What is (induced) seismicity

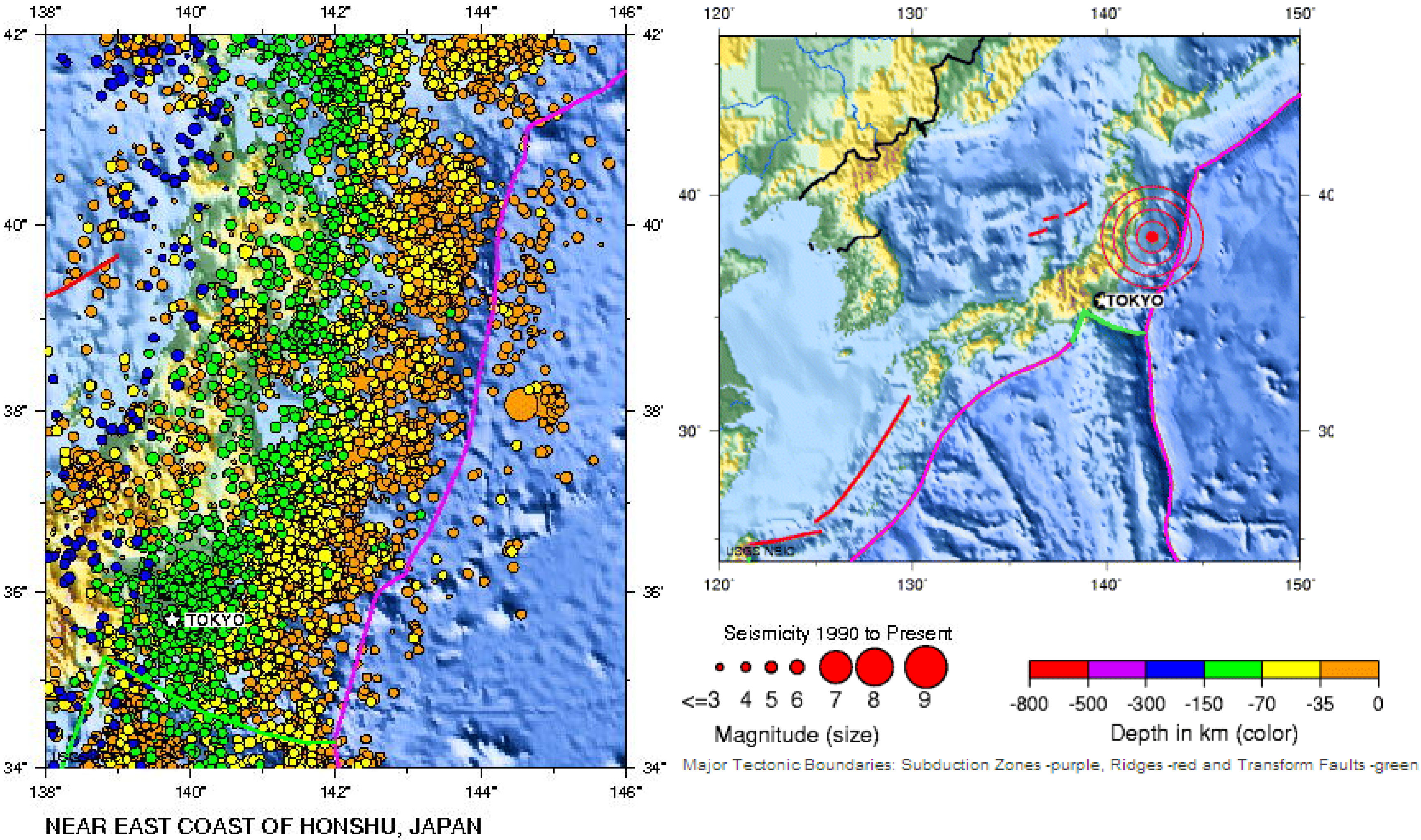
- Earthquakes and Tectonics
  - *Magnitude,*
  - *GR, PGA, recurrence rate*

- Rupture mechanics and modelling
  - *Spatial and depth relationships of seismicity*
  - *Coulomb stress change, rate and state friction*

- Induced seismicity definition and subsurface operations causing IS

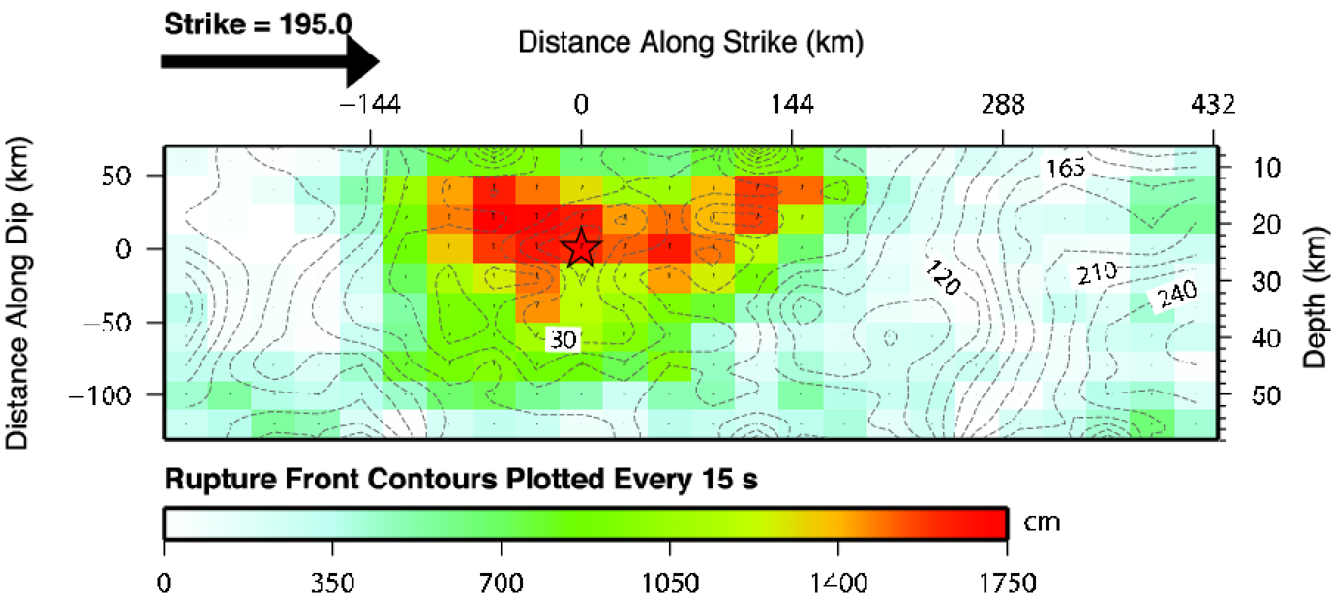
Historic Seismicity

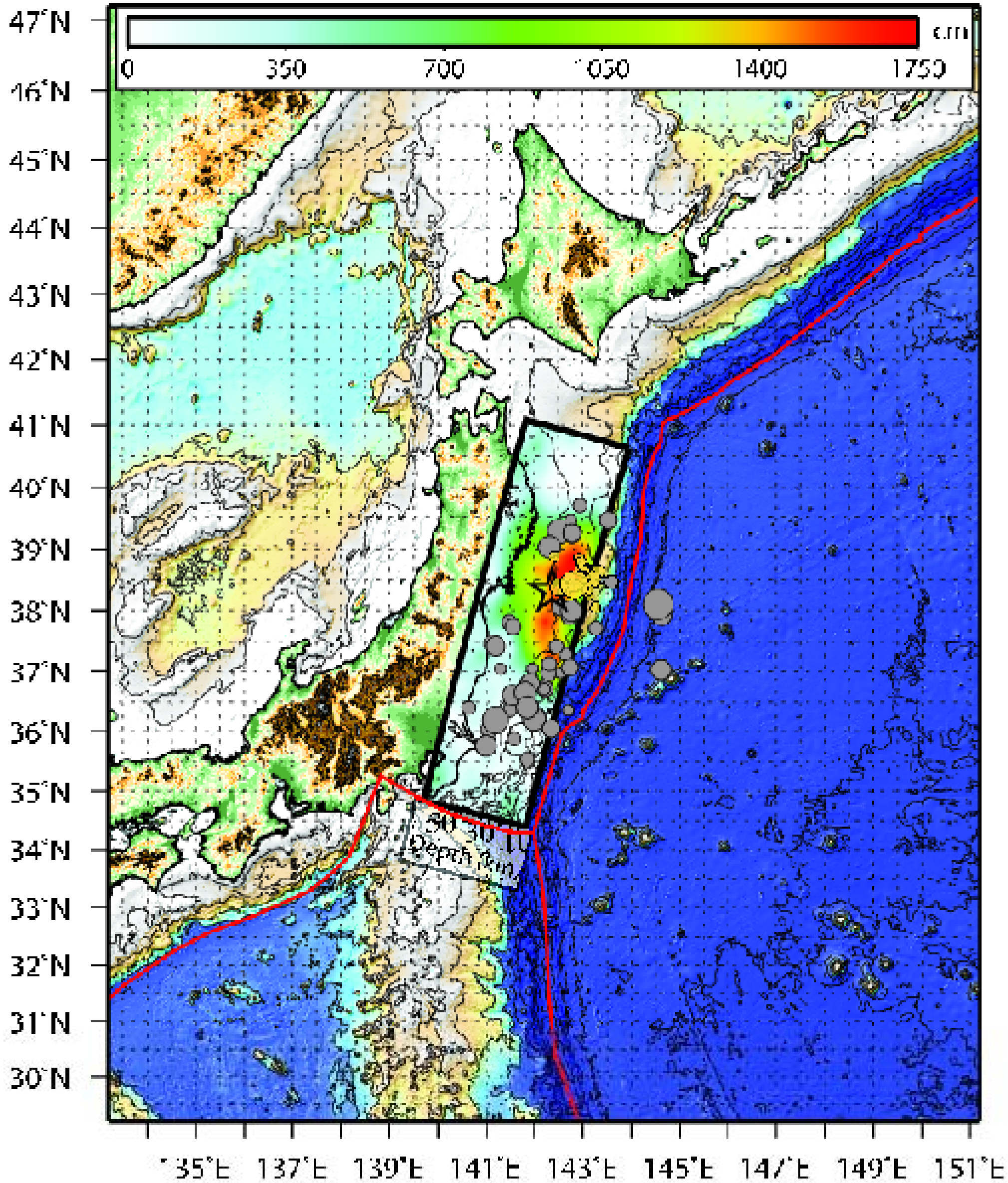
Magnitude 8.9 NEAR EAST COAST OF HONSHU, JAPAN
Friday, March 11, 2011 at 05:46:23 UTC



After analyzing waveform fits based on the nodal planes of the rapid WCMT moment tensor, and those more closely matching the slab geometry, we find that a nodal plane striking 195 deg., and dipping 14 deg., fits the data better. The seismic moment release based upon this plane is 4.04e+29 dyne.cm using a 1D crustal model interpolated from CRUST2.0 (Bassin et al., 2000).

