The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1965-32

9th Workshop on Three-Dimensional Modelling of Seismic Waves Generation, Propagation and their Inversion

22 September - 4 October, 2008

The study of fluid-induced and triggered seismicity: theory
Part I

Torsten Dahm

Institut für Geophysik
Universität Hamburg
Germany

---

torsten.dahm@zmaw.de

The study of fluid-induced and triggered seismicity: theory

ICTP Course 2008

Torsten Dahm
torsten.dahm@zmaw.de
Institut für Geophysik, Universität Hamburg, Germany

Content

1. Theory: Failure criteria and earthquake statistics
2. Case studies:
   a) Long-term, low pressure injection
   b) Hydrofracturing
   c) Hydrocarbon field depletion

Examples of fluid-related seismicity

natural:
- magmatic dike-intrusion (vertical, lateral, sill-like)
- deep degassing through the crust
- water intrusions into glaciers (downward)
- natural hydraulic fracturing (e.g. vein formation)
- rain-induced seismicity

…. initiated by “reservoir” instability or natural inflow

man-made:
- hydraulic fracturing from boreholes
- massiv fluid-injections (CO2, waste, etc.)
- fluid extraction from hydrocarbon reservoirs
- water reservoir filling

… the fluid flow and loading is man-controlled

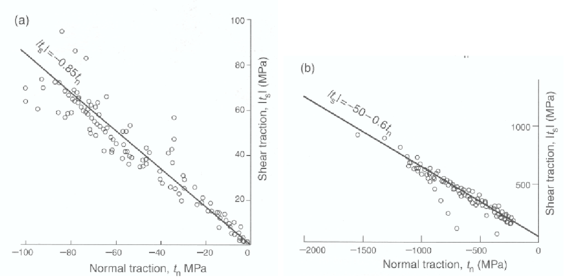
How are earthquakes triggered ?
The internal friction concept (Coulomb failure)

Rupture is
- driven by applied shear stress
- resisted by cohesive strength and normal stress

$$|\sigma_s| = S_0 - \mu_i(\sigma_n + P_p)$$

Shear stress
inherent cohesion
normal stress
pore pressure
internal friction

… frictional strength from sliding experiments



from Pollard & Fletcher (2005)

Coulomb stress and Coulomb failure criteria

$$\sigma_c = |\sigma_s| + \mu_i(\sigma_n + P_p)$$

Coulomb stress

$$\sigma_c \leq S_0$$

- Shear and normal stress depend on local stress and fault orientation
- P depends on local stress and pore pressure
- The internal friction is rate and state and moisture dependent

---

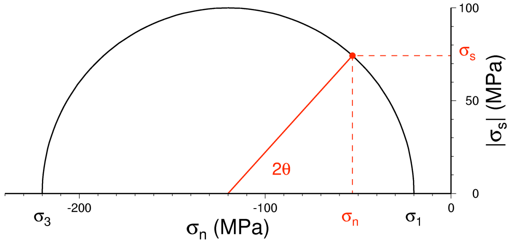
Shear and normal stress: Mohr circle

$$\sigma_n = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \frac{\sigma_{xx} - \sigma_{yy}}{2} \cos 2\Theta$$

