Course description

Week 1 (September 10): Introduction / Heat production in the Earth

Week 2 (September 17): Thermodynamics recap

Week 3 (September 24): Subsurface fluid flow

Week 4 (October 1): Geochemistry – **Assignment 1 due**

Week 5 (October 8): Exploration methods: Geochemistry

Week 6 (October 15): Exploration methods: Geophysics – **Assignment 2 due**

Mid-term break (October 22)

Week 7 (October 29): Resource assessment / Generating power using geothermal

Week 8 (November 5): Generating power using geothermal

Week 9 (November 12): Direct-use

Week 10 (November 19): Enhanced Geothermal Systems – **Assignment 3 due**

Week 11 (Novemer 26): Environment, Societal, and Economic considerations

Week 12 (December 3): Oral exam preparation

Week 13 (December 10): Oral exam preparation – Assignment 4 due

Week 14 (December 1): Oral exam

*Lectures subject to some change, based on course progress.

(gen)AI and teaching

EPFL guidelines:

Should students make use of AI in their assignments, they are expected to acknowledge it explicitly and to apply critical thinking (particularly with respect to sources, potential biases, and data sharing).

AI should be used responsibly as a tool to support learning, rather than as a substitute for students' own work.

Exam format and important dates

26 November 2025, 15h:

Groups of 3, picked at random.

Each group will be given 1 scientific article (approx. 15 pages long) on one of the key topics of the course.

3 December 2025:

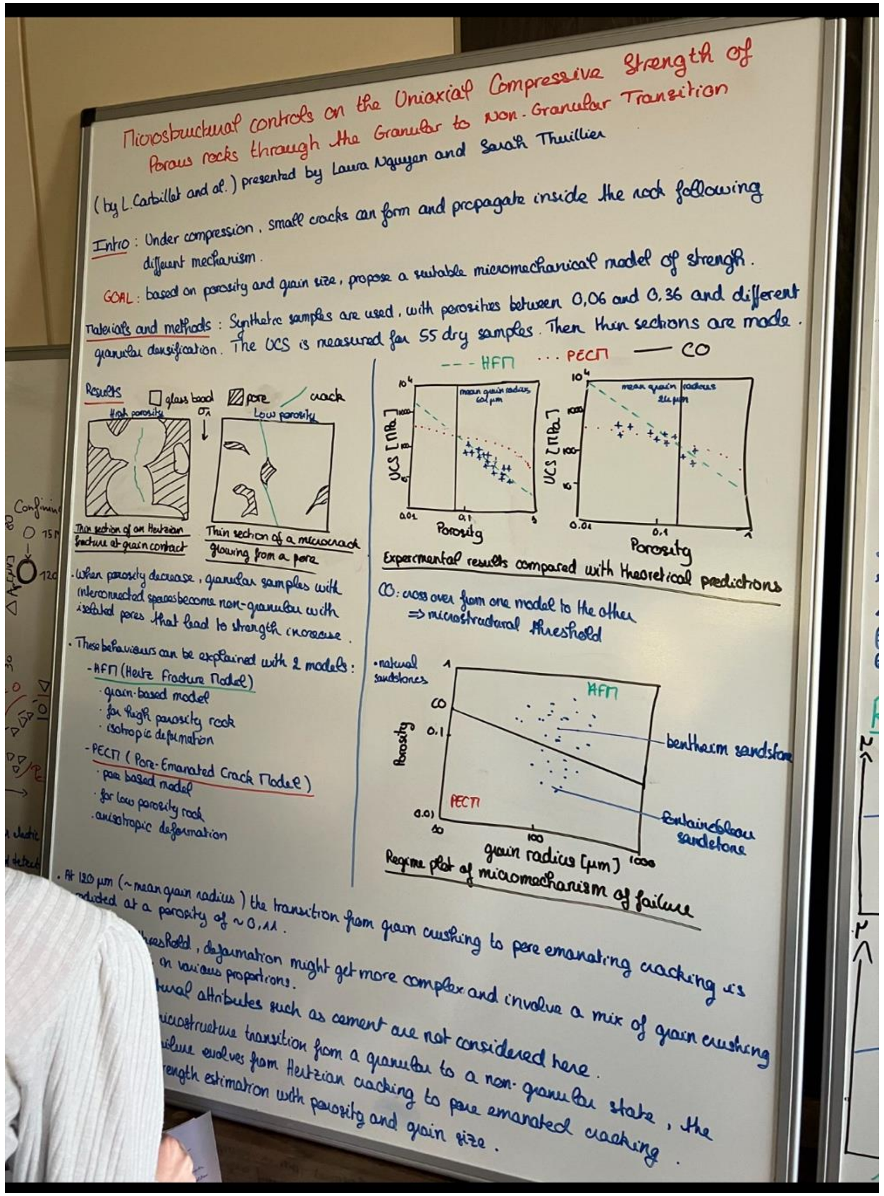
Group preparation.

10 December 2025:

Each group will make a poster summary of the article on a whiteboard.

17 December 2025:

Each group presents their poster to the whole class: 10 minutes presentation, 5-10 minutes questions.



Microstructural controls on the Uniaxial Compressive Strength of Porous rocks through the Granular to Non-Granular Transition

(by L. Carbillet and al.) presented by Laura Nguyen and Sarah Thuillier

Intro: Under compression, small cracks can form and propagate inside the rock following different mechanism.

GOAL: based on porosity and grain size, propose a suitable micromechanical model of strength.

Materials and methods: Synthetic samples are used, with porosities between 0,06 and 0,36 and different granular densification. The UCS is measured for 55 dry samples. Then thin sections are made.

Results

- When porosity decrease, granular samples with interconnected spaces become non-granular with isolated pores that lead to strength increase.
- These behaviours can be explained with 2 models:
  - HFM (Hertz Fracture Model)
    - grain-based model
    - for high porosity rock
    - isotropic deformation
  - PECM (Pore-Emanated Crack Model)
    - pore based model
    - for low porosity rock
    - anisotropic deformation

Experimental results compared with theoretical predictions

CO: cross over from one model to the other
⇒ microstructural threshold

Regime plot of micromechanism of failure

- At 120 µm (~mean grain radius) the transition from grain crushing to pore emanating cracking is
edicted at a porosity of ~0,11.
hreshold, deformation might get more complex and involve a mix of grain crushing
on various proportions.
tural attributes such as cement are not considered here.
icrostructure transition from a granular to a non-granular state, the
ilure evolves from Hertzian cracking to pore emanated cracking.
rength estimation with porosity and grain size.

Geothermal Resource Development

Enhanced Geothermal Systems

Topics covered today...

1. Concept of Enhanced Geothermal Systems
2. Reservoir engineering
3. Reservoir management and sustainability

Concept of Enhanced Geothermal Systems

Viability of geothermal resources

Four conditions for geothermal resource power production:

Existence of **sufficient heat.**

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

Availability of **sufficient fluid for heat transfer.**

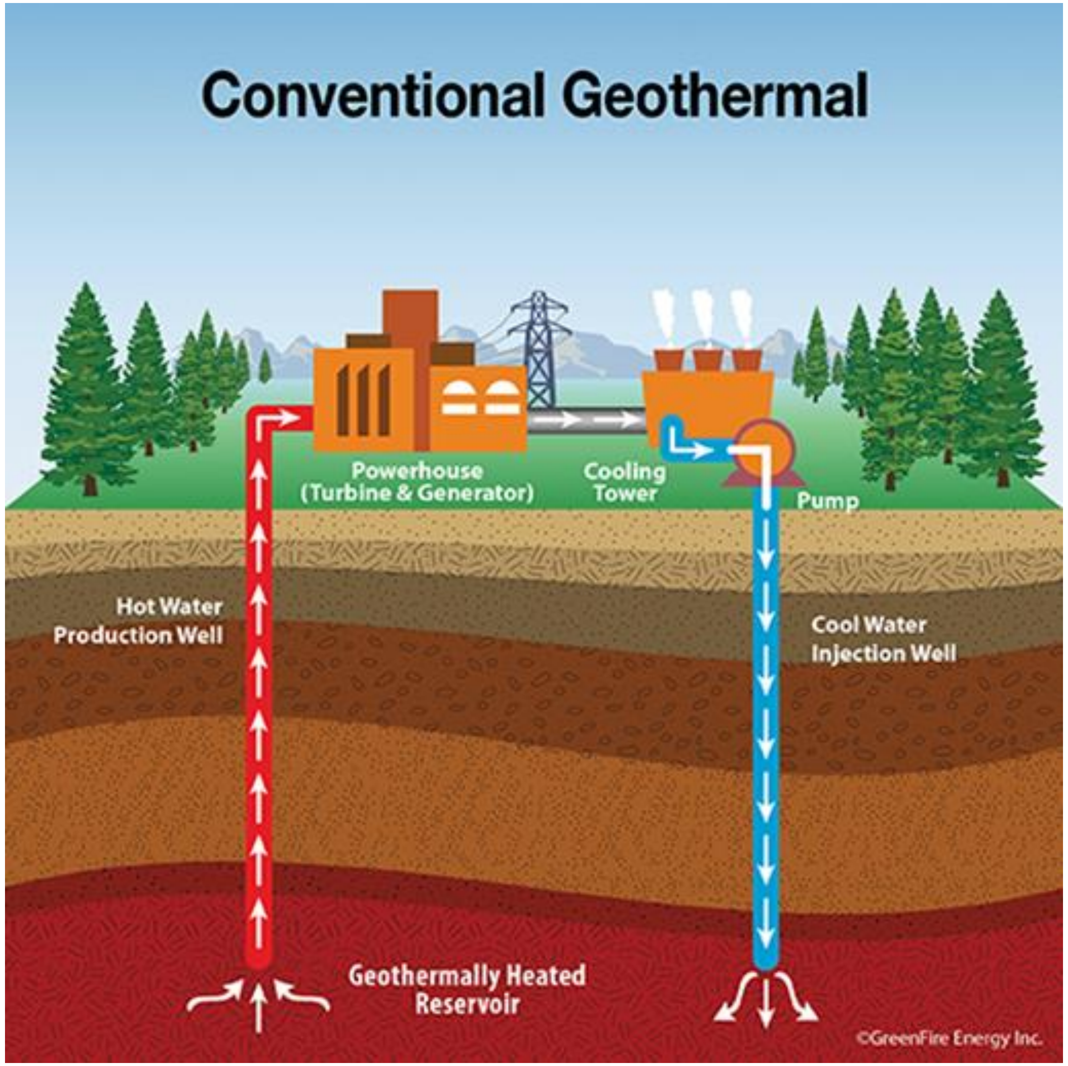
(Commonly water, but brine, seawater, CO_2 can be used.)

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

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

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

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



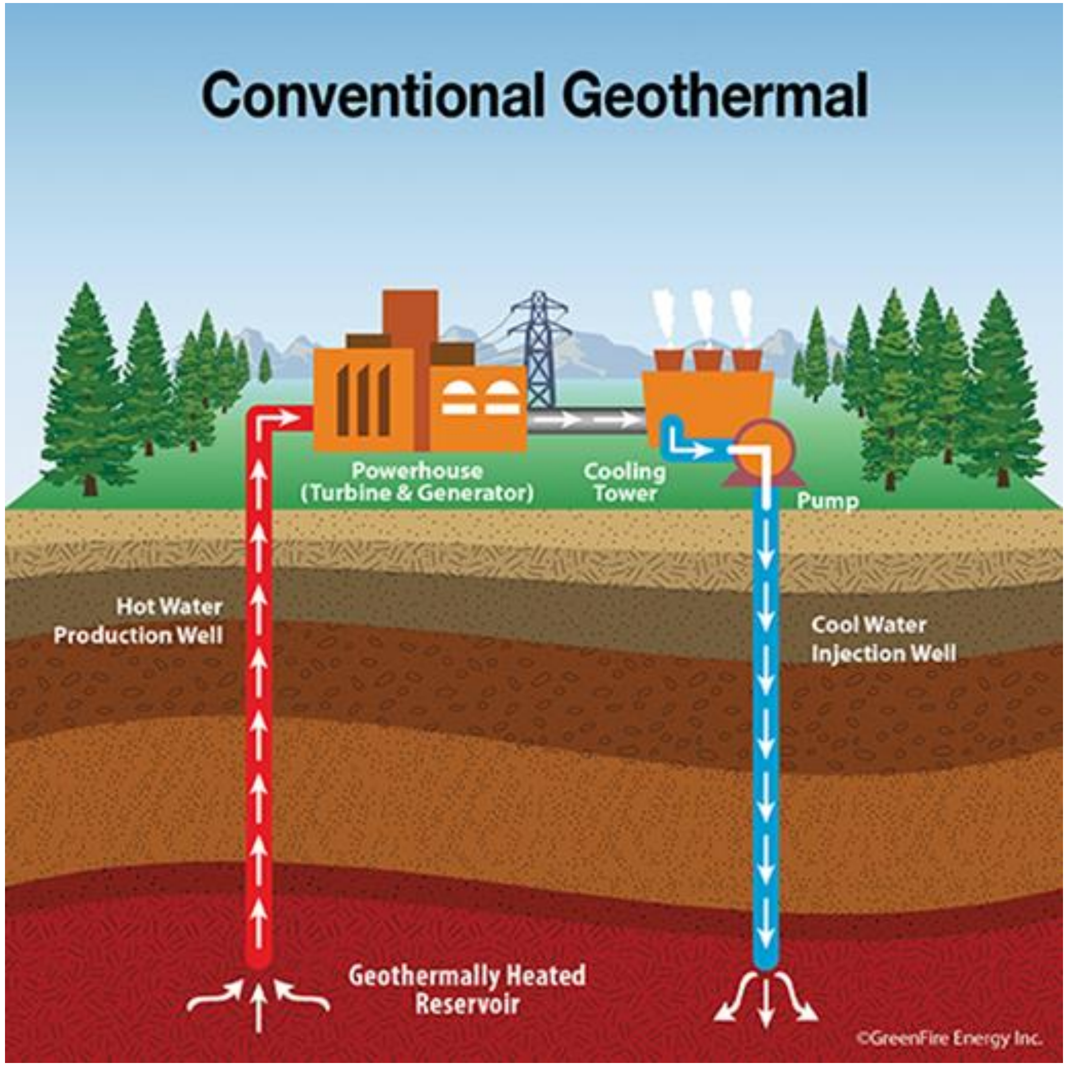
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

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?



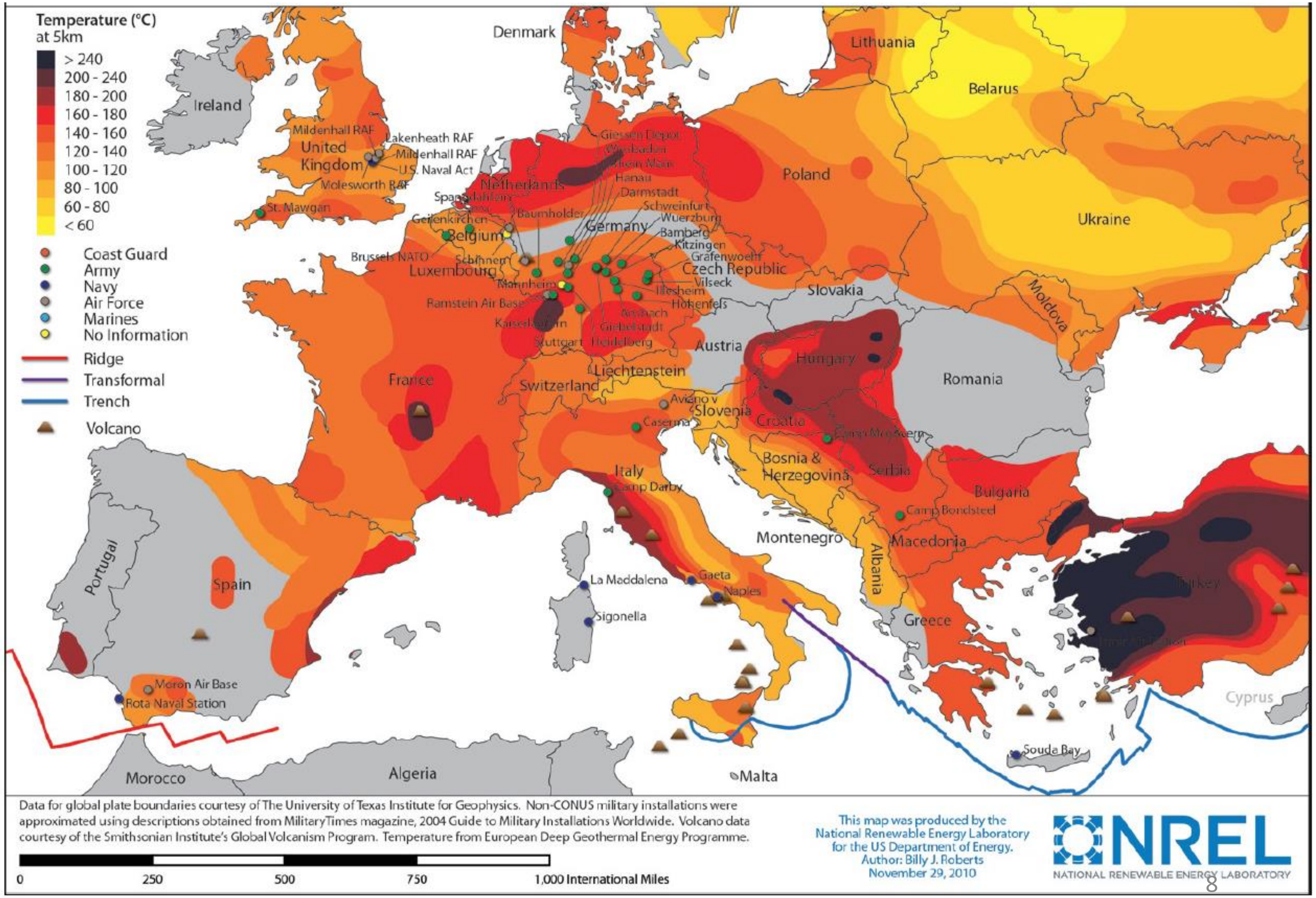
Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

Viability of geothermal resources

Heat map figure made by:
Scattered measurements of geothermal gradient, surface heat flow, thermal conductivities, thickness of rock units.

