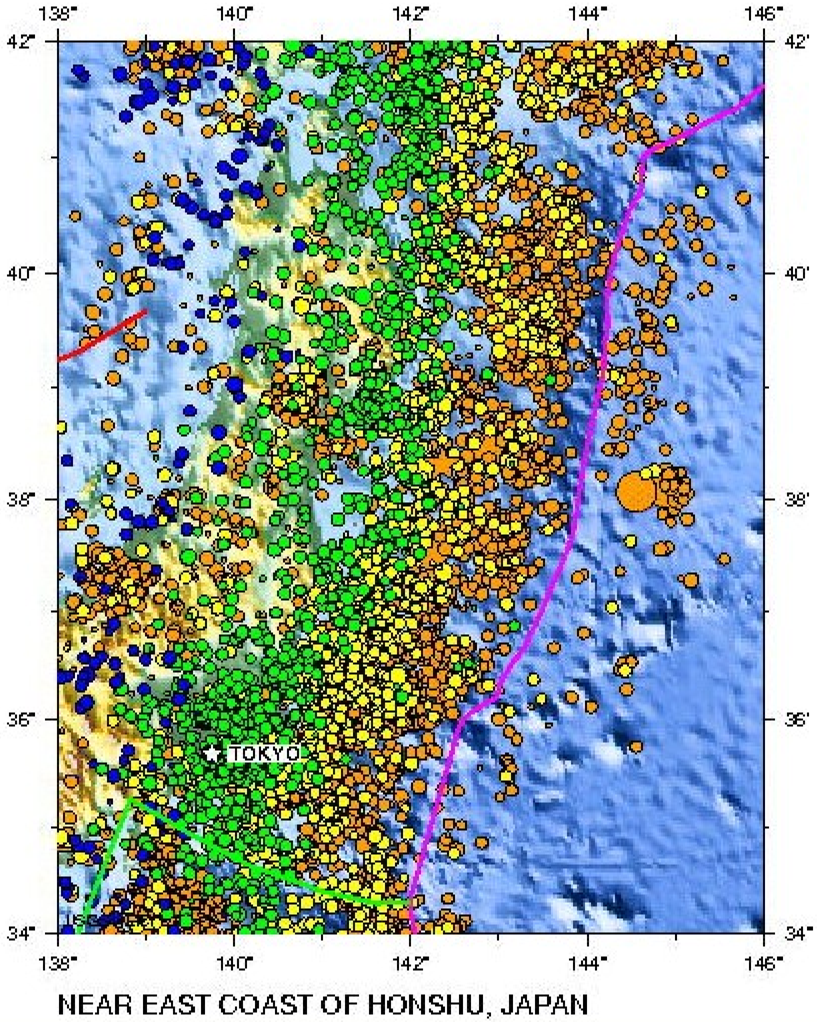
What is (induced) seismicity

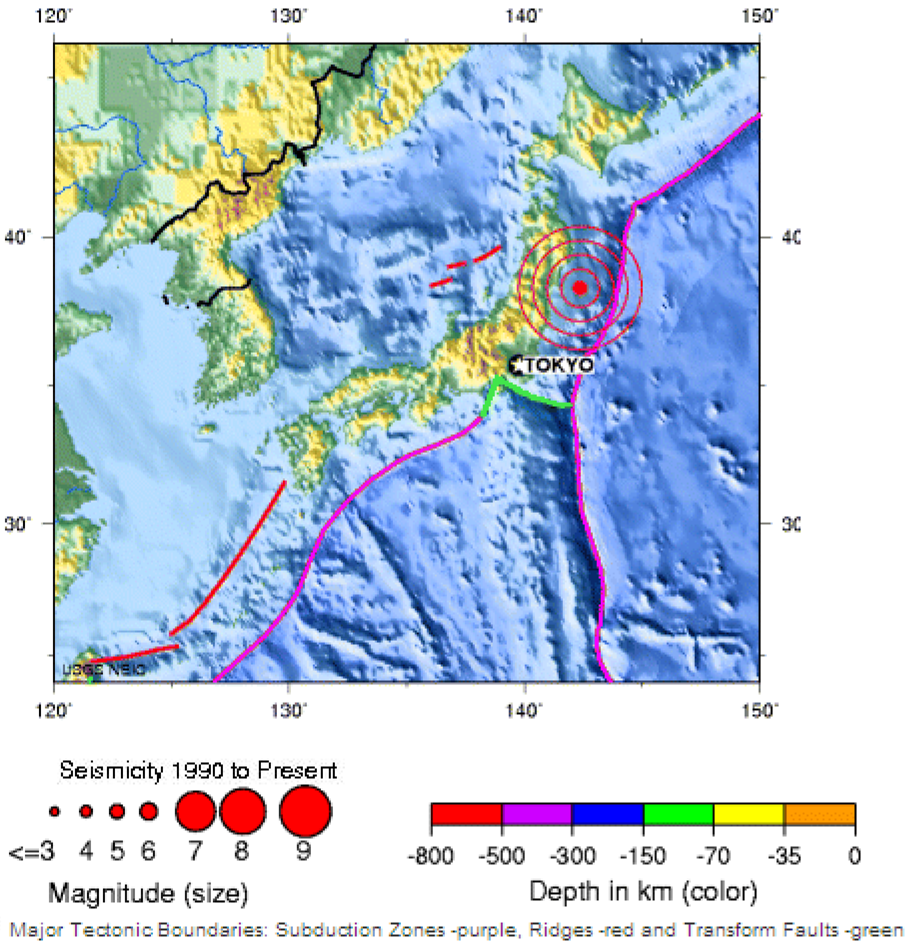
- Earthquakes and Tectonics
  - *Magnitude,*
  - *GR, PGA, recurrence rate*
- Rupture mechanics and modelling
  - *Spatial and depth relationships of seismicity*
  - *Coulomb stress change, rate and state friction*
- Induced seismicity definition and subsurface operations causing IS

