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Rock physics and geomechanics of fluid-induced seismicity

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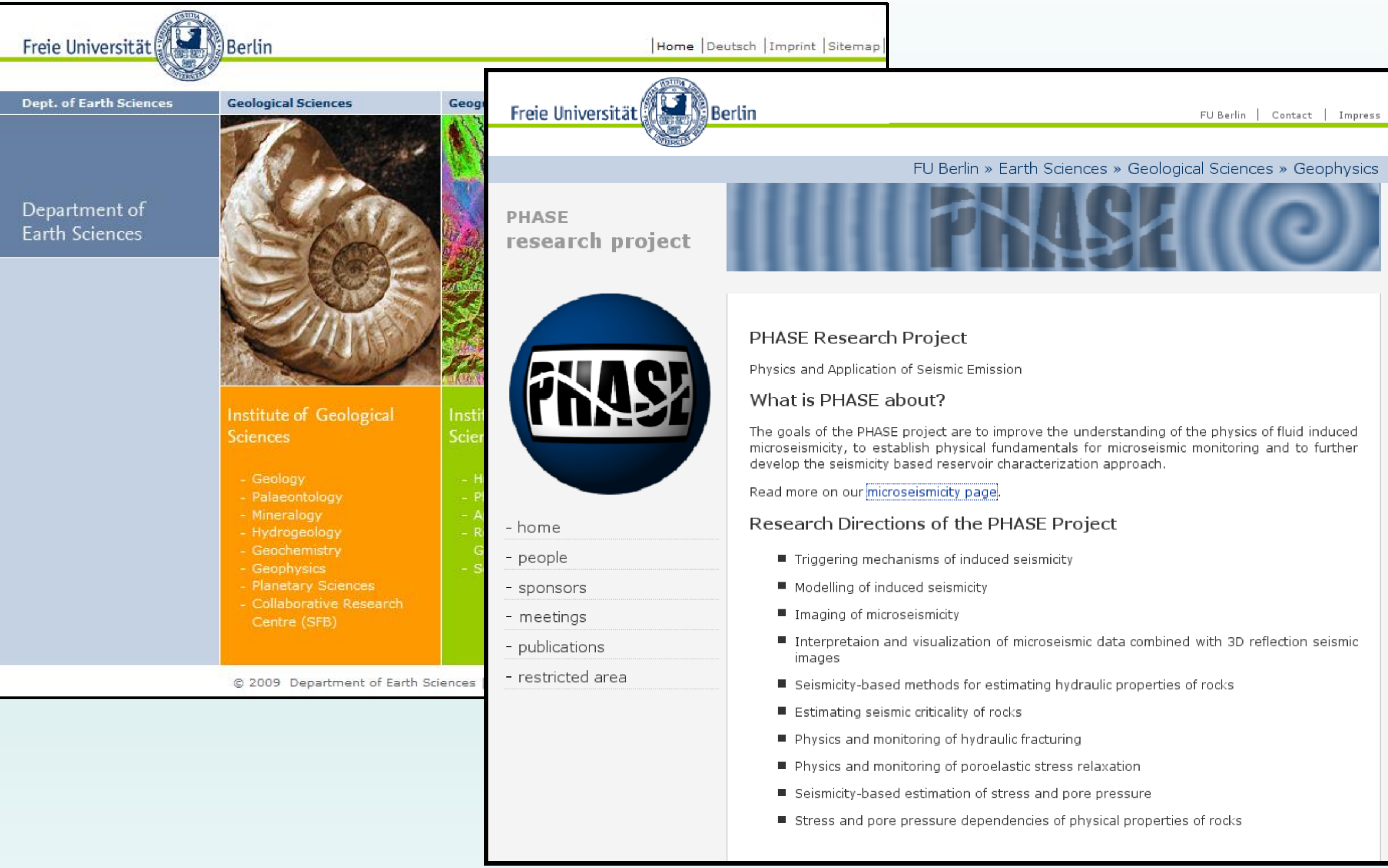
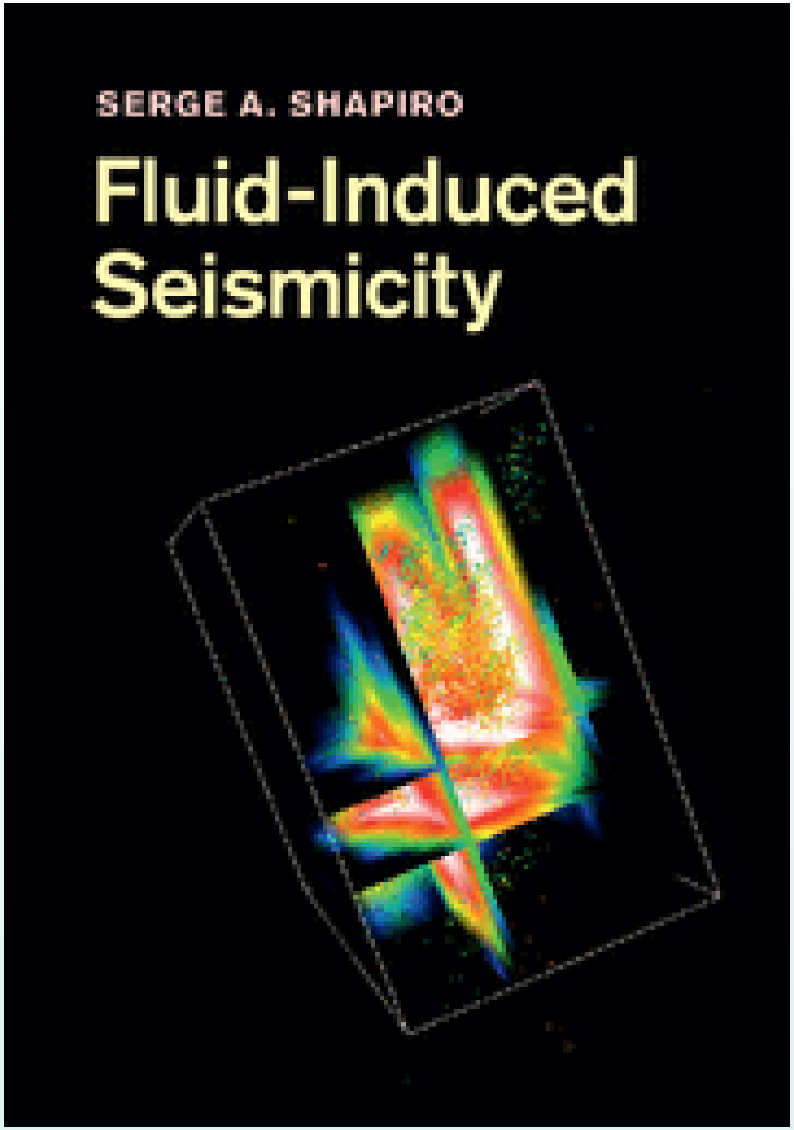
http://phase.geophysik.fu-berlin.de/phase





2015, Cambridge Univ. Press, 289pp.

www.cambridge.org/9780521884570

Outline

- Elasticity and seismic waves
- Porodynamics
- Earthquakes and faulting
- Induced seismicity in reservoirs:
  - linear pressure diffusion
  - classical hydraulic fracturing
  - non-linear pressure diffusion
  - induced seismic hazard

Porodynamics

There are 3 wave modes in poroelastic media:

one S-wave and two P-waves:

a fast P-wave and a slow P-wave

Properties of the slow P-wave

⇨ The solid and fluid movement are out of phase!

⇨ Slow wave is a diffusion-type wave:

For low frequencies it reduces to a diffusion process corresponding to the pore pressure relaxation

