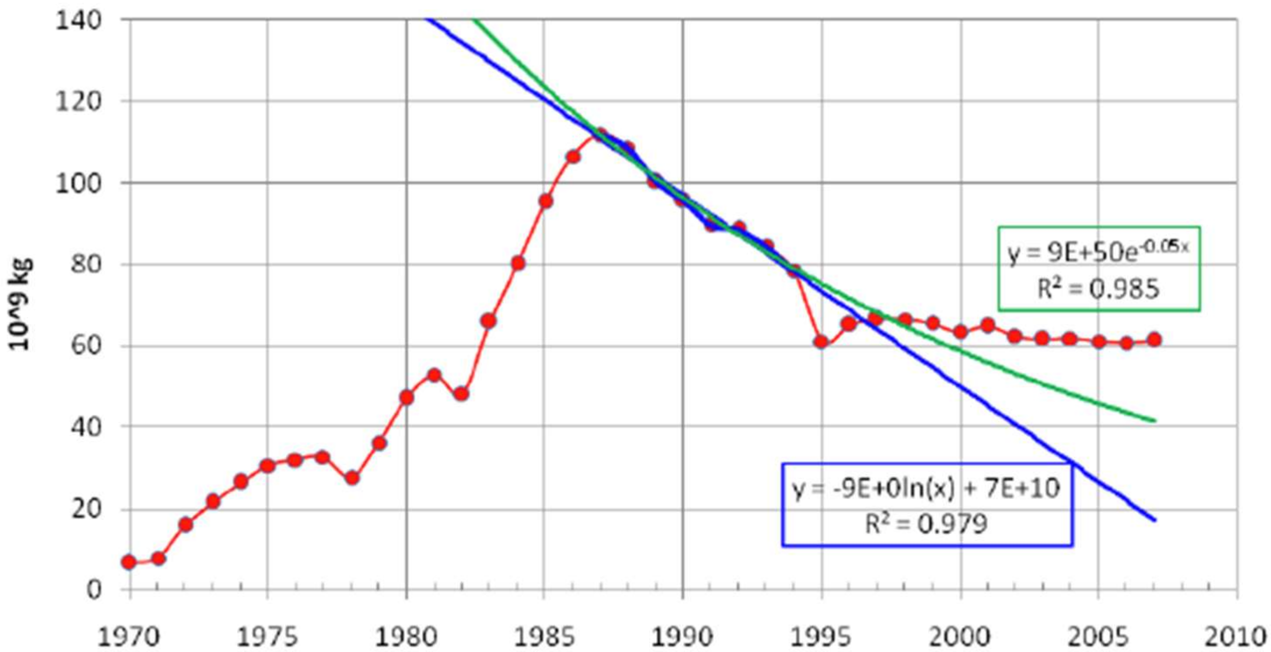


Environmental Effects - Negative

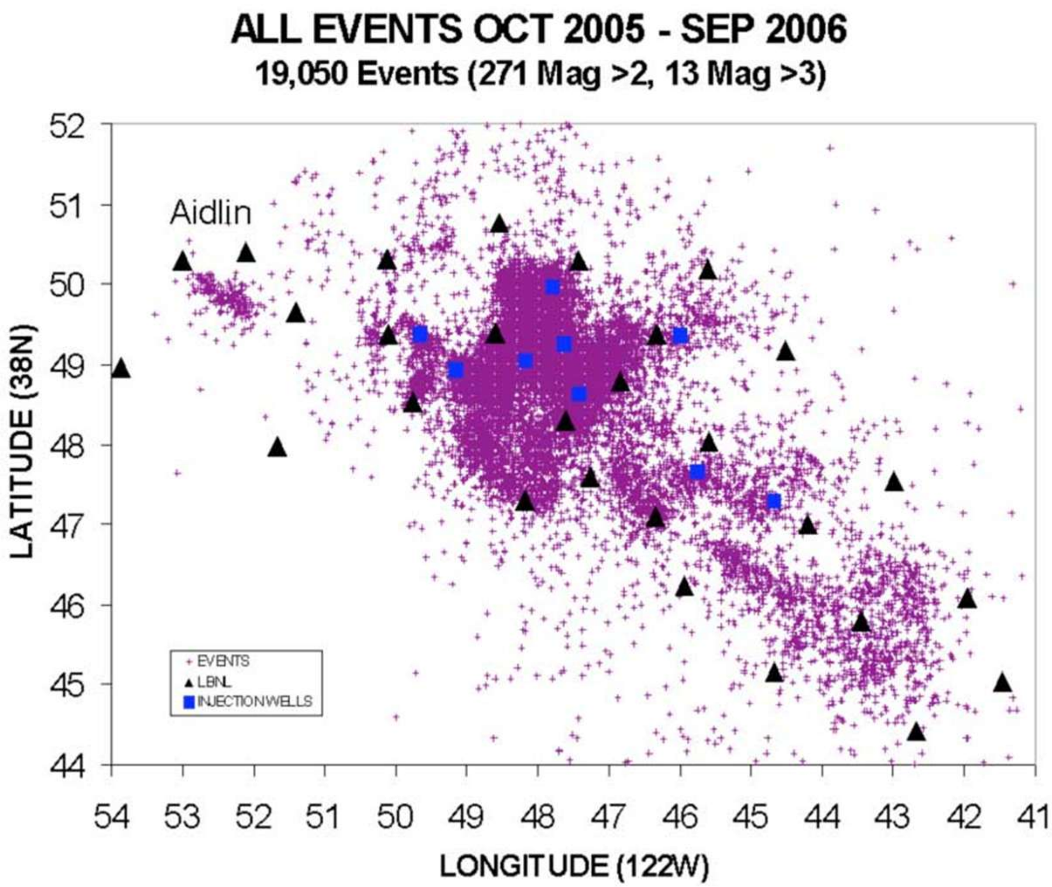


Reinjection

- The Geysers production began 1960
- 1987: 0.25 kg water inj / 1 kg prod
- Lots of energy in the rock but not enough water available to inject to move energy to the surface
- City of Santa Rosa and Lake County have sewage treatment issues cannot discharge into rivers
- Today: 0.85 kg water inj / 1 kg prod