Heterogeneous heat distribution:
Tectonically controlled.

Italy: volcanic regions
Upper Rhine Graben: crustal thinning



Data for global plate boundaries courtesy of The University of Texas Institute for Geophysics. Non-CONUS military installations were approximated using descriptions obtained from MilitaryTimes magazine, 2004 Guide to Military Installations Worldwide. Volcano data courtesy of the Smithsonian Institute's Global Volcanism Program. Temperature from European Deep Geothermal Energy Programme.

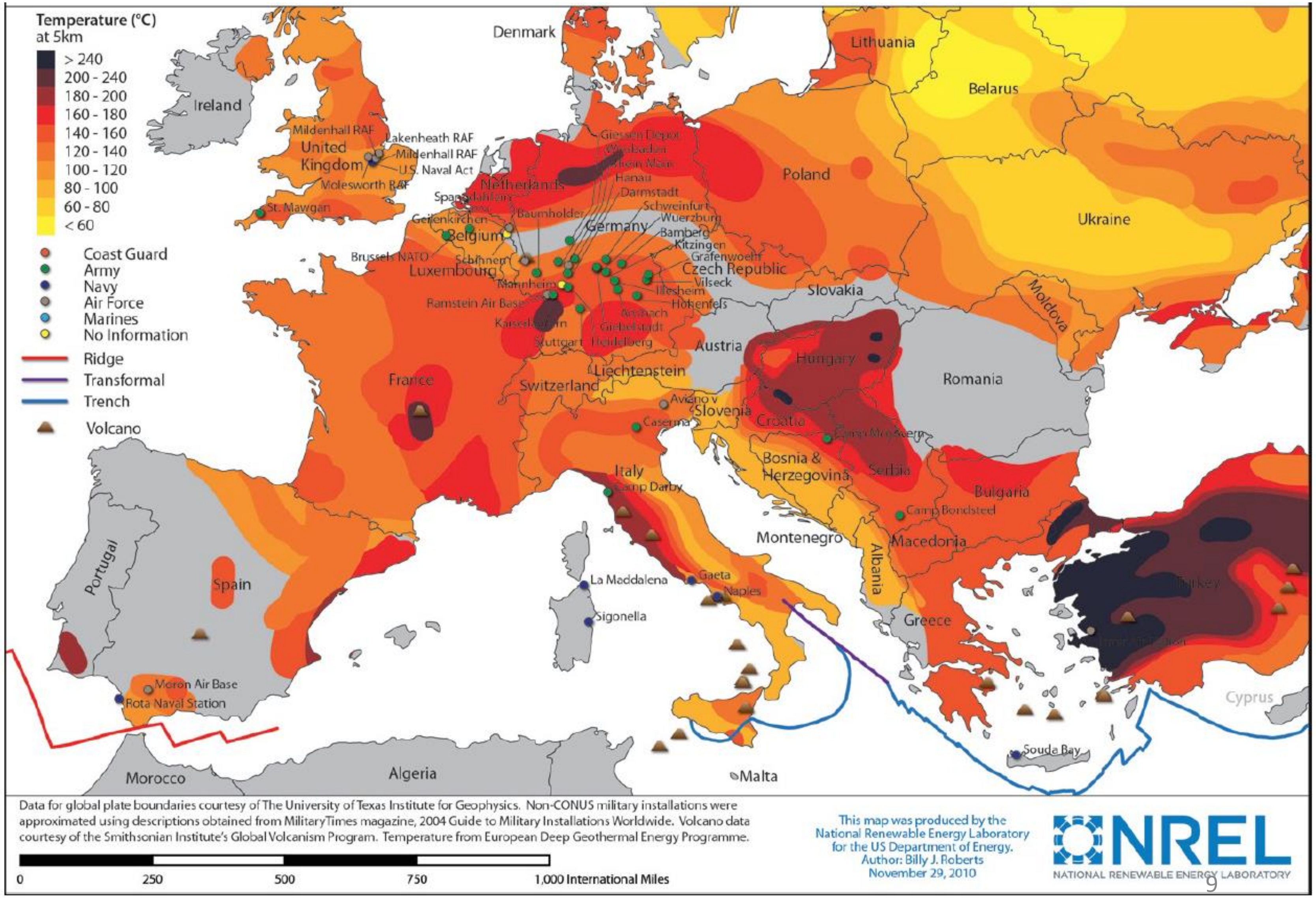
This map was produced by the National Renewable Energy Laboratory for the US Department of Energy.
Author: Billy J. Roberts
November 29, 2010

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?



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Enhanced Geothermal Systems

Heat transfer in geothermal reservoirs:

Convection and conduction

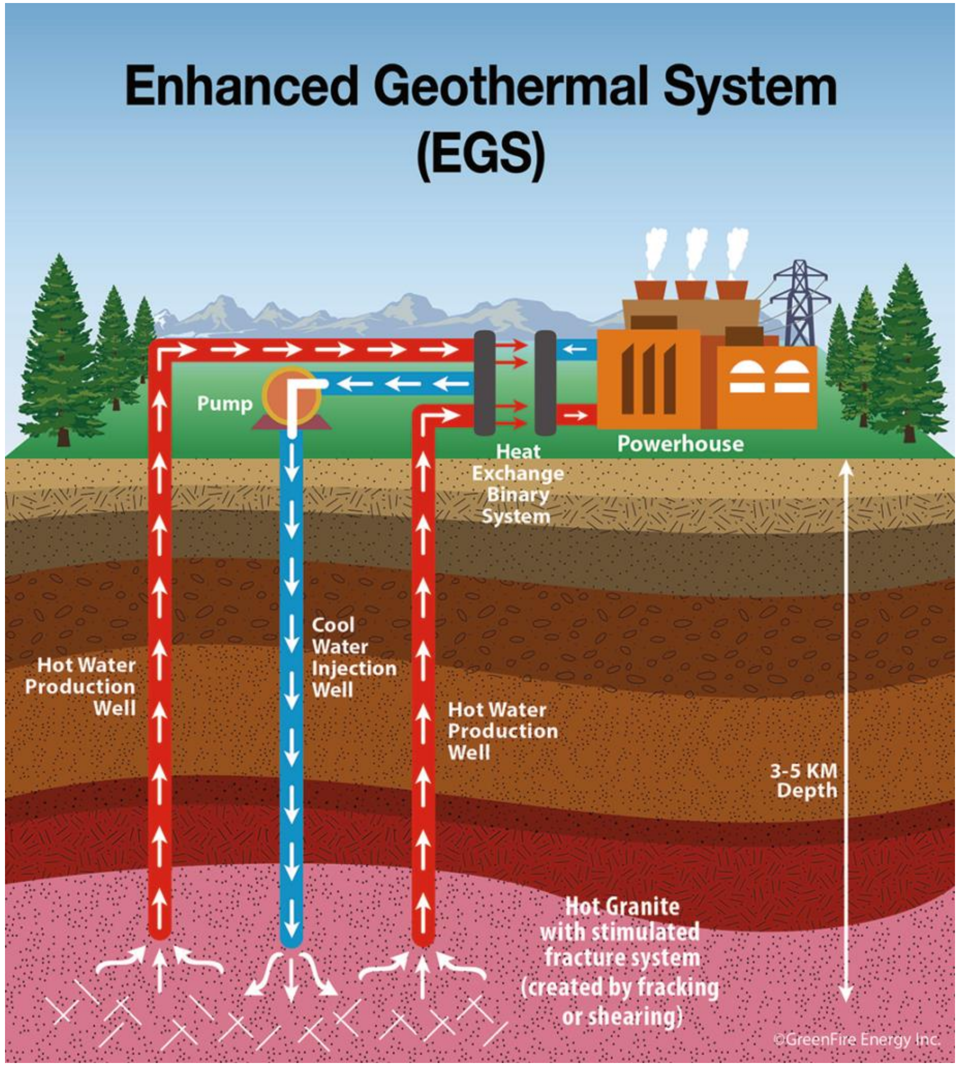
The dominant heat transfer mechanisms reflect the **local geological and hydrological properties** of the site.

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/

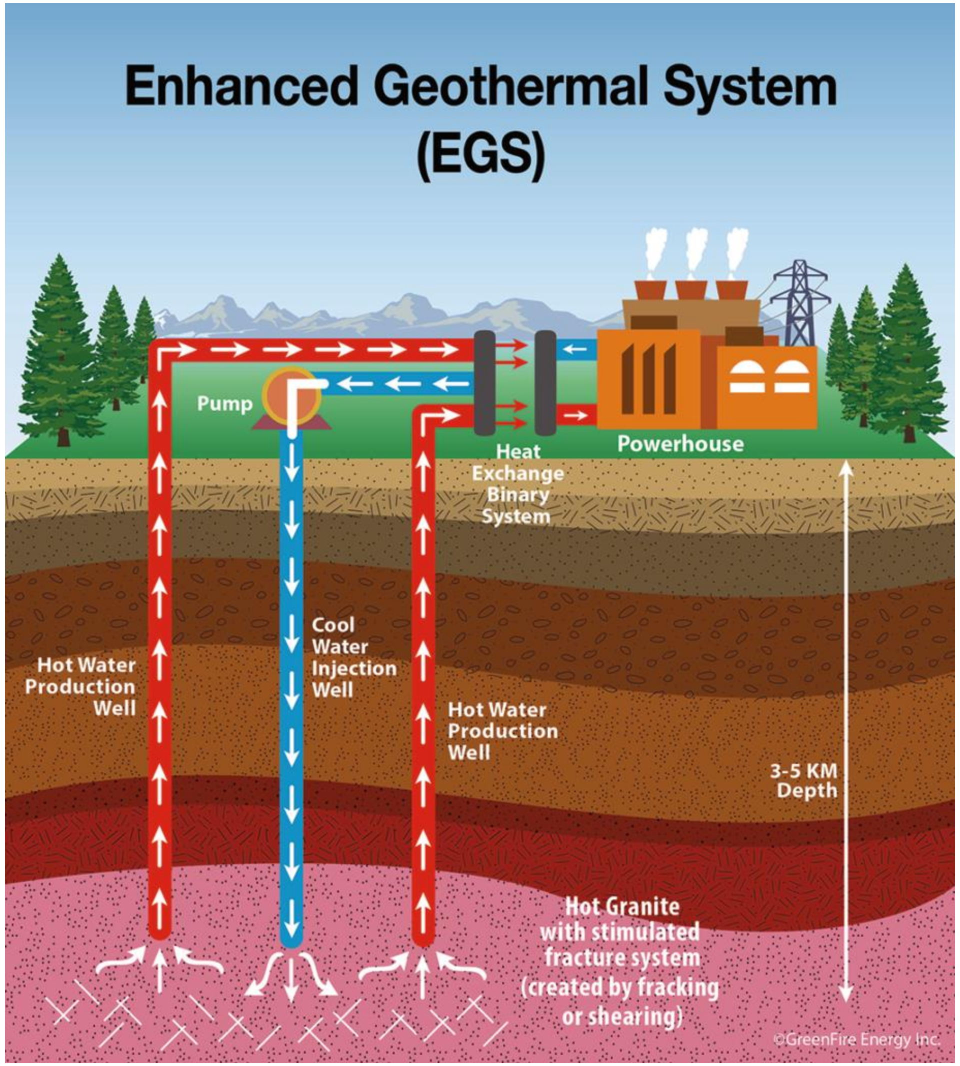
Enhanced Geothermal Systems

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

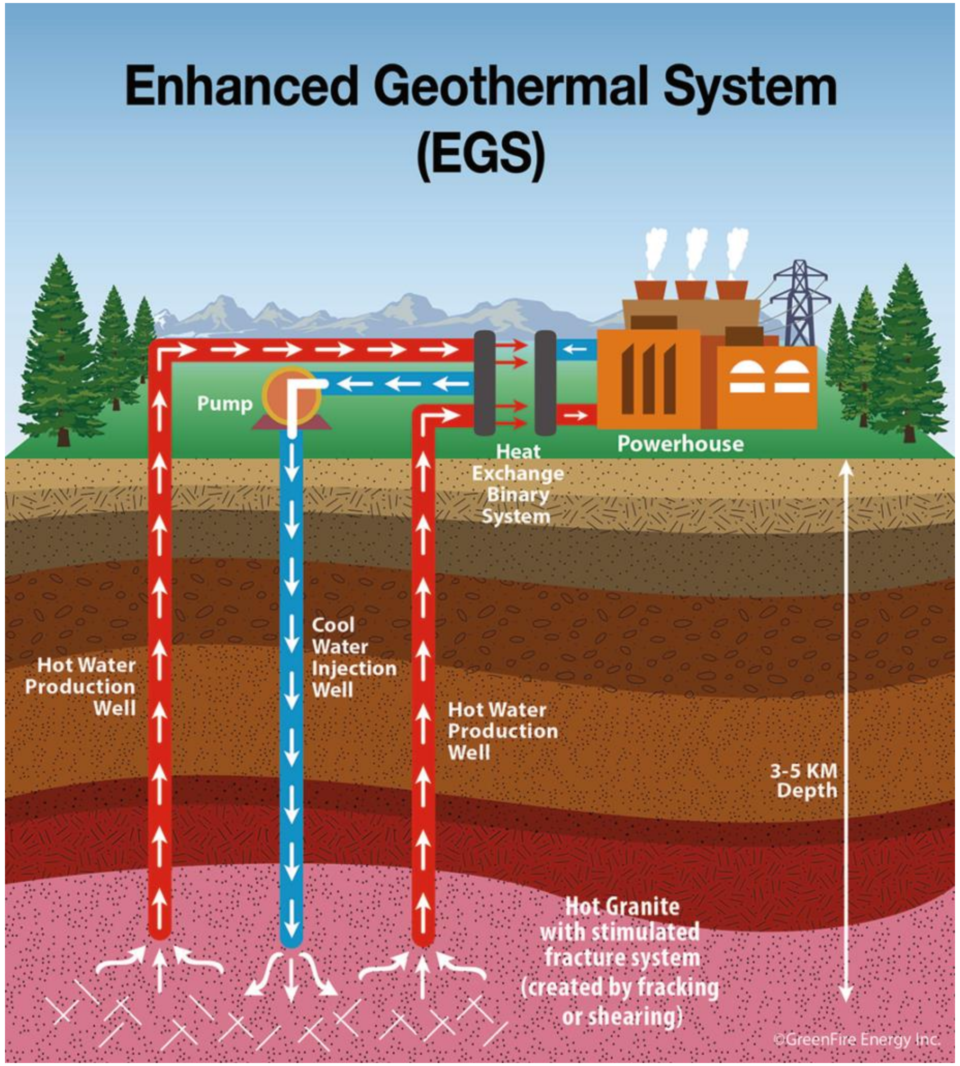
Design lifetime 20-30 years.

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.

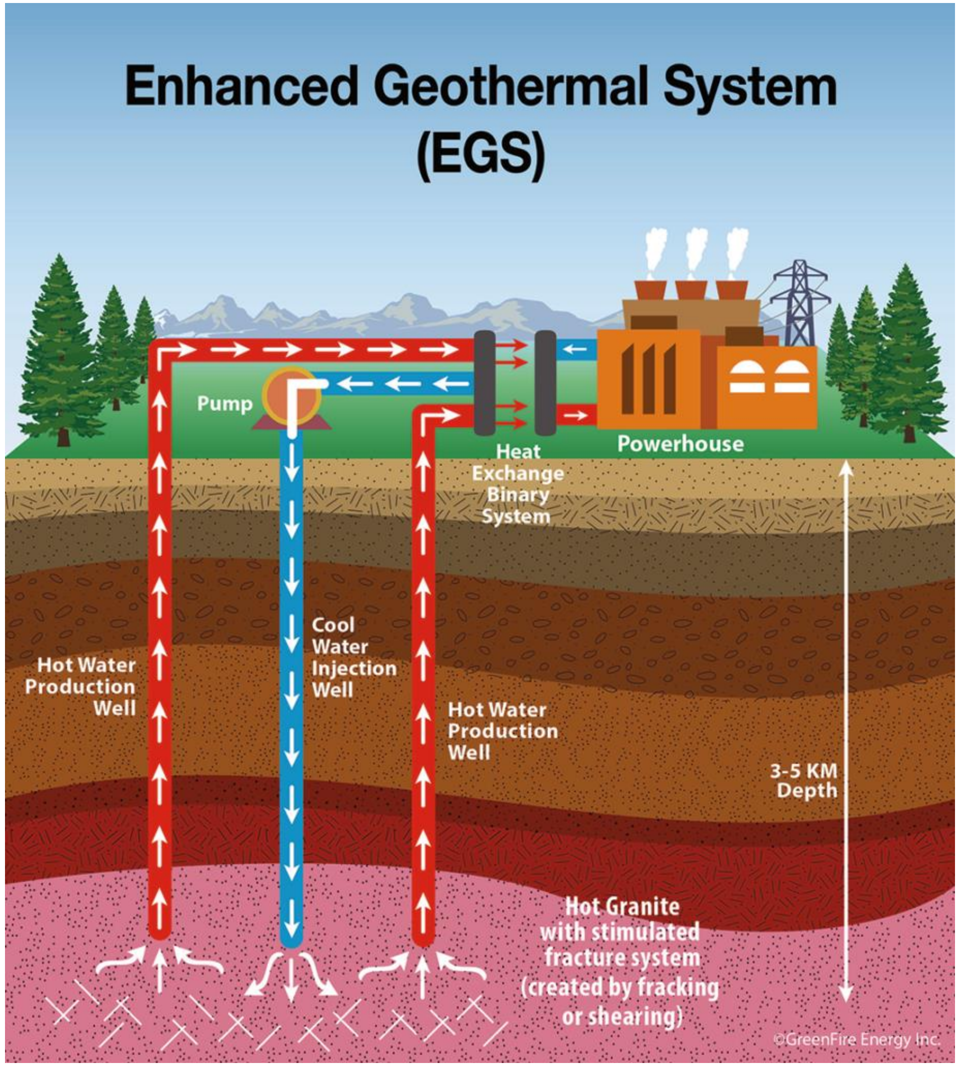


Source: https://www.greenfireenergy.com/geothermal-energy/how-does-geothermal-energy-work/

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



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

Reservoir stimulation

Reservoir stimulation

Create / maintain permeability over the lifetime of the resource.

