Correction: Condensers

Mass flow rate of cooling water can be calculated:

$$\boldsymbol{m_{cw}} = \boldsymbol{m_{te}} \times \left(\frac{\boldsymbol{\Delta H}}{\boldsymbol{C_{Pw}} \times \boldsymbol{\Delta T}}\right)$$

Where:

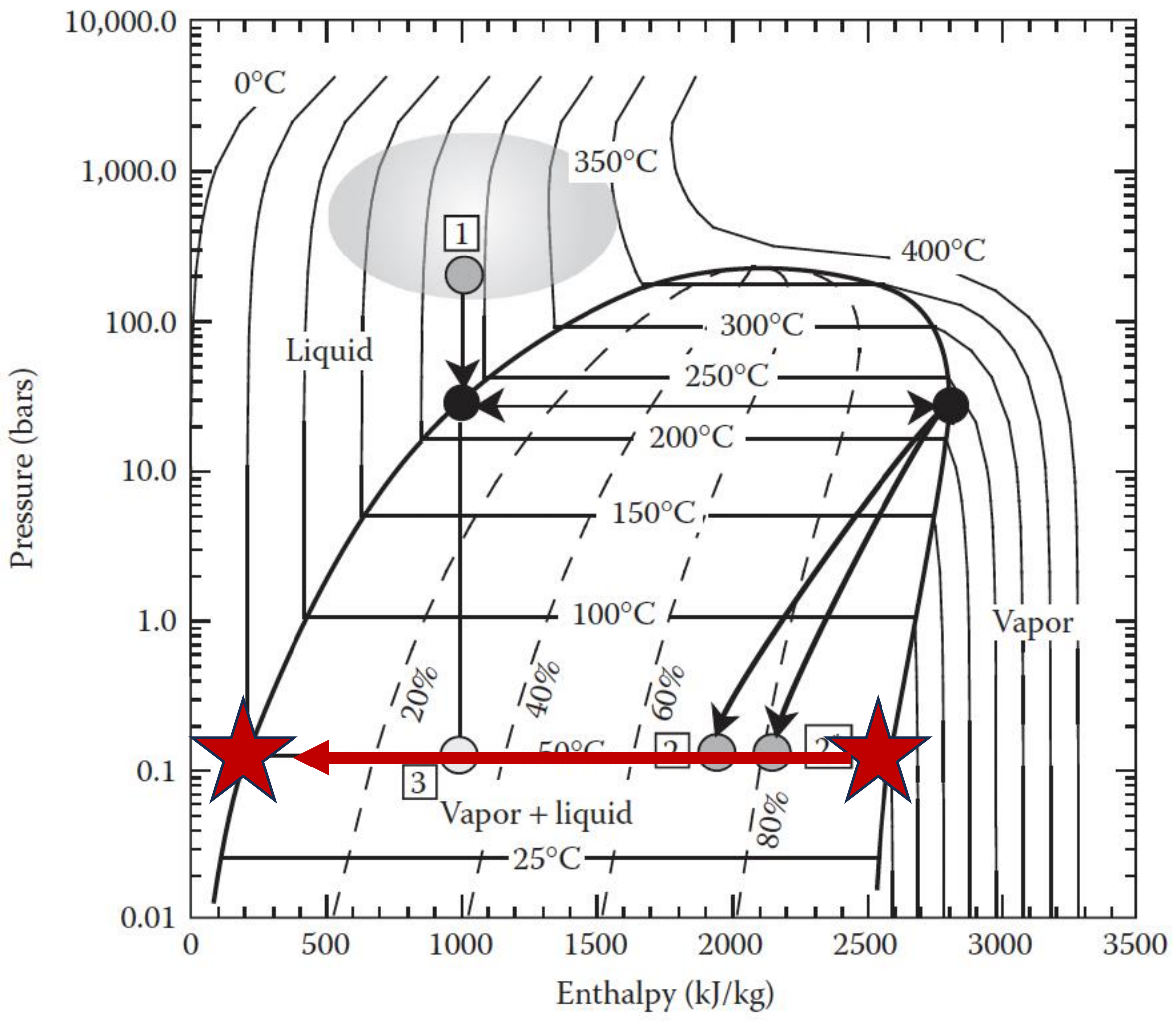
m_{cw} is the mass flow rate of cooling water

m_{te} is the mass flow rate of vapour from the turbine

ΔH is the required change in enthalpy to achieve the desired end state

C_{Pw} is the heat capacity of water

ΔT is the rise in temperature of the cooling water



Source: Glassley, W. E., *Geothermal Energy*

Correction: Condensers

Consider a cooling water temperature of 25°C.

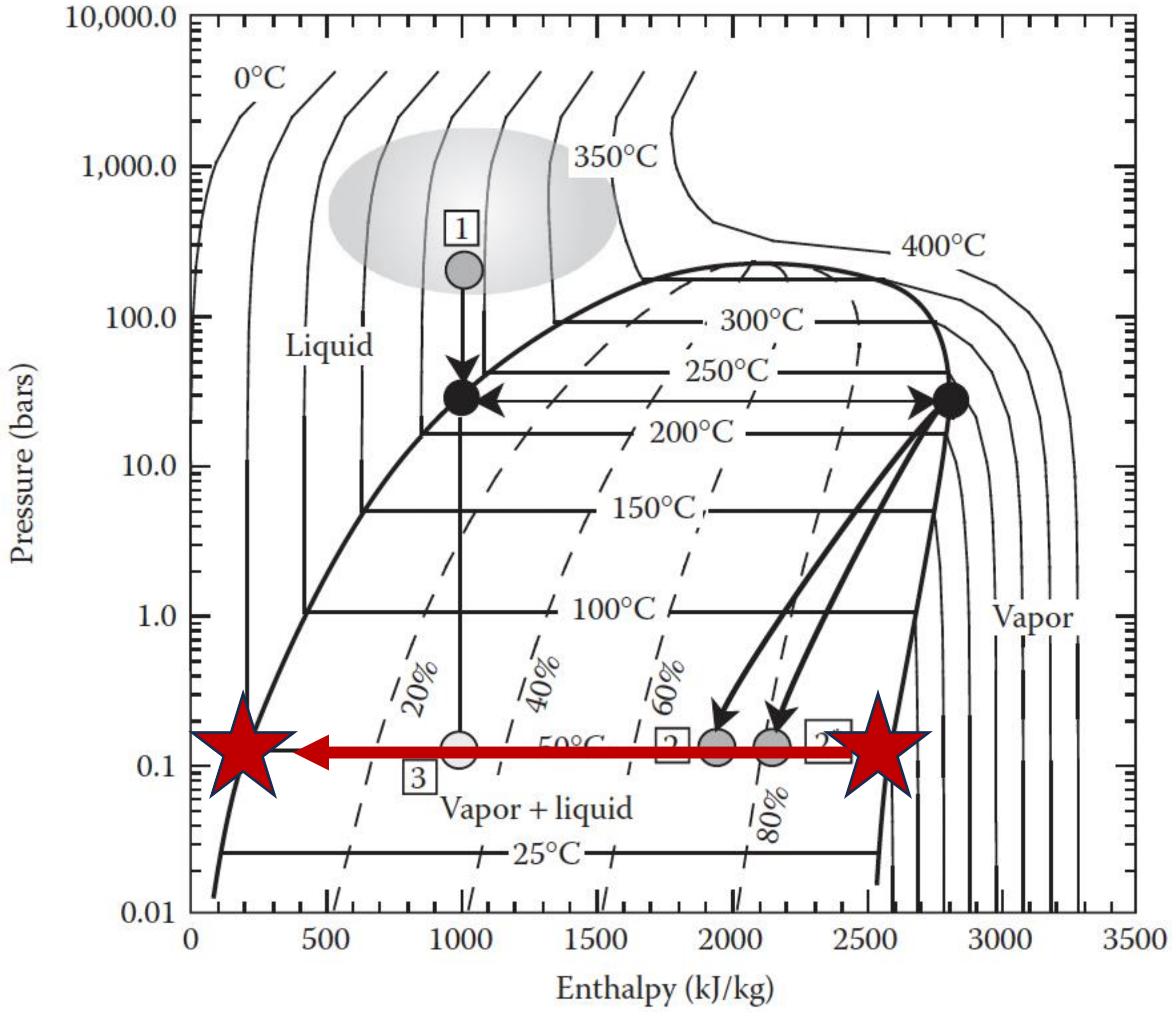
An endstate enthalpy of 50°C liquid water:

$H_{50°C}$ = 200 kJ/kg

Assume the vapour leaving the turbine is at 50°C:

$H_{50°C}$ = 2592 kJ/kg

2387.1 kJ/kg needs to be removed from the vapour for it to condense to liquid.



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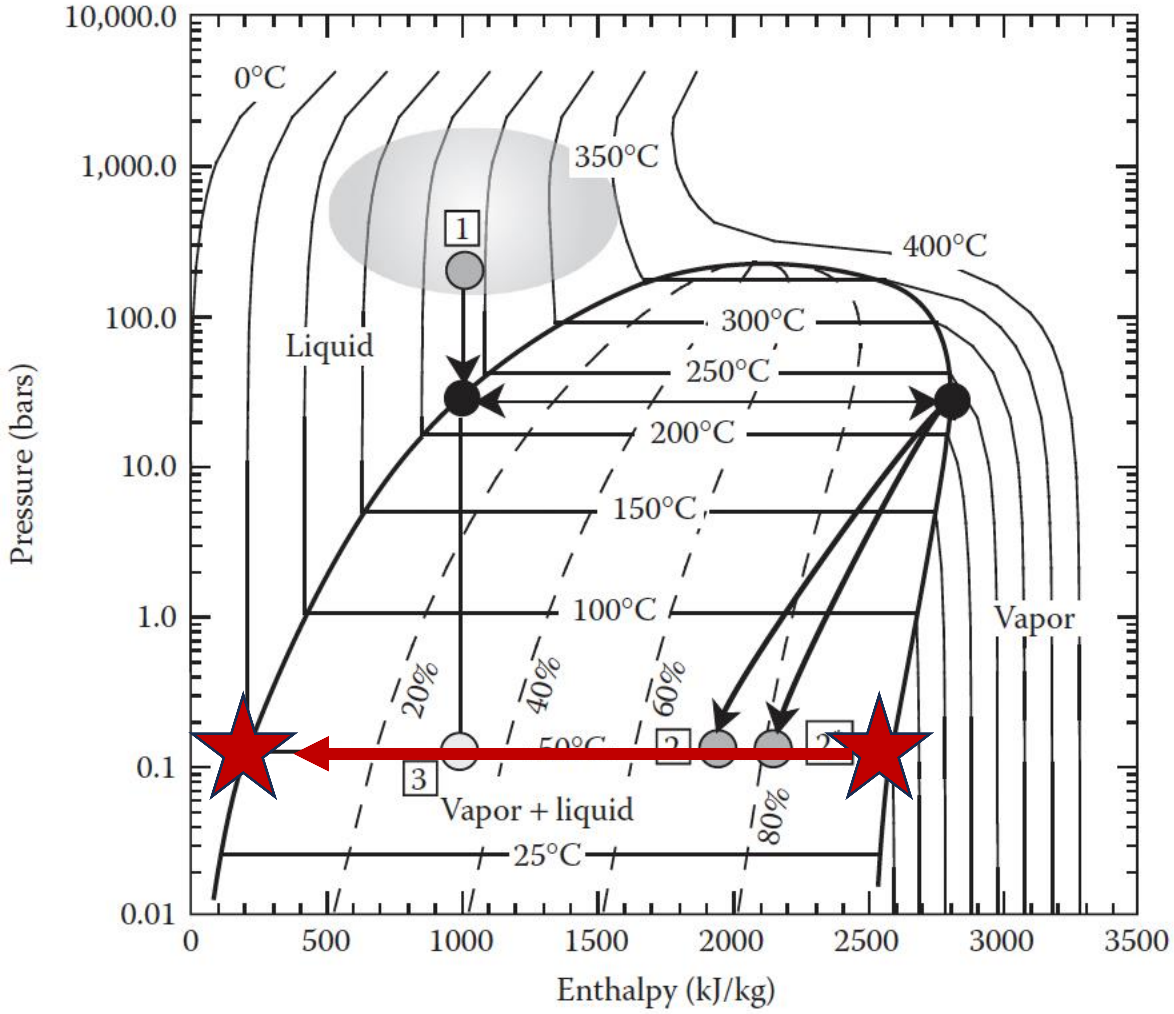
Heat capacity of water is 4.2 kJ/kg.K at these conditions.

Flow rate out of the turbine is 2.5 kg/s.

What is the mass flow rate of cooling water needed to condense the vapour, allowing for an increase in cooling water temperature up to 50°C?



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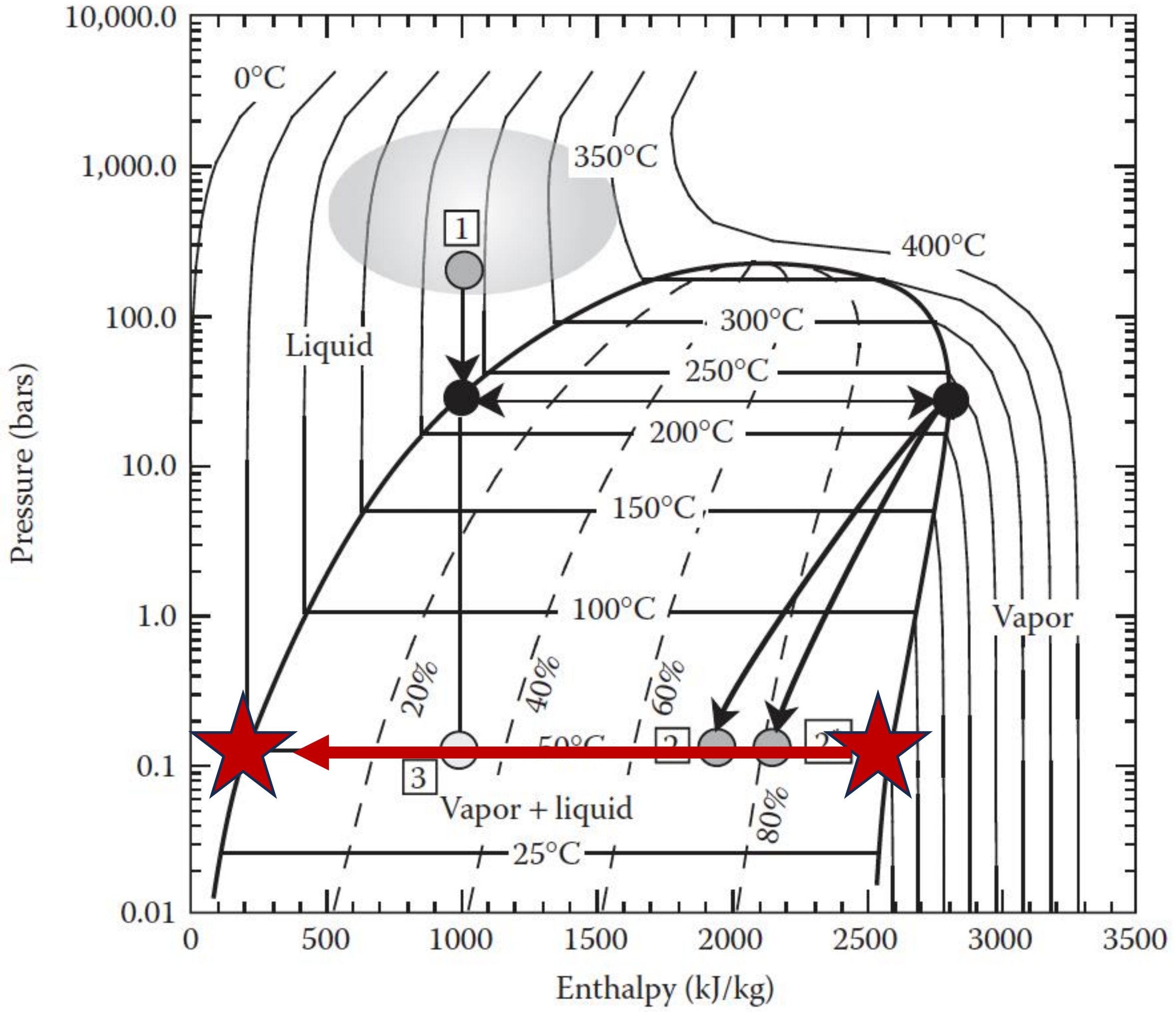
Answer: 57 kg/s



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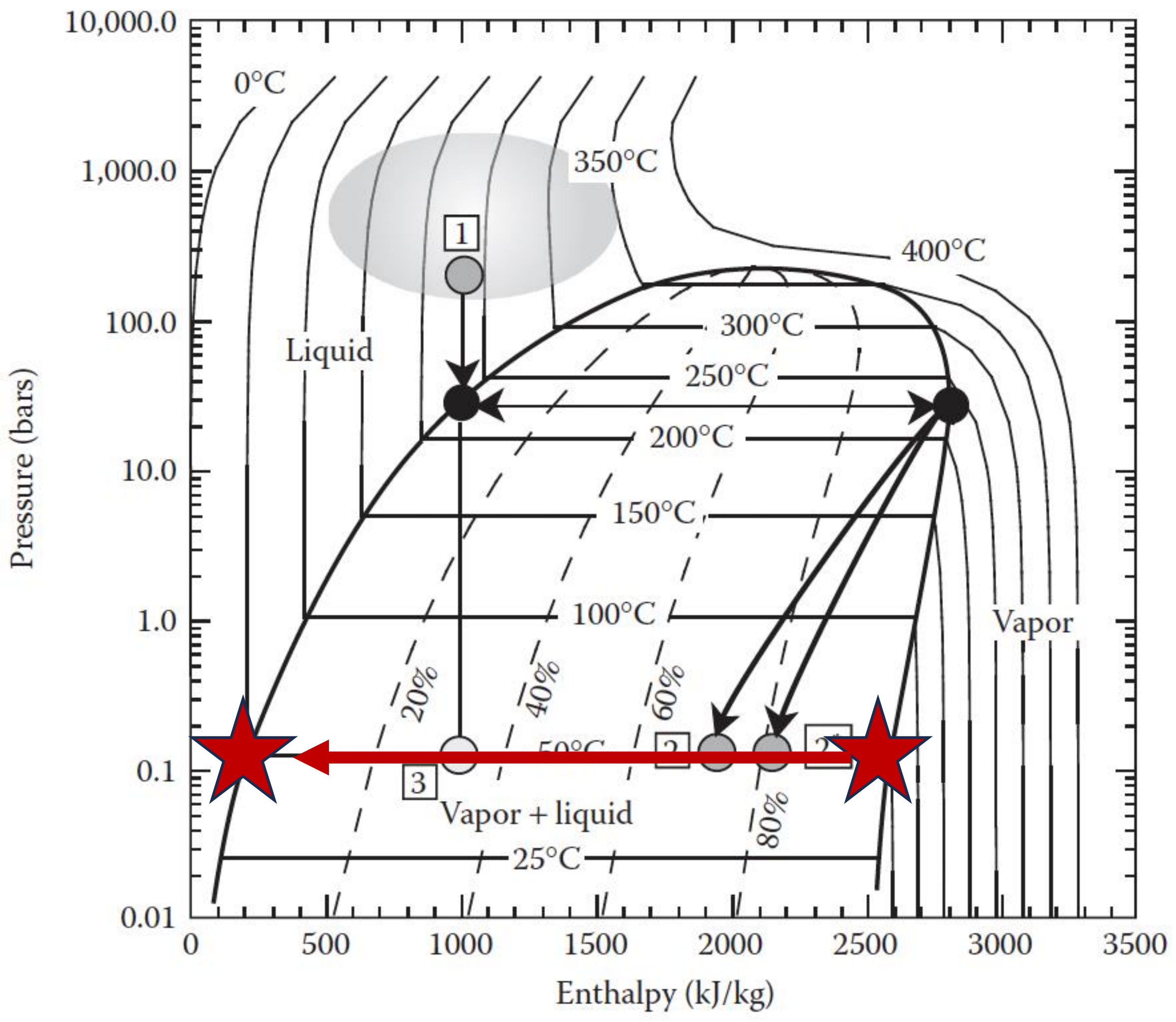
Important for water usage!



Source: Glassley, W. E., *Geothermal Energy*

Geothermal Resource Development

Direct Use of Geothermal Resourses

EPFL

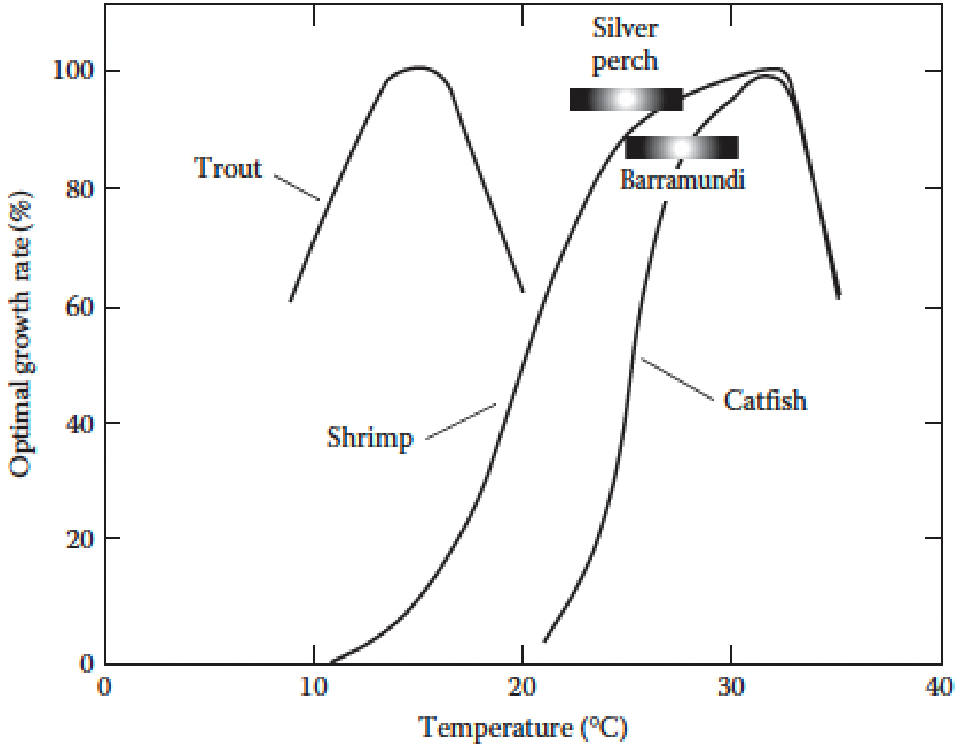
Aquaculture

Aquaculture

Geothermal fluids are used to optimise the temperature for breeding, growth, and the health of aquatic species.

Used to raise:

Carp, catfish, bass, mullet, eels, sturgeon, tilapia, salmon, trout, tropical fish, lobsters, crayfish, crabs, alligators, algea, prawns, shrimp, mussels, scallops, clams, oysters, abalone…



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Example:

Alligators bred under natural conditions reach about 1.2 m in length in 3 years.

Under a constant temepratures of 30°C, they reach 2 m.

(Dickson and Fanelli, 2006)

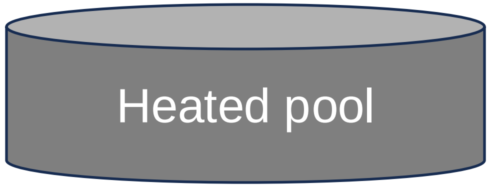

Alligators raised in ponds heated by geothermal energy in Colorado, USA

Source: https://deq.mt.gov/files/Energy/EnergizeMT/Renewables/Geothermal%20Pub/6Aquaculture.pdf

Aquaculture

Aquaculture often uses open pools, buried underground.

What are the sources of heat loss?



Source: https://www.rastechmagazine.com/landing-on-ice/

Aquaculture

Aquaculture often uses open pools, buried underground.

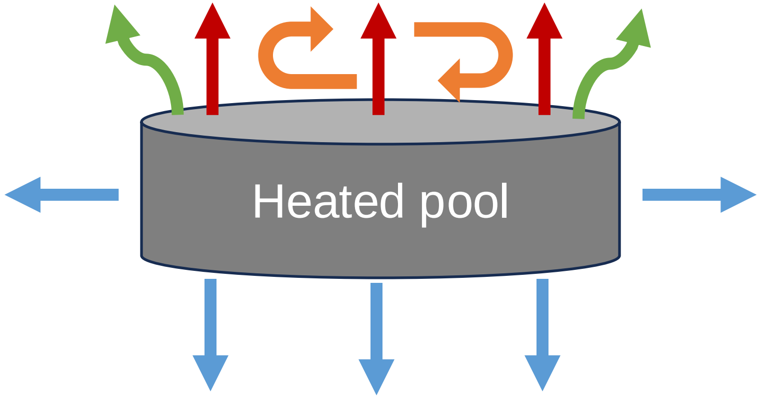
What are the sources of heat loss?

Conduction across pool walls.

Convection, **radiation**, and **evaporation** from the surface of the water.

Arctic char and steelhead geothermal aquaculture, Grindavik, Iceland

Source: https://www.rastechmagazine.com/landing-on-ice/



Aquaculture

Consider a concrete fish pond built into the ground:

10 m × 15 m

1.5 m deep

Pool walls thickness: 10 cm

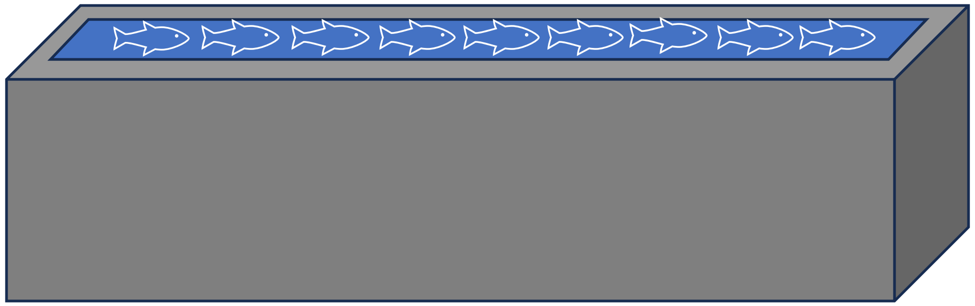
The heat capacity of concrete: 1.40 W/mK

Ground temperature: 15°C

The heat capacity of concrete: 1.40 W/mK

Wind speed: 1.0 m/s,

Air temperature: 10°C



Pond temperature is maintained at 27°C.

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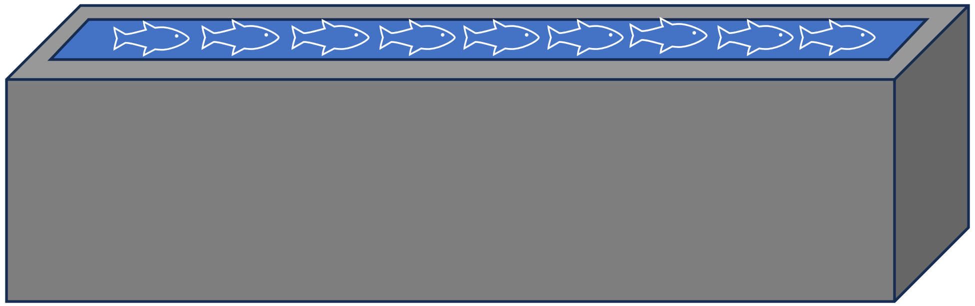
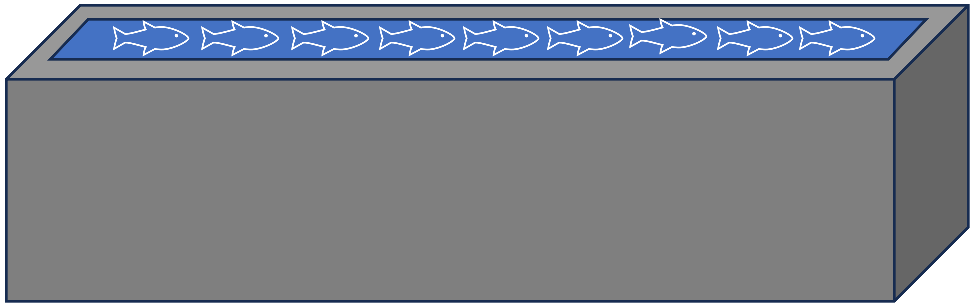


Calculate the heat loss of the pond.

Aquaculture

Calculate the total heat loss:

$$Q_{TL} = Q_{cd} + Q_{cv} + Q_{rd} + Q_{ev}$$



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Air temperature: 10°C

Pond temperature is maintained at 27°C.

