

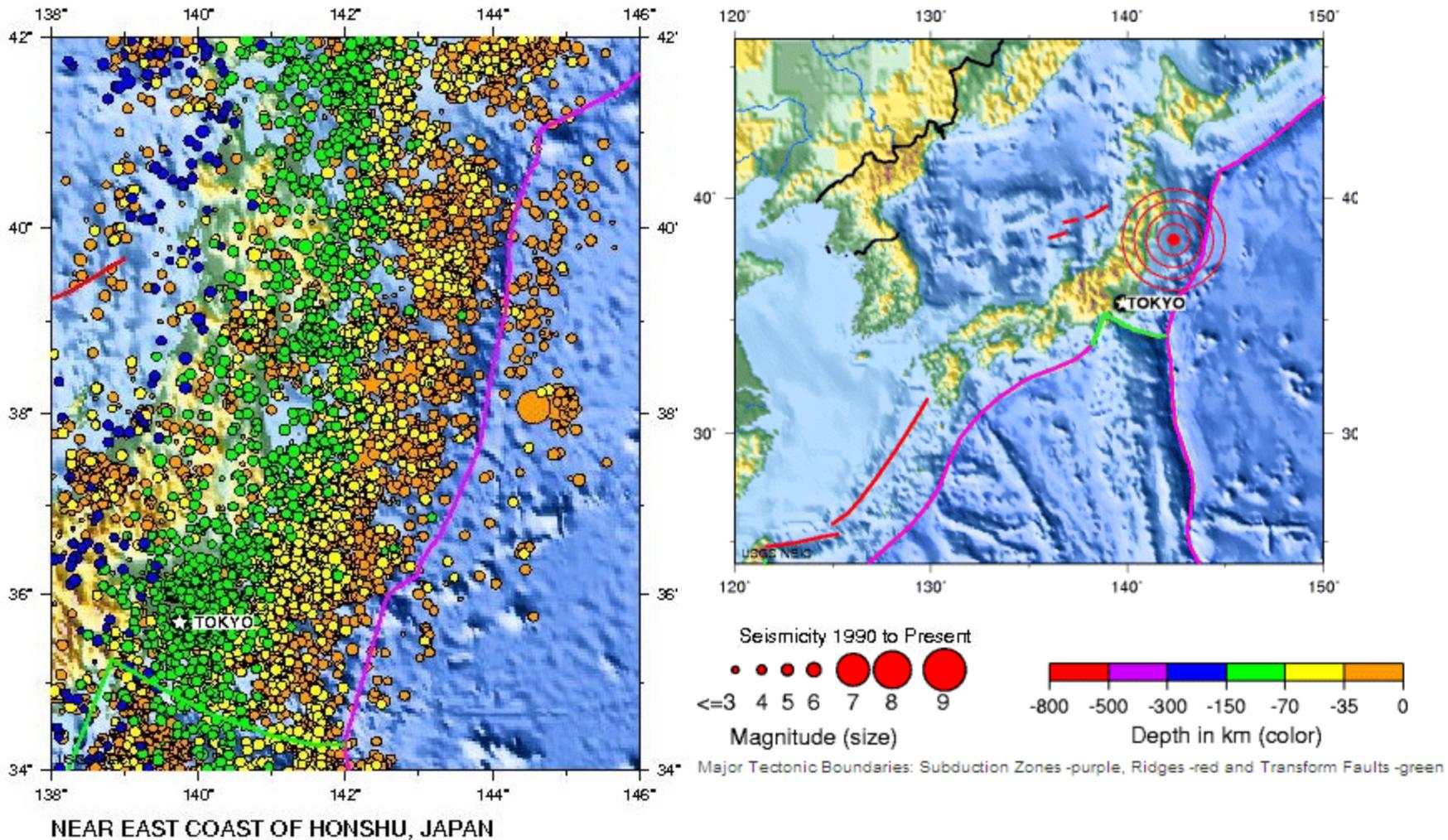
What is (induced) seismicity

- 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

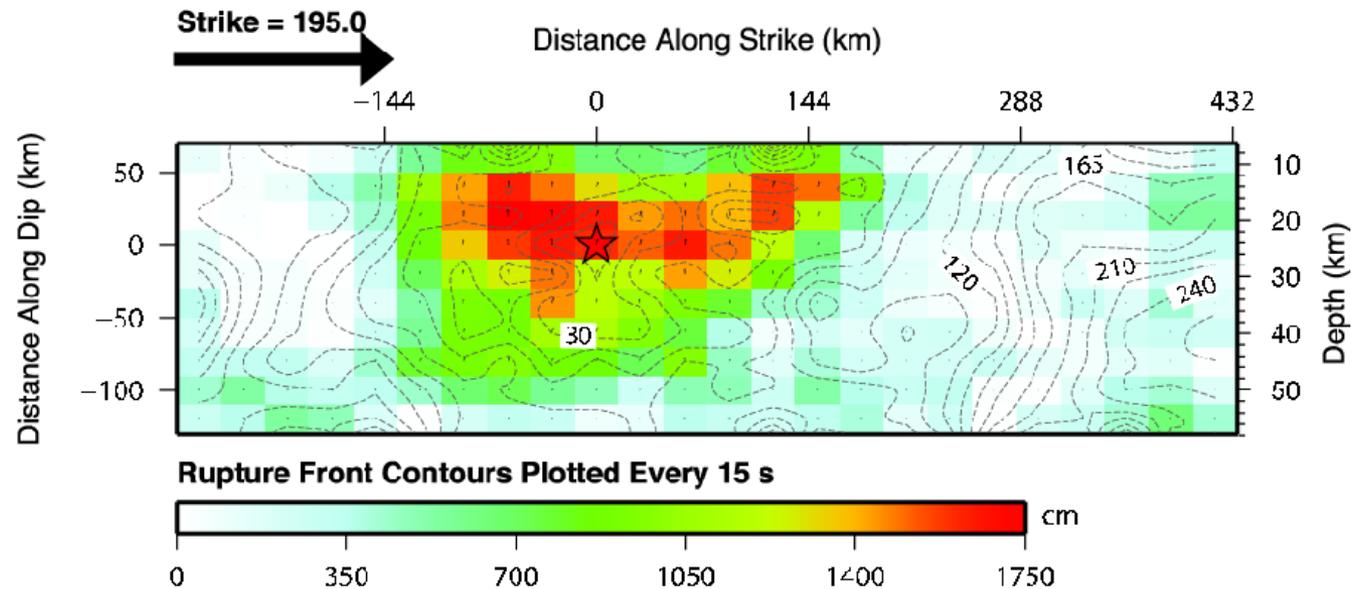
Magnitude 8.9 NEAR EAST COAST OF HONSHU, JAPAN

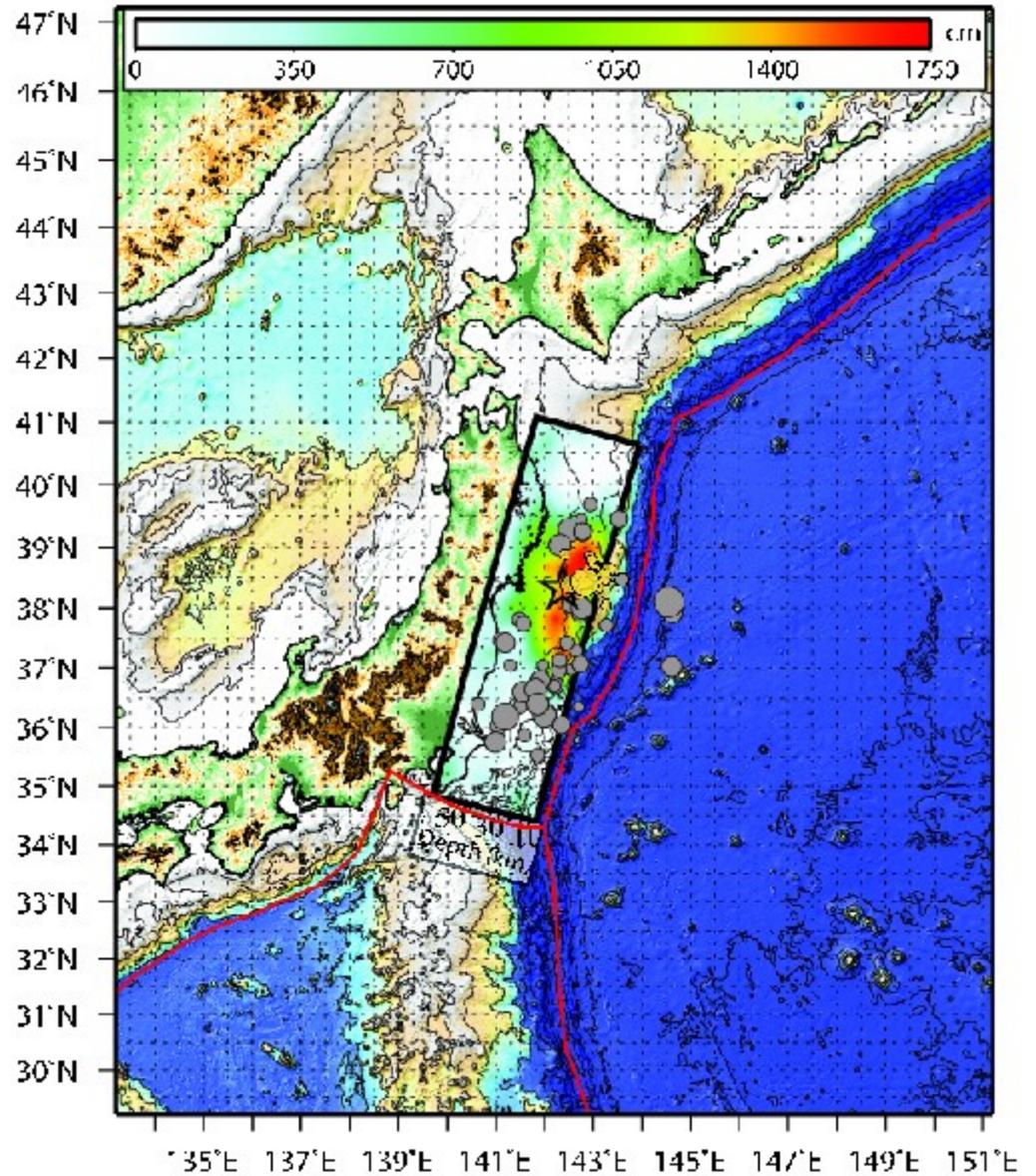
Friday, March 11, 2011 at 05:46:23 UTC



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 4.04×10^{29} dyne.cm using a 1D crustal model interpolated from CRUST2.0 (Bassin et al., 2000).

Cross-section of slip distribution





13-11-2012
tsunami asia

Earthquake in the News

Magnitude 9.0 - SUMATRA-ANDAMAN ISLANDS EARTHQUAKE
OFF THE WEST COAST OF NORTHERN SUMATRA
2004 December 26 00:58:53 UTC

Current Earthquakes

[USA](#)
[World](#)

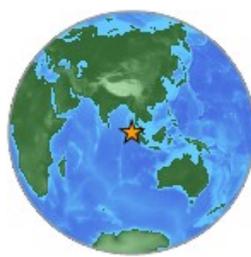
NEIC Current Earthquake Information

ShakeMaps

Seismogram Displays

Past & Historical Earthquakes

Earthquake Notification E-mail



Magnitude 9.0

Date-Time Sunday, December 26, 2004 at 00:58:53 (UTC)
 = Coordinated Universal Time
Sunday, December 26, 2004 at 7:58:53 AM
 = local time at epicenter
[Time of Earthquake in other Time Zones](#)

Location 3.316°N, 95.854°E

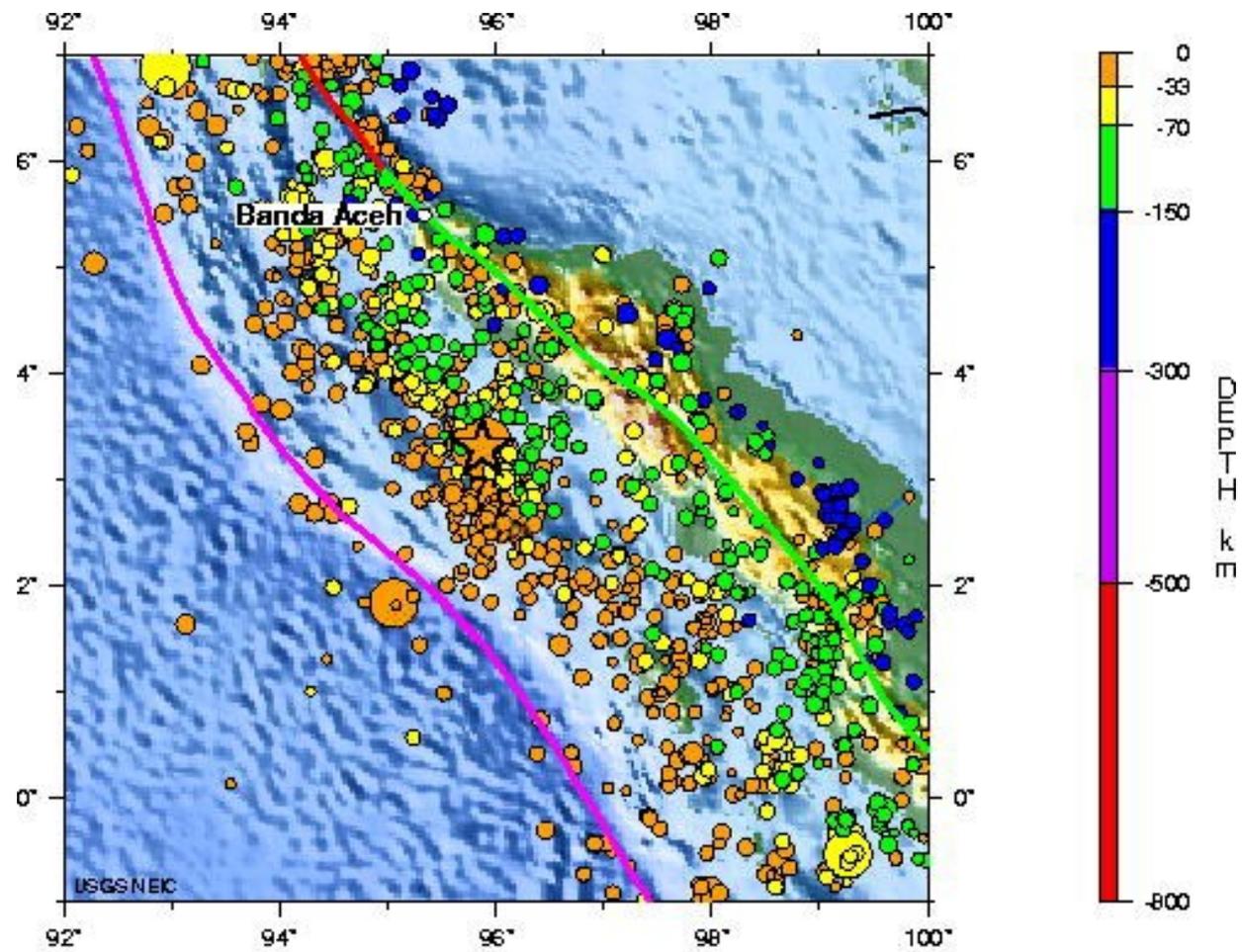
Depth 30 km (18.6 miles) set by location program

Region OFF THE WEST COAST OF NORTHERN SUMATRA

Distances
 250 km (155 miles) SSE of **Banda Aceh, Sumatra, Indonesia**
 310 km (195 miles) W of **Medan, Sumatra, Indonesia**
 1260 km (780 miles) SSW of **BANGKOK, Thailand**
 1605 km (990 miles) NW of **JAKARTA, Java, Indonesia**

Location Uncertainty horizontal +/- 5.6 km (3.5 miles); depth fixed by location program