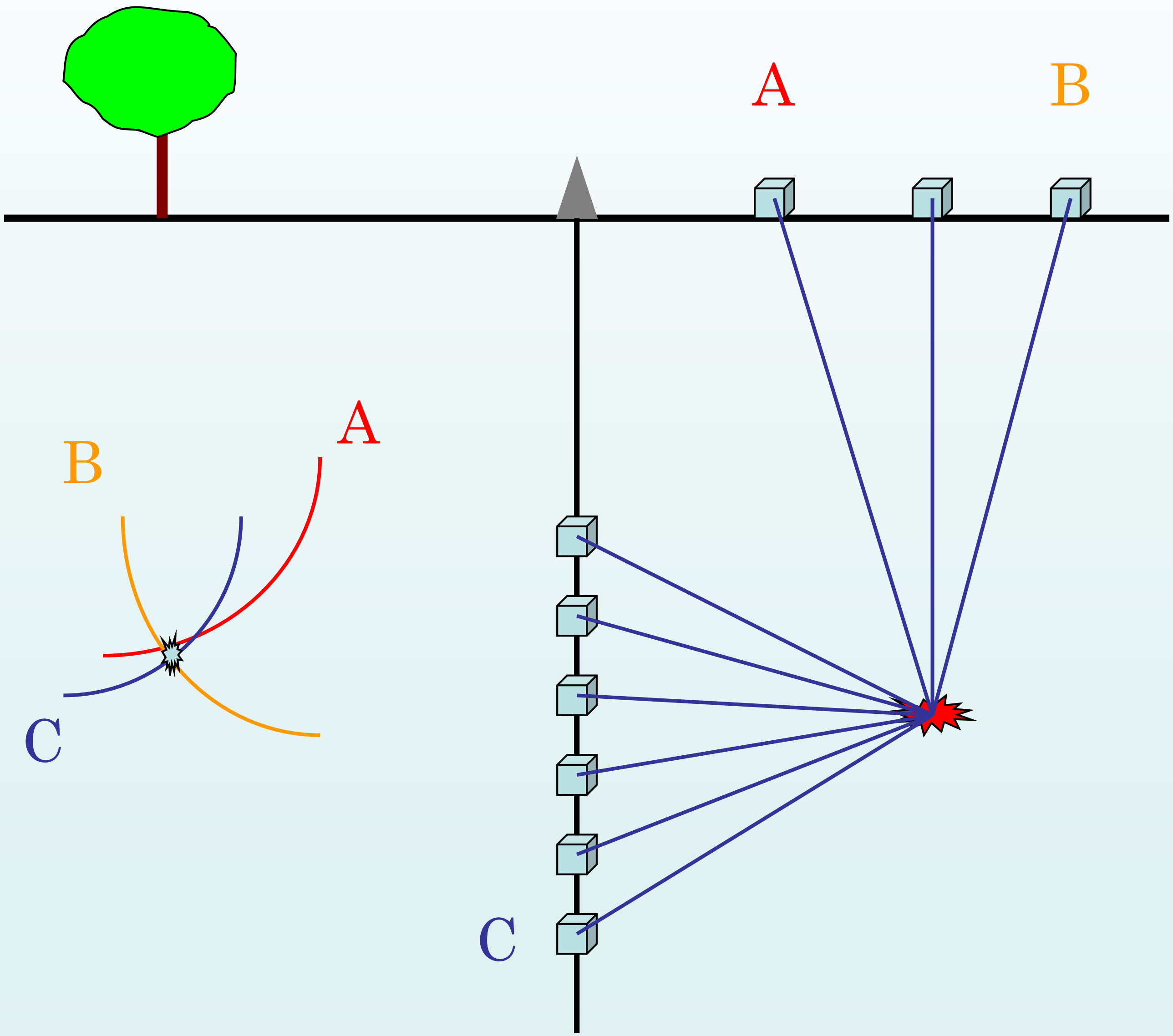
Coefficient of hydraulic diffusivity:

$$D = \frac{k}{\eta} M \frac{P_{dry}}{P_{sat}}$$

Summary 1.

- Elastic waves: P and S
- Slow wave: diffusion
- Global flow, squirt, mesoscopic flow
- Flow-related seismic wave attenuation
- Reservoir properties: permeability, porosity, fluid viscosity, fluid elasticity, rock elasticity

Earthquakes and faulting


A
B
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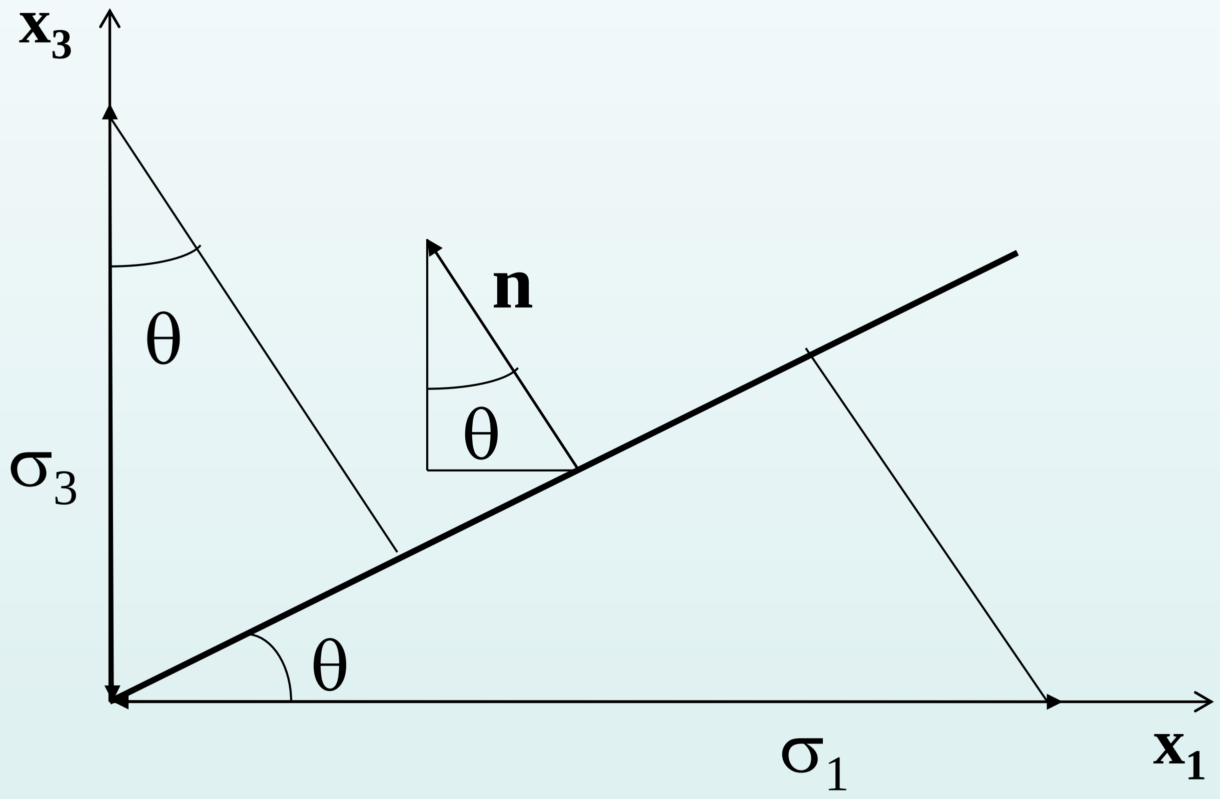
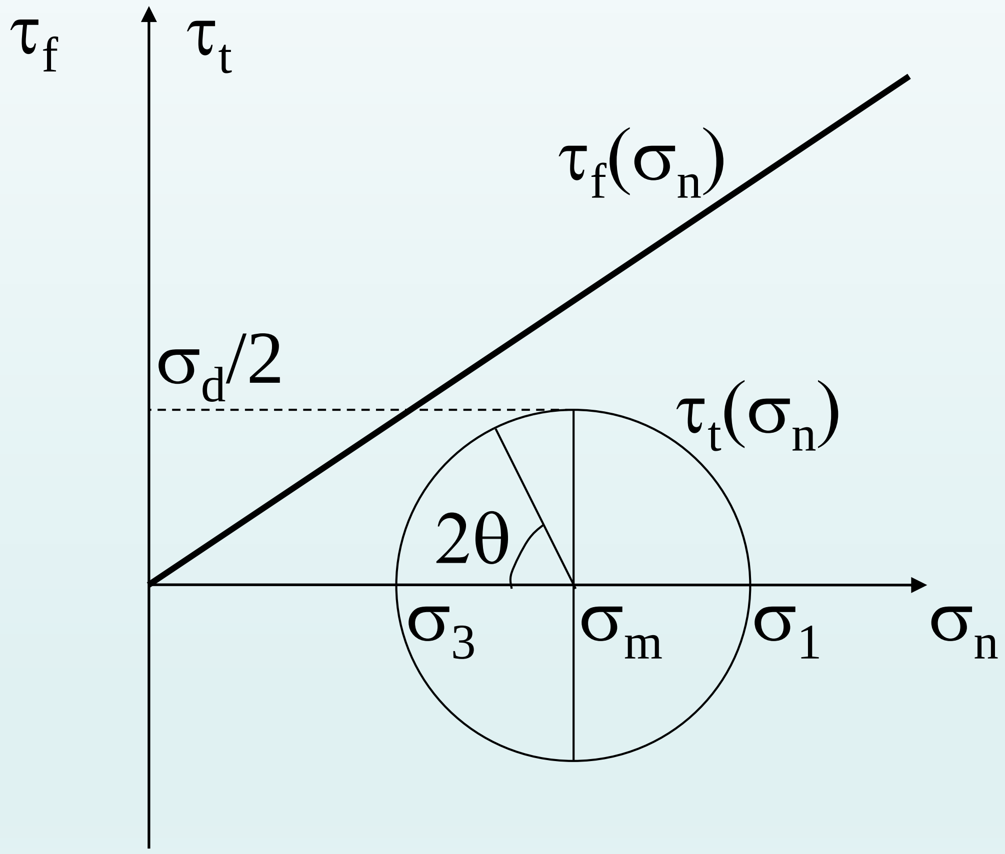
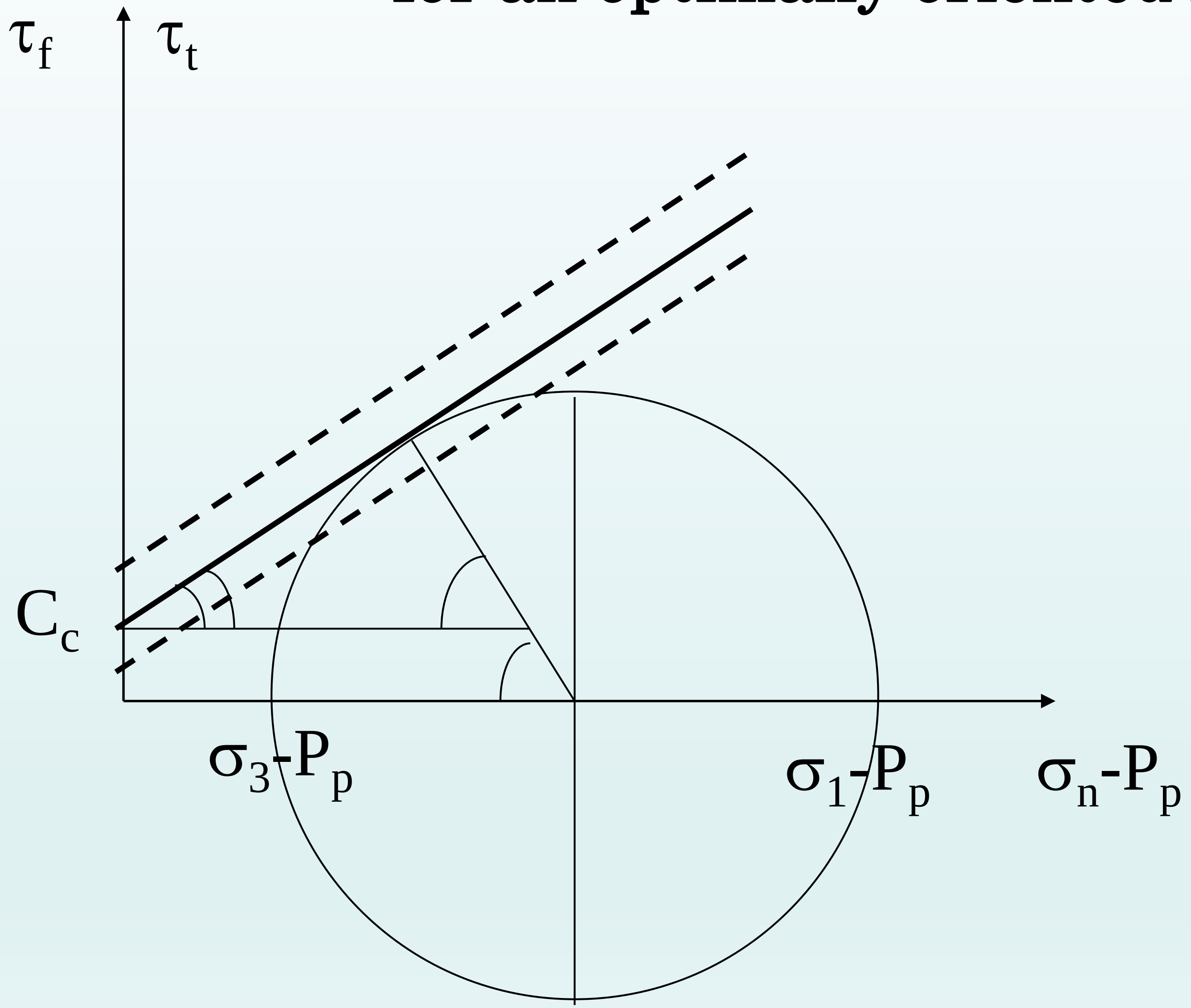
A fault normal to the plane of maximum and minimum stresses