Historic Seismicity

Magnitude 8.9 NEAR EAST COAST OF HONSHU, JAPAN

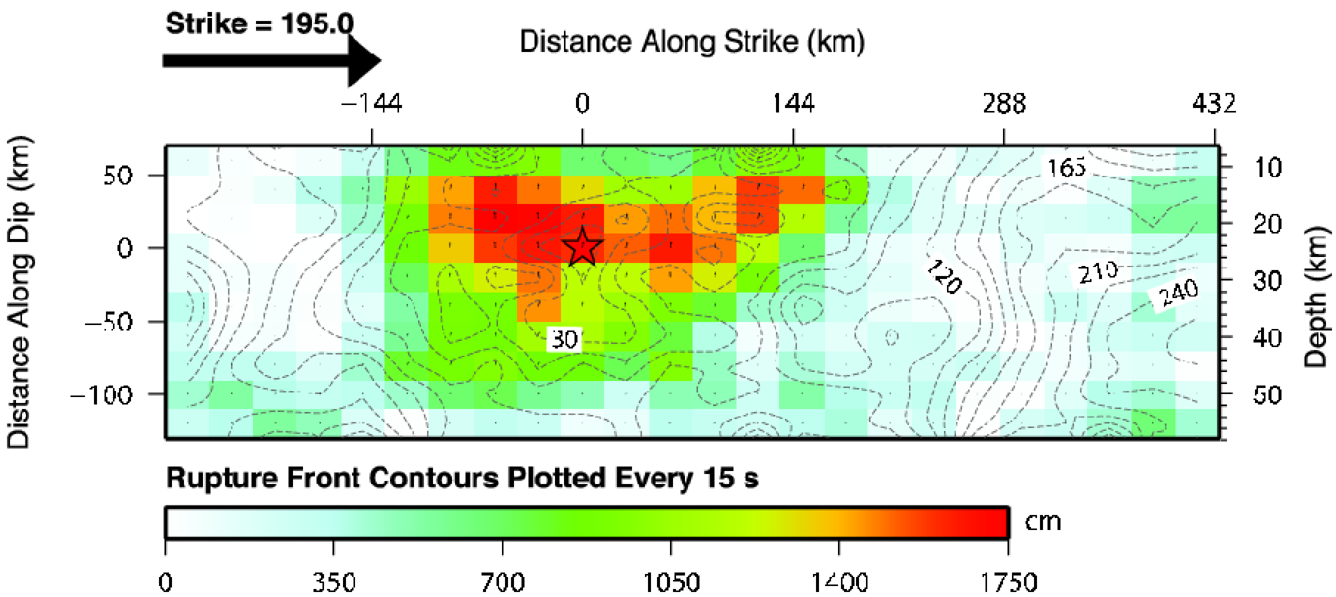
Friday, March 11, 2011 at 05:46:23 UTC

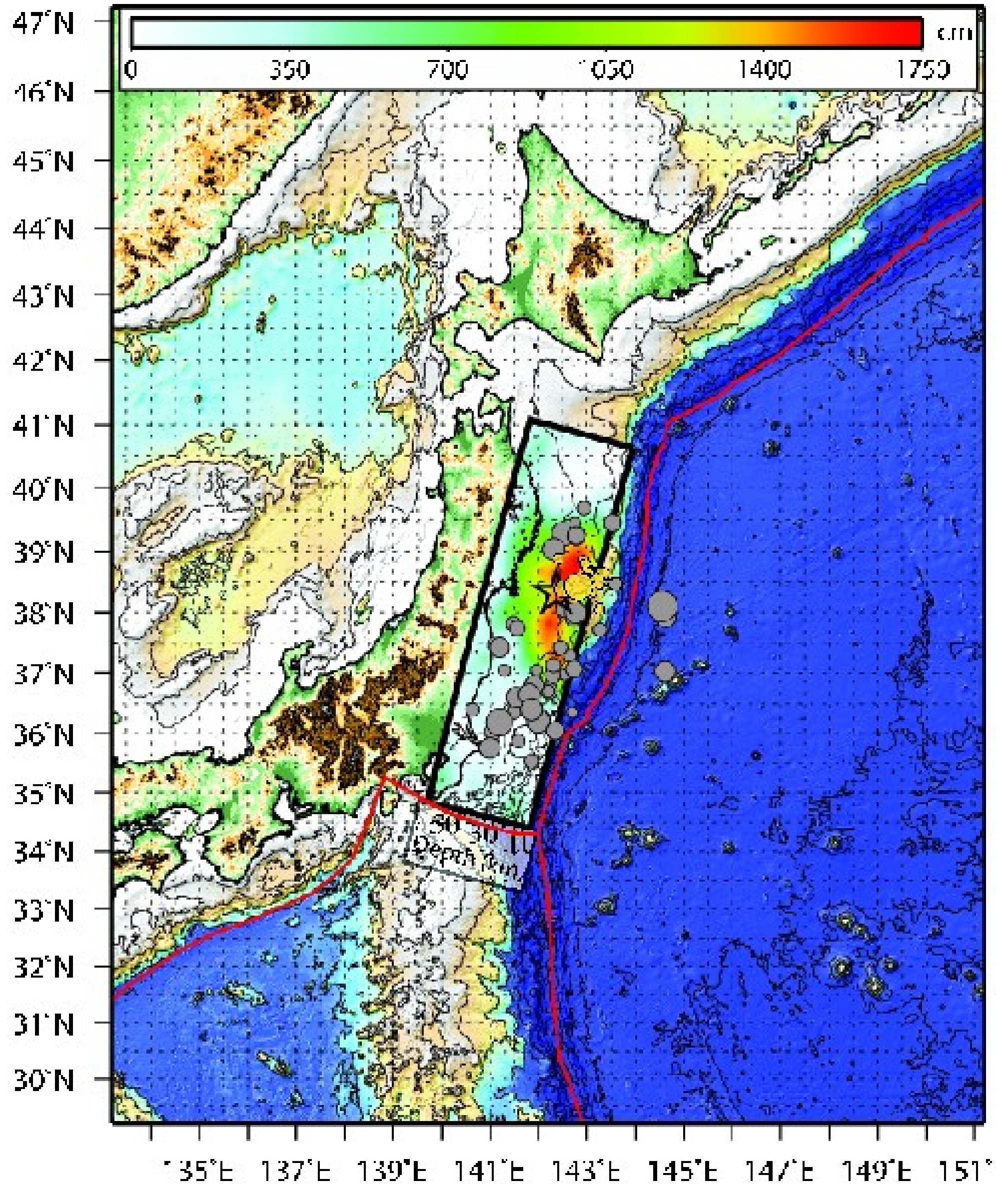




After analyzing waveform fits based on the nodal planes of the rapid WCMT moment tensor, and those more closely matching the slab geometry, we find that a nodal plane striking 195 deg., and dipping 14 deg., fits the data better. The seismic moment release based upon this plane is 4.04e+29 dyne.cm using 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

USGS Earthquake Hazards Program-Latest Earthquakes - Microsoft Internet Explorer

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Address http://earthquake.usgs.gov/eqinthenews/2004/usslav/ Go Links

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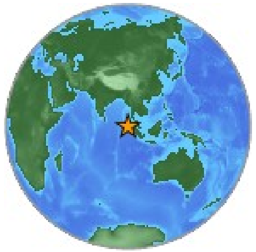
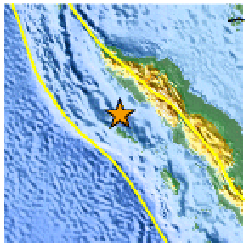
Magnitude 9.0 - SUMATRA-ANDAMAN ISLANDS EARTHQUAKE

