Webinars

Geomechanics for geothermal energy development

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SPE International

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Agenda

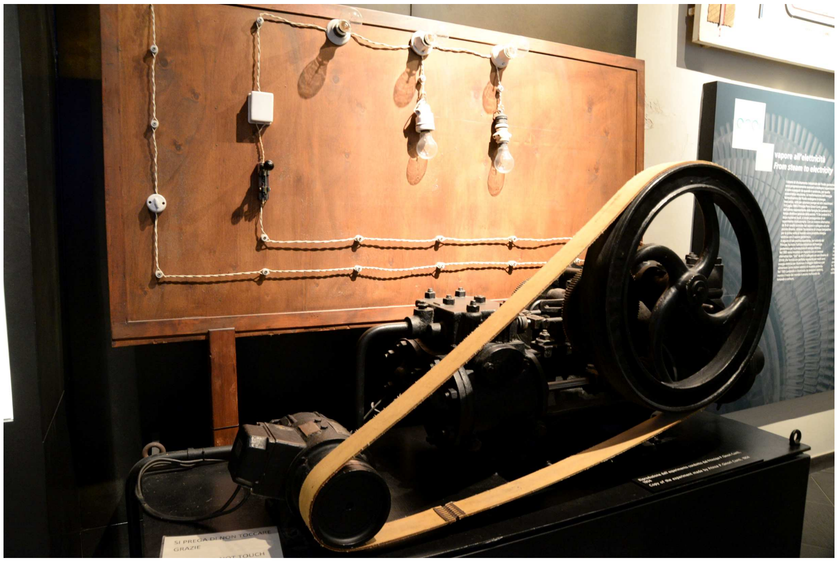
- Variety of geothermal reservoirs – associated challenges
- Drilling and completion
- Hydraulic stimulation versus hydraulic fracturing
- Induced seismicity

The first geothermal power plant

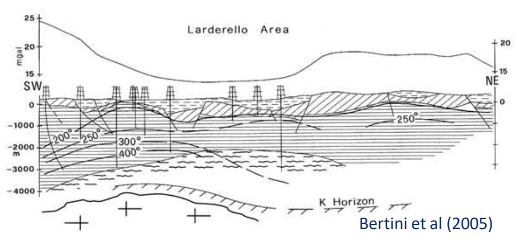
Principe P. Ginero-Conti 1904

- Larderello (Tuscany, Italy)
  - Shallow level of igneous intrusions (Eurasian / African plate boundary)
  - 1904: able to light 5 light bulbs

The first geothermal power plant



The first geothermal power plant



Bertini et al (2005)

[Enel green power]

- Larderello (Tuscany, Italy)
  - Shallow level of igneous intrusions (Eurasian / African plate boundary)
  - Shallow (500m-1km) carbonates reservoir with T 200°C and above
  - Deep reservoir (2-3.5km) in the permeable metamorphic formations with T in the range 300°-430°C
  - Dry steam
    - H_2O ~ 97.5%
    - CO_2 ~ 0.046%
    - H_2S ~ 2.3%
    - K_2 ~ 0.05%
    - CH_4 ~ 0.032%

The first geothermal power plant

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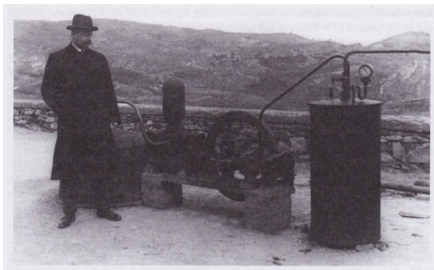
Principe P. Ginero-Conti 1904



[Enel green power]

- Larderello (Tuscany, Italy)
  - Shallow level of igneous intrusions (Eurasian / African plate boundary)
  - 1904: able to light 5 light bulbs
  - 1913: 250kW
  - 1915: 15MW (dry steam)
  - From 1931: 500m deep wellbores (T~200°C)
  - 1939: 66MW
  - 1943-44 Complete destruction
  - Today: 545 MW from 34 plants (1.6% of Italy electricity production)

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Guess where it's hot?

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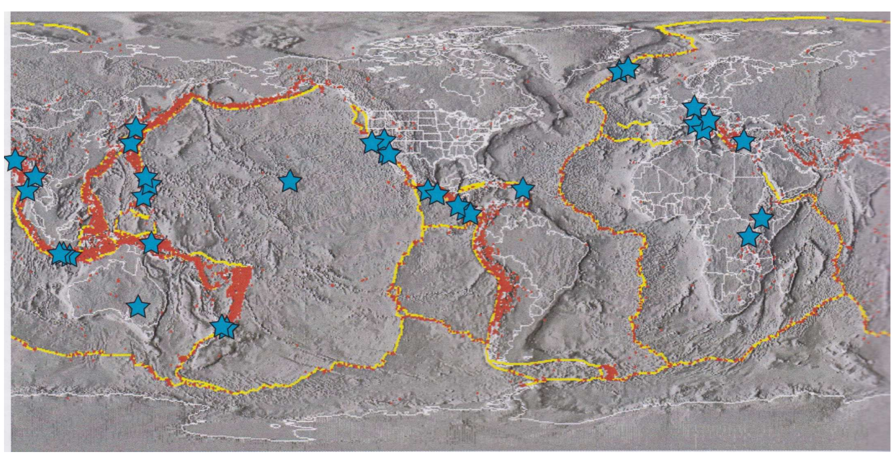

[Glassley, 2010]

Geothermal plant
Earthquakes
Plate boundary

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Keeping things in perspective

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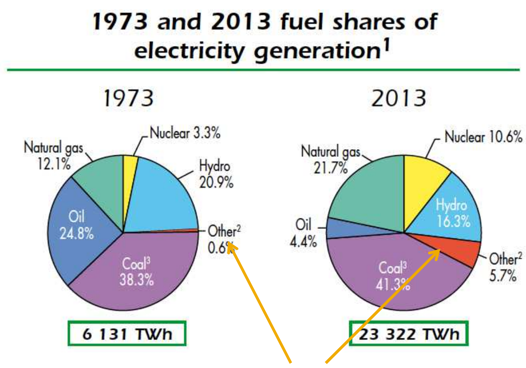

Wind, Solar, Biomass, Geothermal etc.