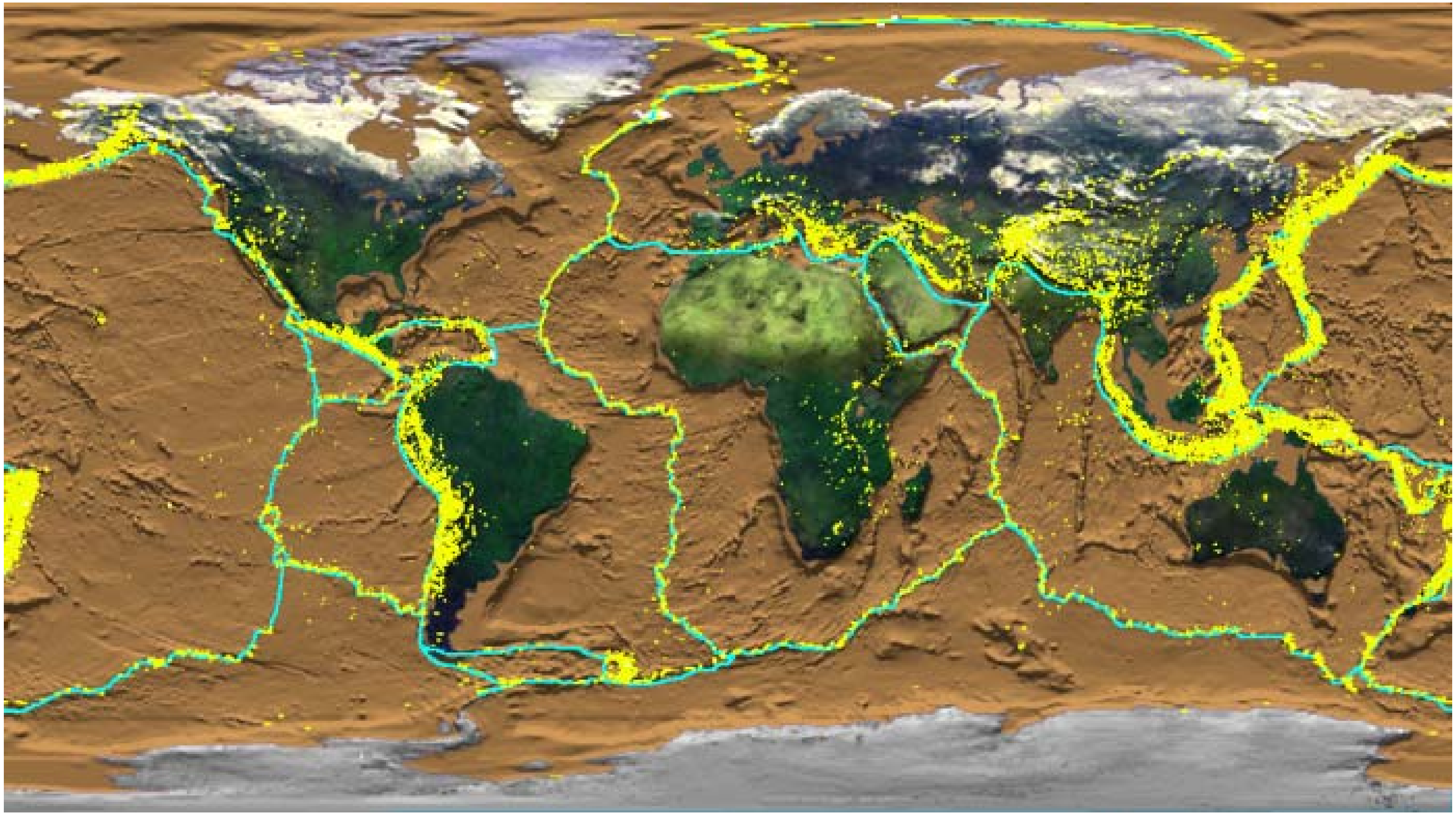
Cross-section of slip distribution



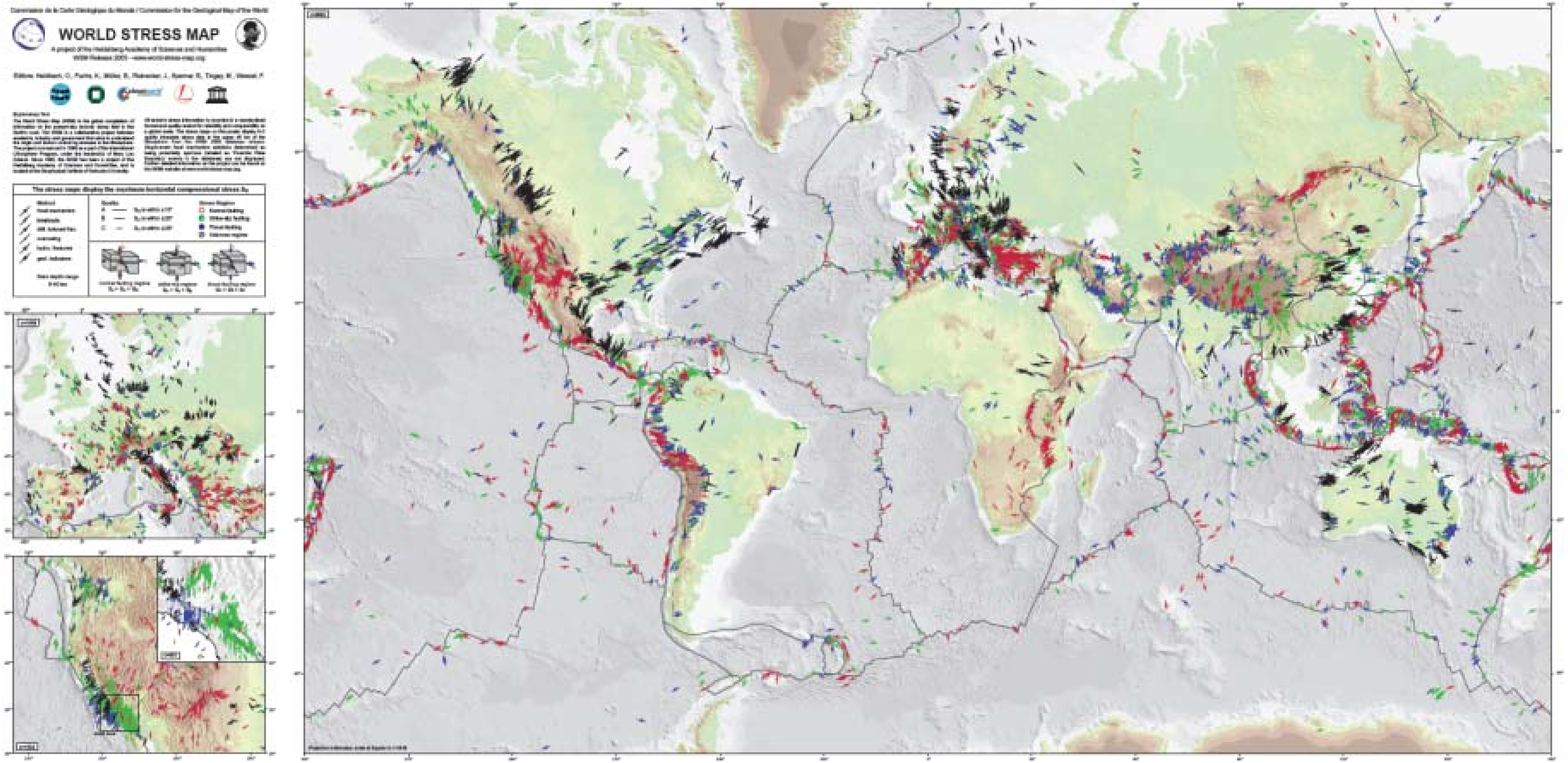

cm
0
350
700
1050
1400
1750
47°N
46°N
45°N
44°N
43°N
42°N
41°N
40°N
39°N
38°N
37°N
36°N
35°N
34°N
33°N
32°N
31°N
30°N
135°E
137°E
139°E
141°E
143°E
145°E
147°E
149°E
151°E