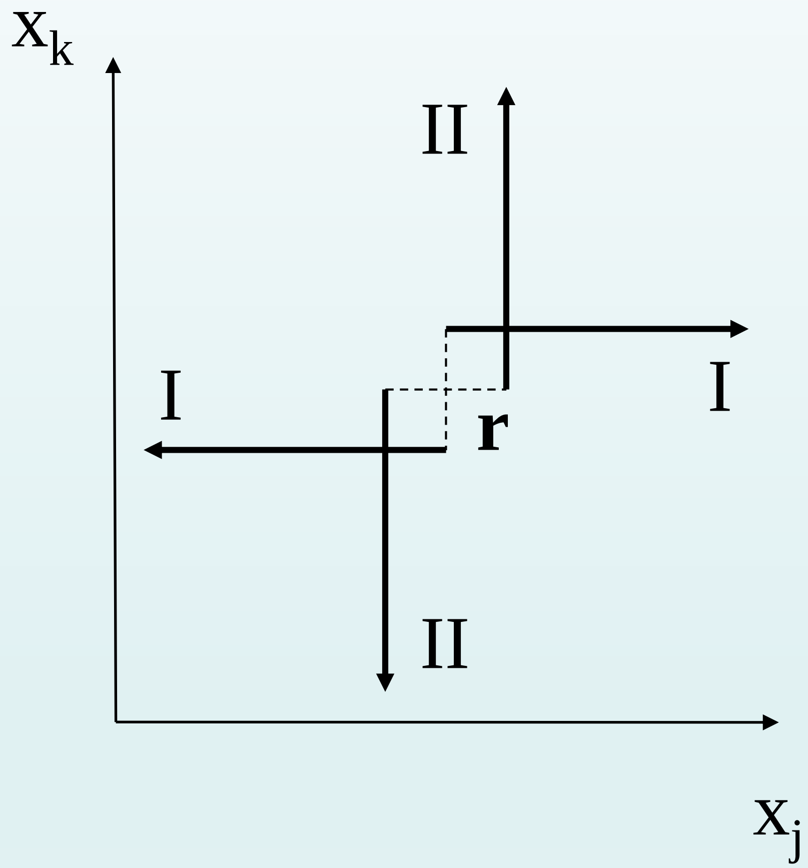
Friction force and shear stresses on a fault



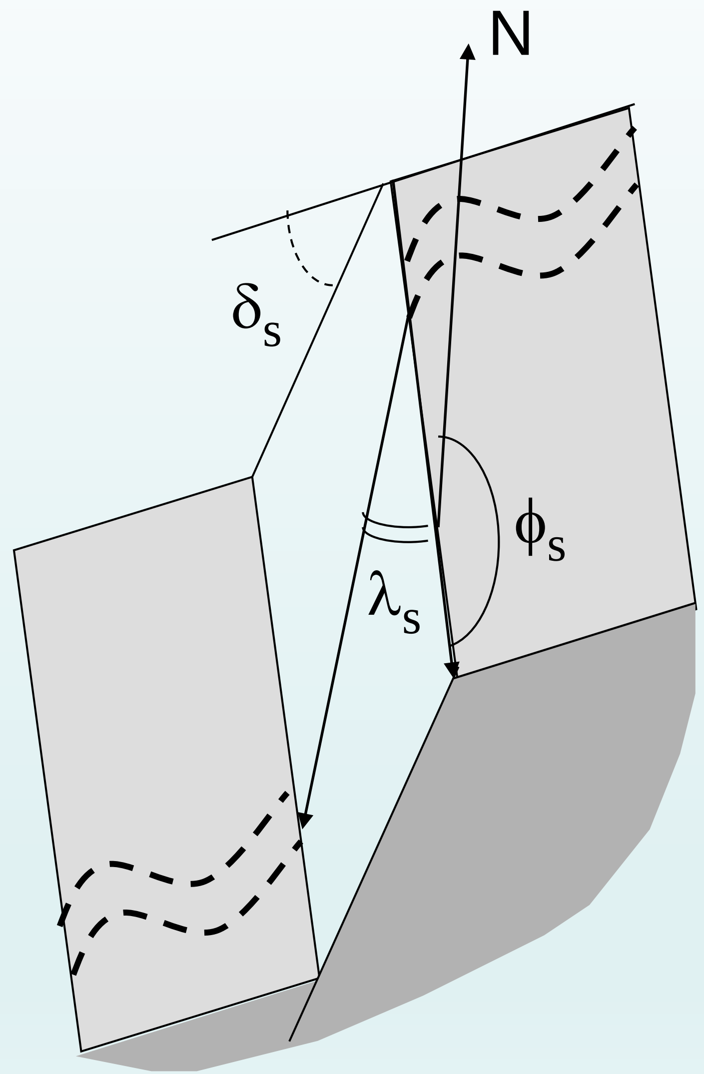
Shear stress and friction force for an optimally oriented fault



Double couple of forces



Parametrization of earthquake faults



Seismic moment and moment magnitude

Seismic Moment $M_0 = \mu * \text{Slip} * \text{Rupture Area}$

Moment Magnitude $M_w = 2*(\log_{10} M_0 - 9.1)/3$

Fault Length [m] is approx. $10**(M_w/2 + 1)$

Stress drop of approx. 1 MPa is assumed.

Summary 2.