[IEA, 2015]

~0.5% of Electricity generation from geothermal

Installed geothermal electric capacity

Country	2007 (MW)	2015 (MW)
USA	2687	3450
Philippines	1969	1870
Indonesia	992	1340
Mexico	953	1017
New Zealand	471.6	1005
Italy	810	916
Iceland	421.2	665
Kenya	128.8	594
Japan	535	519
Turkey	38	397
World Total	**9,731.9**	**12,635.9**

[Bertani, 2015]

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Focus on electricity production

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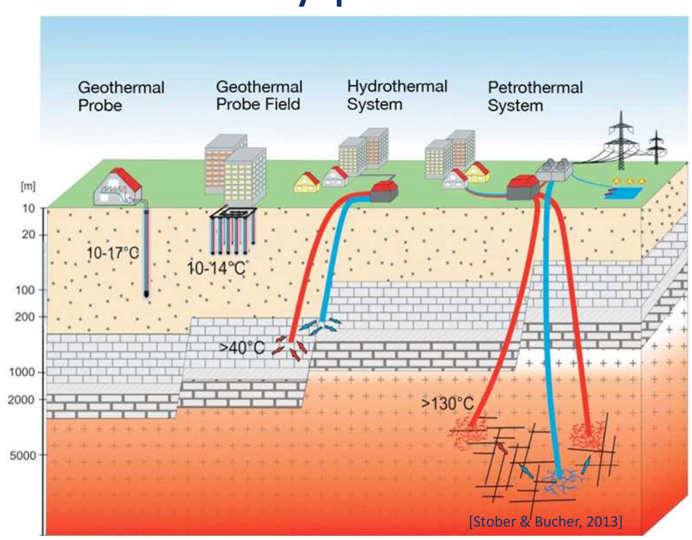

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Water EoS & subsurface conditions

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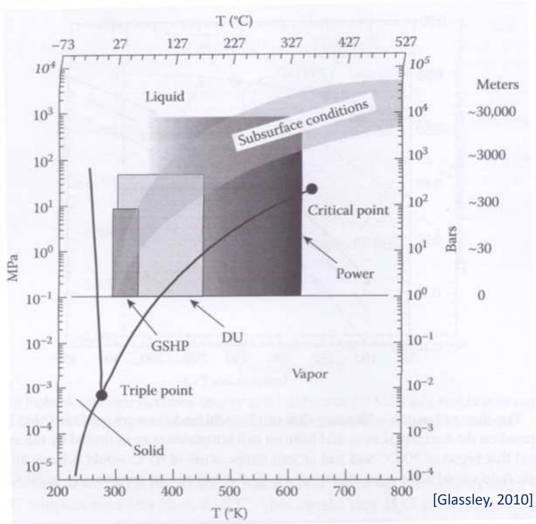

[Glassley, 2010]

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Types of geothermal plant

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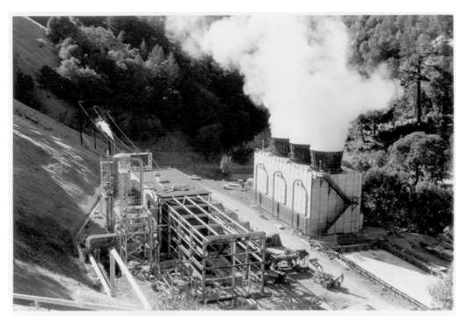
- Dry steam
  - Steam in the reservoir
- Flash steam
  - Phase change in the well
    dissolved solids in the produced fluid is an issue
  - Double, triple flash (at lower T, P)
- Binary cycles
  - ORC, Kalina - Reservoir fluids do not go through the turbine
  - As low as 75°C up to 180°C



The Geysers, CA circa 1960s

- Power output $P = \epsilon_{gen}\epsilon_{turb}\Delta H \times \dot{m}$
  - The mass flow rate needs to be sustained over time
    ~ 50 liter / sec. (for ~10MW) [18BPM]

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Reservoir types

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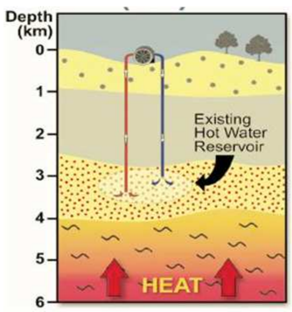
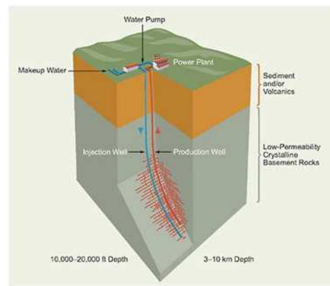
Hydrothermal



In permeable sedimentary rocks
at reasonable depth
located above a heat flux anomaly
(e.g. Larderello, Geysers)

Petro-thermal (EGS)



In 'tight' crystalline rocks deeper,
permeability is THE issue
Temperature somehow location "independent" if 'deep' enough (not exactly)

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Technical Challenges

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- Hydrothermal
  - An exploration problem (thermal anomaly in a permeable sedimentary layers)
  - Reservoir management mostly a hydro-thermal problem
  - All wells always require a degree of stimulation

- EGS
  - Drilling cost / drilling & completion issues
  - Hydraulic stimulation is critical (and often performed blindly)
  - Induced seismicity
  - Cost has a direct consequence on characterization and thus risk

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Drilling

- Crystalline rocks, TVD in excess of 3500m (11’000 ft),
  - High stress, high temperatures - pervasive breakouts (15” for a 8”1/2)
  - Loss circulation issues (good news for the project)

BS-1 well

SPE-195523

Courtesy B. Valley (Unine)

Completions

- Large diameters (to minimize friction)
- Typically barefoot
  - Minimize friction *but* no real control on the flowing zones
- Challenges for cemented / perf.
  - High T
  - Break-outs: cement volumes
  - Efficiency of perforation in crystalline rocks
- Sliding sleeves
- Multi-packer systems in open-holes