Aquaculture

Heat loss from conduction:

$$Q_{cd} = k_{th} \times A \times \frac{dT}{dx} = 1.4\frac{\mathrm{W}}{\mathrm{m}\times\mathrm{K}} \times 225\mathrm{m}^2 \times \frac{12\mathrm{K}}{0.1\mathrm{m}} = \mathbf{37\,800\ J/s}$$

Heat loss from convection:

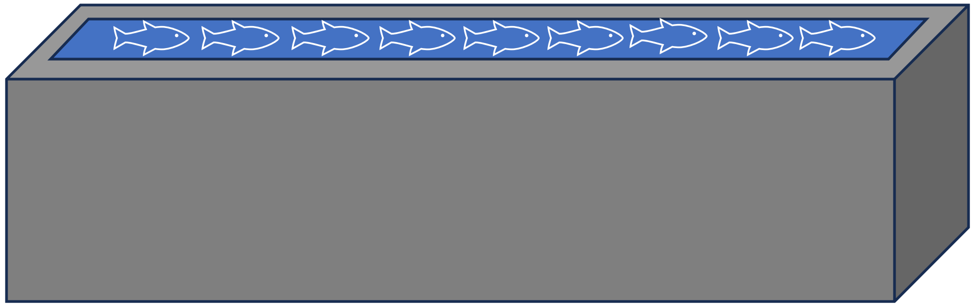
$$Q_{cv} = (9.045 \times v) \times A \times dT$$
$$= \left(9.045 \times 1.0\frac{\mathrm{m}}{\mathrm{s}}\right) \times 150\mathrm{m}^2 \times 17\mathrm{K} = \mathbf{6407\ J/s}$$

Heat loss from radiation:

$$Q_{rd} = \varepsilon \times \xi \times \sigma \times A \times (T_1^4 - T_2^4) = 1 \times 1 \times \left(5.669 \times 10^{-8}\frac{\mathrm{W}}{\mathrm{m}^2\times\mathrm{K}^4}\right) \times 150\mathrm{m}^2 \times (300\mathrm{K}^4 - 283\mathrm{K}^4) = \mathbf{14\,191\ J/s}$$

Heat loss from evaporation:

$$Q_{ev} = a \times (P_w - P_a)^b \times A \times H_w = 196.88 \times (3.57\mathrm{kPa} - 1.23\mathrm{kPa})^{1.068} \times 150\mathrm{m}^2 \times 2400\frac{\mathrm{J}}{\mathrm{g}} = \mathbf{51\,713\ J/s}$$



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Pond temperature is maintained at 27°C.

Aquaculture

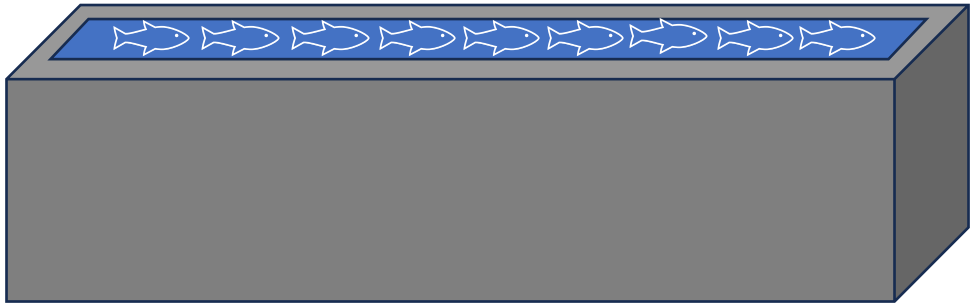
Calculate the total heat loss:

$$Q_{TL} = Q_{cd} + Q_{cv} + Q_{rd} + Q_{ev} = 110\,111\ \mathrm{J/s}$$

This is an overestimate:

Heat loss due to conduction decreases over time.

Calculation made for winter conditions and modest wind speed, not likely to be average.



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Wind speed: 1.0 m/s,

Air temperature: 10°C

Pond temperature is maintained at 27°C.

Aquaculture

What is the flow rate of incoming fluid needed to keep the pond temperature at 27°C?

$$F_{in} = \frac{Q_L}{C_p \times (T_R - T_p)}$$

Where:

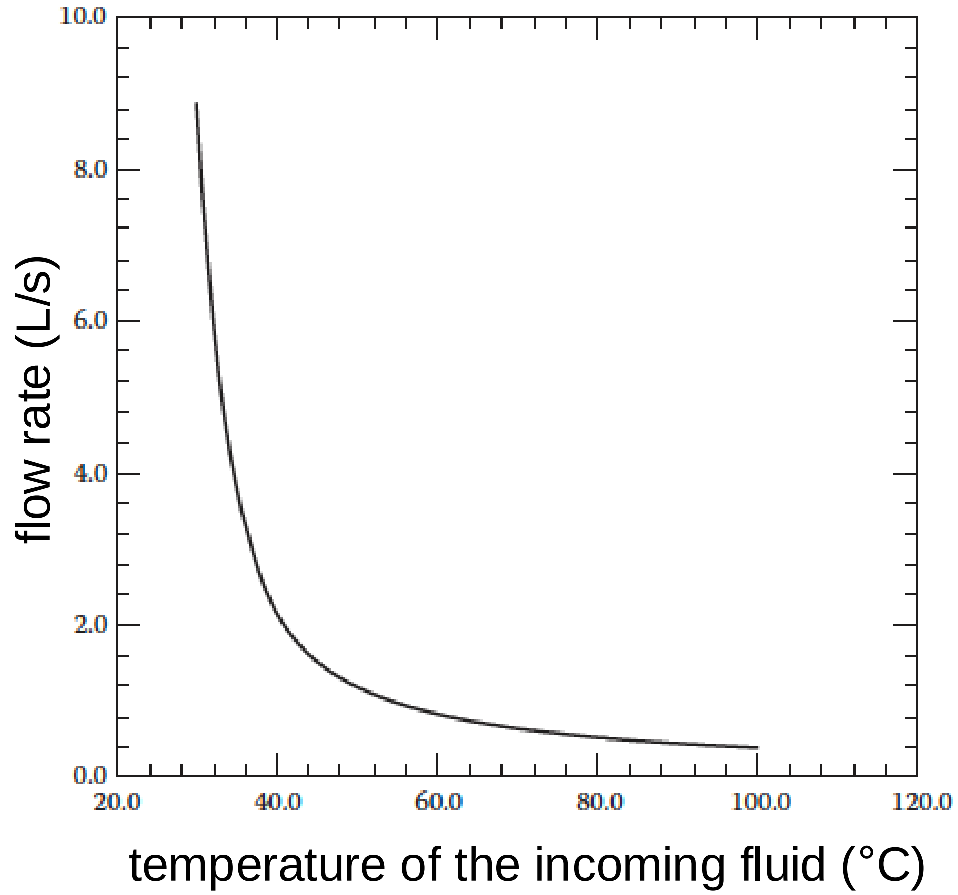
F_{in} is the rate at which fluid must be added (L/s)

Q_L is the total heat loss (J/s)

C_p is the constant pressure heat capacity of water (J/LK)

T_R is the temperature of the geothermal fluid (K)

T_p is the temperature of the pond (K)



Source: Glassley, W. E., *Geothermal Energy*

Aquaculture

Water quality also matters!

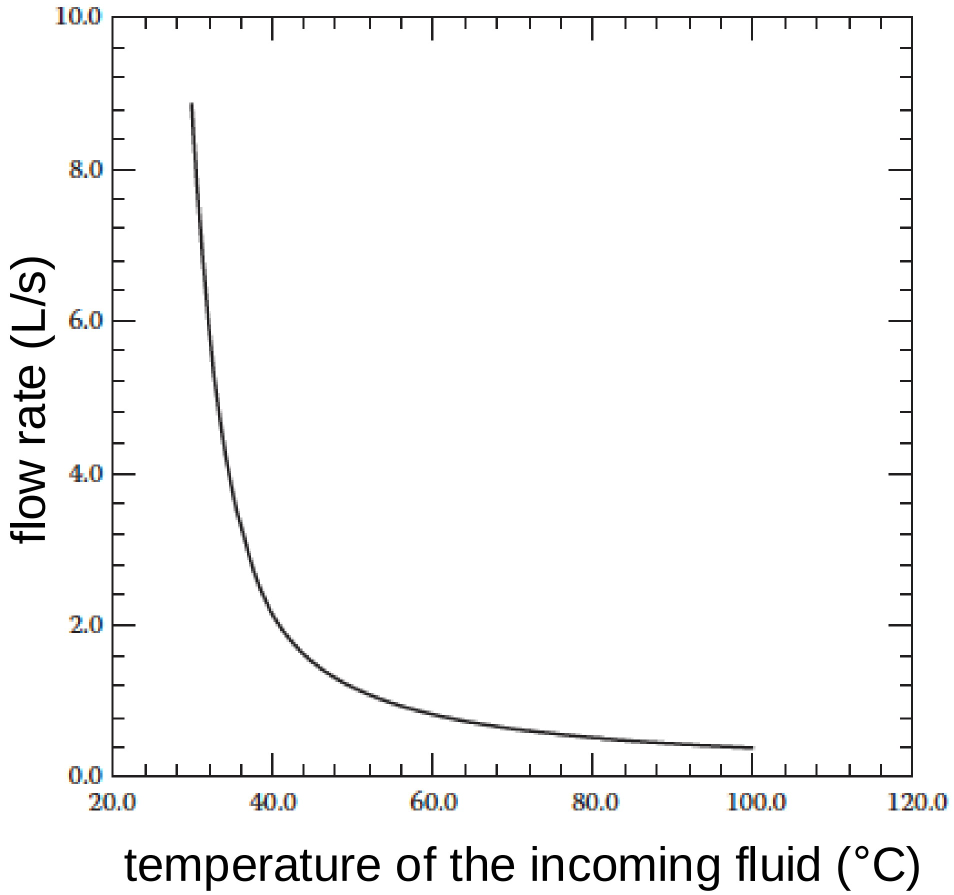
Animals and plants are sensitive to:

Nutrient and trace metal concentrations

pH

Dissolved gases

If the local water chemistry is incompatible with the stock, **heat exchanges** can be used.



Source: Glassley, W. E., *Geothermal Energy*

Drying

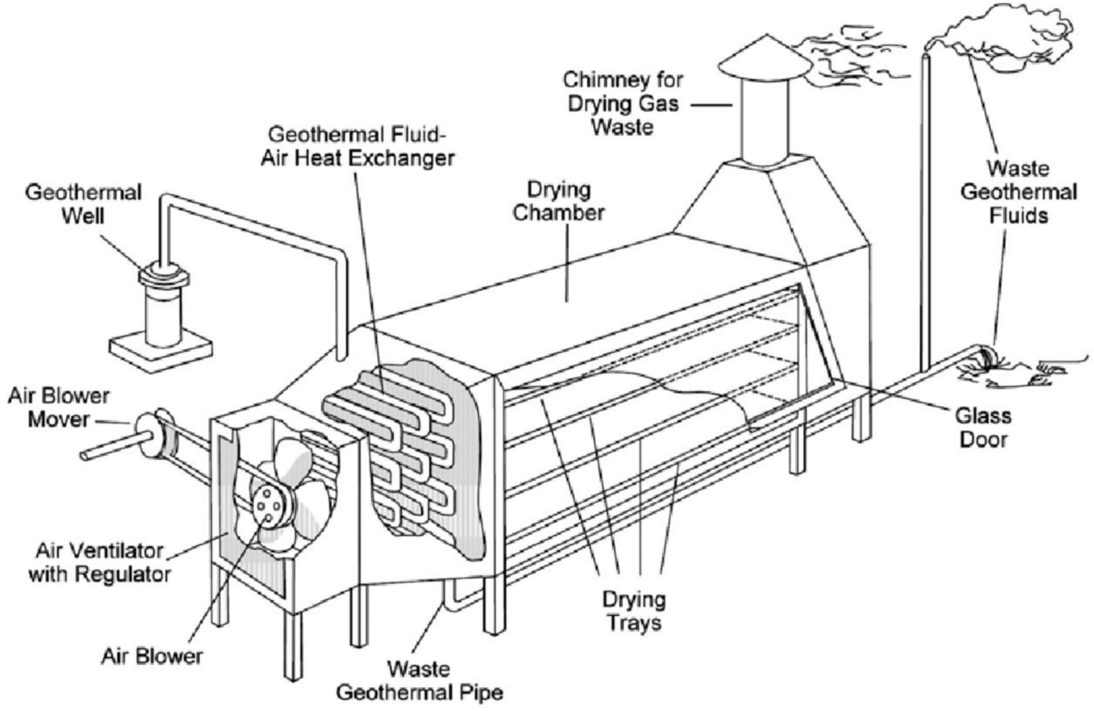
Drying

Reduce the water content of commodities.

Drying commodities include:

Onions, garlic, coconut, meat, fruits, lumber, potatoes, spices, sugar, concrete blocks, grain, etc.

Depending on the commodity, water content will need to be reduced by 3% to 50-60%.



Design of a geothermal energy dryer for beans and grains in Indonesia

Source: Sulotarto, 2007

Drying

Advantages:

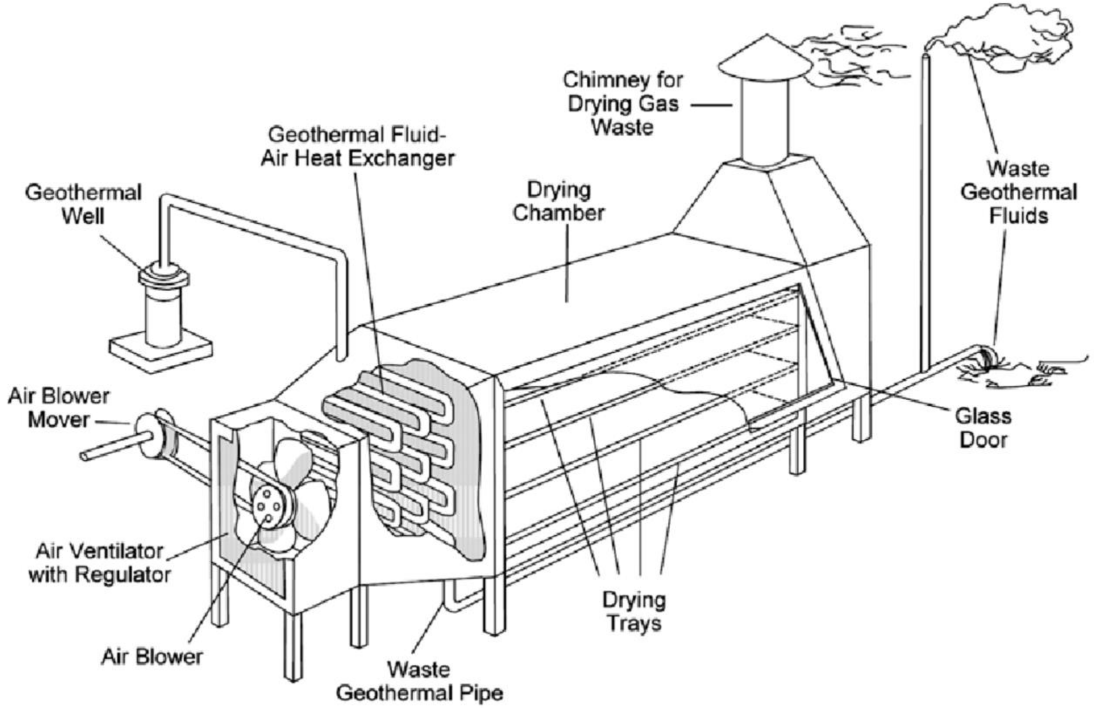
Eliminates fuel costs to fire boilers and heaters.

Reduces the risk of fire by eliminating the need for combustion.

Zero emissions for the heating process.

Easy scheduling for indefinite durations.

Predictable and constant cost.



Design of a geothermal energy dryer for beans and grains in Indonesia

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Foodstuff drying

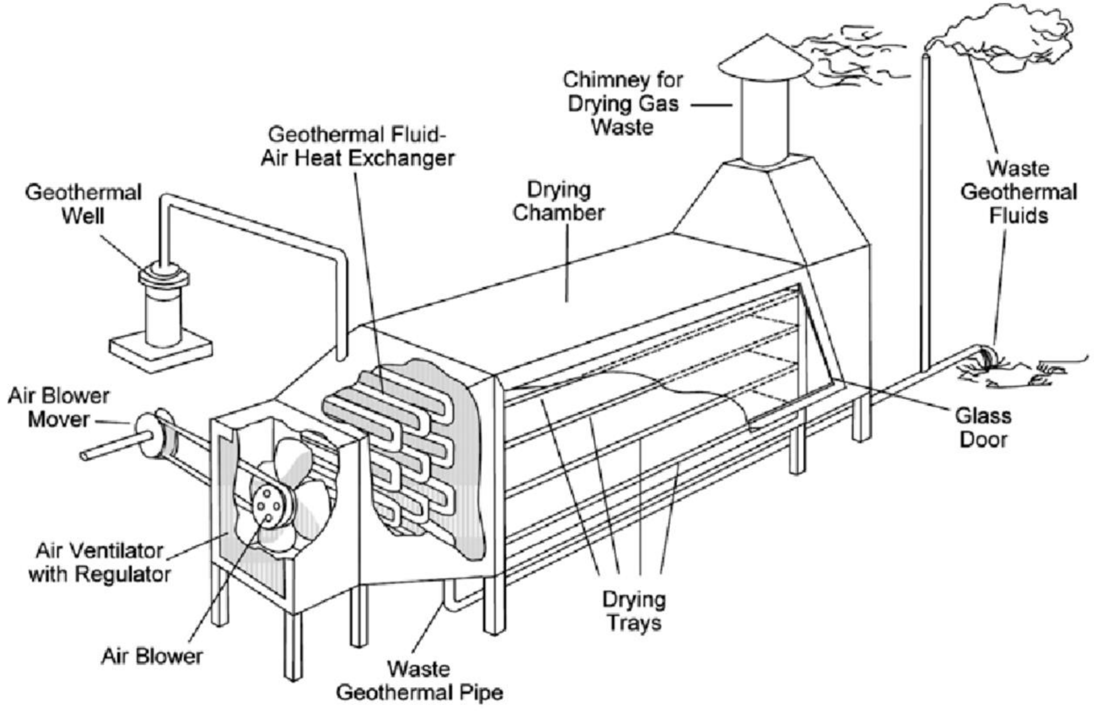
Geothermal fluid temperatures: 110°C to 170°C.

Geothermal fluid passes through a hot-water-to-air heat exchanger.

Heated air blown through drying ovens with perforated stainless steel conveyer belt or heating cabinets.

End product moisture: 3% – 6%

Output temperature: 30°C to 50°C



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Rittershoffen geothermal site, Alsace, France

Roquette Frères in Beinheim.

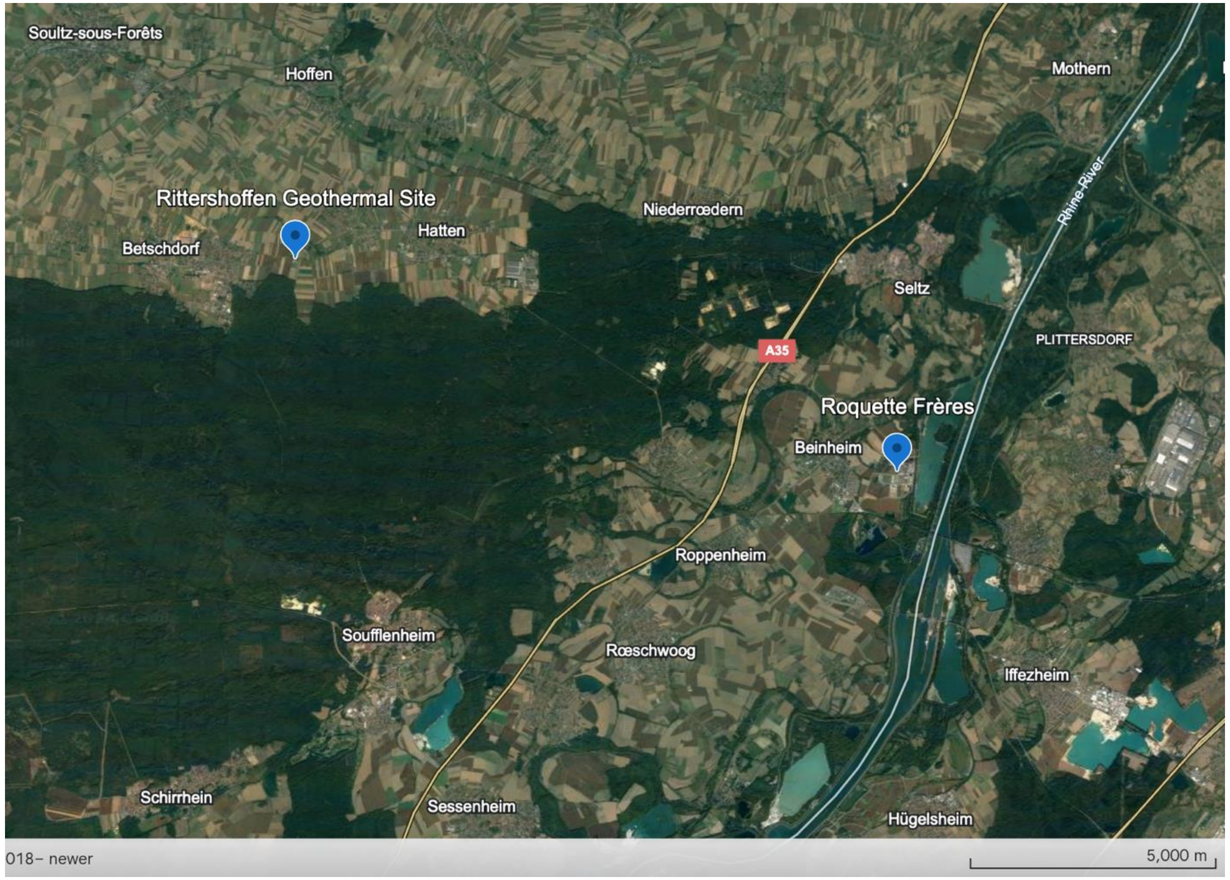
Biorefinery on the Rhine River.

2000 tons of wheat and corn converted to starch, daily.

Annual needs: 100 MWth

Deep geothermal project, designed to provide up to 25% of total heat demand.

Geothermal site located at Rittershoffen, 12.5 km from Beinheim.

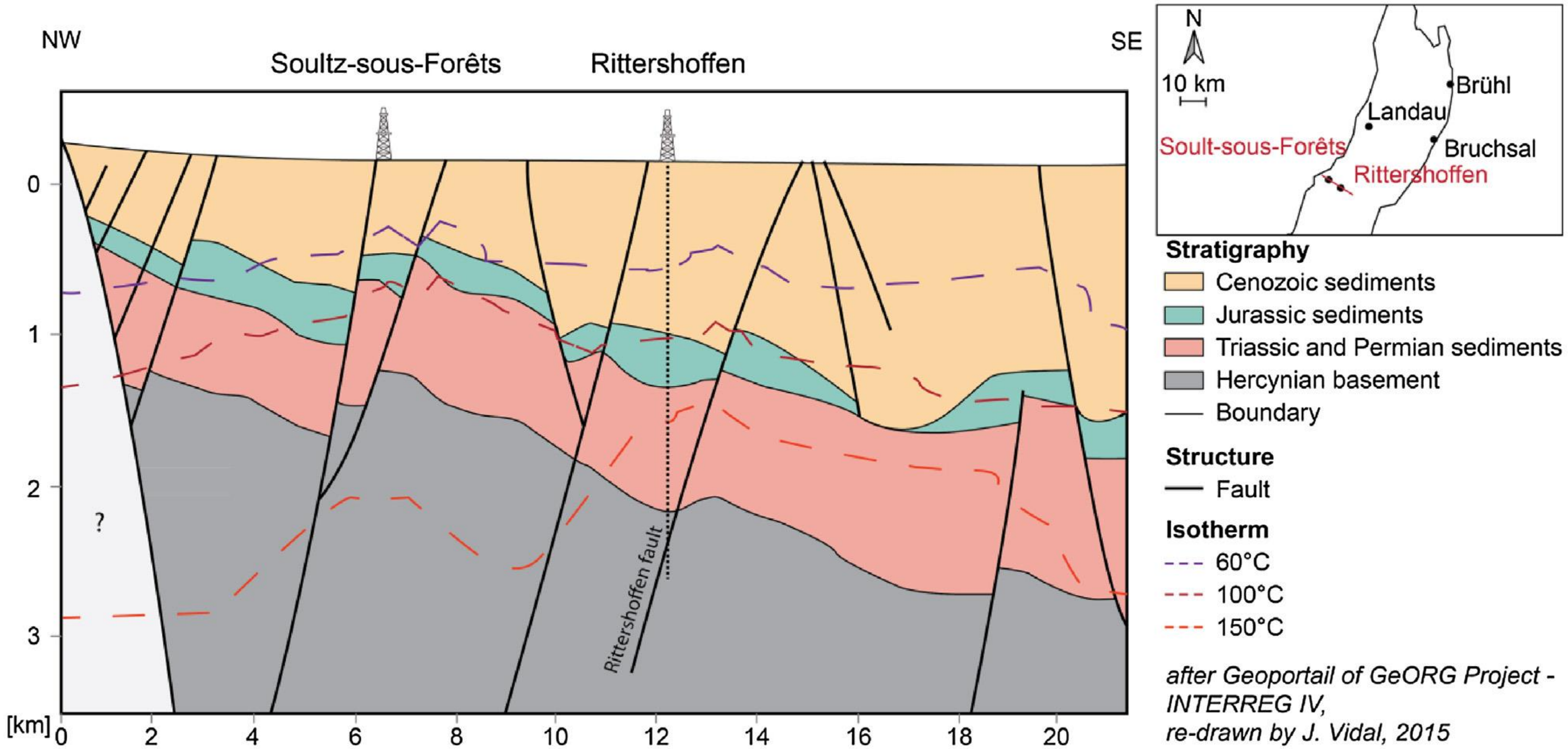


Source: Google Earth

Rittershoffen geothermal site, Alsace, France

Targets a permeable fault.

Between 2500 m and 2700 m deep.