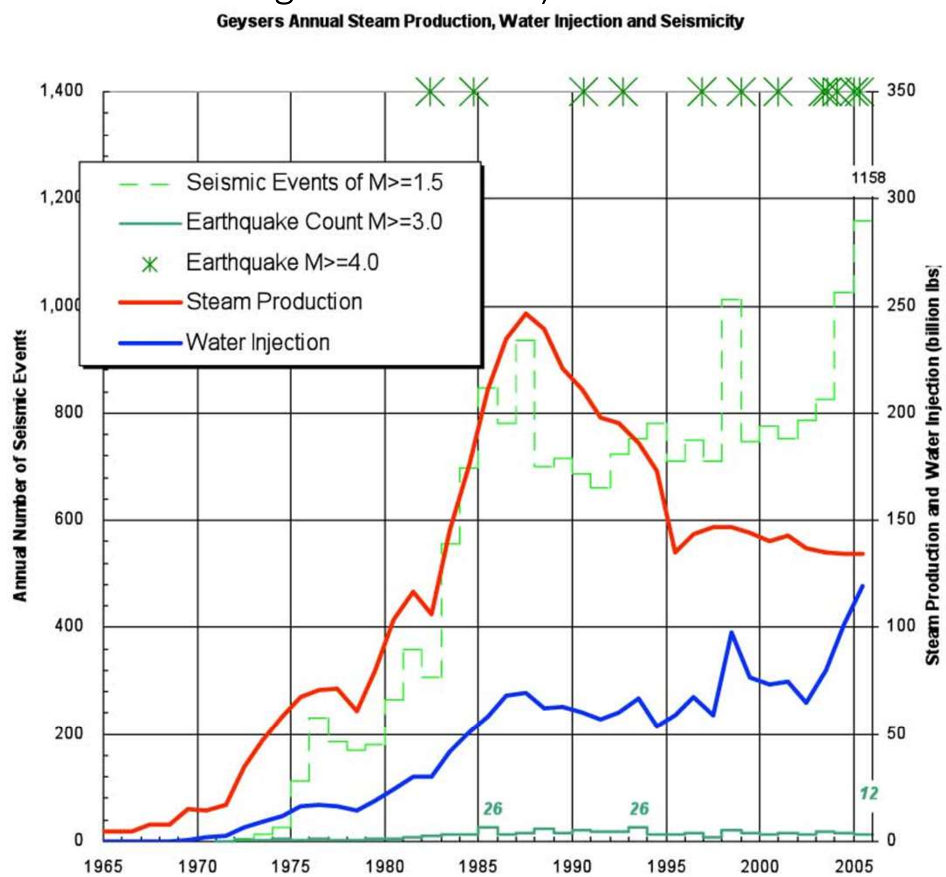
Induced Seismicity at the Geysers



http://esd.lbl.gov/research/projects/induced_seismicity/egs/geysers.html

Induced Seismicity at the Geysers

(measurements began mid 1970's)



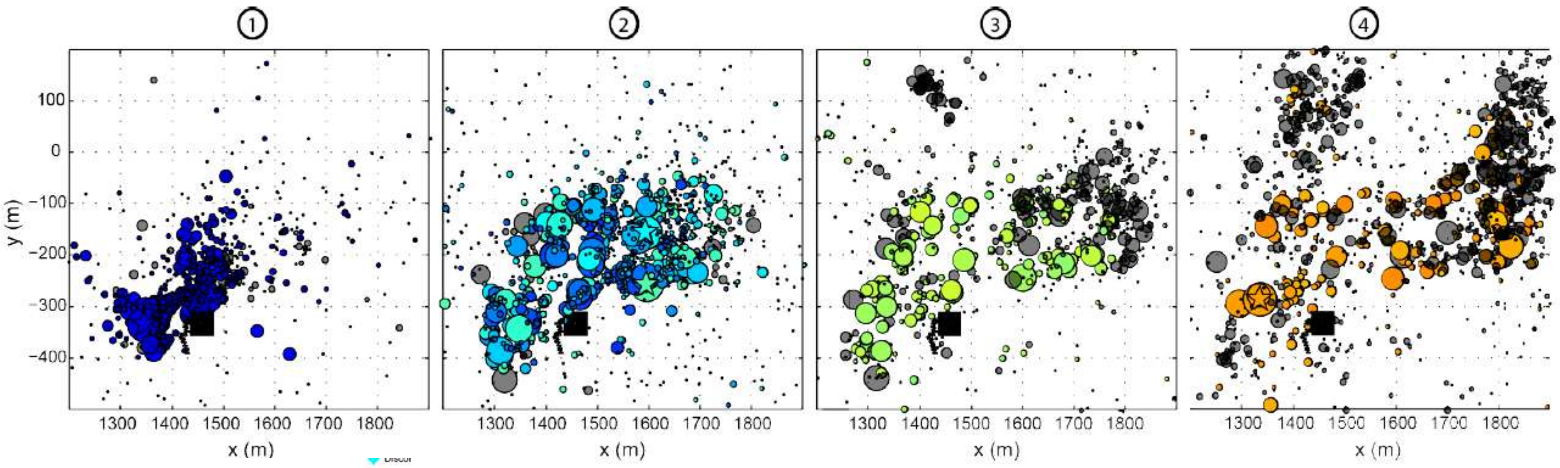
http://esd.lbl.gov/research/projects/induced_seismicity/egs/geysers.html

Is there risk of a "big" quake at the Geysers?

- Water injection is acknowledged as a cause of seismicity
- Largest event recorded is 4.6
- Seismic conditions limit the maximum magnitude to about 5

http://stevecotler.com/tales/2009/09/27/geothermal-energy-public-nuisance/

Induced seismicity cont.



