COMSOL CONFERENCE ROTTERDAM2013

Modelling Seismicity Due to Reservoir Stimulation in Enhanced Geothermal Systems

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Main Goals

- Identify the crucial parameter to describe induced/triggered seismicity: Pressure or Coulomb stress changes?
- Propose a way to evaluate permeability enhancement in EGS stimulation

TOUGH2 (Pruess, 1991)

Fluid flux: $F = -K\,\mu\rho\,(\nabla P - \rho g)$

Heat flux: $F_H = -\lambda\nabla T + hF$

where K is the permeability
μ is the viscosity
h is specific enthalpy
λ is the thermal conductivity

COMSOL Multiphysic

Compute the stress tensor at each volume grid point from T and P changes computed by THOUGH2.
Displacement sources are of the kind:

$$\Delta P + \frac{2G(1+\nu)\alpha}{3(1-2\nu)}\Delta T$$

G=shear modulus
ν= Poisson's ratio
α = termal expansion

Coulomb Stress

$$\Delta\sigma_f = \Delta\tau_s + \mu(\Delta\sigma_n - \Delta P)$$

where $\Delta\tau_s$ is the shear stress change
$\Delta\sigma_n$ is the change of stress normal to the plane
ΔP is the pore pressure change and μ is the friction coefficient.

Permeability enhancement

$$k' = \begin{cases} 1 - \left(\frac{1}{K_n b} + \frac{1}{K_n s} + \frac{1}{E}\right)\left[\nabla\sigma_i - v(\nabla\sigma_j + \nabla\sigma_k)\right] + \\ -\left(\frac{1}{K_n b} + \frac{1}{K_n s} + \frac{1}{E}\right)\left[\nabla\sigma_j - v(\nabla\sigma_i + \nabla\sigma_k)\right] \end{cases}$$

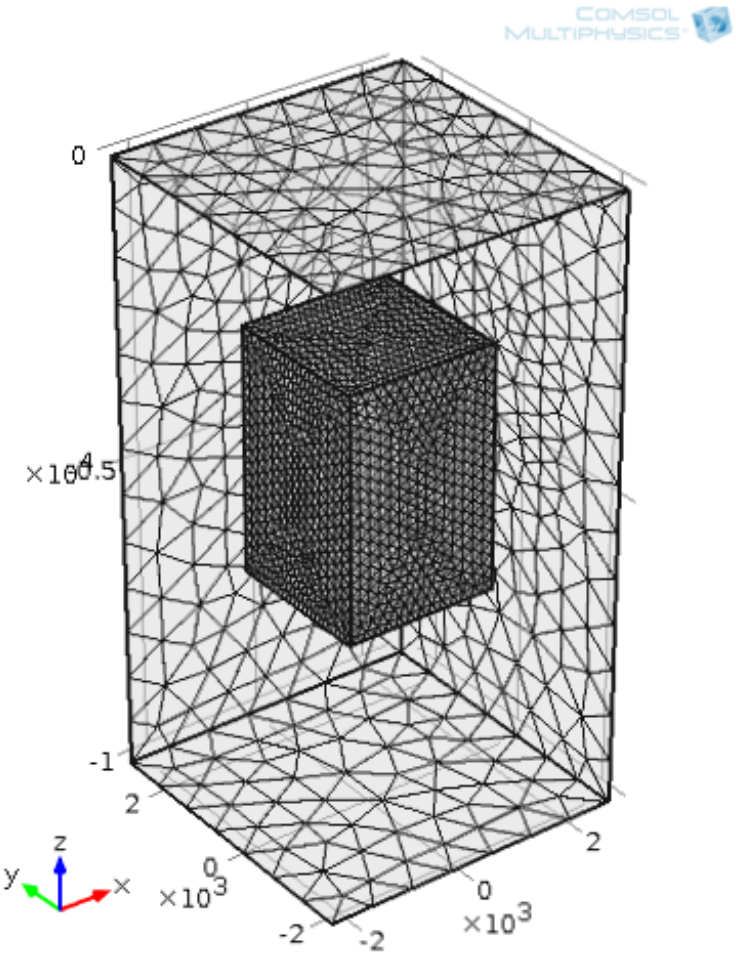
An homogeneous medium of $1.8*10^{-16}$ m^2 permeability has been assumed.