- Earthquake detection
- Earthquake location
- Earthquake mechanisms
- Earthquake magnitudes

Types of fluid-induced seismicity

Two limiting cases of fluid-induced seismicity

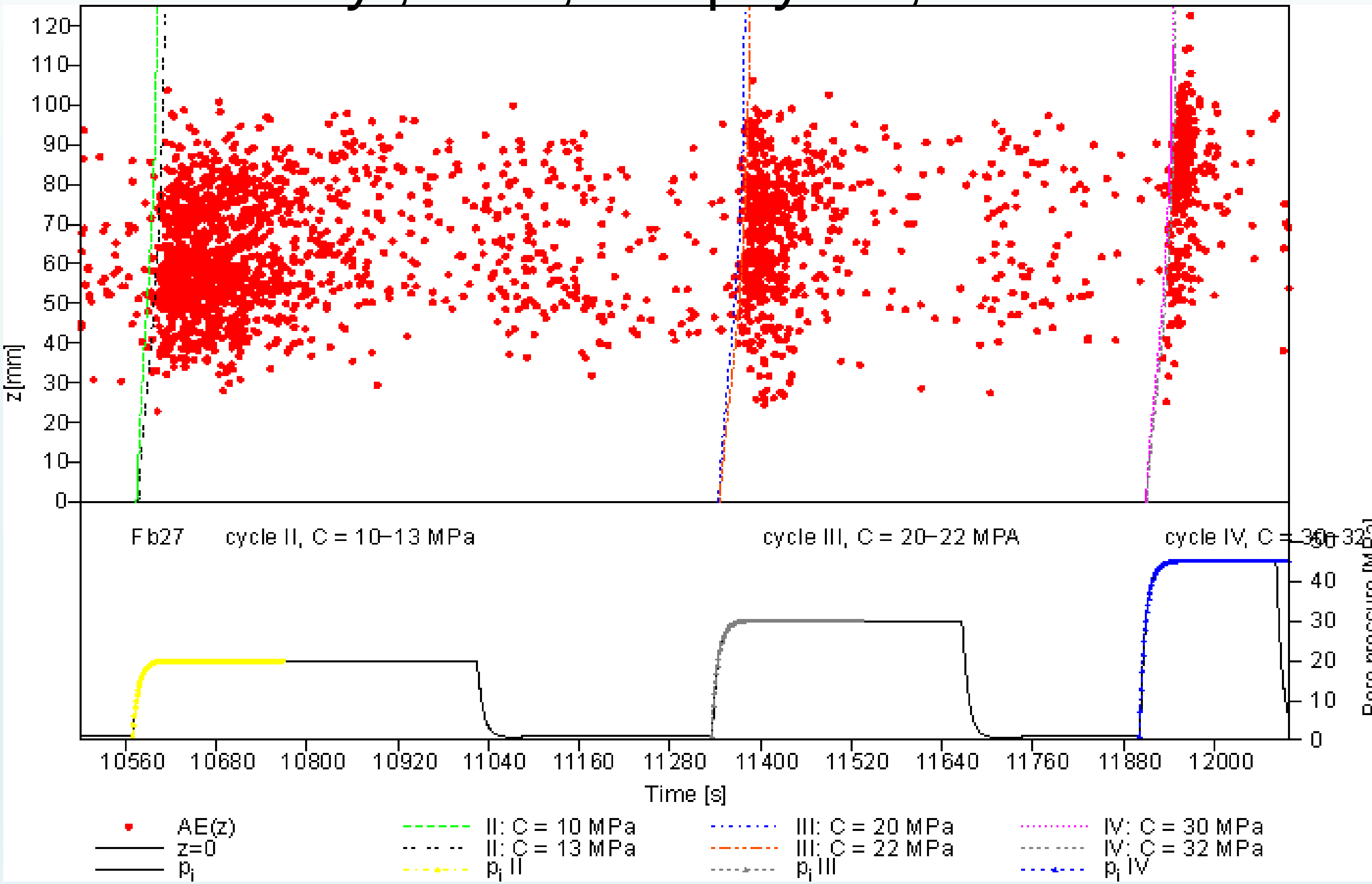
- Diffusion-controlled triggering:
  Injections in geothermic reservoirs.

- Volume-creation-controlled triggering:
  Hydraulic fracturing of gas reservoirs.

Linear pore pressure diffusion and triggering fronts

Fluid injection into a saturated sample:

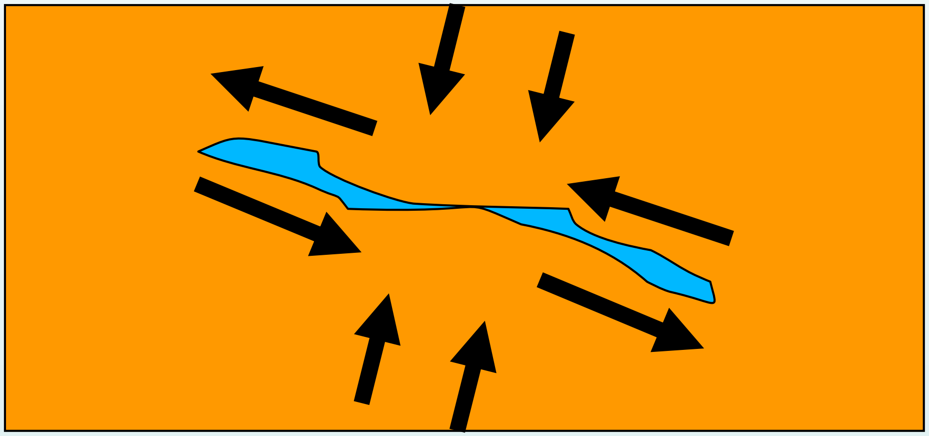
Mayr, et al., Geophysics, 2011



Physical Concept

- At some locations the state of stress is close to a critical one:

  ➡ A criticality field, C(x,y,z): strength of pre-existing cracks (e.g., critical pore pressure).



- Seismicity triggering process is a dynamic perturbation of the stress state:

  ➡ Pore-pressure diffusion. A field of the hydraulic diffusivity, D(x,y,z).

Poroelastic coupling

Poromechanics [Biot, 1962]

$$\frac{B}{3}\cdot\frac{\partial\sigma_{kk}}{\partial t}+\frac{\partial p}{\partial t}=\frac{DSBK_{dr}}{\alpha}\cdot\nabla^{2}p$$

Hydraulic diffusivity:

$D = 10^{-4}$-10 m²/s

[*Wang* 2000, *Scholz* 2002]

Pore-Pressure Diffusion

Pressure diffusion:

$$\frac{\partial p}{\partial t} = D \cdot \nabla^2 p$$

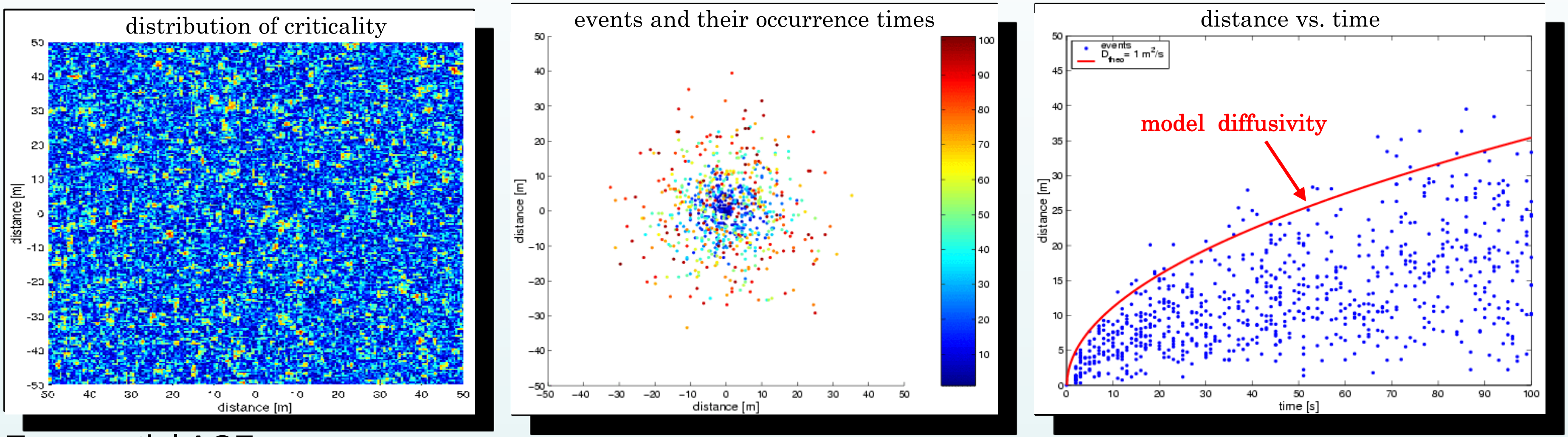
Hydraulic diffusivity:

$$D = k/(S\eta)$$

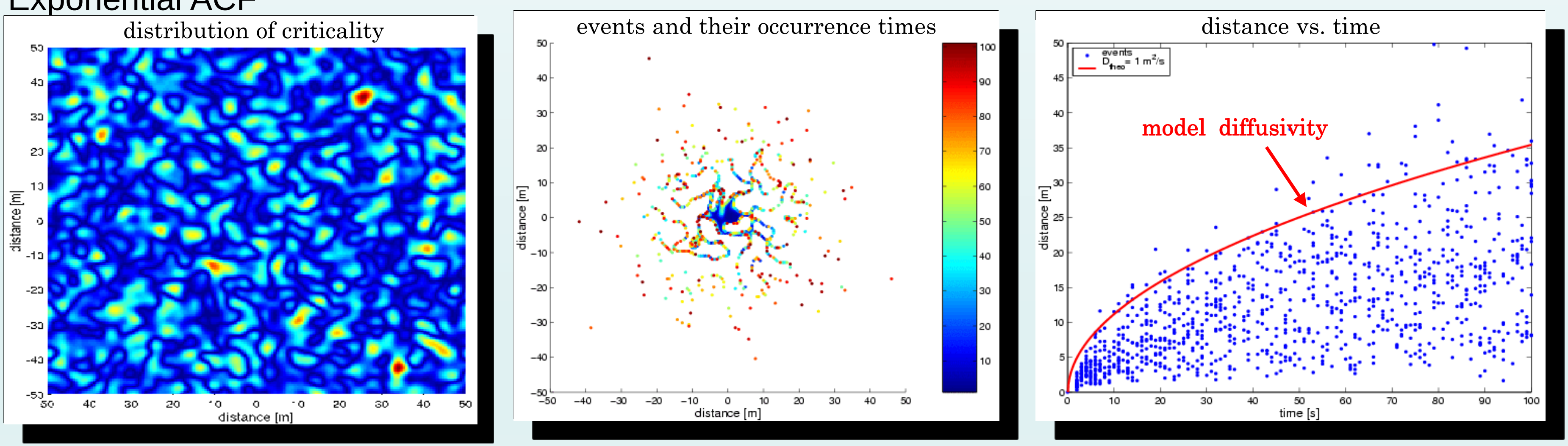
Triggering front:

$$r = \sqrt{4\pi D t}$$

Numerical modelling of seismicity: linear diffusion



Exponential ACF



Gaussian ACF

Summary 3.

- Triggering of earthquakes
- Pore pressure diffusion
- Hydraulic diffusivity
- Triggering front
- Synthetic microseismic clouds
- Anisotropic diffusivity

Microseismicity after a termination of injection

$$p_a(r,t) = \frac{q}{4\pi Dr} \cdot \left[erfc\left(\frac{r}{\sqrt{4Dt}} \right) - erfc\left(\frac{r}{\sqrt{4D(t-t_0)}} \right) \right]$$

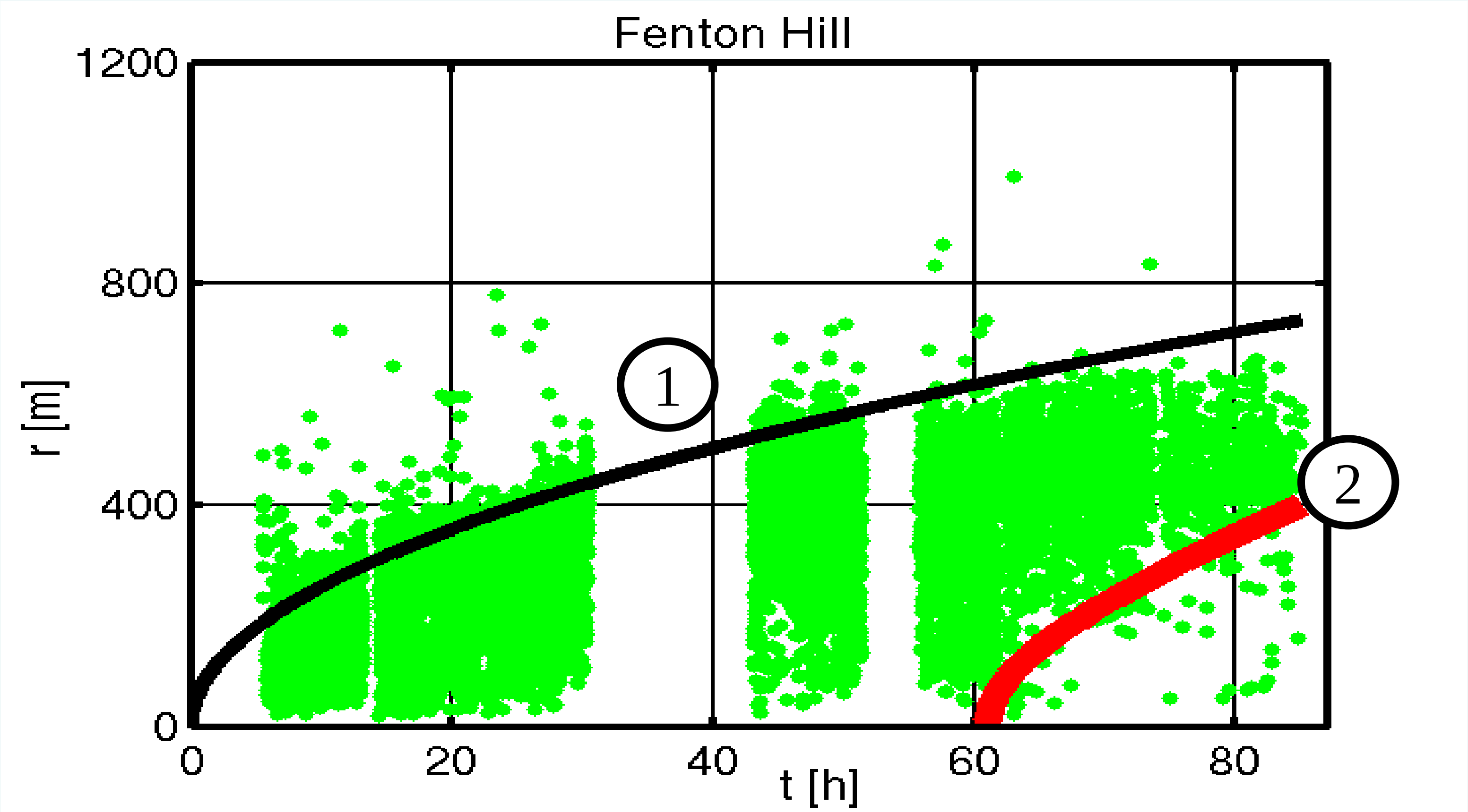
BACK FRONT

$$r = \sqrt{6 \cdot D \cdot t \cdot \left(\frac{t}{t_0} - 1 \right) \cdot \ln\left(\frac{t}{t - t_0} \right)}$$