Hydraulic fracturing vs hydro-shearing

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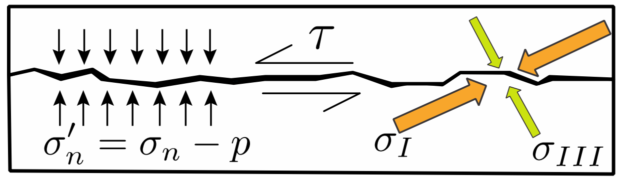
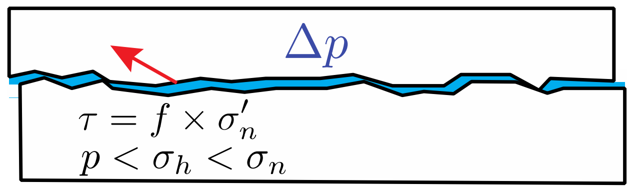
$p > \sigma_h$

Use of proppant





Self-propping via dilatancy
(not in shales, effect decrease with initial normal stress)

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Fluid Injection – the 4 levels of pressure

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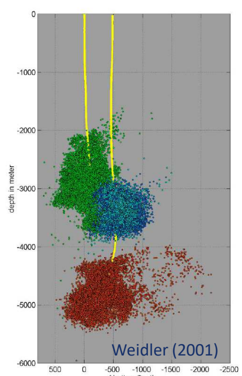
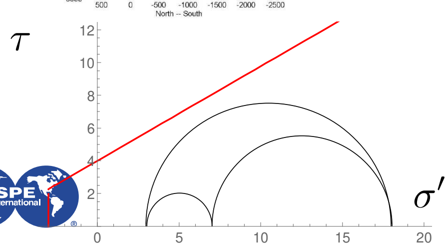
Cornet (2016)

1





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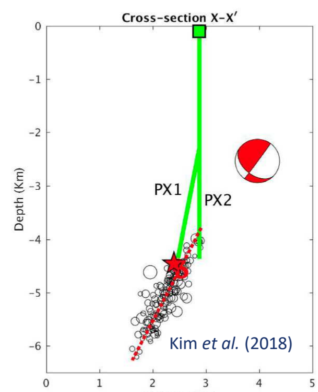

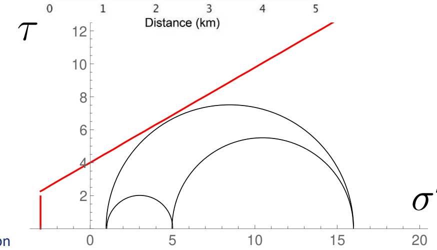

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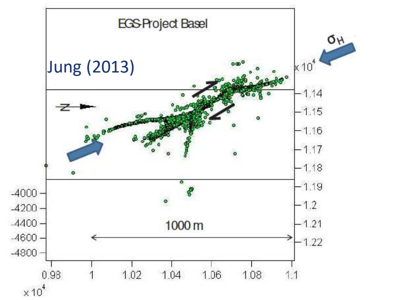
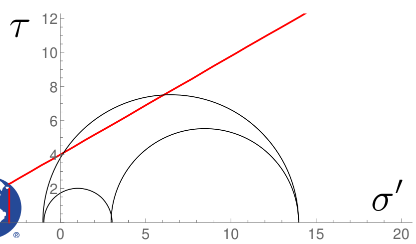
Fluid Injection – the 4 levels of pressure

3





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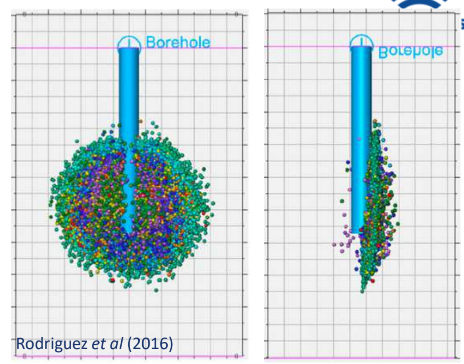
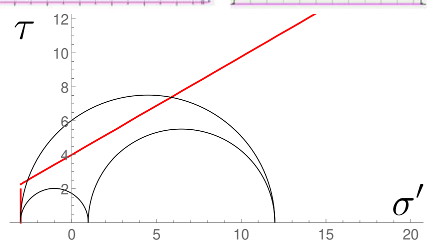
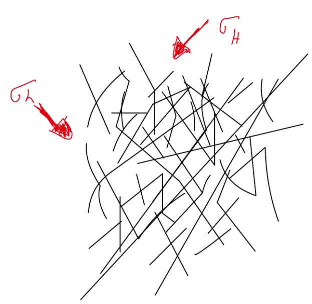
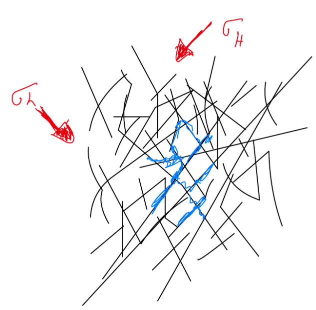




RVE scale ? When do we see "order"?



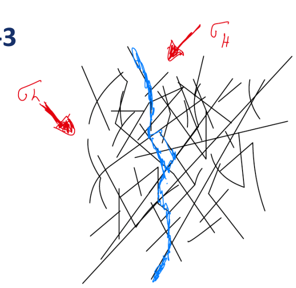
1



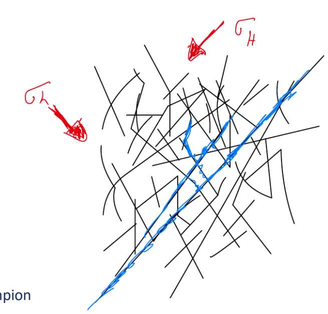
$$L_{rve} \sim \sqrt{4\alpha t}$$

will also depend on p

2-3



3-4



L_{rve} ~ 50 m
in Soult-sous-Forêts
[Cornet, 2021]

Hydraulic fracturing:
the proper way to engineer permeable pathways

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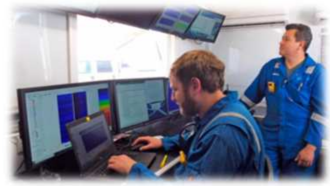

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Hydraulic Fracturing design 'workflow'