OFF THE WEST COAST OF NORTHERN SUMATRA

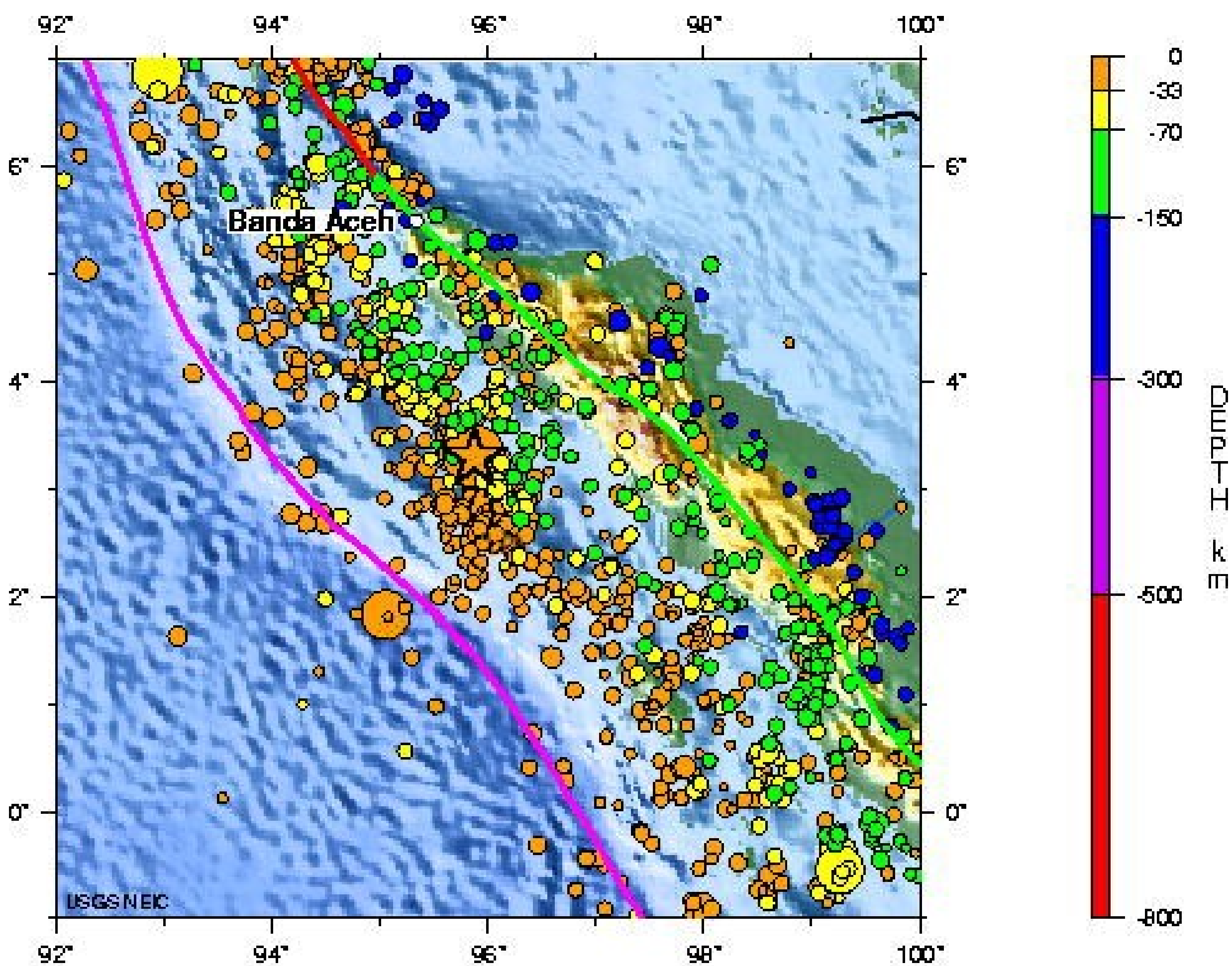
2004 December 26 00:58:53 UTC





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, Nph=276, Dmin=654.9 km

Internet



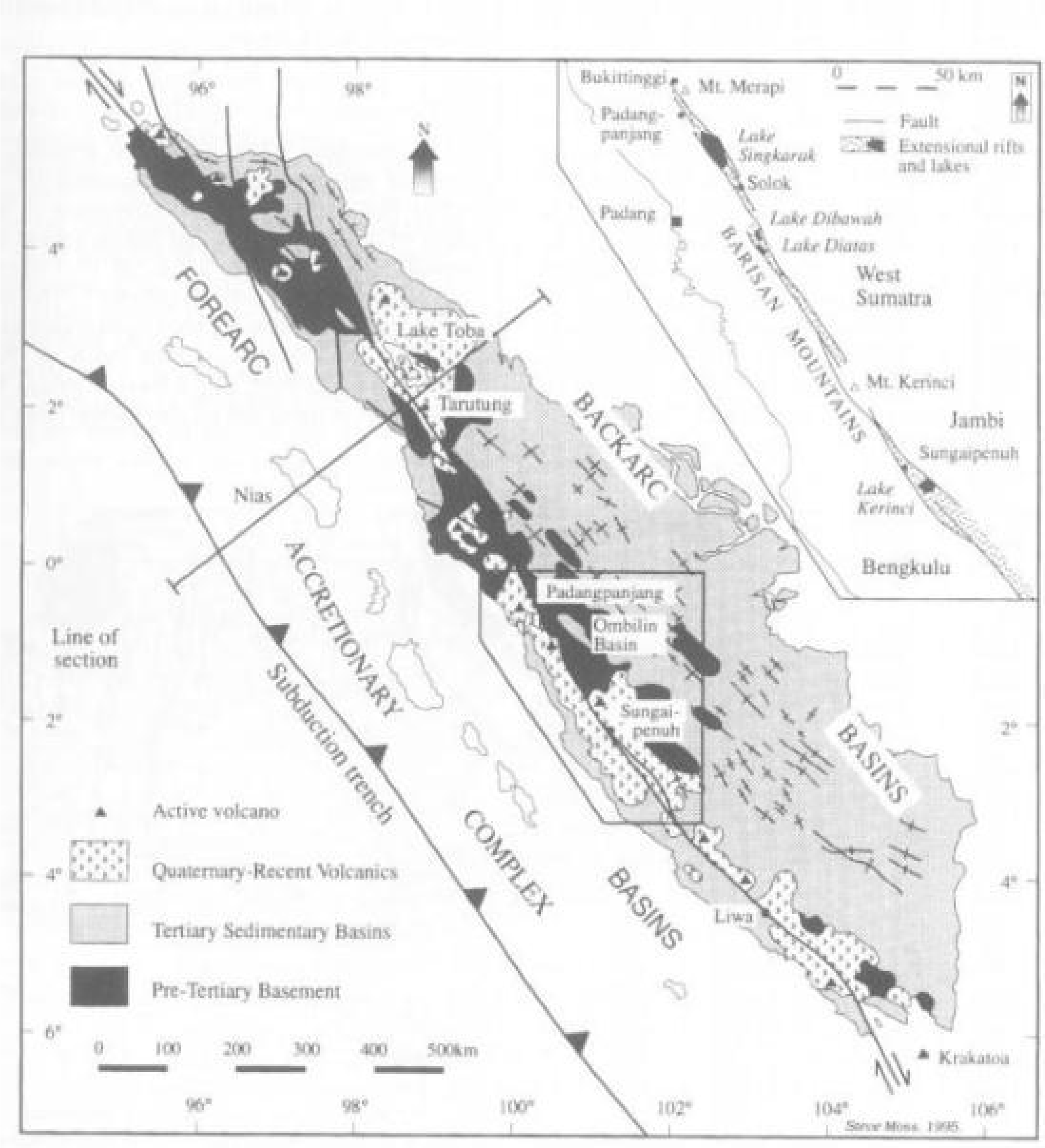
OFF THE WEST COAST OF NORTHERN SUMATRA

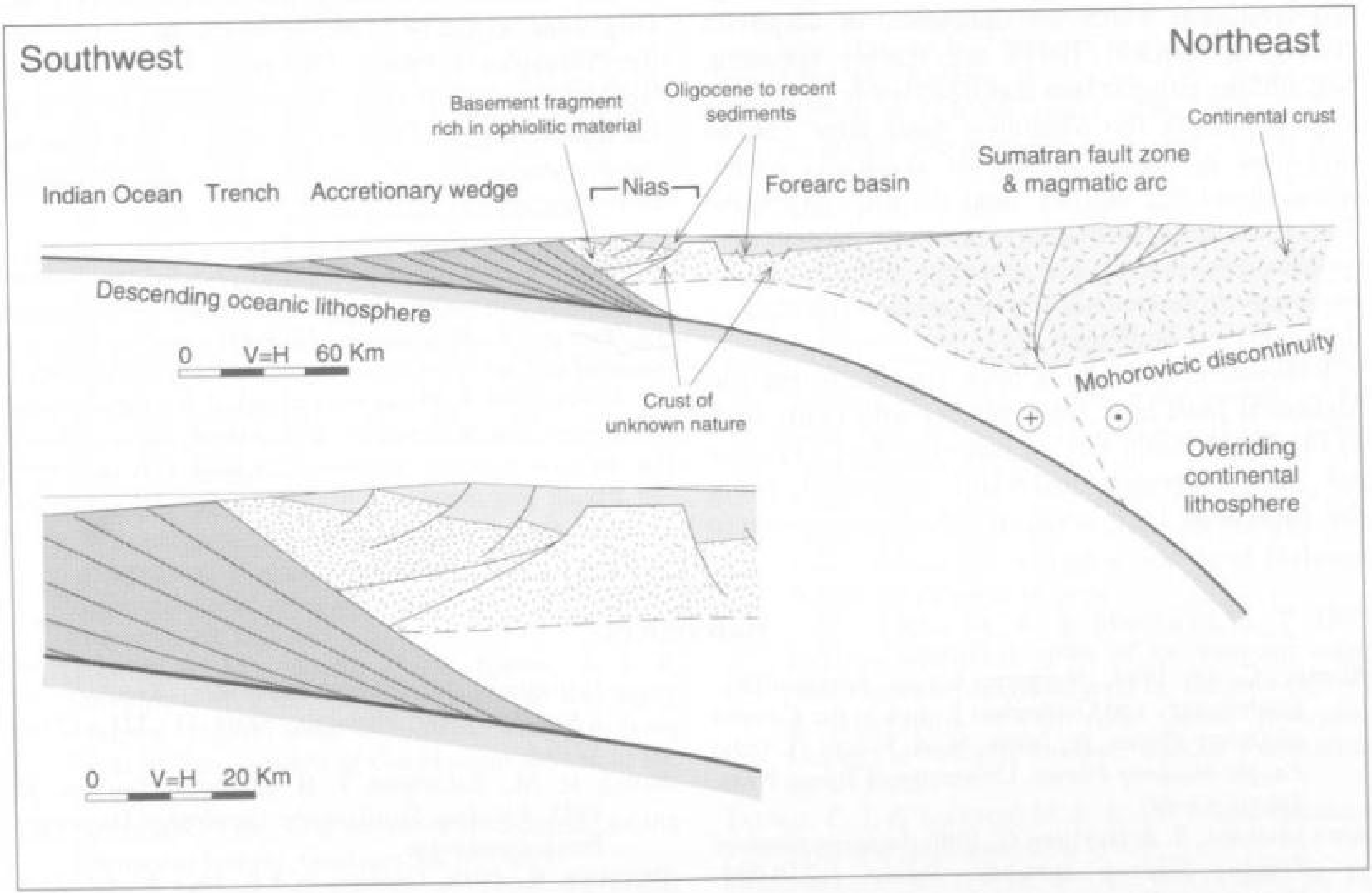
2004 12 26 00:58:53 UTC 3.30N 95.87E Depth: 30 km, Magnitude: 9.0

