Seismicity induced by hydraulic stimulation – seismic efficiency of injection

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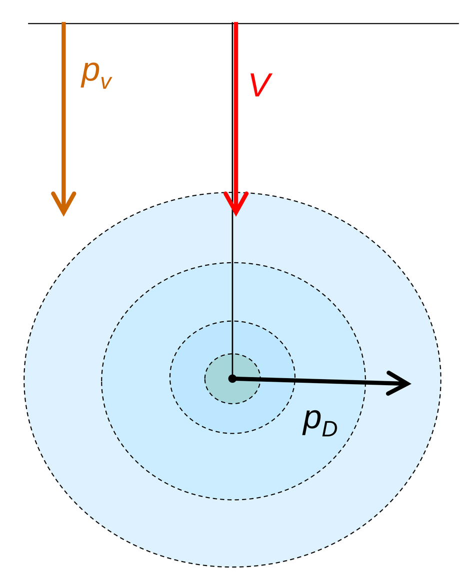
Summary

Hydraulic fracturing of rocks is accompanied by induced microseismicity, which enables imaging of the fracture, but can cause seismic risk of these operations. The number of events and their magnitude depends on injected hydraulic energy, geology, stress state and many other factors. We quantify the associated seismic risk by the parameter of seismic efficiency of injection η_i as the ratio of released seismic moment and injected hydraulic energy. Application to three data sets shows that eta ranges from 10^{-6} in sediment formations to 10^{0} in crystalline rocks. The rather stable evolution in time enables rough prediction of the seismic risk from the first period of stimulation.

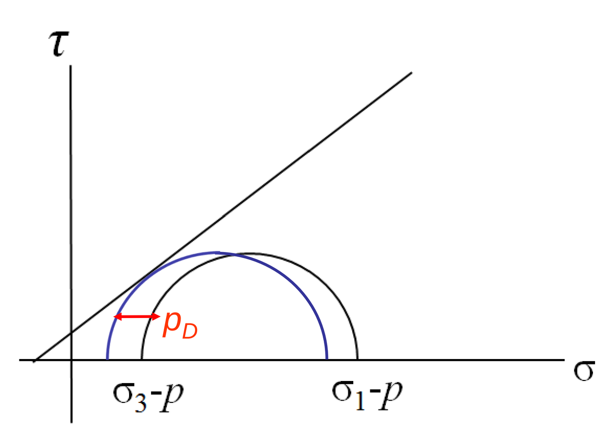
Motivation

Hydraulic fracturing: Method using high-pressurized fluid injection in the well to increase permeability of reservoir. Enhanced fluid pressure causes decrease of effective stress brings the rock close to failure. This is expressed in shift of the Mohr's circle to the left and as the circle touches the strength envelope, the rock fails either in shear or tensile mode, which is accompanied by the radiation of seismic waves.



The observations of injection-induced seismicity show that different injections generate a wide range of event magnitudes. This accounts probably for different level of accumulated strain energy in the rock formation.

We aim for quantifying the amount of injected hydraulic energy and the energy released in seismic events in different environments



Theory

Injected hydraulic energy is calculated as product of downhole fluid pressure (p_D) and total volume (V) of injected fluid (Gibbs et al., 1973):

$$E_H = p_D V$$

The total radiated energy is proportional to the product of lithostatic stress (p_v), static seismic moment (M_0) and shear modulus (μ):

$$E_S = \frac{p_V M_0}{\mu}$$

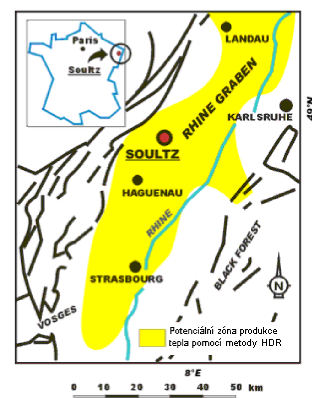
We define the ratio of total released and hydraulic energy as seismic efficiency of hydraulic injection:

$$\eta_i = \frac{E_S}{E_H} = \frac{p_V M_0}{\mu p_D V}$$

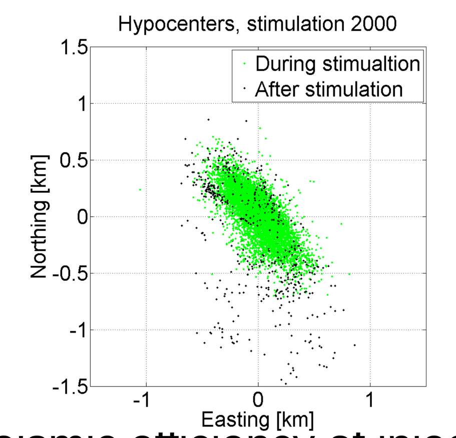
High magnitudes of seismic efficiency of injection (η_i>1) indicate the release of accumulated strain energy by fracturing, which is often termed as the triggered seismicity. Small magnitudes of eta show that only hydraulic energy is converted to the seismic energy (induced seismicity). The uncertainty of eta is rather high; it originates from the uncertainty of hydraulic energy and of seismic moment determination. In particular, p_D is converted to seismic energy only partially; a significant part corresponds to the elastic rock deformation.