$$\sigma_s = -\frac{(\sigma_{xx} - \sigma_{yy})}{2} \sin 2\Theta \quad .$$

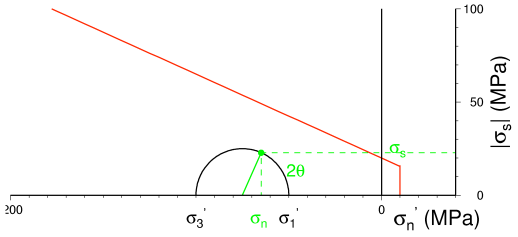
Here: tensional stress is positive

Shear and normal stress: Mohr circle



Theta is the angle between max. compressive stress and fault plane

Coulomb criterion and Mohr's circle

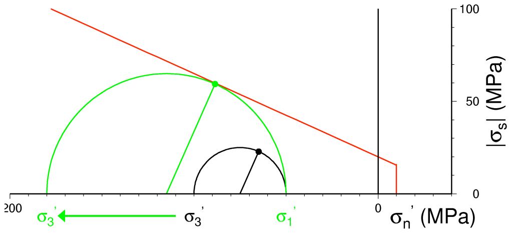


$$\sigma_1 \geq \sigma_2 \geq \sigma_3$$

---

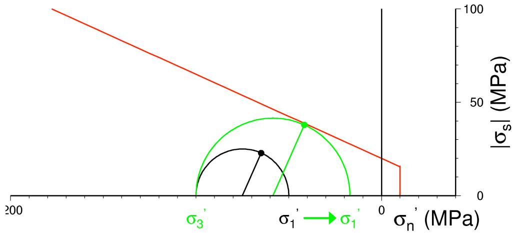
four ways to trigger an earthquake

(1) increasing the maximal compressive stress



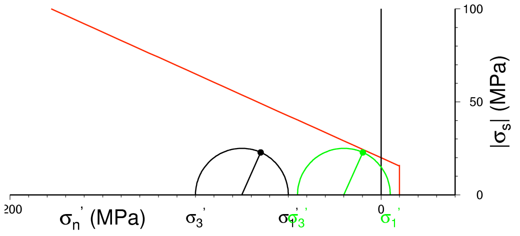
---

(2) Decreasing the least compressive stress

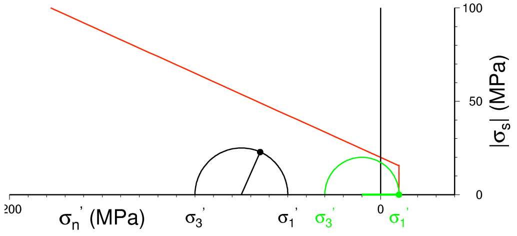


---

(3) increasing the pore pressure & shear fracturing



(4) increasing the pore pressure & tensional fracturing



Coulomb stress increase: how much?

Several studies indicate that 0.01 MPa (0.1 bar) is sufficient to trigger an earthquake (Seeber and Armbruster, 2000)

Compare with typical values:

• Average stress drop during earthquake:	1-10 MPa
• Pore pressure reduction in reservoirs	10 MPa
• Head pressure for hydrofrac exper.	10 MPa
• Head pressure for waste fluid injection	10 MPa

Triggered or induced seismicity ?

Triggered:

- the nucleation of rupture is controlled by the loading (man-made, inrusion, …)
- the length of the rupture is mainly controlled by the pre-existing tectonic stress on the fault

-> the earthquake would have occurred in anay case, but now it was slightly earlier

-> the size of the event is not related to the loading-related stress perturbation

Induced:

- both, nucleation and rupture are controlled by the stress perturbation from the loading

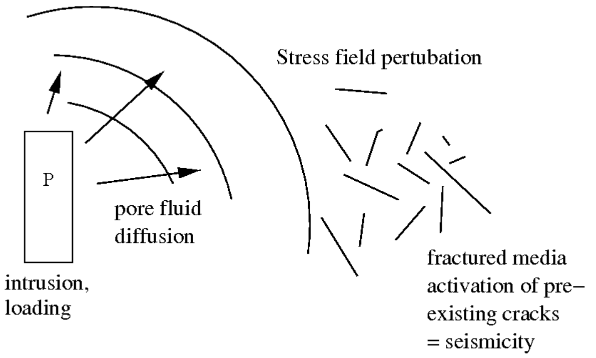
---

Are rocks in a critical state ready to be always triggered?
Can we avoid any triggering at all?

A possible reason for a threshold criterion are:

- geometry and statistics of pre-existing fracture is uneven
- The Kaiser effect and past evolution

pre-existing fractures play a role



Stress field pertubation

pore fluid
diffusion

intrusion,
loading

fractured media
activation of pre–
existing cracks
= seismicity

Pre-existing faults with different orientation are everywhere

photo from: Oates

Statistical earthquake relations

(1) magnitude-frequency relation (Gutenberg-Richter)

$$\log N = a_1 - b\, M_S$$

equivalently moment-frequency relation

$$\log N = \alpha - \frac{b}{1.5} \log(M_0) = \alpha - \beta \log(M_0)$$

----> for tectonic earthquakes b is about 1. For earthquake swarms b is often higher