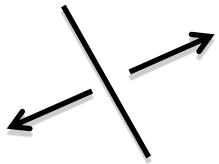
1. Appropriate initial condition, boundary condition and rocks physical parameters are assumed.

2. Cold water is injected at -5000 m depth.

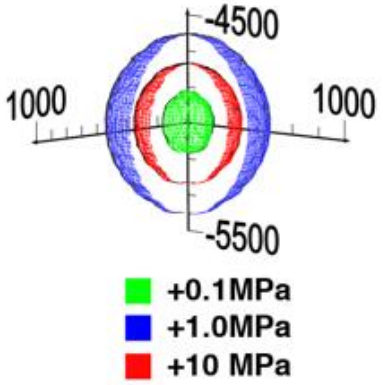
3. A continuous water injection cycle of 16 days is simulated.

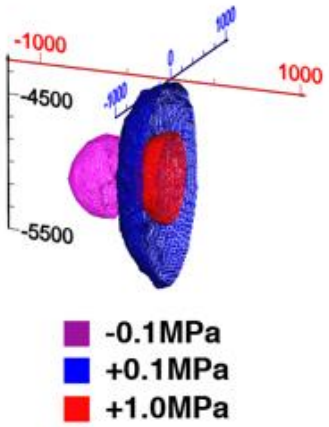
4. Tectonic stress 3 MPa, with $\sigma_3 \rightarrow$N110° W, $\sigma_1 \rightarrow$Vertical



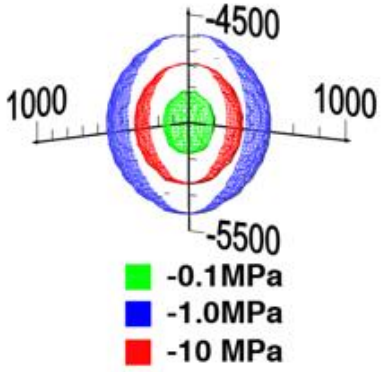


Tectonic Stress
$\sigma_3 \rightarrow$N110° W

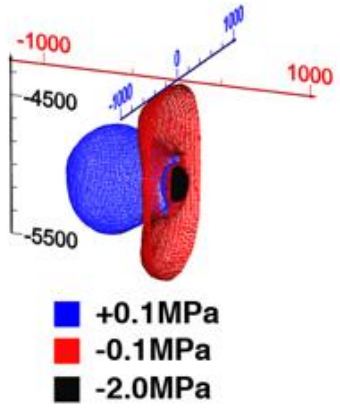




Water injection



ΔP (MPa)

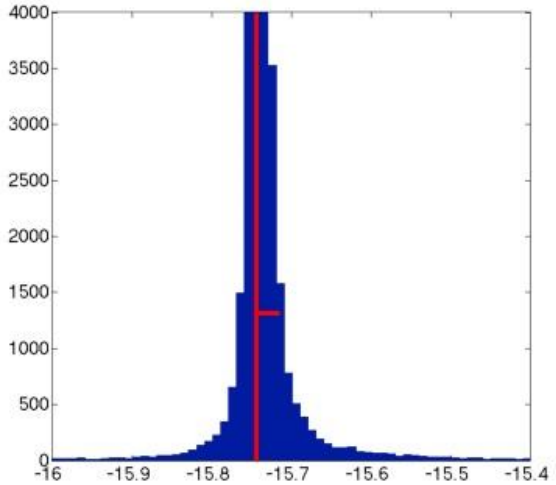


$\Delta\sigma_c$ (MPa)