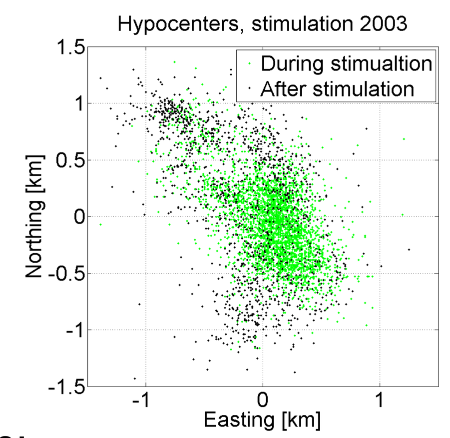
Soultz-sous-Forets (Cuenot et al., 2006)

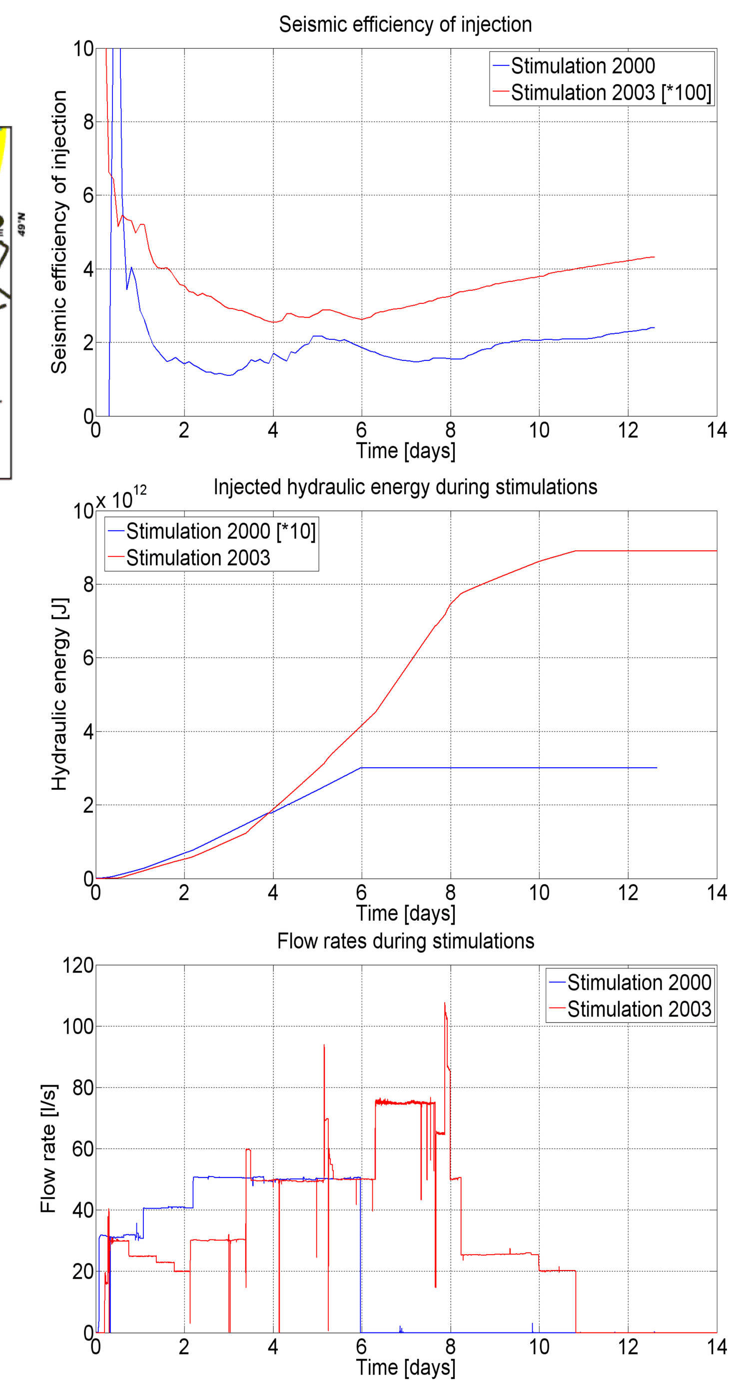
Stimulation 2000, well GPK2:
23,400 m³ of fluid injected,
depth 4400-5000 m, fluid pressure up to 13 MPa flow rates up to 50 l/s,
More than 10,000 located events, M_L<2.5.