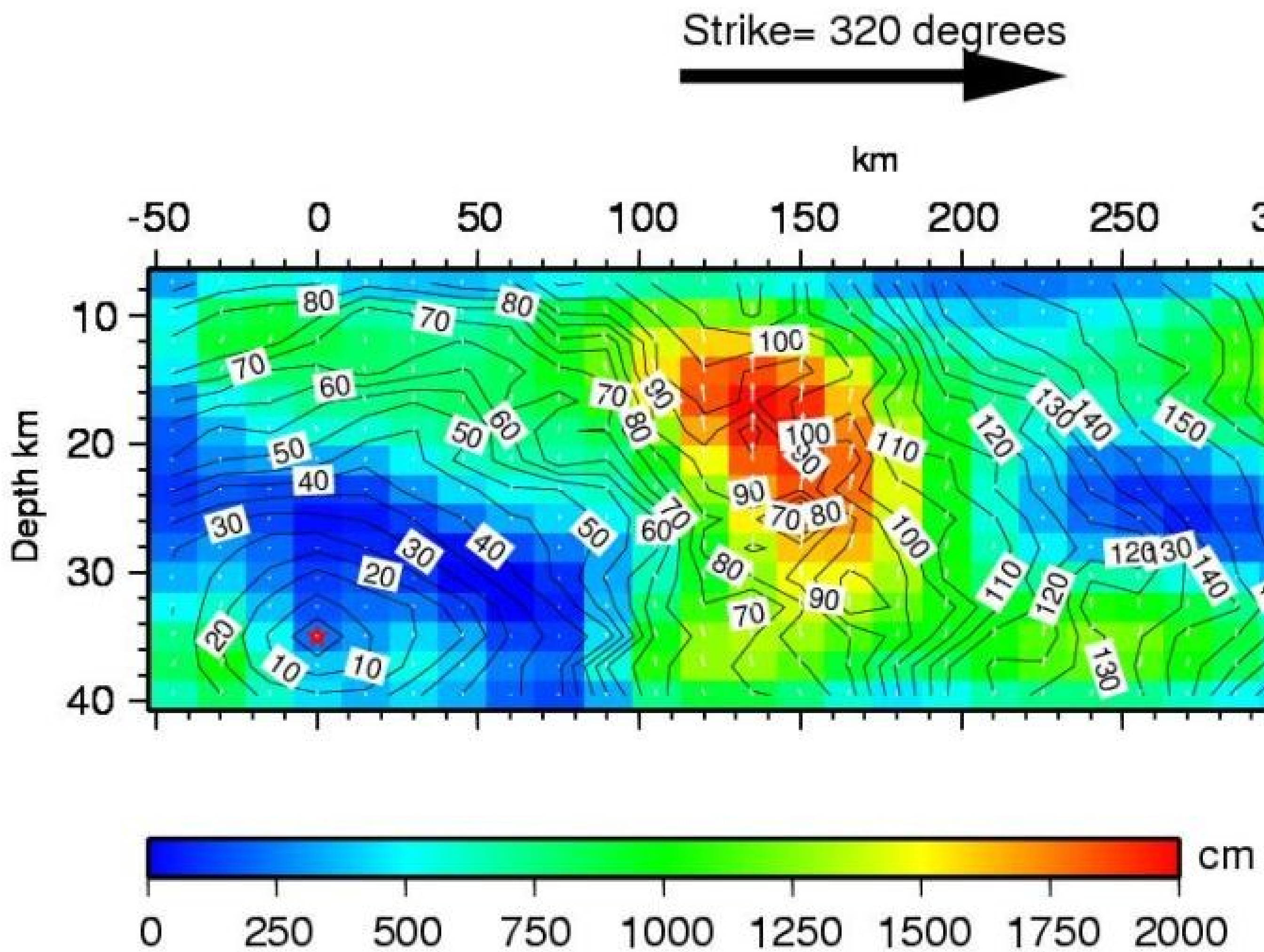
Seismicity 1990 to Present

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

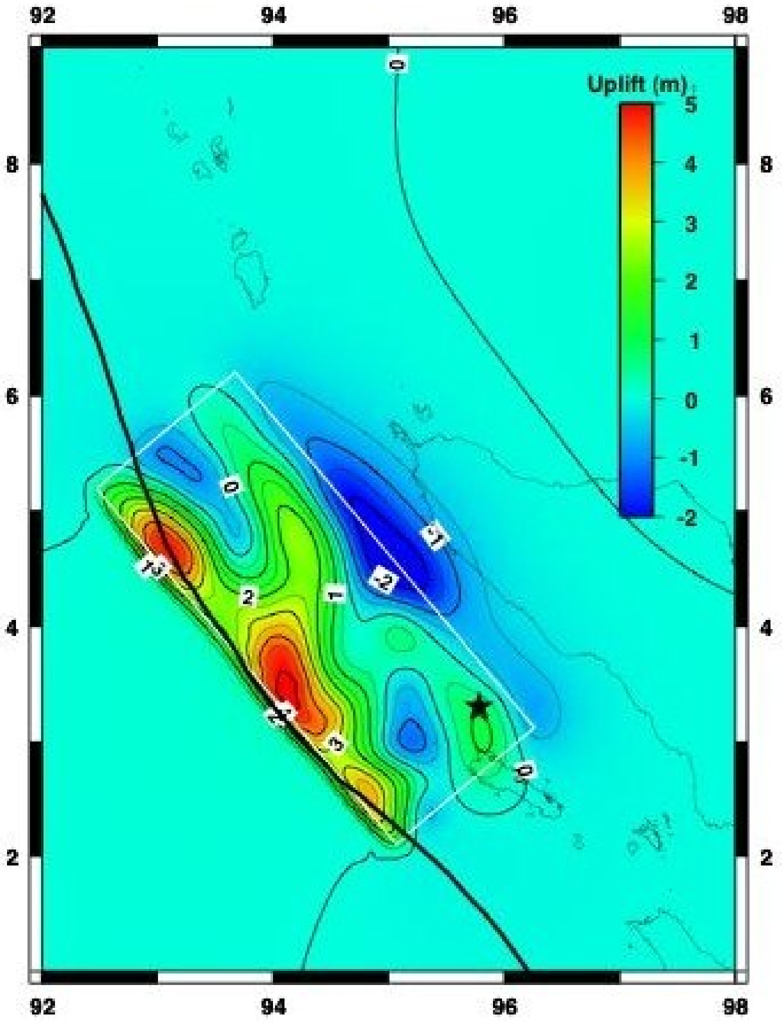
USGS National Earthquake Information Center


Bukittinggi
Mt. Merapi
Padang-panjang
Lake Singkarak
Solok
Padang
BARISAN MOUNTAINS
Lake Dibawah
Lake Diatas
West Sumatra
Mt. Kerinci
Jambi
Sungaipenuh
Lake Kerinci
Bengkulu
0 50 km
N
Fault
Extensional rifts and lakes
FOREARC
Lake Toba
Tarutung
BACKARC
Nias
ACCRETIONARY
COMPLEX
BASINS
Subduction trench
Padangpanjang
Ombilin Basin
Sungai-penuh
BASINS
Line of section
Liwa
Krakatoa
Active volcano
Quaternary-Recent Volcanics
Tertiary Sedimentary Basins
Pre-Tertiary Basement
0 100 200 300 400 500km
96° 98° 100° 102° 104° 106°
4° 2° 0° 2° 4° 6°
Steve Moss 1995


Southwest
Northeast
Basement fragment rich in ophiolitic material
Oligocene to recent sediments
Continental crust
Sumatran fault zone & magmatic arc
Indian Ocean
Trench
Accretionary wedge
Nias
Forearc basin
Descending oceanic lithosphere
0 V=H 60 Km
Crust of unknown nature
Mohorovicic discontinuity
Overriding continental lithosphere
0 V=H 20 Km


Strike= 320 degrees
km
-50
0
50
100
150
200
250
300
350
Depth km
10
20
30
40
cm
0
250
500
750
1000
1250
1500
1750
2000

Site response



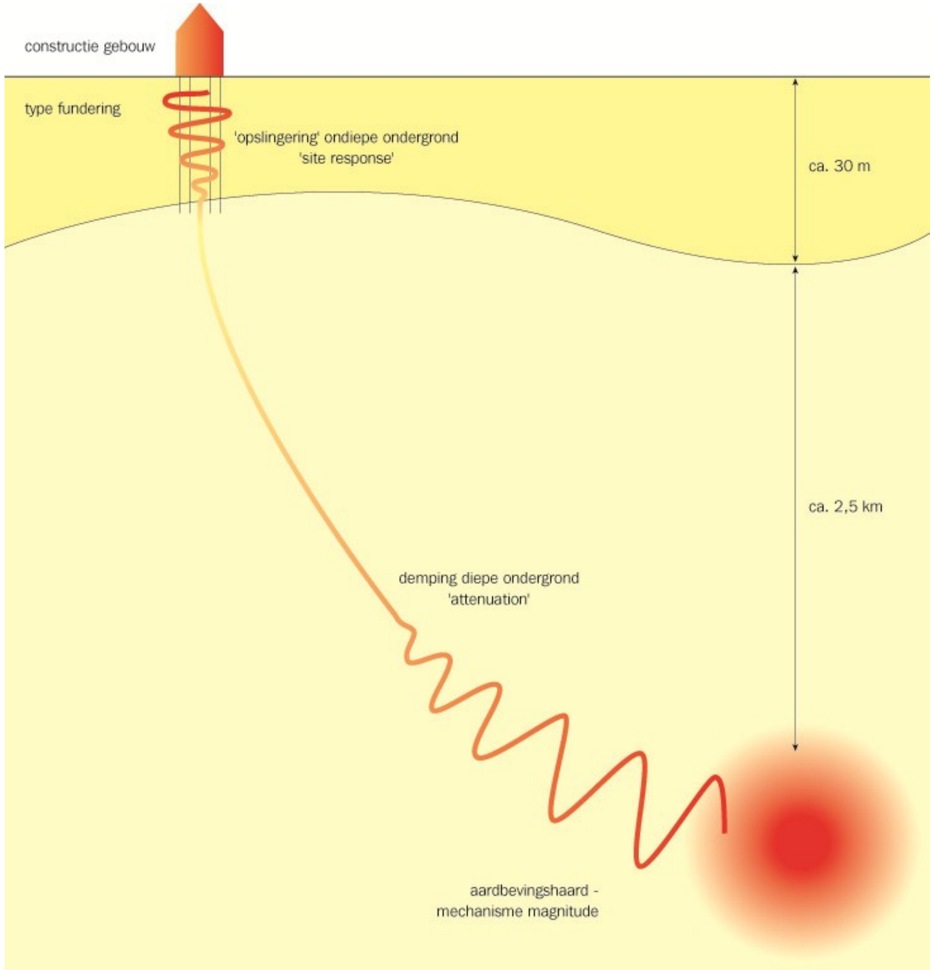
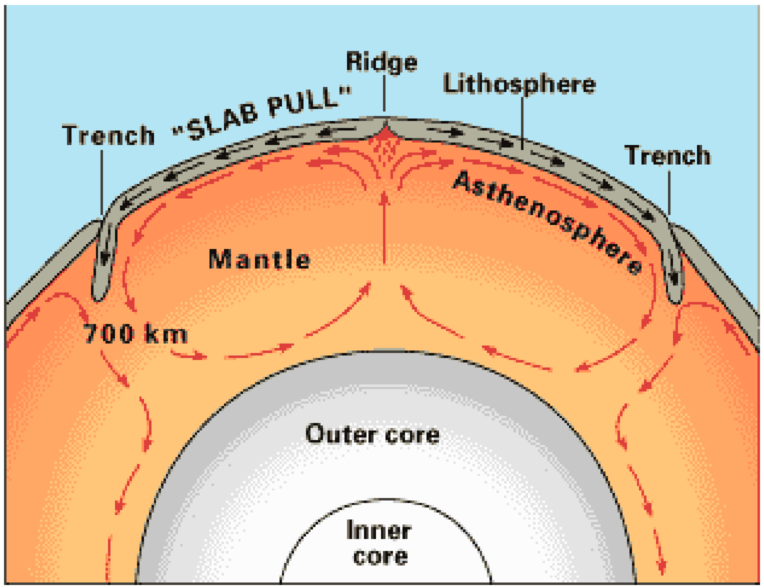
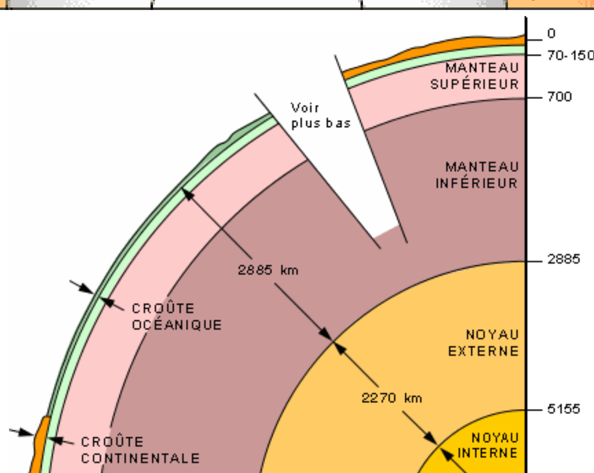