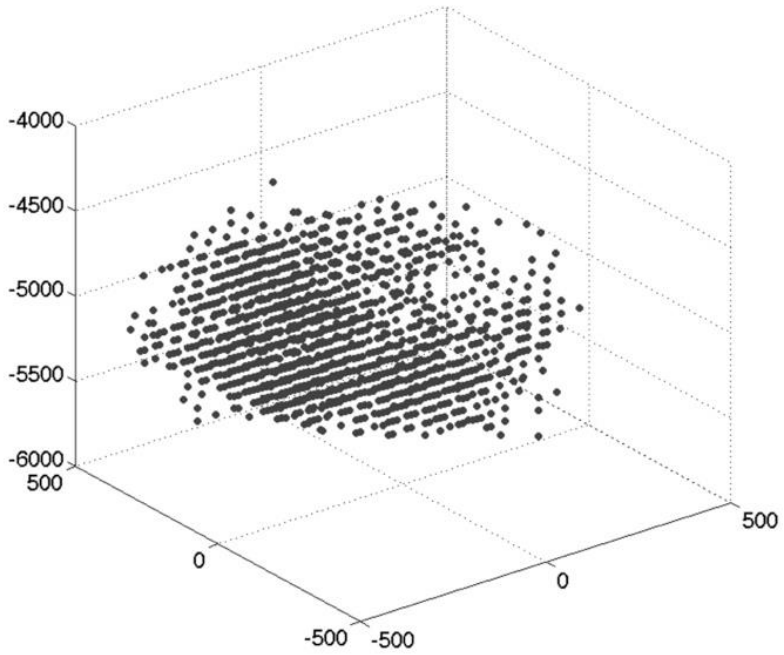
Water withdrawal

Pressure changes

Coulomb Stress changes



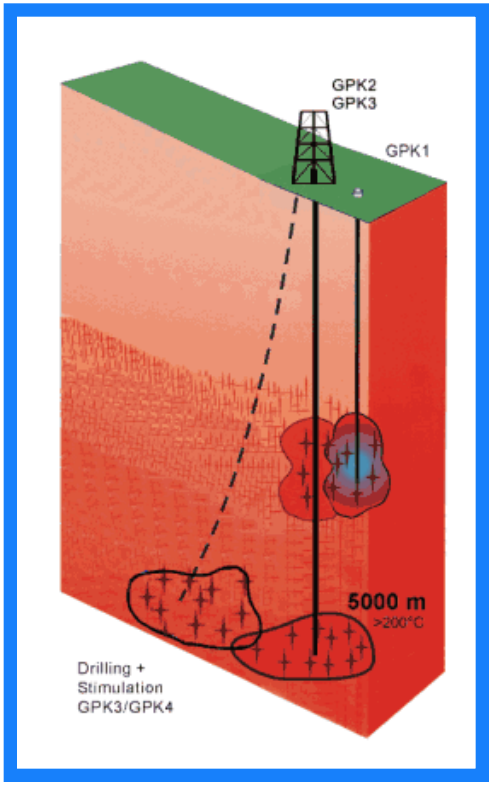
Histogram of k', the new medium permeability after fluid stimulation.
The histogram show a gaussian distribution of permeability values around the volume, centered around k_0, the initial permeability value.
Mean value and standard deviation are represented with the red lines. Only the values exceeding one standard deviation have been selected to evaluate the permeability enhancement.