Stimulation 2003, well GPK3:
37,000 m³ of fluid injected,
depth 4400-5000 m, fluid pressure up to 16 MPa, flow rates up to 90 l/s,
More than 5,000 located events, M_L<2.9.



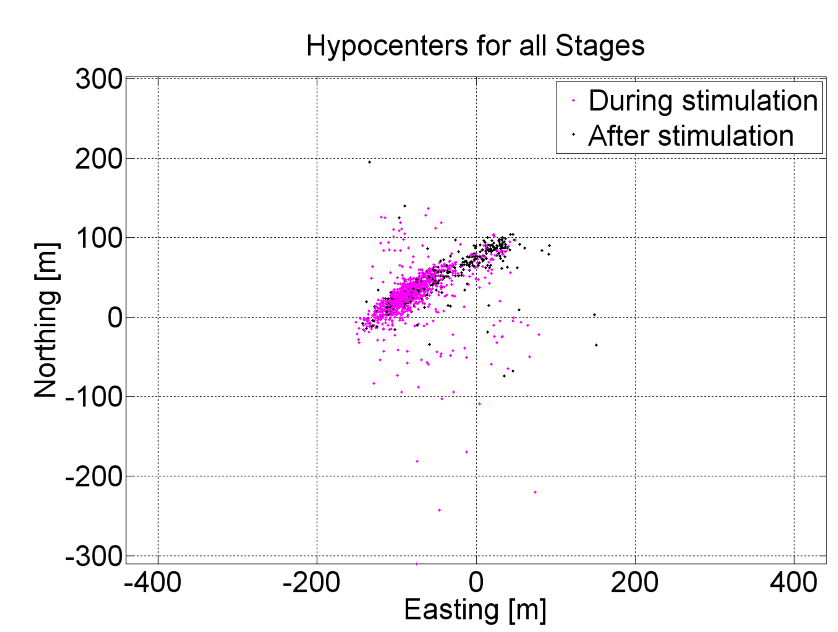


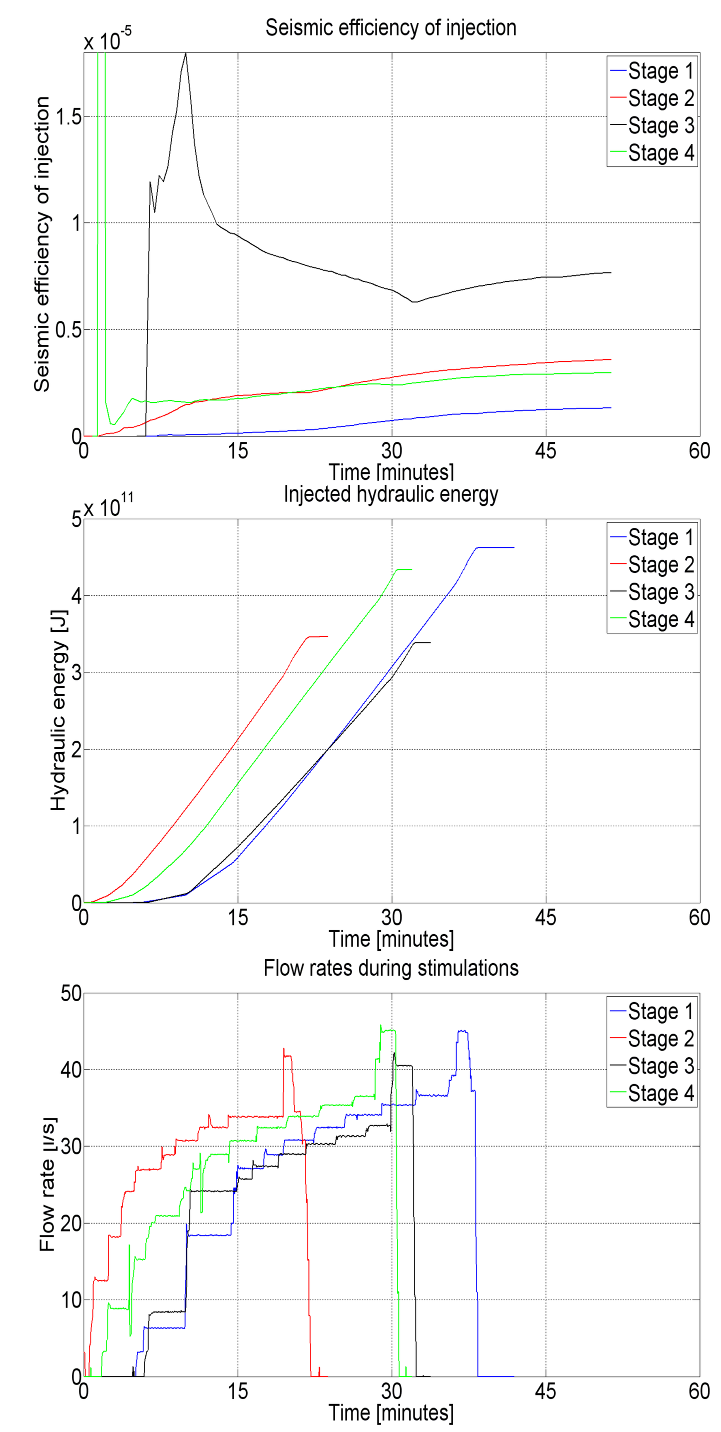


Seismic efficiency of injection:
- Decreases in the beginning of injection
- Slow increase after injection
- Values about 1 (year 2000), 0.05 (year 2003)
- Stable range during treatment after decrease the start

Canyon Sands (Fischer et al. 2008)

Totally 6 stages in depth interval 1518-1858 m.
Each stage – stimulation of different depth horizon
Flow rates up to 100 l/s.