Plate tectonics, how does it function?





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

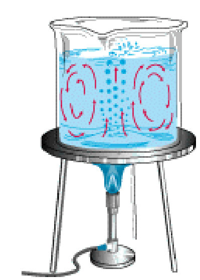
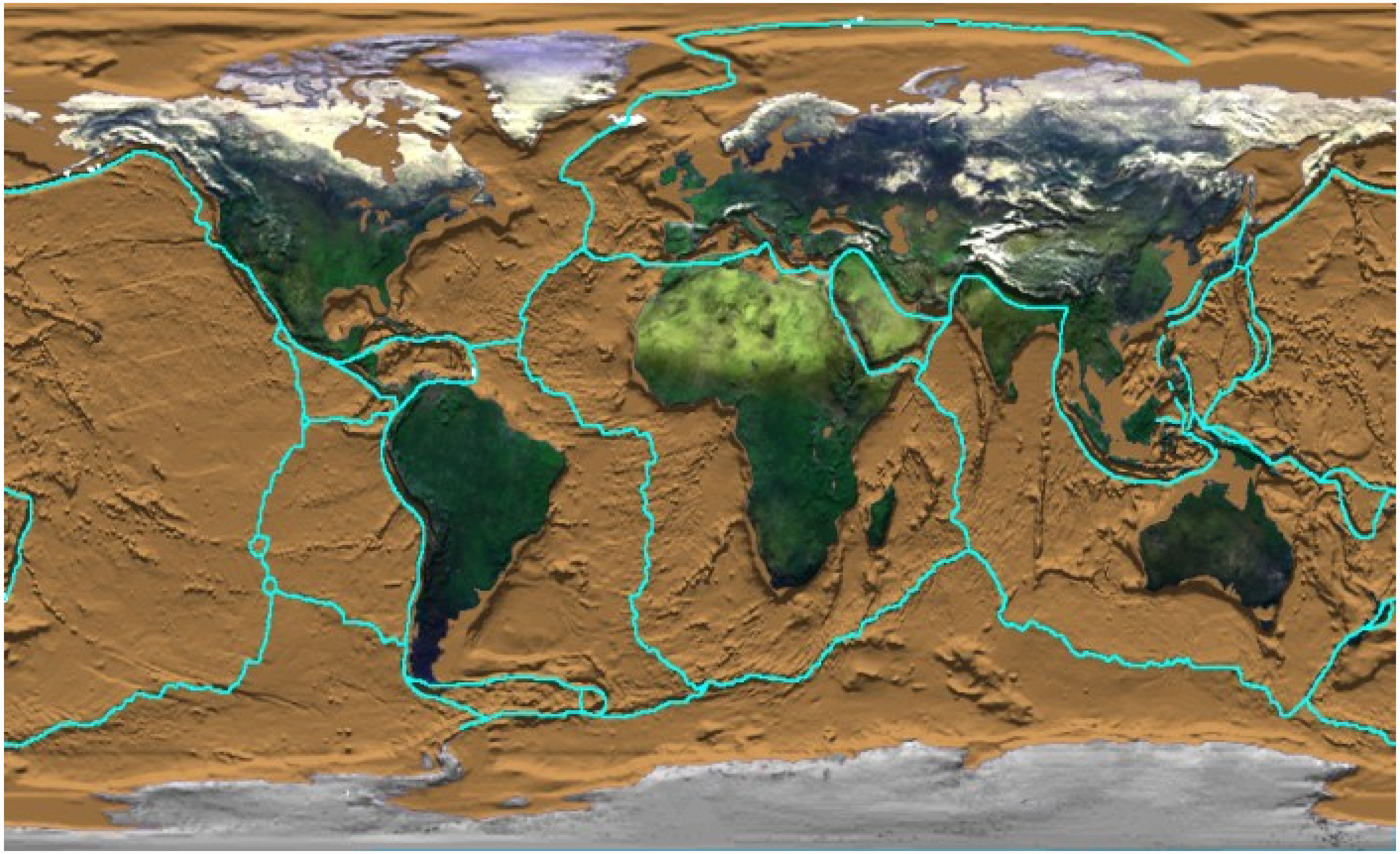