Hydro-shearing (hydraulic stimulation):

Activate existing fractures without inducing new fractures.

Hydro-fracturing:

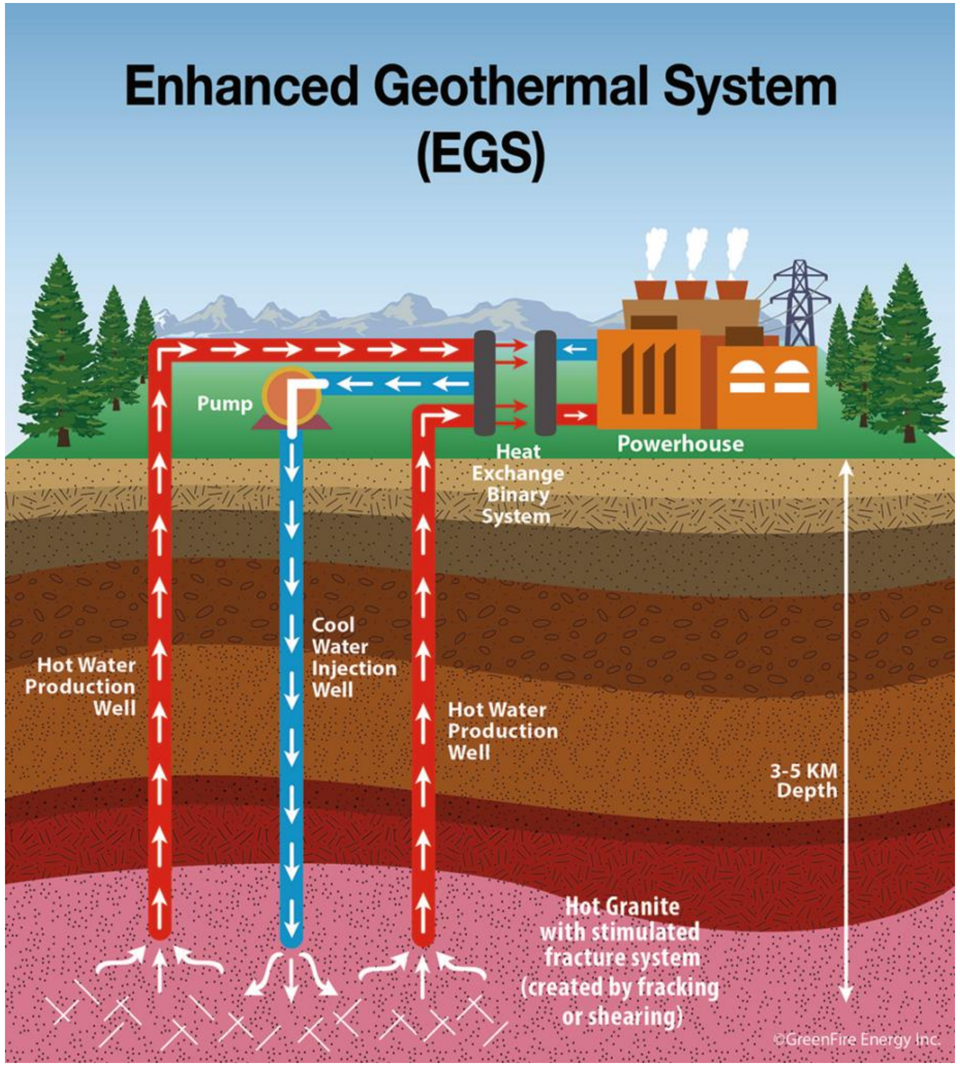
Induce new fractures in impermeable rock in order to create fracture permeability.

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

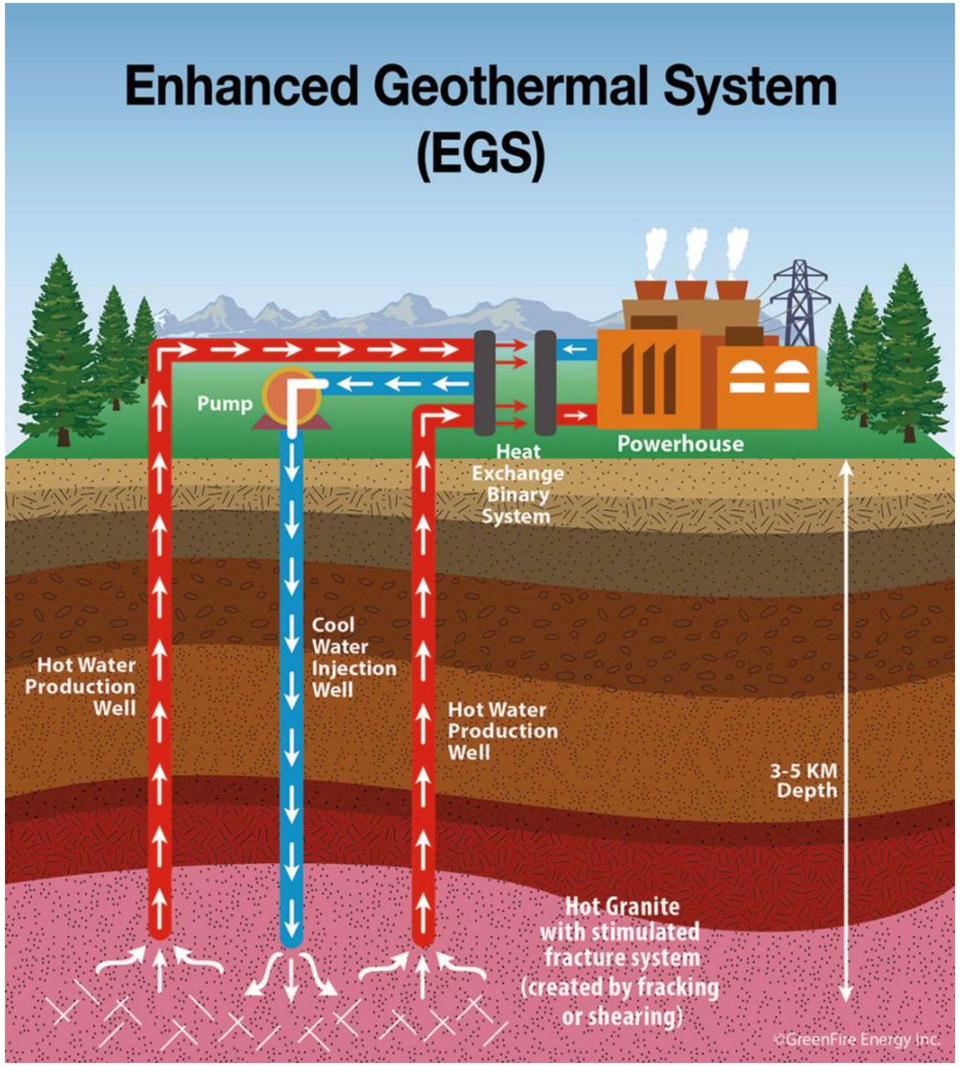
Things to keep in mind when stimulating a reservoir:

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

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

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

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):

For a 5 MW power plant, with resource temperature of 200–250°C and mass flow rates of 50 kg/s.

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

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

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

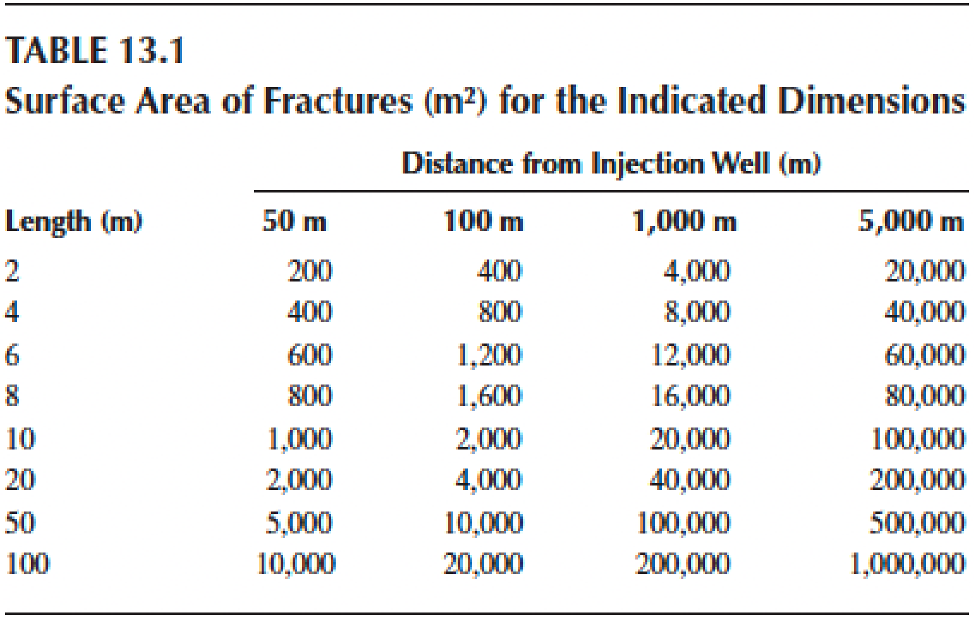


TABLE 13.1

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*

Stimulated reservoir volume

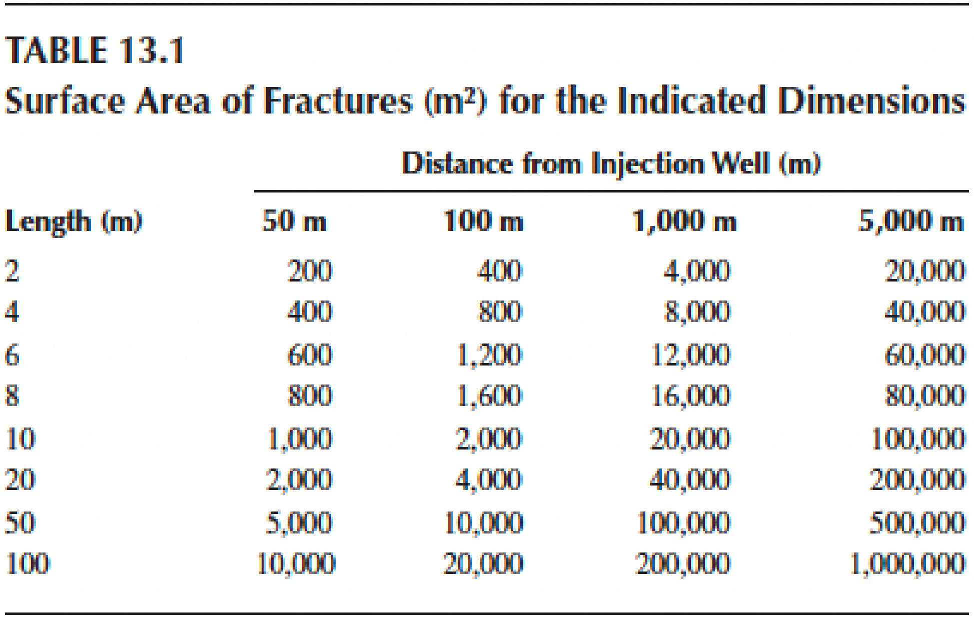
Fractures propogate in specific directions.

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.



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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

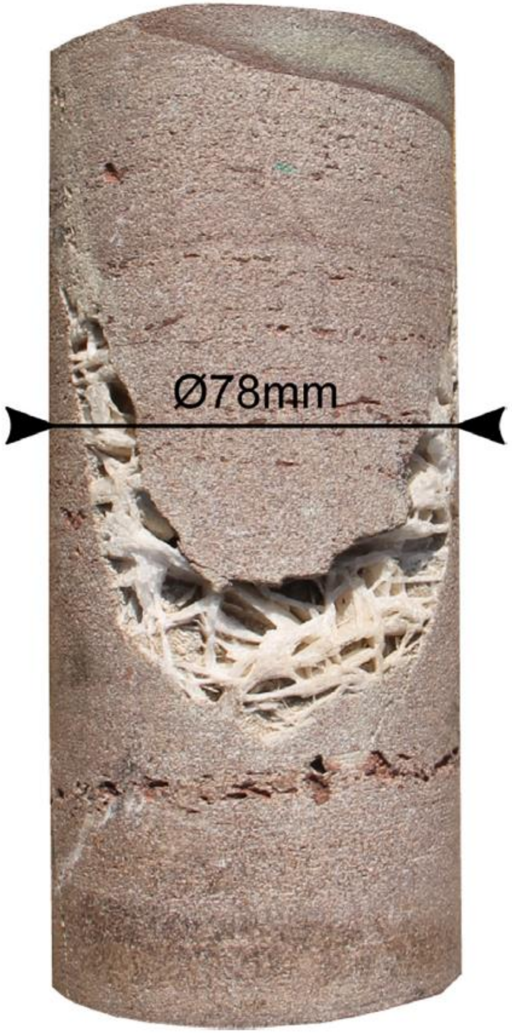
Fractures are approximately planes and are weaker than interwoven minerals in rocks.

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:

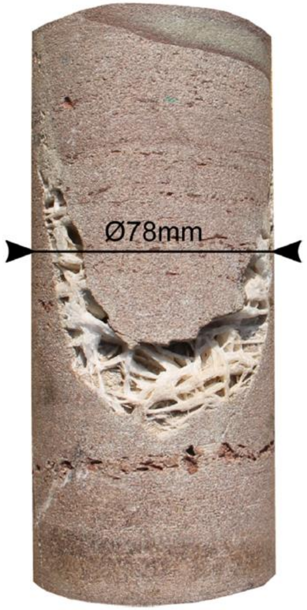
$$\sigma_n = \frac{(\sigma_1 + \sigma_3)}{2} + \frac{(\sigma_1 - \sigma_3)}{2} \times \cos 2\theta$$

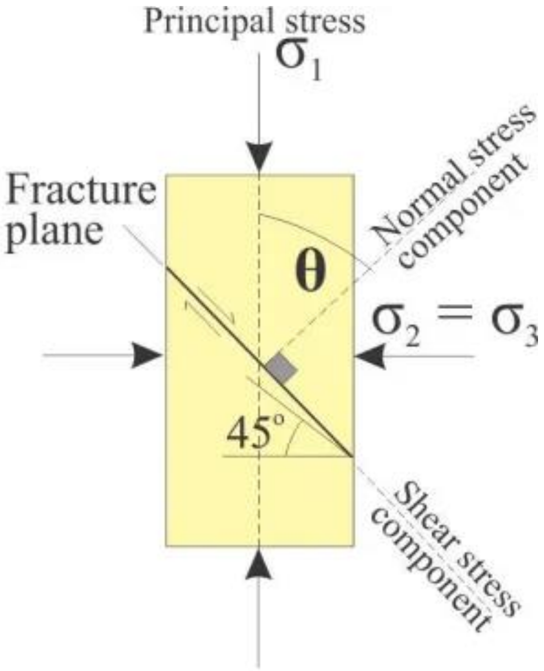
$$\sigma_s = \frac{(\sigma_1 - \sigma_3)}{2} \times \sin 2\theta$$

Convention:

Compressive stress are positive.

Tensional stresses are negative.