Earthquakes since 1960

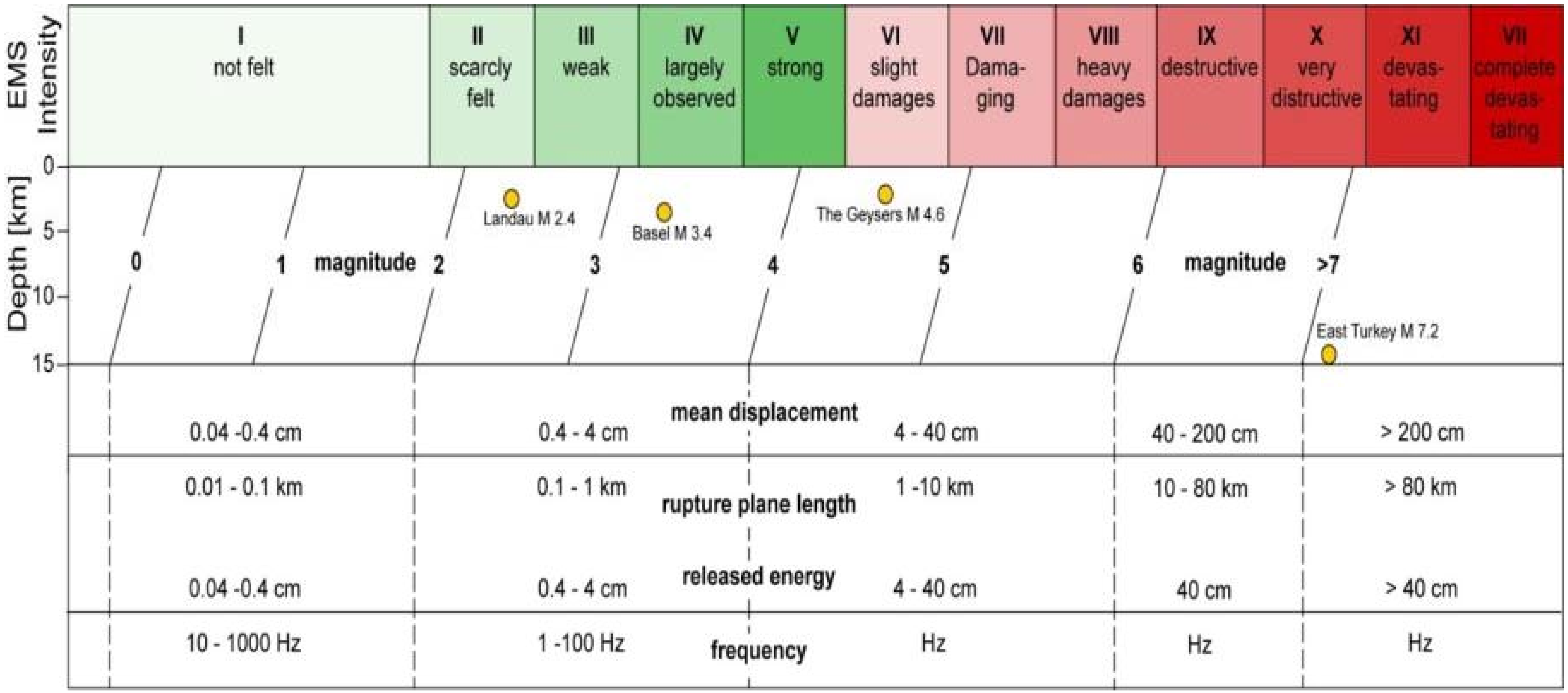
Plate tectonics & seismic activity



Intra-plate-stresses



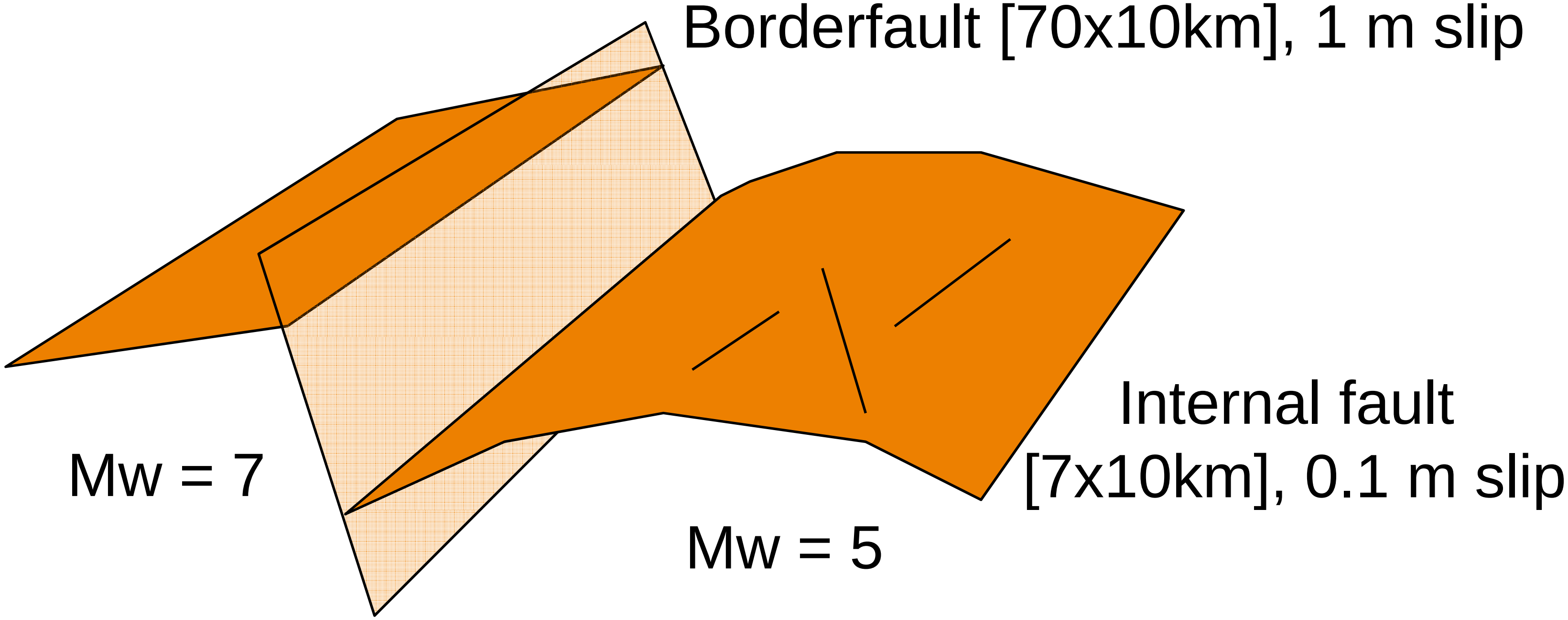
Magnitude of earth quakes



What is the relation with magnitude and surface slip

- Hanks and Kanimori (1979)