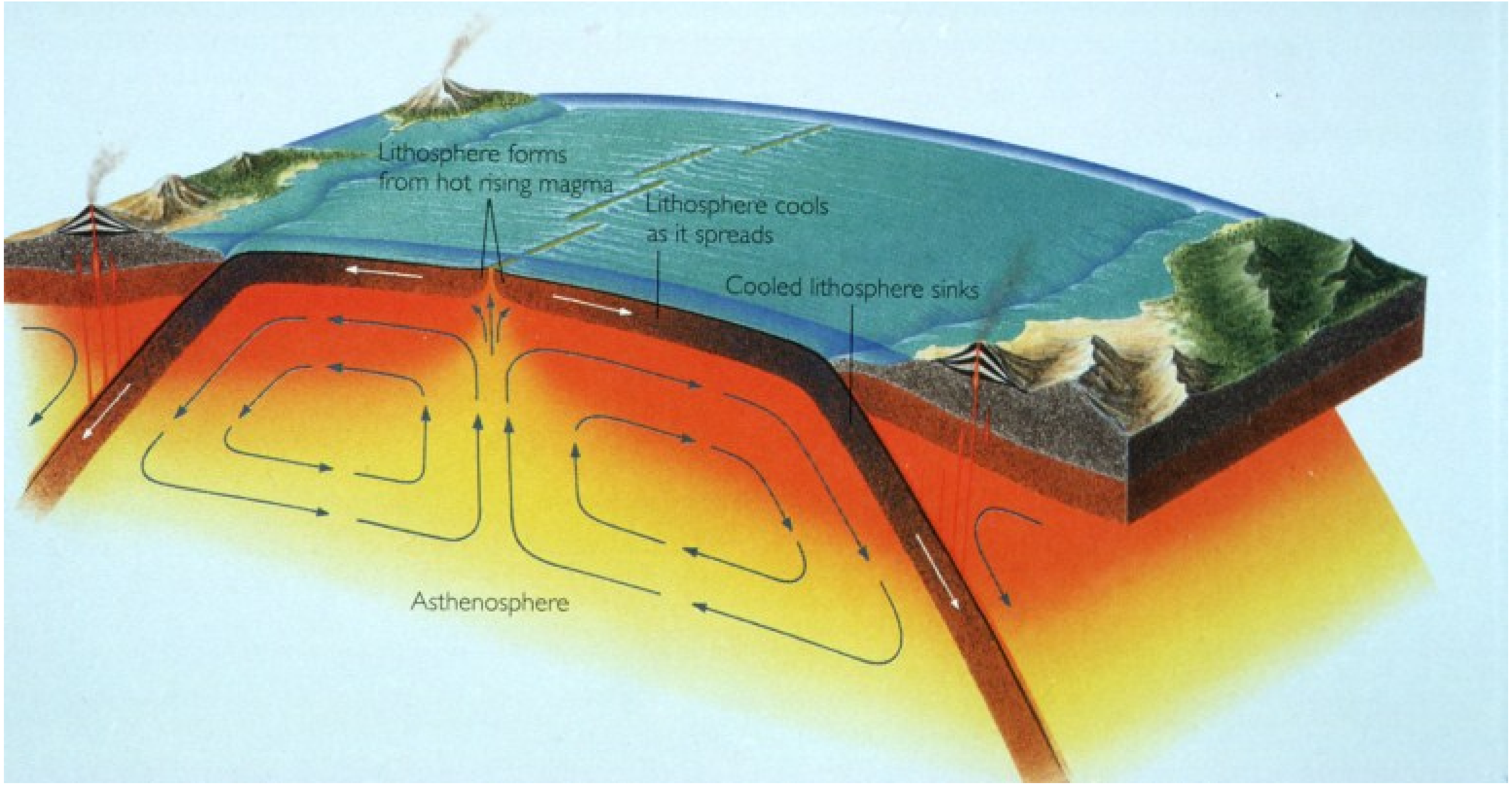
Plate tectonics

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



Kinematics of plate tectonics

Plates should not regarded 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).

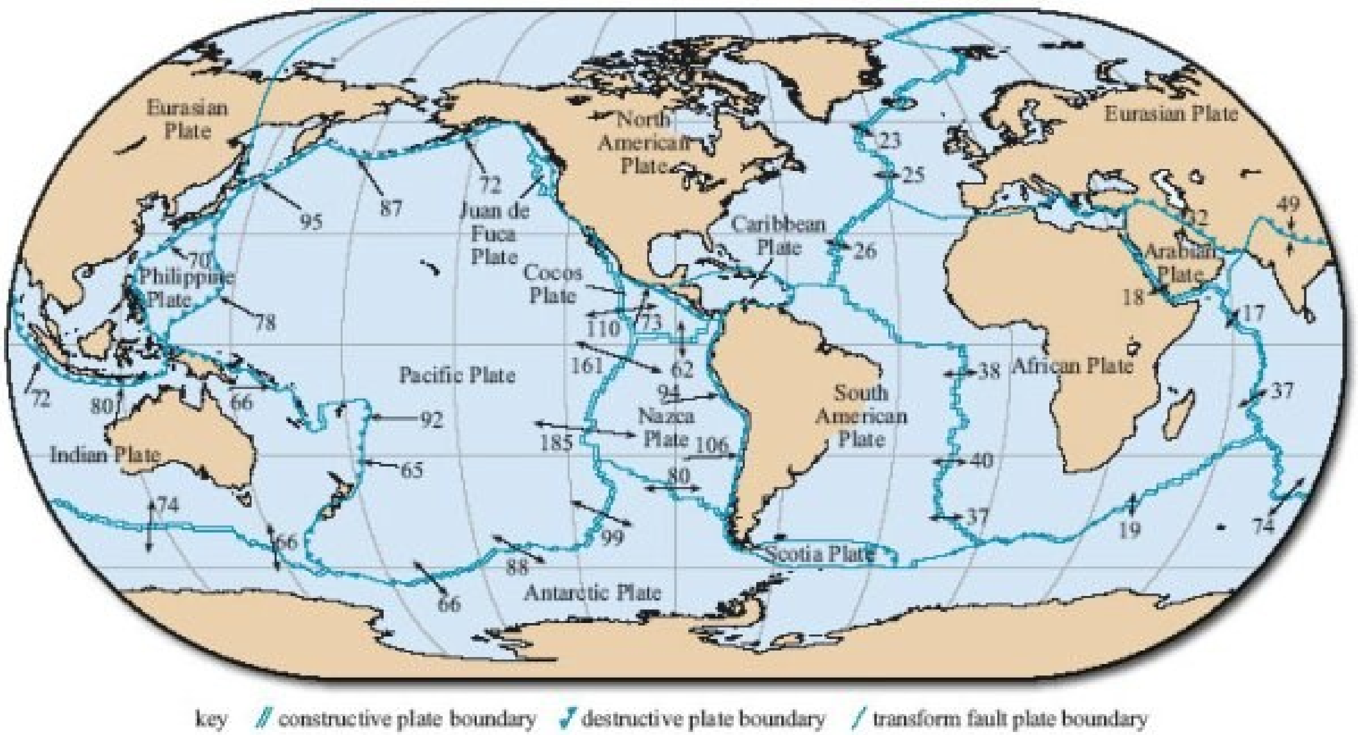
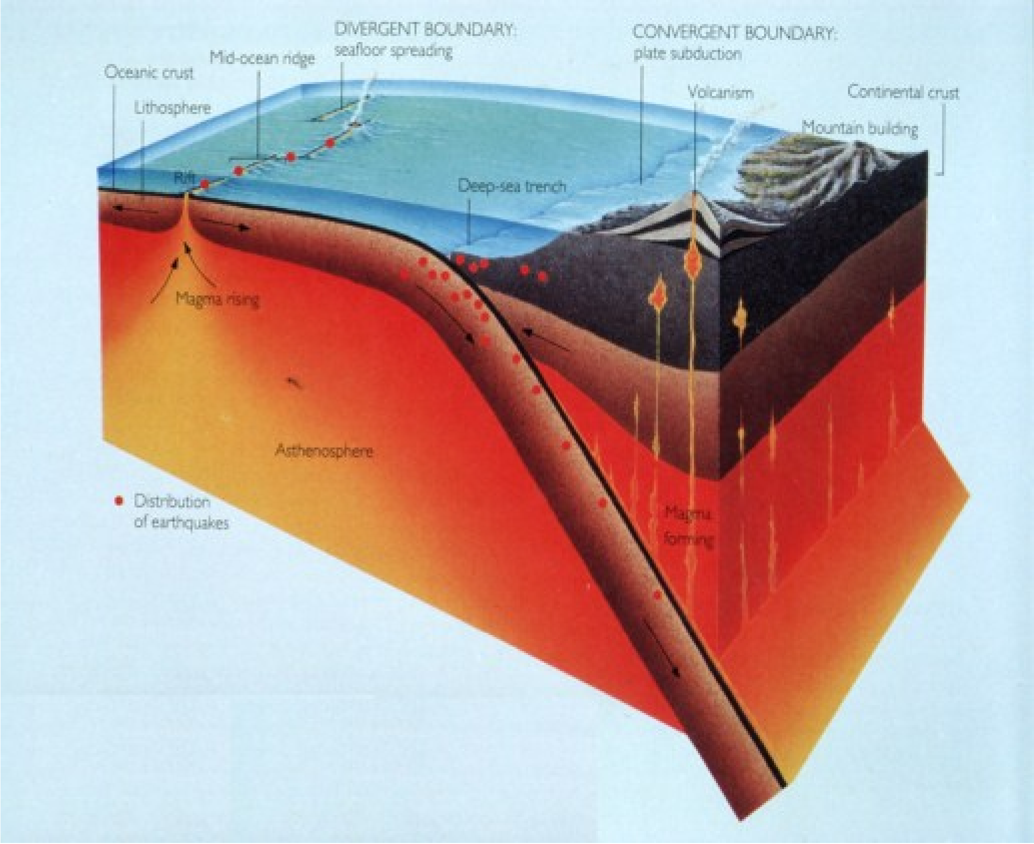


Plate tectonic forces

Plate interaction generates enormous forces (1012-1013 N/m)