---

(2) Omori law for aftershock occurrence

$$n = \frac{C}{(K+t)^P}$$

n : number of aftershocks
t : time
C, K, p : constants

Three brief examples

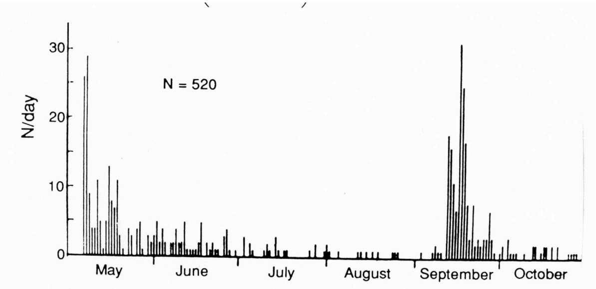
A) Tectonic case

B) Volcanic earthquake swarm

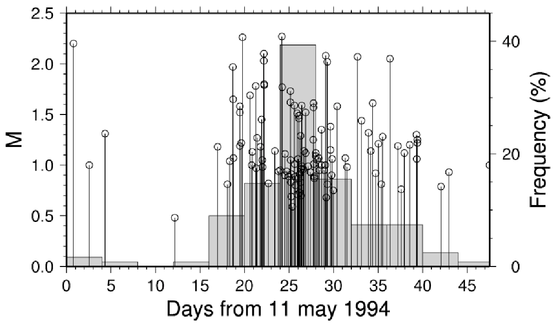
C) Cyclic thermal loading of rock

A) Typical main- & aftershocks: Friuli 1976, Italy

Number of earthquakes per day

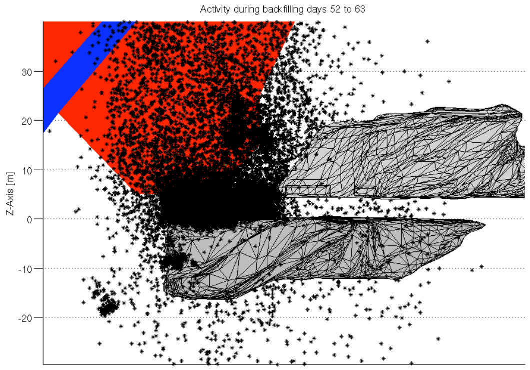


B) Typical "volcanic swarm": Eyjafjallajökull 1994, Iceland



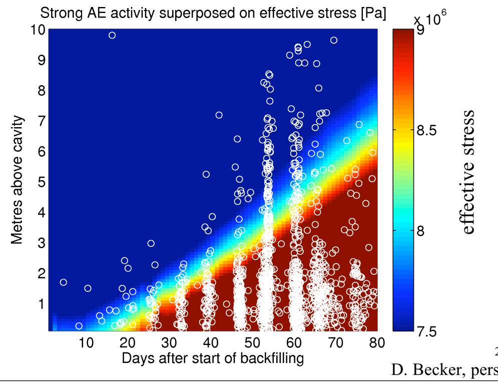
Dahm & Brandsdottir (1997) GJI 130, 183-192

C) Thermal loading of a salt mine



Köhler, Spies, Dahm (2008)

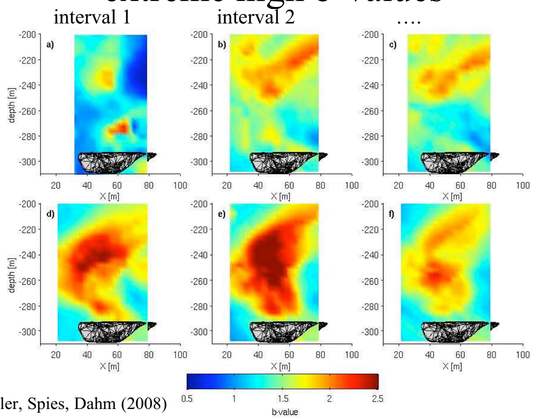
Event rate correlates with stress or stress rate



D. Becker, pers. comm.

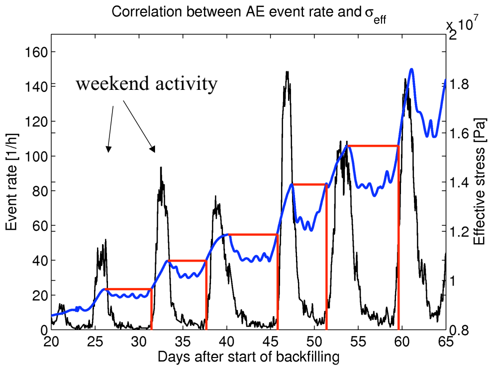
---

extreme high b-values



Köhler, Spies, Dahm (2008)