$$M_w = 0.67 \log(M0) - 10.7$$

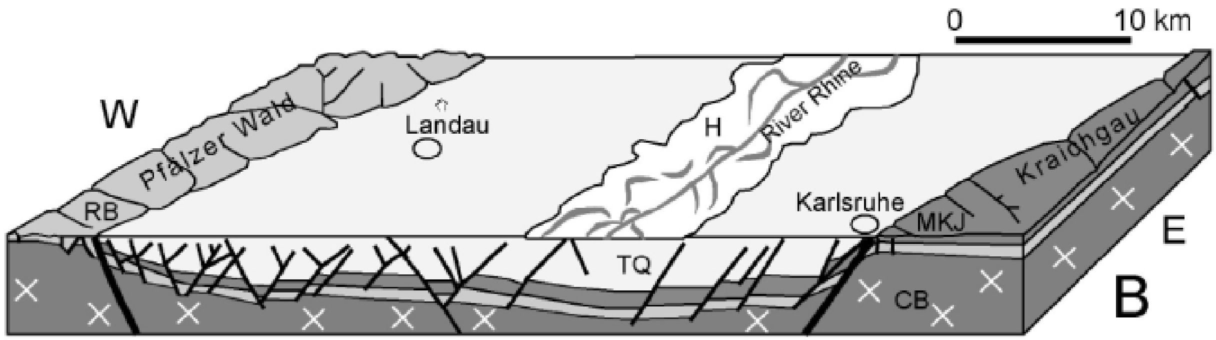


M=7, 70x10 km fault, 1m displacement

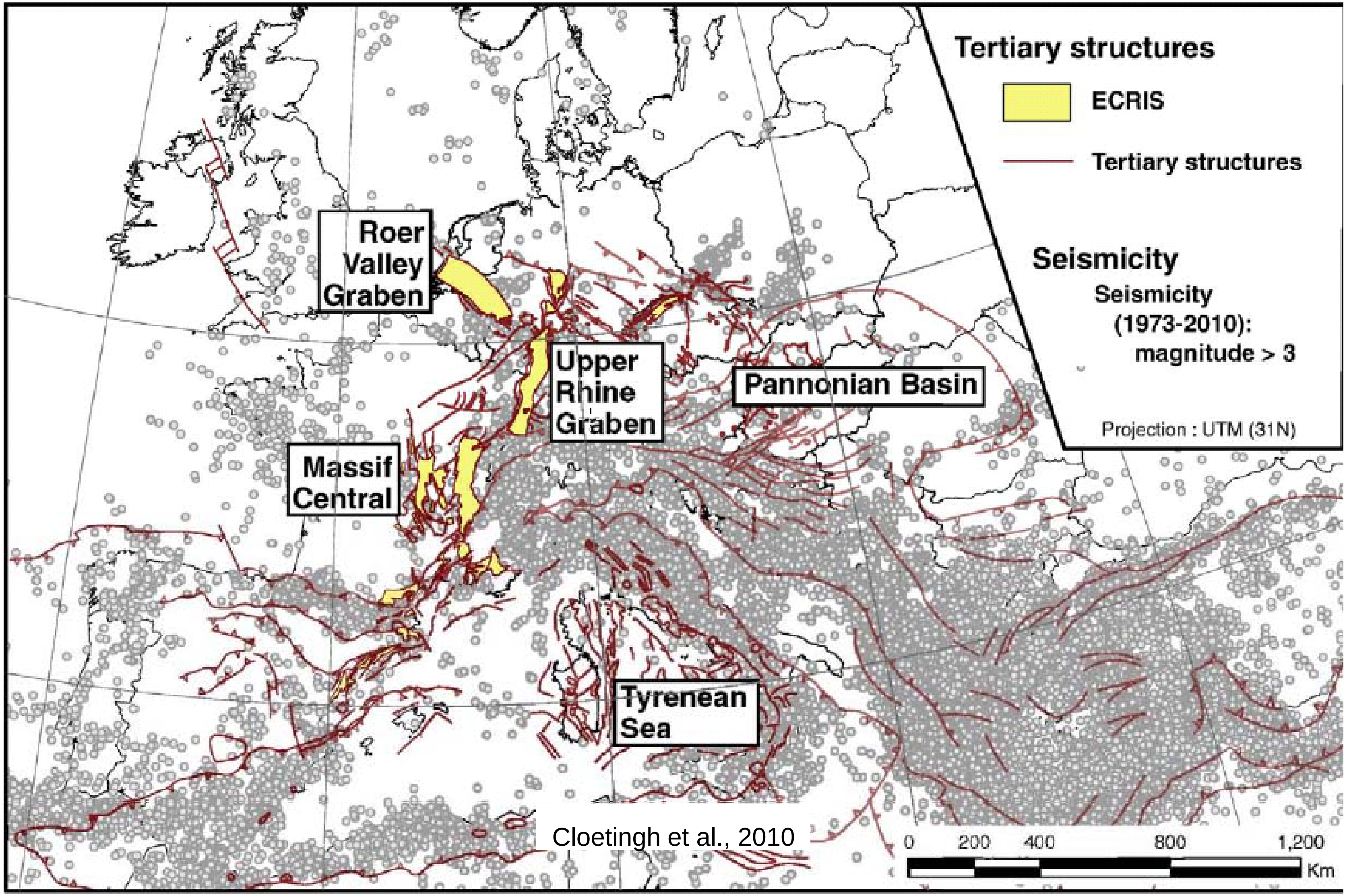
M=6, 30x5 km fault, 0.4m displacement

M=5, 15x5 km fault, 0.15m displacement

Big earth quakes
Located at
Mapped Major faults

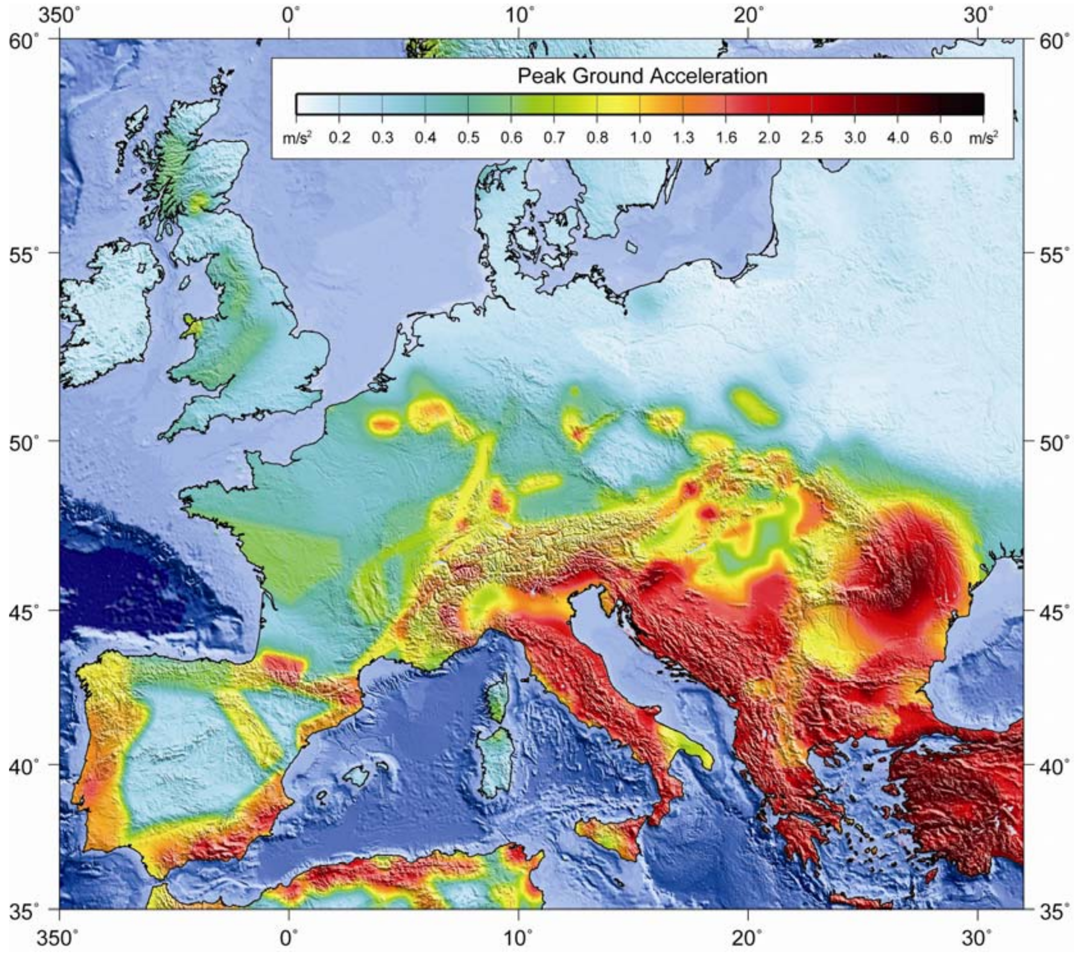


→ Lesson: stay away from seismically active faults



Cloetingh et al., 2010

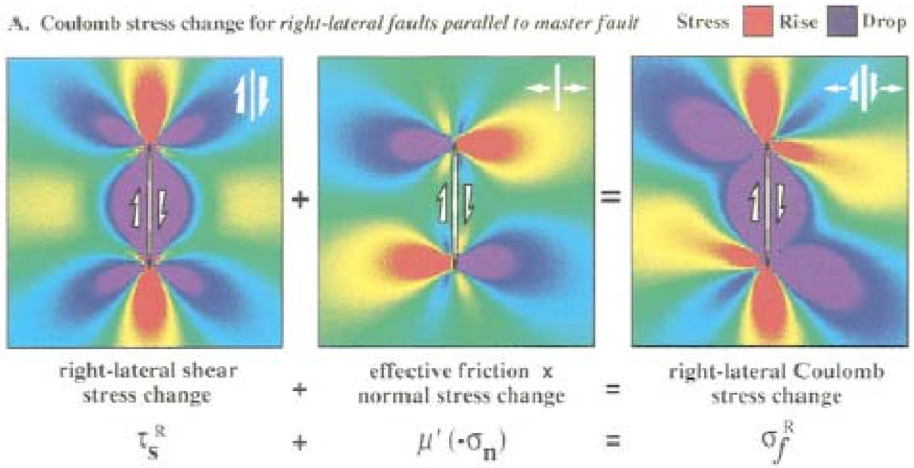
PGA hazard map



Seismic Hazard Map of Europe as part of the Global Seismic Hazard Map (Giardini et al., 2003; Grünthal et al., 1999). The map depicts the seismic hazard as Peak Ground Acceleration (PGA, ms^{-2}) with 10% probability of exceedence (or a 90% chance of non-exceedance) in 50 years, corresponding to a return period of 475 years (source GFZ, oliver Heidbach)

Coulomb Stress Change

Calculated numerically in elastic medium using Okada (1992)



King et al., 1994

Input parameters

- Young's modulus, Poisson's ratio
- Calculated for a specific orientation of faults
  - Pre-determined
  - Optimally oriented faults
- Slip distribution source fault (often uncertain)

RED is closer to failure, purple away from failure→

Slip only possible if during faulting friction

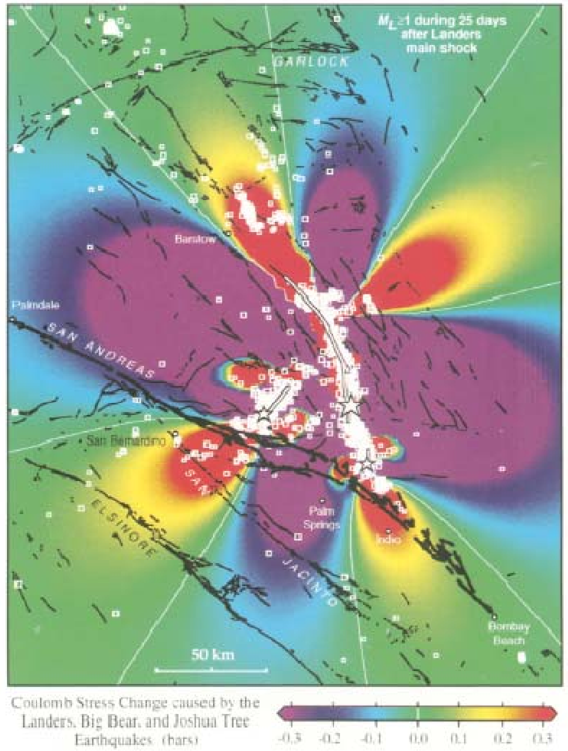
Stress-based modeling: rupture propagates

Landers M 7.3 1994

- From one point stress release
- Mechanism: redistribution of stress after an earthquake

Applied in natural seismicity

- Static stress change due to coseismic slip governed by Coulomb Failure Function:

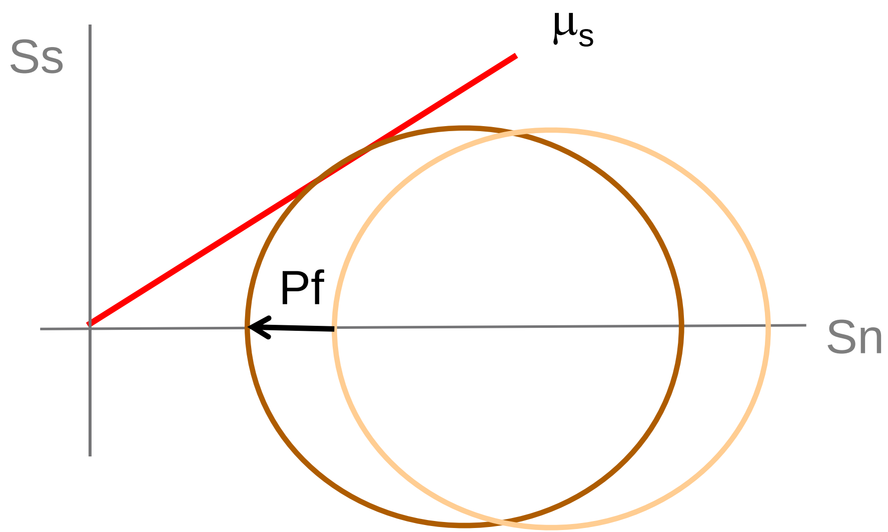


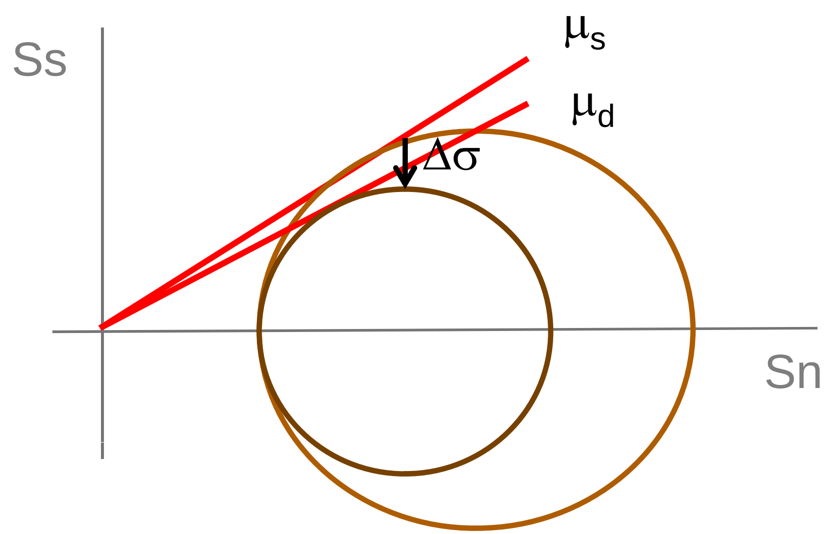
King et al., 1994

Measure of whether a fault has been brought closer (positive, red areas) or further away (negative, blue areas) from failure

GEOELEC
Supported by INTELLIGENT ENERGY EUROPE
BRGM GFZ
TNO innovation for life

Fluid pressure loading on existing fracture and rate and state friction → stress drop





Failure:
Fluid pressure (Pf) increase results in a reduction of the effective normal stress (Sn) on the fracture wall and causes the fracture to fail when $Ss/Sn>\mu_s$

Rupture:
rate (μ_d) and state/dynamic (μ_s) friction causes the shear stress (Ss) to drop ($\Delta\sigma$=stress drop) close to dynamic friction. This stress change is caused by slip along the rupture surface