Parameters Nst=276 Nbh=276 Dmin=654.9 km



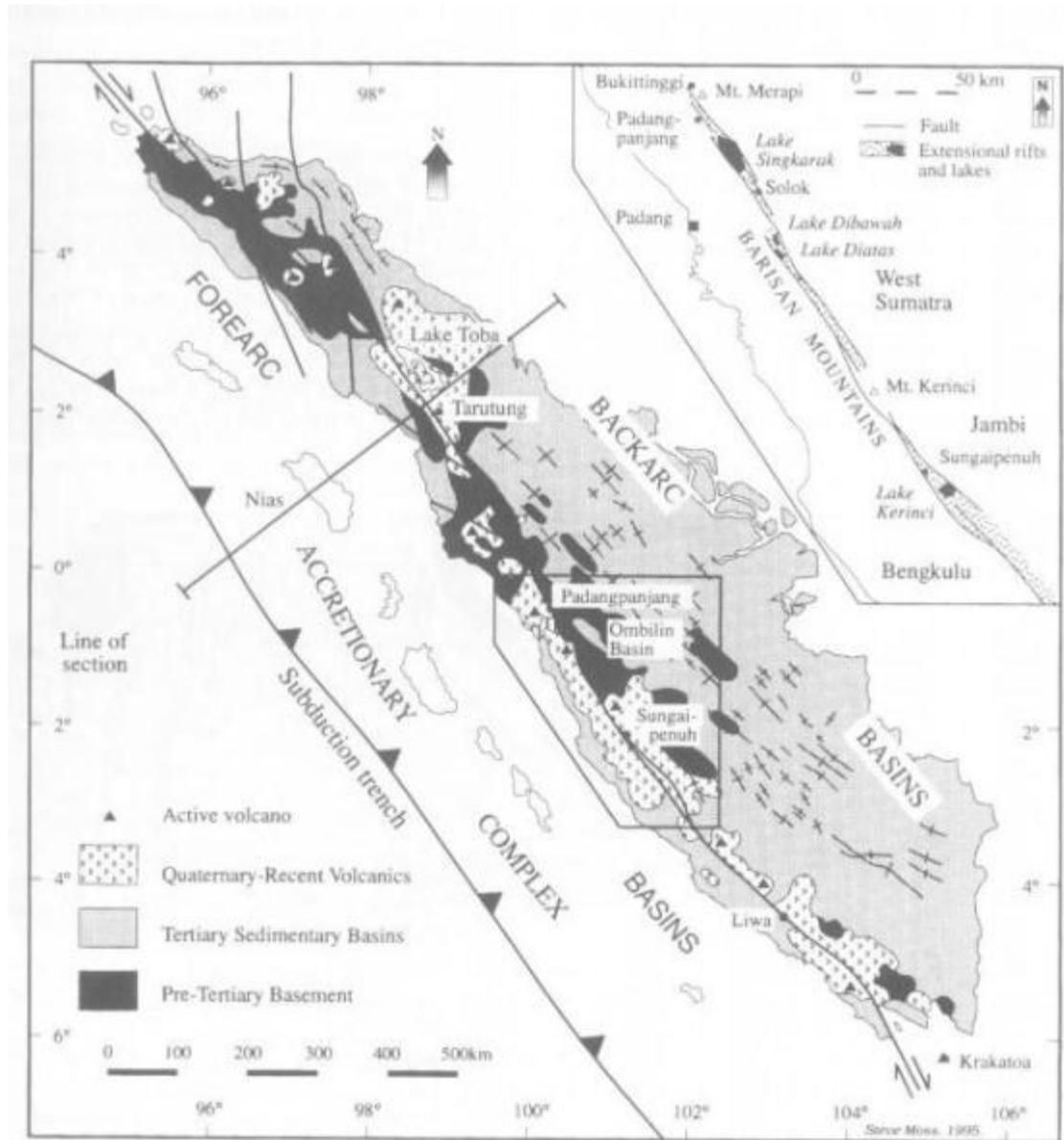
OFF THE WEST COAST OF NORTHERN SUMATRA

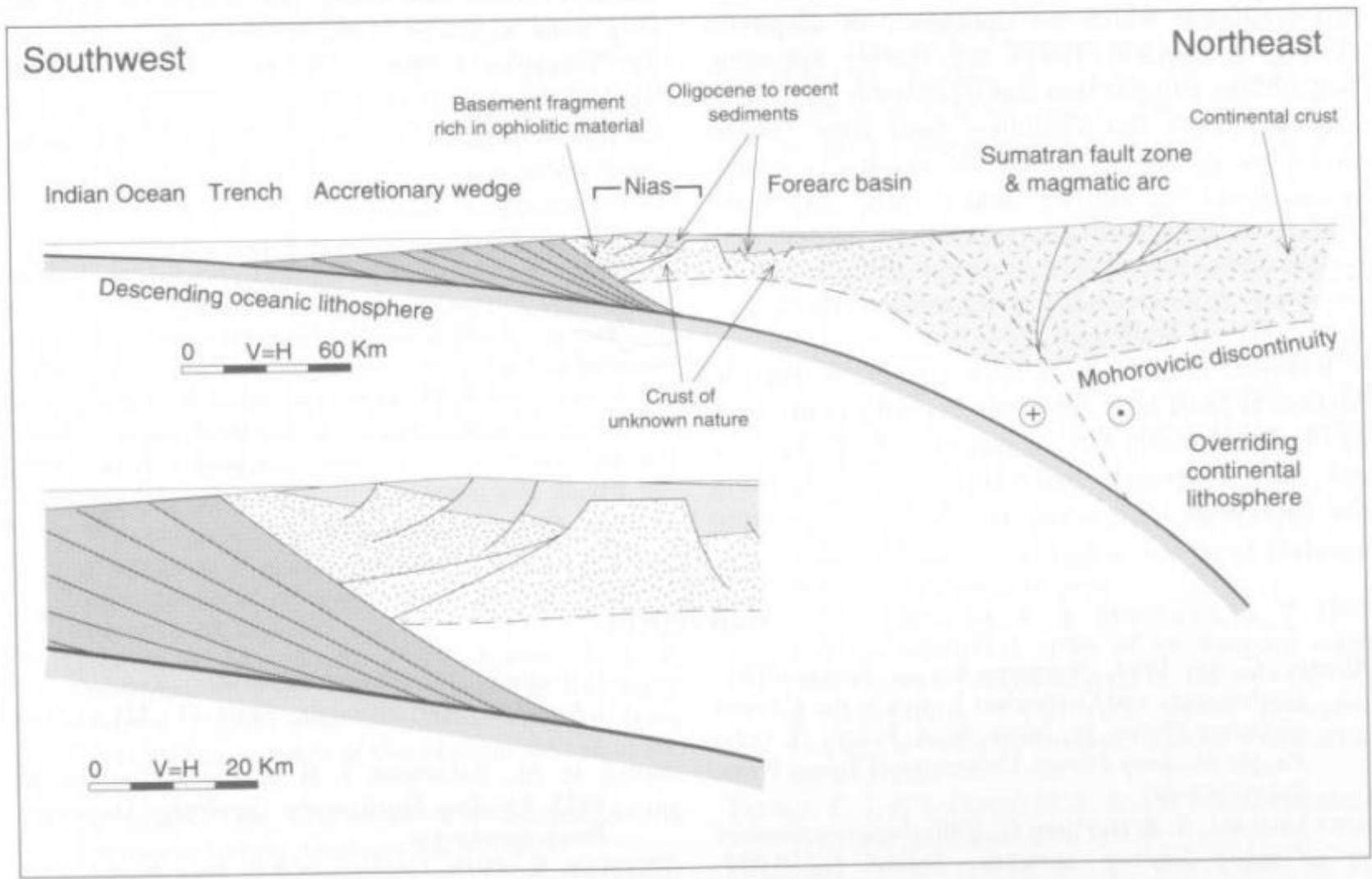
2004 12 26 00:58:53 UTC 3.30N 95.87E Depth: 30 km, Magnitude: 9.0

Seismicity 1990 to Present

Major Tectonic Boundaries: Subduction Zones -purple, Ridges -red and Transform Faults -green

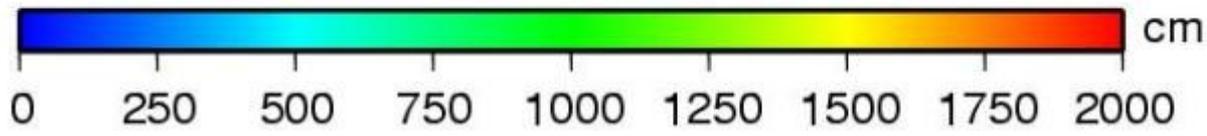
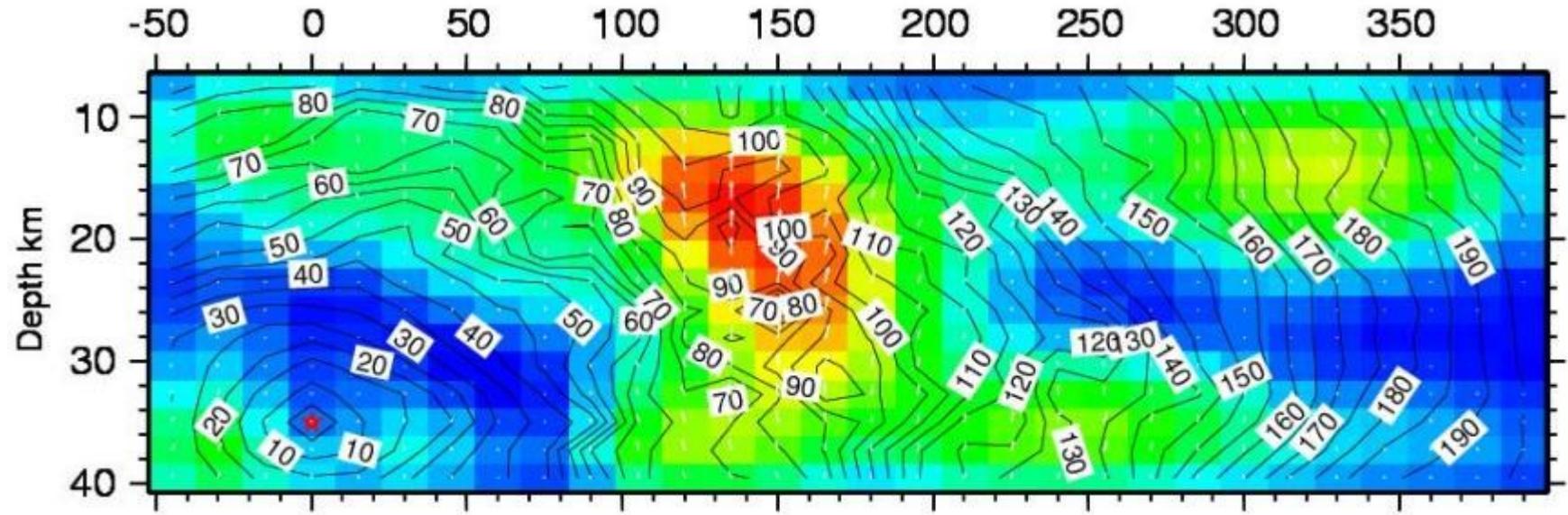
USGS National Earthquake Information Center





Strike= 320 degrees
→

km



Site response

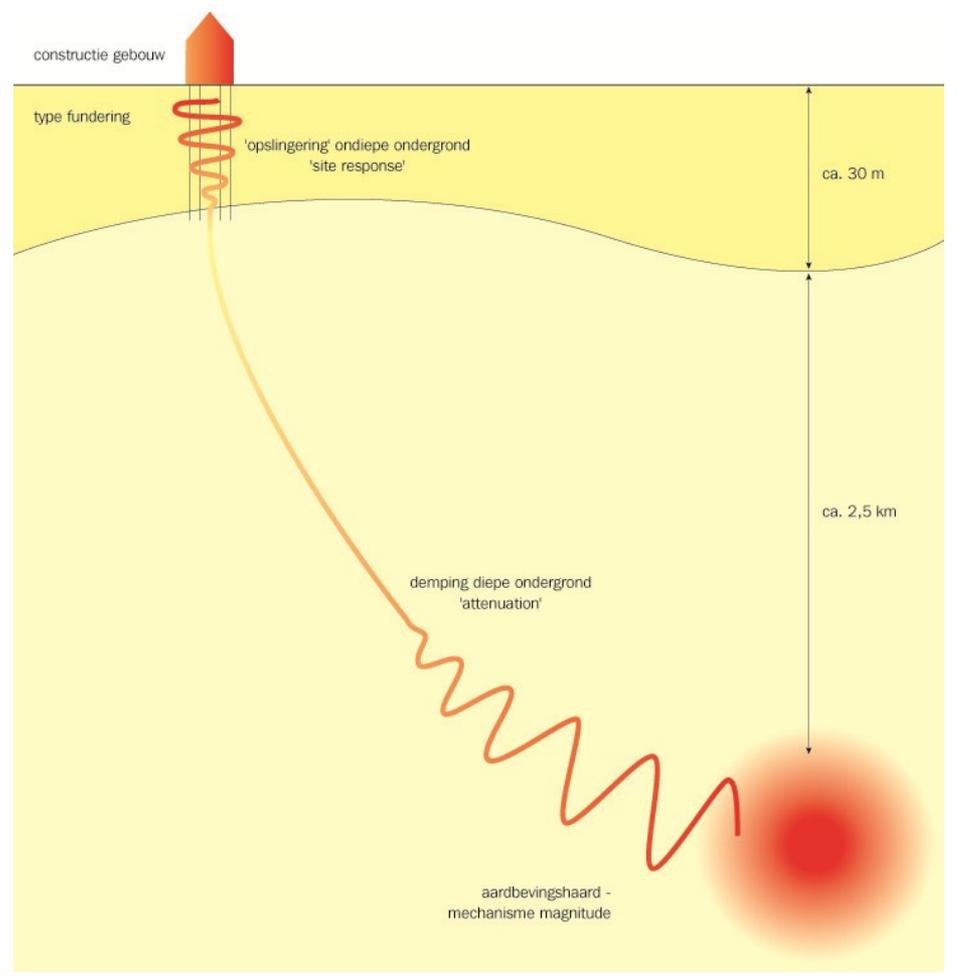
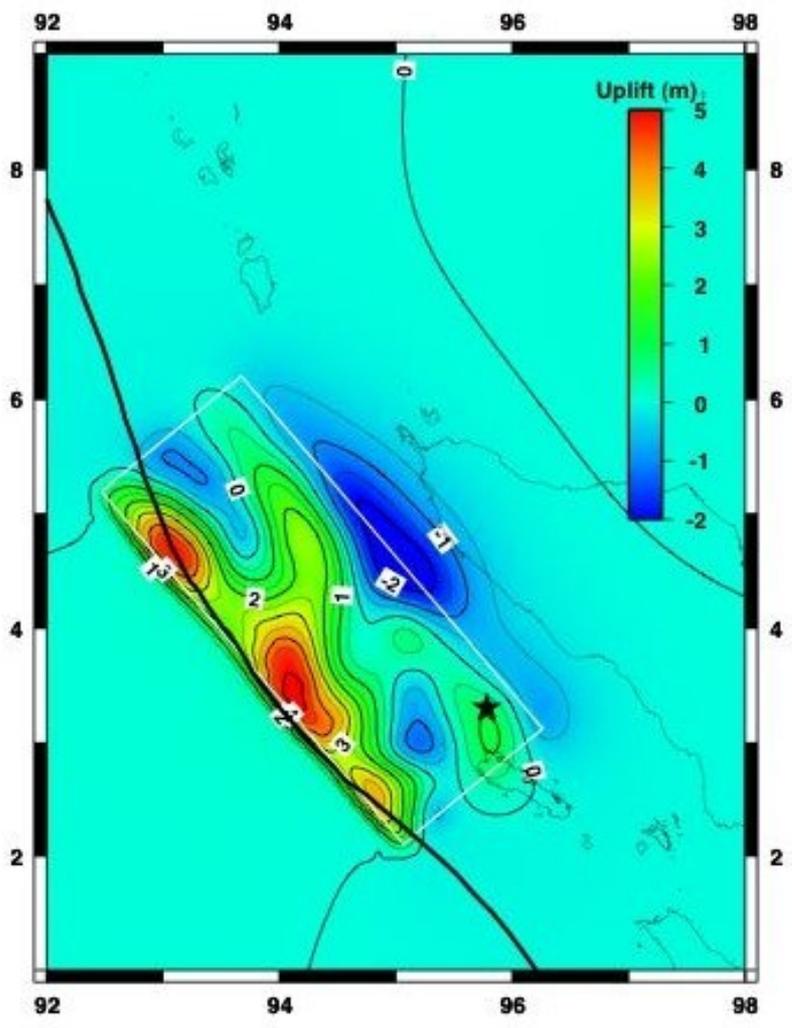
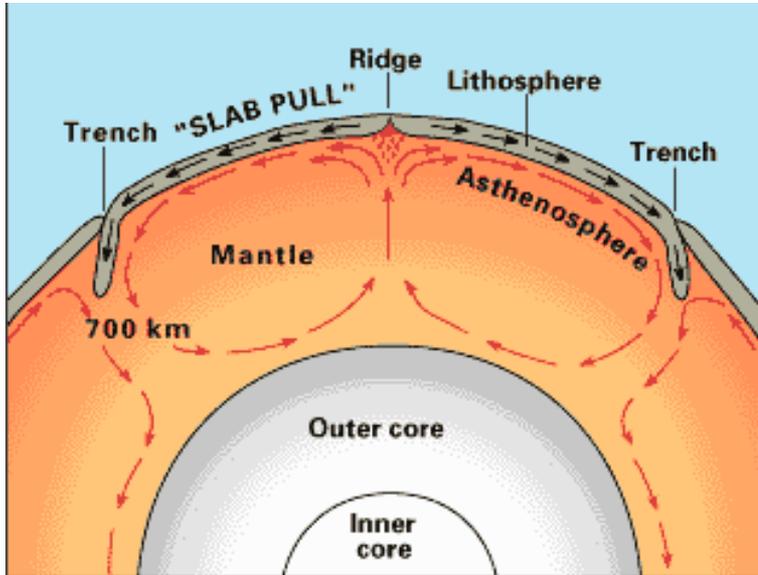
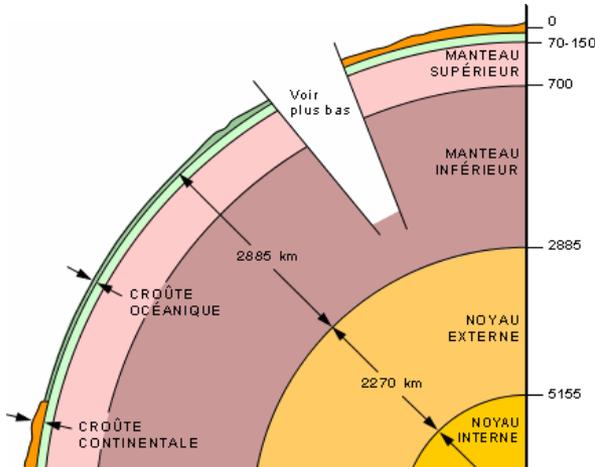