Triggering Front and Back Front: linear diffusion

$$r = \sqrt{4\pi D t}$$

$$r_{bf} = \sqrt{6Dt(1 - t/t_0)\ln(1 - t_0/t)}$$

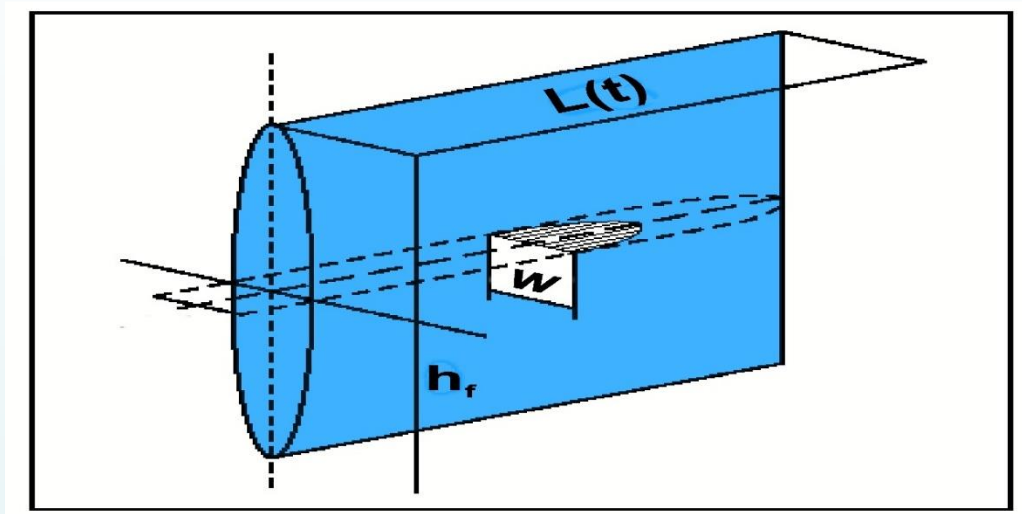


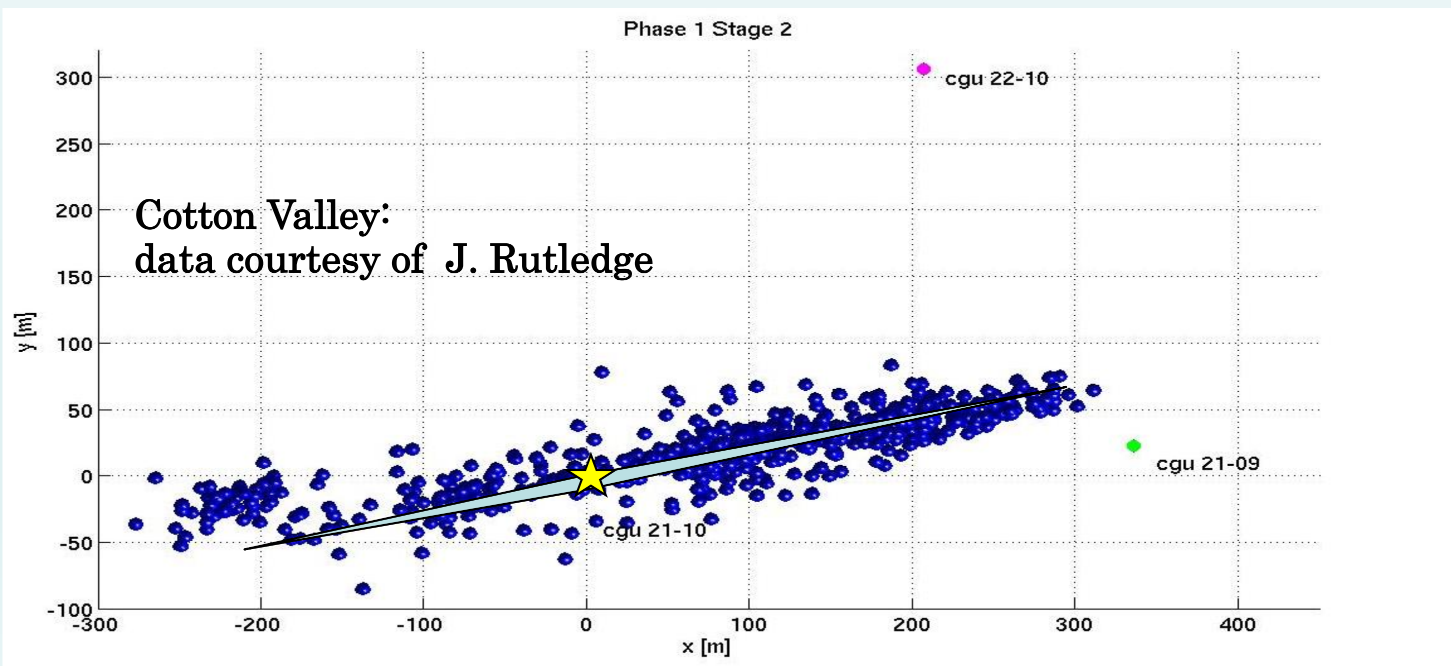
Summary 4.

- Back front of seismicity
- Event rate
- Spatial density of microseismic clouds
- Pore pressure diffusion explains spatio-temporal distributions of events
- It explains also statistics of events
- Characterization of hydraulic properties of rocks.
- Characterization of criticality (strength) of rocks.

Microseismicity by hydraulic fracturing

Perkins-Kern-Nordgren (PKN) Model of Hydraulic Fracture





Volume Balance Principle

Volume of injected fluid = fracture volume + lost fluid volume

$$Q_I\, t \;=\; 2\, L\, G \;+\; 6\, L\, h_f\, C_L\, t^{1/2}$$

t injection time,

Q_I average injection rate,

C_L fluid loss coefficient,

$G = w*h_f$ vertical cross section of the fracture.

Hydraulic Fracture Propagation

The half-length **L** of the fracture as a function of the injection time **t**：

$$L(t) = \frac{Q_I t}{S_L \sqrt{t} + G}$$

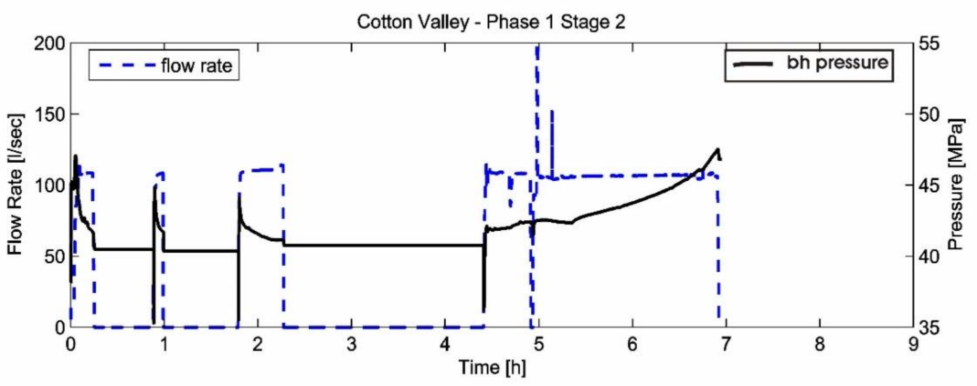
$\mathbf{Q_I}$ is the average injection rate,

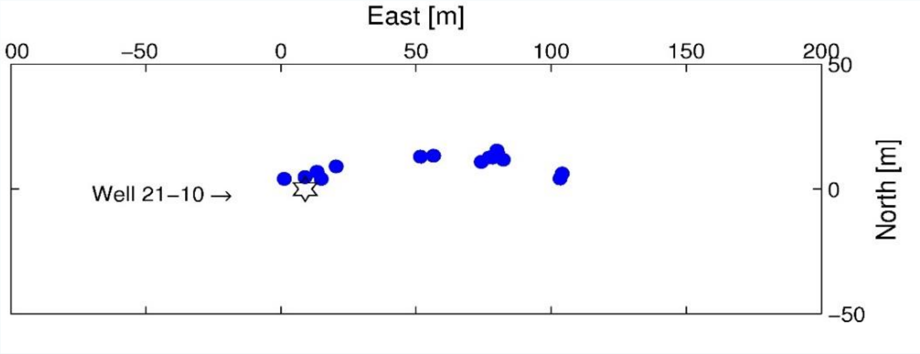
$\mathbf{S_L}$ describes the fluid loss,

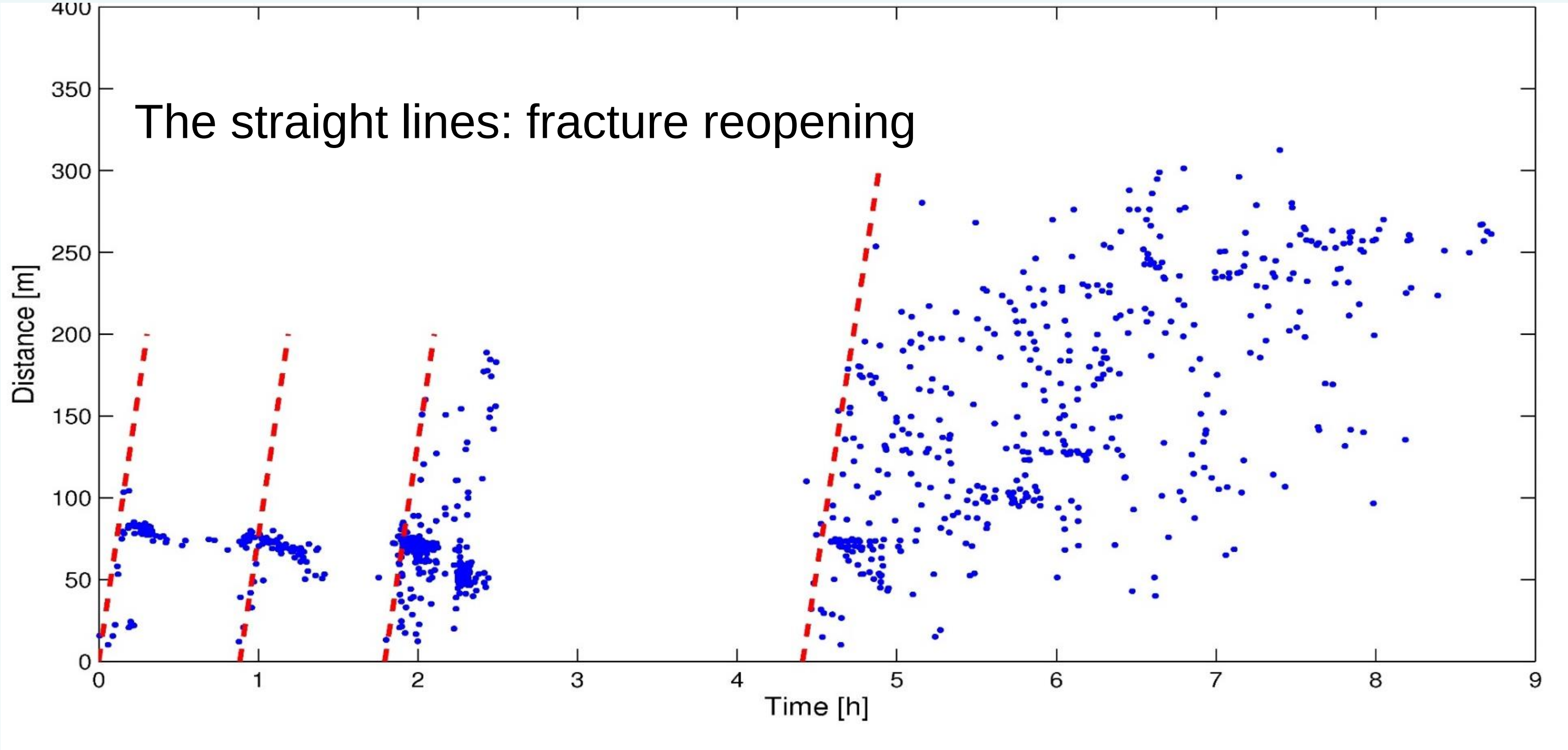
G represents the effective fracture volume contribution