Source: Baujard et al., 2017

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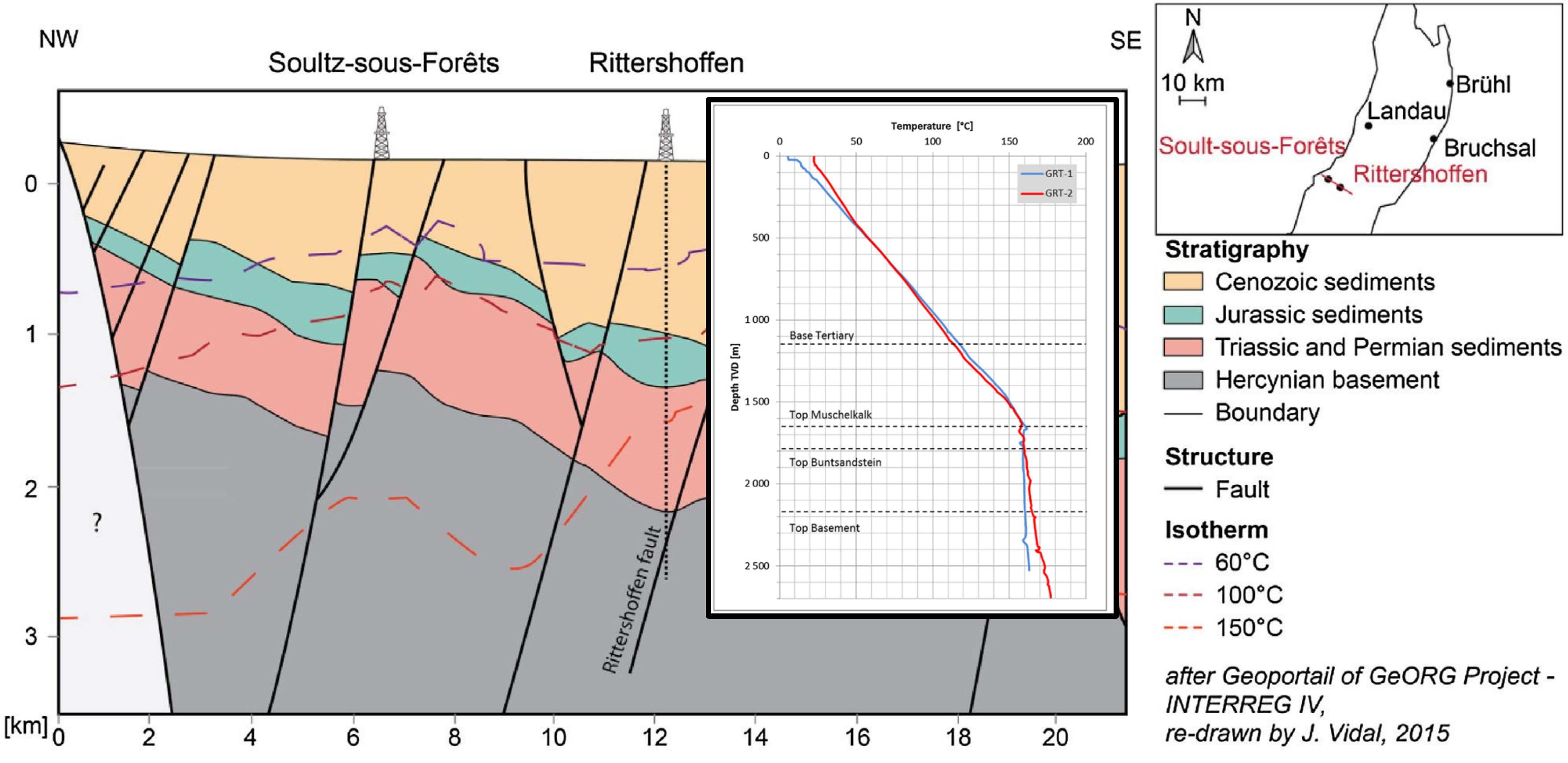
Geothermal fluid:

high salinity brine, 100 g/L

168°C

Enhanced Geothermal System.



after Geoportail of GeORG Project - INTERREG IV,
re-drawn by J. Vidal, 2015

Source: Baujard et al., 2017

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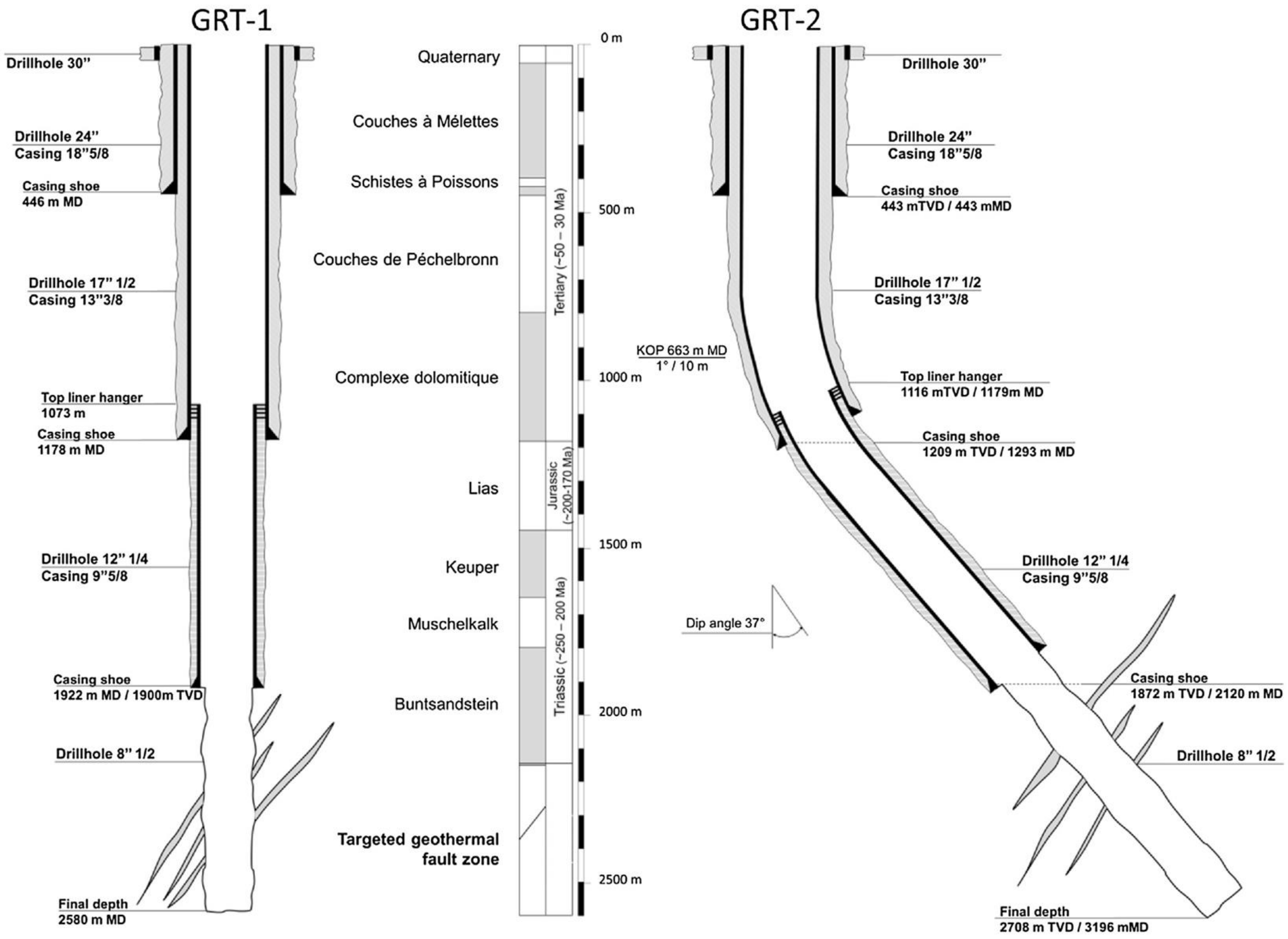


Source: Baujard et al., 2017

Rittershoffen geothermal site, Alsace, France

Organic Rankine Cycle (isobutane).

15km transport loop between Rittershoffen and Beinheim.

Wellhead temperature: 168°C

Reinjection temperature: 80°C

Average production flowrate: 70 to 75 kg/s

90% availability

24 MWth installed (of total 100 MWth thermal needs)

In 2020: 45 000 tCO_2 saved (natural gas burning)

Source: https://www.geodeep.fr/esg-rittershoffen-geothermal-plant-in-northern-alsace-producing-heat-at-high-temperature/

Key points:

Direct-use resources can have temperature ranges between 10°C and 150°C.

Total direct-use installed capacity worldwide in 2020 was 107 727 MWt.

Heat loss in direct-use applications depends on fundamental heat transfer processes: conduction, convection, radiation, evaporation.

Systems need to be evaluated for heat losses, demand load, magnitude of the potential geothermal heat supply.

Benefits: Reduce/eliminate the need for fuel, have a high capacity factor, reduce fire risk.

Reduce the need for electricity generation and reduce greenhouse gases.

Geothermal Resource Development

Enhanced Geothermal Systems

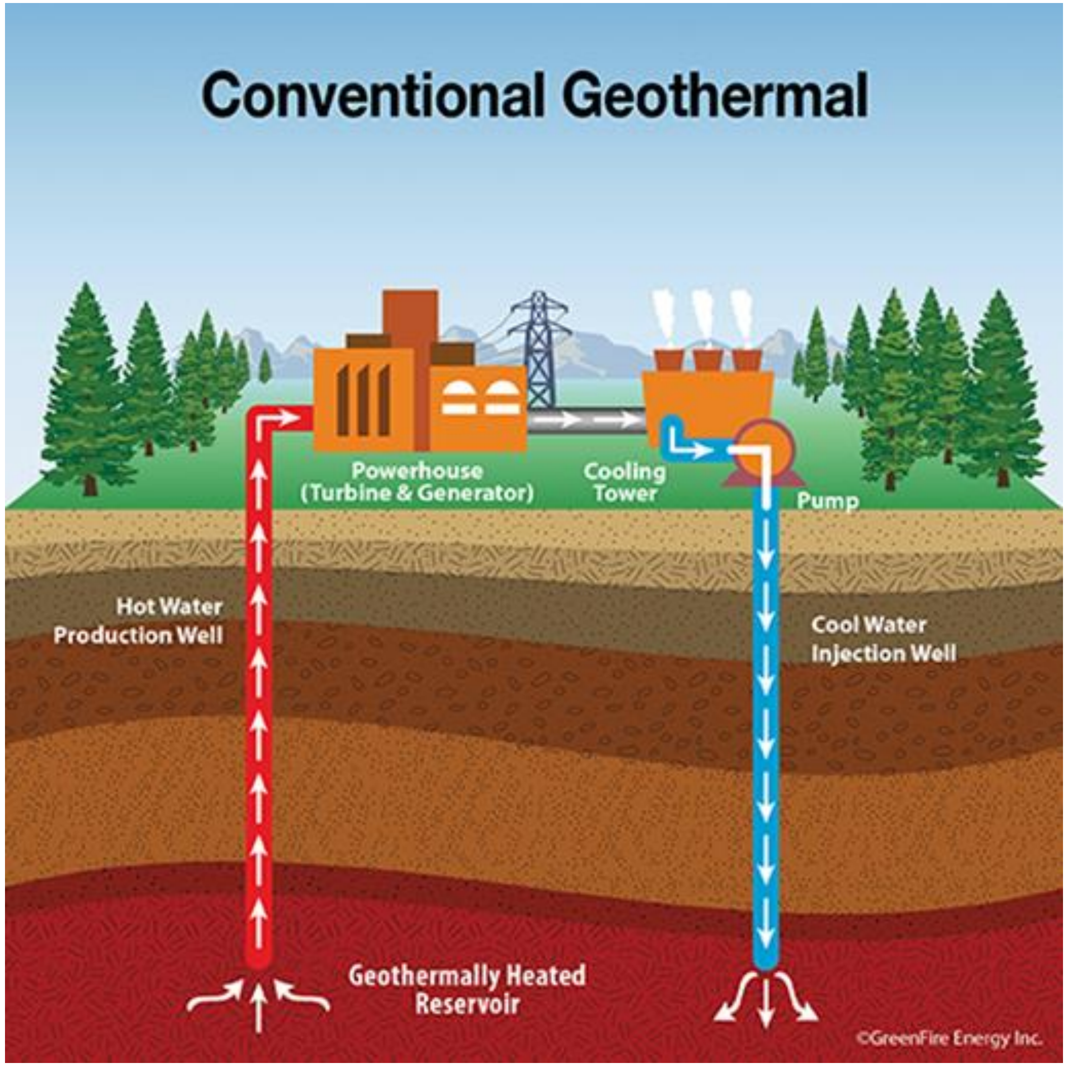
Topics covered today...

1. Concept of Enhanced Geothermal Systems
2. Reservoir stimulation
3. Induced seismicity
4. Reservoir management and sustainability

Concept of Enhanced Geothermal Systems

Viability of geothermal resources

Four conditions for geothermal resource power production:



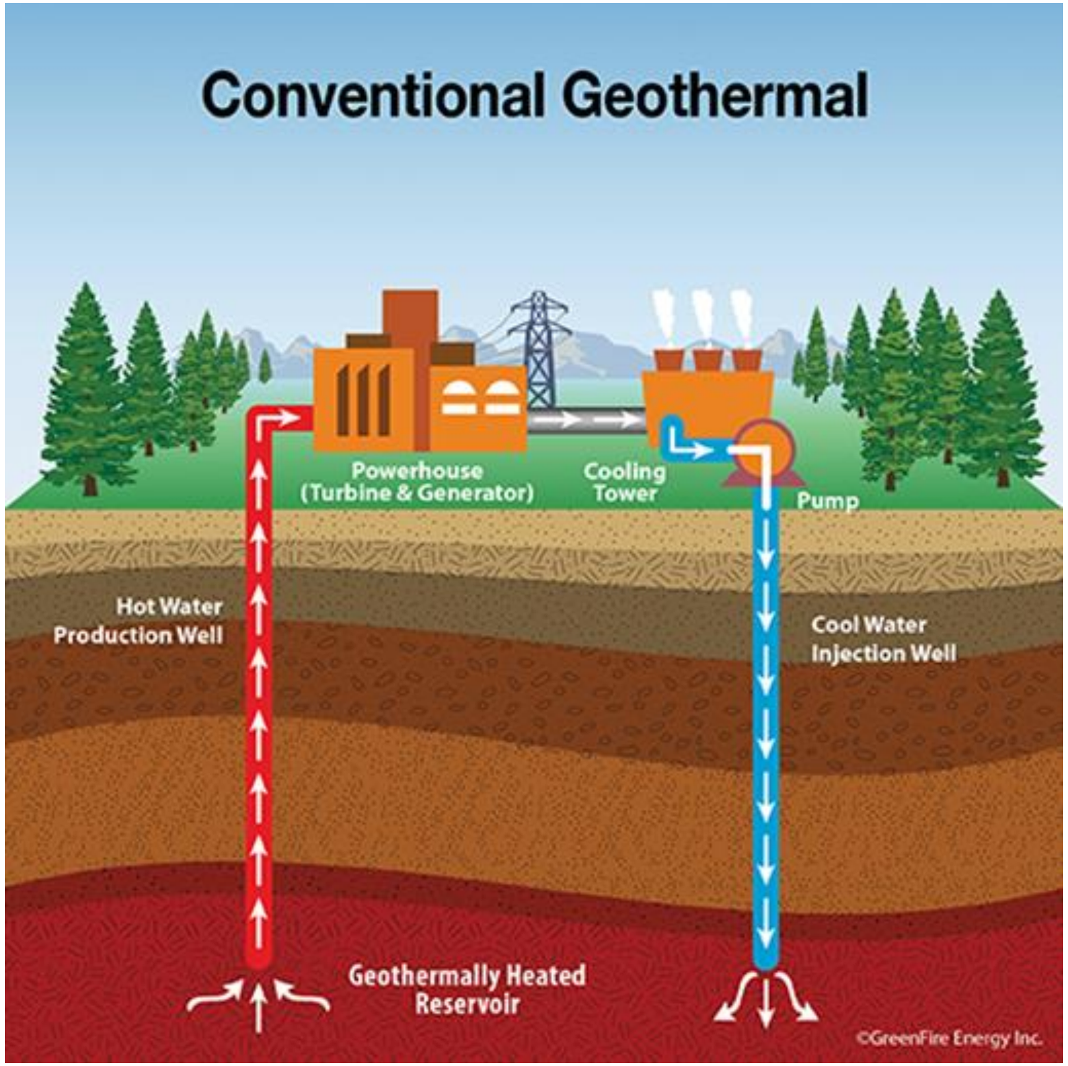
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Viability of geothermal resources

Four conditions for geothermal resource power production:

Existence of **sufficient heat.**

(Minimum geothermal fluid temperature of about 130°C.)



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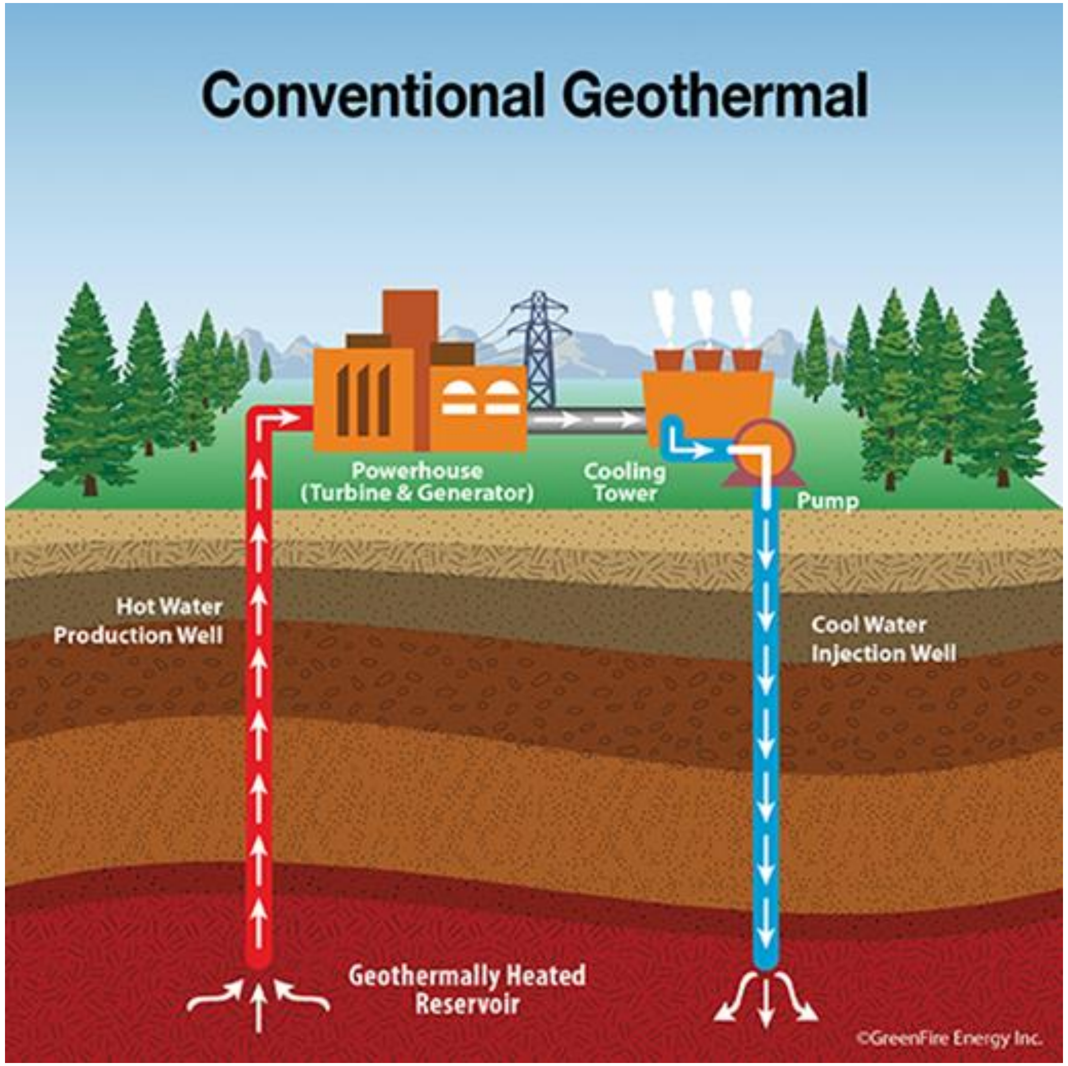
(Commonly water, but brine, seawater, CO_2 can be used.)



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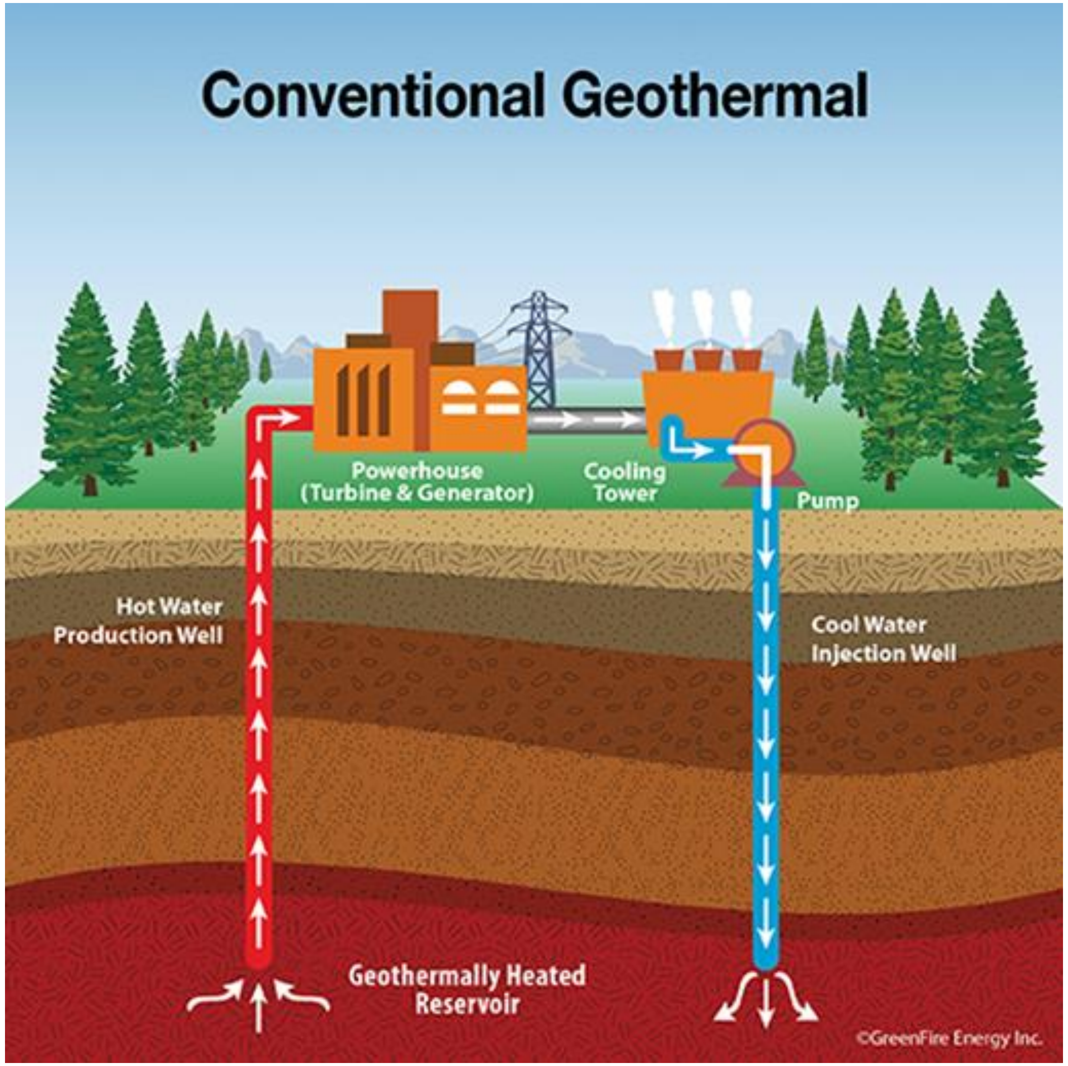
Sufficient permeability to allow enough mass of fluid to circulate through the geothermal reservoir.

(Flow rates of 10 kg/s or higher are ideal.)



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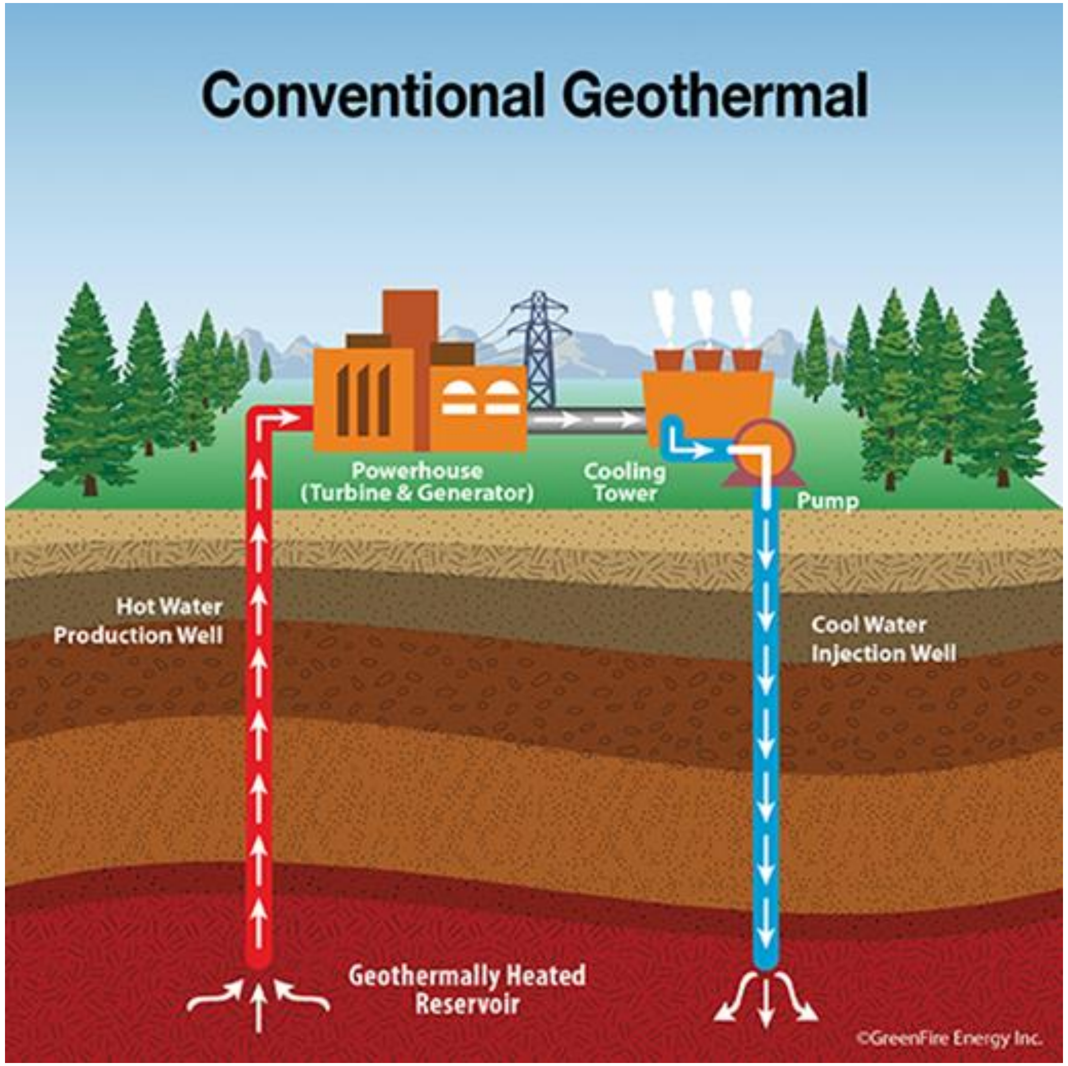
Sufficient **reservoir stability** for sustainable power generation.

(Minimum target lifetime of 20 years for a facility.)



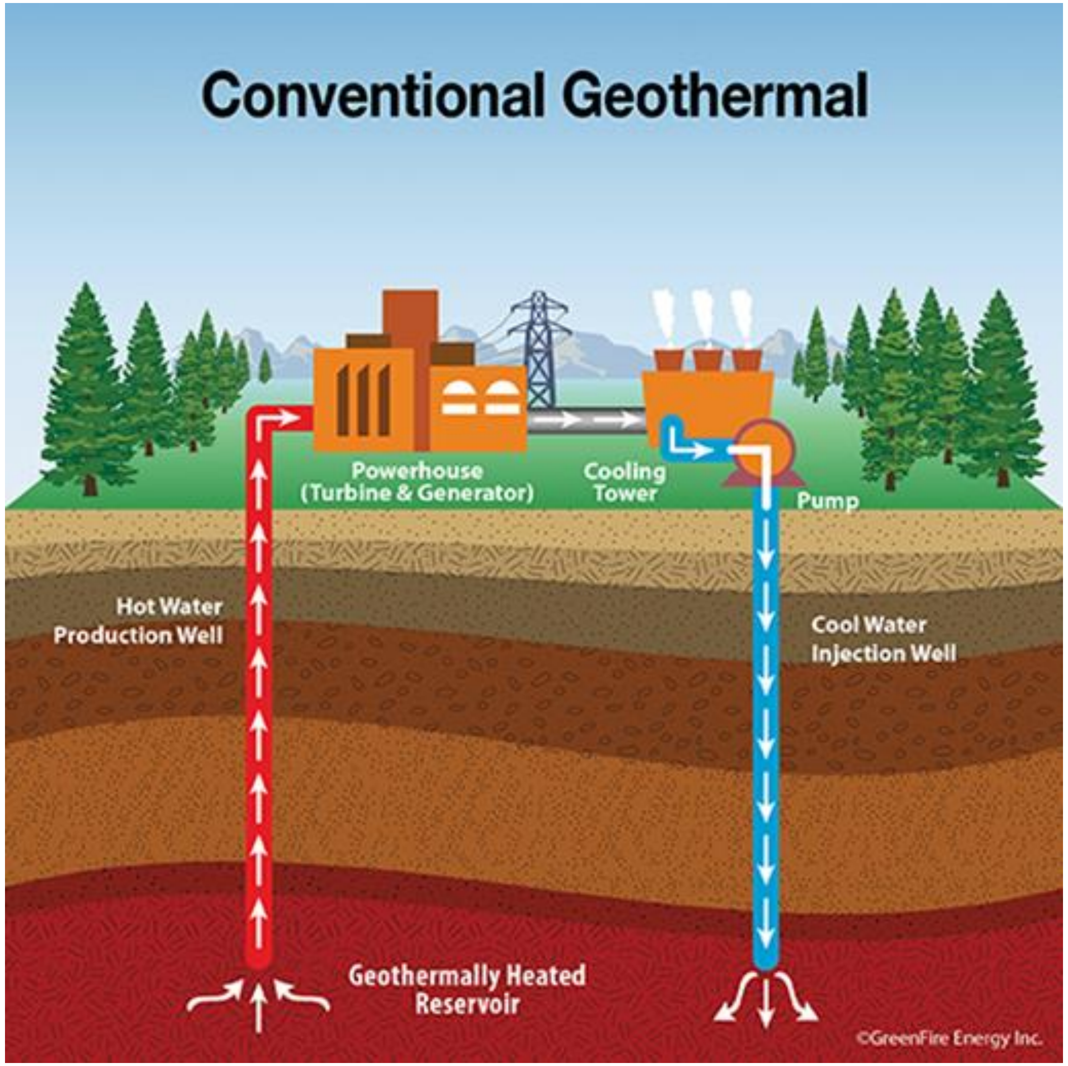
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Viability of geothermal resources

Electricity generation needs geothermal temperatures greater than about 130°C to 150°C.

In theory, we can find these temperatures anywhere on Earth.

But how deep?