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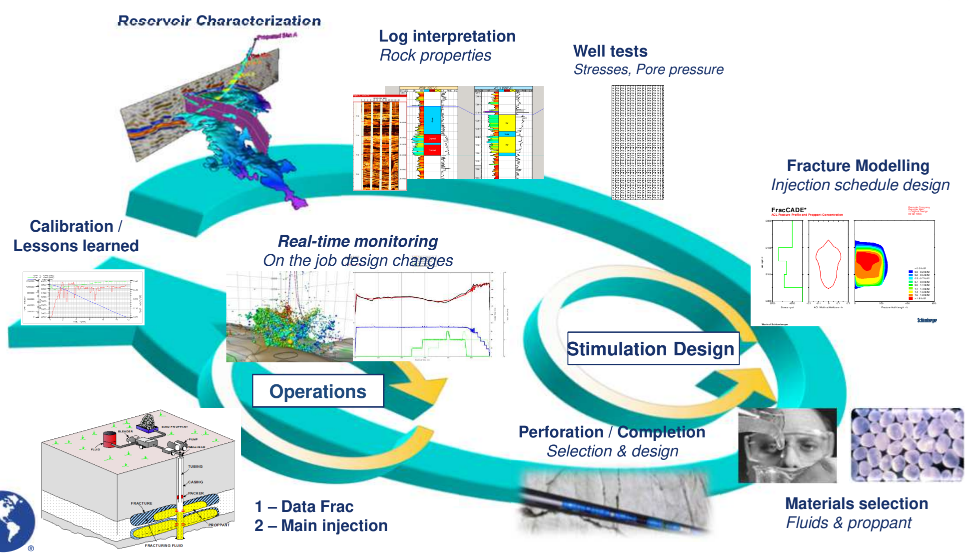
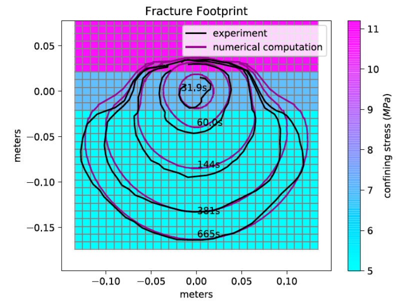
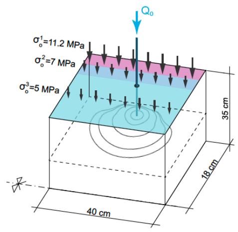


Complexity depends on criticality of the job: *from hours to months of preparation*

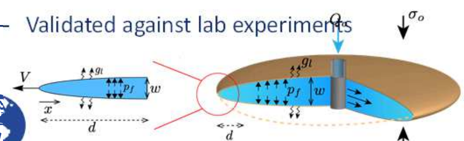
Hydraulic fracture modeling

- Planar 3D fluid driven fracture propagation (tensile mode)
  - Inhomogeneous confining stress material properties, transverse Isotropy, fluid rheologies
  - Growth and closure, complex injection sequence
  - Fully benchmarked on existing HF growth solutions
    Detournay, ARFM (2016)
    Lecampion et al., IJNGSE (2018)
  - Validated against lab experiments





Zia & Lecampion (2019) - Experiment of Wu *et al.* (2008)



Pyfrac – an open source solver:
https://github.com/GeoEnergyLab-EPFL/PyFrac

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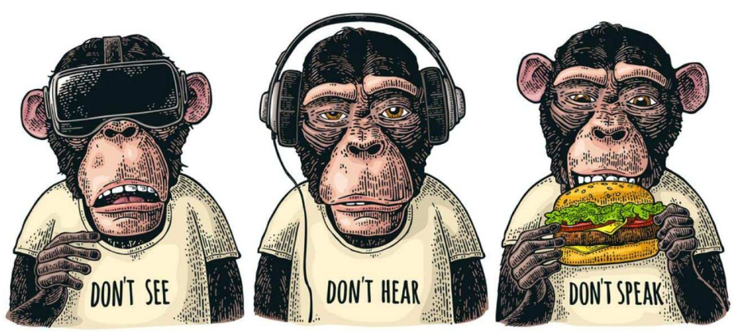
Geothermal hydraulic stimulation design ?



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EGS stimulation examples

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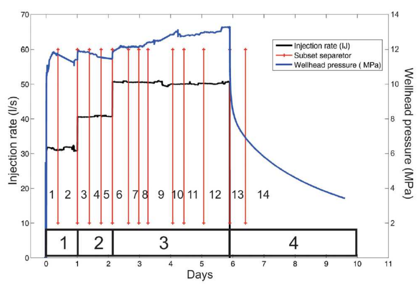
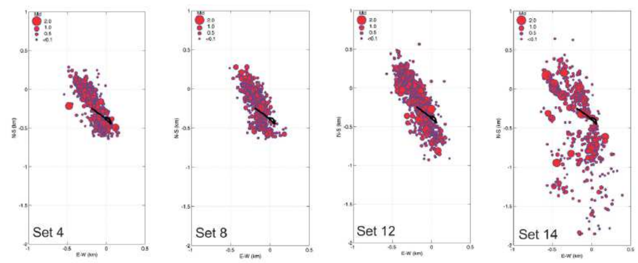
GPK-2 Soultz-sous-Forêts





Seismic clouds 25º from SH direction
Larger features activated after shut-in

Inj. Vol. 23400m^3 (GPK-2)
P smaller (but close) to Sh
Flow in discrete zones along the OH section
(meters thick fractured zones)

Prior to injection 17 fractures identified as permeable, 95 after stimulation
17 fold increase in hydraulic transmissivity

EGS stimulation examples

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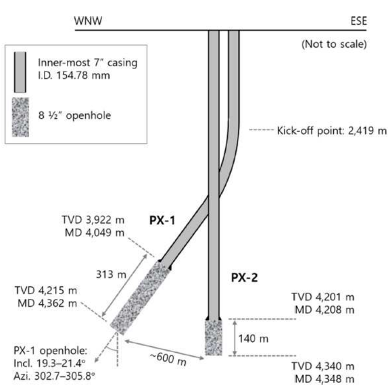
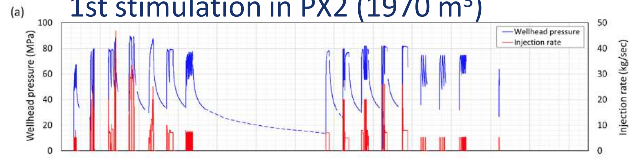
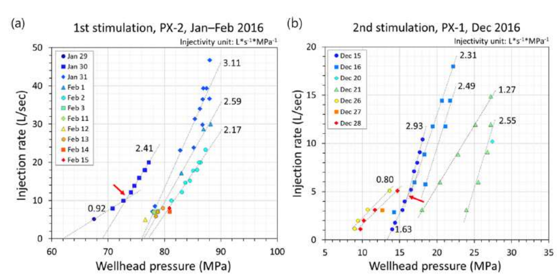
Pohang