Wellhead pressures between 25 and 30 MPa.
About 100 m³ of water and 20 m³ of proppant during stimulation of each stage.
Very low magnitudes up to M_W<-1.5
Stages 1-4 analyzed in this study.





Seismic efficiency of injection:
- Decrease in the beginning of injection only for two Stages; probably caused by former stimulations
- Values stable in range 10^{-5} to 10^{-4} during treatment

Acknowledgments

The study was possible thanks to the data provided by Albert Genter (GEIE Exploitation Minière de la Chaleur, France) and James Rutledge.

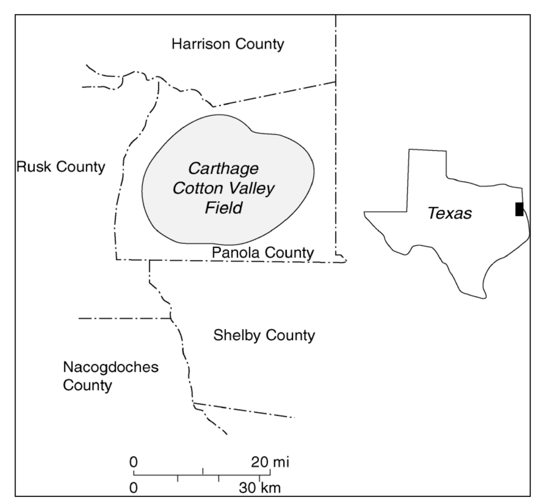
Cotton Valley (Rutledge, Phillips, 2003)