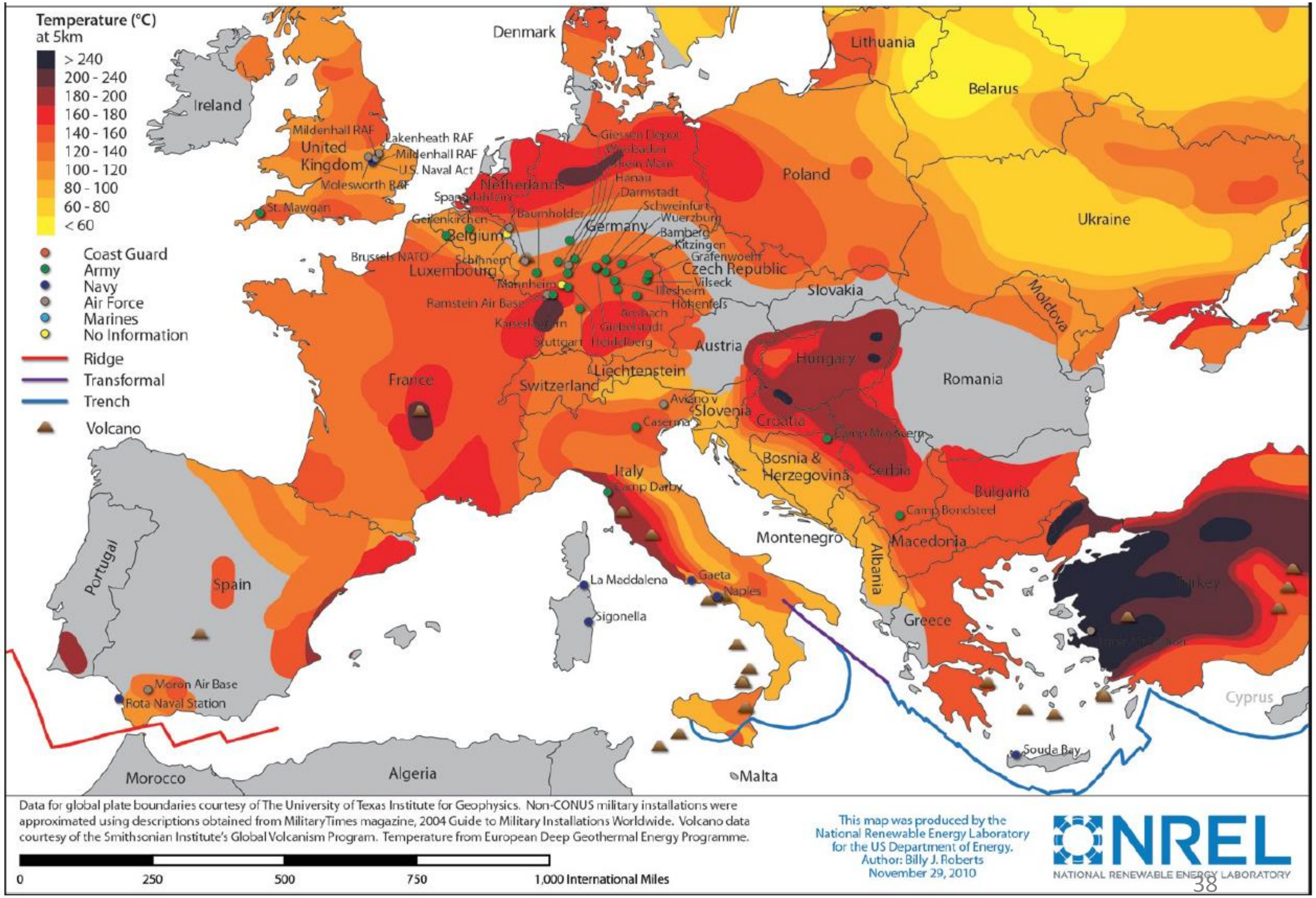
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Viability of geothermal resources

Large portions of Europe have subsurface temperatures in excess of 120°C at 5 km depth.

At these depths, rock often lacks sufficient permeability to support mass flow rates needed for heat extraction.

How can we extract that heat?



Enhanced Geothermal Systems

Heat transfer in geothermal reservoirs:

Convection and conduction

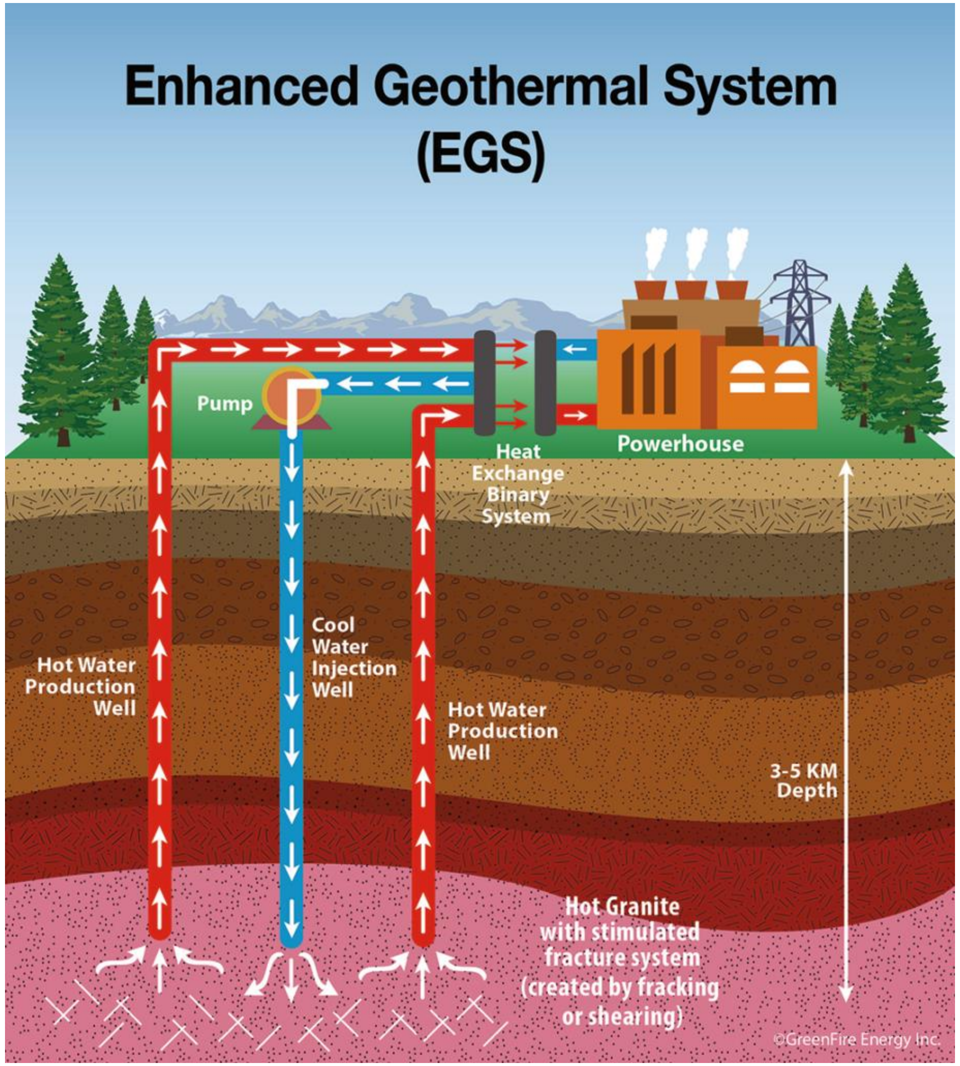
The dominant heat transfer mechanisms reflect the **local geological and hydrological properties** of the site.

Convection: Pre-existing permeability and fluids.

(e.g., hydrothermal and natural dry steam systems)

Conduction: These systems **lack permeability and *in situ* fluids.**

EGS often targets the latter scenario: Turning a conductive system into a convective system.



Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

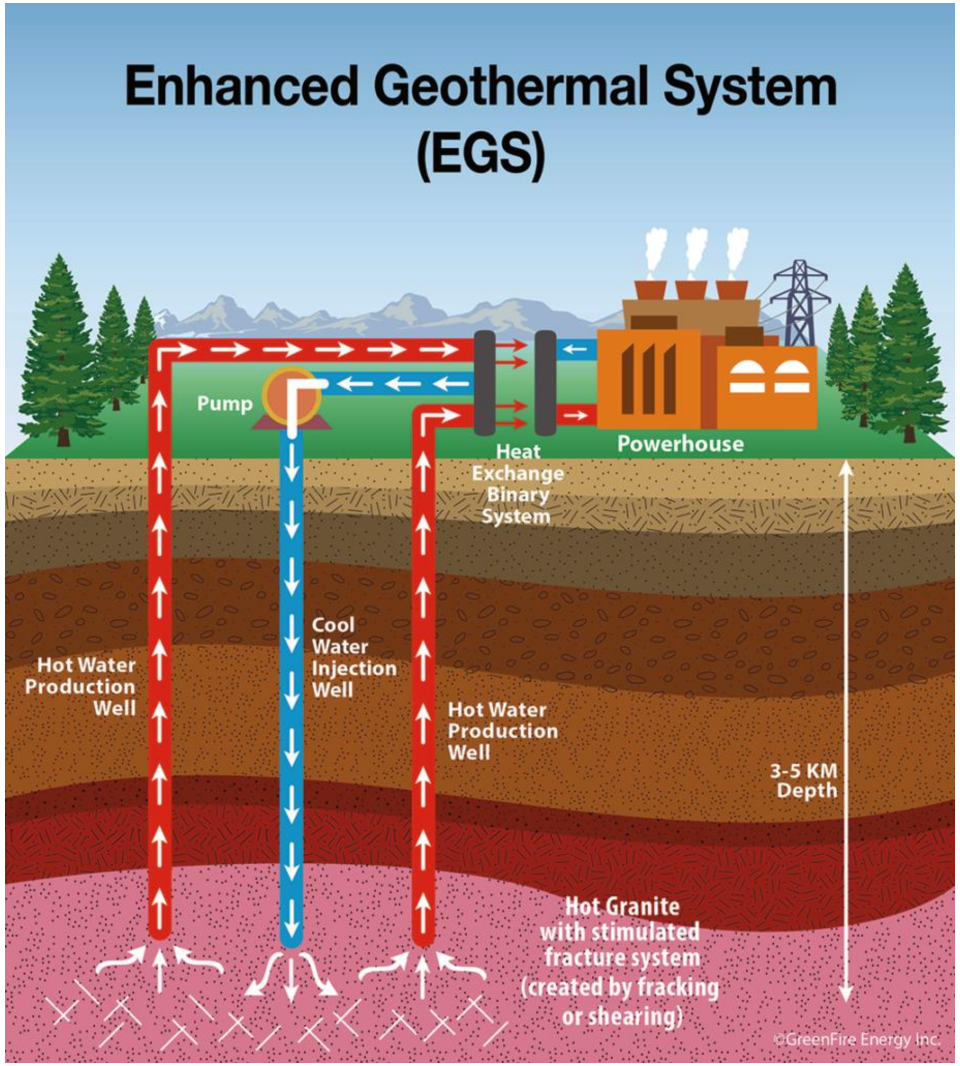
Enhanced Geothermal Systems

Often talk about EGS in the context of deep (>4 km) geothermal.

EGS is applicable at any depth.

Critical:

Reservoir has to be engineered to improve permeability and mass flow rate.



Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Characteristics of EGS

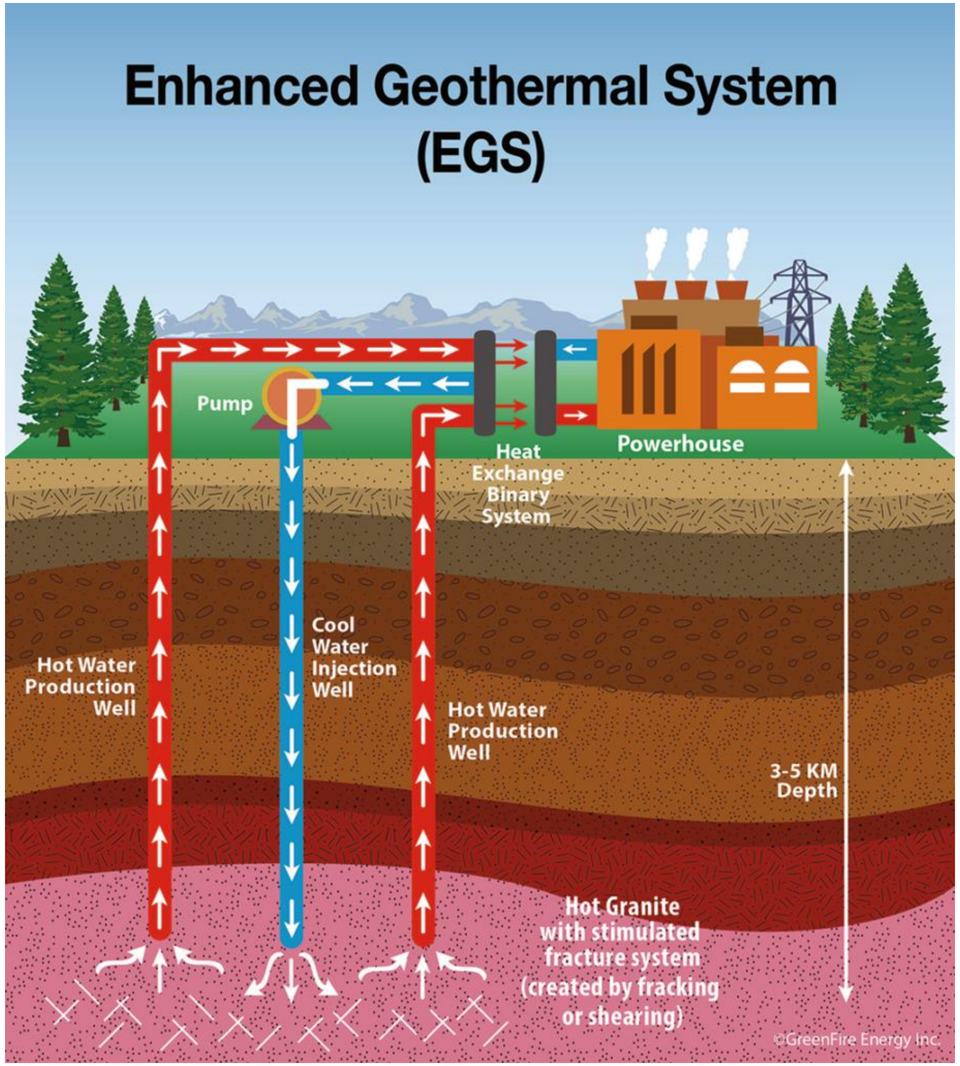
Design lifetime 20-30 years.

Reservoir needs to be managed to provide required heat to power the facility over this time.

This places contraints on the rate at which heat can be extracted from the reservoir.

We need to maximise the exposed fracture surface area over which a given amount of heat is extracted.

This minimises the temperature drop in the system, per unit area of fracture space.

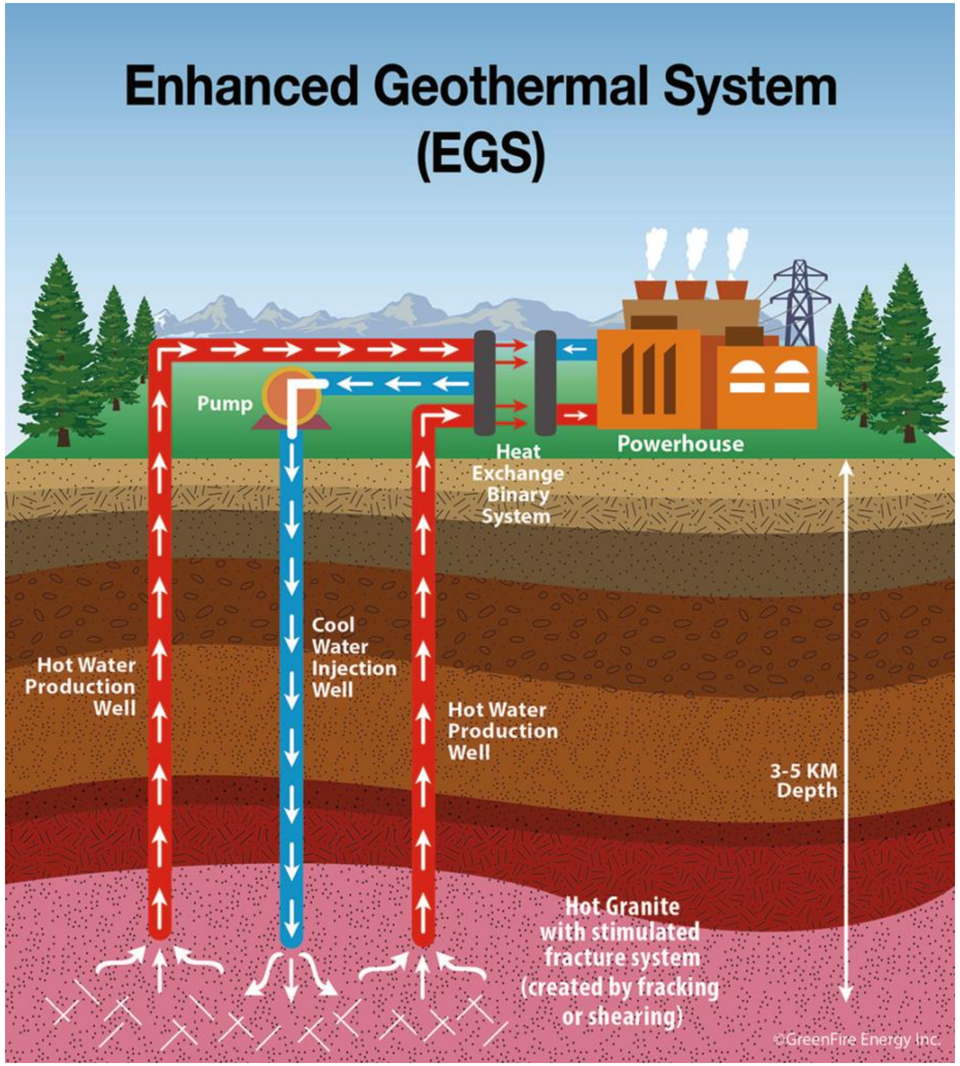


Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Characteristics of EGS

For a 5 MW power plant, with resource temperature of 200°C – 250°C, flow rates need to be about 50 kg/s.

By maximising permeable zone surface area, flow rate can be maintained while minimising the thermal draw down.



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Reservoir stimulation

Reservoir stimulation

Create / maintain permeability over the lifetime of the resource.

Hydro-shearing (hydraulic stimulation):

Inject fluids at high pressure to activate existing fractures without inducing new fractures.

Hydro-fracturing:

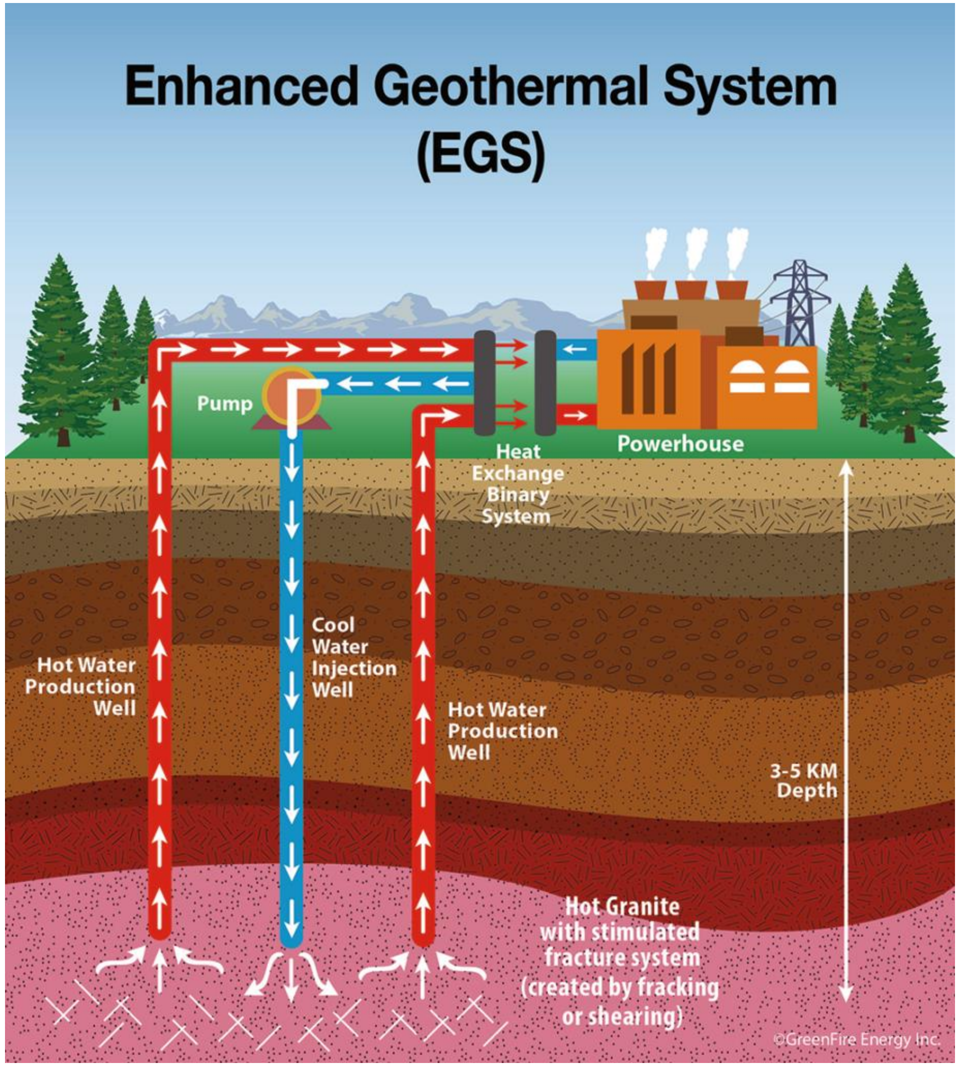
Inject fluids at high pressure to induce new fractures in impermeable rock in order to generate fracture permeability.

Thermal stimulation:

Inject cold fluids into a hot reservoir to induce thermal cracking in the reservoir.

Chemical stimulation:

Inject glutamate-based acids that target clay minerals, secondary quartz, carbonates, and sulphates for dissolution.



Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Reservoir stimulation

Create / maintain permeability over the lifetime of the resource.

Hydro-shearing (hydraulic stimulation):

Inject fluids at high pressure to activate existing fractures without inducing new fractures.

Hydro-fracturing:

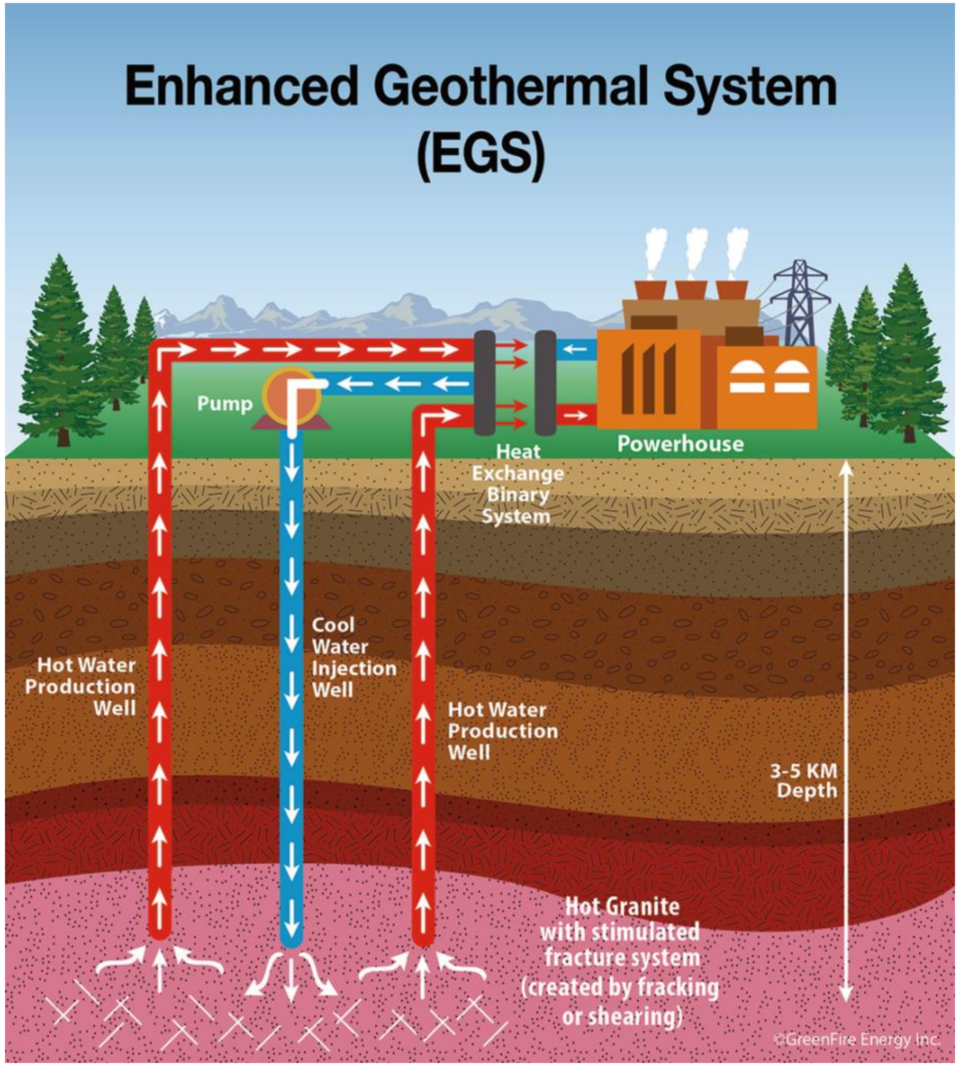
Inject fluids at high pressure to induce new fractures in impermeable rock in order to generate fracture permeability.

Thermal stimulation:

Inject cold fluids into a hot reservoir to induce thermal cracking in the reservoir.

Chemical stimulation:

Inject glutamate-based acids that target clay minerals, secondary quartz, carbonates, and sulphates for dissolution.



Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Reservoir stimulation

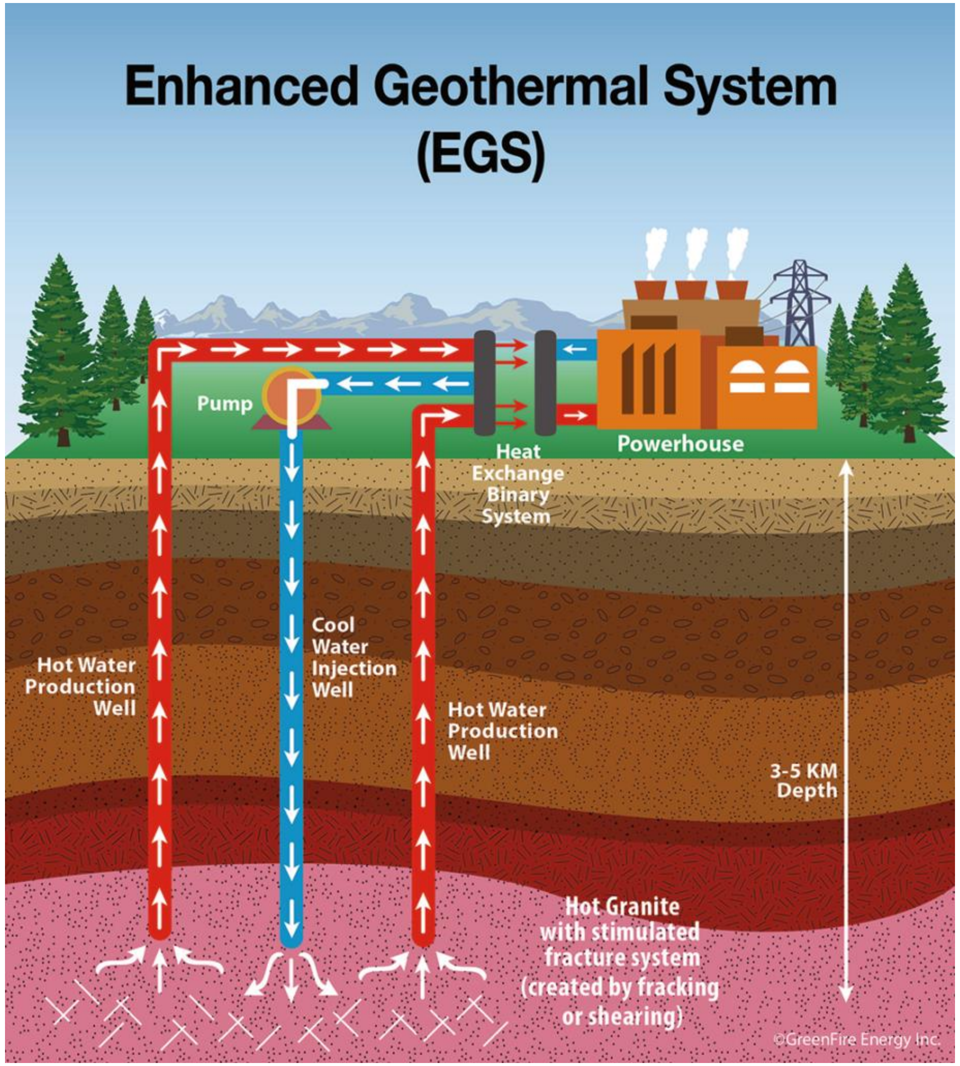
Things to keep in mind when stimulating a reservoir:

Ensure **enough ΔT** to maximise ΔH and achieve efficient power generation.