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

- Earthquakes (red dots)
- Volcanism
- Orogenesis



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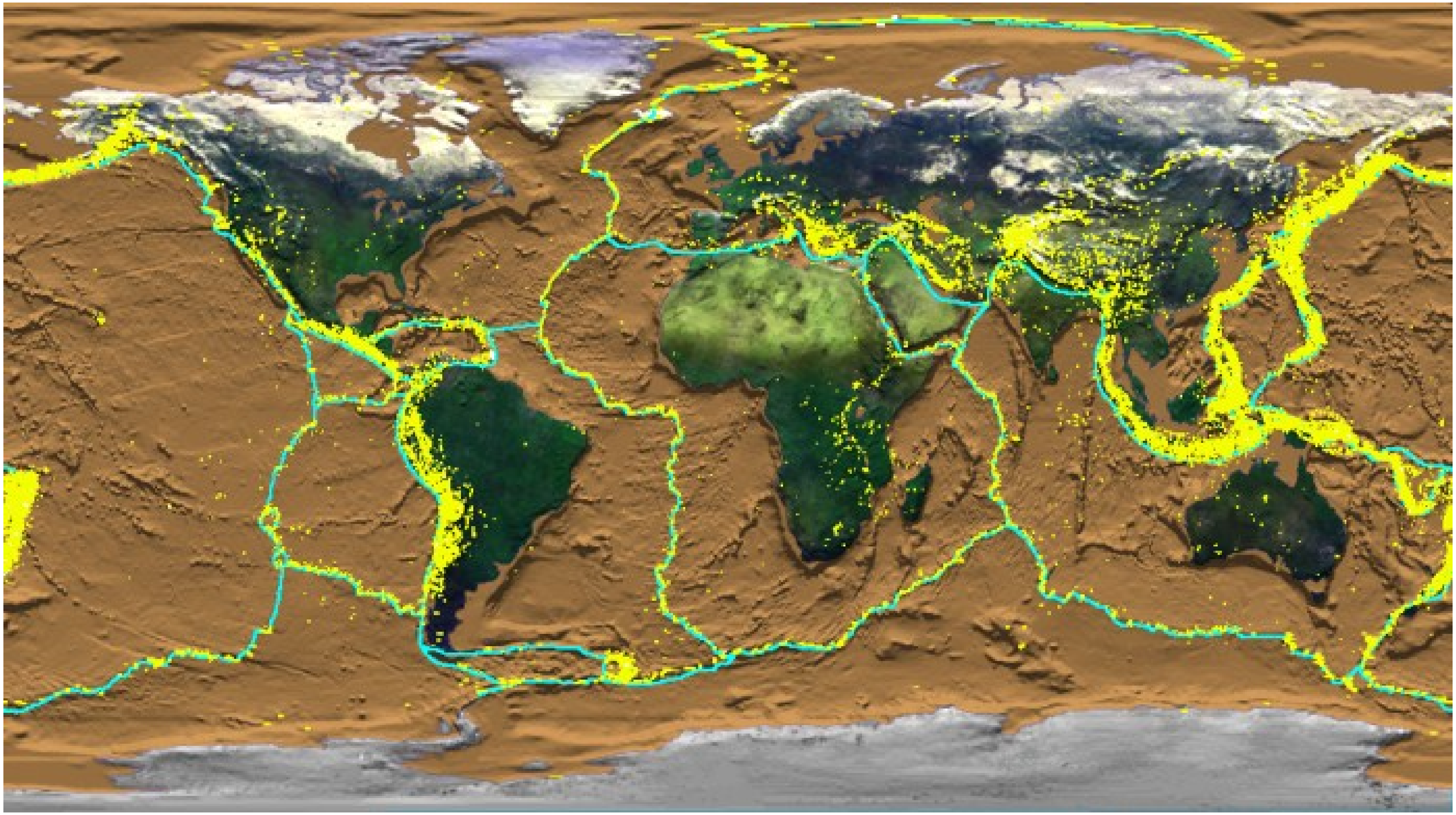
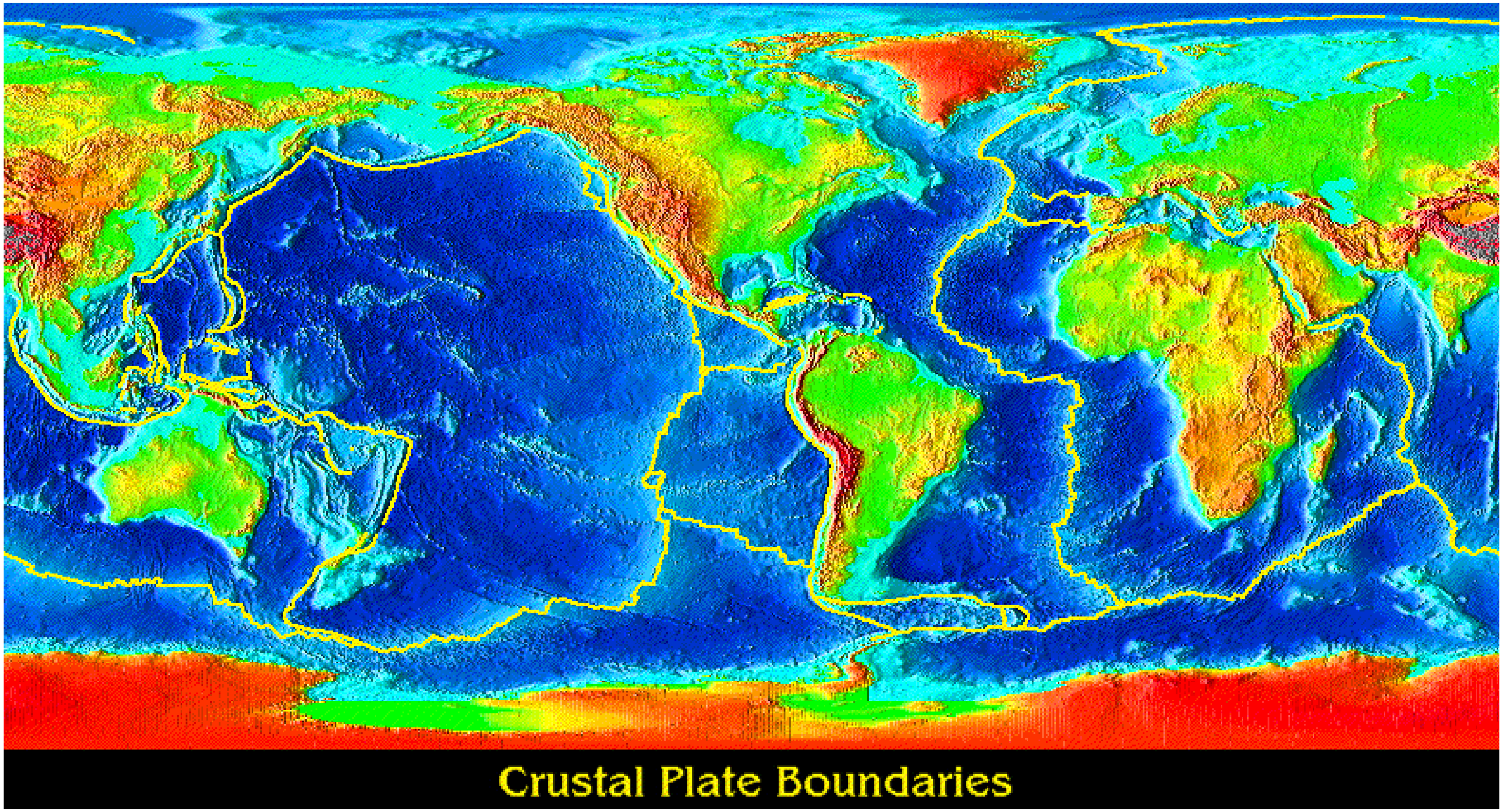
Earthquakes since 1960