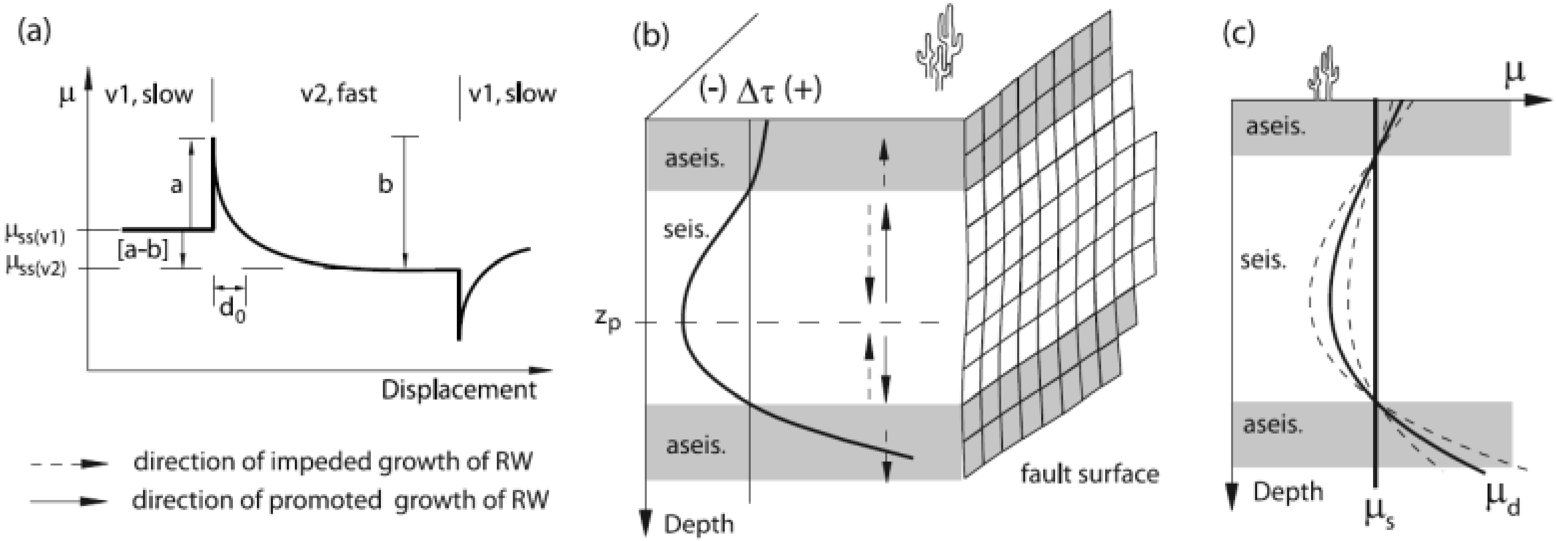


Figure 1. (a) Evolution of friction coefficient μ during a velocity stepping experiment, $v_1 \rightarrow v_2 \rightarrow v_1$). The slip rate dependent change of μ is expressed by $[a - b]$. (b) Depth variation of coseismic stress drop $\Delta\tau$ and inferred non-uniform evolution of rupture width. Shaded areas highlight aseismic zones, where velocity strengthening prohibits earthquake initiation. Also shown is an example of a non-planar self-similar fault plane as it is used in our simulations. (c) Depth evolution of μ_s and μ_d, the latter derived from depth evolution of $[a - b]$. Solid lines indicate average values for μ_s and μ_d. Dashed lines indicate the range of possible dynamic friction values.

$$\mu_d(z) = \mu_s - \left(\frac{2 \ to \ 10\% \mu_s}{mean[a-b]_{seis}} \right) [a-b](z)$$

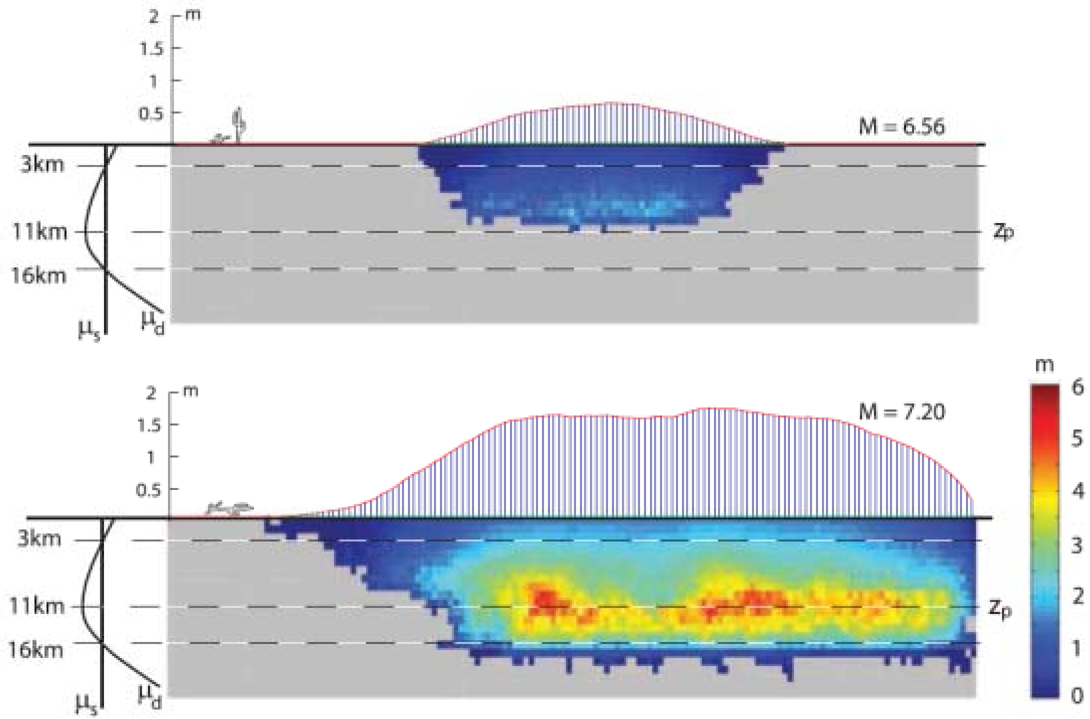
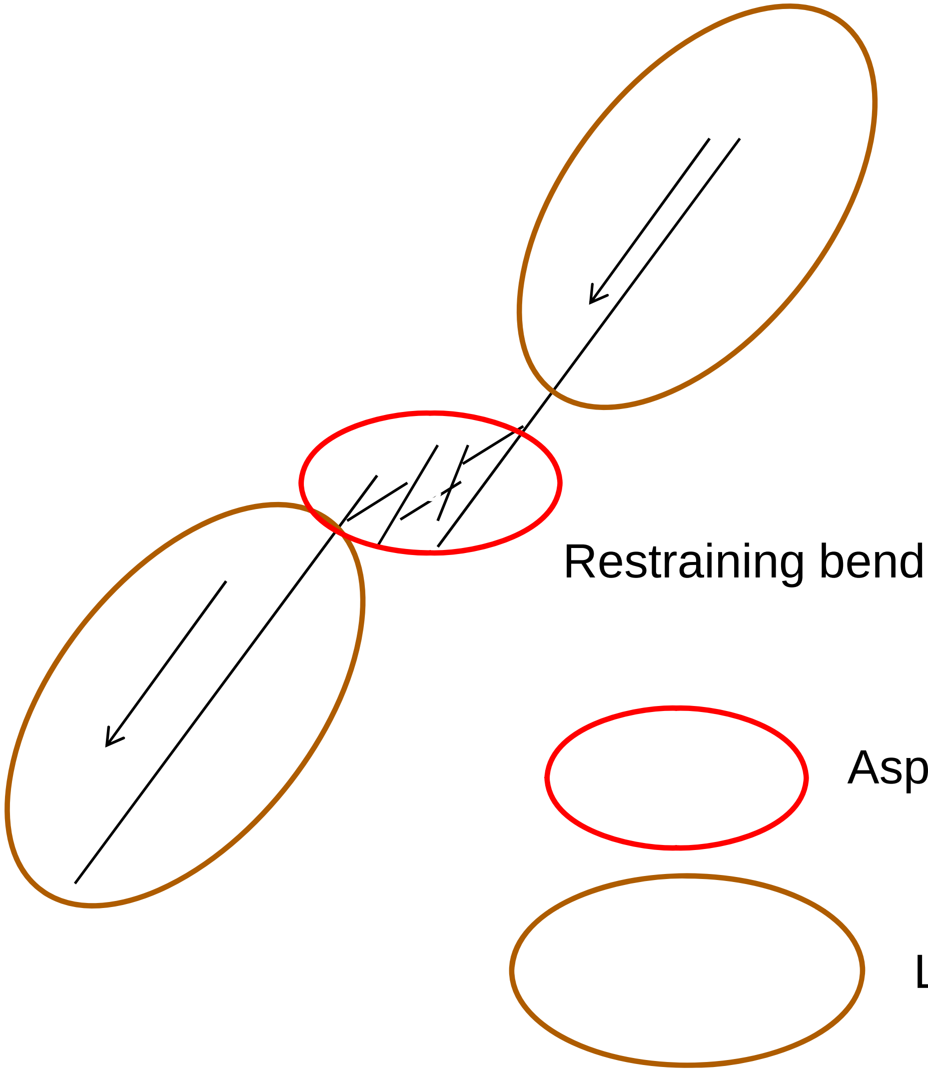


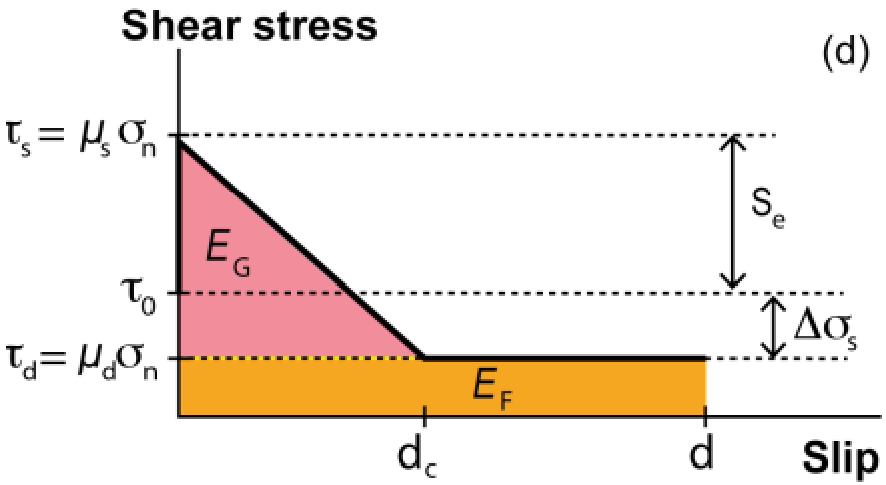
Figure 2. Color-coded amount of slip (22 km wide, 150 km long sub-vertical strike-slip fault with amplitude-wavelength ratio $\lambda = 0.003$) of a typical small and large earthquake. Gray fault patches did not slip in the respective events. Shown above is the respective surface-slip distribution. On the left is the average depth distribution of μ_s and μ_d and the location of z_p.