Keep **reservoir temperature reduction to a minimum**, maximising reservoir lifespan.

Stimulate a **sufficiently large volume** to support adequate heat extraction.

Maintain adequate **mass flow rate** to meet power generation (MW) needs.



Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Stimulated reservoir volume

From Armstead and Tester (1987):

Target fracture permeabilities: 10-50 mD (1×10^{-14} to 5×10^{-14} m^2)

100 000 m^2 per fracture required to keep temperature drop low enough to sustain the resource over its designed lifetime.

Minimum volume of fractured rock that can satisfy these criteria is about 2 km^3 (Baria et al., 2006).

TABLE 13.1
Surface Area of Fractures (m^2) for the Indicated Dimensions

	Distance from Injection Well (m)			
Length (m)	**50 m**	**100 m**	**1,000 m**	**5,000 m**
2	200	400	4,000	20,000
4	400	800	8,000	40,000
6	600	1,200	12,000	60,000
8	800	1,600	16,000	80,000
10	1,000	2,000	20,000	100,000
20	2,000	4,000	40,000	200,000
50	5,000	10,000	100,000	500,000
100	10,000	20,000	200,000	1,000,000

Source: Glassley, W. E., *Geothermal Energy*

Hydraulic stimulation

Fractures propogate in specific directions.

These directions are determined by the **local stress state**, which depends on the **maximum, minimim, and intermediate principal stresses**.

The orientations of the principal stresses depend on tectonic forces acting on the rock body.

Permeability develops in preferred orientations:

Flow pathways occur in a limited number of directions.

TABLE 13.1
Surface Area of Fractures (m^2) for the Indicated Dimensions

	Distance from Injection Well (m)			
Length (m)	**50 m**	**100 m**	**1,000 m**	**5,000 m**
2	200	400	4,000	20,000
4	400	800	8,000	40,000
6	600	1,200	12,000	60,000
8	800	1,600	16,000	80,000
10	1,000	2,000	20,000	100,000
20	2,000	4,000	40,000	200,000
50	5,000	10,000	100,000	500,000
100	10,000	20,000	200,000	1,000,000

Source: Glassley, W. E., *Geothermal Energy*

Hydraulic stimulation: Fracture reactivation

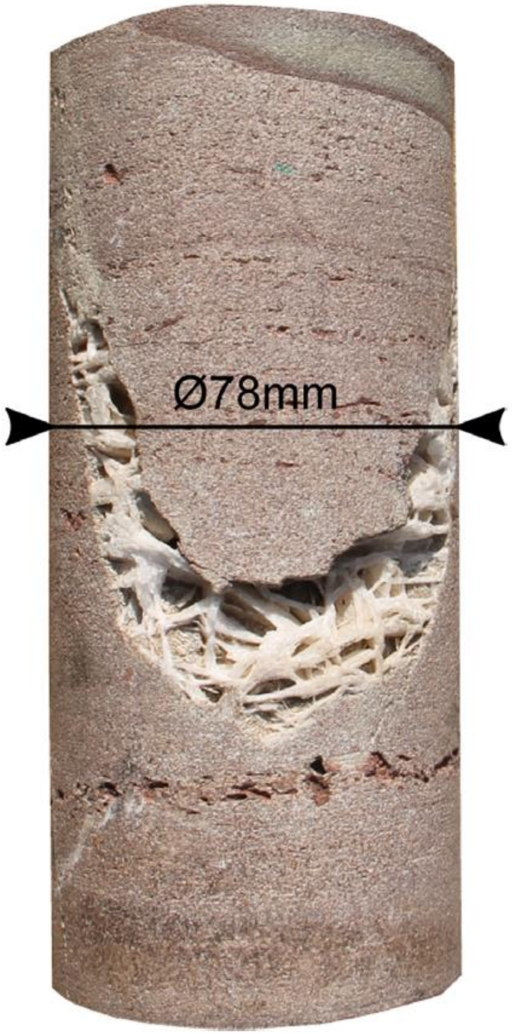
Fractures are approximately planes and are weaker than interwoven minerals in rocks.

Are sealed fractures weaker?

Commonly, but not always.

Depends on fracture sealing material and host rock.

Precipitated minerals may have well-defined cleavages, be hydrous, or just generally weak.



Hydraulic stimulation: Fracture reactivation

Principal stresses resolve into **normal and shear stresses on a plane**, and depend on the orientation of the plane with respect to the principal stress directions:

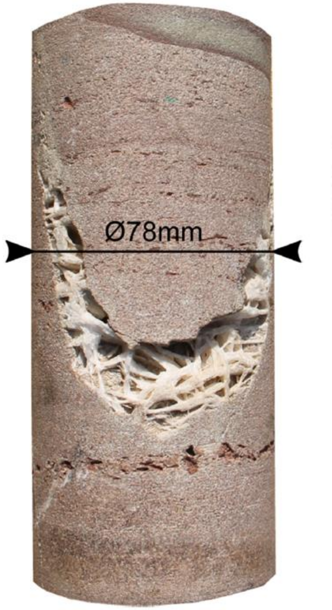
$$\sigma_n = \frac{(\sigma_1 + \sigma_3)}{2} + \frac{(\sigma_1 - \sigma_3)}{2} \times \cos 2\theta$$

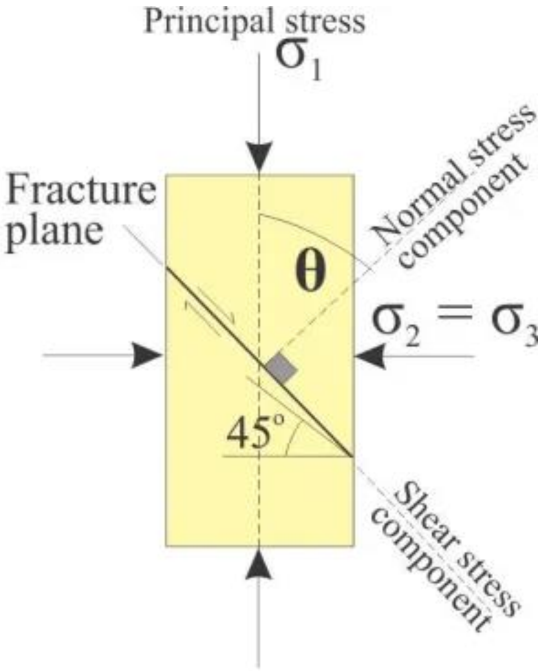
$$\sigma_s = \frac{(\sigma_1 - \sigma_3)}{2} \times \sin 2\theta$$

Convention:

Compressive stress are positive.

Tensional stresses are negative.





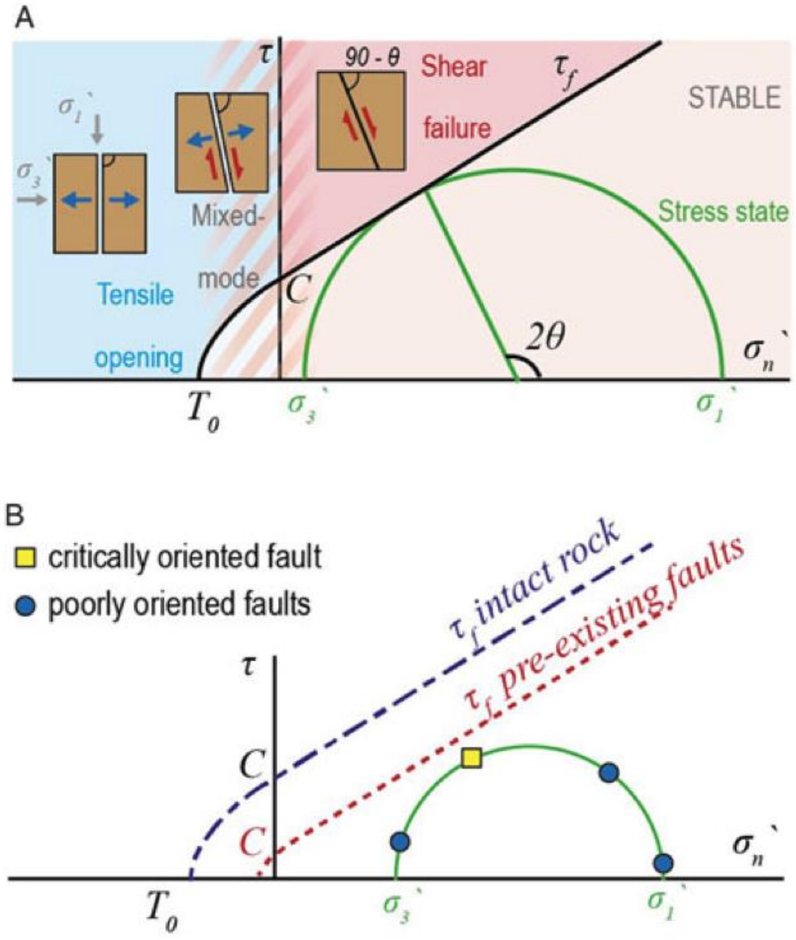
Hydraulic fracturing and hydraulic stimulation

Inject fluid into the reservoir at high pressure.

New fractures will form at an orientation of θ to the maximum principal stress.

Pre-existing fractures oriented at θ to the maximum principal stress will be sheared.

Increasing pore fluid pressure reduces the effective stress on the rock, moving the Mohr circle toward the failure envelope for intact rock.



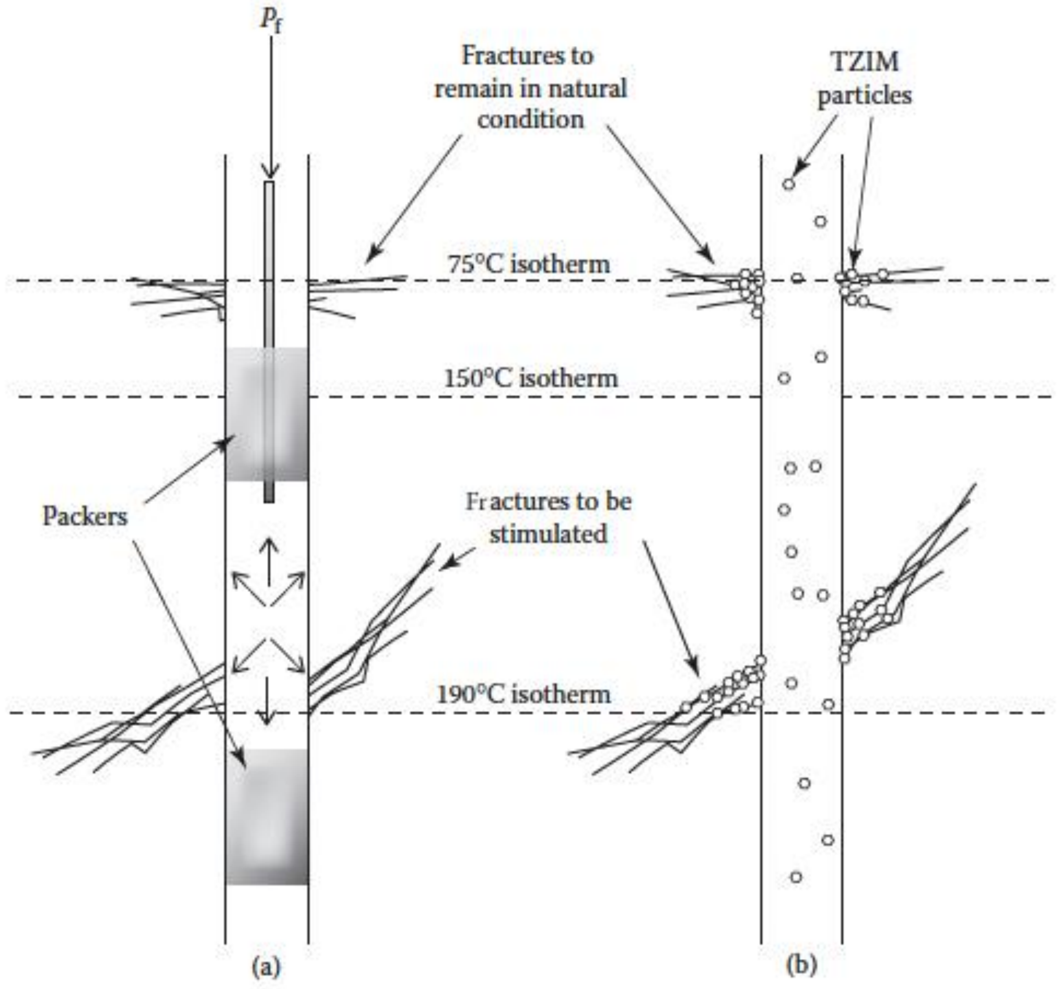
Source: Buijze et al., 2019

Managing hydraulic fracturing and stimulation

Permeability enhancement: develop a network of fractures that provide access for fluids to extract heat from a sufficiently large rock volume.

To do this: Inject fluids at sufficiently high pressures to induce brittle fracture of existing fractures or intact rock.

But…how do you control where you apply these high pressures?



Source: Glassley, W. E., *Geothermal Energy*

Managing hydraulic fracturing and stimulation

Borehole are long!

You can't (and don't want to!) stimulate the whole borehole: isolate selected regions for permeability enhancement.

Packers:

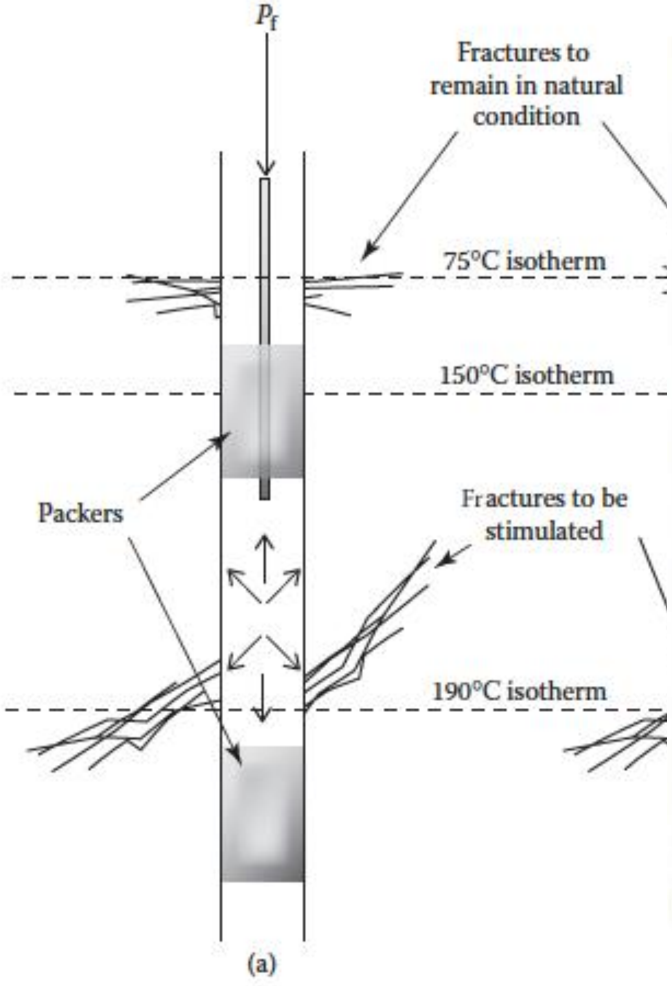
Mechanical or pneumatic devices that seal the borehole above and below the region being stimulated:

Expandable, accordion-like segments of flexible metal that are pressurised to seal the borehole.

Elastomeric materials that can be inflated.

Pipe crosses the packer to increase fluid pressure in the isolated zone.

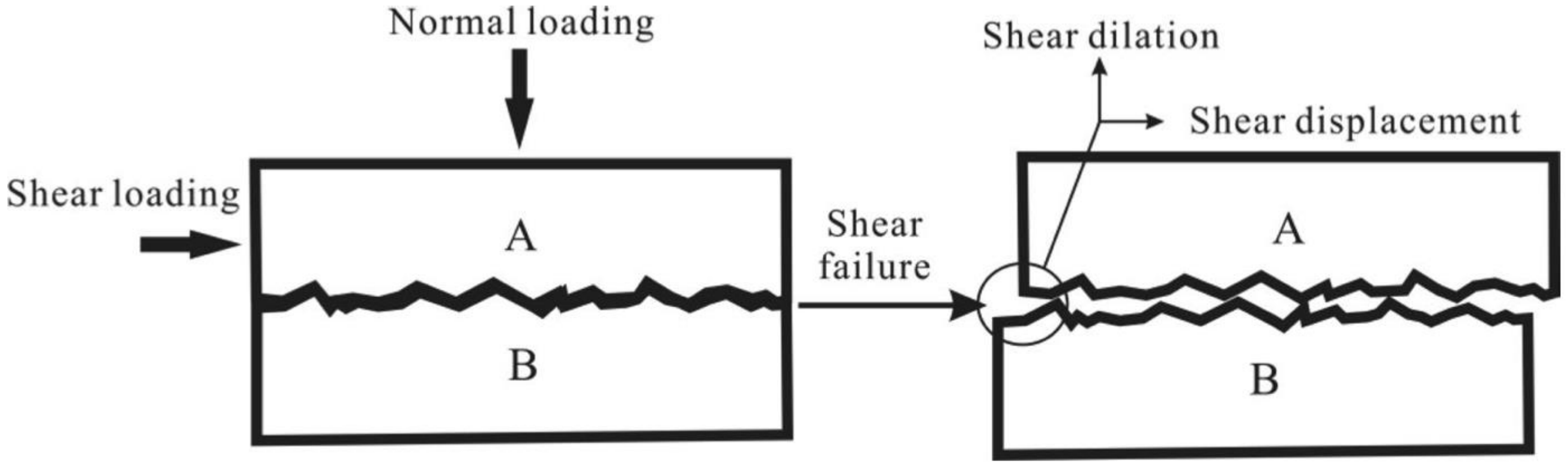
Problem: above 200°C, packer materials will likely start to fail.



Source: Glassley, W. E., *Geothermal Energy*

Managing hydraulic fracturing and stimulation

Fractures need to stay propped open after stimulation.

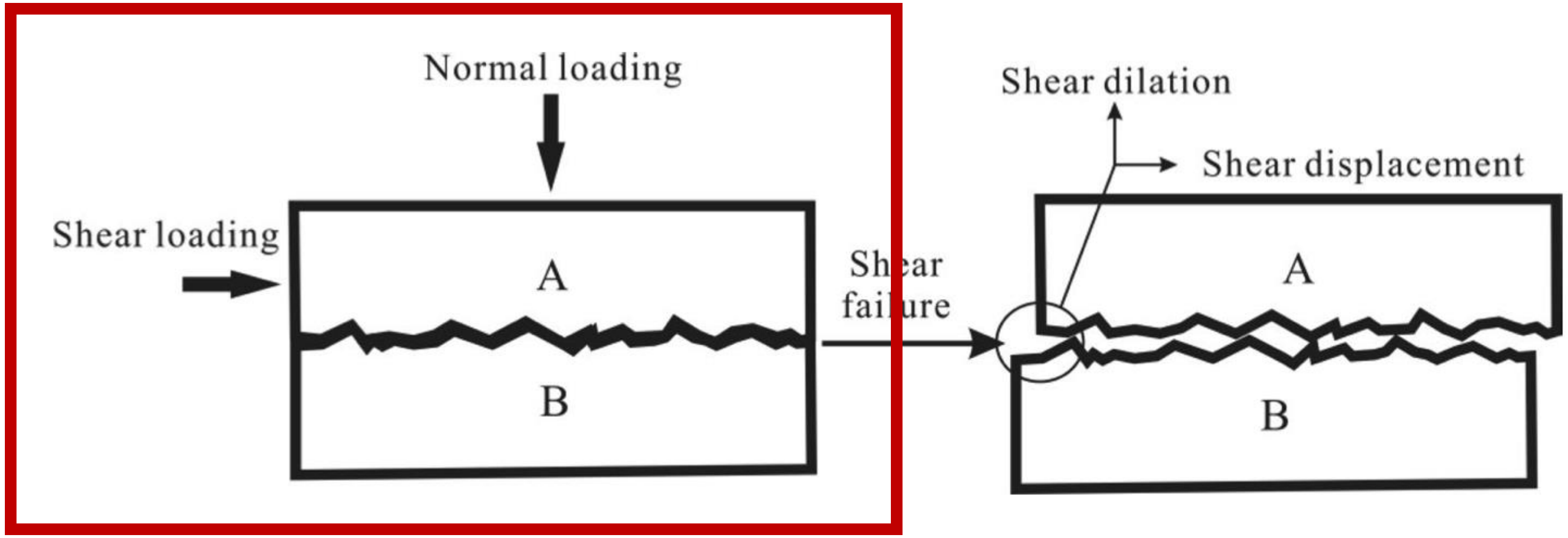


Source: Yuan et al., 2020; https://link.springer.com/content/pdf/10.1007/s00603-020-02227-8.pdf

Managing hydraulic fracturing and stimulation

Fractures need to stay propped open after stimulation.

Tensile fractures are easy to close when pore fluid pressure is reduced.



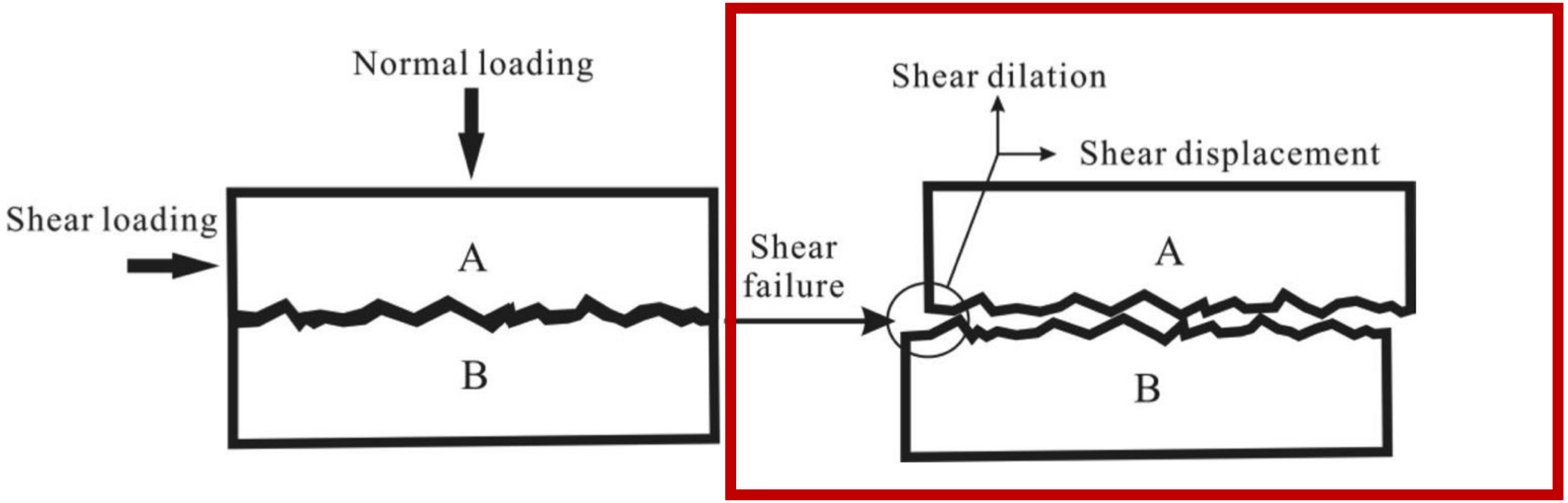
Source: Yuan et al., 2020; https://link.springer.com/content/pdf/10.1007/s00603-020-02227-8.pdf

Managing hydraulic fracturing and stimulation

Fractures need to stay propped open after stimulation.

Tensile fractures are easy to close when pore fluid pressure is reduced.

Shear along fractures helps to prop them open: fracture surfaces are rough and, when displaced with respect to each other, the fracture remains propped open on asperities.

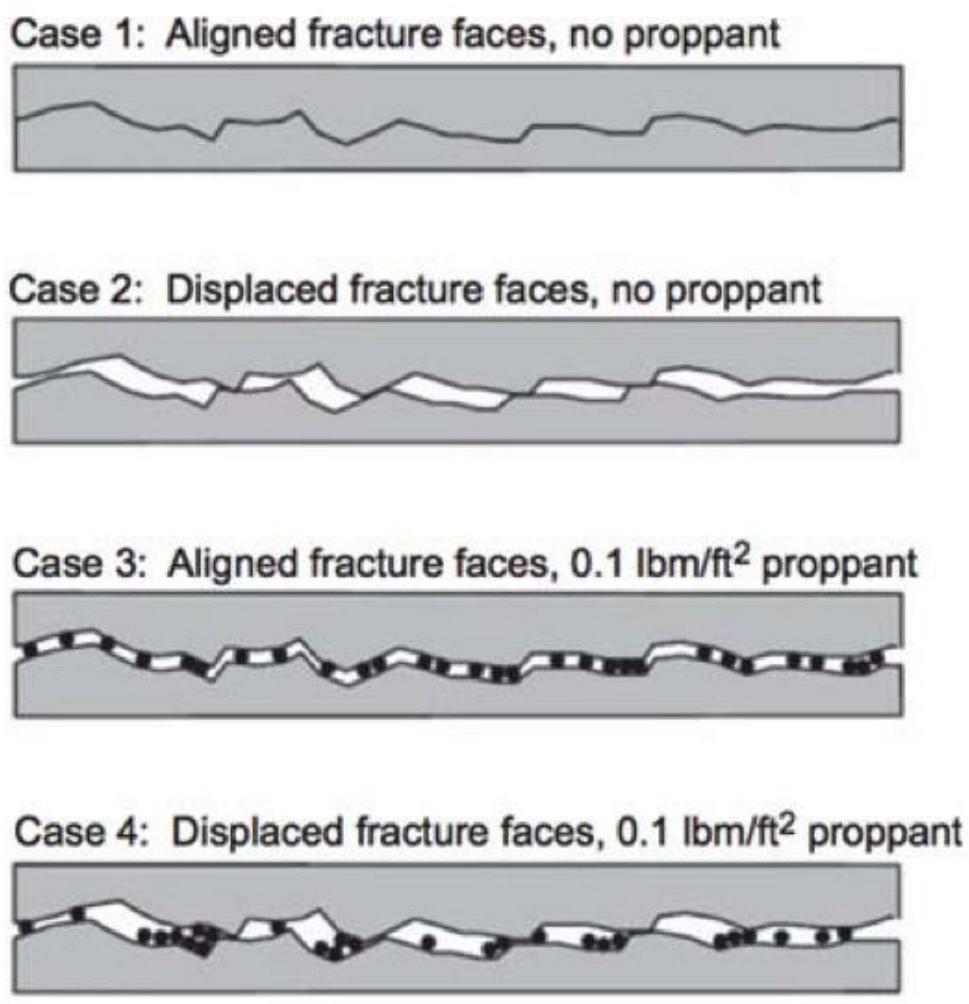


Source: Yuan et al., 2020; https://link.springer.com/content/pdf/10.1007/s00603-020-02227-8.pdf

Managing hydraulic fracturing and stimulation

Fractures need to stay propped open after stimulation.

Artificial proppants: Sand or other materials of selected sizes and hardness to maintain fracture aperture.



Source: Barati and Liang, 2014; https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/app.40735

Induced seismicity

Induced seismicity

Seismicity caused by anthropogenic intervention.