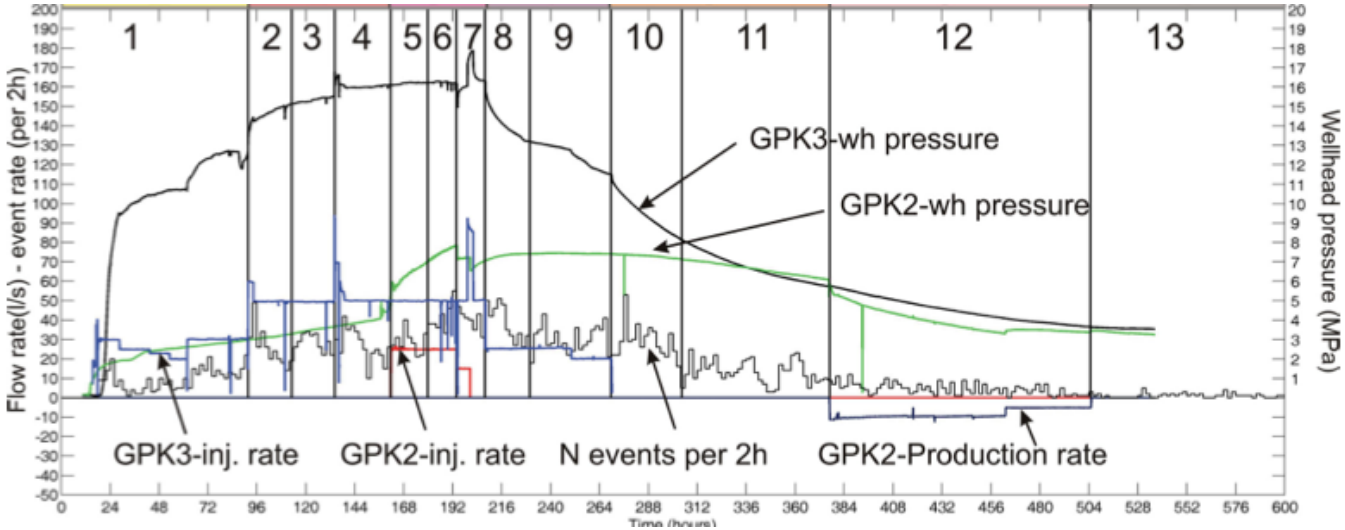


$k_0 = 1*10^{-16}\ m^2$

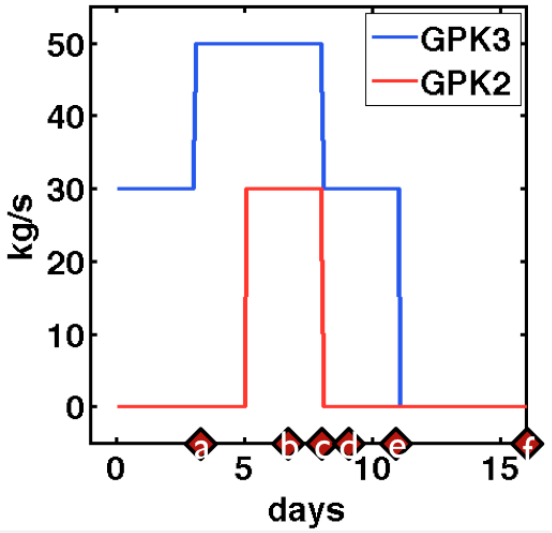
$k' = 4.2*10^{-16}\ m^2$

Estimate of the Volume where permeability has been enhanced due to fluid stimulation