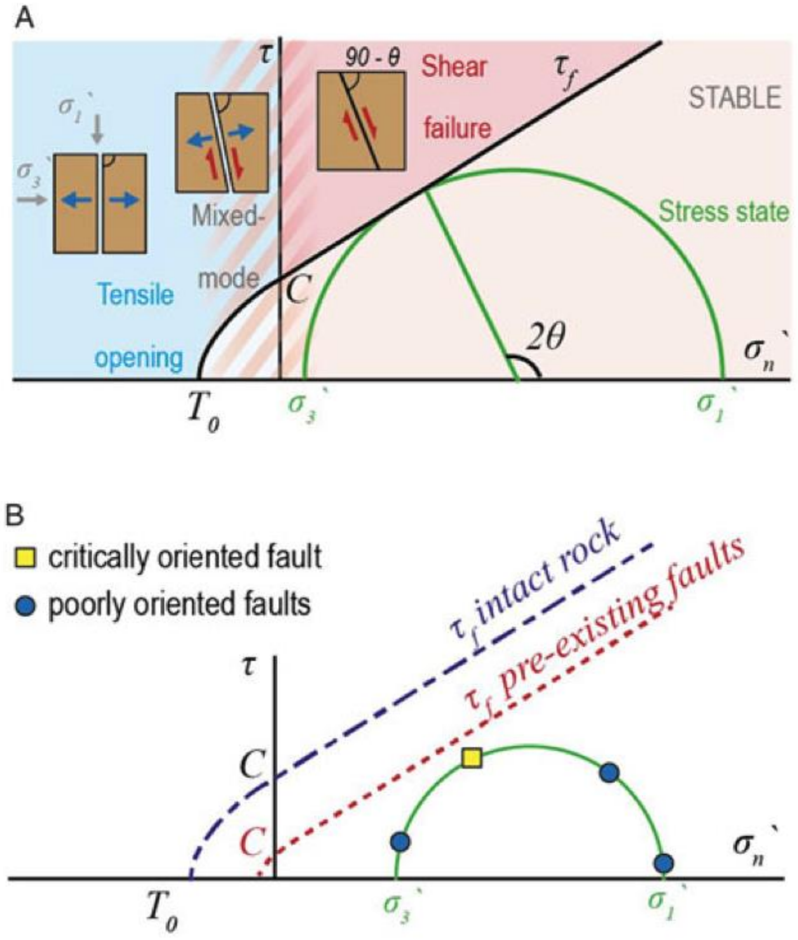
Hydraulic fracturing and hydraulic stimulation

Inject fluid into the reservoir at high pressure.

New fracture 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.



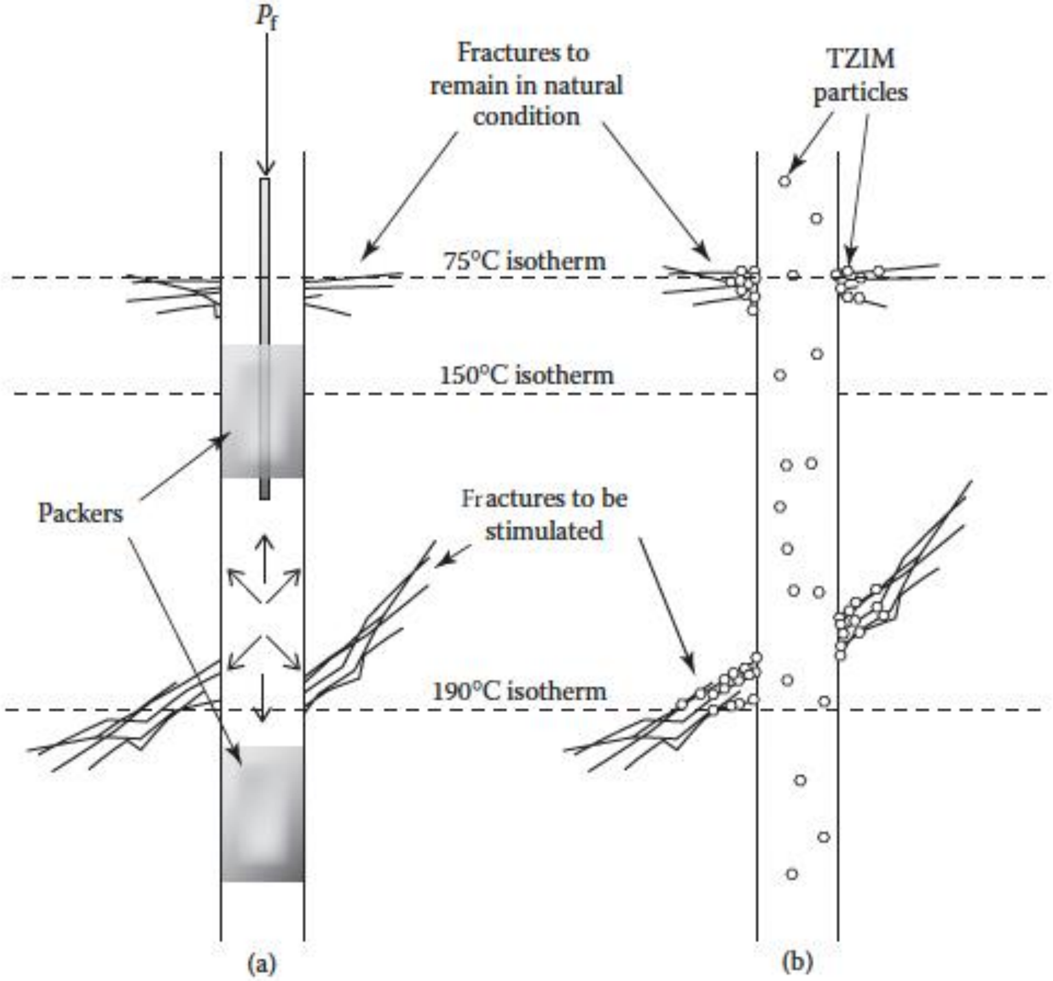
Source: Buijze et al., 2019

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

Boreholes are long!

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

Packers:

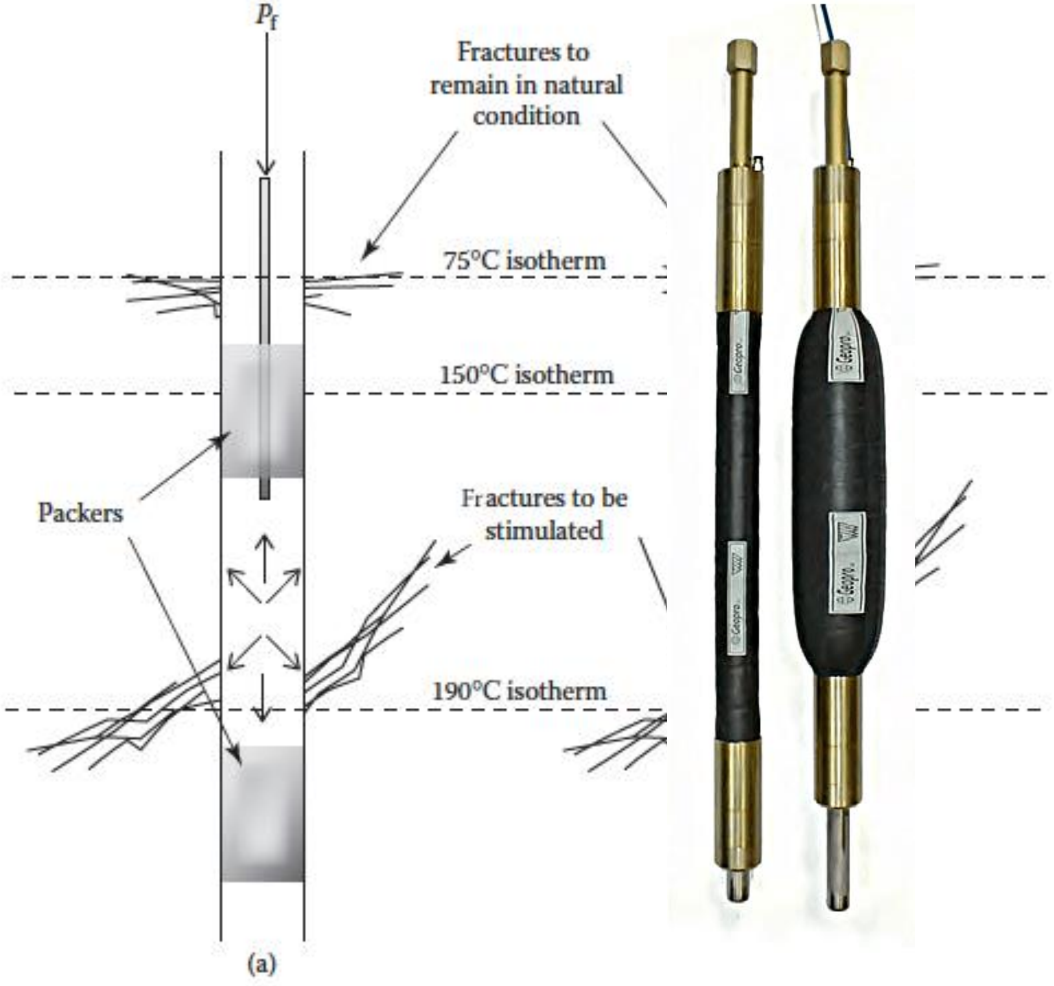
Mechanical or pneumatic devices that seal the borehole above and below the region being stimulated:

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.



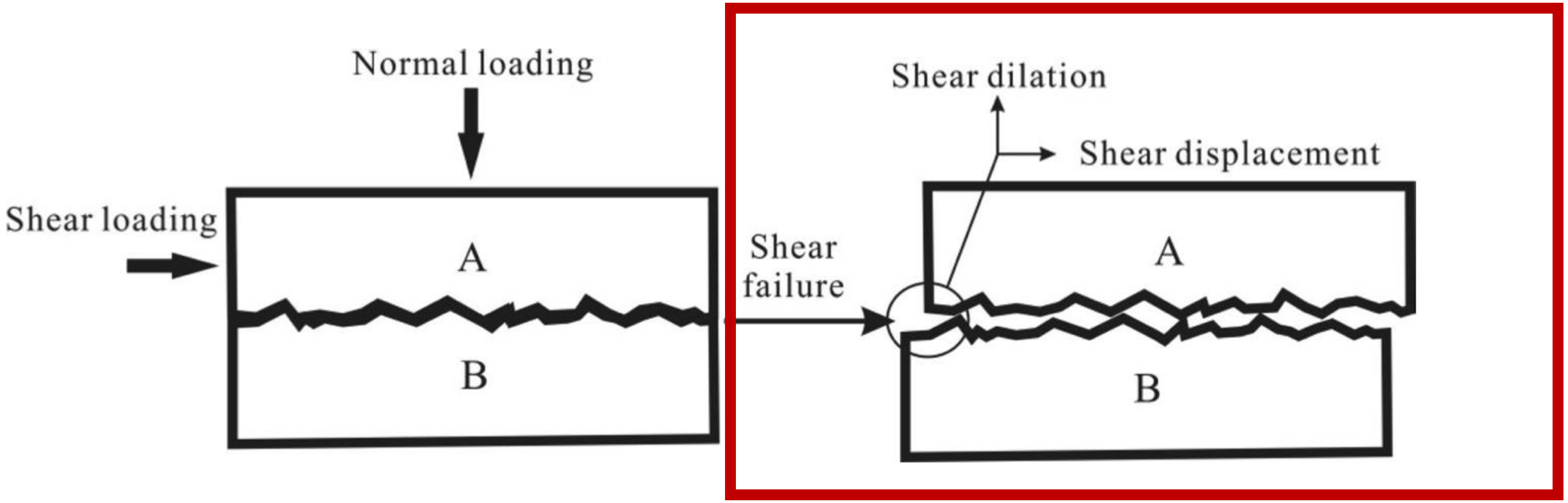
Source: Glassley, W. E., *Geothermal Energy*

Managing hydraulic fracturing and stimulation

Fractures need to stay propped open after stimulation.

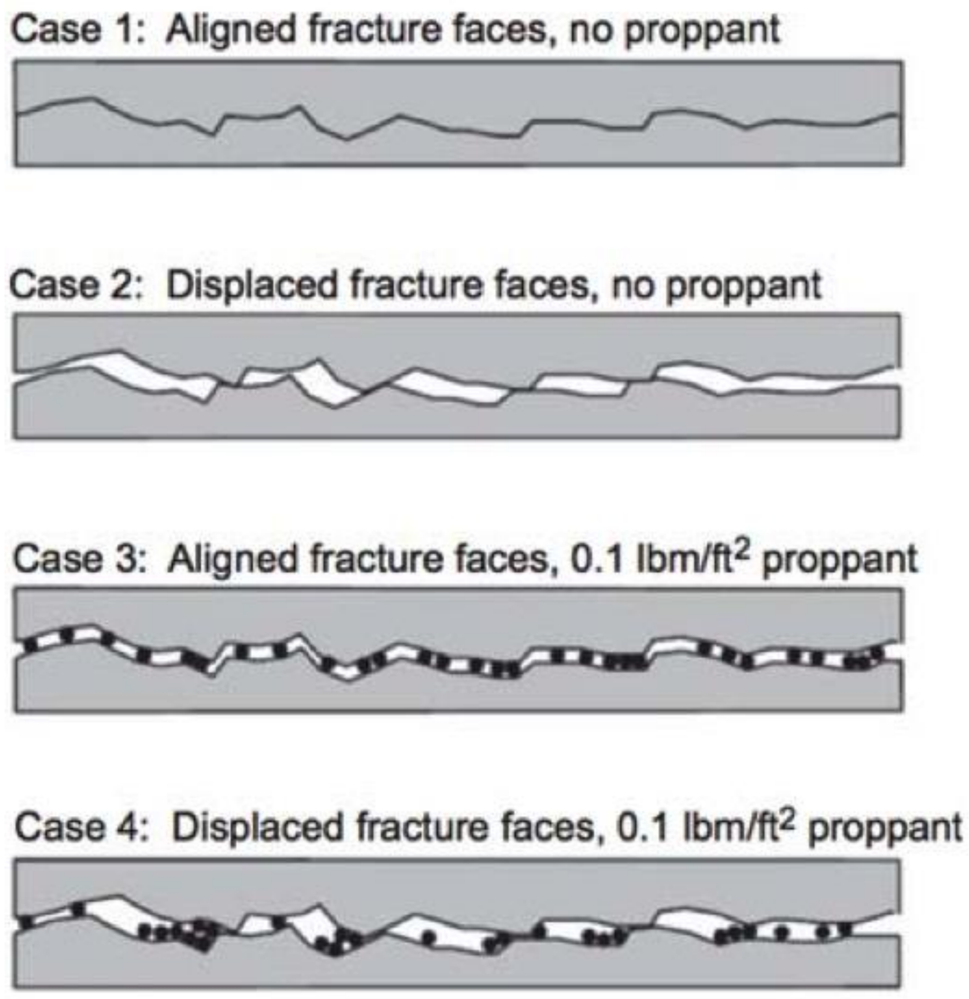
Tensile fractures are easy to close when pore fluid pressure is reduced.

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.

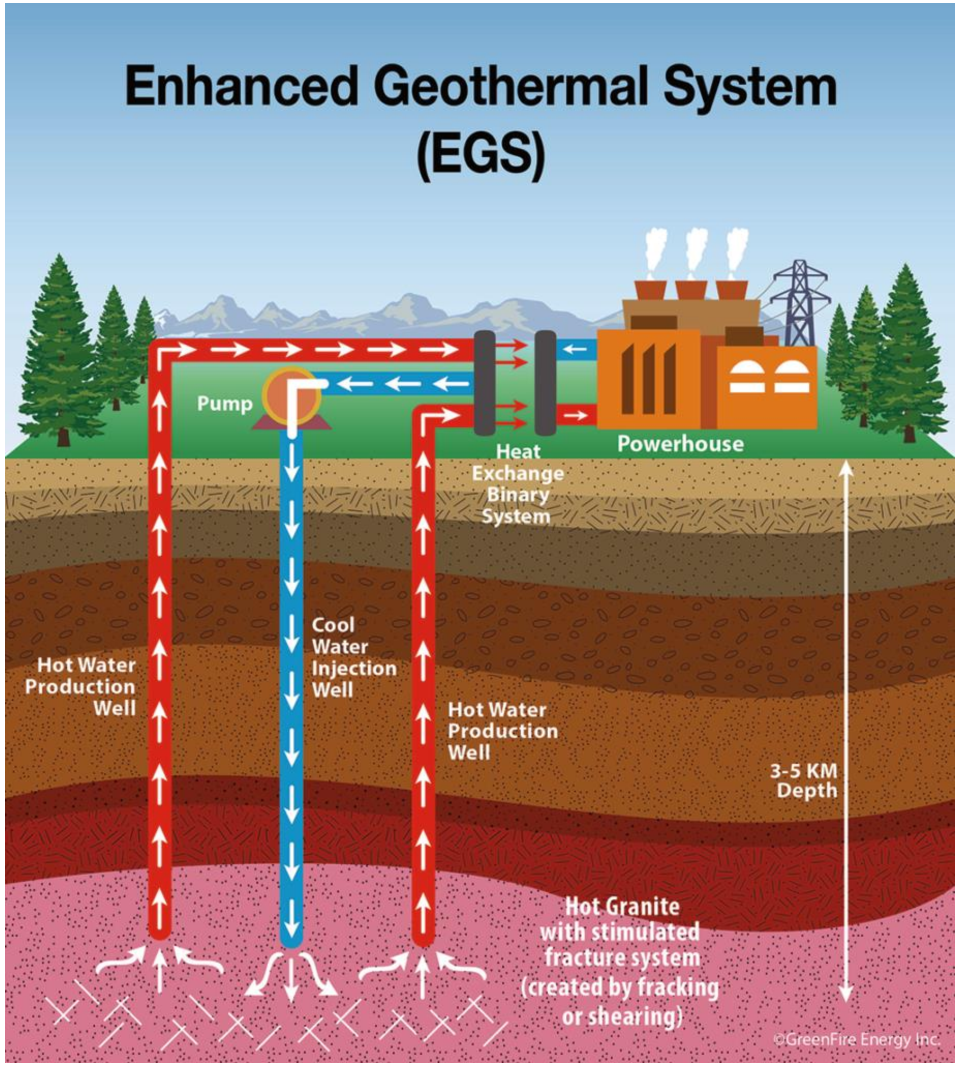
In geothermal systems, induced sesimicity can be caused by:

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/

Rupture area and magnitude

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

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

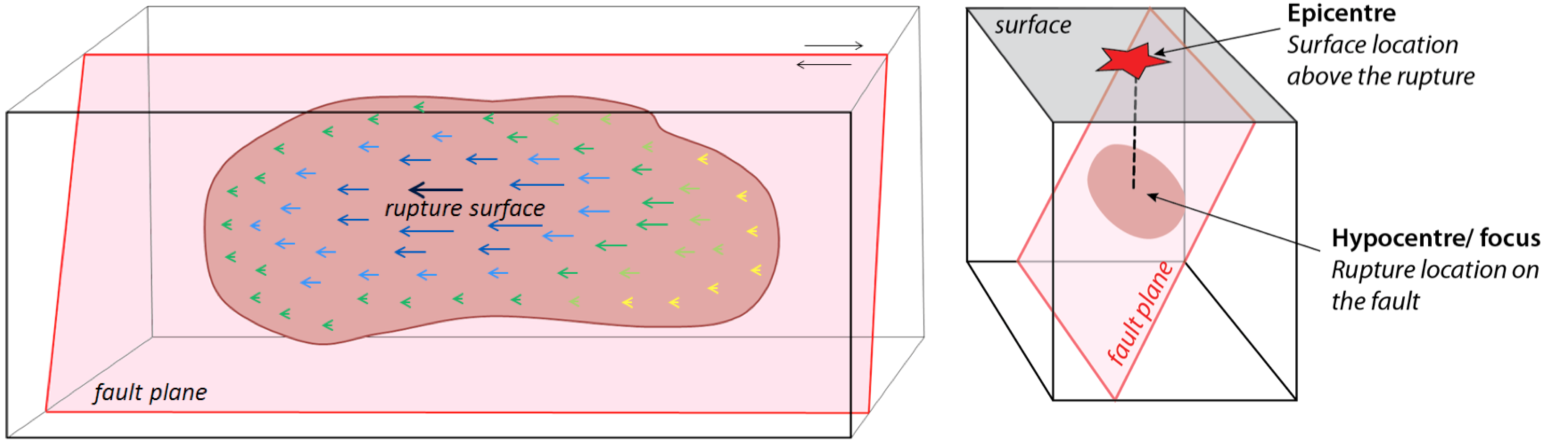
Where:

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: Left: Steven Earle (2015), CC BY 4.0. [View source.](). Right: Karla Panchuk (2017) CC BY 4.0; https://pressbooks.bccampus.ca/geoclone/chapter/12-1-what-is-an-earthquake-2/

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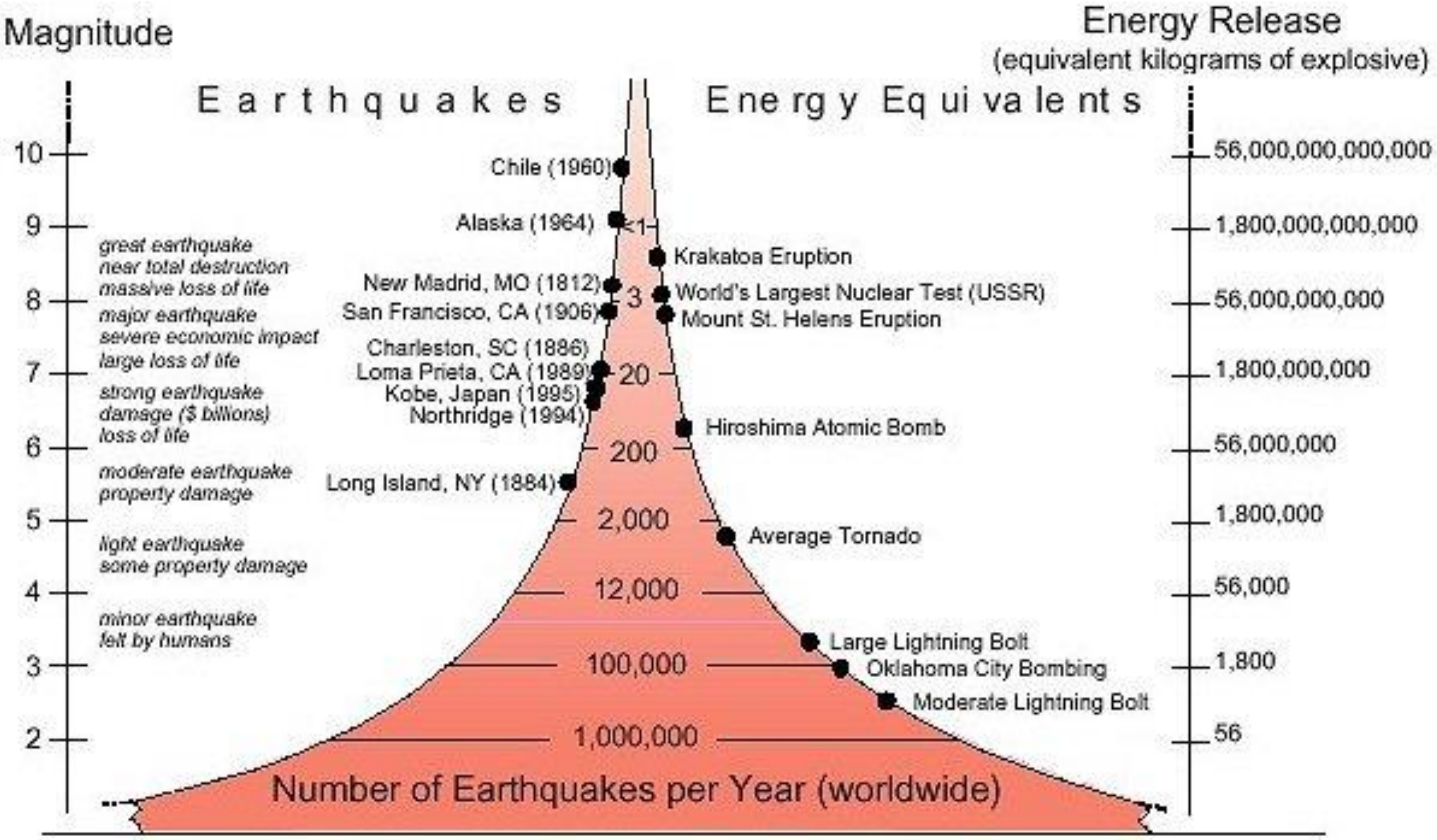


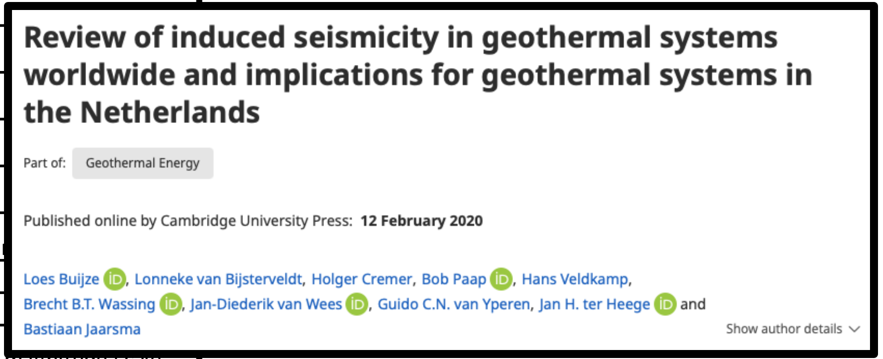
Source: https://www.usgs.gov/media/images/graph-showing-earthquake-magnitudes-and-equivalent-energy-release

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

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.

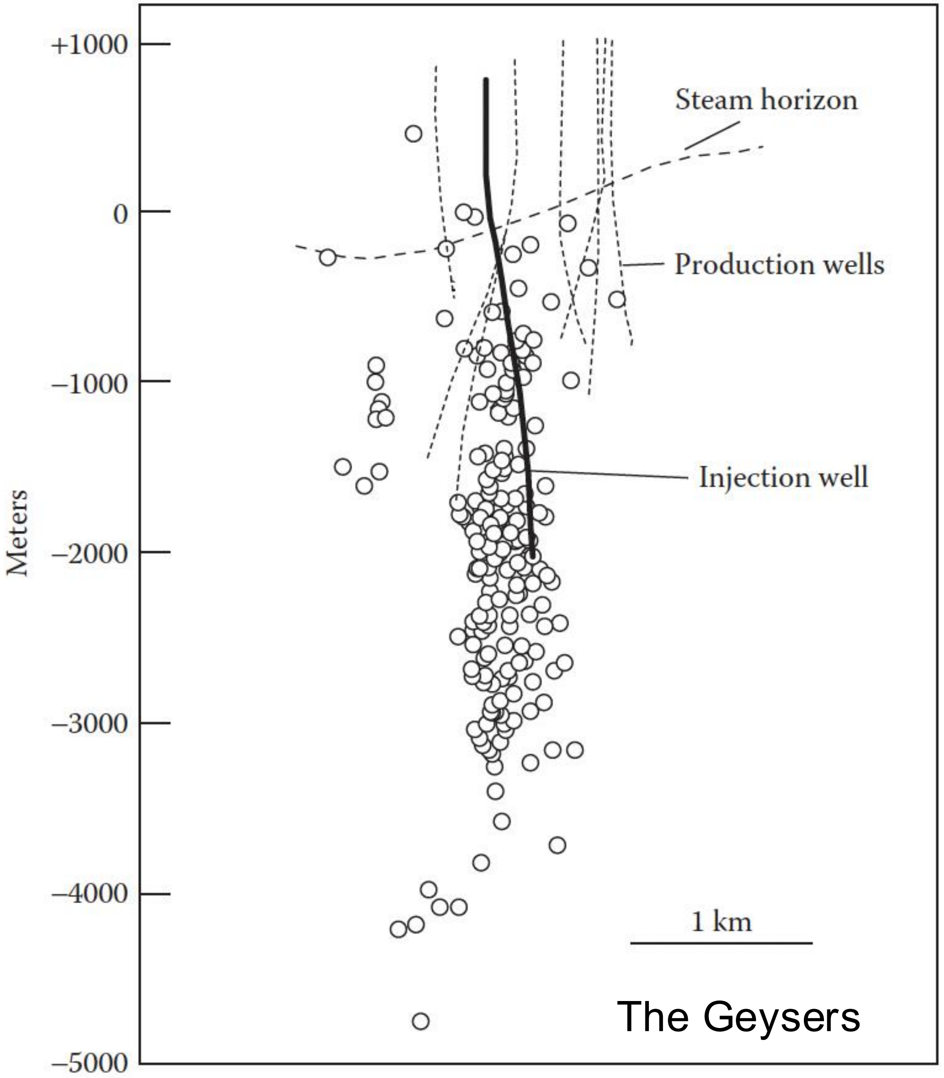
Monitoring seismic activity during stimulation: Install seismometers on the Earth's surface and down monitoring wells.

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*

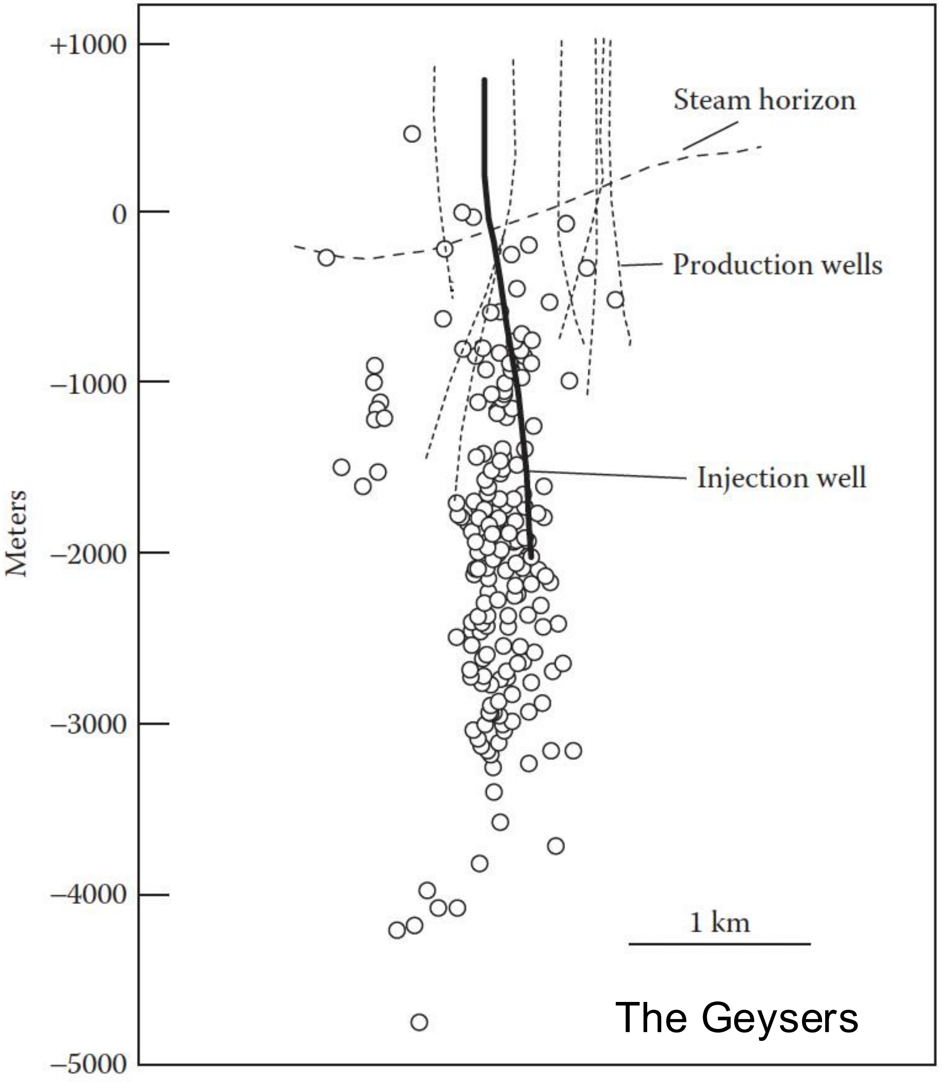
Induced seismicity

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

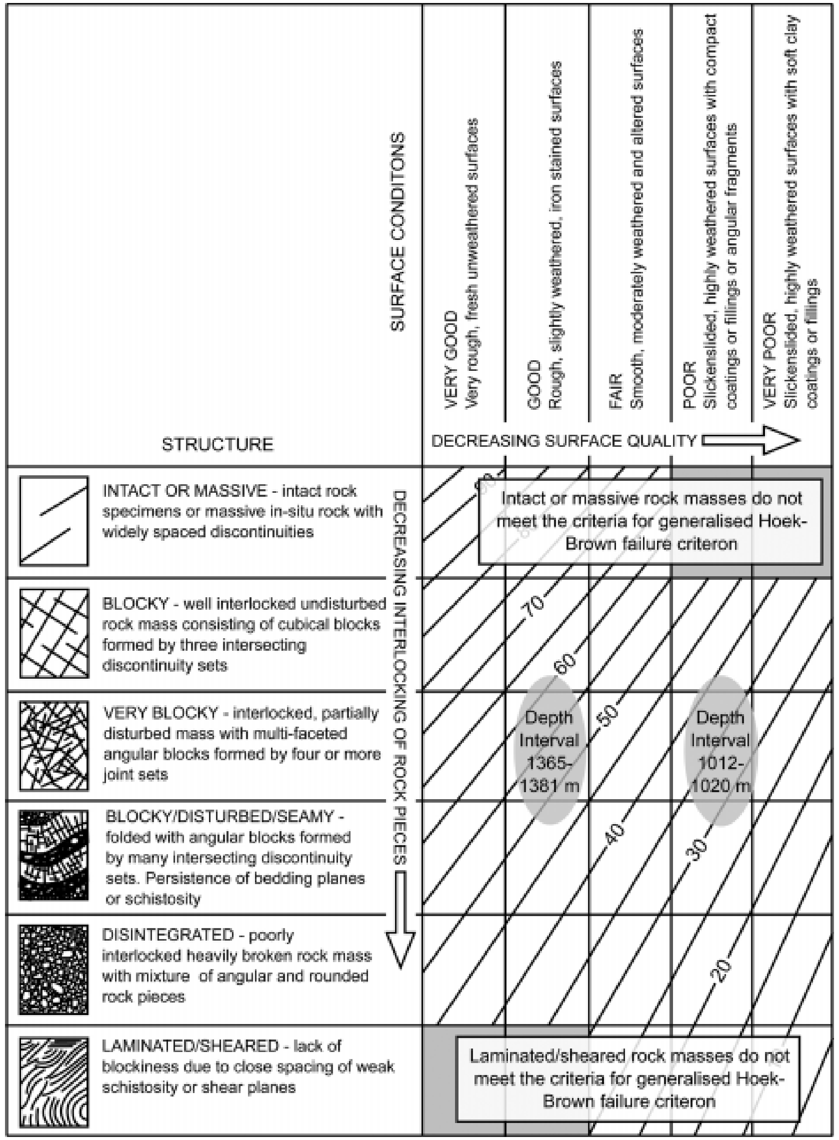
Degree of secondary mineralisation

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

Mechanics of seismic events

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

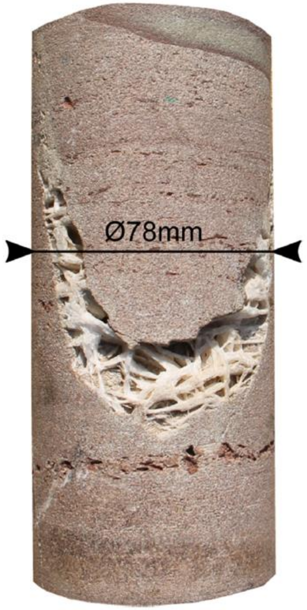
$$\mu_f = \frac{\tau_{peak}}{\sigma_n}$$