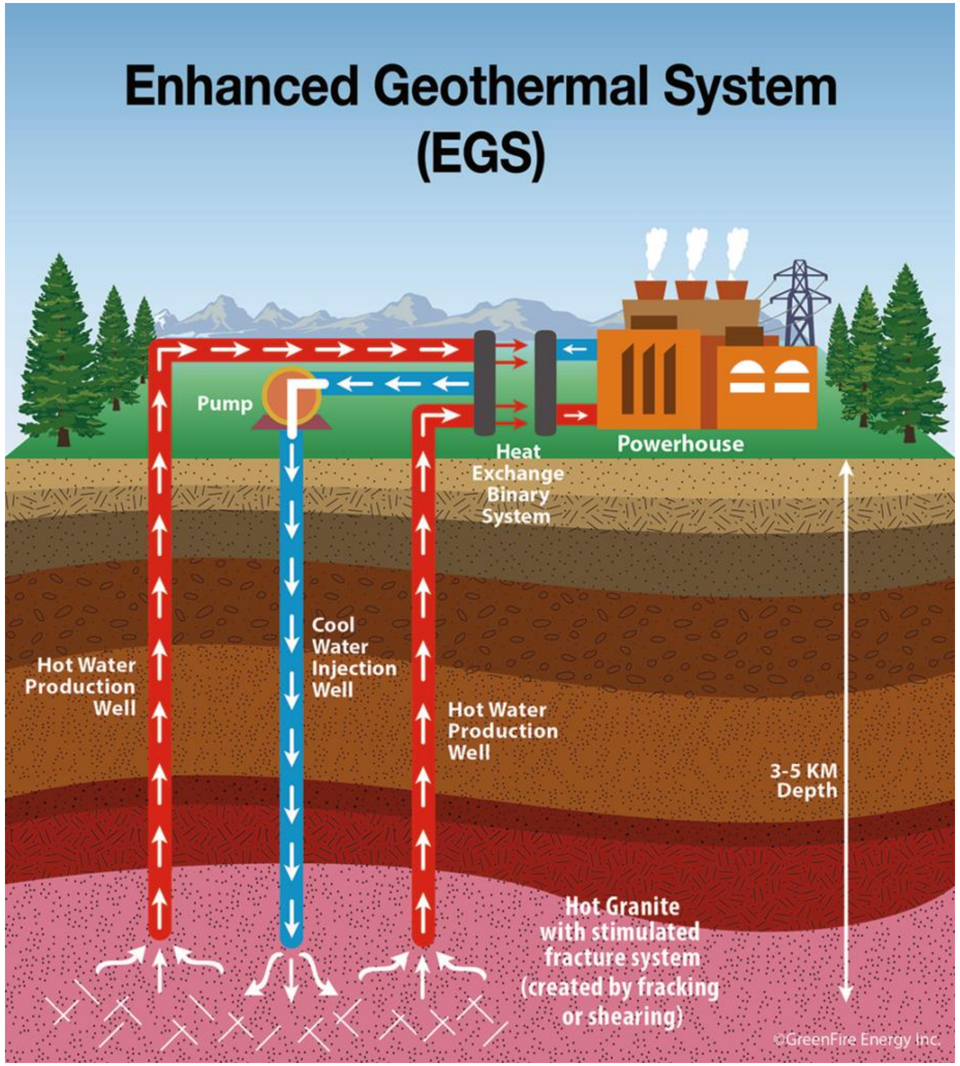
In geothermal systems, induced sesimicity can be caused by:

Thermal cracking: Injection of cold fluids into a hot reservoir.

Change in local stress field: Fluid extraction.

Reduction of effective normal stress: High pressure fluid injection for reservoir stimulation.

(Microseismic events are not felt, but can be recorded by seismometer.)



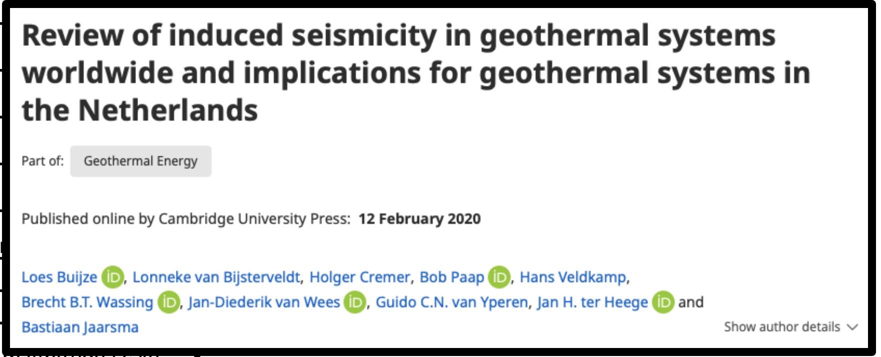
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Induced seismicity: Hydraulic stimulation

Geothermal project	Country	Rock type	Magnitude	Scale
Cerro Prieto	MEX	Sands & Shales	**6.6**	Local magnitude scale
Pohang (PX-1 + PX-2)	KOR	Granodiorite	**5.4**	Moment magnitude scale
Salton Sea	USA	Sands & Shales	**5.1**	-
The Geysers	USA	Metamorphic	**5.0**	-
Yanaizu-Nishiyama (Okuaizu)	JPN	Volcaniclastic	**4.9**	Moment magnitude scale
Los Humeros	MEX	Andesite	**4.6**	Magnitude duration
Coso	USA	Crystalline	**4.4**	-
Húsmúli reinjection (Hellisheidi field)	ISL	Basalt	**4.0**	Local magnitude scale
Piancastagnaio (Monte Amiata)	ITA	Metamorphic	**3.9**	Local magnitude scale
Miravalles	CRI	Volcaniclastic	**3.8**	Local magnitude scale
Berlín	SLV	Andesite	**3.7**	Moment magnitude scale
Habanero 1 2003	AUS	Granite	**3.7**	Local magnitude scale
Vendenheim	FRA		**3.6**	Local magnitude scale
Sankt Gallen	CHE	Carbonate	**3.5**	Local magnitude scale
Basel	CHE	Granite	**3.4**	Local magnitude scale
Rotokawa	NZL	Volcaniclastic	**3.3**	-
Nesjavellir	ISL	Basalt	**3.2**	
Svartsengi	ISL	Volcaniclastic	**3.2**	Local
Kawerau	NZL	Metamorphic	**3.2**	
Mokai	NZL	Volcaniclastic	**3.2**	
Larderello	ITA	Carbonate	**3.2**	Local
Chipilapa-Ahuachapán	SLV	Andesite	**3.0**	Mag
Habanero 1 2005	AUS	Granite	**3.0**	Local
Habanero 4 2012	AUS	Granite	**3.0**	Local
Reykjanes	ISL	Volcaniclastic	**3.0**	Local magnitude scale
Torre Alfina RA1	ITA	Carbonate	**3.0**	
Vendenheim	FRA	granite	**3.0**	Local magnitude scale
Soultz-sous-Forêts GPK3 2003	FRA	Granite	**2.9**	Local magnitude scale

Data compilation courtesy of B. Lecampion.

Data from Buijze et al. (2019).


Review of induced seismicity in geothermal systems worldwide and implications for geothermal systems in the Netherlands

Part of: Geothermal Energy

Published online by Cambridge University Press: **12 February 2020**

Loes Buijze, Lonneke van Bijsterveldt, Holger Cremer, Bob Paap, Hans Veldkamp, Brecht B.T. Wassing, Jan-Diederik van Wees, Guido C.N. van Yperen, Jan H. ter Heege and Bastiaan Jaarsma

Show author details

Induced seismicity: Hydraulic fracturing

Formation/place	Country	Magnitude	Date
Horn river	BC, Canada	M_L 3.6	May 2011
Exshaw	AL, Canada	M_w 3.0	Dec 2011
Marcellus	PA, USA	M_L 2.7	Jul 2013
Oklahoma	TX, USA	M_w 3.4	Jul 2015
Arkansas	TX, USA	M_w 3.5	Jul 2015
Montney	BC, Canada	M_w 4.6	Aug 2015
Duvernay	AL, Canada	M_w 4.1	Jan 2016
Utica	PA, USA	M_L 3.7	Jun 2017
Eagleford	TX, USA	M_w 4.0	May 2018
Delaware	TX, USA	M_L 3	May 2018
Sichuan	China	M_L 5.7	Dec. 2018
Bowland	UK	M_L 2.9	Aug. 2019

Hydraulic Fracturing-Induced Seismicity

Ryan Schultz[1], Robert J. Skoumal[2], Michael R. Brudzinski[3], Dave Eaton[4], Brian Baptie[5], and William Ellsworth[1]

Data compilation courtesy of B. Lecampion.

Data from Schultz et al. (2020); Reviews of Geophysics

Induced seismicity

When fractures form, seismic energy is released.

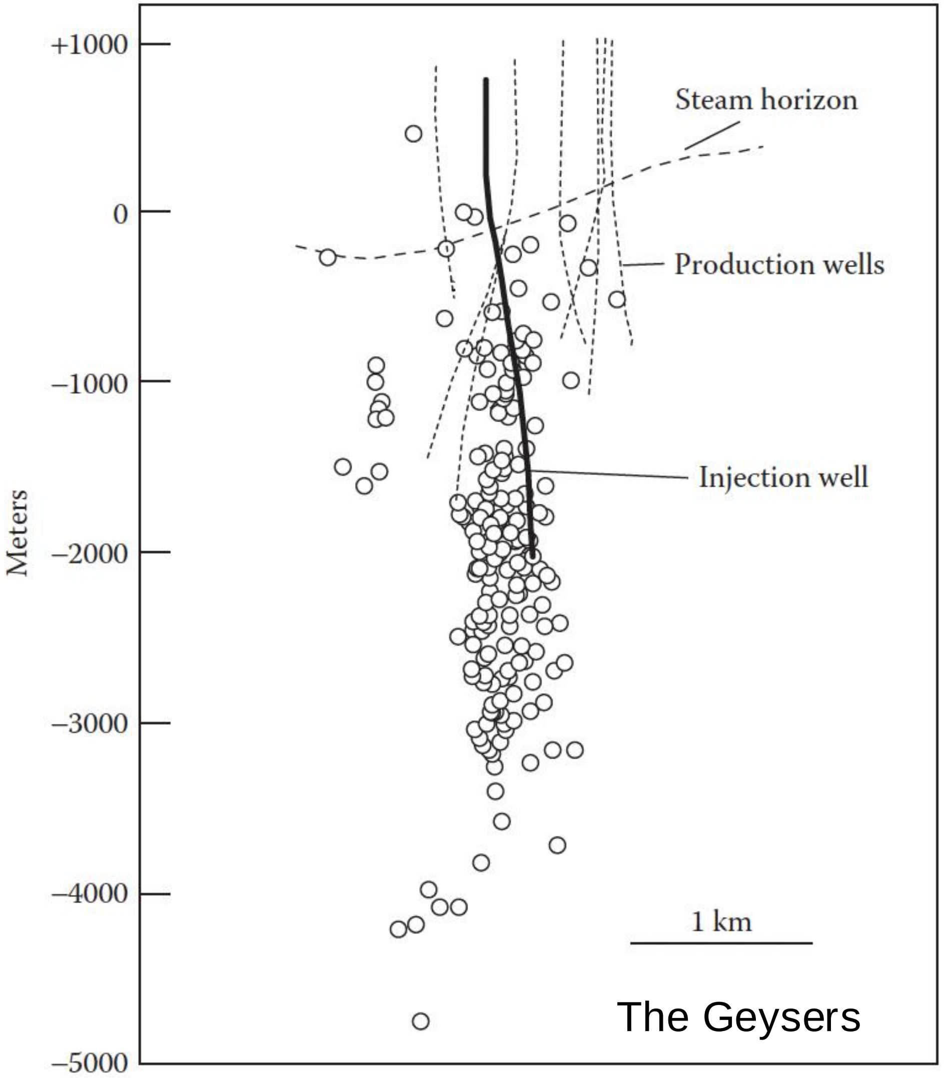
Monitoring seismic activity during stimulation:
Install seismometers on the Earth's surface and down monitoring wells.

In addition to monitoring for induced seismic magnitude, this helps us **map out the stimulated volume** of the reservoir:

Identify zones being stimulated.

Detect stimulation in untargeted zones and remedy this.

Detect unexpected seismic response.



Source: Glassley, W. E., *Geothermal Energy*

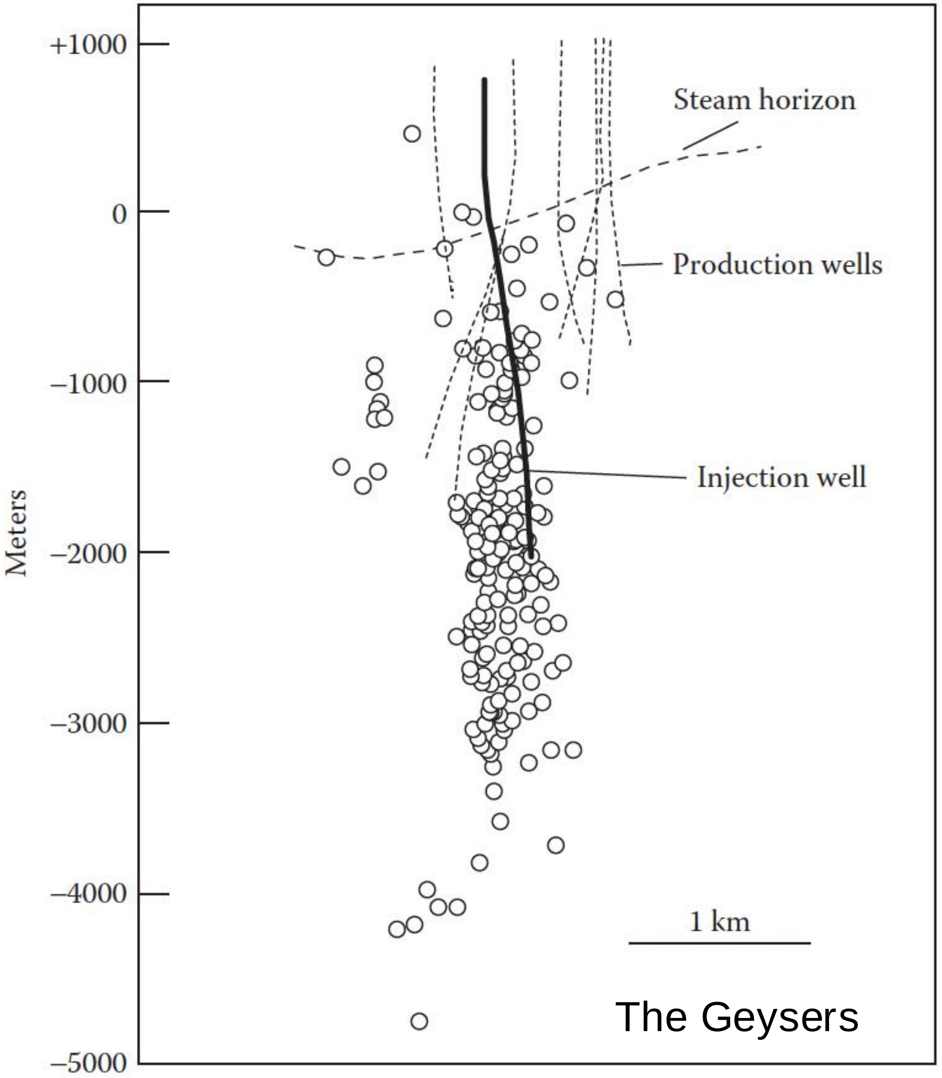
Induced seismicity

Seismic mapping during stimulation allows for the targeted placement of production wells.

Knowing where the reservoir has been stimulated reduces the risk to **production well placement**, because it identifies where permeability has been developed.

Microsesimicity also gives us the orientation of slip along fractures:

This can give us information about the stress state of the system, which gives us information about how the rock mass will fail.



Source: Glassley, W. E., *Geothermal Energy*

Rock mass strength

Rock mass strength depends on rock matrix strength and the presence of fractures:

Fracture length

Fracture orientation

Planarity

Roughness

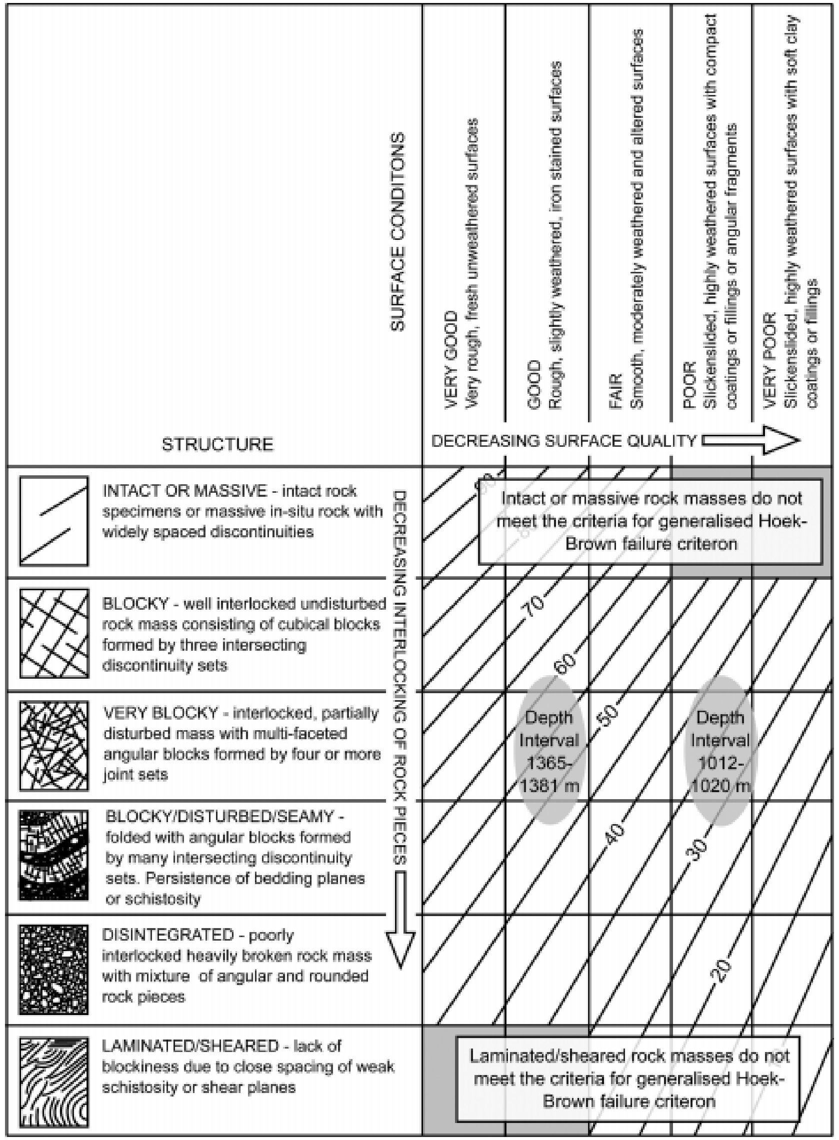
Degree of secondary mineralisation

Rock mass response depends on the local stress field:

Magnitude of imposed stress

Orientation of the principal stresses

Rate at which stress is applied



Source: Marinos et al. 2005

Rupture area and magnitude

Empirical relationship between earthquake magnitude (M) and area (A) over which the rupture occurs (Wells and Coppersmith, 1994):

$$M = 4.07 + 0.98 \log(A)$$

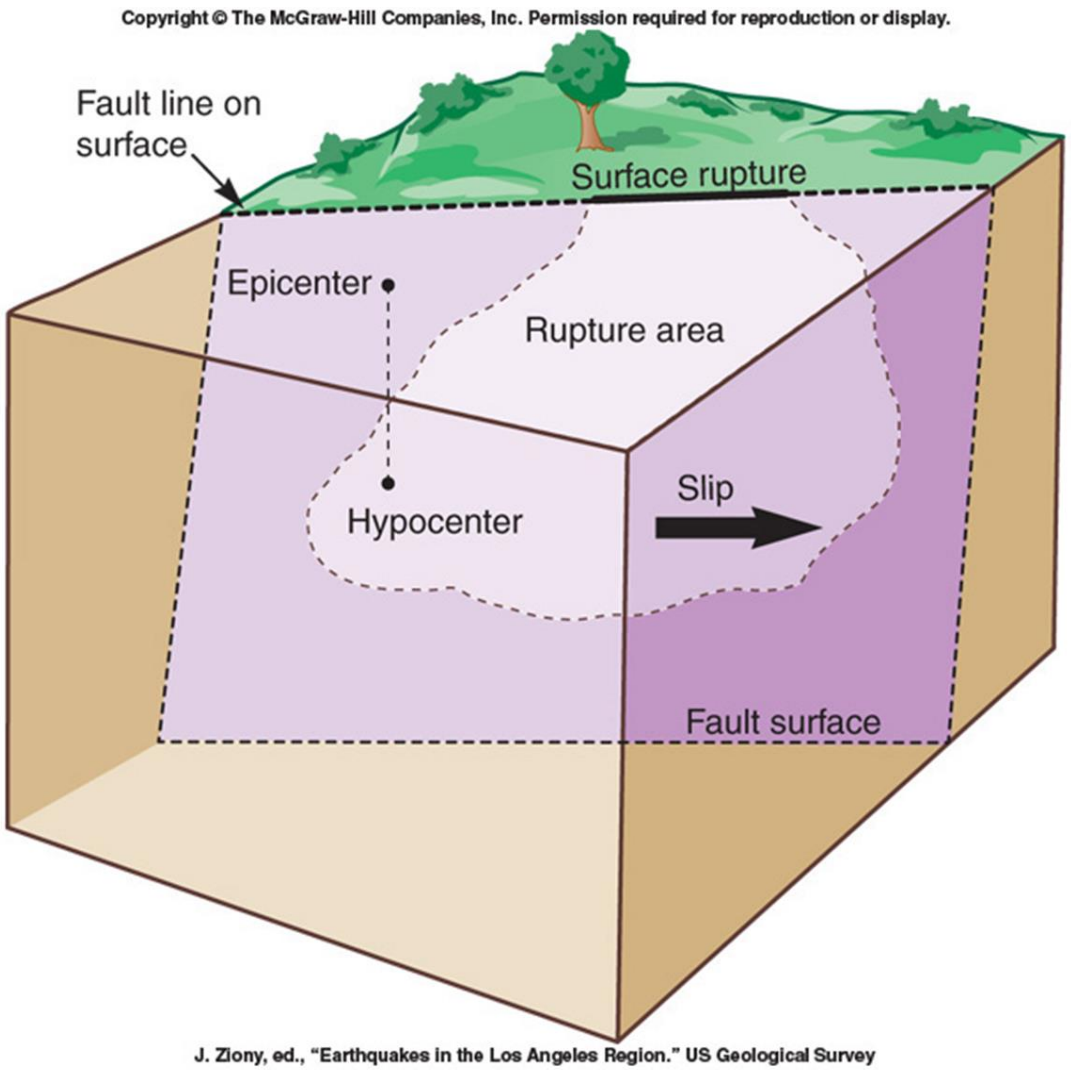
Where:

M is magnitude of the event

A is the rupture area in km^2

Most seismic events associated with cold water injection have magnitudes less than 2.5, with rupture areas less than 0.2 km^2.

For equant rupture areas, the slip along them would be about 100-150 m



Source: https://geophile.net/Lessons/Earthquakes/Earthquakes_03.html

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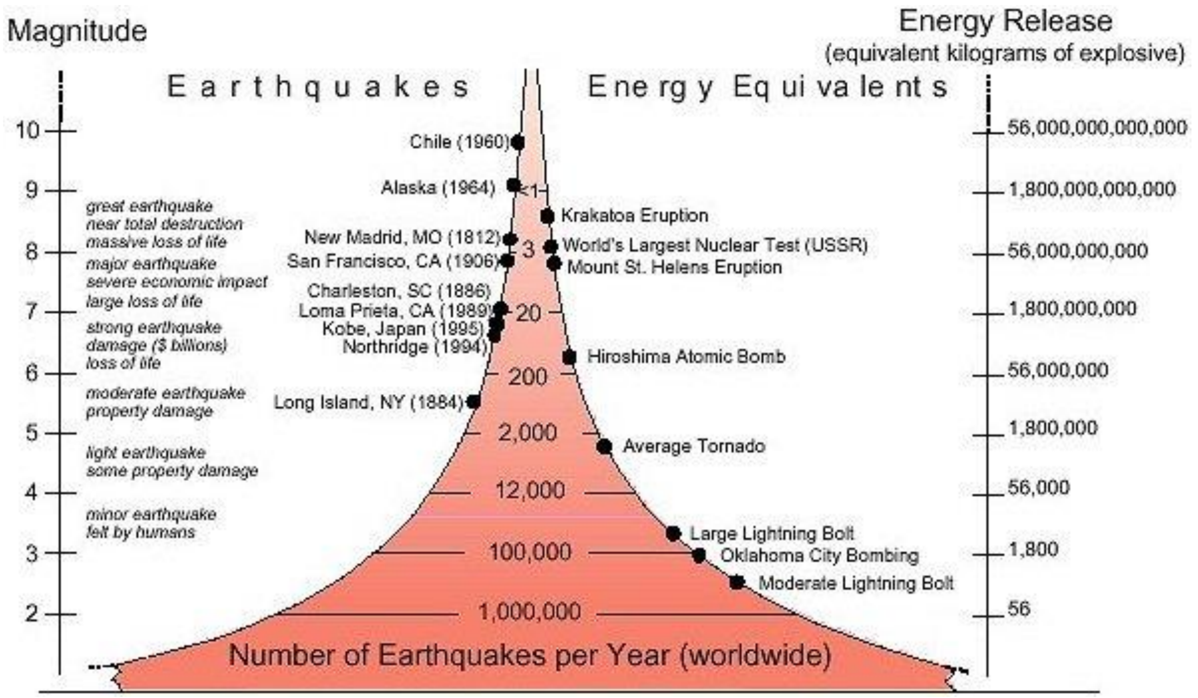


Source: https://www.usgs.gov/media/images/graph-showing-earthquake-magnitudes-and-equivalent-energy-release

Mechanics of seismic events

Assuming a fractured/faulted rock mass, the criterion for failure is based on the **static** coefficient of friction, μ_f:

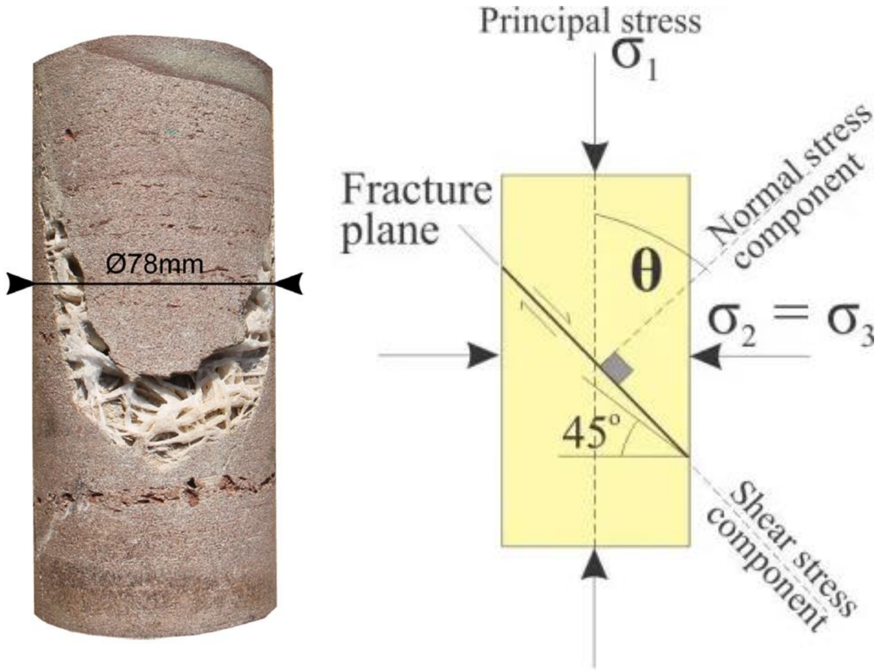
$$\mu_f = \frac{\tau_{peak}}{\sigma_n}$$

Where:

τ is the shear stress on a plane

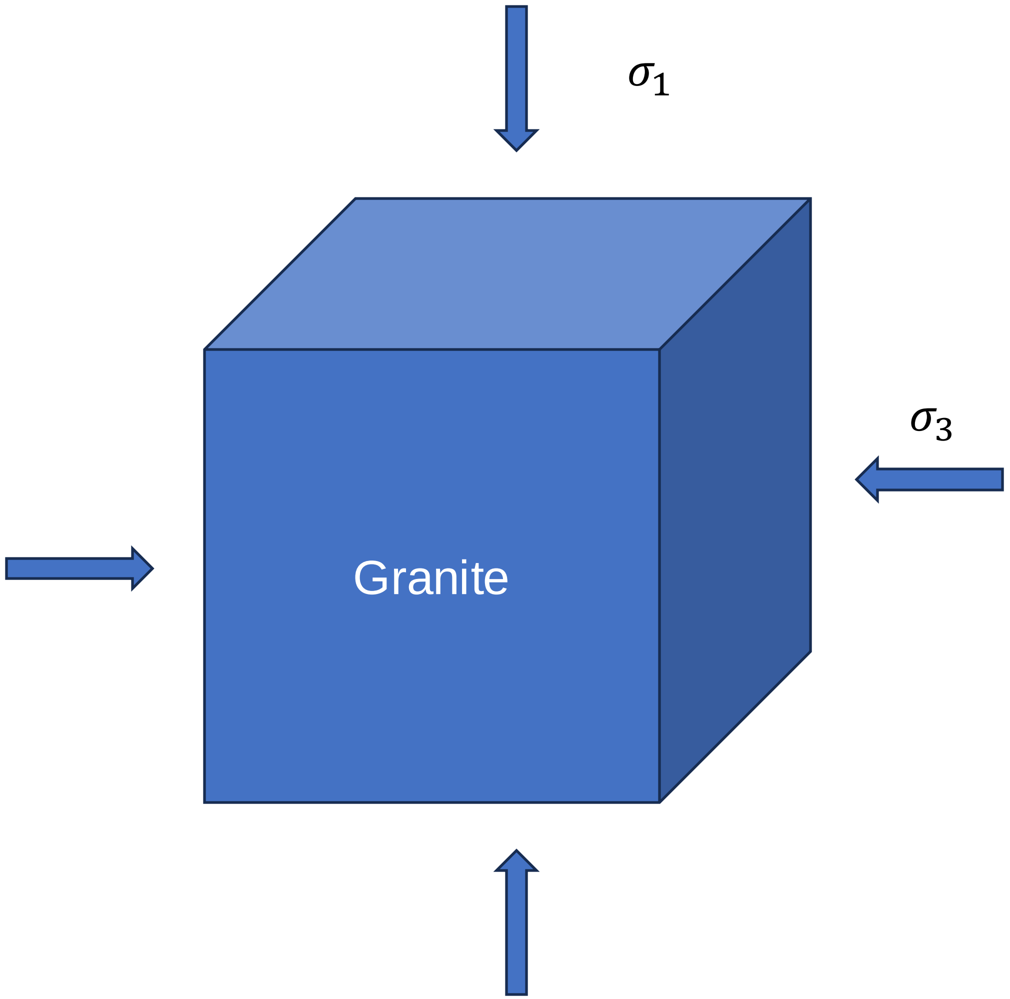
σ_n is the normal stress on a plane

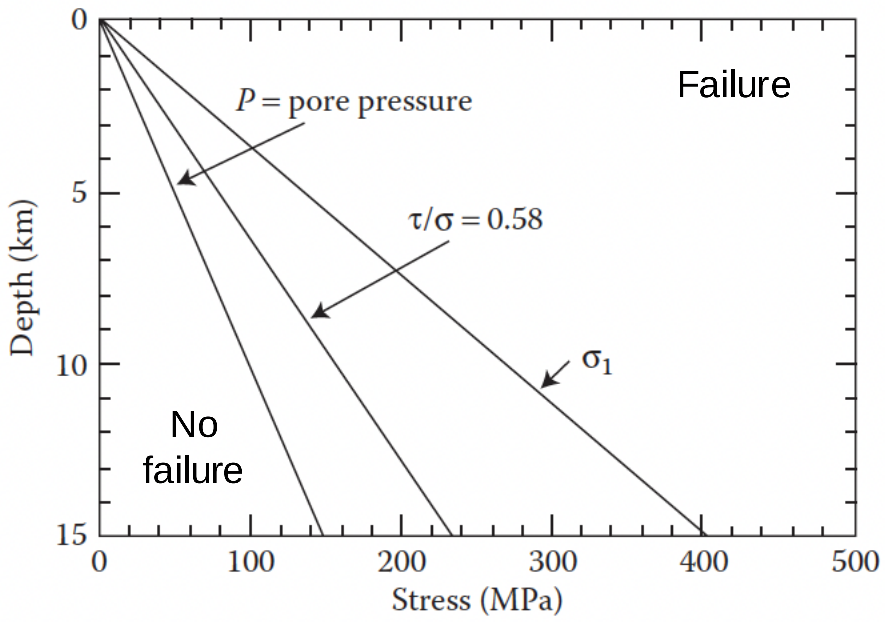
This defines the lower limit of internal friction of a fracture or faulted rock: if μ_f is exceeded, the rock will fail by slip along the fracture or fault.