Heterogenity in **stress drop (depth dependent) relative to stress criticallity (dependent on natural stress and fault geometry and rheology)**

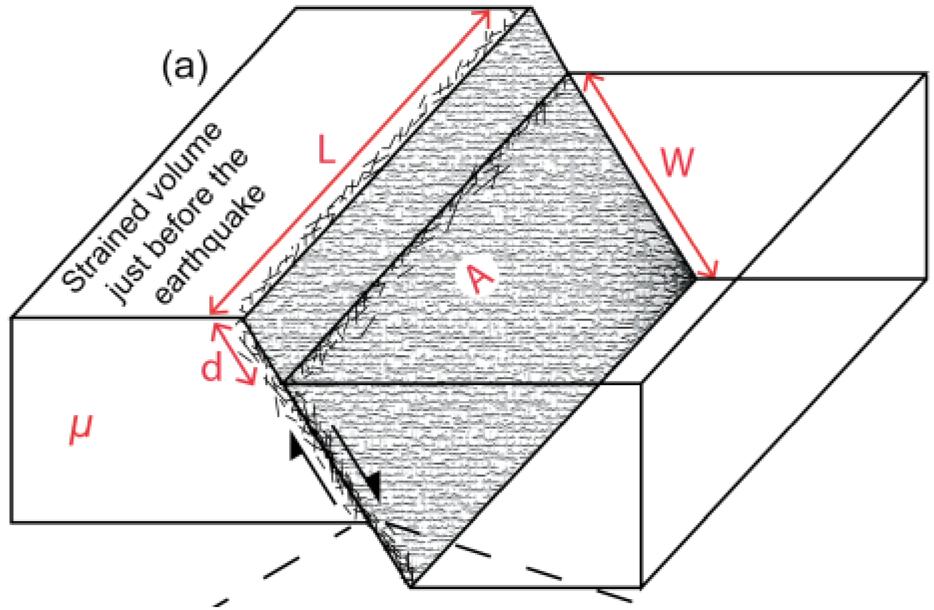


Earth quakes

- Fault rupture responsible for energy release
  - Faults=fractures
  - faults are zones of weakness, more likely to shear than rock matrix → taking up seismicity
  - Rupture mechanism-models require **stress drop** (state and rate friction), otherwise there is no movement