Plate tectonics, how does it function?



Kind of *Mickey Mouse* plate tectonics
 The picture is mainly a result of observations along spreading ridges
 There is little images from the deep mantle and little mechanics

Problems arise when one looks at the “strange” movements experienced by many plates and by the small oceans.
 Is there a convection everywhere?

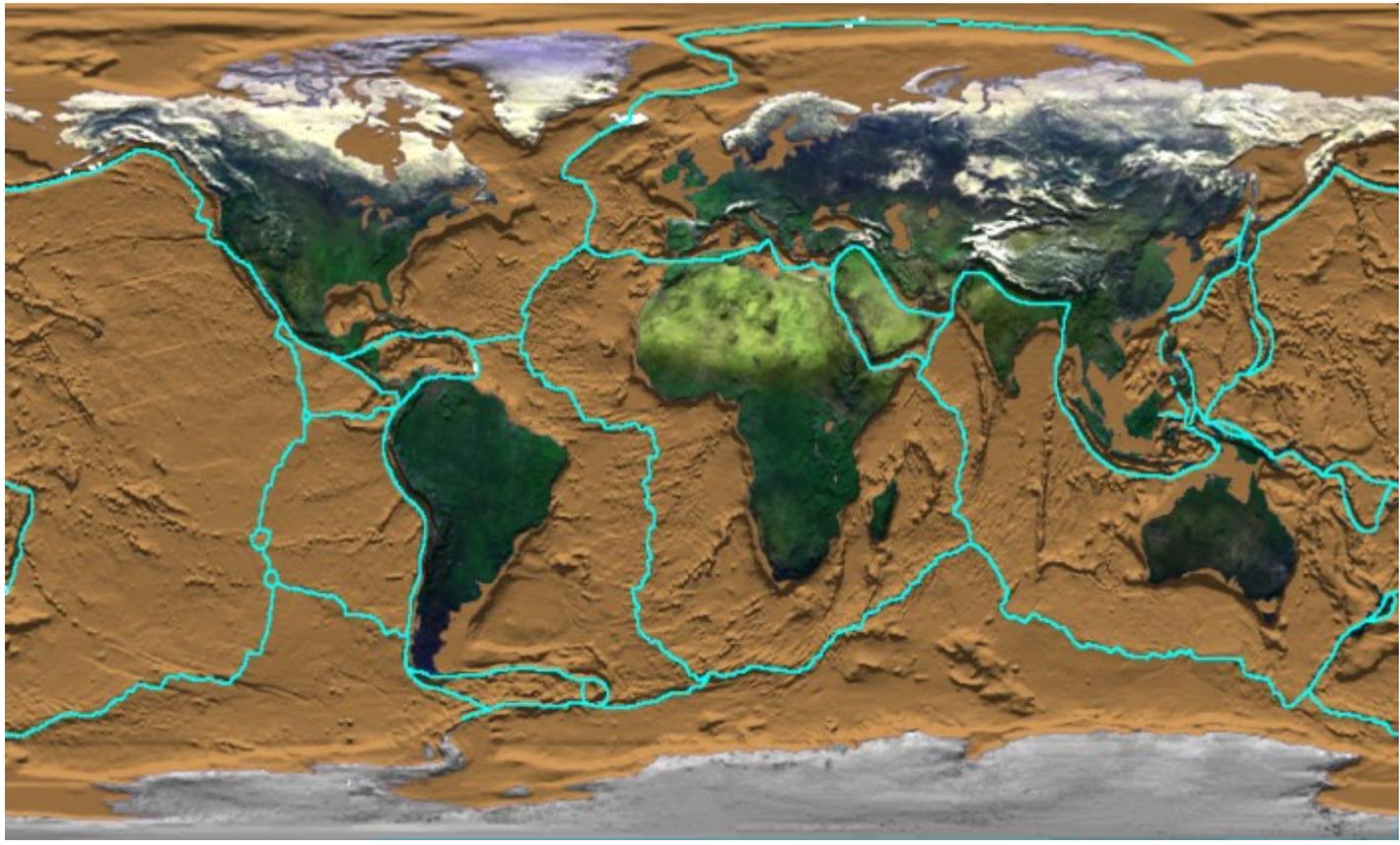


Particularly important is the dynamics of convection



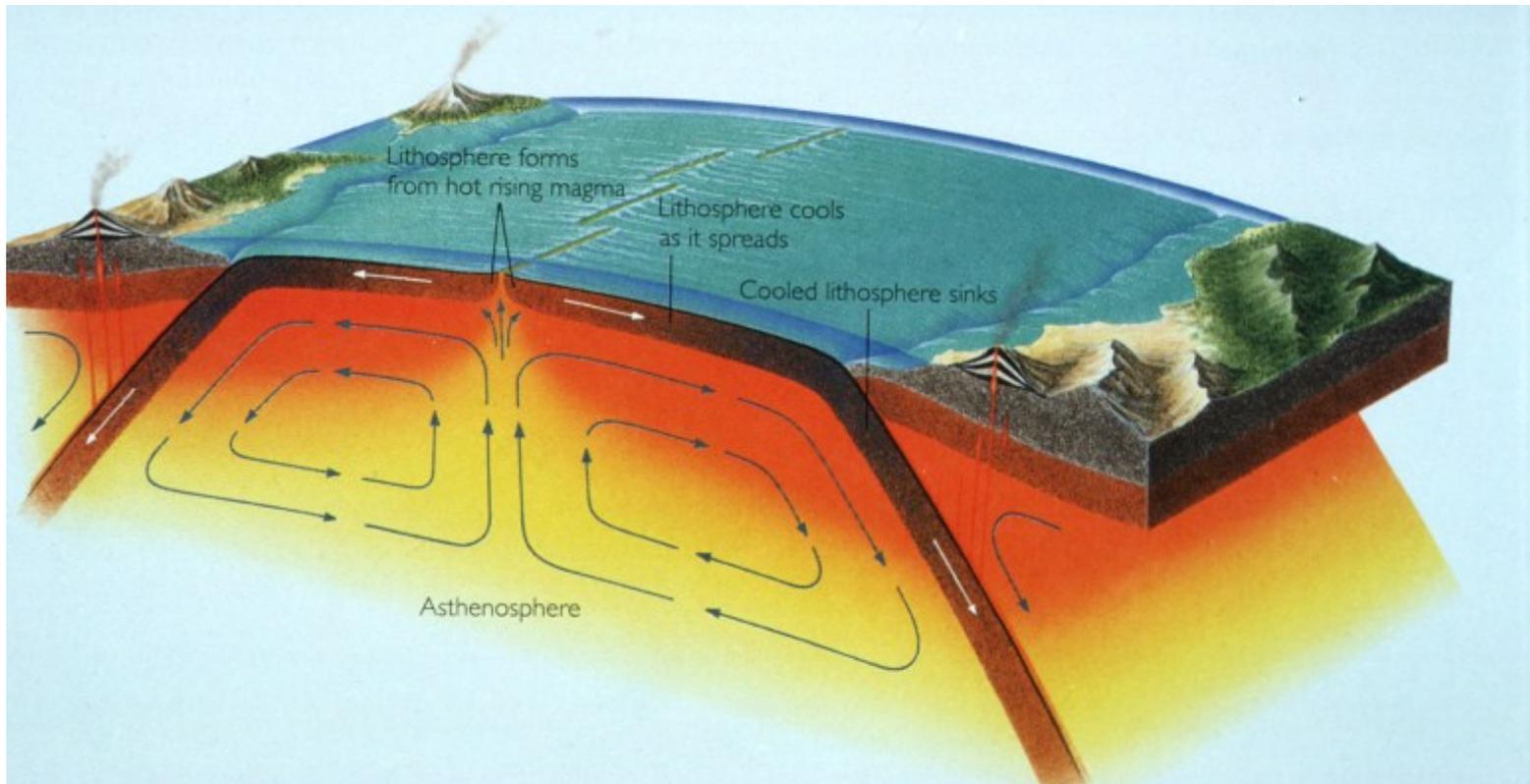
Plate tectonics

The crust of the Earth is broken-up in several 'tectonic' plates.



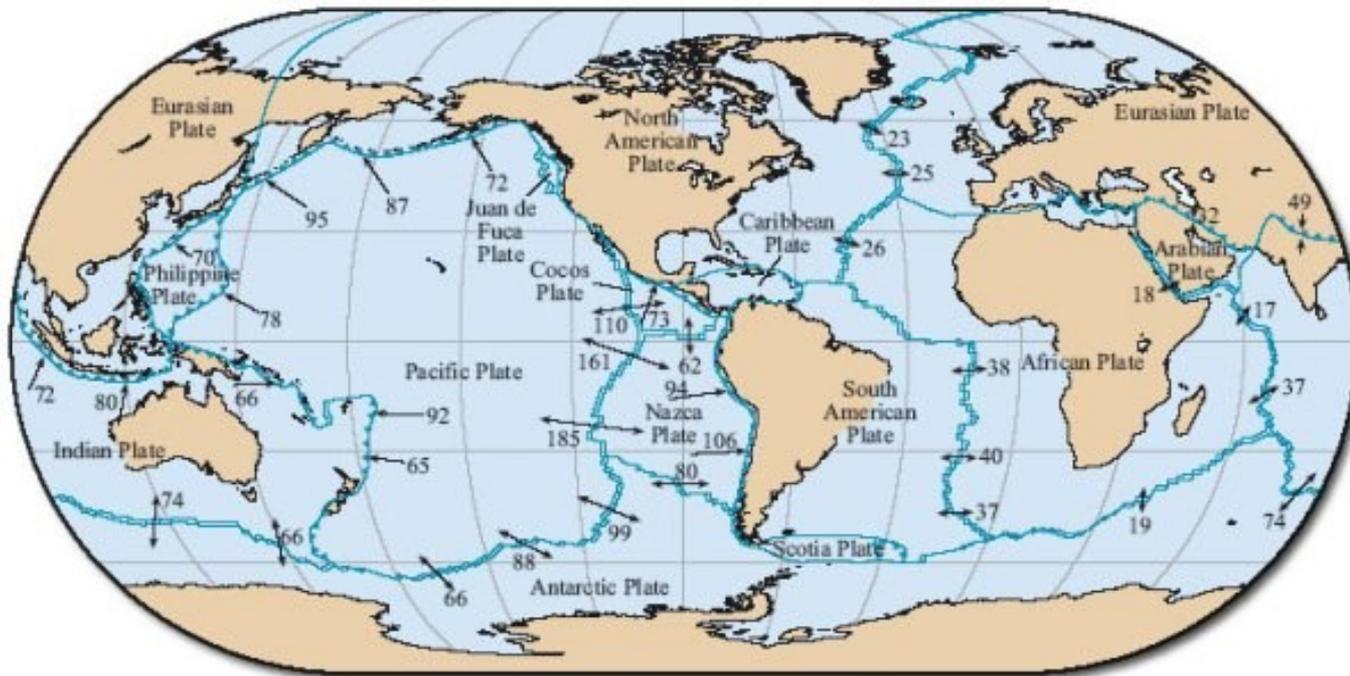
Kinematics of plate tectonics

Plates should not be regarded as static features. Heat from Earth's core generates huge convection cells in the viscous mantle of the Earth. Plate motion is driven by friction at their base. The high weight of the plates also promotes plate motion during plate subduction.



Kinematics of plate tectonics

Spreading rate (mm/yr) of tectonic plates at Mid Ocean Ridges (MORs).