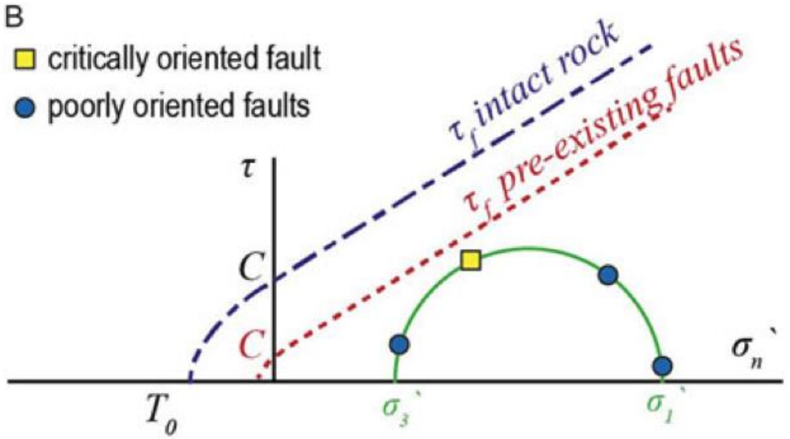


Shear stress, normal stress, and frictional properties

Assume a simple geometry:







Shear stress, normal stress, and frictional properties

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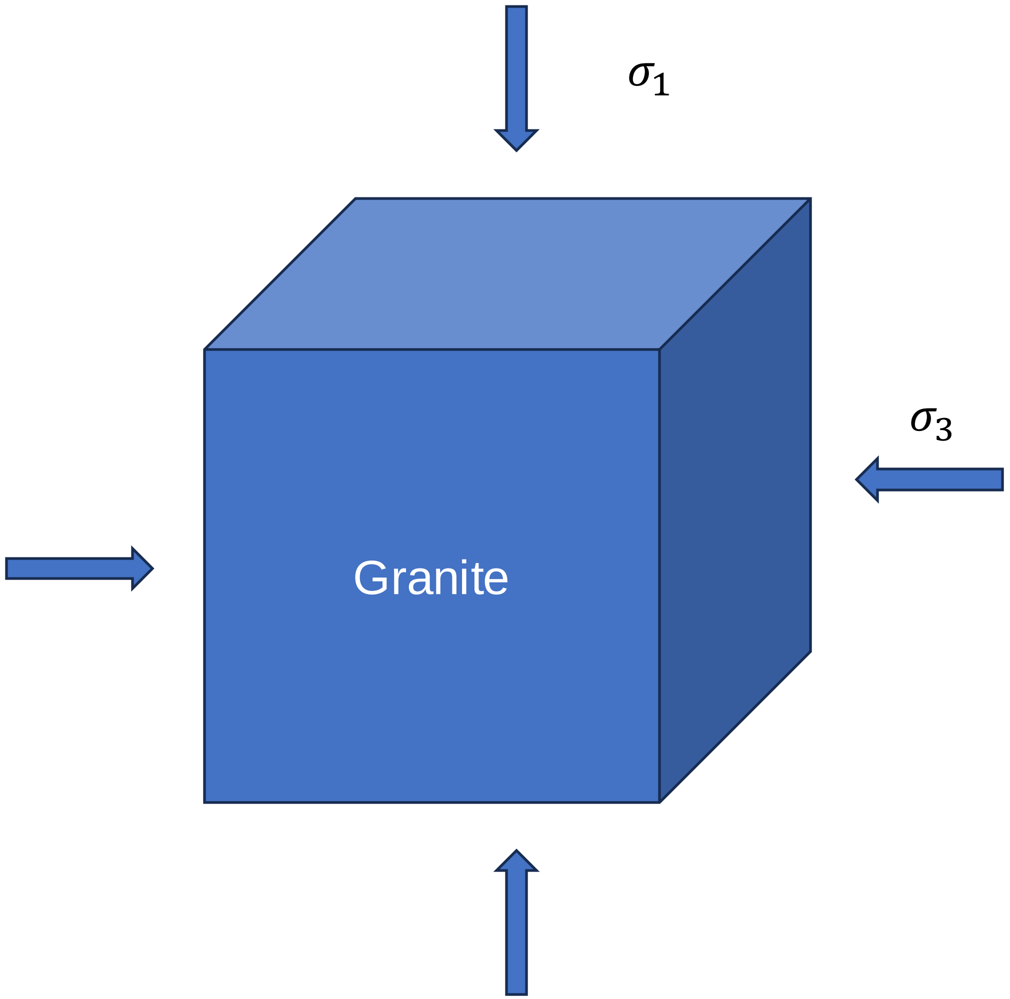

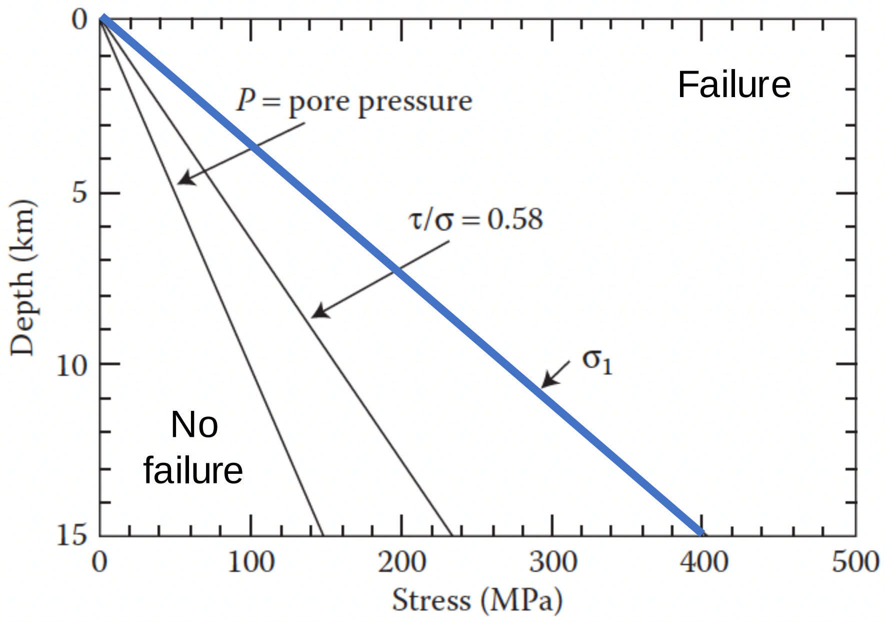

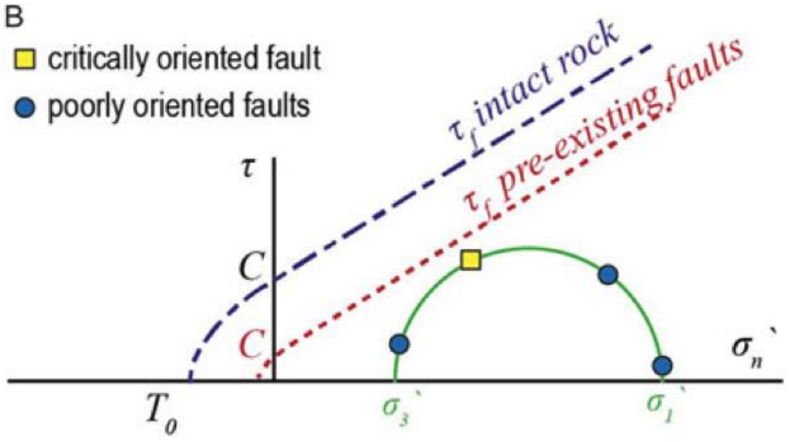

Shear stress, normal stress, and frictional properties

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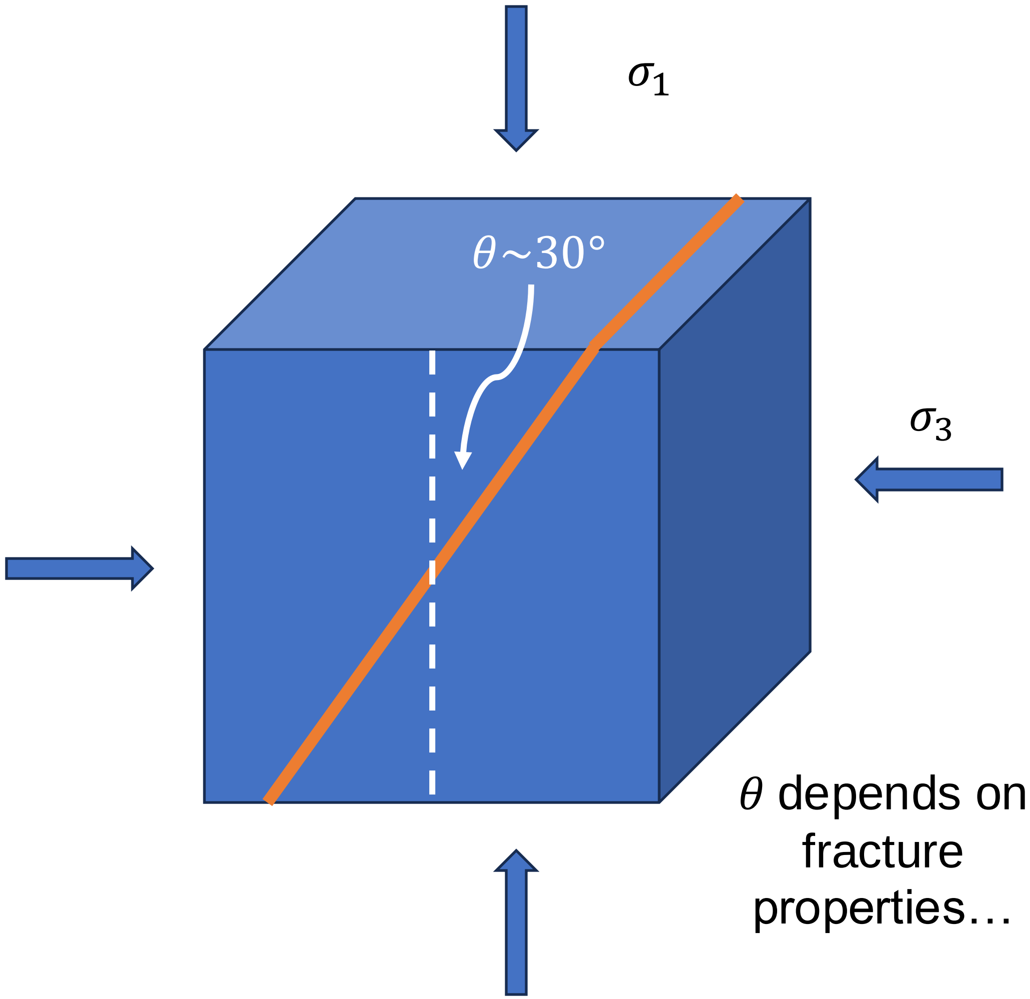
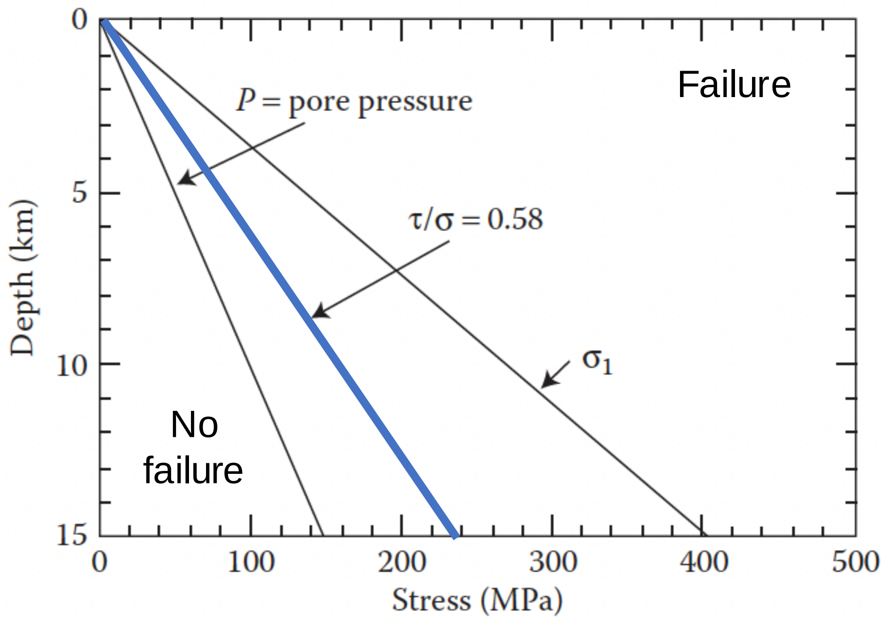
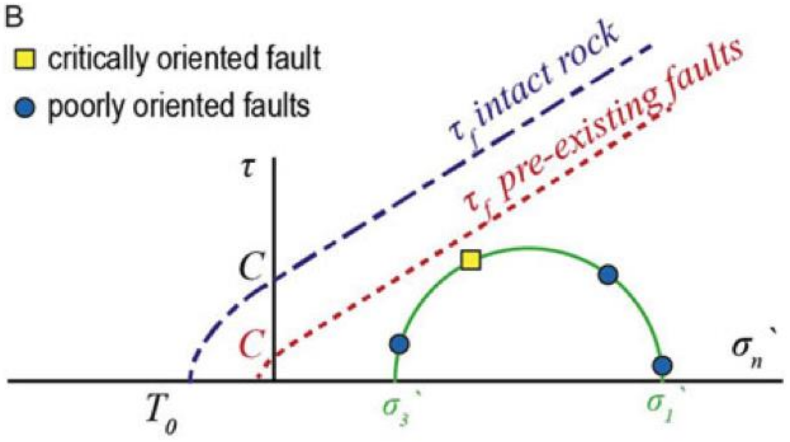


θ depends on fracture properties…





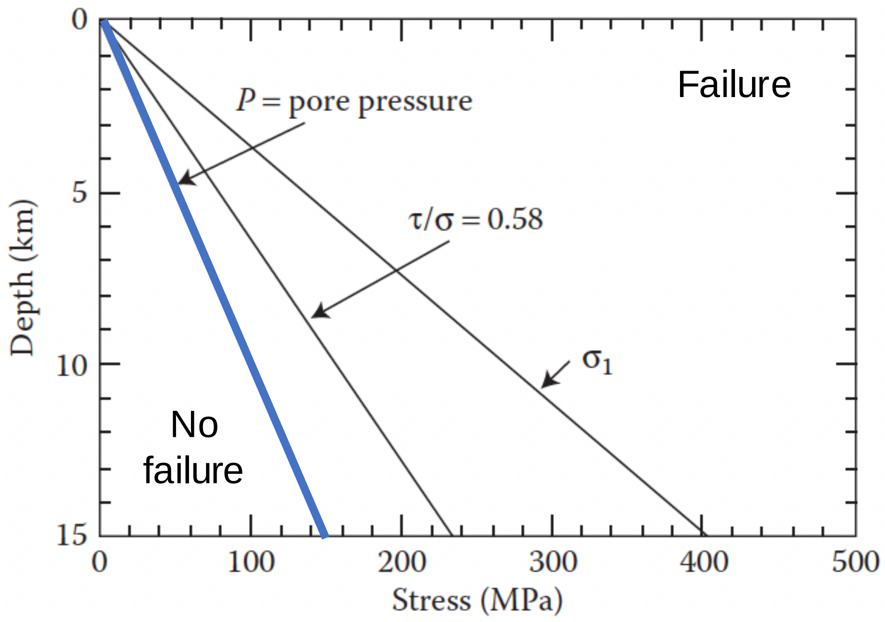
Pore fluid pressure

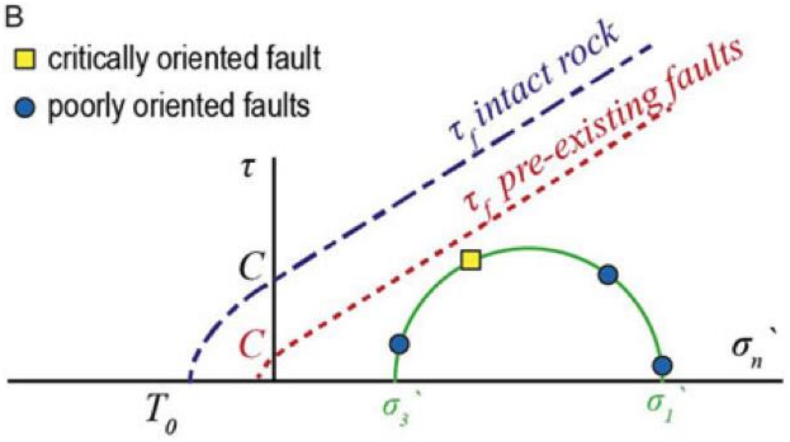
Pore fluid pressure acts against confining pressure, reducing the effective normal stress acting on the plane:

$$\sigma_n^{effective} = \sigma_n - P_p$$

Where

P_p is the pore fluid pressure





Induced seismicity

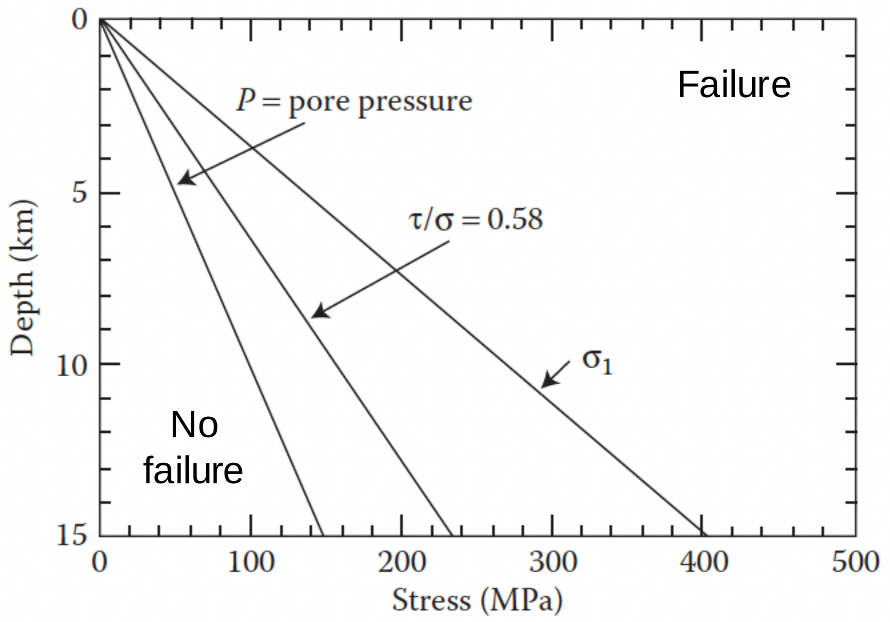
Predicting seismicity is difficult.

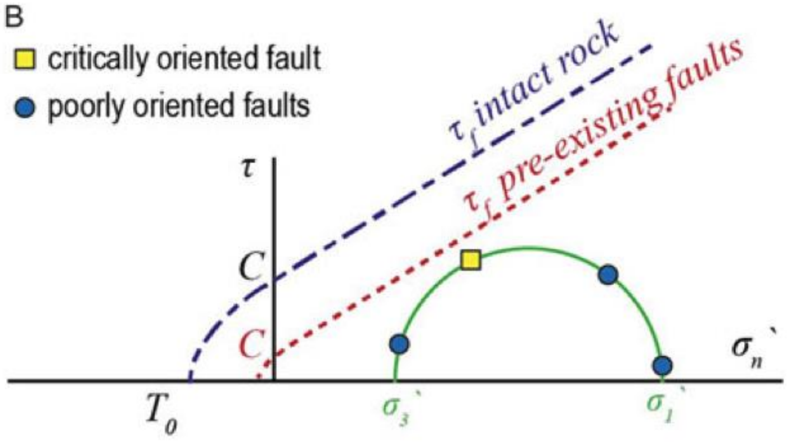
Need to know:

The properties of the rock matrix.

The condition of the fractures at depth.

The local stress field.





Seismicity: Cold water injection

Most minerals expand when heated and contract when cooled.

The extent of expansion depends on mineral structure.

Volumetric coefficient of thermal expansion:

$$\alpha_V = \frac{\Delta V / V_0}{\Delta T}$$

Where

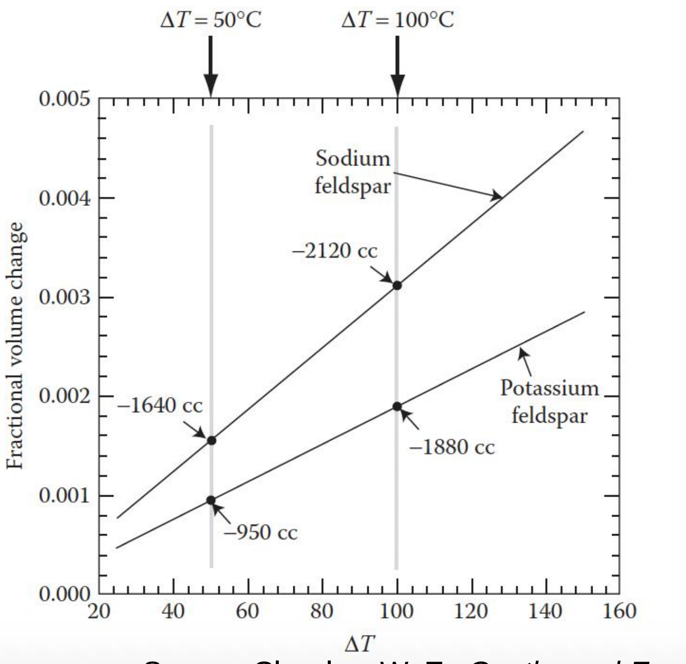
ΔV is the change in volume with respect to some reference volume V_0

ΔT is the change in temperature

TABLE 15.2
Coefficients of Thermal Expansion for Feldspar Minerals

Minerals	α (T^{-1})	Reference Volume (Å^3)
Microcline[a]	1.86×10^{-5}	722.02
Sanidine[b]	1.92×10^{-5}	723.66
Low albite[a]	3.07×10^{-5}	664.79
High albite[c]	3.15×10^{-5}	666.98

Sources: [a] Hovis and Graeme-Barber 1997
[b] Hovis et al. 1999
[c] Stewart and von Limbach 1967.



Source: Glassley, W. E., *Geothermal Energy*

Seismicity: Cold water injection

Volume changes are small, but sufficient to cause microseismicity:

Cause existing fractures to grow and create new micro-fractures.

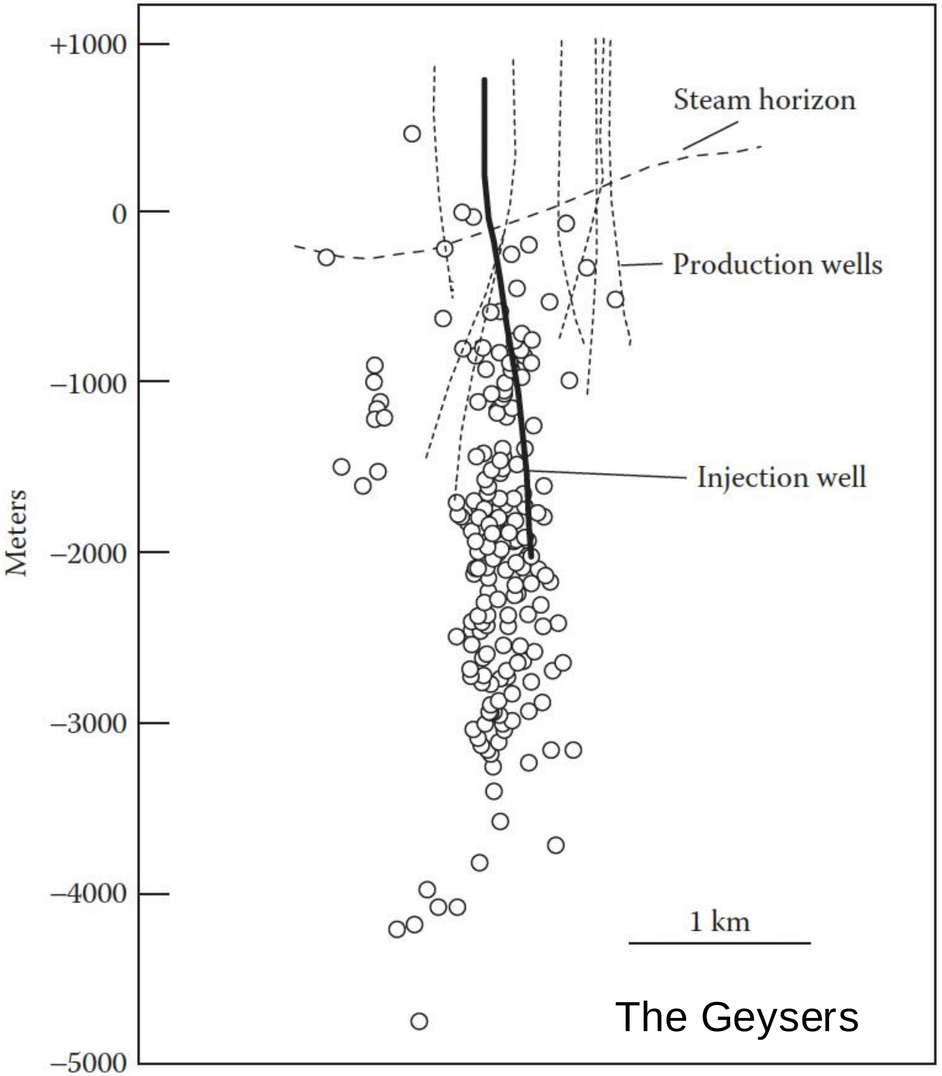
The Geysers:

Distribution of microsesimic events recorded in November 2007.

Related to fluid injections at well 42B-33 (labelled injection well).

Injected fluid was more than 100°C colder than the reservoir.

In general, the magnitude of cold fluid injection microseismic events is limited to 2.5.