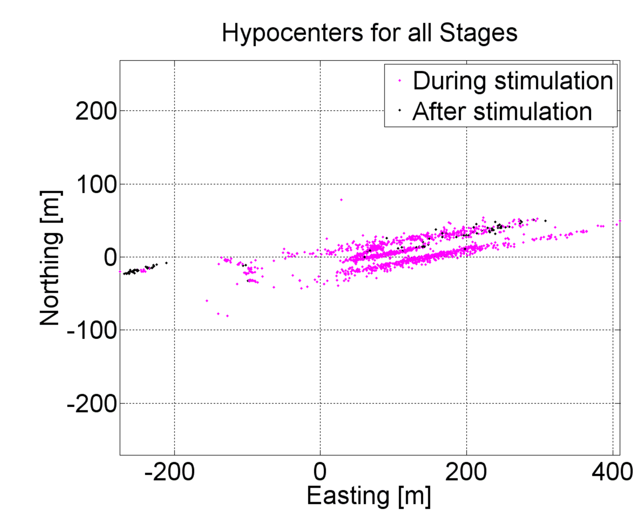
Several stages and stimulations

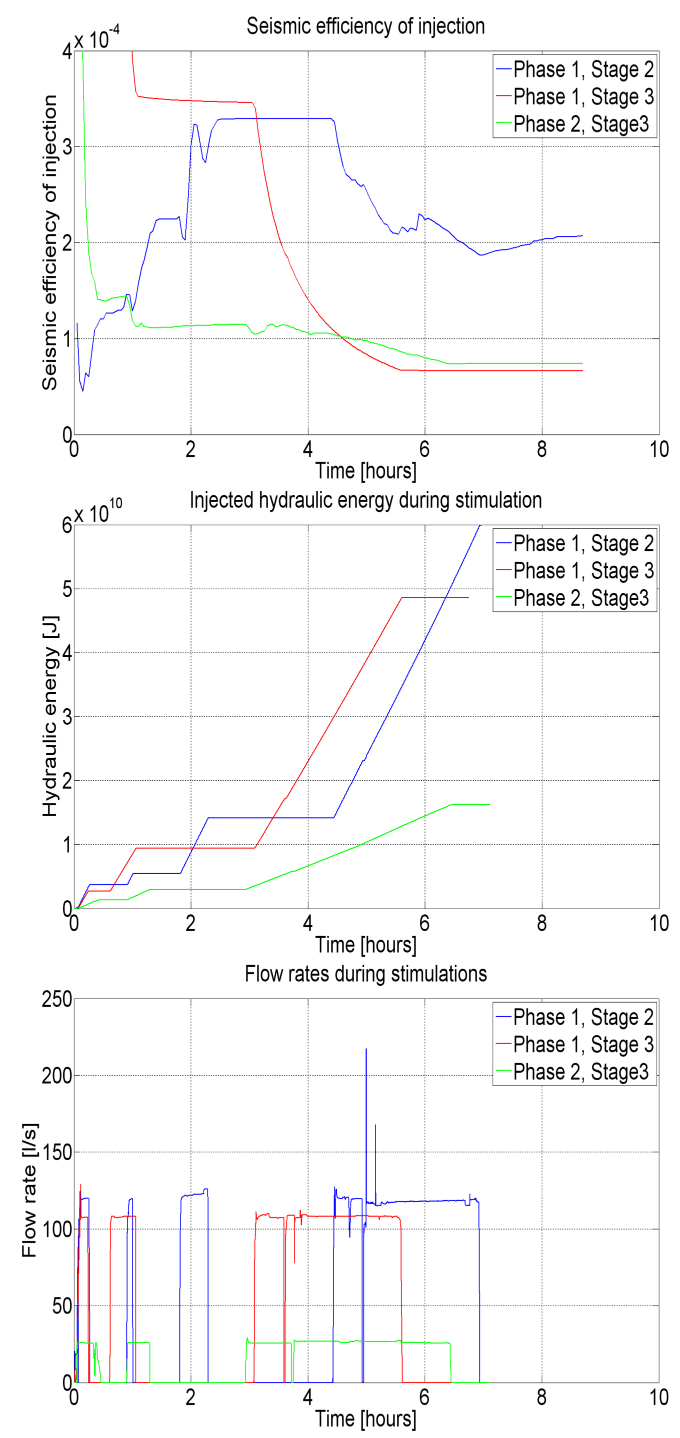
Phase 1, Stage 2:
1340 m³ of fluids injected,
depth 2800 m,
flow rate up to 120 l/s,
almost 900 located events,
M_W<-0.6.

Phase 1, Stage 3:
1250 m³ of fluids injected,
depth 2800 m,
flow rate up to 100 l/s,
over 600 located events,
M_W<-1.2.

Phase 1, Stage 2:
419 m³ of fluids injected,
depth 2800 m,
flow rate up to 26 l/s,
almost 400 located events,
M_W<-1.7







Seismic efficiency of injection:
- Slow increase after injection
- Decrease form beginning for two stages
- Later stable range about 10^{-4} during stimulation

Discussion

Seismic efficiency of injection - seems to have quite a stable range in time, so it might be possible to use it for prediction of seismic risk even from short term hydraulic stimulation tests. Sometimes it has higher values at the beginning, that can be caused by events connected with previous stimulations on site. Error in determination of seismic efficiency of injection is about one order due to uncertainty of the inputs.

Site	Geology	Depth	Stimulation	Total seismic efficiency of injection
Soultz-sous-Forets	Granite	4400-5000 m	2000 2003	2.2 0.045
Cotton Valley	Sandstone	2600-2800 m	Phase 1, Stage 2 Phase 1, Stage 3 Phase 2, Stage 4	$2.2 \cdot 10^{-4}$ $8 \cdot 10^{-5}$ $3 \cdot 10^{-5}$
Canyon Sands	Sandstone	1518-1858 m	Stage 1 Stage 2 Stage 3 Stage 4	$1.3 \cdot 10^{-6}$ $3.6 \cdot 10^{-6}$ $7.8 \cdot 10^{-6}$ $2.4 \cdot 10^{-6}$

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