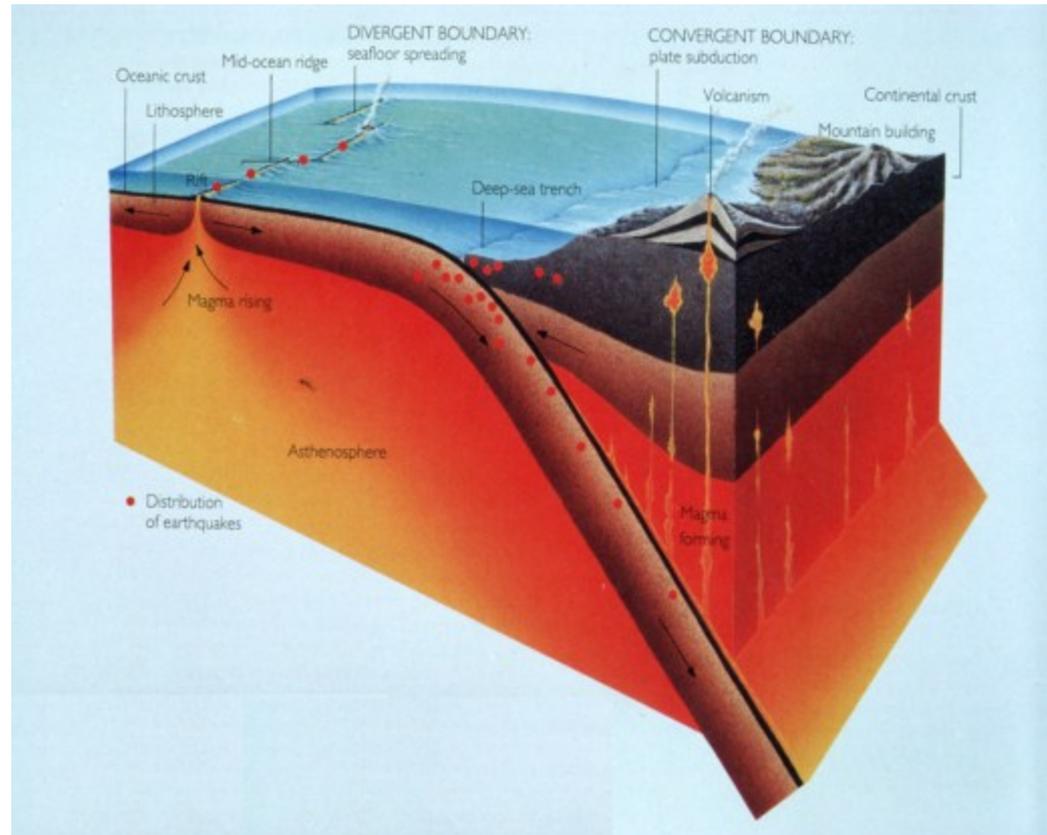
key // constructive plate boundary ✓ destructive plate boundary / transform fault plate boundary

Plate tectonic forces

Plate interaction generates enormous forces (10^{12} - 10^{13} N/m)

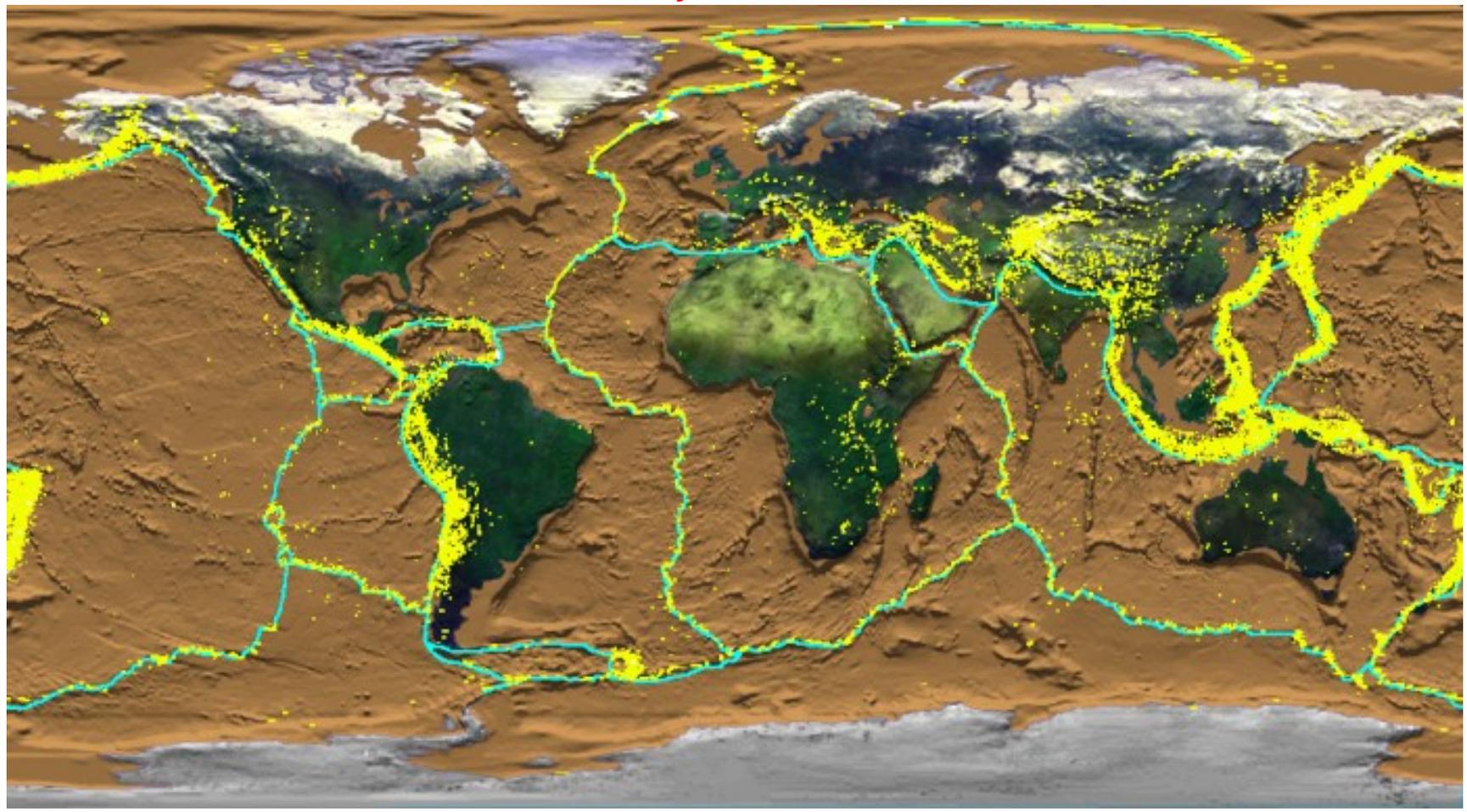
This will result in several deformation processes at tectonic plate boundaries:

- Earthquakes (red dots)
- Volcanism
- Orogenesis



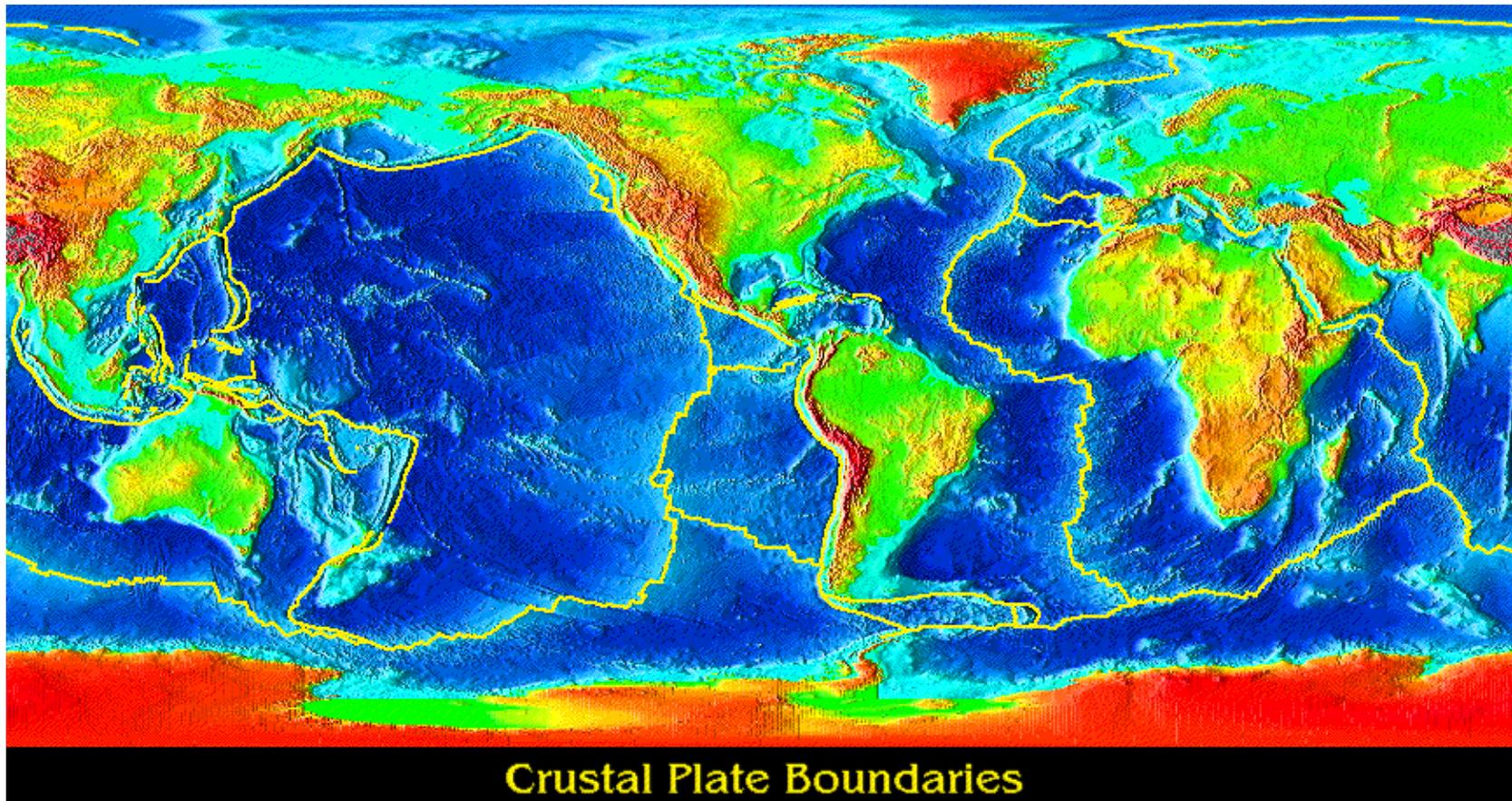
Earthquakes since 1960

Plate tectonics & seismic activity

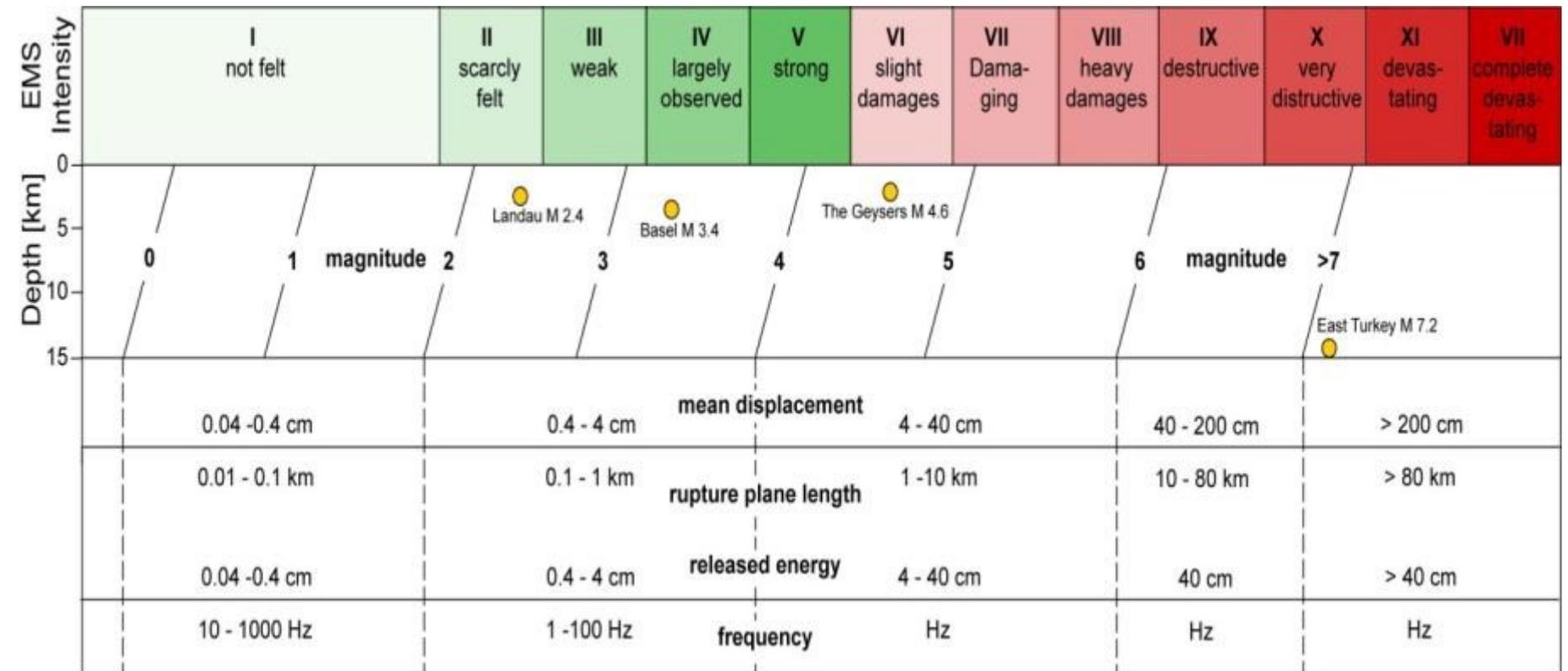


Large mountain belts (Andes, Himalayas, Alps) are located along plate boundaries

Plate tectonics and mountain formation (orogenesis)



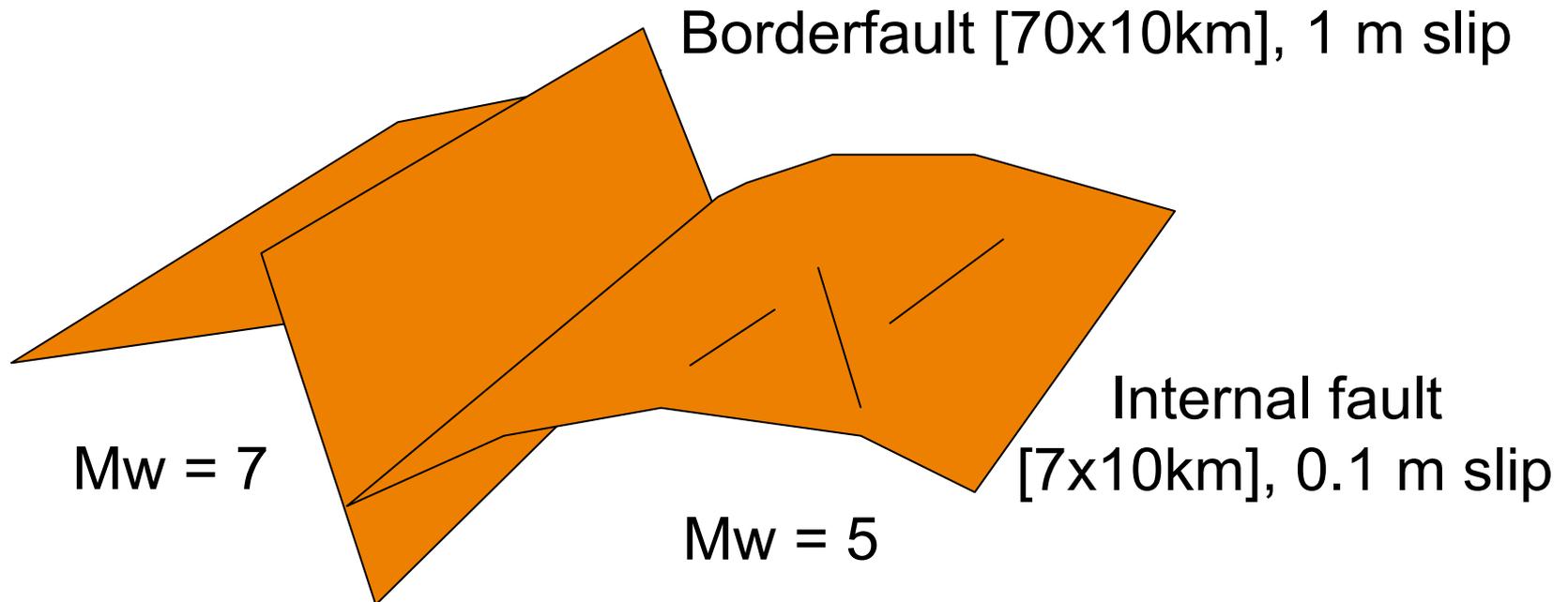
Magnitude of earth quakes



What is the relation with magnitude and surface slip

› Hanks and Kanimori (1979)