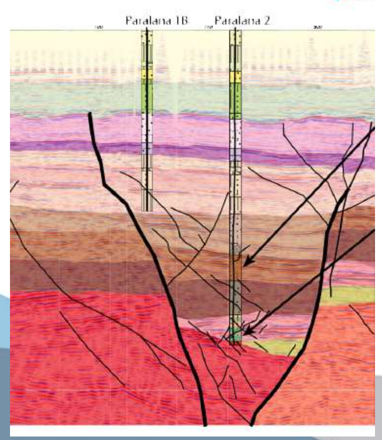
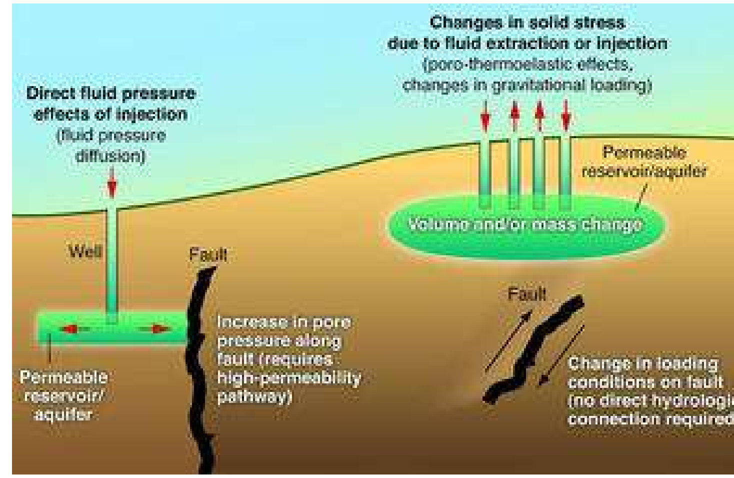


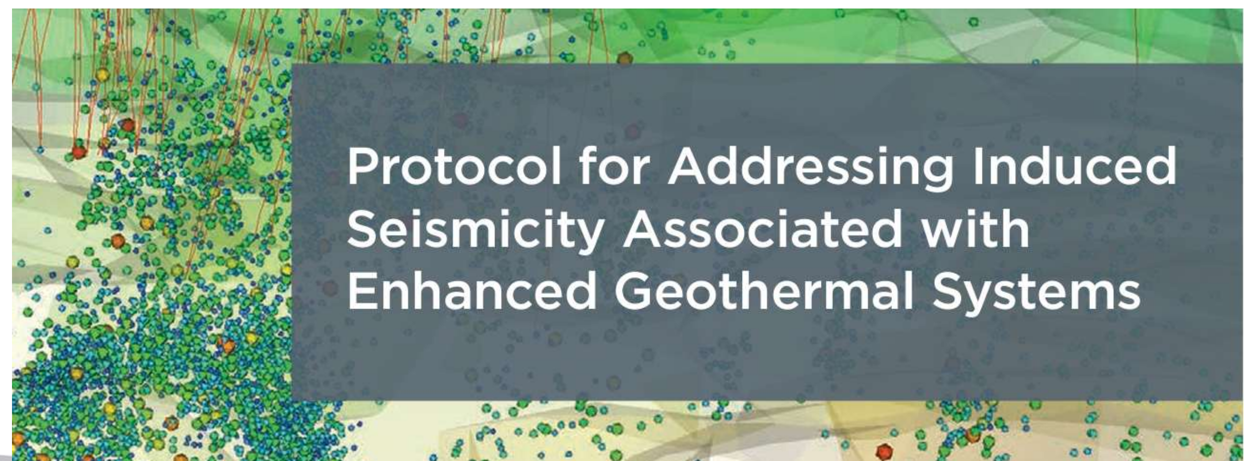
Figure: Different stages of injection for the Paralana EGS project, Cooper Basin Australia. Color events during injection, gray events after shut-in. Size of events correspond to size of circles. Largest event 2.3. [Albaric et al., 2013, submitted to Geothermics]

Induced seismicity makes it possible to understand how large and in which direction the reservoir has been created.

Induced Seismicity cont.

- Common in geothermal in general (not just EGS)
- Four causes, Majer et al. (2007)
  - Pore pressure increase
  - Fluid volume removal (poroelasticity)
  - Temperature decrease (thermoelasticity)
  - Chemical changes
- Geysers 4.6, Cooper Basin 3.x, Soultz 2.9, Basel, Switzerland 3.4





Day 4

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

03 Geothermal reserve estimation and unconventional geothermal systems

04 Oil and gas well conversions, future trends