Kaiser effect for cyclic loading



D. Becker, pers. comm.

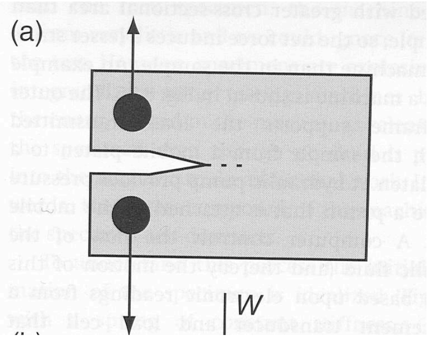
Kaiser effect for cyclic loading

…. events are triggered only after the stress exceeds the level of the previous cycle

What was different for the three examples ?

1. The loading (impulsive - long-lasting - cyclic)
2. The “stressing history” (fracture statistics)

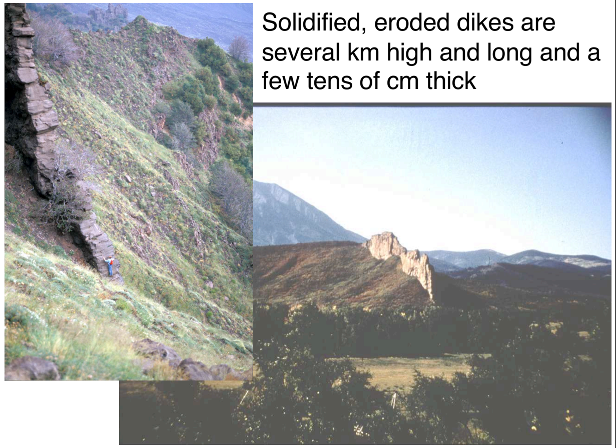
Is there a difference to tensile cracking ?



How do intrusions look like ?

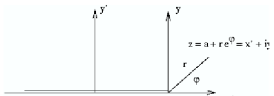
Solidified dike in Iceland

Photo: Rubin



Solidified, eroded dikes are several km high and long and a few tens of cm thick

Stress intensity factor and intrusion tip



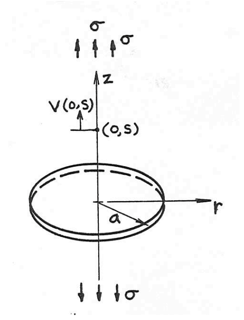
crack tip

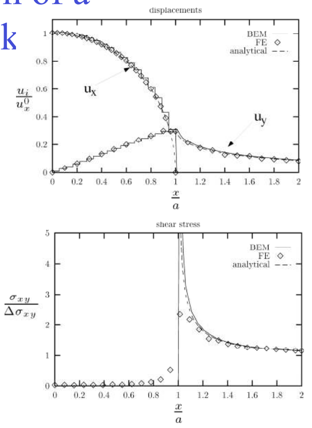
$$\sigma_{ij} \;=\; \Delta\sigma^{(m)}\sqrt{\pi a}\,\frac{1}{\sqrt{2\pi r_1}}\,f_{ij}^{(m)}(\theta_1)$$

$$K \;=\; \Delta\sigma^{(m)}\sqrt{\pi a}$$

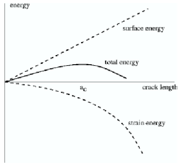
09/23/08

Theoretical solution of a penny-shaped crack





Griffith criterion to describe intrusion growth



$$\mathcal{G} \;=\; \frac{\pi(1-\nu)}{2\mathcal{N}}\Delta\sigma^2 a \;=\; \frac{(1-\nu)}{2\mathcal{N}}K^2 \;\geq\; 2\gamma_0\,.$$

Griffith force

Surface energy density

shear modulus

$$K(a) \;\geq\; K_c = \left[\frac{4\gamma_0\mathcal{N}}{(1-\nu)}\right]^{1/2}.$$

fracture toughness

Poisson ratio

09/23/08

Examples for lab-derived fracture toughness

rock type	K_c range $(MPa\,m^{1/2})$
Granite	1.66 - 3.52
Basalt	0.99 - 3.75
Quarzite	1.31 - 2.10
Marble	0.87 - 1.49
Limestone	0.86 - 1.65
Sandstone	0.34 - 2.66
Shale	0.17 - 2.61

09/23/08