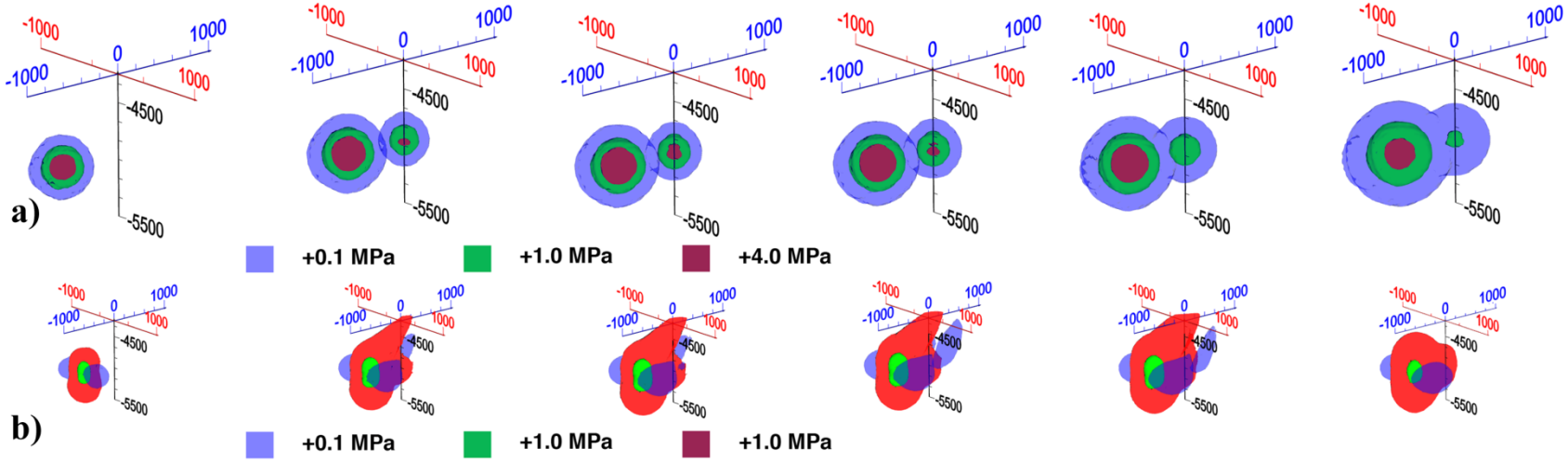


Reproducing a real case: Soultz sous Forets

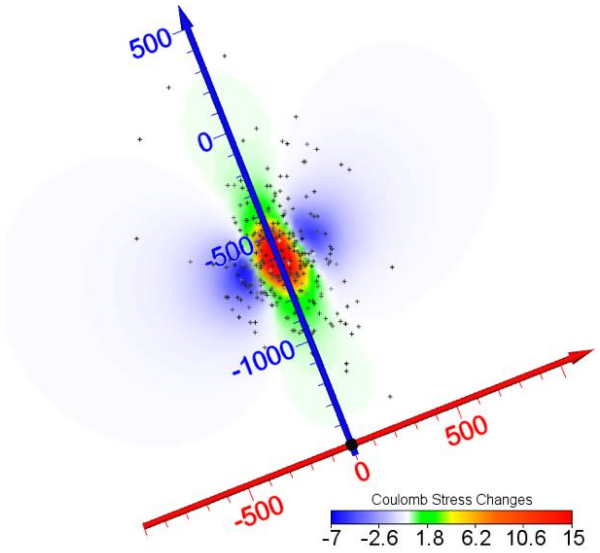


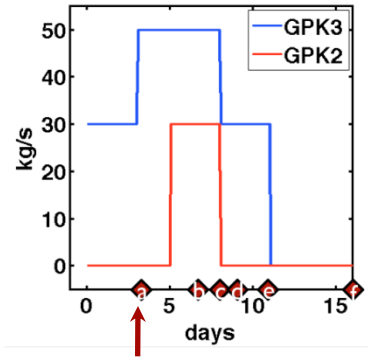
Right: water injection rates simulating the Soltz stimulations

Bottom: a) Pressure and b) Coulomb stress changes at the six times indicated by letters on the injection rate/time diagram