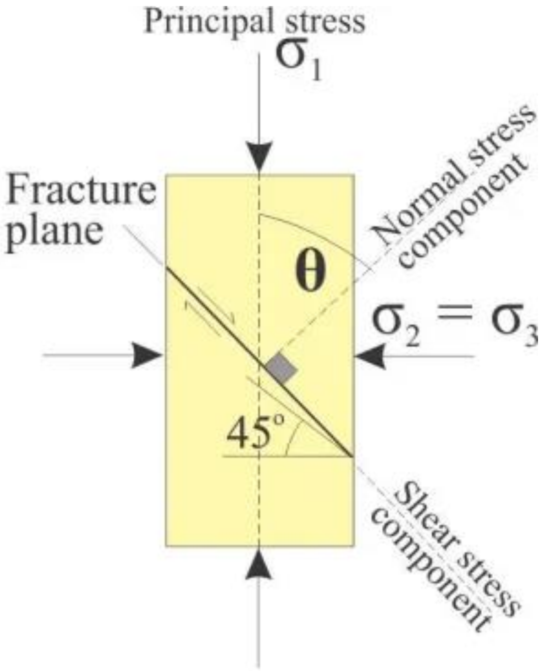
Where:

τ is the shear stress on a plane

σ_n is the normal stress on a plane

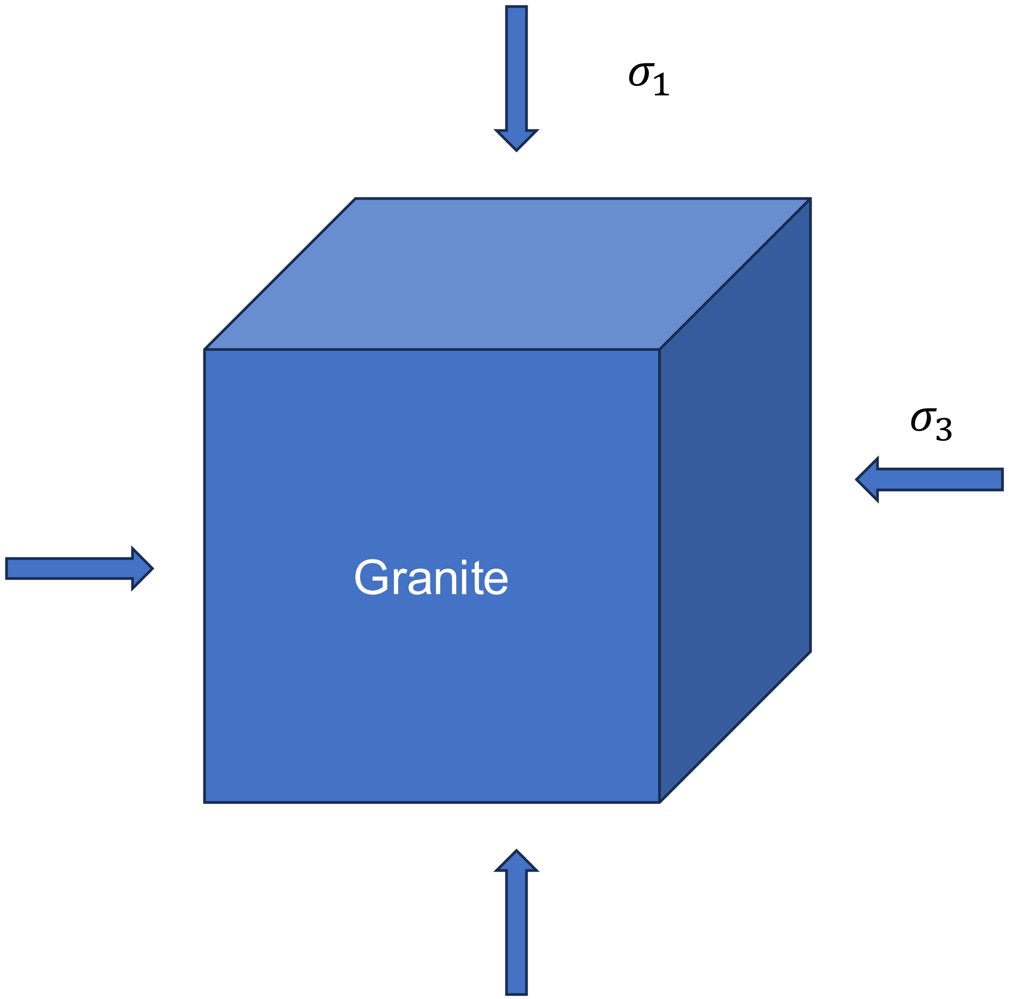
This defines the lower limit of internal friction of a fracture or faulted rock: if μ_f is exceeded, the rock will fail by slip along the fracture or fault.

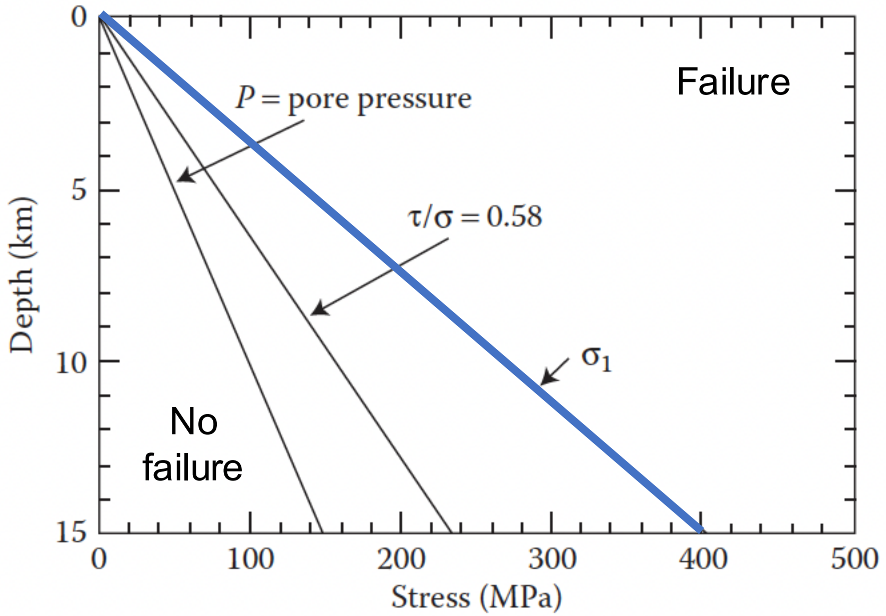


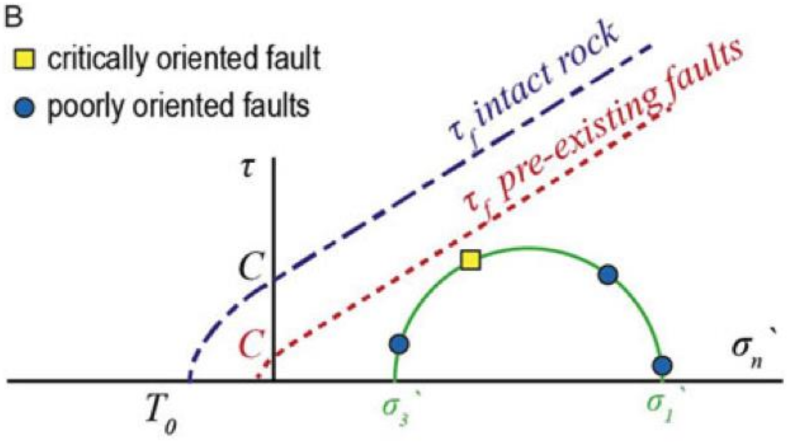


Shear stress, normal stress, and frictional properties

Assume a simple geometry:

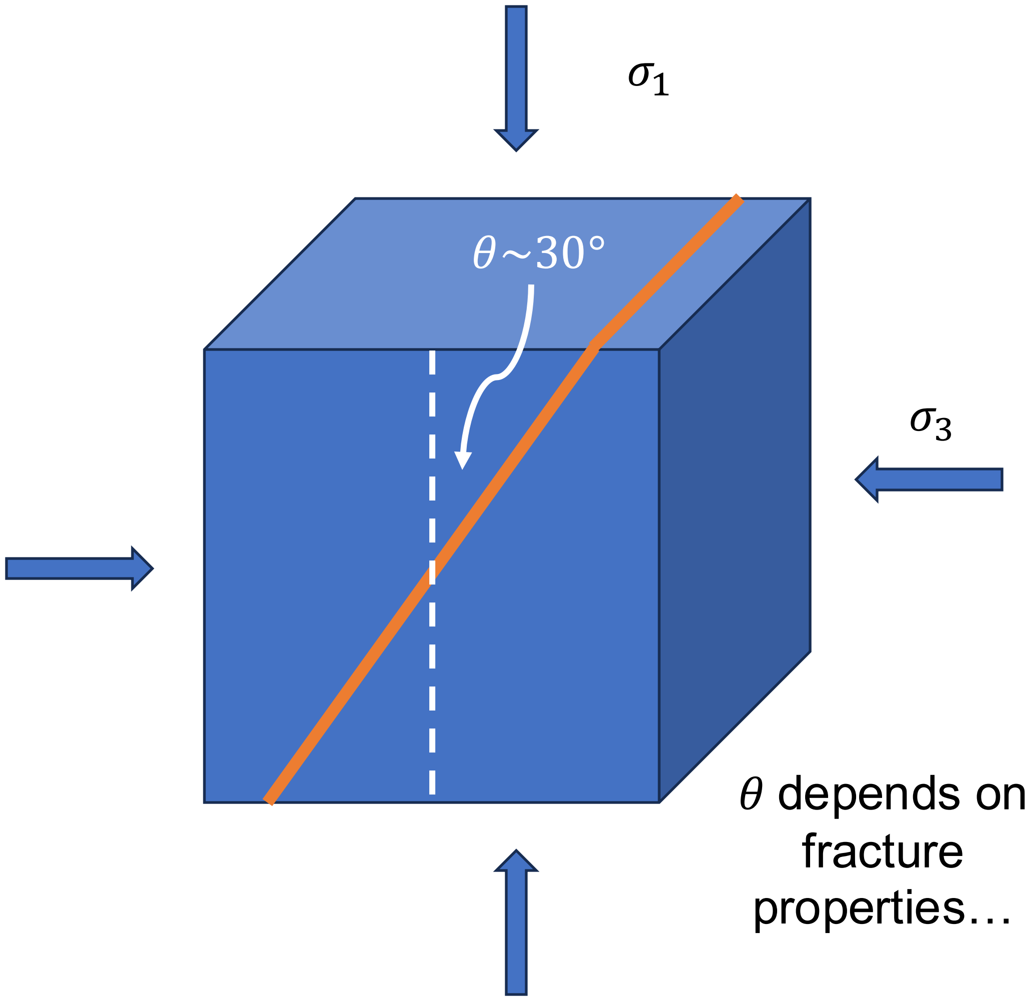




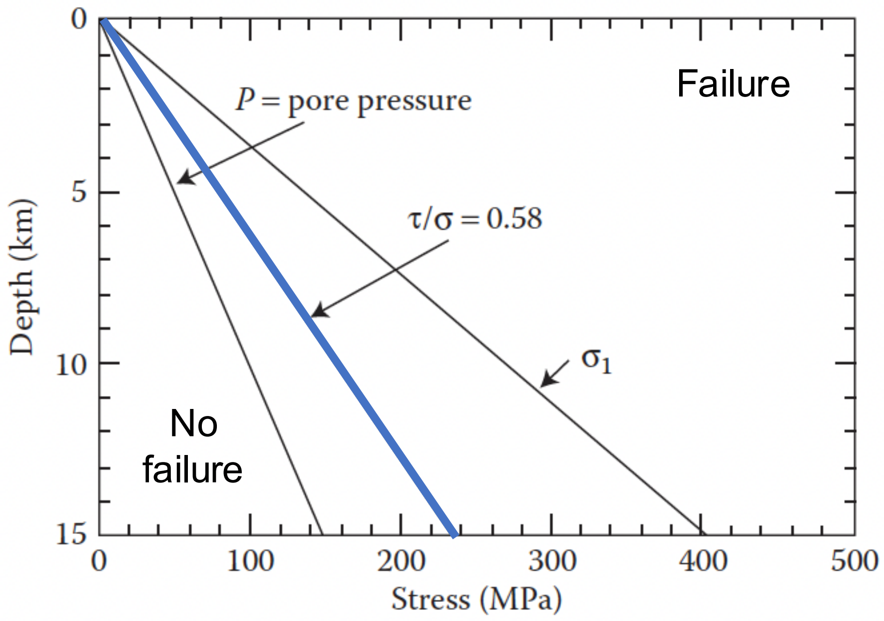


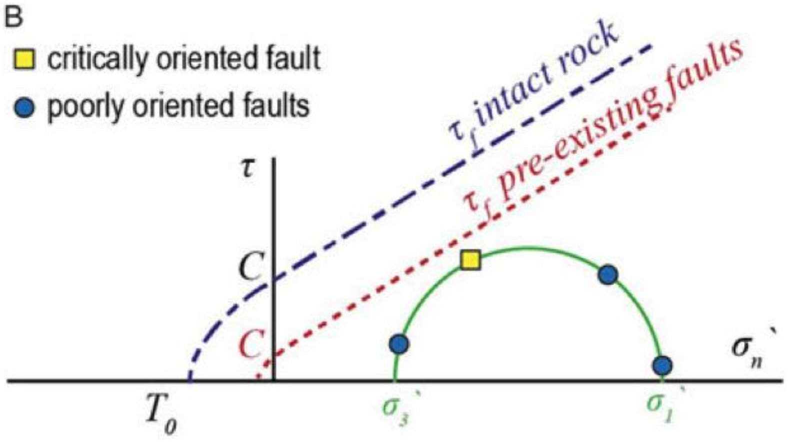
Shear stress, normal stress, and frictional properties

Assume a simple geometry:



θ depends on fracture properties…





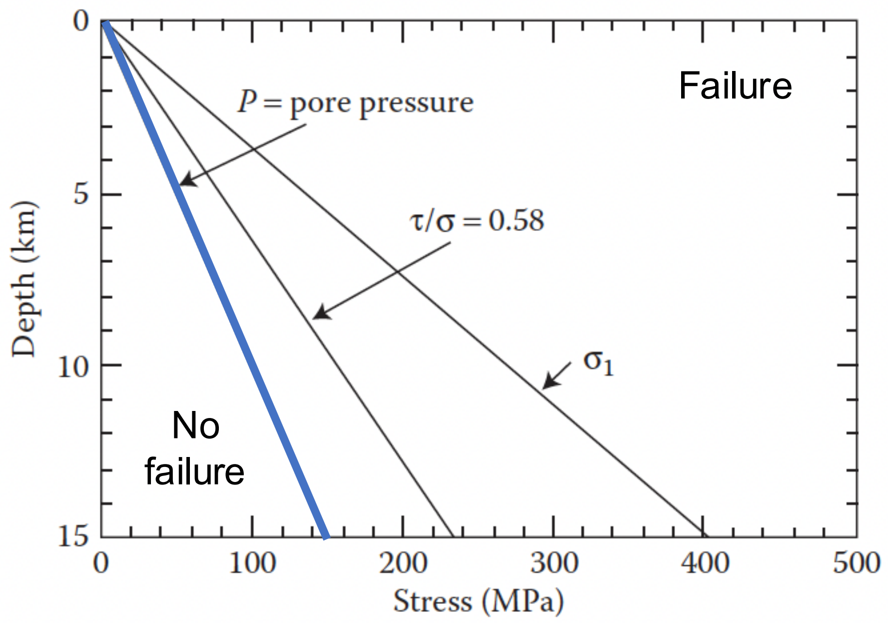
Pore fluid pressure

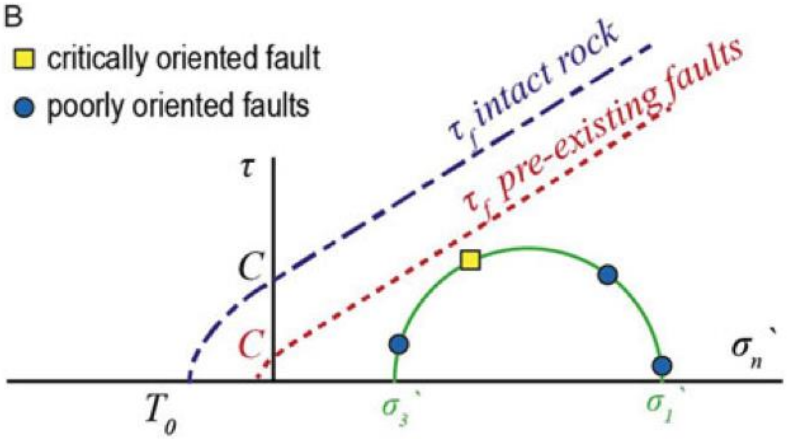
Pore fluid pressure acts against confining pressure, reducing the effective normal stress acting on the plane:

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

Where

P_p is the pore fluid pressure





Induced seismicity

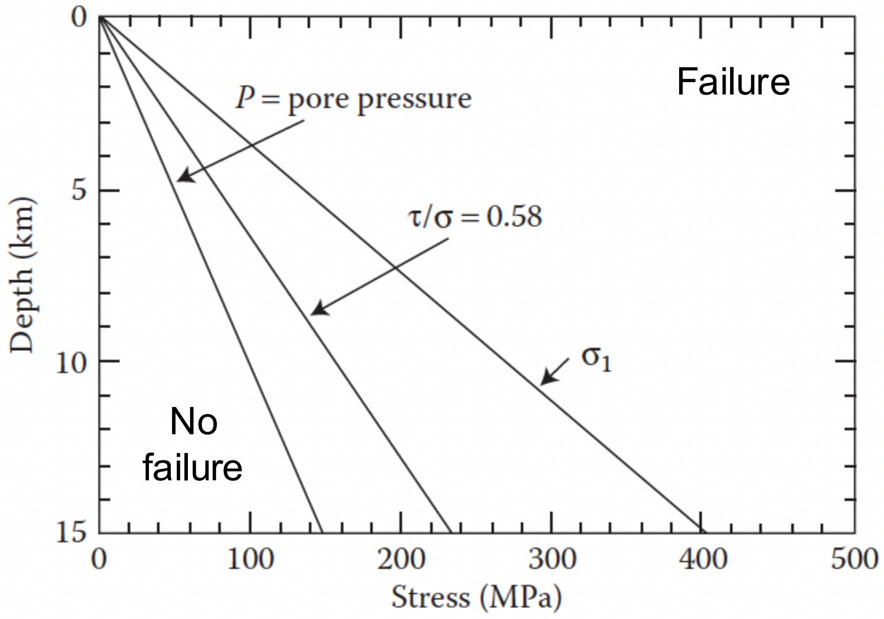
Predicting seismicity is difficult.