Source: Glassley, W. E., *Geothermal Energy*

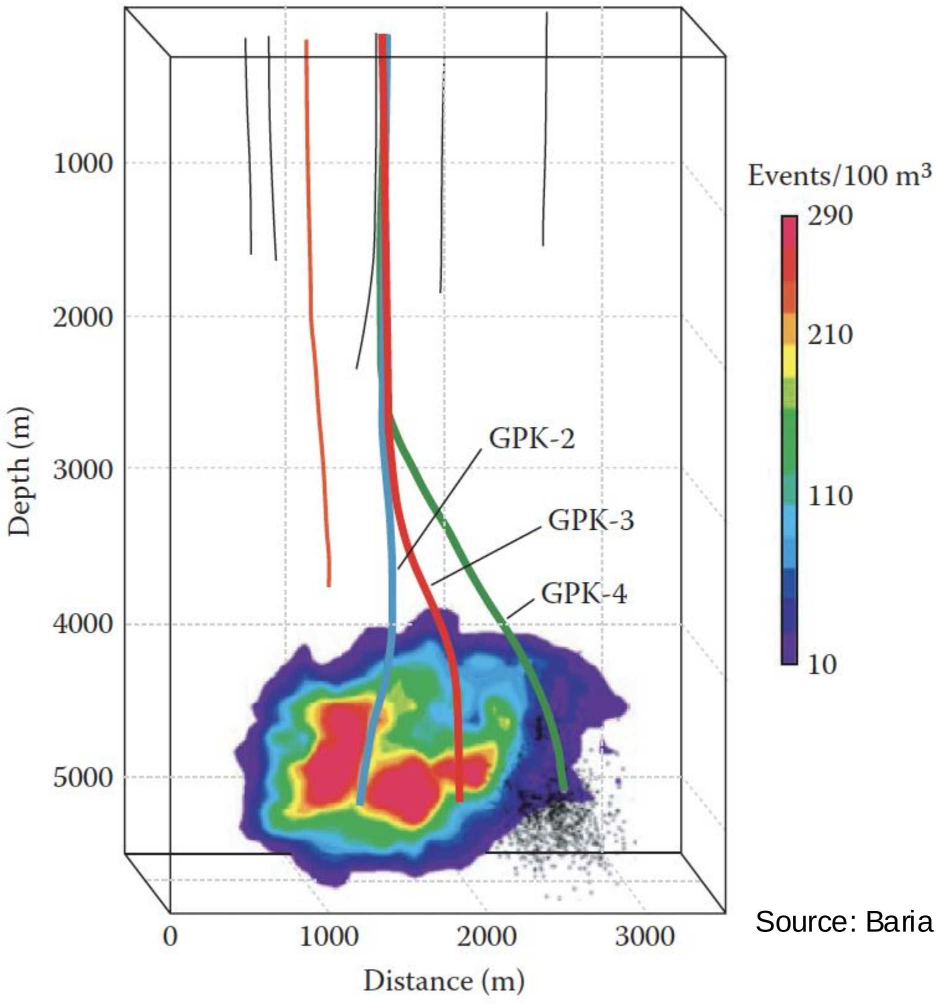
Seismicity: High-pressure fluid injection

Typical injection pressures: 20 to 200 MPa.

Either new fractures are formed or pre-existing, optimally oriented fractures are reactivated.

Fluid injection reduces normal stress, allowing the system to exceed the frictional strength of pre-existing fractures.

Rupture area is typically 100s to 1000s of m^2.



Source: Baria et al., 2006

Seismicity: High-pressure fluid injection

Number of sesimic events associated with stimulation of the crystalline rock reservoir at Soultz-sous-Forets.

Stimulation was carried out from 2000 to 2004.

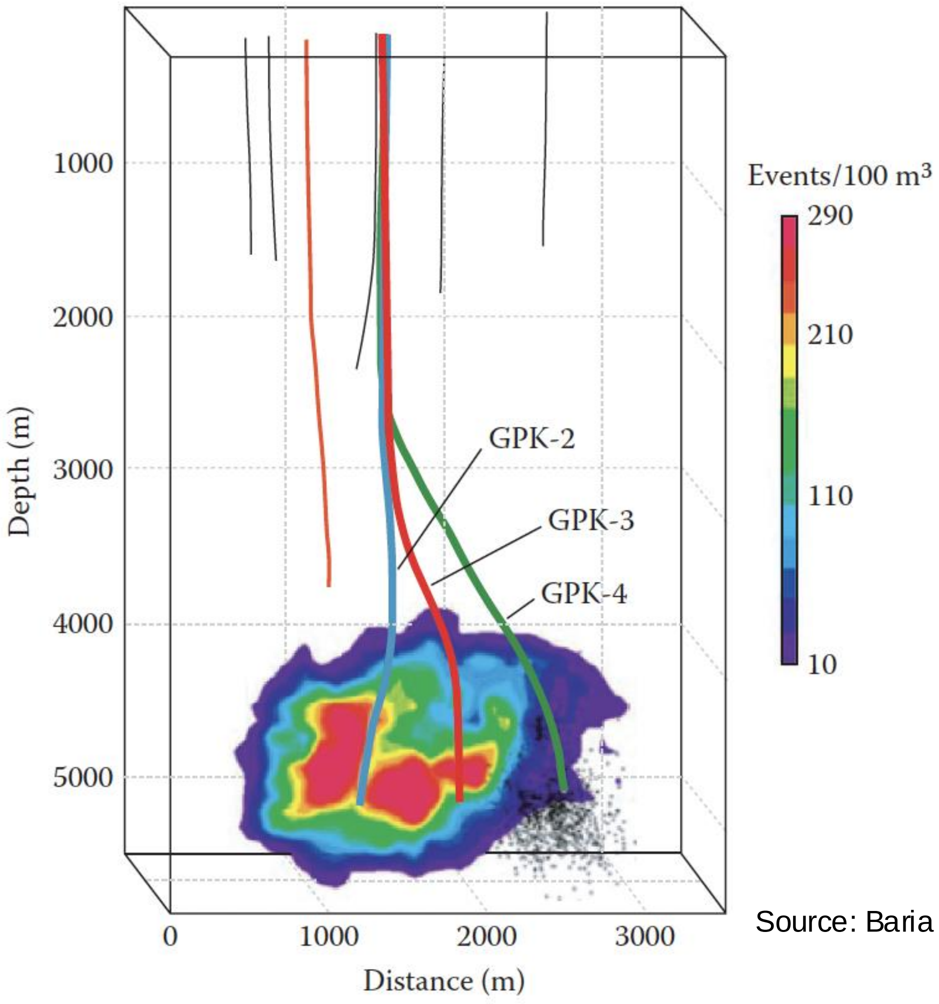
2 perdiods of hydro-fracturing carried out on GPK-1 and GPK-3.

Dots are hydro-fracturing on GPK-4

Density map encloses tens of thousands of seismic events.

Strongest magnitudes: 2.6 and 2.9.

Most events had magnitudes less than 2.0.



Source: Baria et al., 2006

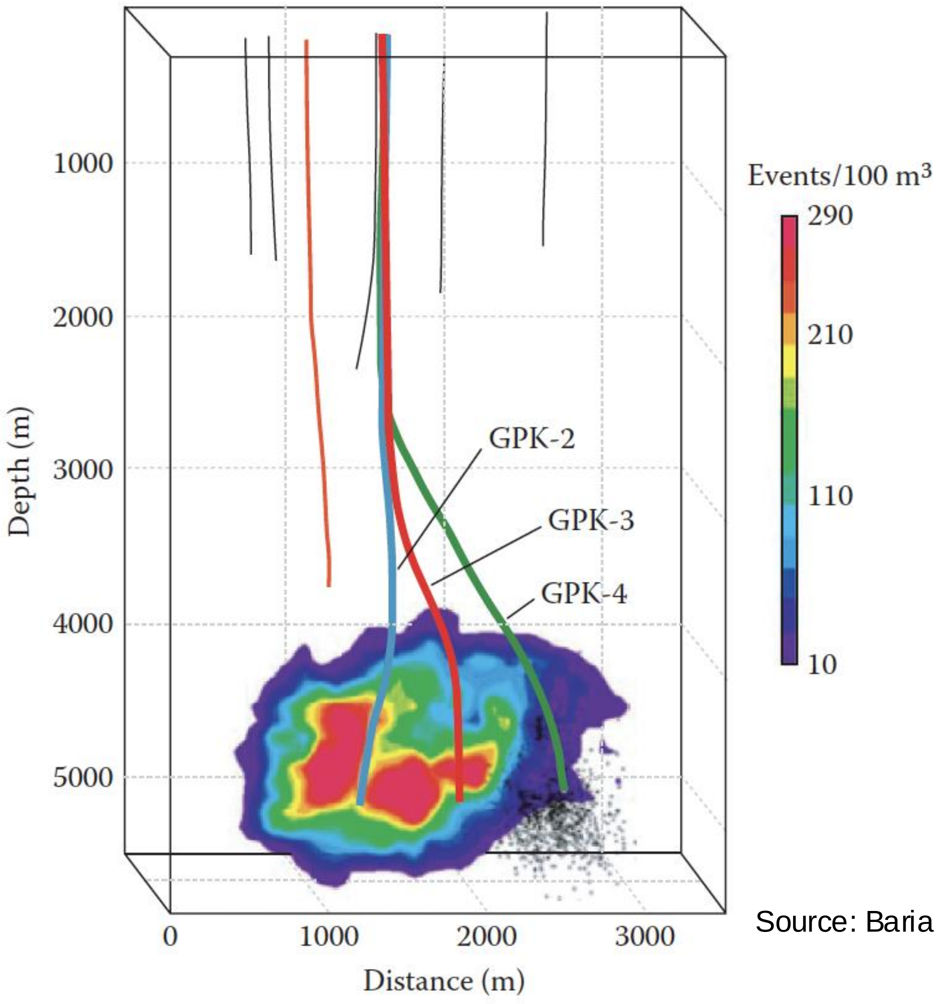
Seismicity: High-pressure fluid injection

Basel, 2006: 3.4M seismic event.

No structural damage reported.

Event occured several hours after injection was stopped.

***Post shut-in* seismic events.**



Source: Baria et al., 2006

Seismic mitigation

Seismicity resulting from reservoir stimulation cannot be fully avoided.

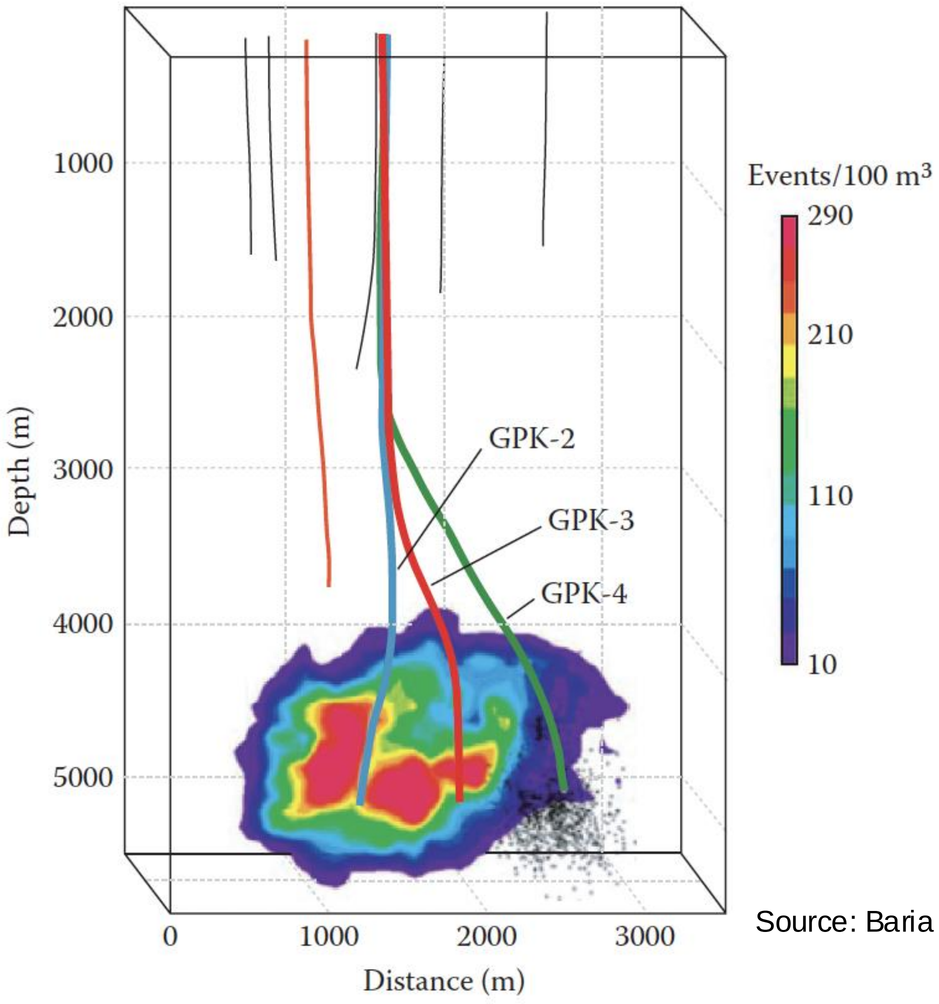
To understand induced seismicity:

Understand the local geology and stress state.

Monitor microseismic response to changes in injection rate, injection volume, and injection presures.

Create guidelines stimulation that minimize sesismic risk.

Consult with local communities!



Source: Baria et al., 2006

Reservoir management and sustainability

Reservoir management and sustainability

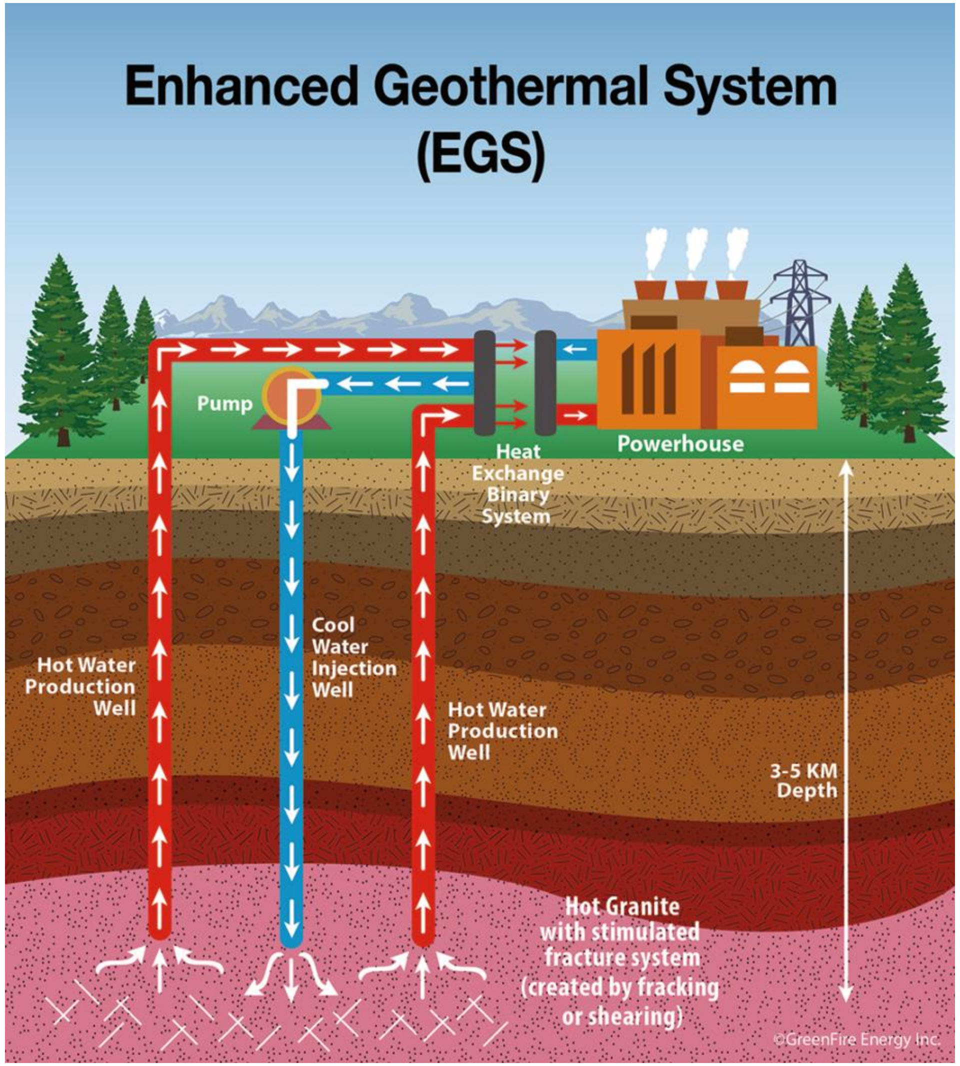
EGS often turns a conductive system into a convective system.

This artificial convective system will remove heat faster than it can be replenished by conduction:

We begin to deplete the heat available in our reservoir.

Realistic modelling of the heat budget of a reservoir needs to take into account fluid flow, chemical reactions, and heat transfer in complex, 3D fracture networks, etc.

But we can also approximate the behaviour of these systems…



Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Reservoir management and sustainability

The time needed to propogate a tempearture decrease of 1°C (1K) from an injection well to a production well can be approximated (modified from Gringarten and Sauty, 1975):

$$\boldsymbol{T_b = \frac{\pi \times \gamma_r \times d^2 \times t}{3 \times \gamma_f \times v}}$$

Where

γ_r is the heat capacity of the reservoir (J/m^{3}K)

γ_f is the heat capacity of the fluid (J/m^{3}K)

d is the distance between the wells (m)

t is reservoir thickness (m)

v is the flow rate (m^3/h)

Reservoir management and sustainability

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Consider a theoretical reservoir:

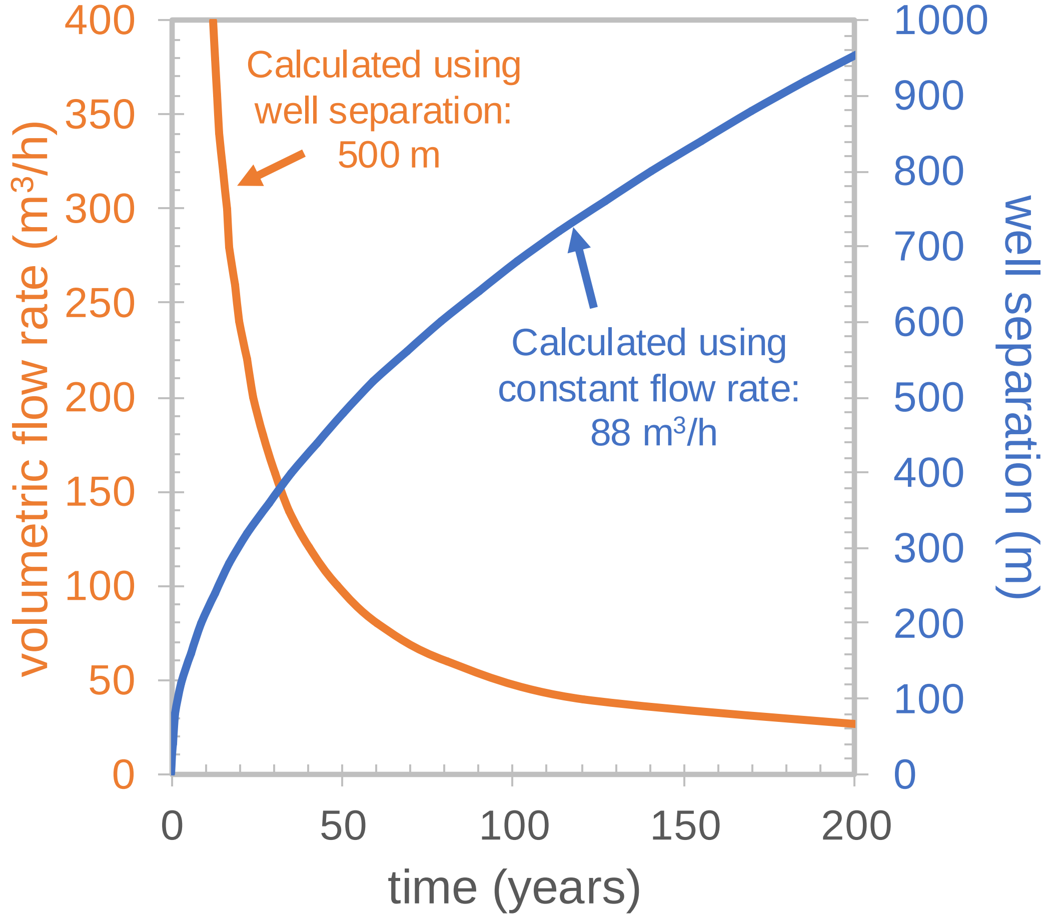
Reservoir porosity: 0.001

Heat capacity of the rock: 2.7×10^6 J/m^{3}K

Heat capacity of the fluid: 4.18×10^6 J/m^{3}K

Reservoir thickness: 25 m

Time needed to achieve a 10°C temperature drop



Reservoir management and sustainability

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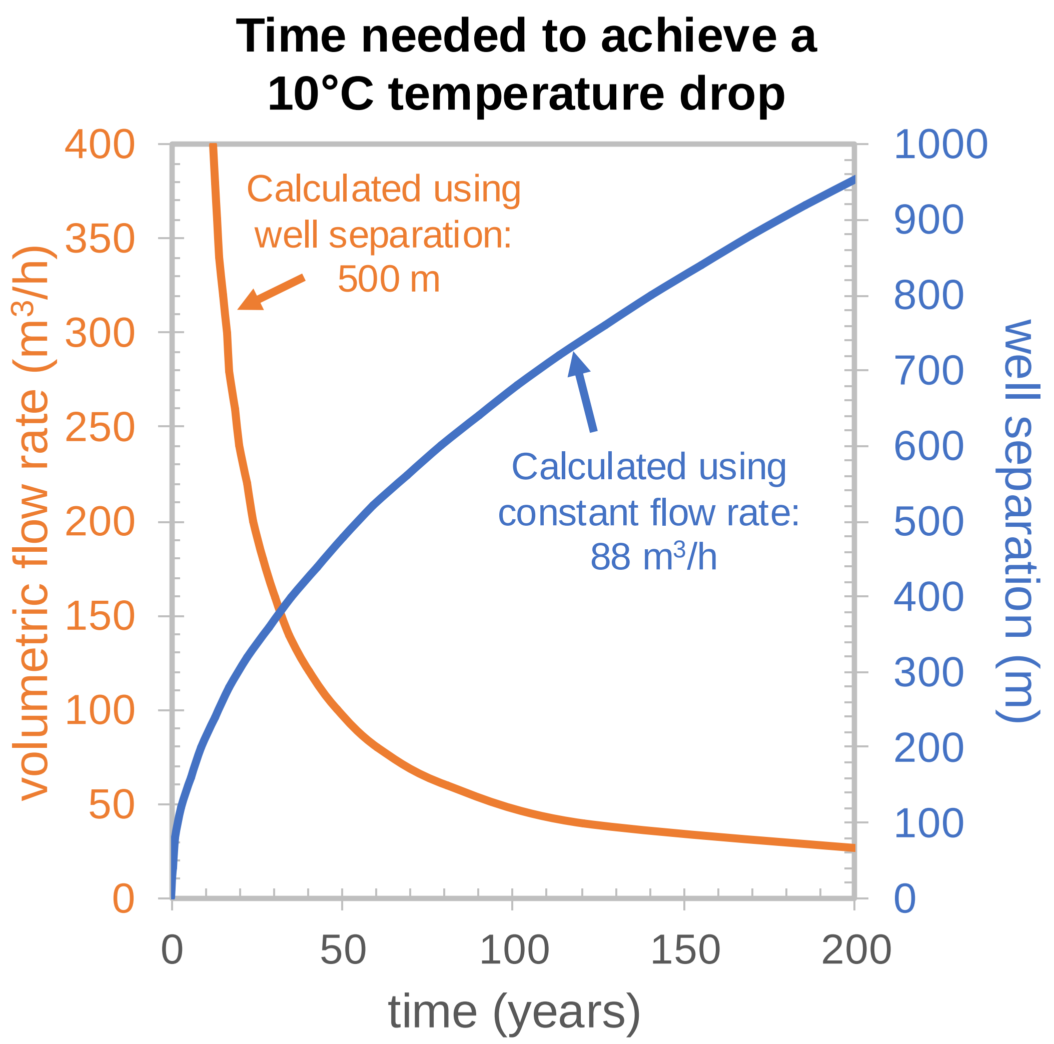
Does not take into account:

Temperature dependence of thermal conductivity

Flow geometry

Exposed surface area along flow path

Local heat flow



Reservoir management and sustainability

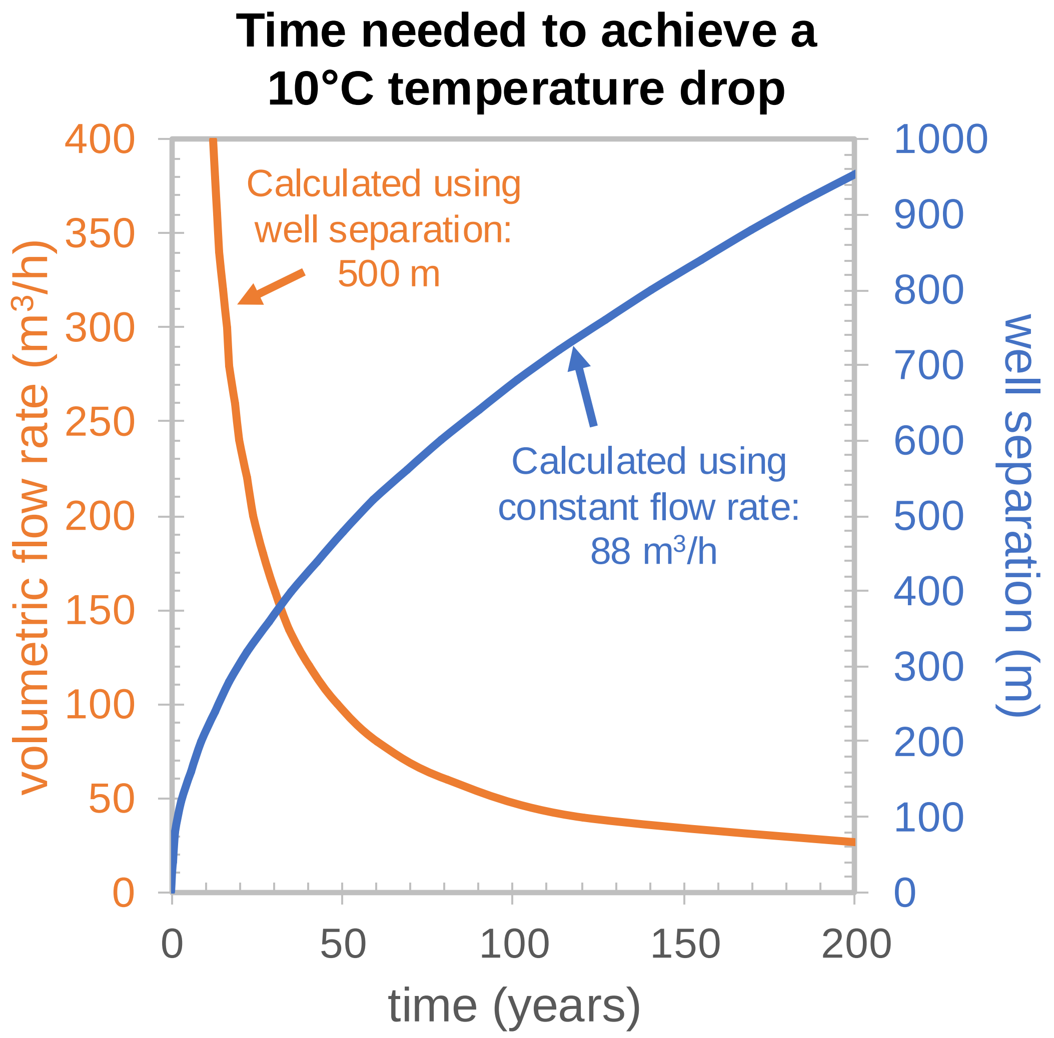
Pritchett (1998) and Tester et al. (2006):

To replenish 90% of the heat in an EGS-stimulated region would take approximately 3 times the operational period.

2 scenarios:

Use the resource for 30 years, abandon the system for 100 years, then restart operations.

Drill deviated wells to increase reservoir volume, and exploit portions of the reservoir at a time (rotating portions over time).



Key points:

Resources of 250°C generally occur between 3 and 10 km depth.

Resource access is difficult: permeabilities (and circulating fluids) at these depths may not be high enough to support heat extraction.

Enhanced Geothermal Systems (EGS): Geothermal rservoirs that require some degree of reservoir engineering to create and sustain reservoir permeability over the lifespan of the resource.

Rule of thumb: Stimulated zone with a volume of a few km^3, with a fracture network able to sustain flow rates of 50 kg/s for about 30 years.

Location of stimulated zone needs to be sufficiently well know to target production well locations.

Flow rates need to be adjusted for the permeability of the reservoir.

Reservoir stimulation inevitably causes induced seismicity: Careful reservoir engineering planning can help mitigate the magnitude of these events.