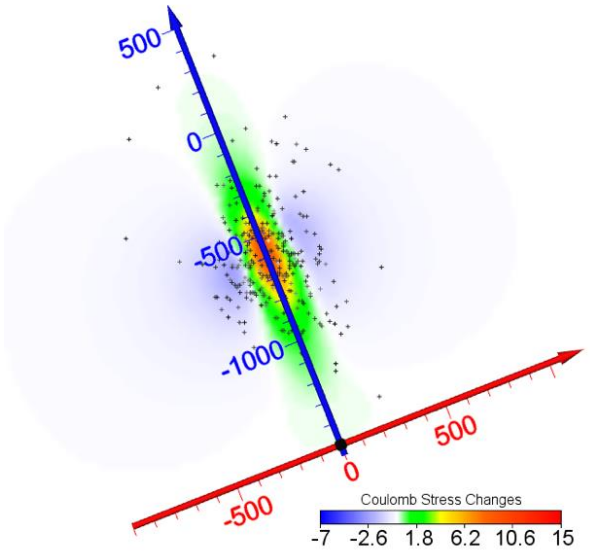


Isotropic permeability

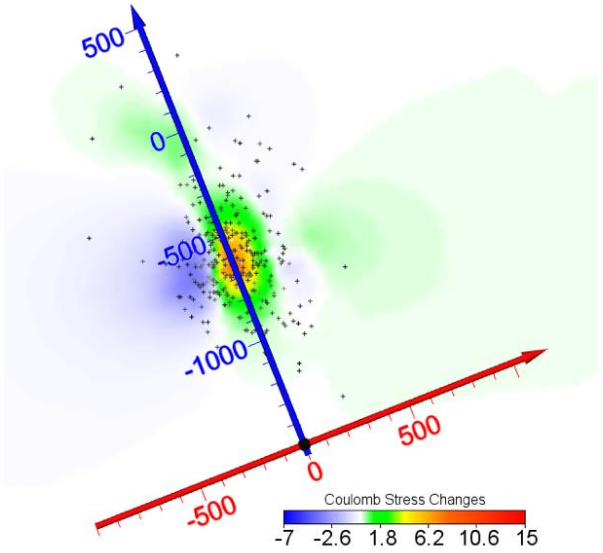




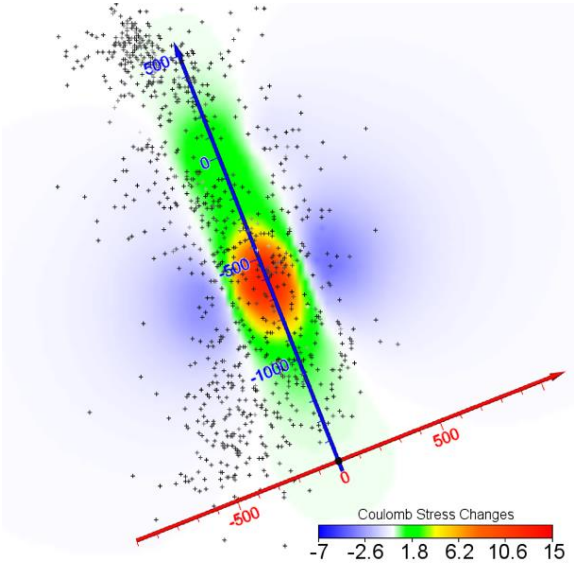
Anisotropic permeability



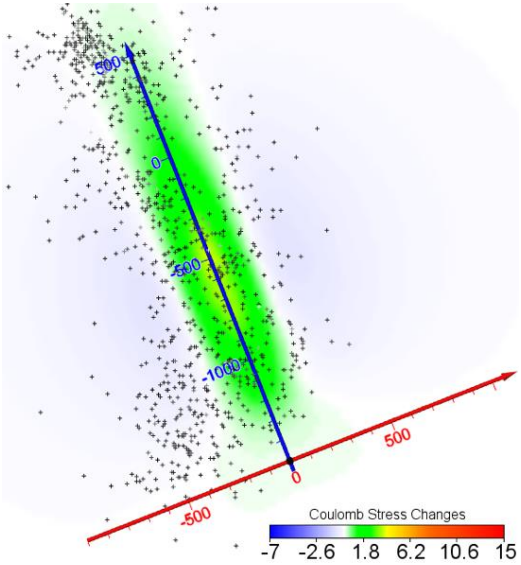
Enhanced permeability



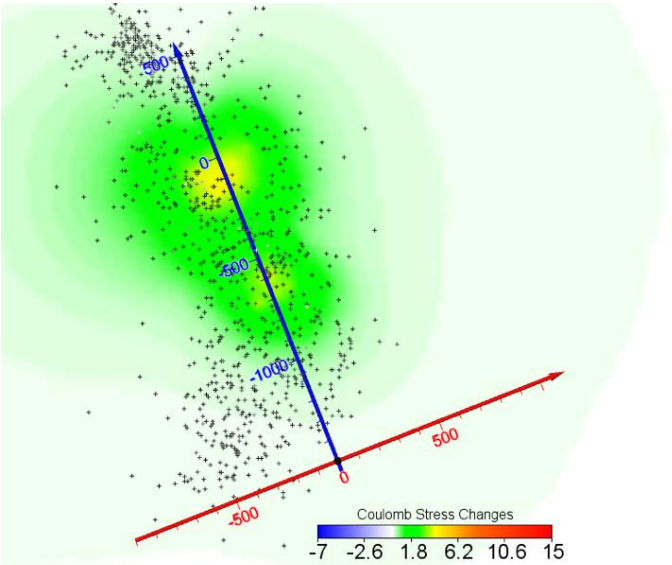
Isotropic permeability

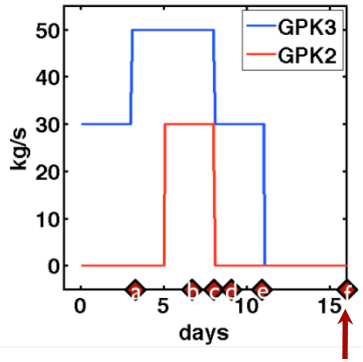


Anisotropic permeability

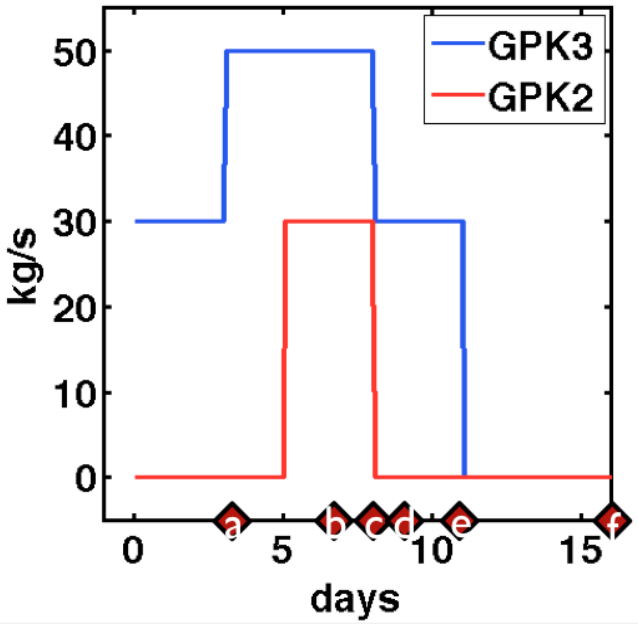


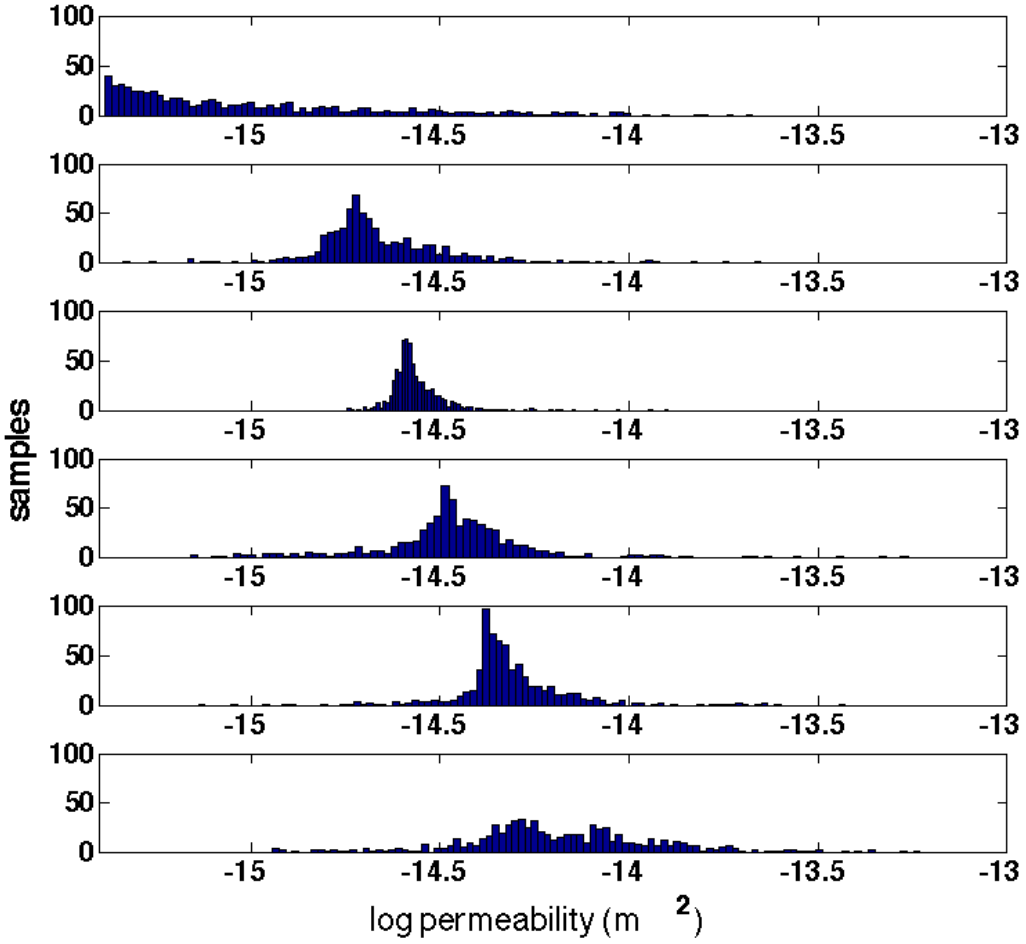
Enhanced permeability