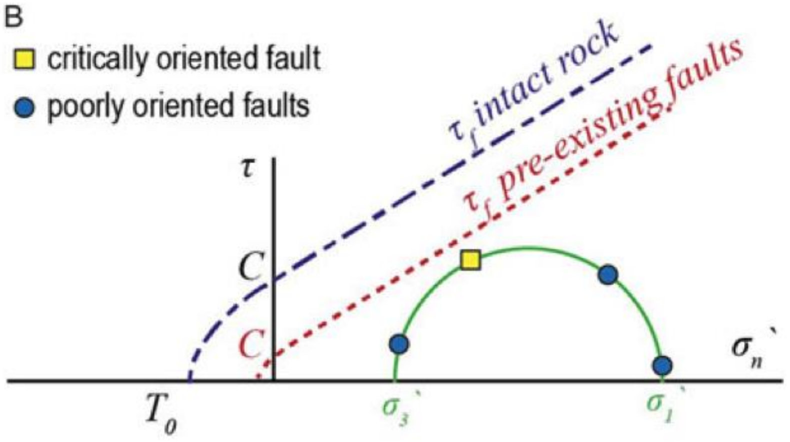
Need to know:

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

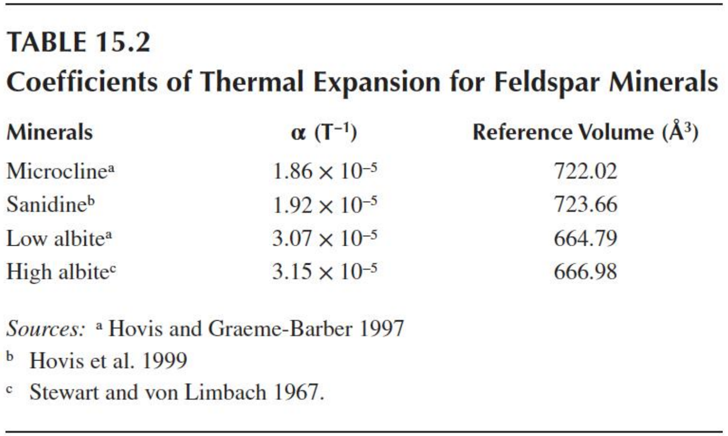


TABLE 15.2

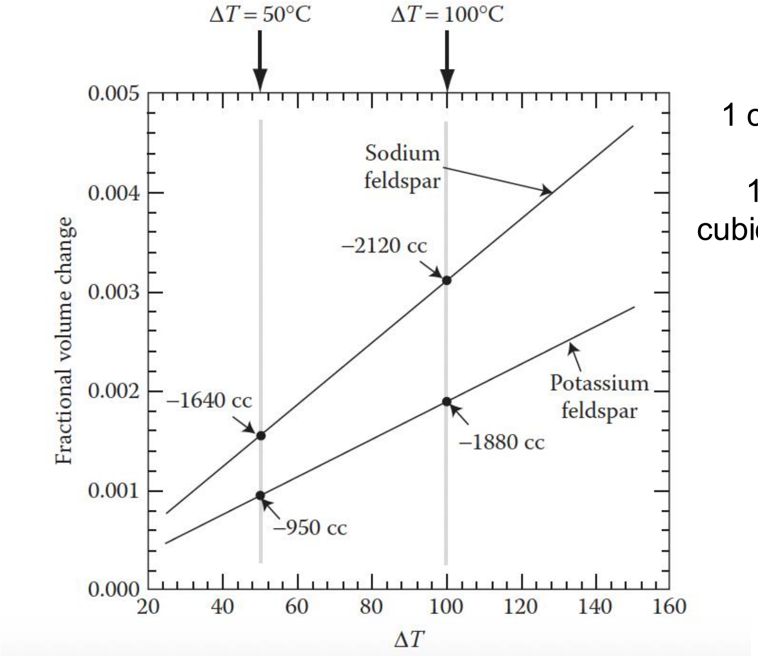
Coefficients of Thermal Expansion for Feldspar Minerals

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.



1 cubic meter
=
1,000,000
cubic centimeters

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.

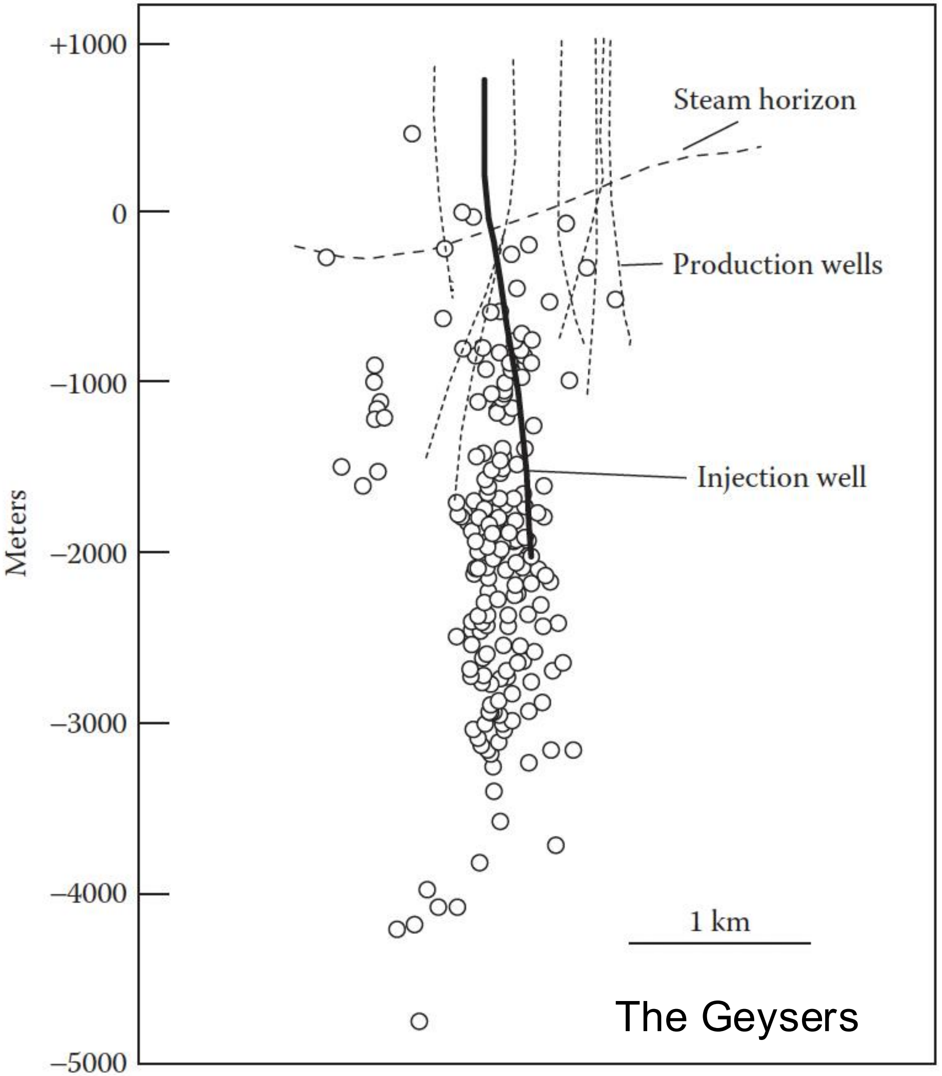
The Geysers:

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*

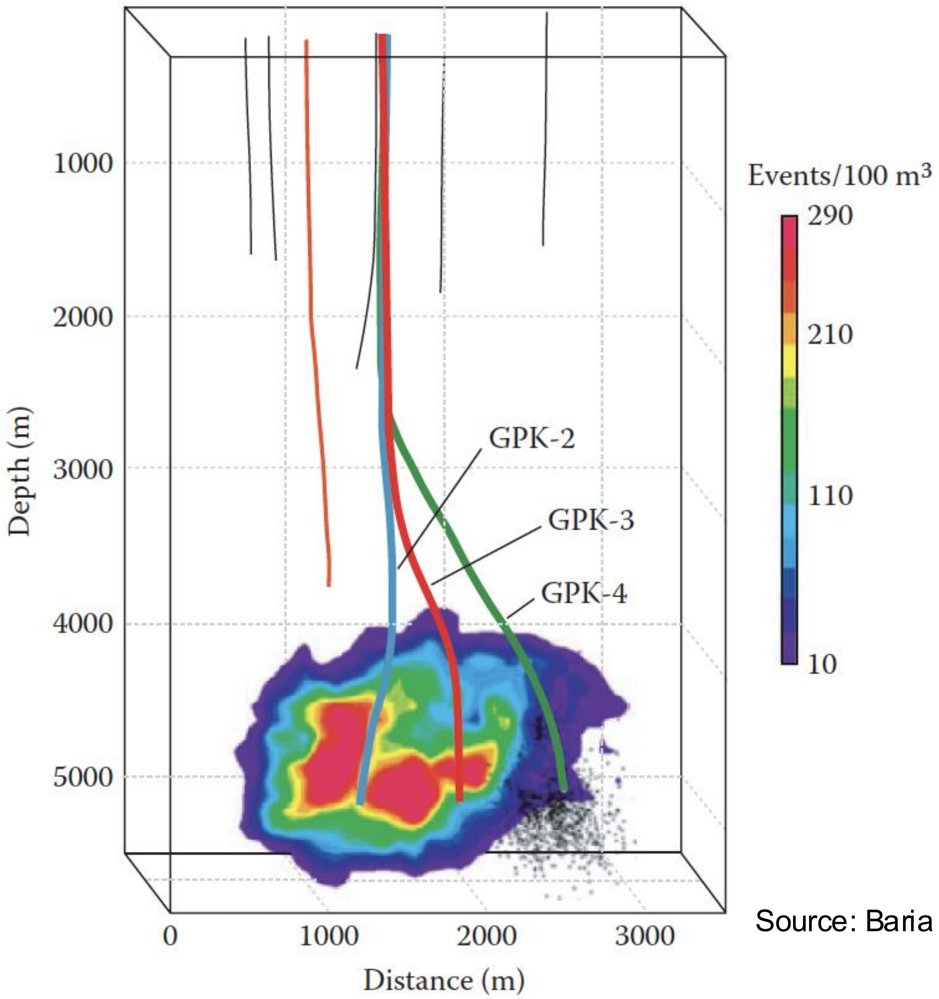
Seismicity: High-pressure fluid injection

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 100's to 1000's 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.

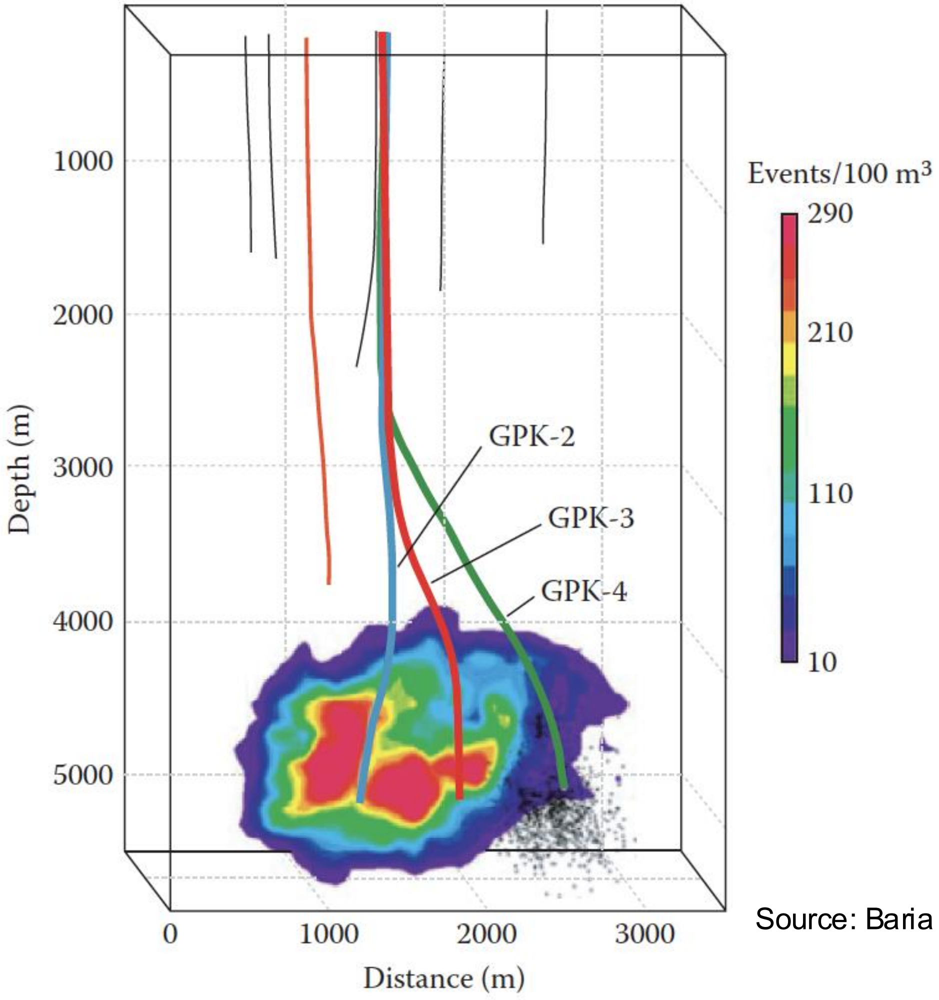
2 periods of hydro-fracturing carried out on GPK-2 and GPK-3.

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

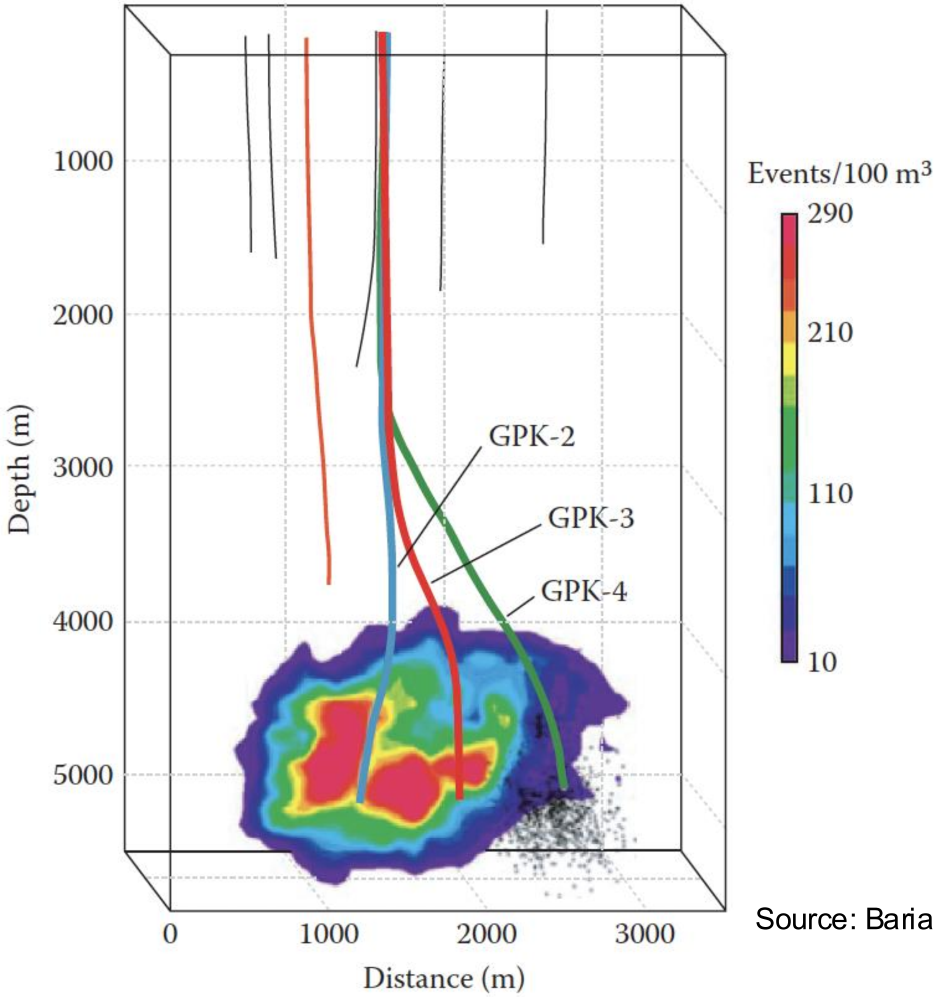
Seismicity: High-pressure fluid injection

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.