1st stimulation in PX2 (1970 m^3)





Taken from Park *et al.* *Geothermics* 2020

5 stimulations (2 in PX1, 3 in PX2)
Mw 5.5 2 months after the last stimulations

EGS stimulation examples

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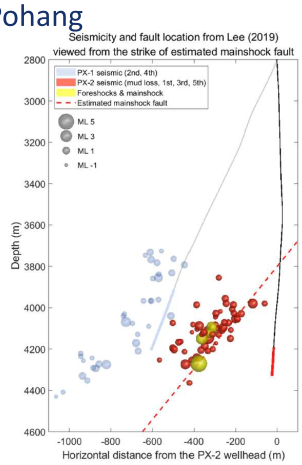
Pohang



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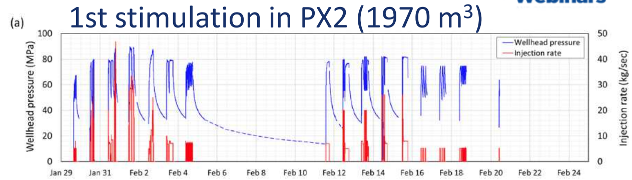

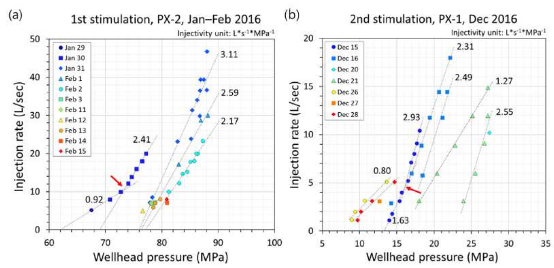

Taken from Park *et al.* *Geothermics* 2020

5 stimulations (2 in PX1, 3 in PX2)
Mw 5.5 2 months after the last stimulations

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EGS stimulation examples

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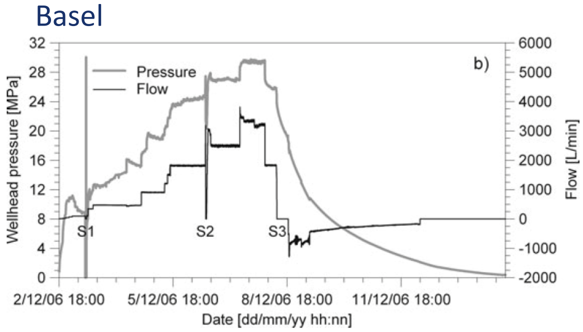
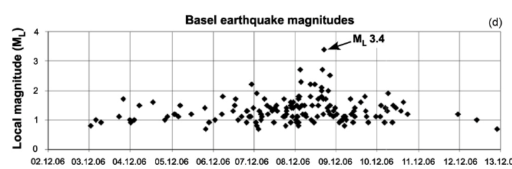
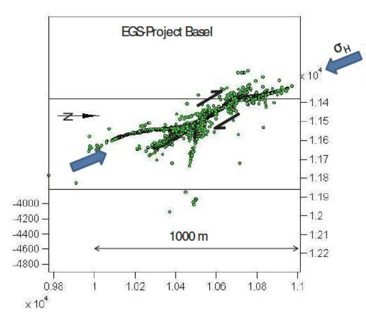
Basel





Taken from Haring *et al.* (2008)

Basel-I (5000m TVD)
371m long open-hole (8”1/2)
Injected volume 1170 m^3
Project stopped after the occurrence of a M_L 3.4 (after shut-in)
Max injection pressure close to Sh
Likely shear fluid-driven fractures combined with opening (Wing crack)



Taken from Jung (2013)

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Fracture constitutive relations

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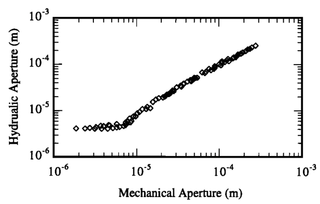
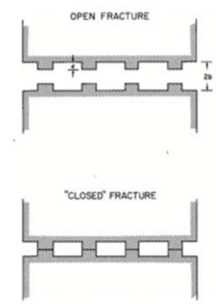
- When mechanically open – fractures in rocks are "hydraulic fractures"
  - Poiseuille (cubic) law apply: extremely strong H-M coupling
- Under compressive effective stress (when mechanically closed/in contact), fracture compliance and hydraulic transmissivity are strongly non-linear (with effective stress)



Witherspoon *et al*, *WRR* (1980)
Renshaw *JGR* (1995)



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(closed) Fracture constitutive relations

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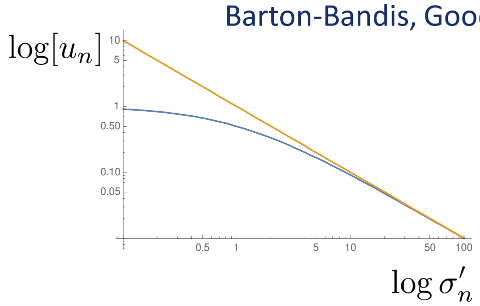
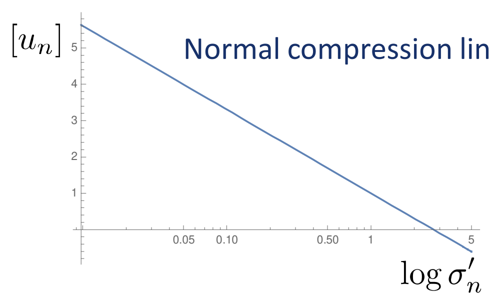
- Non-linear elasticity (contact area increases with compressive effective stress)

Barton-Bandis, Goodmann





Shear stiffness taken as a 'fraction' of normal stiffness

$\sigma'_n > 0$ in compression

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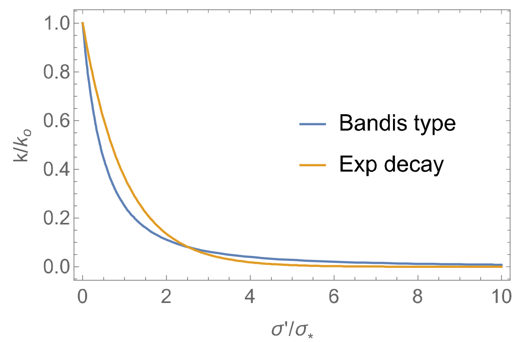
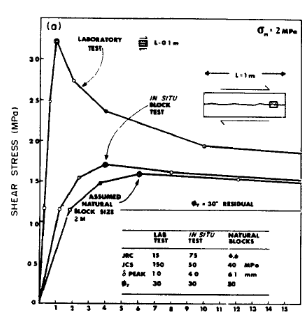
Permeability non-linearity with effective stress