$$M_w = 0.67 \log(M_0) - 10.7$$



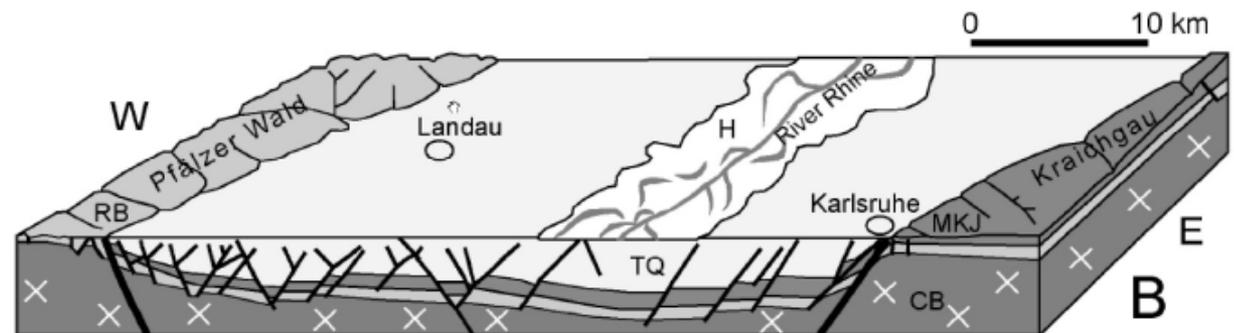


M=7, 70x10 km fault, 1m displacement

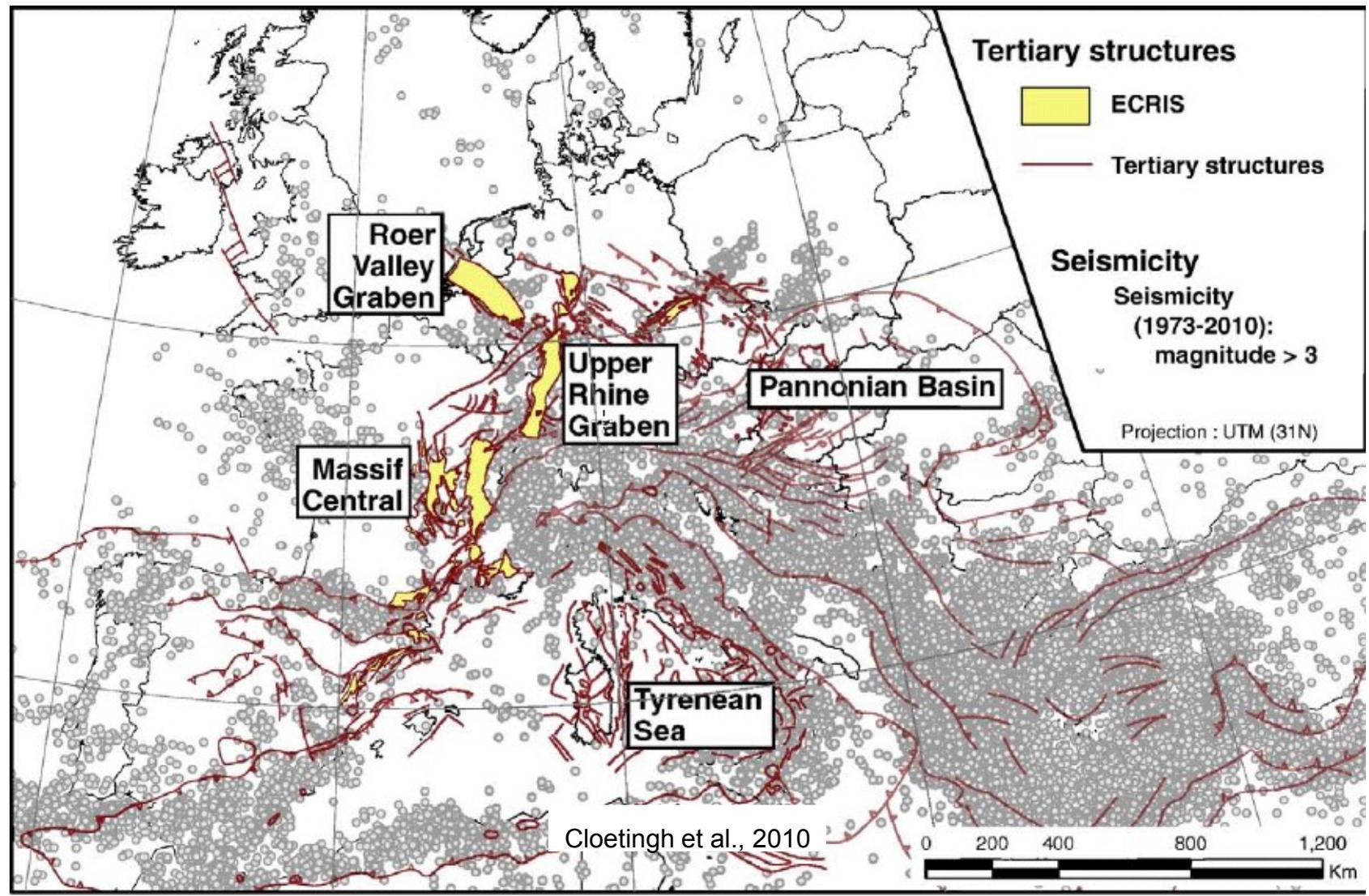
M=6, 30x5 km fault, 0.4m displacement

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

Big earth quakes
Located at
Mapped Major faults

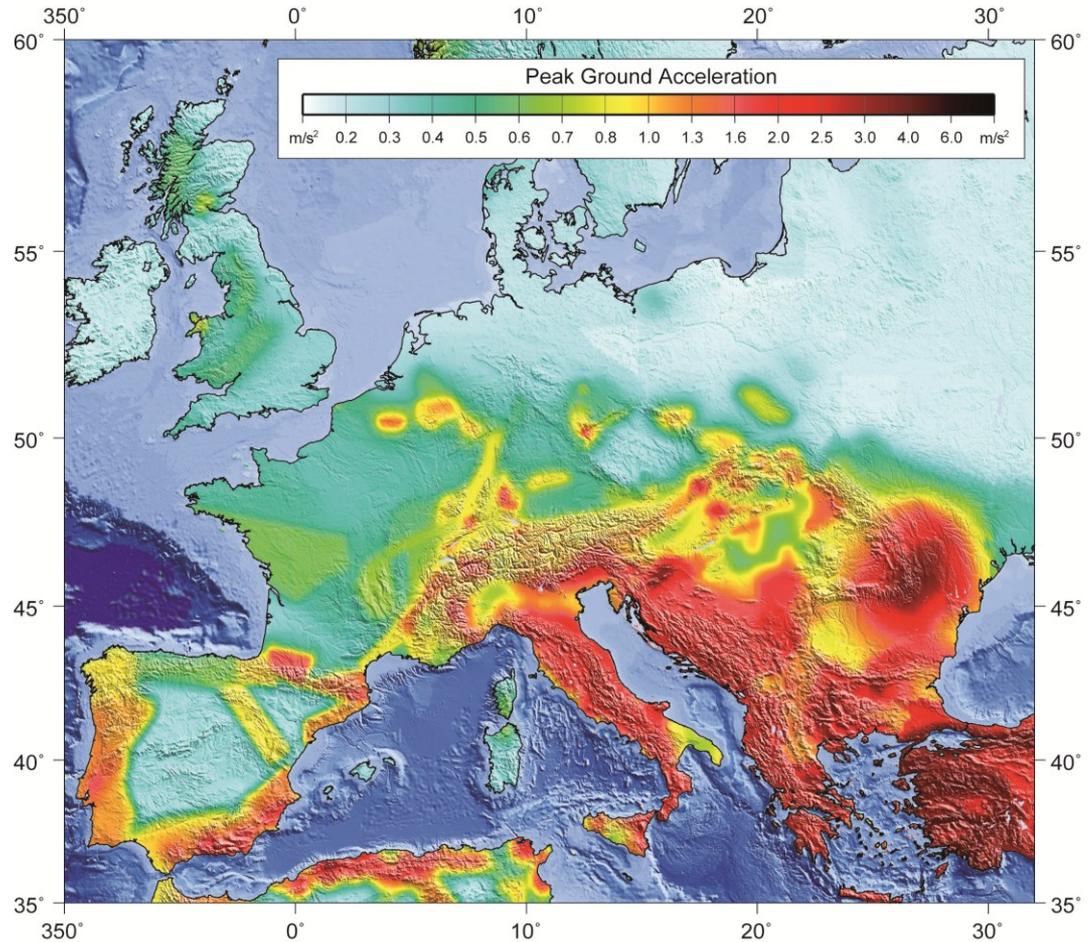


→ Lesson: stay away from seismically active faults



Cloetingh et al., 2010

PGA hazard map

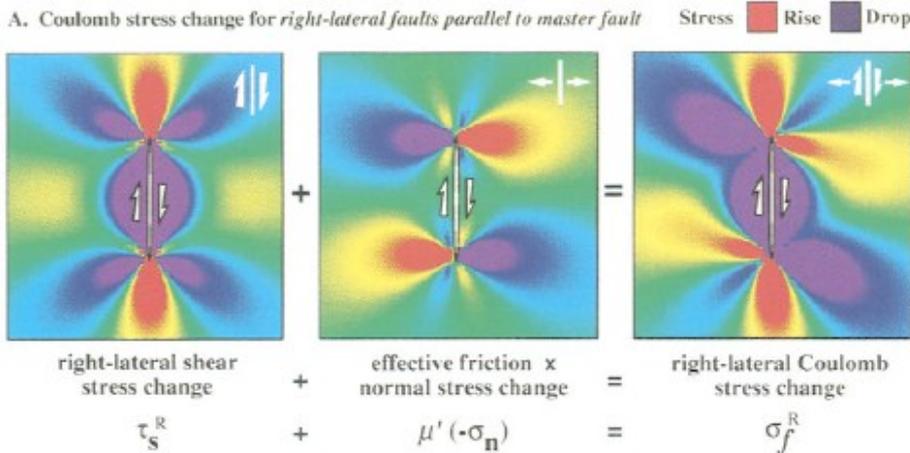


Seismic Hazard Map of Europe as part of the Global Seismic Hazard Map (Giardini et al., 2003; Grünthal et al., 1999). The map depicts the seismic hazard as Peak Ground Acceleration (PGA, ms^{-2}) with 10% probability of exceedence (or a 90% chance of non-exceedance) in 50 years, corresponding to a return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

Coulomb Stress Change

Calculated numerically in elastic medium using Okada (1992)

A. Coulomb stress change for right-lateral faults parallel to master fault



King et al., 1994

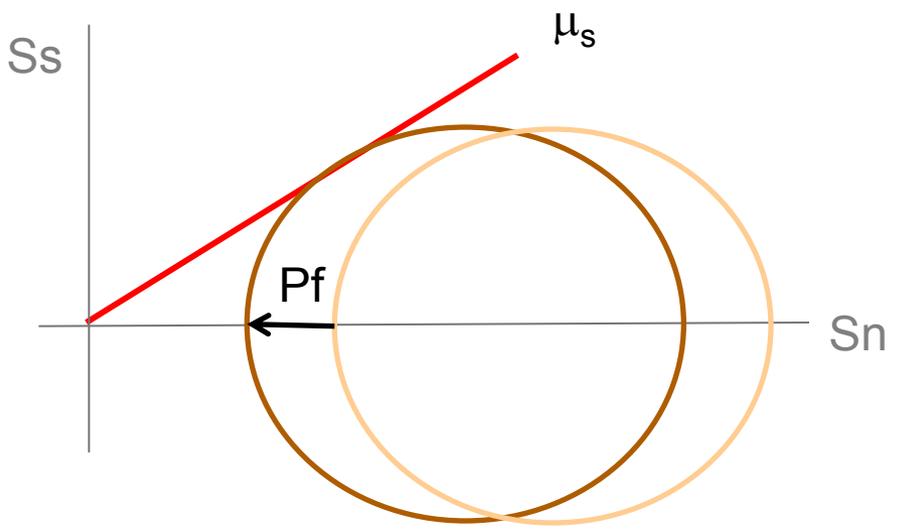
Input parameters

- › 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 →

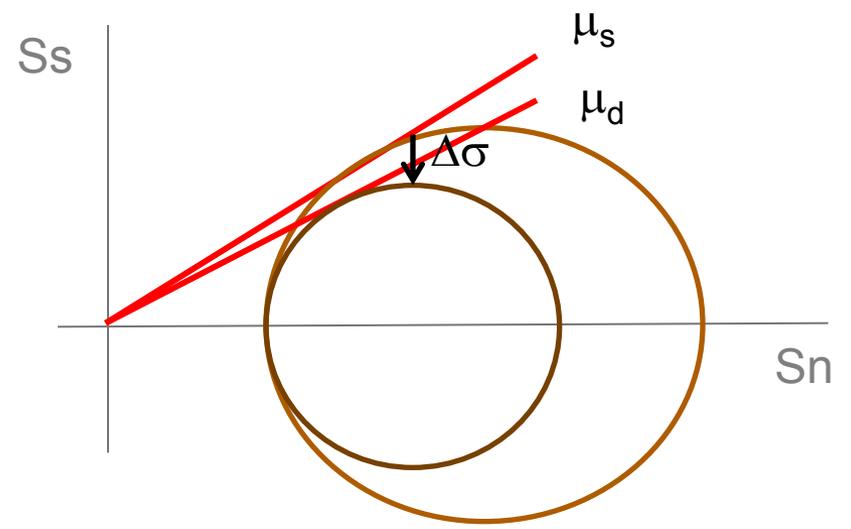
Slip only possible if during faulting friction

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



Failure:

Fluid pressure (P_f) increase results in a reduction of the effective normal stress (S_n) on the fracture wall and causes the fracture to fail when $S_s/S_n > \mu_s$



Rupture:

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

L24301

ZIELKE AND ARROWSMITH: STRESS DROP EFFECT ON MAG.-FREQ. DIST.

L24301

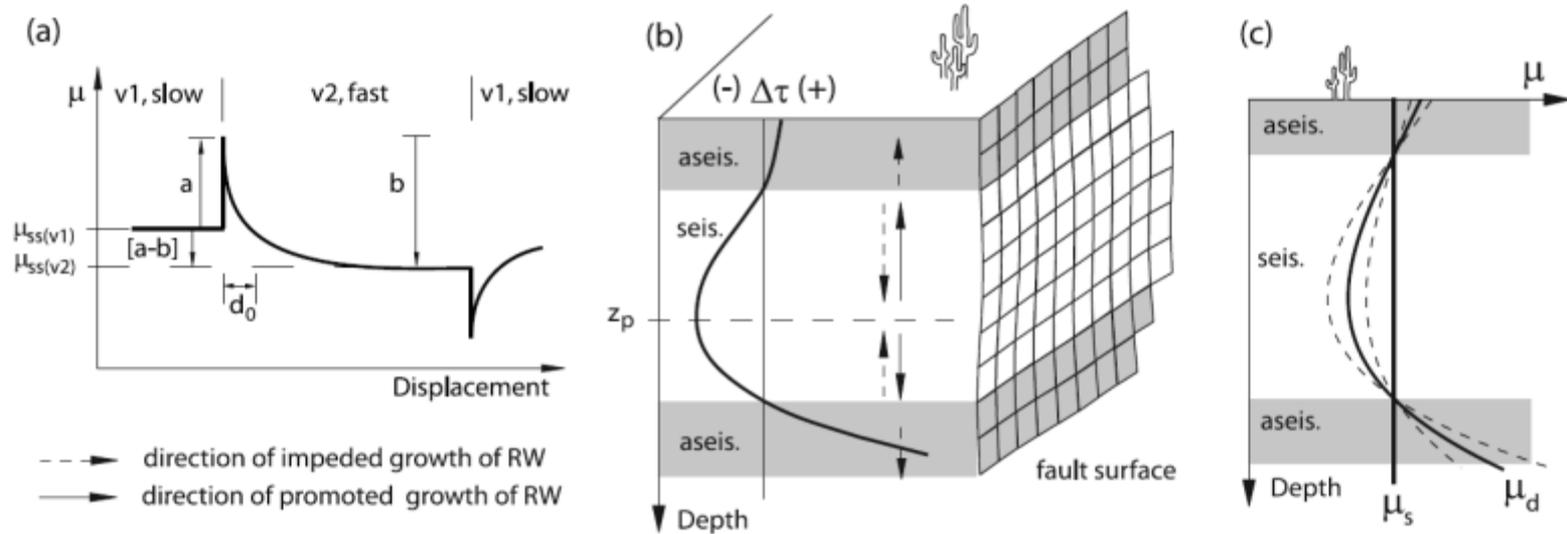


Figure 1. (a) Evolution of friction coefficient μ during a velocity stepping experiment, $v_1 \rightarrow v_2 \rightarrow v_1$). The slip rate dependent change of μ is expressed by $[a - b]$. (b) Depth variation of coseismic stress drop $\Delta\tau$ and inferred non-uniform evolution of rupture width. 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.

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

L24301

ZIELKE AND ARROWSMITH: STRESS DROP EFFECT ON MAG.-FREQ. DIST.