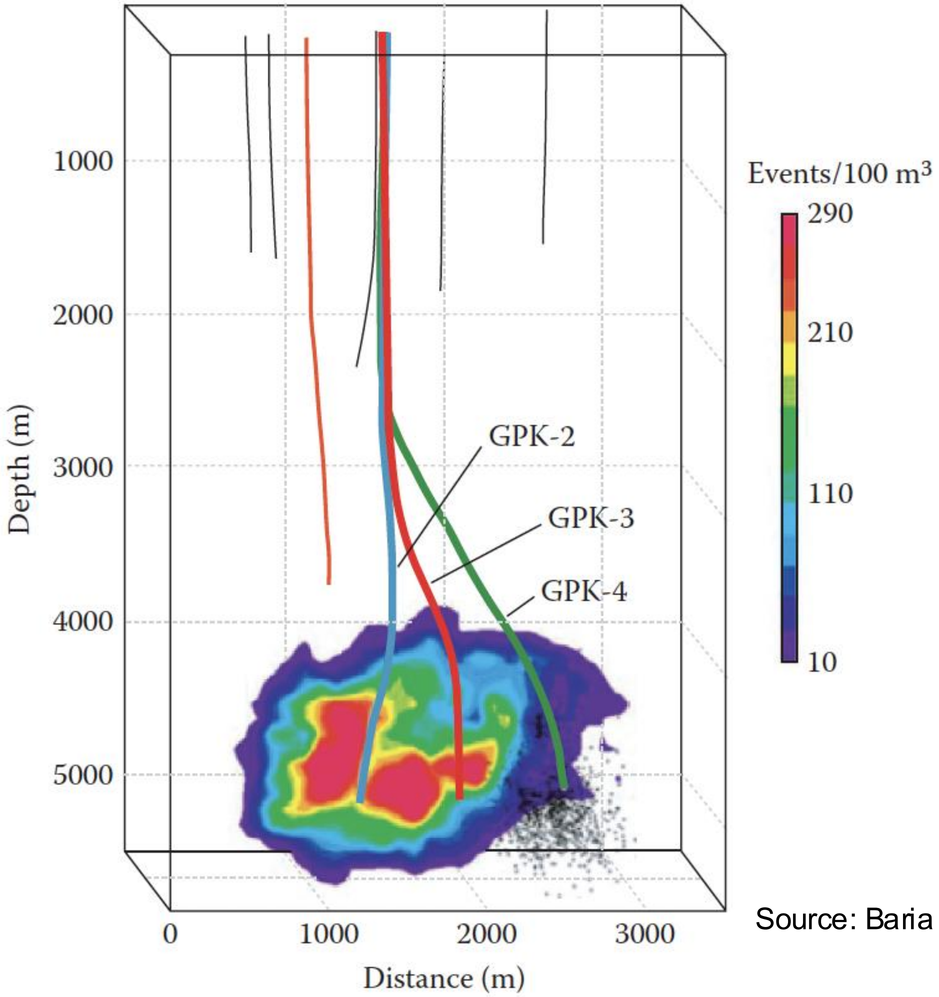
To understand induced seismicity:

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 seismic risk.

Consult with local communities!



Source: Baria et al., 2006

Reservoir management and sustainability

Reservoir management and sustainability

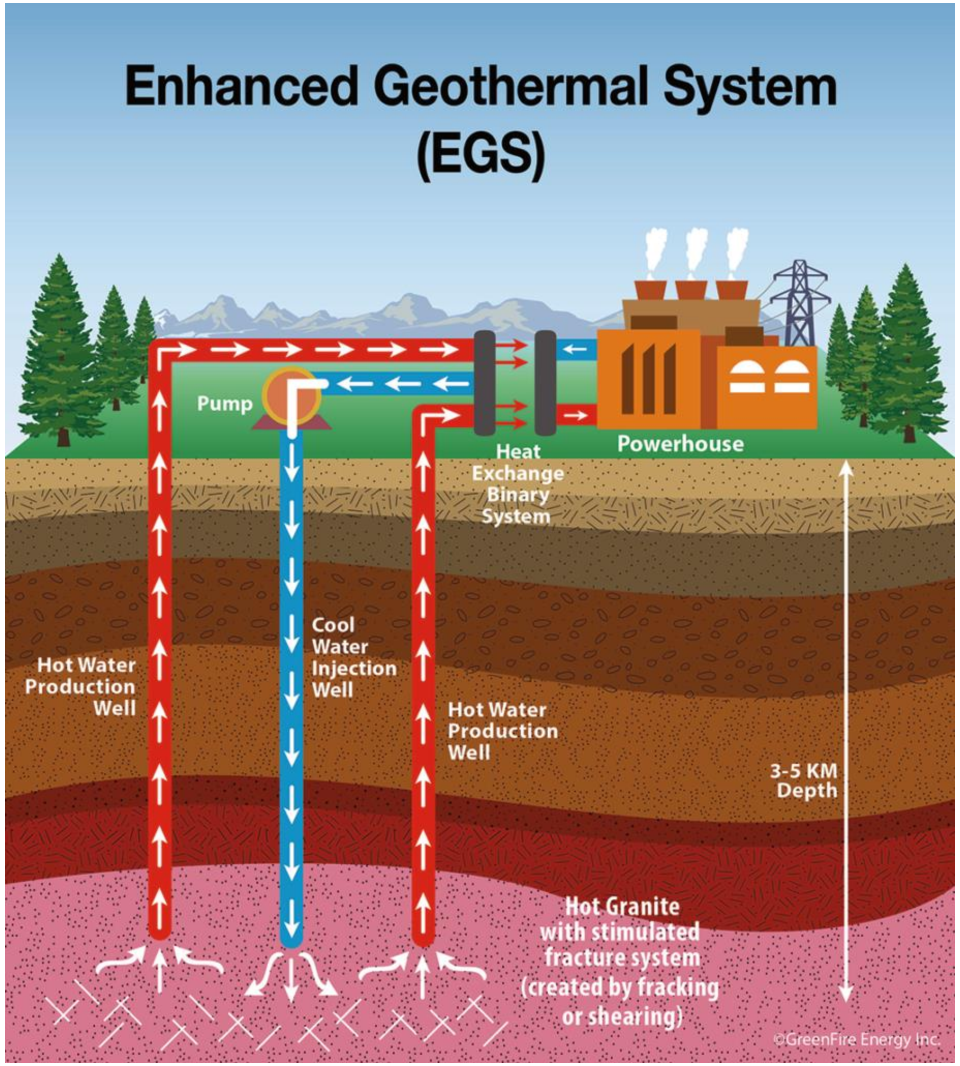
EGS often turns a conductive system into a convective system.

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

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):

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

Consider a theoretical reservoir:

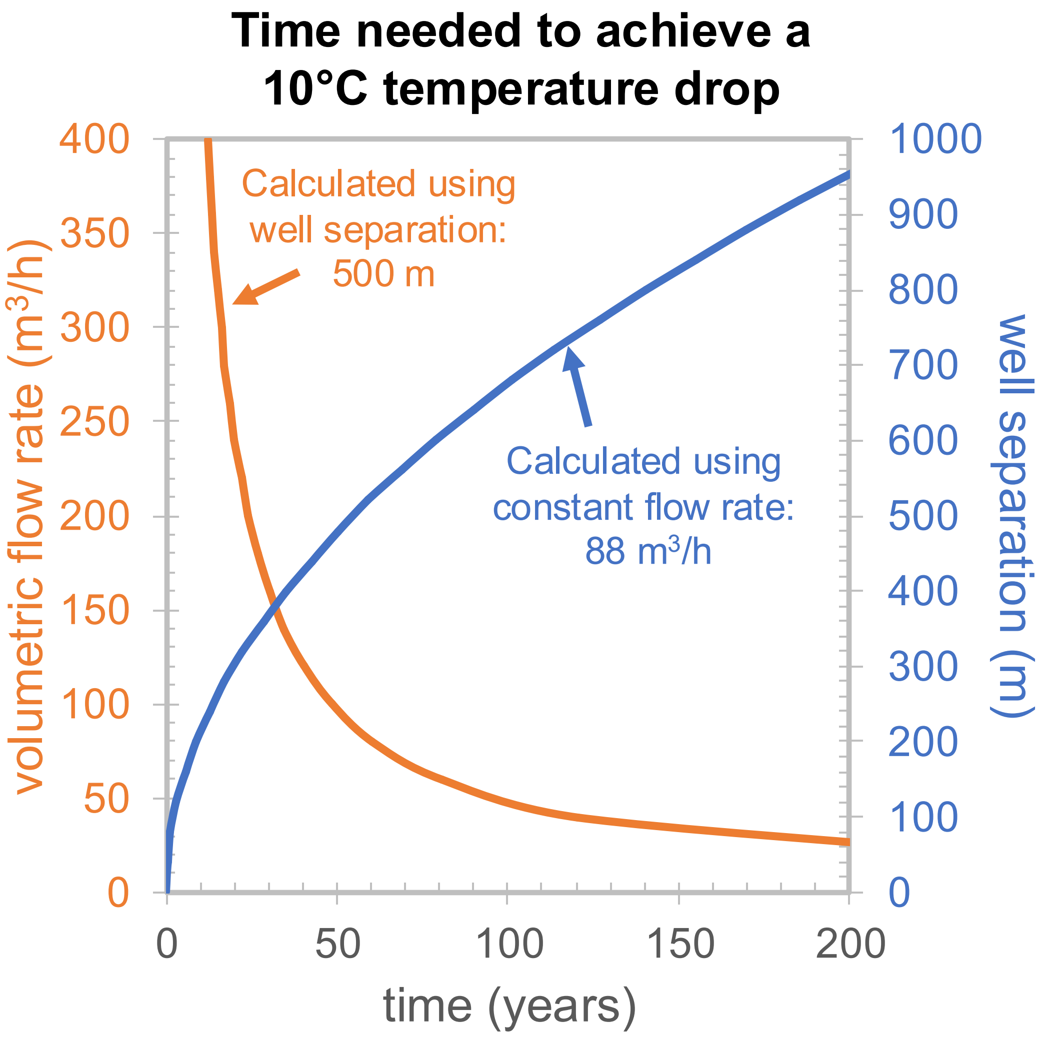
Reservoir porosity: 0.001

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

Injection temperature is constant, but unspecified.



Reservoir management and sustainability

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

Does not take into account:

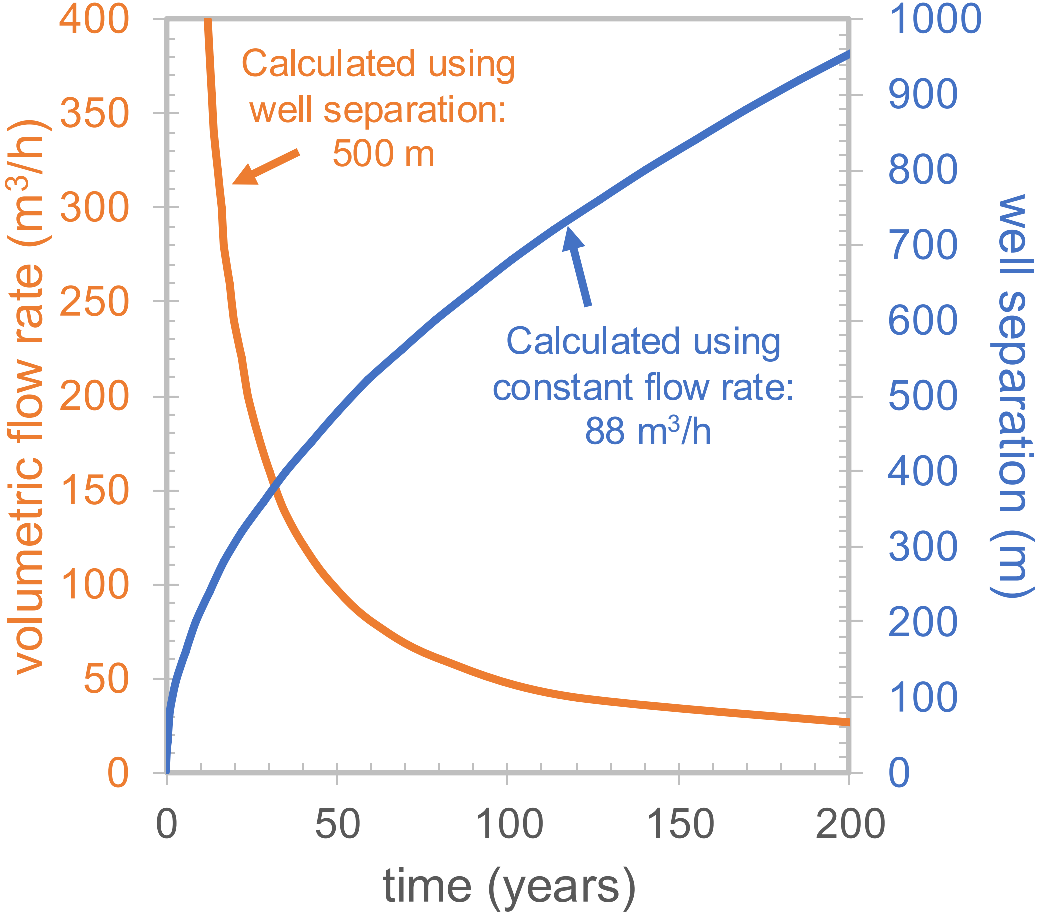
Temperature dependence of thermal conductivity

Flow geometry

Exposed surface area along flow path

Local heat flow

Time needed to achieve a 10°C temperature drop



Reservoir management and sustainability

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

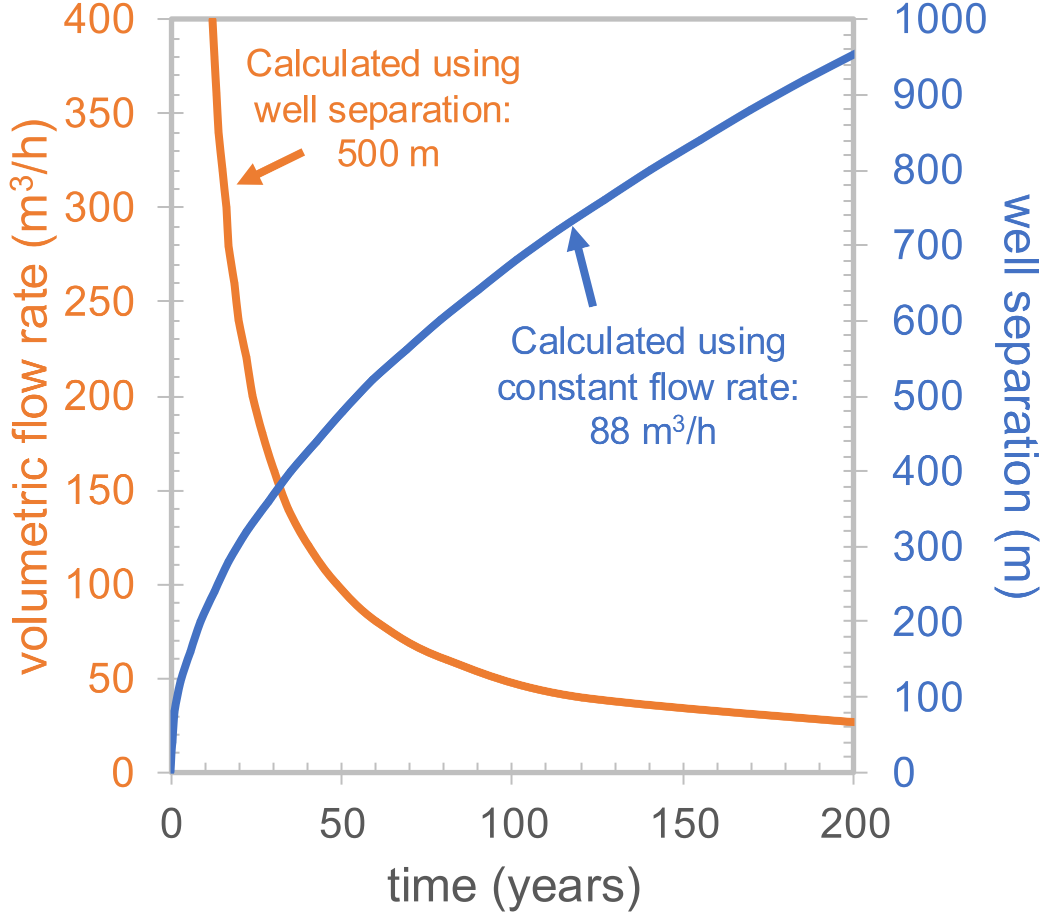
To replenish 90% of the heat in an EGS-stimulated region would take approximately 3 times the operational period.

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).

Time needed to achieve a 10°C temperature drop



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.