- Either cubic law with non-linear stiffness
  or directly via exponential relation with normal effective stress



Friction $\|\tau\| \leq f(\chi) \times \sigma'_n$

- At normal effective stress lower than 100MPa (depths<5.5km)
  - f_{peak} *~ 0.85* (with a <u>huge</u> scatter)
  - At effective stress below 10-20MPa (Barton *et al* – for rock Joints)



$$f = \tan\left(JRC \log \frac{JCS}{\sigma'_n} + \phi_r\right) \qquad JRC \in [0-15] \quad JCS \in [20-150]\text{MPa}$$

JRC decreases with slip beyond a peak value to 0 at large slip (softening)
Associated dilation angle (decreases with slip up to critical state)

$$\frac{[\dot{u}_n^p]}{[\dot{u}_s^p]} = \tan\psi(\chi) \qquad \psi = \frac{JRC}{2}\log\frac{JCS}{\sigma'_n}$$

Be careful in lab tests:
effect of sample size (shear strength decreases with size)
is effective normal stress constant ?

Barton *et al.* (1985)
Barton, (1976)
Byerlee (1976)

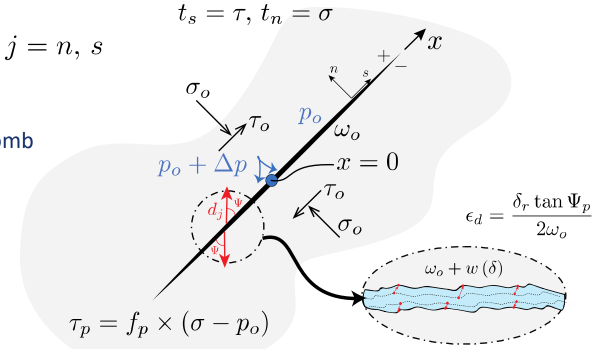
A model for hydro-shearing

- Quasi-static elasticity

$$t_i(x,t) = t_i^o(x) + \int_{-a}^{a} K_{ij}(\xi, x) d_j(\xi, t) \mathrm{d}\xi, \text{ for } i,\, j = n,\, s$$

$d_s = \delta,\ d_n = w$

$t_s = \tau,\ t_n = \sigma$



$\epsilon_d = \dfrac{\delta_r \tan \Psi_p}{2\omega_o}$

- Fault behavior- Non-associated Mohr-Coulomb

$$F(\tau, \sigma'; \delta) = |\tau| - f(\delta)\sigma' \leq 0$$

$$\dot{d}_i = \lambda \frac{\partial G}{\partial t'_i}$$

$$G(\tau, \sigma'_n; \delta) = |\tau| - \tan(\psi(\delta))\, \sigma'$$

$\tau_p = f_p \times (\sigma - p_o)$

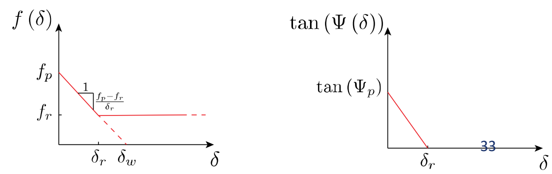
$\tau_r = f_r \times (\sigma - p_o)$

Ciardo & Lecampion, JGR (2019)

- Fluid flow – (restricted to the fault)

$$\beta \omega_o \frac{\partial p}{\partial t} + \frac{\partial w}{\partial t} + \frac{\partial w V}{\partial x} = 0$$

$$wV = -\frac{w k_f}{\mu} \frac{\partial p}{\partial x} \qquad \alpha = k_f / (\beta \mu)$$



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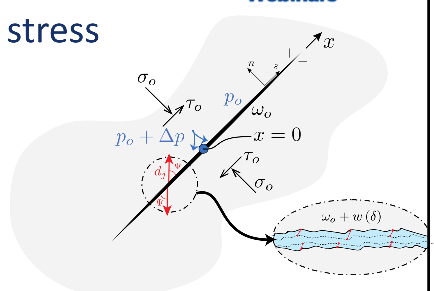
Scaling – accounting for friction weakening

- σ'_o characteristic pressure & effective normal stress
- $\tau_p = f_p \sigma'_o$ characteristic shear stress
- δ_w characteristic slip scale
- $a_w = \dfrac{G}{2\tau_p}\delta_w$ characteristic nucleation length-scale
- $\sqrt{\alpha t}$ Pressure front location length-scale



$$\left(\frac{\delta}{\delta_w}, \frac{\tau}{\tau_p}, \frac{\sigma}{\sigma'_o}, \frac{p - p_o}{\sigma'_o}, \frac{a}{a_w}\right) = \mathcal{F}\left(\frac{\tau_o}{\tau_p}, \frac{f_r}{f_p}, \frac{\Delta p}{\sigma'_o}, \frac{\epsilon_d}{\beta \sigma'_o}; \frac{x}{a_w}, \frac{\alpha t}{a_w^2}\right)$$