L24301

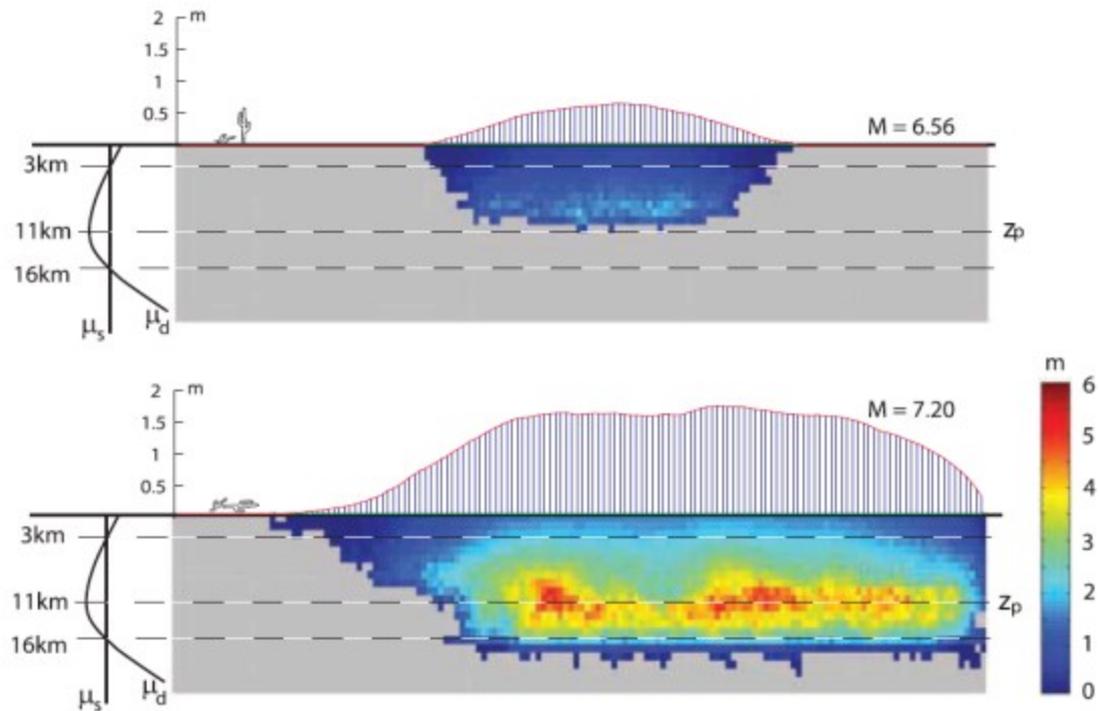
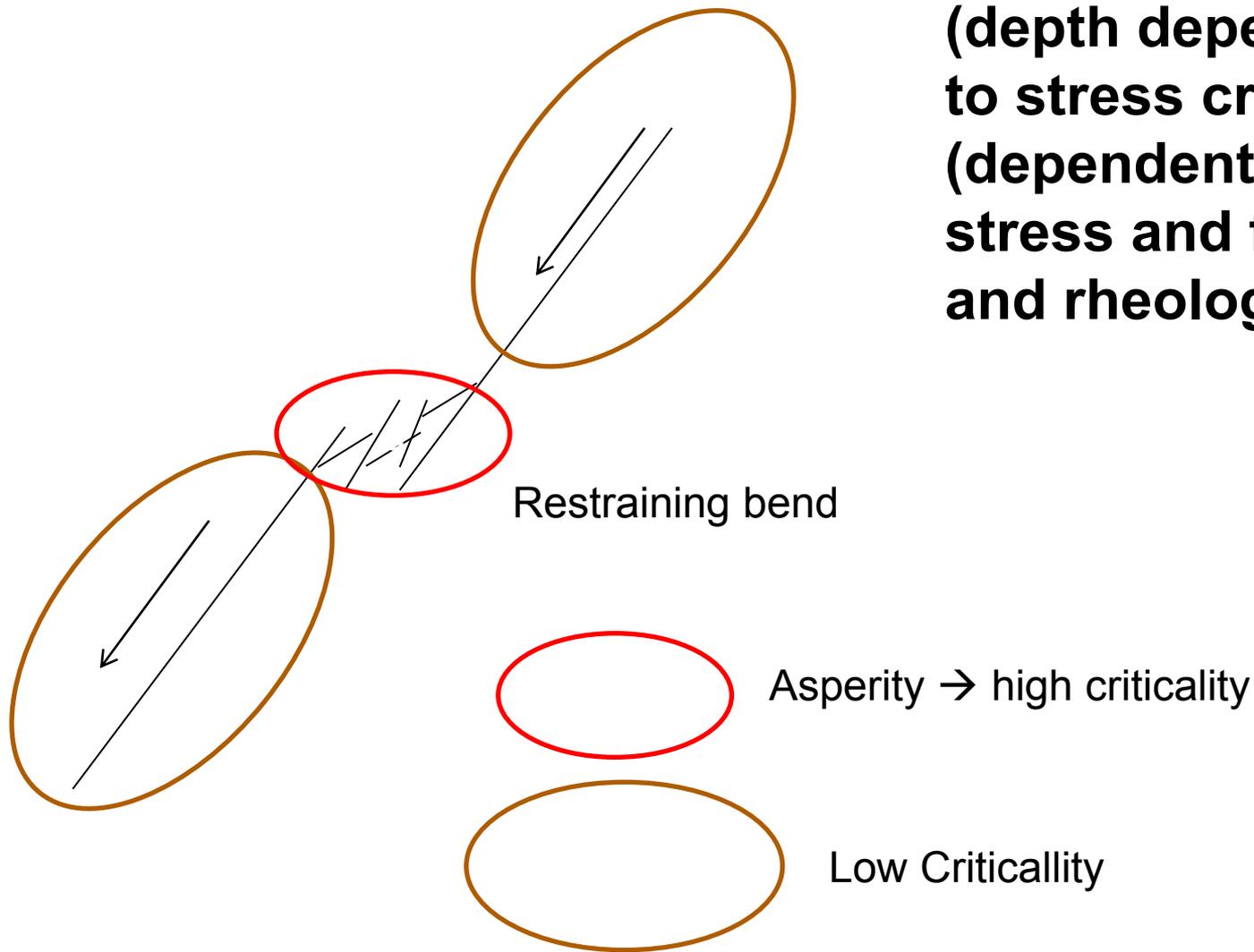


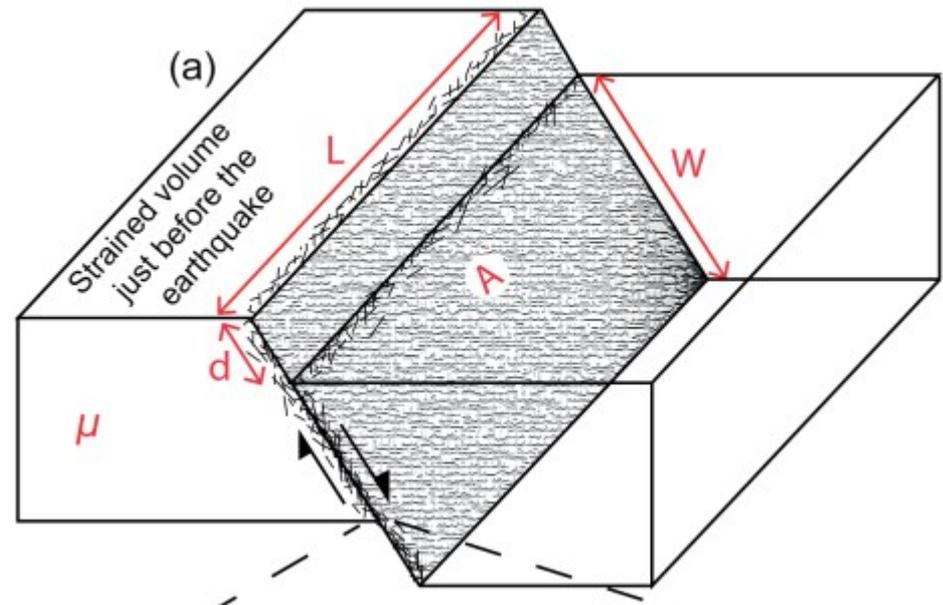
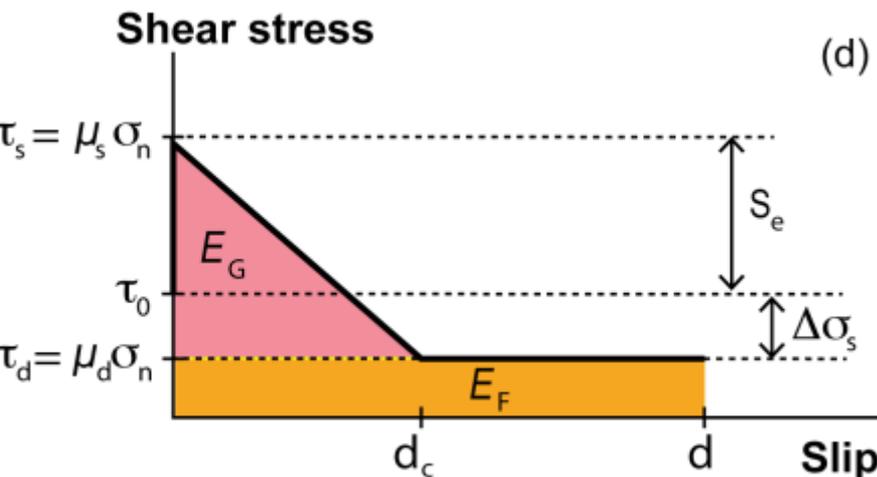
Figure 2. Color-coded amount of slip (22 km wide, 150 km long sub-vertical strike-slip fault with amplitude-wavelength ratio $\lambda = 0.003$) of a typical small and large earthquake. Gray fault patches did not slip in the respective events. Shown above is the respective surface-slip distribution. On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