Geometry- and Fluid-Loss- Controlled Fracture Growth

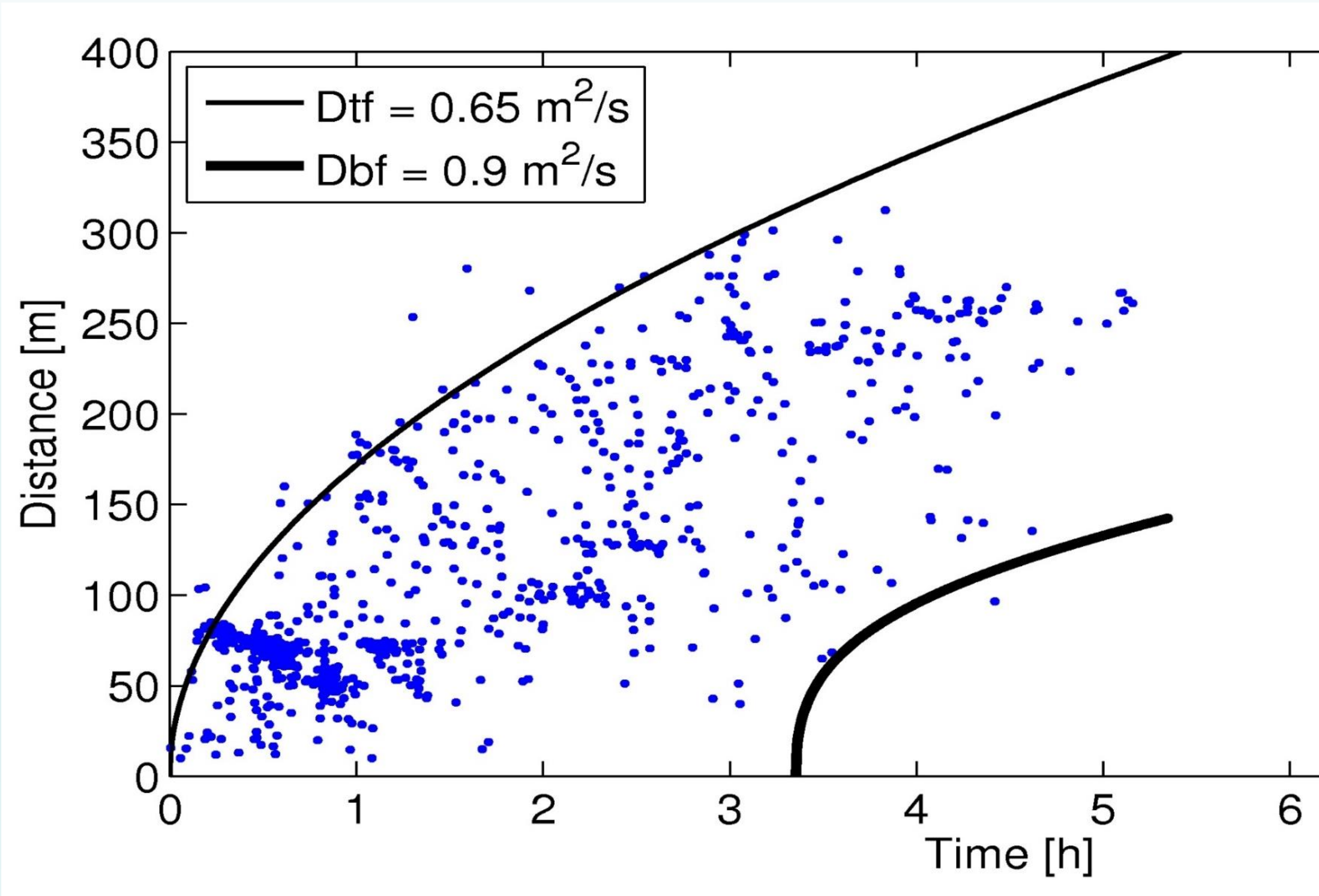
Microseismicity induced by hydraulic fracturing







Triggering Front and Back Front



Estimation of Fluid Loss and Permeability

Apparent hydraulic diffusivity characterizes fluid loss:

$$C_L = \frac{Q_I}{8h_f\sqrt{2\pi D_{tf}}}$$

Using fluid loss coefficient, porosity, compressibility and viscosity of the reservoir fluid we can estimate reservoir permeability:

$$C_L \approx \Delta p \sqrt{\frac{\kappa \varphi c_t}{\pi \eta}}$$

Summary 5.

- Spatio-temporal dynamics of microseismic clouds contributes to characterization of hydraulic fractures.
- r-t-plots show signatures of fracture volume growth, fracturing fluid loss, as well as diffusion of the injection pressure into rocks and inside the fracture.
- Diffusion controlled triggering: Kaiser effect is obeyed. Injections in geothermic reservoirs.
- New volume creation controlled triggering: Kaiser effect is violated. Hydraulic fracturing of gas reservoirs.

Non-Linear Diffusion and Triggering Front

Pressure diffusion:

$$\frac{\partial p}{\partial t} = \nabla D \nabla p$$

Hydraulic diffusivity:

$$D \propto p^n$$

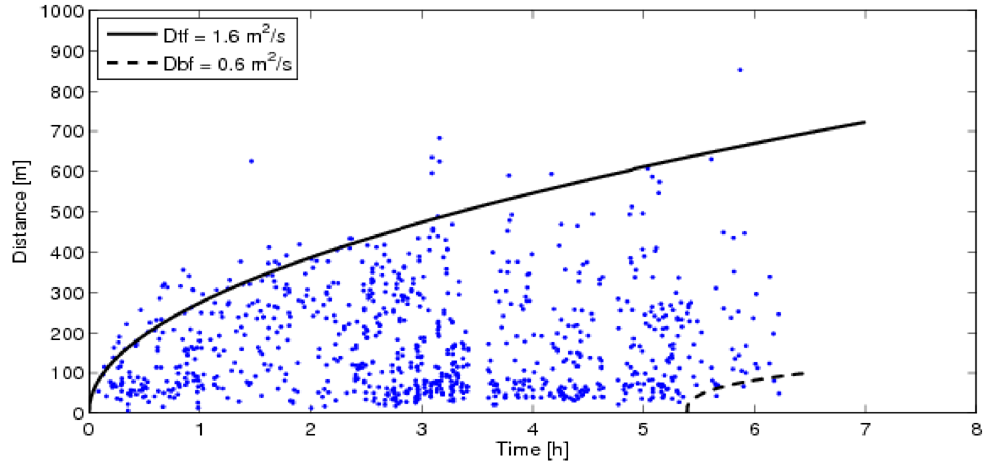
Triggering front:

$$r \propto \sqrt[3n+2]{D Q_I^n t^{n+1}}$$

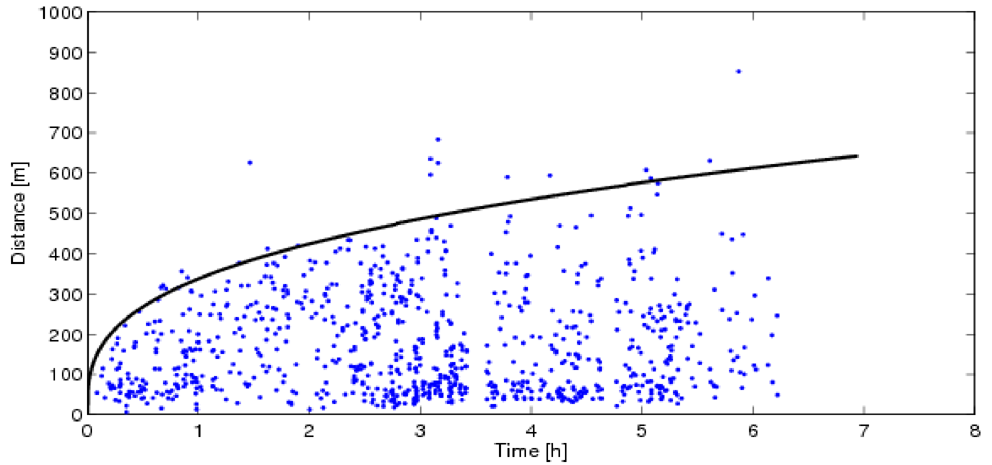
$$r = \sqrt{4\pi D t}$$

$$r \propto \sqrt[3]{Q_I t}$$

r =At^1/2



r =At^1/3



Summary 6.