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Constant friction case

It is possible to further show that the solution only depends on

$$T = (1 - S)/P$$

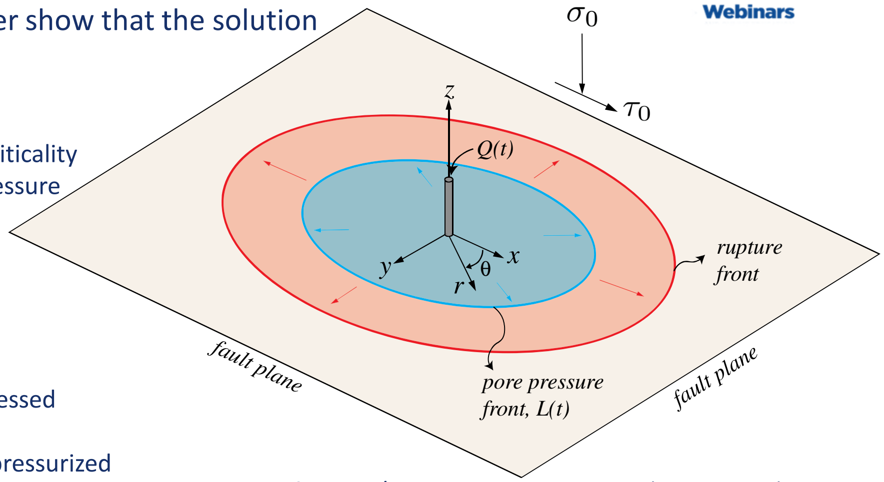
S: dimensionless stress criticality
P: dimensionless over-pressure

$$T = \frac{f\sigma'_o - \tau_o}{f\Delta p}$$

$$\Delta p = \frac{Q\mu}{4\pi kh}$$

$T \ll 1$ Critically stressed

$T \gg 1$ Marginally pressurized



For constant friction / constant transmissivity (ct injection)
The rupture and fluid front evolves in self-similar manner

$$L_f(t) \propto \sqrt{\alpha t} \qquad R(t) \propto \sqrt{\alpha t} \qquad \gamma = R/L_f$$

Bhattacharya & Viesca, *Sci.* (2019)
Saez *et al*, in prep. (2021)

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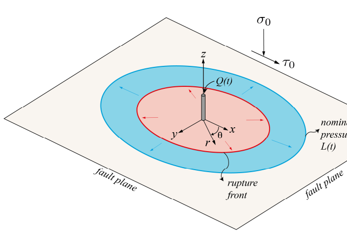

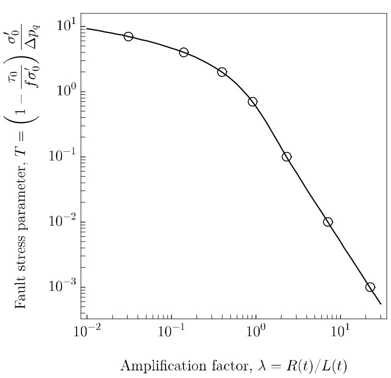

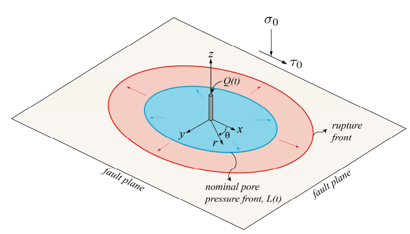

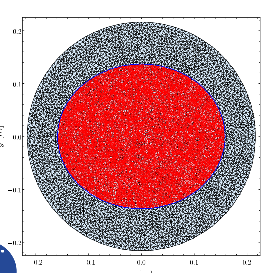

$$A_r(t) = 4\pi\alpha\lambda^2 t$$

Sàez *et al*, in prep. (2021)

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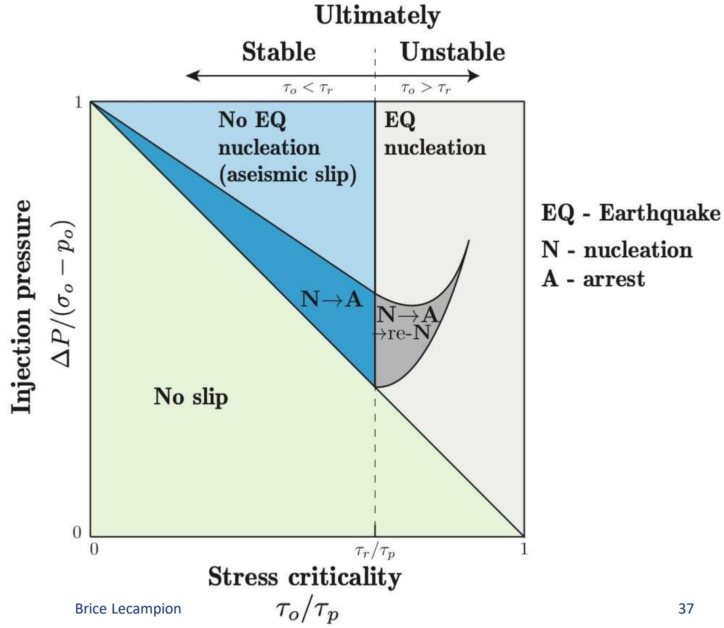
Frictional weakening – EQ nucleation diagram

- Linear weakening of friction
- with slip
- Constant injection overpressure
- Constant fault permeability
- No dilatancy



Adapted from
Garagash & Germanovich *JGR, (2012)*
Ciardo & Lecampion, *JGR, (2019)*

Undrained fault response: dilatant hardening

Over short-time scales, the fluid has no time to flow to balance the variation of volume

$$\omega_o \beta \Delta p_u + \Delta w = 0 \rightarrow \Delta p_u = -\frac{\Delta w}{\omega_o \beta} = -\frac{\epsilon_d}{\beta}$$

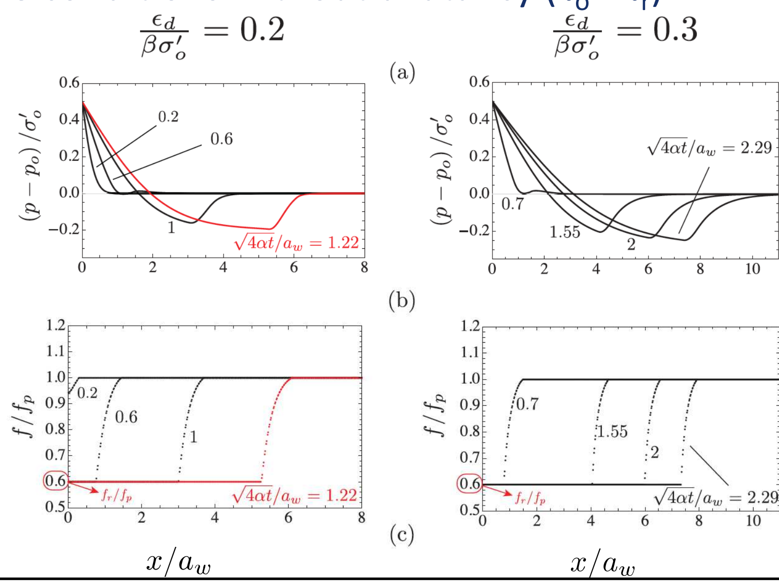
The associated pore-pressure drops locally strengthen the fault

$$\tau_r^u = \tau_r - f_r \Delta p_u = \tau_r \left(1 + \frac{\epsilon_d}{\beta \sigma_o'}\right)$$