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



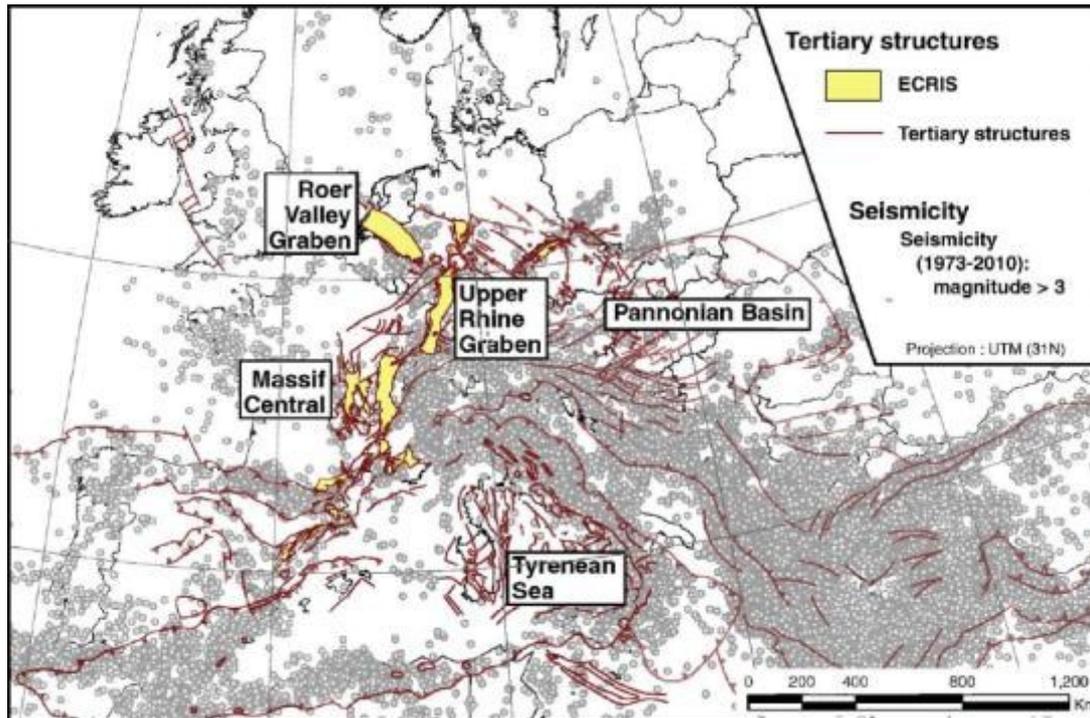
Earth quakes

- › 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



Baseline seismicity in the european central rift

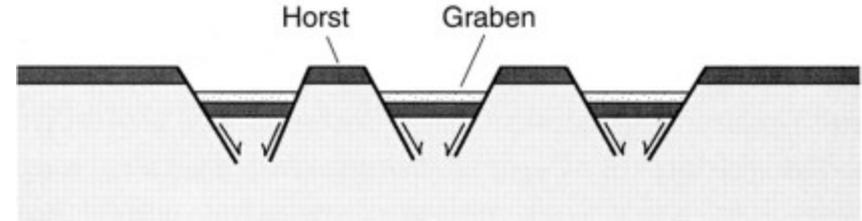
- Extensional and strike slip setting



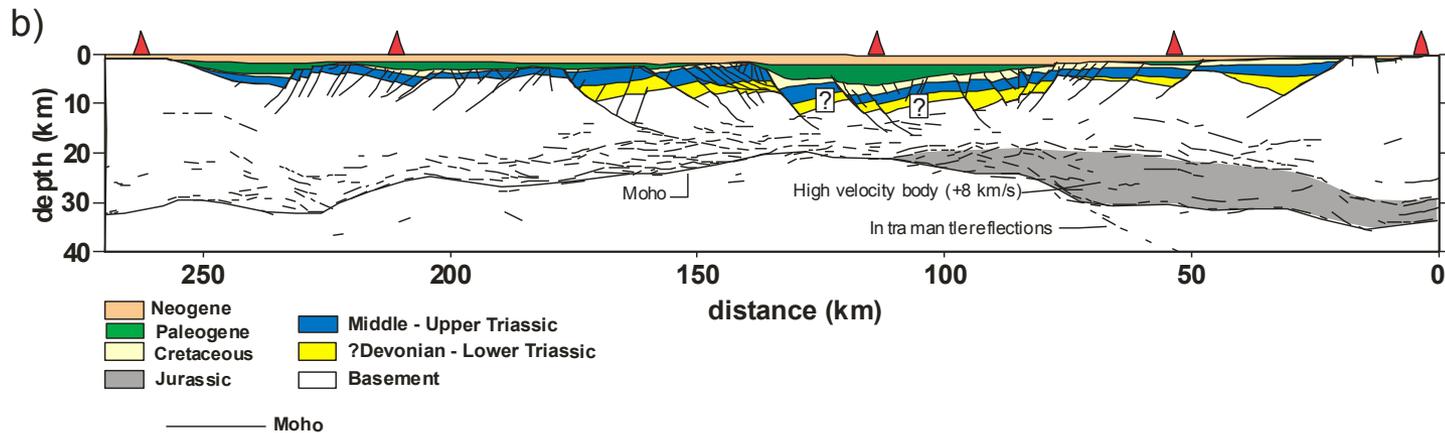
rate (depth dependency and spatial

FAULT SYSTEMS

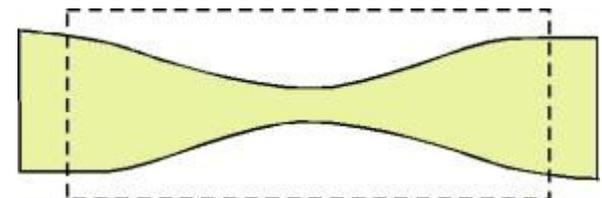
Assemblage of planar faults

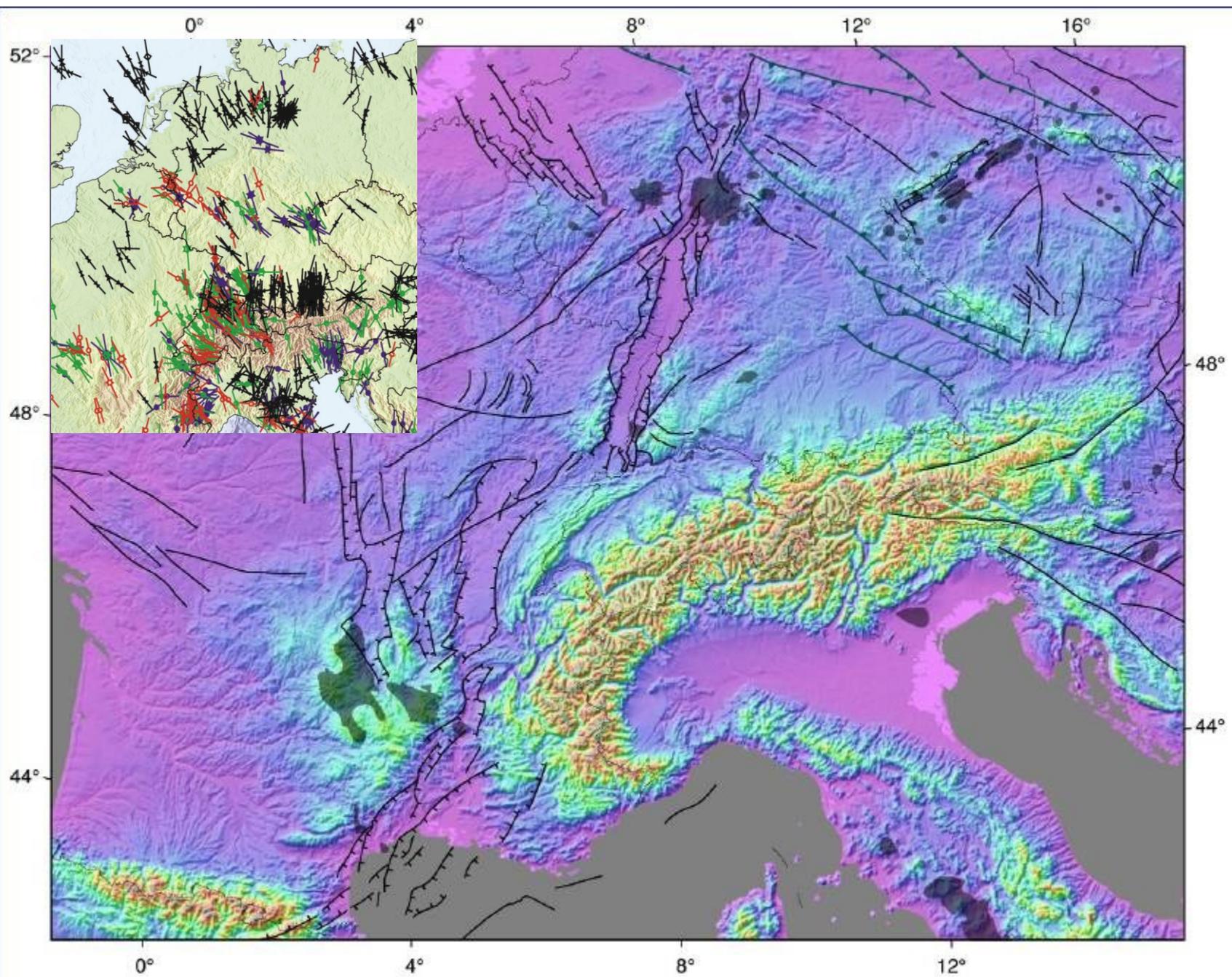


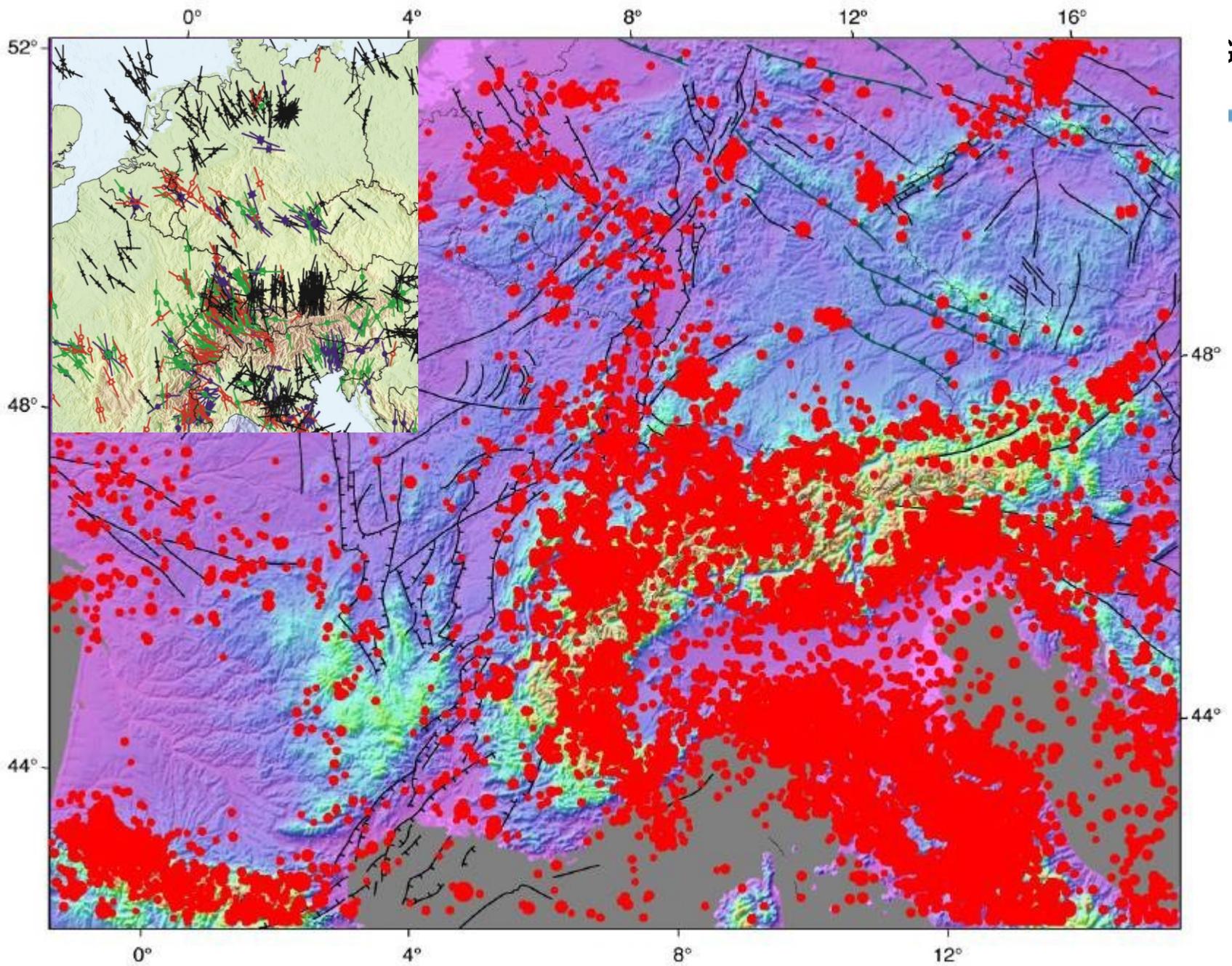
Assemblage of listric faults



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







IFZ



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

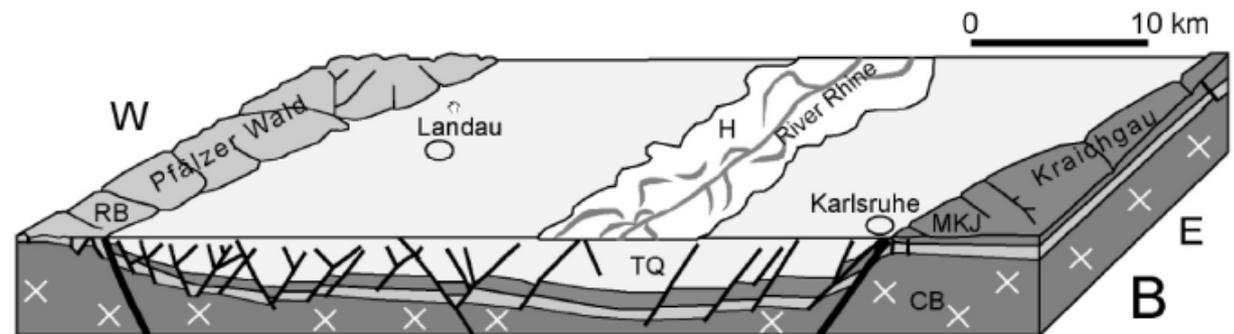


M=7, 70x10 km fault, 1m displacement

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

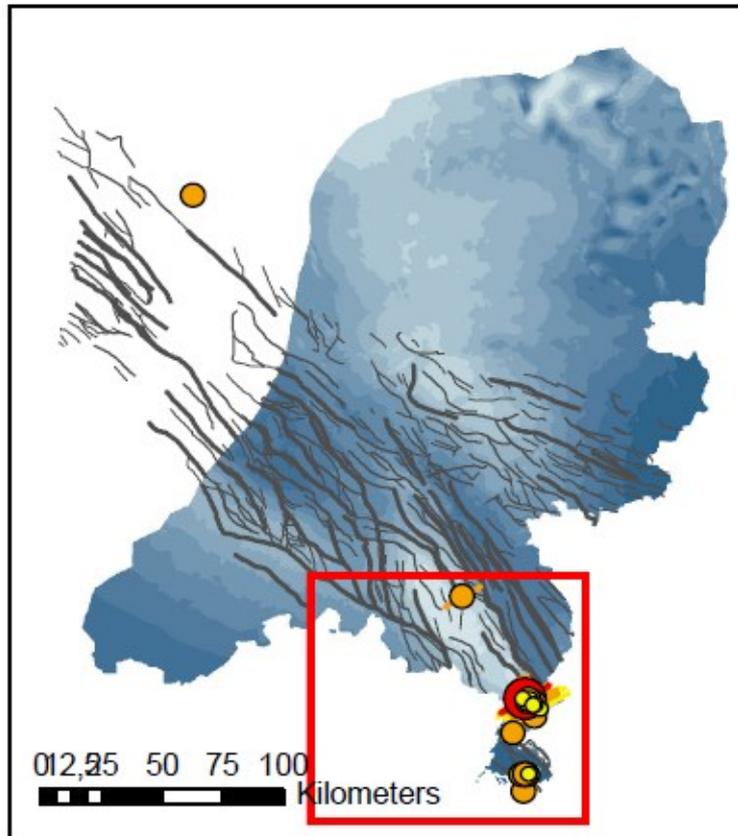
M=5, 15x5 km fault, 0.15m displacement

Big earth quakes
Located at
Mapped Major faults

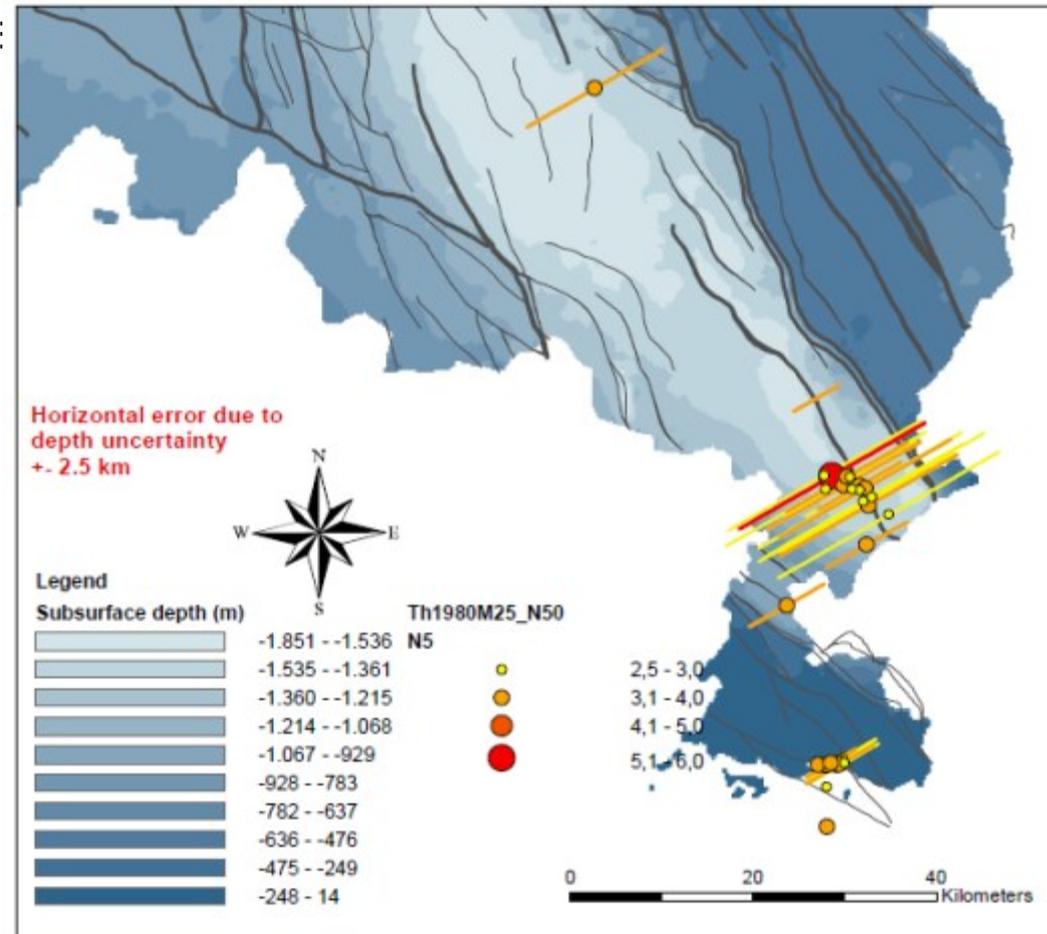


→ Lesson: stay away from seismically active faults

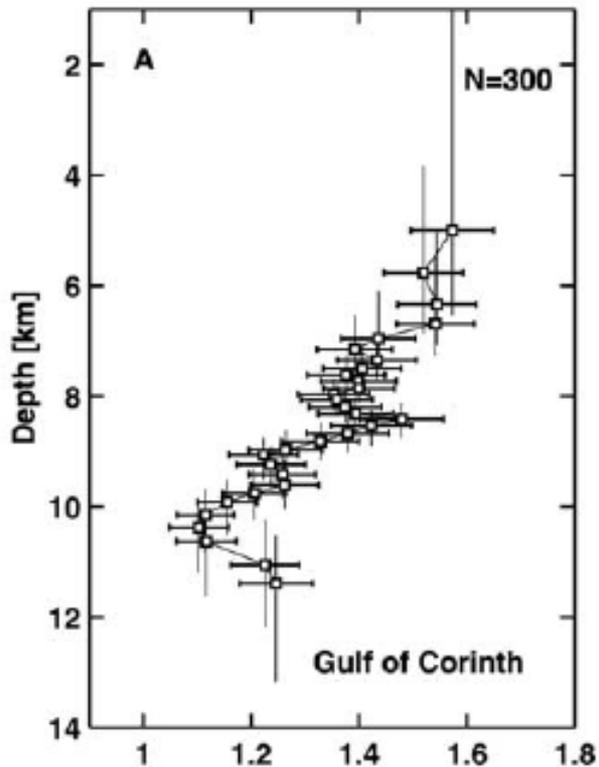
Can we identify M7-M5 faults prior to stimulation: most say yes - some say no