- A linear pore pressure relaxation and a hydraulic fracturing are end members of a set of non-linear diffusion phenomena responsible for seismicity triggering.

- A non-linear diffusion equation takes into account a strong enhancement of permeability. A linear pressure relaxation and hydraulic fracturing, can be obtained as limiting cases of such an equation.

- Triggering front of fluid induced seismicity can deviate from $t^{1/2}$ – behavior, in the case of a non-linear pore pressure diffusion.

- The Barnett Shale case study corresponds to a non-linear pressure diffusion with a very strong permeability enhancement. It is a 3-D opening of preexisting fractures embedded into impermeable compliant matrix. The triggering front shows a cubic-root parabolic behavior.

Magnitudes of seismicity

Magnitude distribution

Number of all events triggered till time t with magnitude larger than M

$$N_M(t) = N_{\mathrm{ev}}(t) \times W(M)$$

The Gutenberg-Richter distribution:

$$\log W(M) = a - bM$$

$$\log N_M = const + \log Q_c(t) - bM$$

Seismogenic index

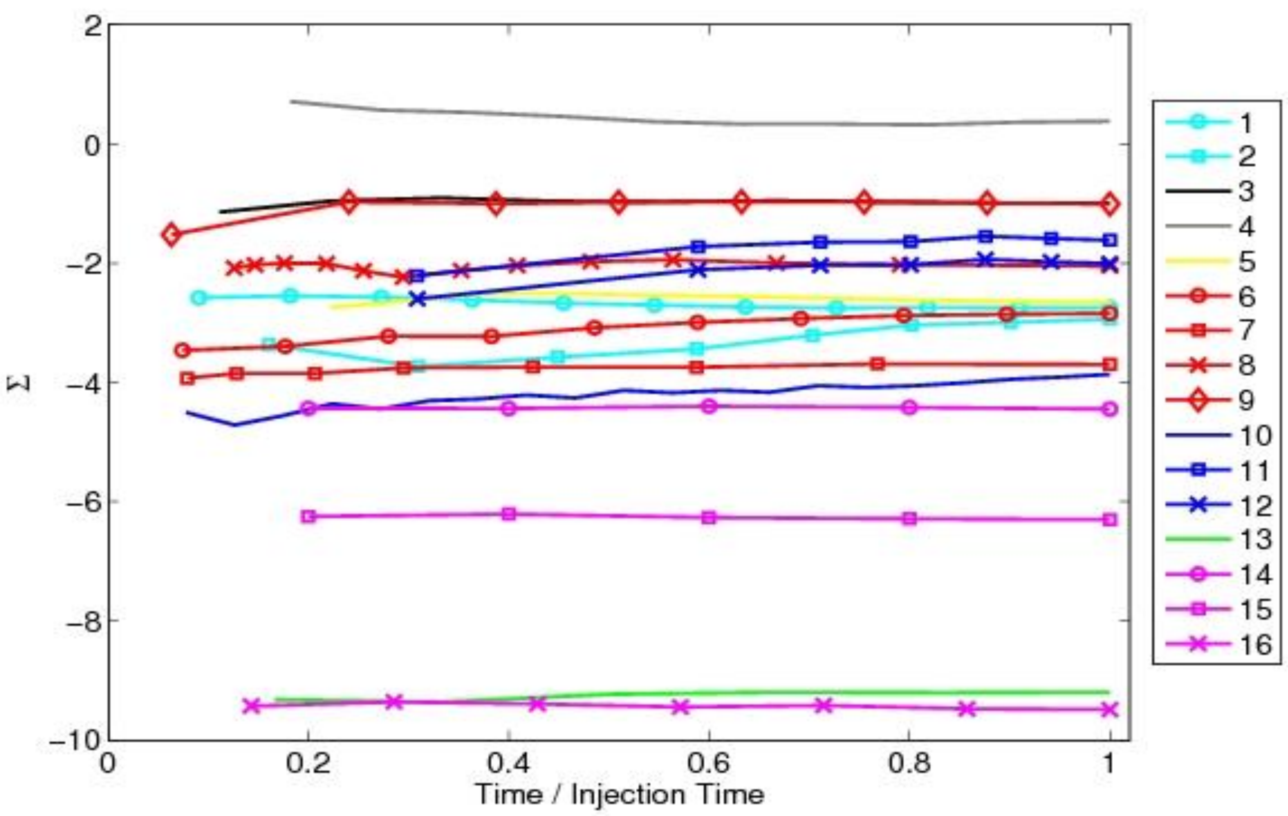
$$\log N_M(t) = \Sigma + \log Q_c(t) - bM$$

Seismogenic index: $$\Sigma = a - \log SF_t$$

Tectonic potential: $$F_t = C_{\max} / N$$

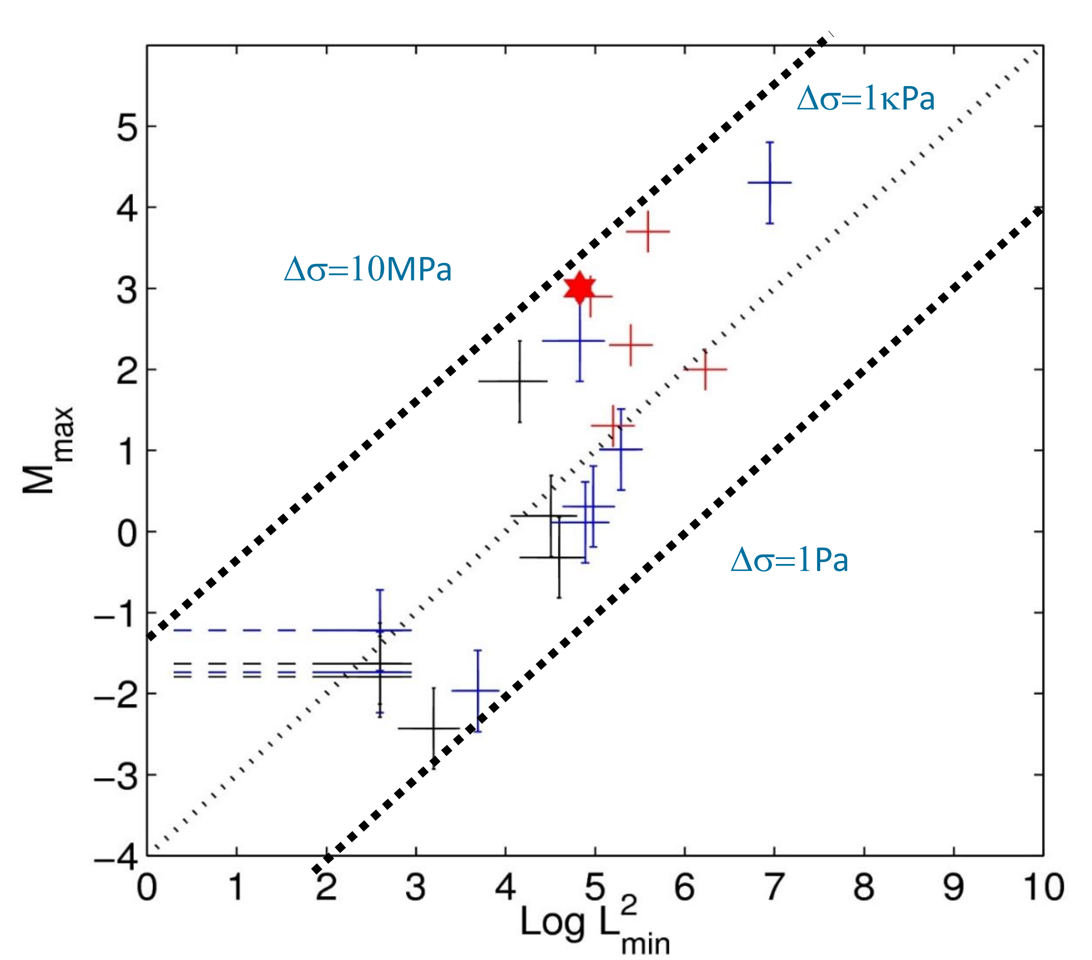
The classical
Gutenberg-Richter law: $$\log N_M(t) = a(t) - bM$$

Seismogenic index, Σ



1-2: Ogachi 1991/93, **3**: Cooper Basin 2003, **4**: Basel 2006, **5**: Paradox Valley, **6-9**: Soultz 1996/95/93/00. **10-12**: KTB 2005/94.13: Barnett Shale, **14-16**: Cotton Valley stages A, B,C.

Maximum magnitude vs minimum axis



$$MAX\{M_{max}\} \approx 2 \log L_{min} - 1$$

Summary 7.

- Magnitude probability increases like the injected volume.
- Magnitude distribution are inherited from the statistics of preexisting fracture systems (Gutenberg-Richter law).
- Seismogenic index quantifies a seismic activity by fluid injections.
- The largest seismogenic index was observed at the Basel EGS. The smallest - at hydrocarbon reservoirs.
- Hydrocarbon reservoirs require more sensitive monitoring systems then geothermal reservoirs.
- Geometry of a stimulated volume influences statistics of induced seismicity

Selected references

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