Rice & Rudnicki, *JGR* (1979)
Ciardo & Lecampion, *JGR, (2019)*

The stabilizing effect of dilatancy

- Unstable conditions without dilatancy ($\tau_o > \tau_r$)

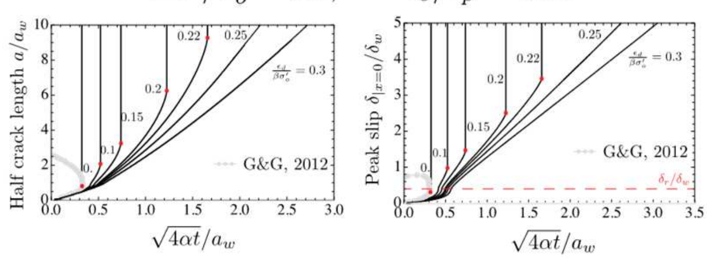


Ciardo & Lecampion, *JGR, (2019)*

The stabilizing effect of dilatancy

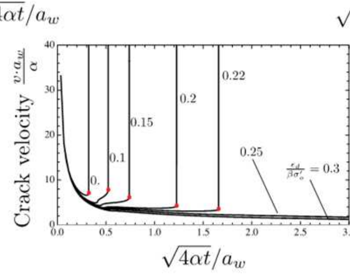
- Unstable conditions without dilatancy ($\tau_o > \tau_r$)

$$\Delta P/\sigma'_o = 0.5, \quad \tau_o/\tau_p = 0.75$$



$$f_r/f_p = 0.6$$

$$\frac{\epsilon_d^c}{\beta\sigma'_o} = 0.25$$



Ciardo & Lecampion, *JGR, (2019)*

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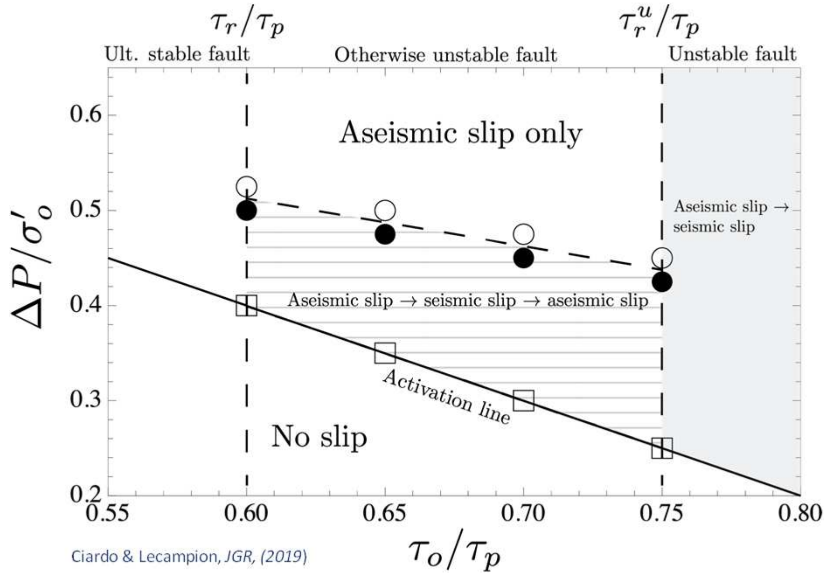
Effect of injection over-pressure

Webinars



Ciardo & Lecampion, *JGR, (2019)*

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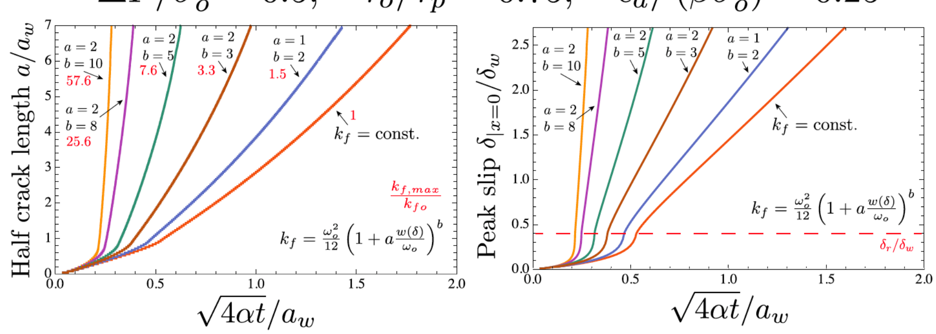
Non-linear increase of fault transmissivity

Webinars

$$\Delta P/\sigma'_o = 0.5, \quad \tau_o/\tau_p = 0.75, \quad \epsilon_d/\left(\beta\sigma'_o\right) = 0.25$$



- Acceleration as fault hydraulic transmissivity increases (non-linearly) with slip (or decreases with effective normal stress)
- … but no effect on the nucleation of dynamic rupture

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Some thoughts (in relation to EGS)

- Multi-stages stimulation please !
  - Long OH sections should simply be abandoned
- Never stimulate a large scale discontinuity (or near by)
- Combined shear + opening mode fracturing prevails
- Prefer hydraulic fracturing (if you can)
- Characterize the in-situ stress field in details
  - Estimate T !
  - Characterize the pre-existing fractures
- Monitoring seismicity is required
  - but do not simply rely on "Traffic Light Systems" without proper stress characterization and modeling

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Conclusions

- The development of hydro-thermal systems will (hopefully) accelerate
  - Risks are lower, the technologies are mature
  - Sedimentary rocks make things much easier
  - Hydraulic fracturing can unlock some lower perm plays
- Deep enhanced geothermal systems
  - Suffer from lack of investment & limited return of experience
  - Oil and gas know-how can (and will) make a difference
  - Geomechanics (stress-field characterization, fluid-driven fracture mechanics) is a key discipline
    - Combined shear and opening mode hydraulic fracture models needs to be pushed further to improve stimulation design
      - Understanding of propagation regimes still in its infancy
      - Verification examples are critical
      - … as well as carefully monitored scaled down lab experiments

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