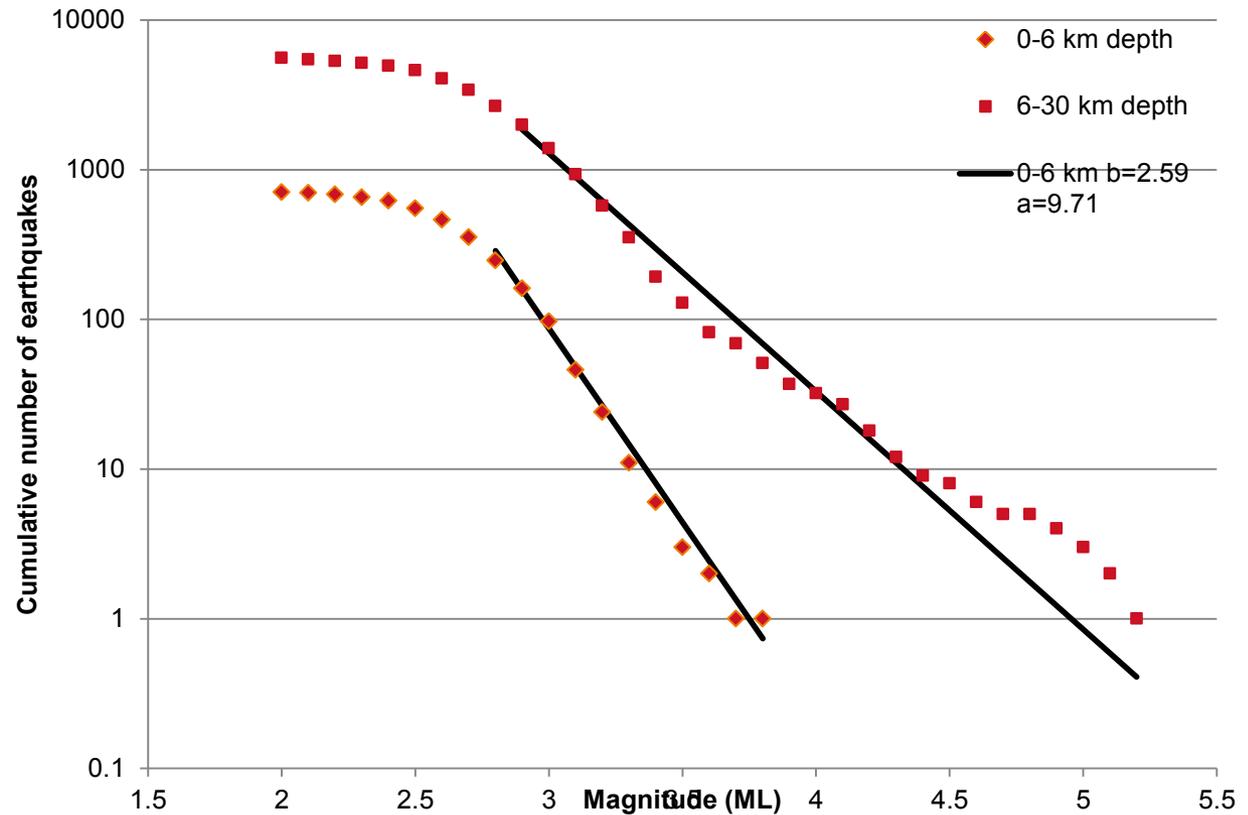
EQ after 1980



Likely to increase with increasing confining pressure
 → Depth-dependency (**extensional setting** Gulf of Corinth)



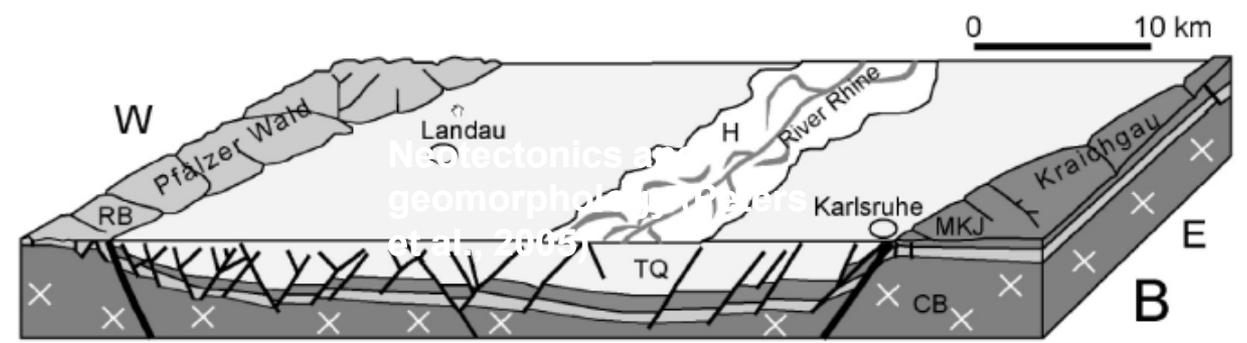
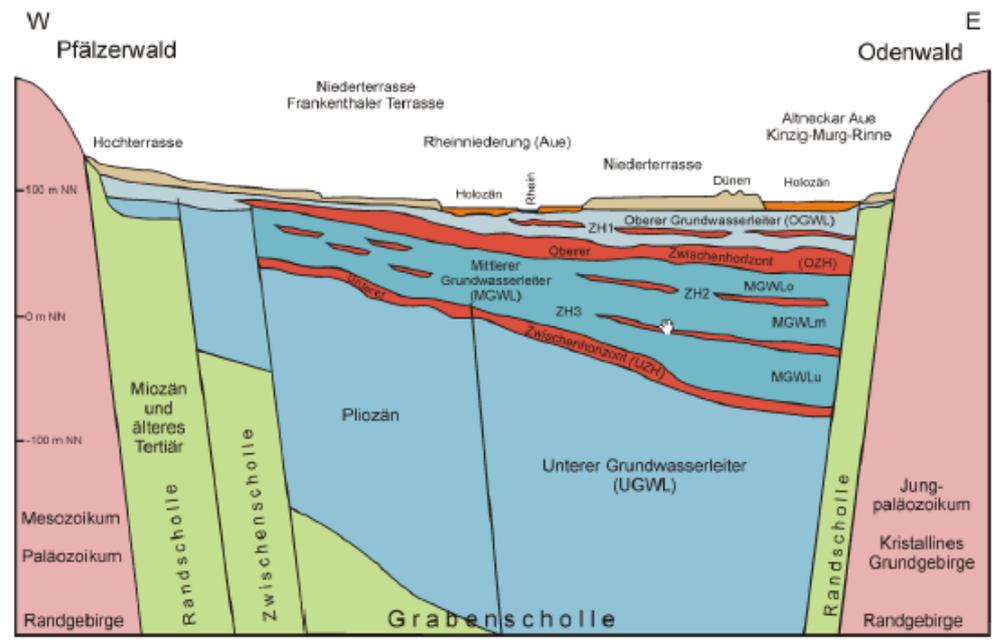
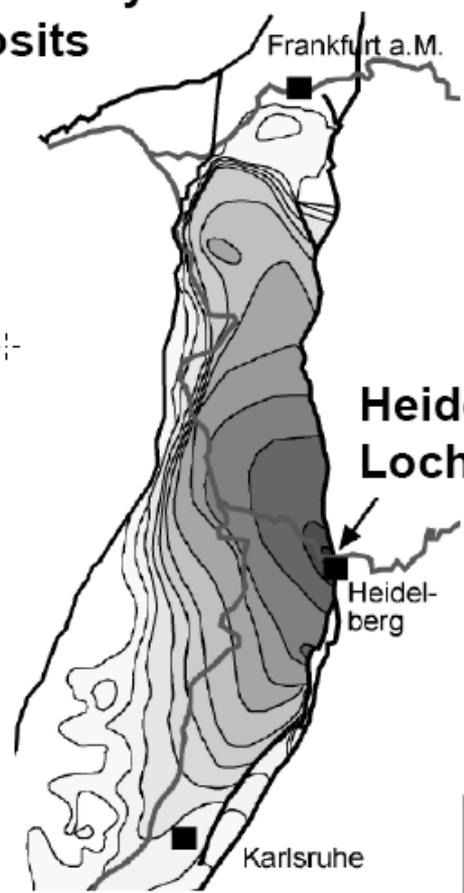
Wyss et al., 2008



Peters and Van Balen, 2008

Asymmetry of the northern URG

Quaternary deposits



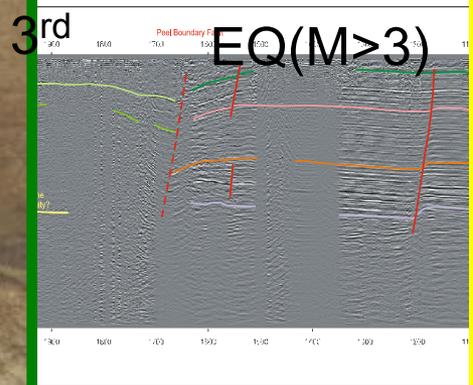
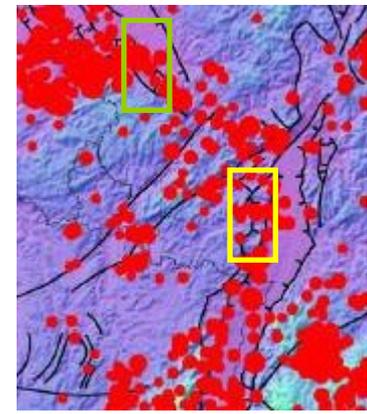
Neotectonics and geomorphology of the northern URG
 Peters and Van Balen, 2008

Strain at neotectonic timescales Trenching 10^4 years

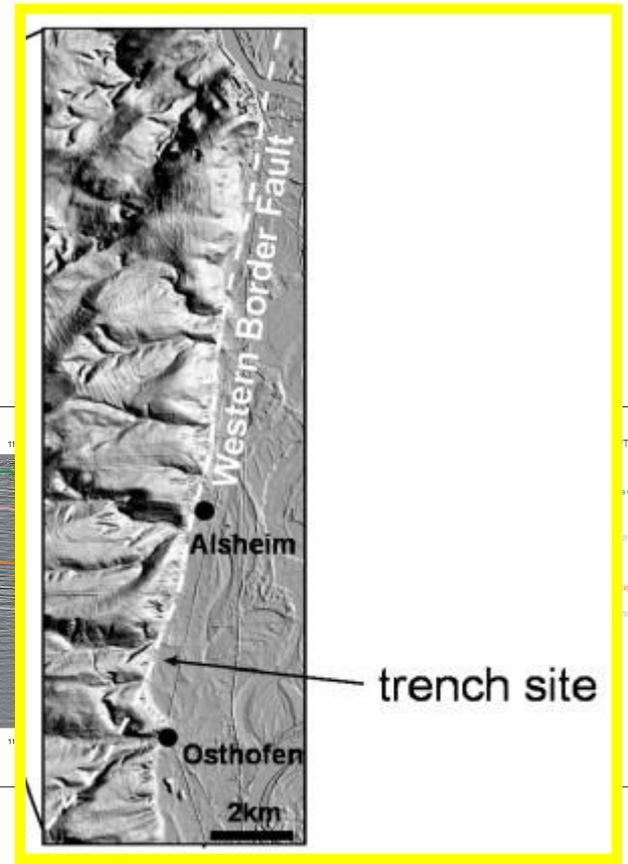
Roer Valley Graben



Houtgast et al., 2002



Upper Rhine Graben



Peters et al., 2005

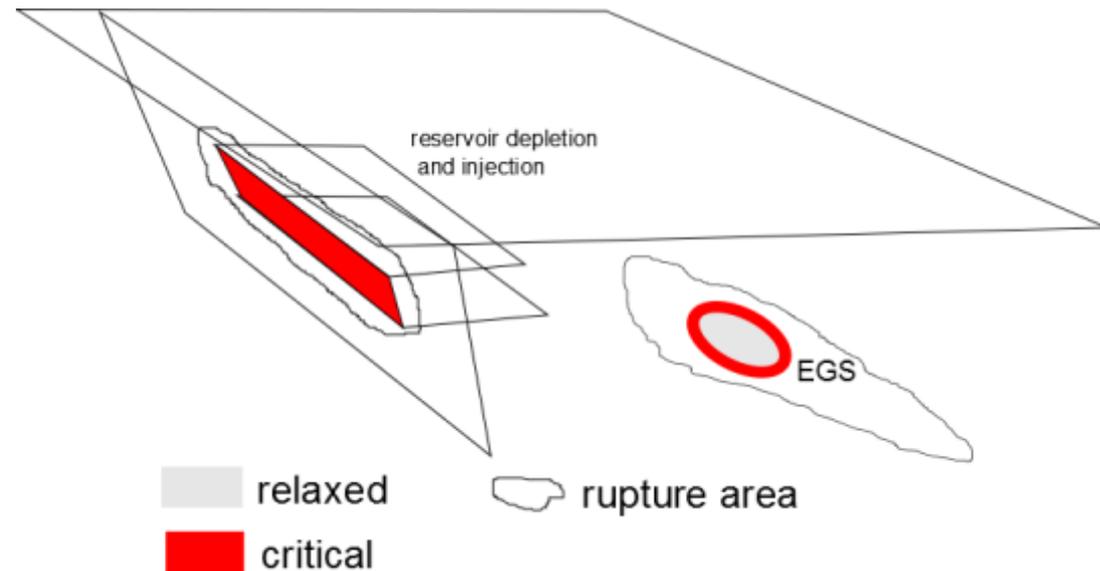
M = 7 highly unlikely, it would require a rupture area of 70x10km and 1 meter slip

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



mcGarr, 2002

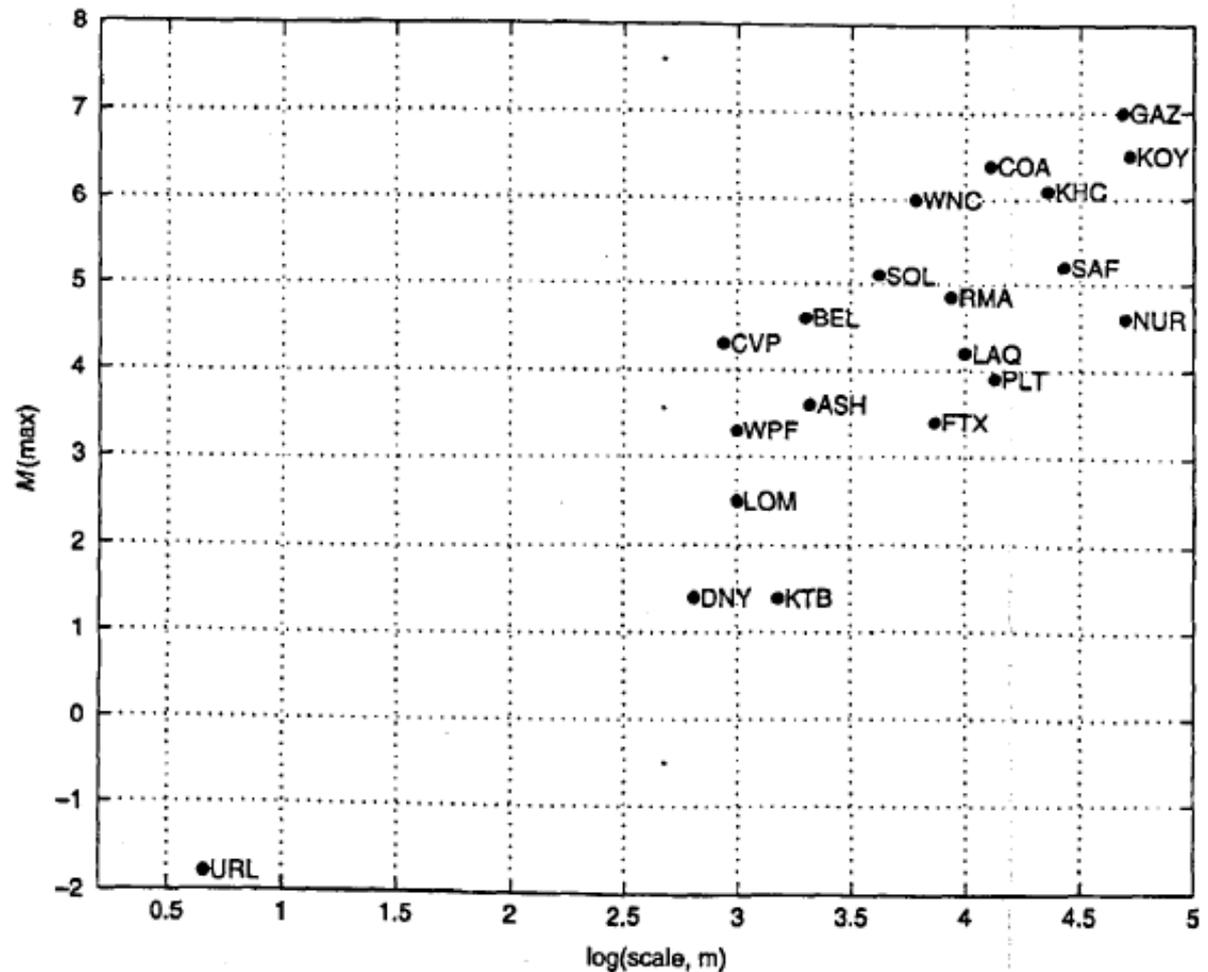


FIGURE 3 Maximum magnitude as a function of scale for 20 case histories. The scale is the maximum dimension of the causative activity as explained in the text. The letter identifications for the case histories, in the same order as they appear in the text, are: underground mining: SAF, deep gold mines 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.