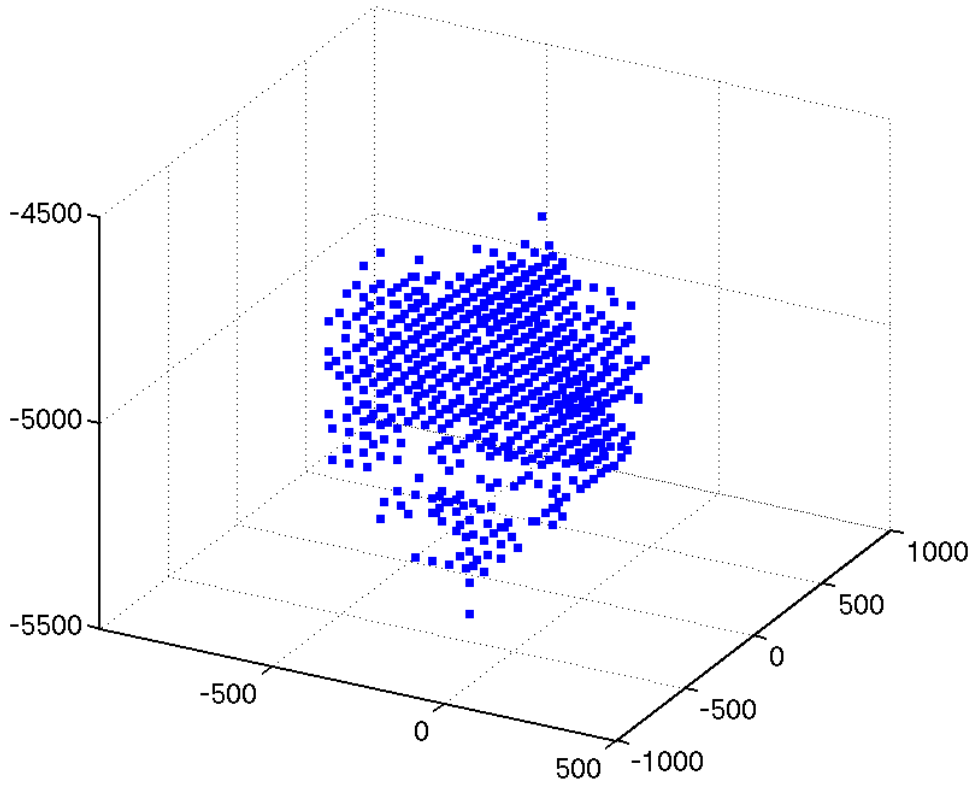




The histograms show the samples extracted from k', the new medium permeability after fluid stimulation, exceeding the mean value of the whole permeability distribution more than 1 standard deviation.
Every plot is related to a different time sample, ranging from a to f (fig. below).







$k = 1*10^{-16}$

$k' = 8*10^{-15}$

Estimate of the Volume where permeability has been enhanced due to fluid stimulation

- These simulations show that Coulomb stress changes, rather than simple pore pressure, control the induced seismicity during pumping and withdrawal activity in deep boreholes.

- They also indicate we can at some extent to theoretically predict the seismically activated volumes during such activities, including EGS reservoir stimulation.

- Thus, we have a powerful method to control both permeability enhancement and seismogenic potential, in order to prevent, in the future, they can approach a critical threshold to cause disasters