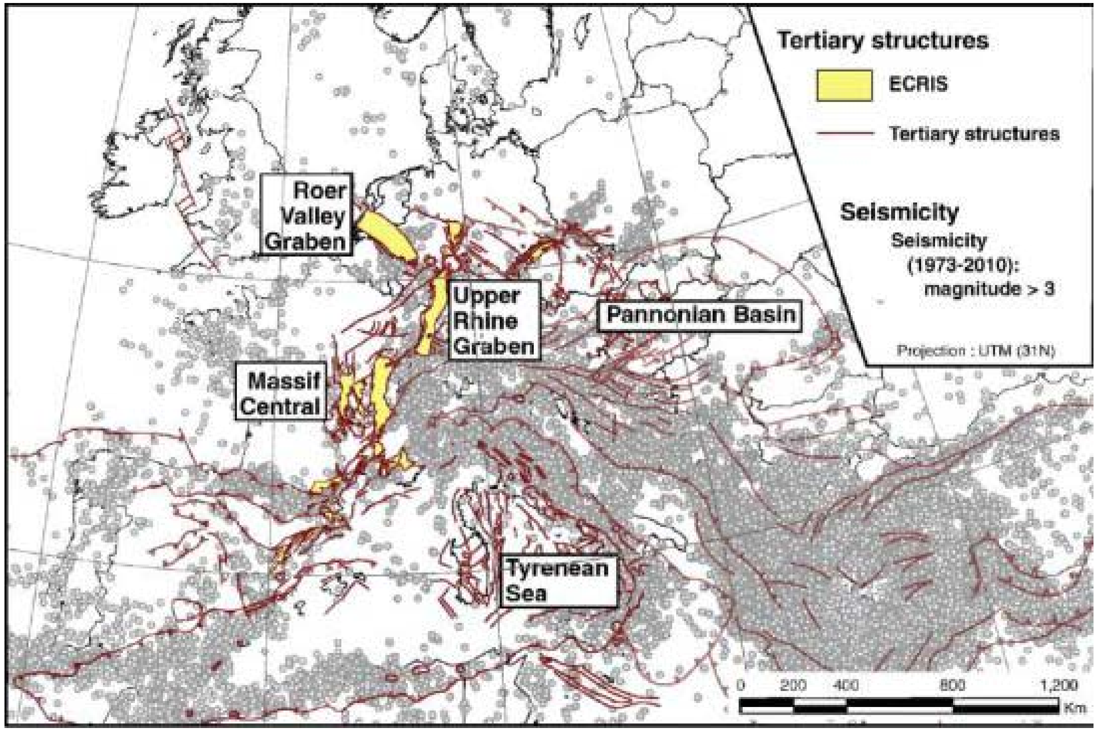


Cappa and Rutquist, 2011



Baseline seismicity in the european central rift

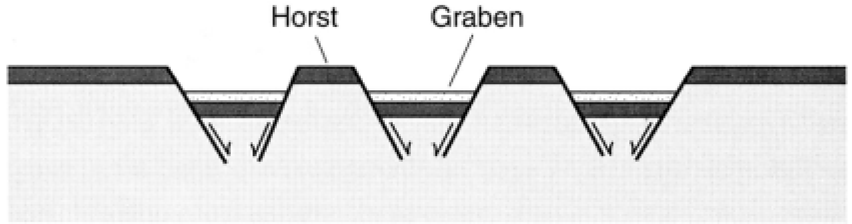
- Extensional and strike slip setting



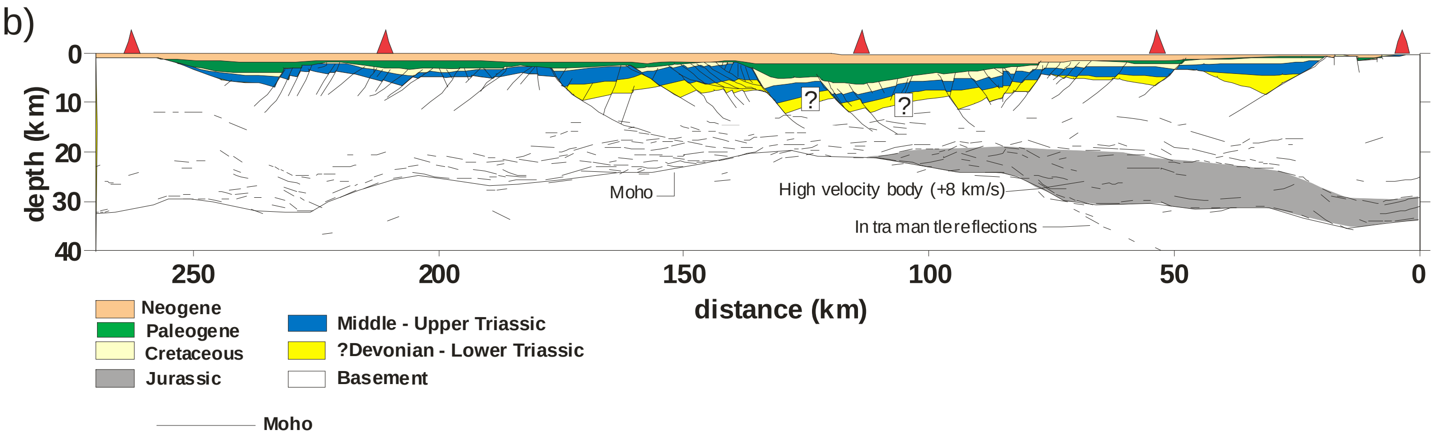
rate (depth dependency and spatial

FAULT SYSTEMS

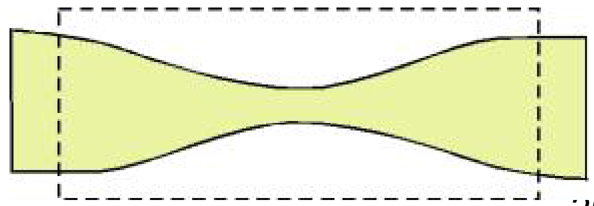
Assemblage of planar faults



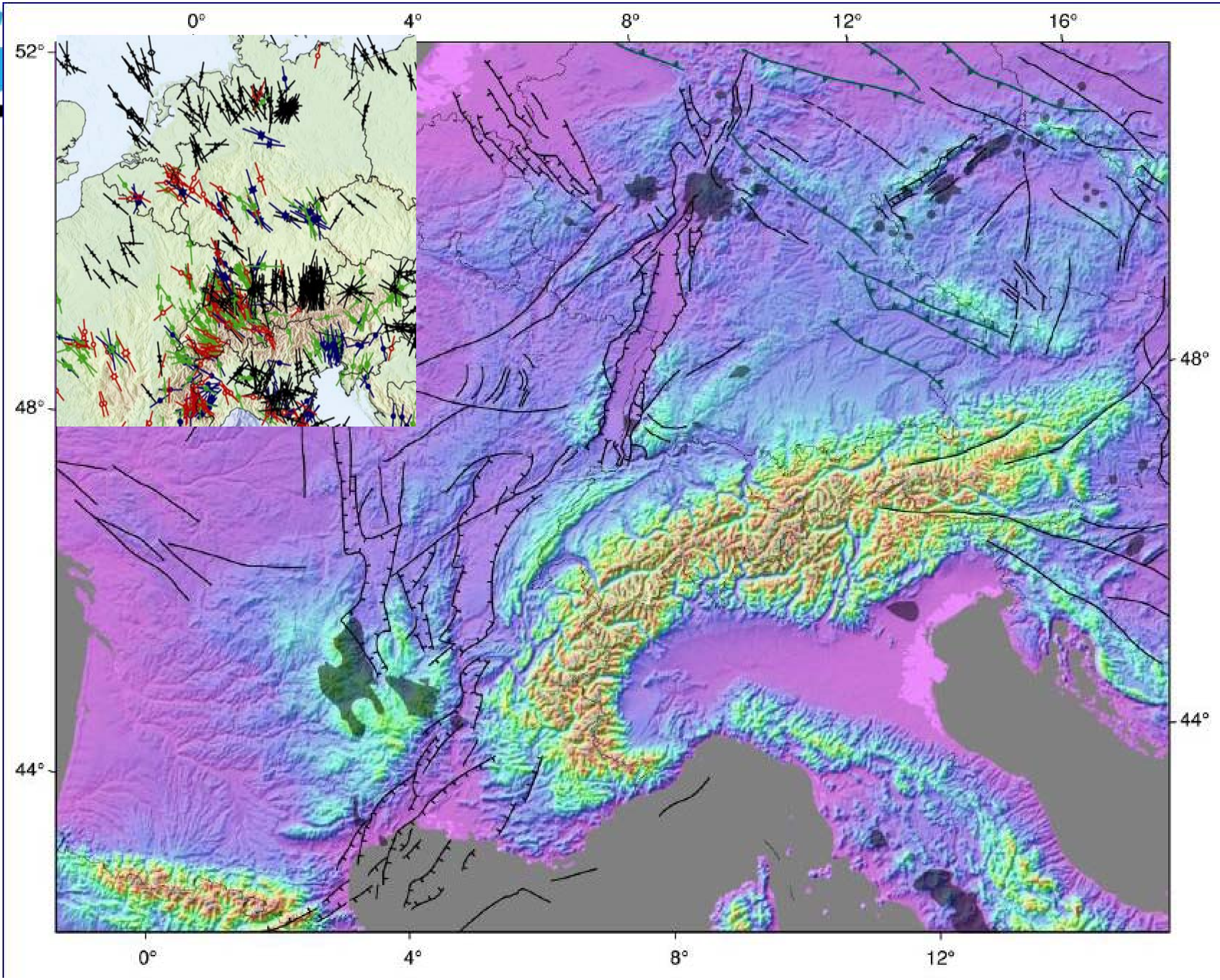
Assemblage of listric faults



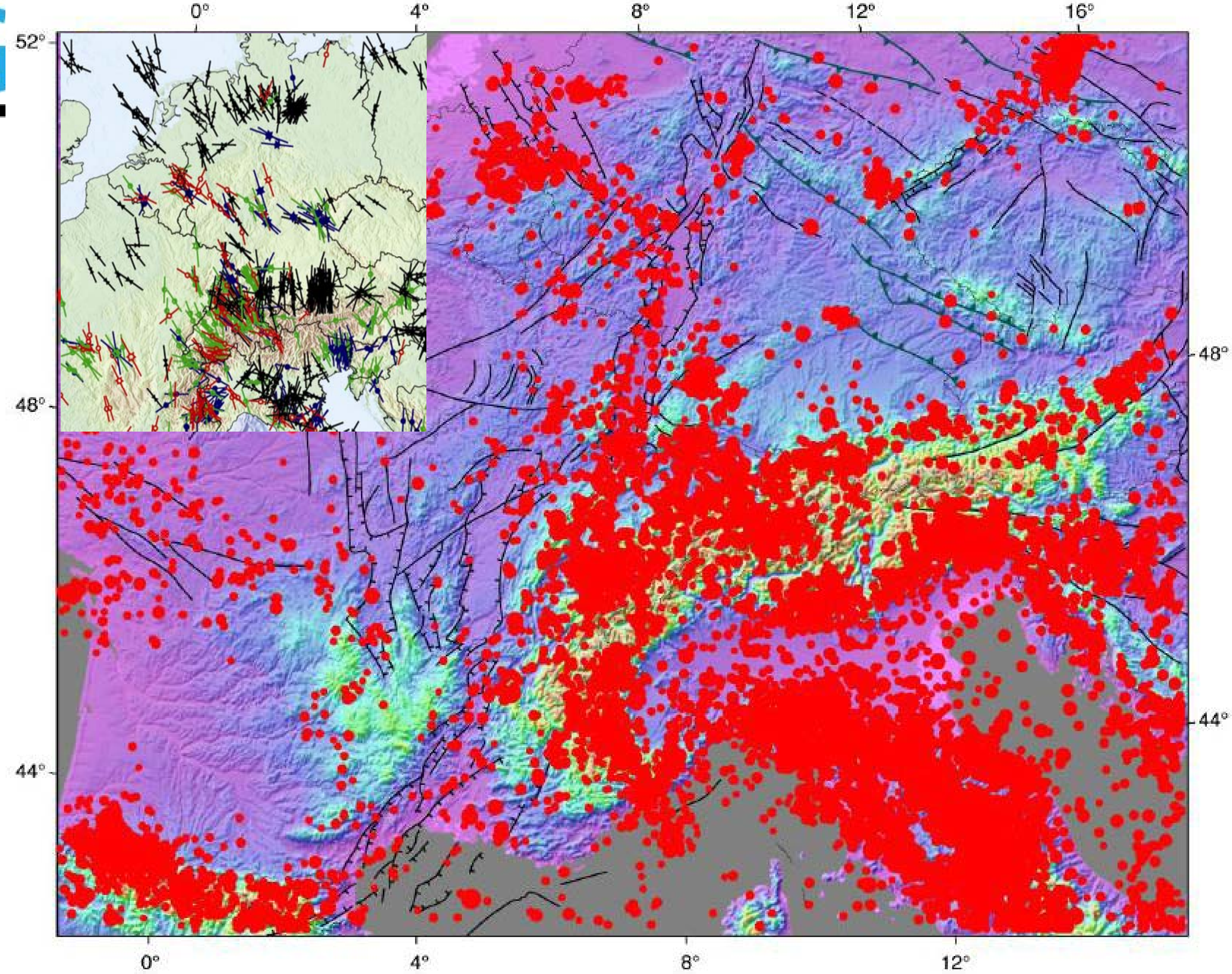
Note: these faults accommodate a pure shear deformation (also called non rotational



FZ



Ziegler and Dezes, 2008



NOAA NEIC EPIC earthquake catalogue 1900 - 2003 (Mag > 3.0)

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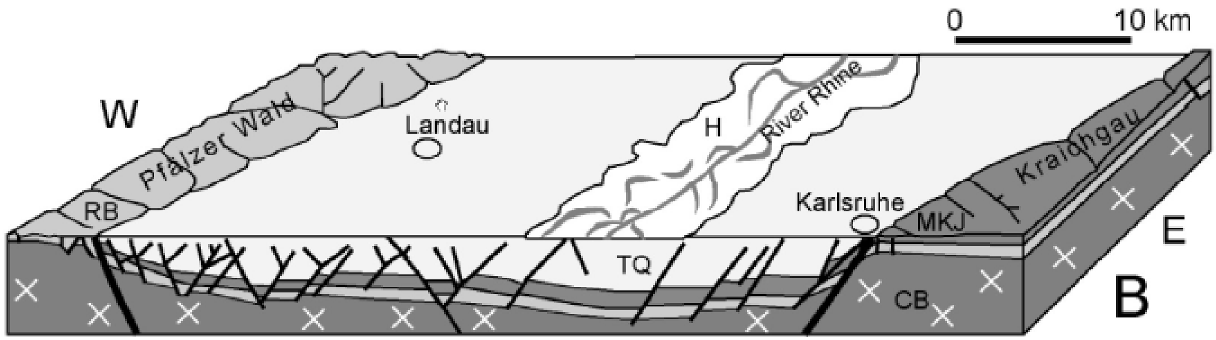
M=6, 30x5 km fault, 0.4m displacement

M=5, 15x5 km fault, 0.15m displacement

Big earth quakes
Located at
Mapped Major faults

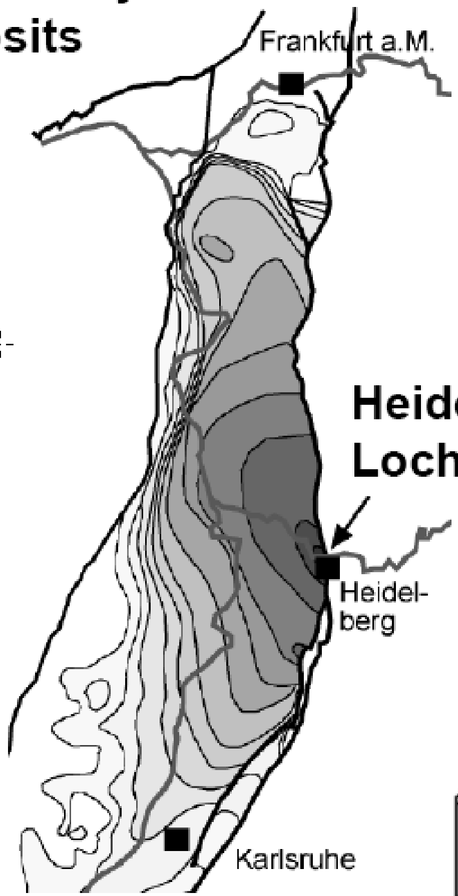


→ Lesson: stay away from seismically active faults

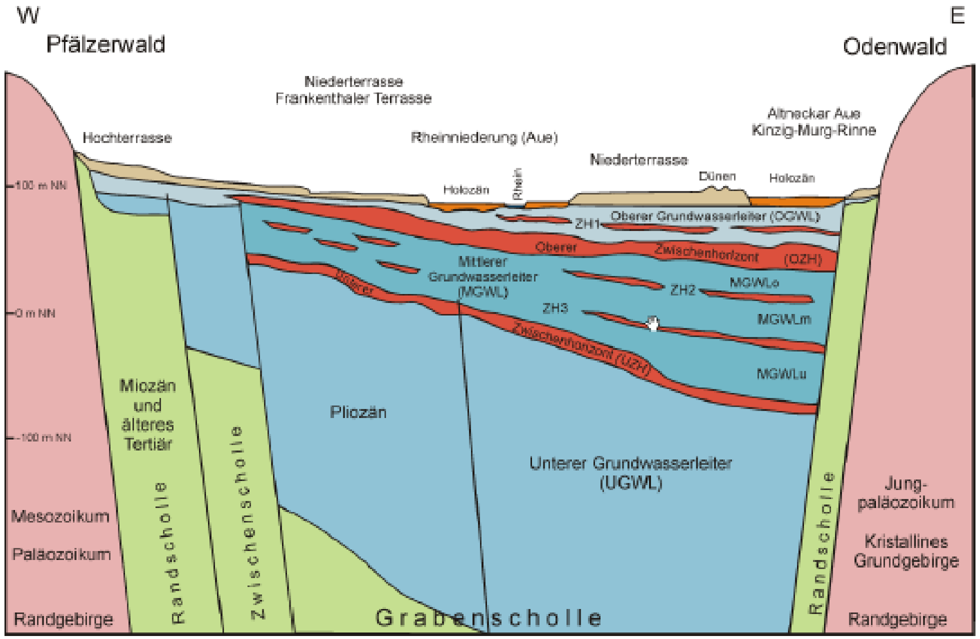
Peters and Van Balen, 2008

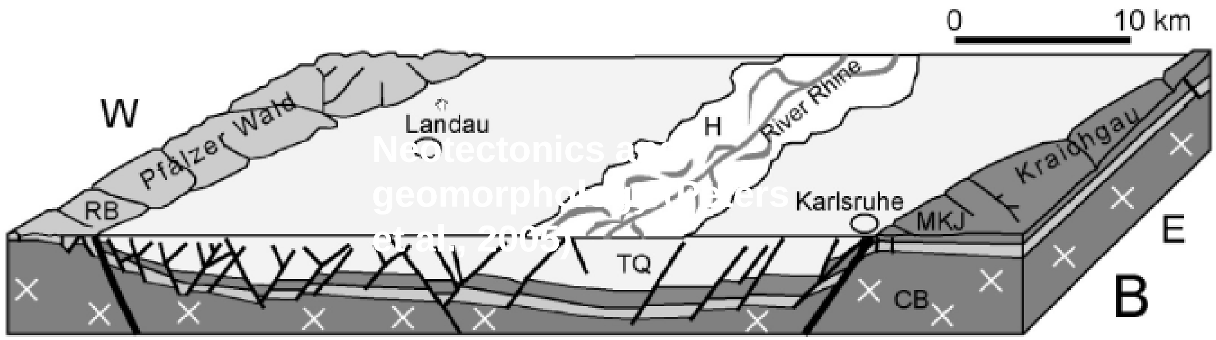
Asymmetry of the northern URG

Quaternary deposits



Heidelberger Loch

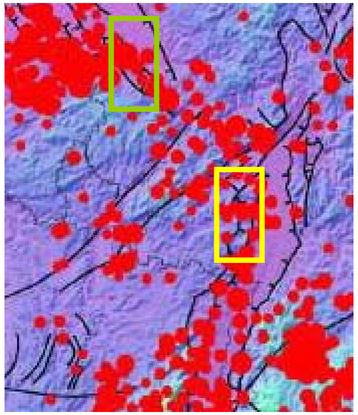


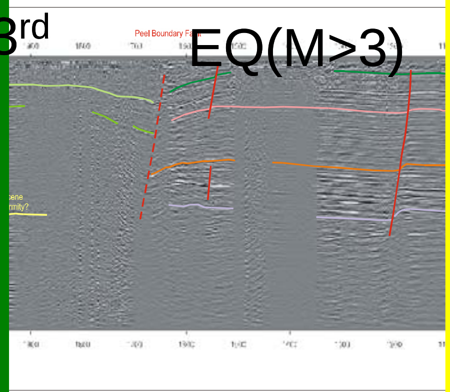


Strain at neotectonic timescales Trenching 10^4 years

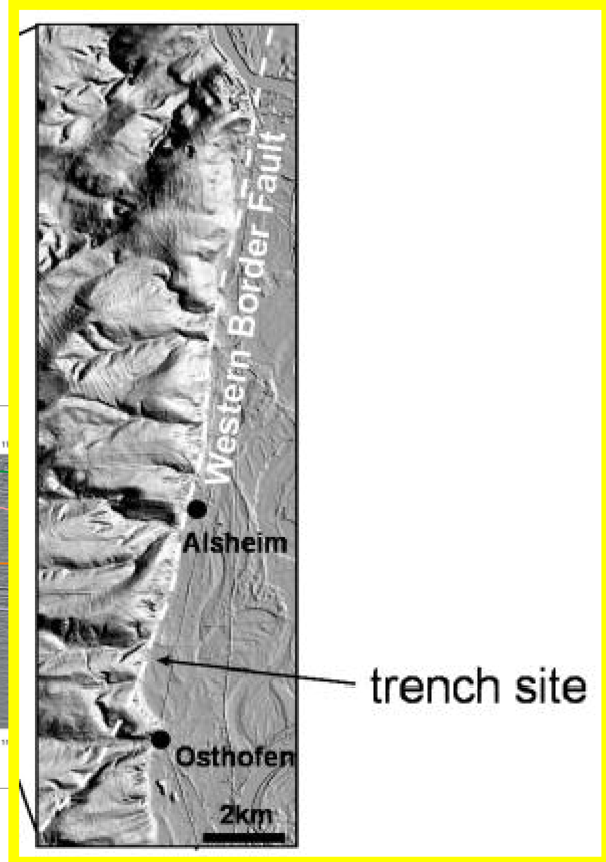
Roer Valley Graben

Houtgast et al., 2002





Upper Rhine Graben



Peters et al., 2005

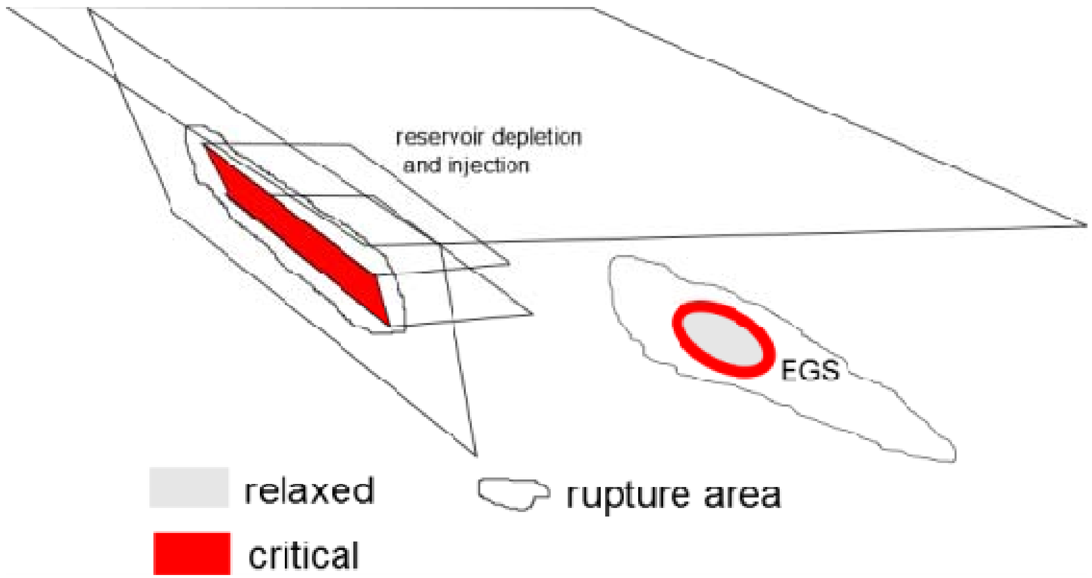
M =7 highly unlikely, it would require a rupture area of 70x10km and 1 meter slip

What is induced seismicity

- Triggered natural seismicity (event which would happen anyhow, but now earlier)
- Seismicity which otherwise would not happen → in tectonically stable areas
- No distinction is made

Which operations involve induced seismicity

- Natural dams (increasing fluid pressure)
- Mining instabilities and pressure
- Hydraulic fracturing
- Subsurface storage and depletion



Supported by

mcGarr, 2002

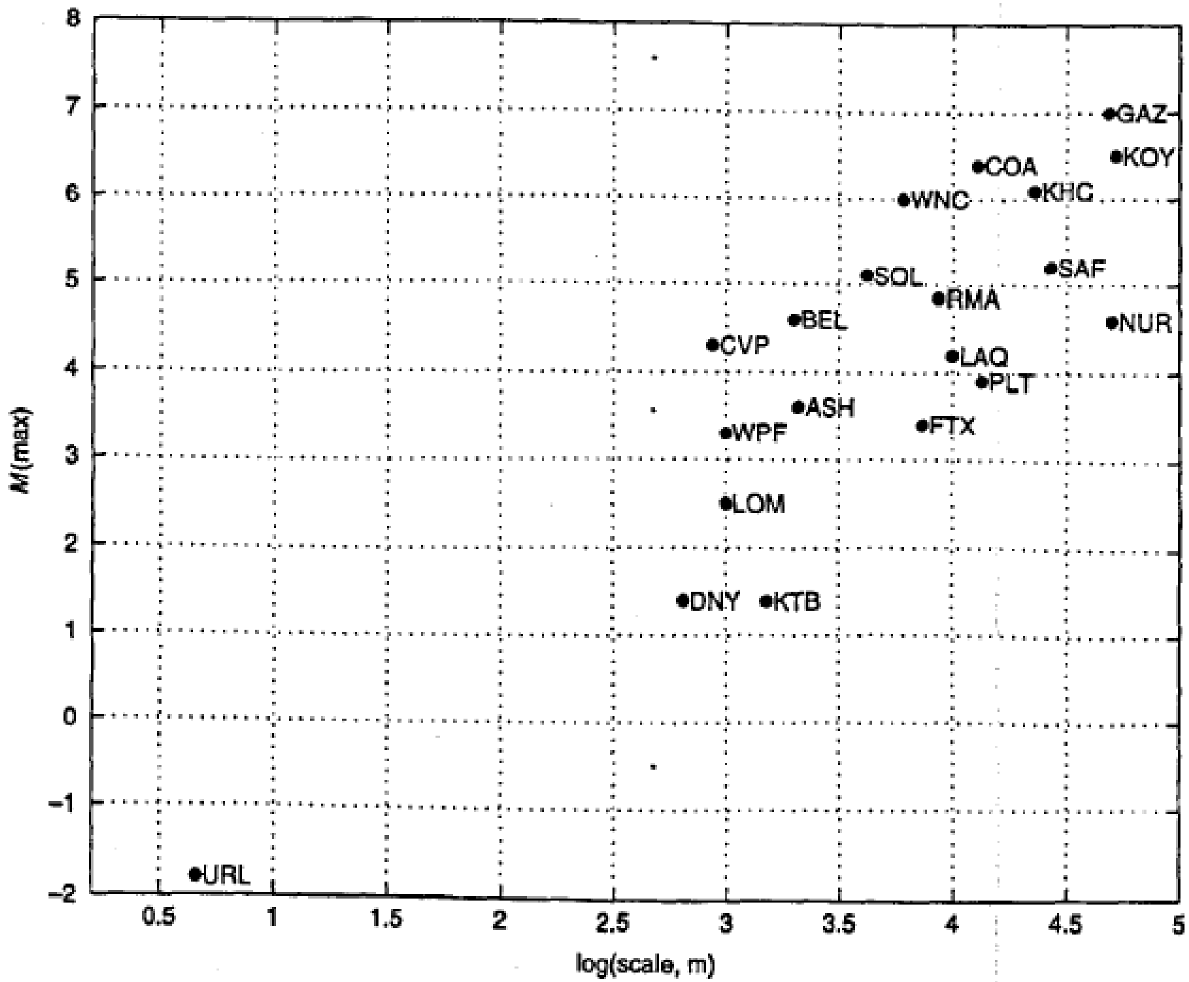


FIGURE 3 Maximum magnitude as a function of scale for 20 case histories. The scale is the maximum dimension of the causative activity as explained in the text. The letter identifications for the case histories, in the same order as they appear in the text, are: underground mining: SAF, deep gold mines in South Africa; URL, Underground Research Laboratory; SOL, Solvay Trona; quarry and surface mining: WPF, Wappingers Falls; CVP, Cacoosing Valley; BEL, Belchatow; LOM, Lompoc Diatomite; Liquid injection: RMA, Rocky Mountain Arsenal; ASH, Ashtabula; DNY, Dale NY; KTB, KTB, Germany; reservoir impoundment: KOY, Koyna; NUR, Nurek; Oil/gas production: LAQ, Lacq; PLT, Pleasanton TX; FTX, Fashing TX; COA, Coalinga; KHC, Kettleman North Dome; WNC, Whittier Narrows; GAZ, Gazli.