Plate tectonics & seismic activity

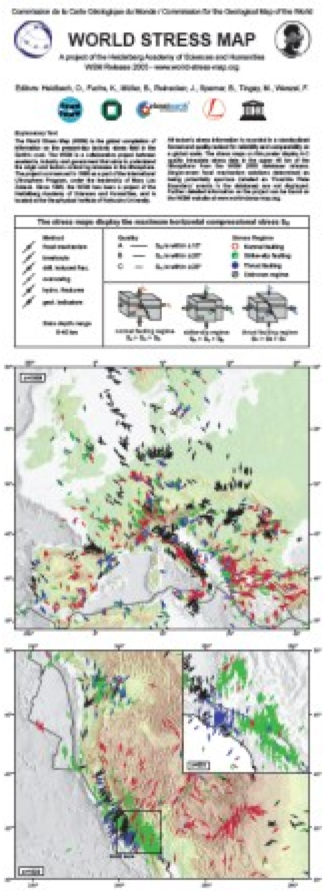


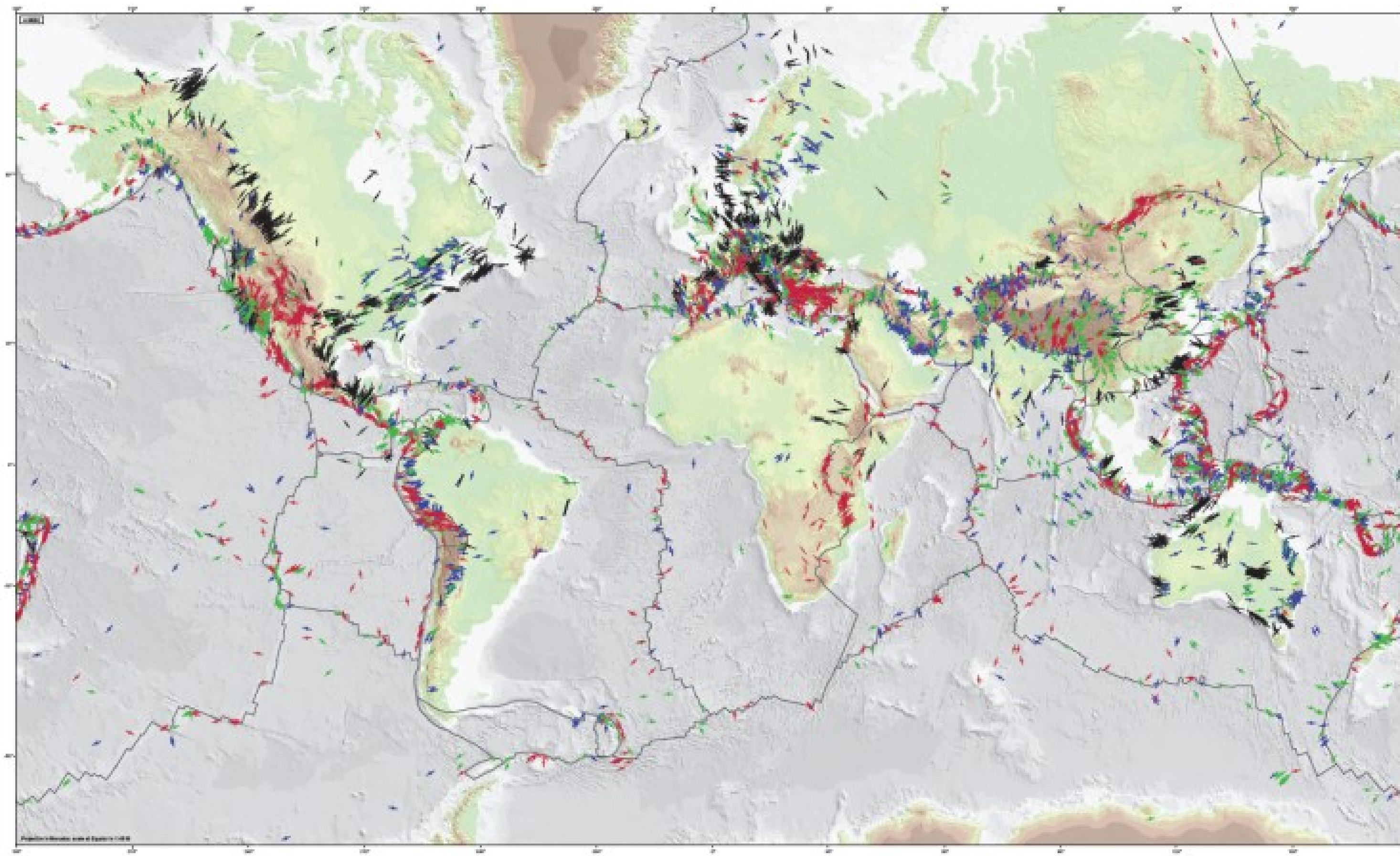
Large mountain belts (Andes, Himalayas, Alps) are located along plate boundaries

Plate tectonics and mountain formation (orogenesis)

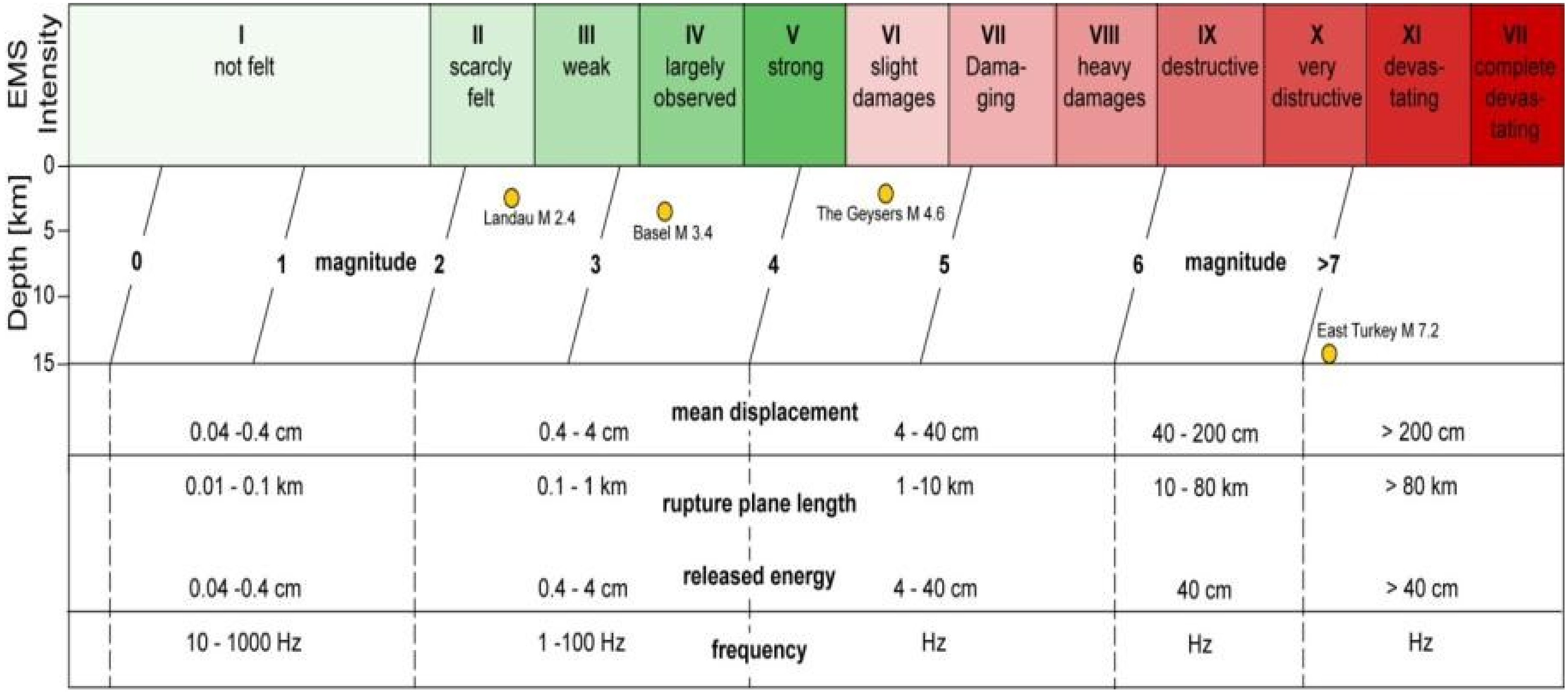


Intra-plate-stresses





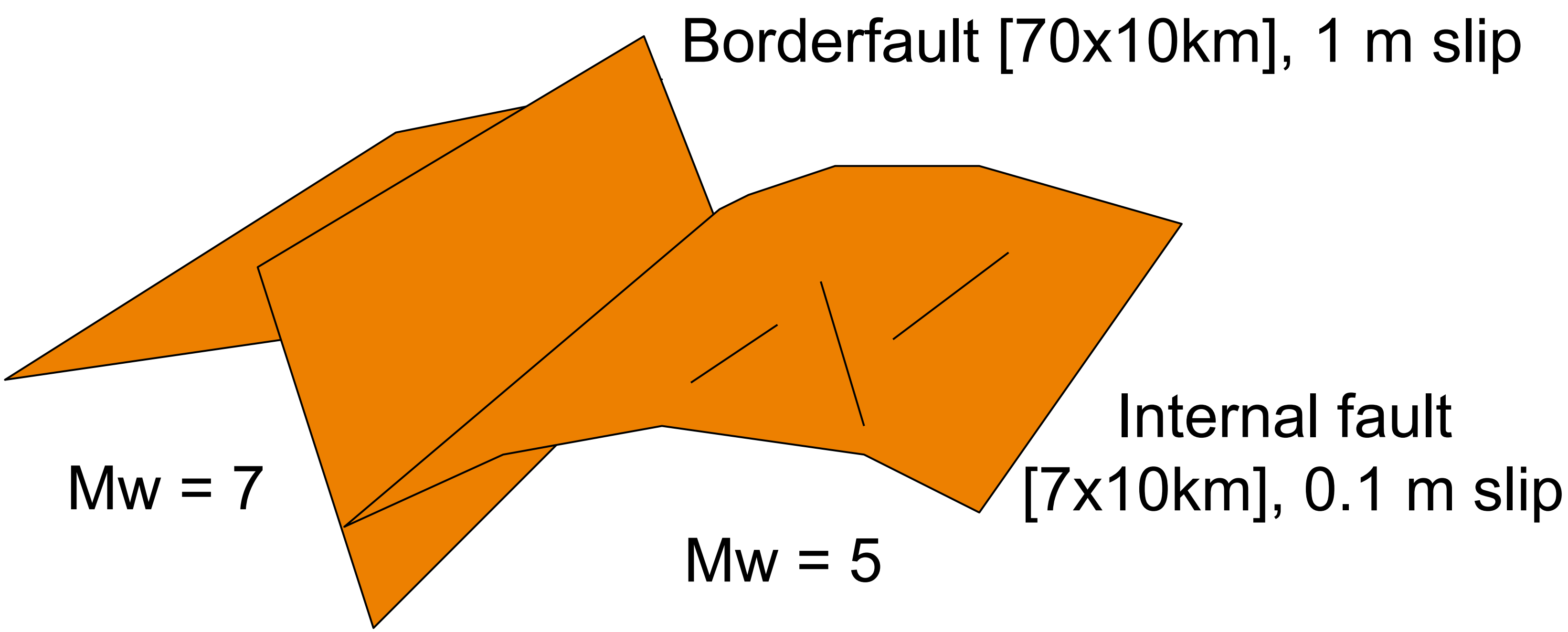
Magnitude of earth quakes



What is the relation with magnitude and surface slip

- Hanks and Kanimori (1979)

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

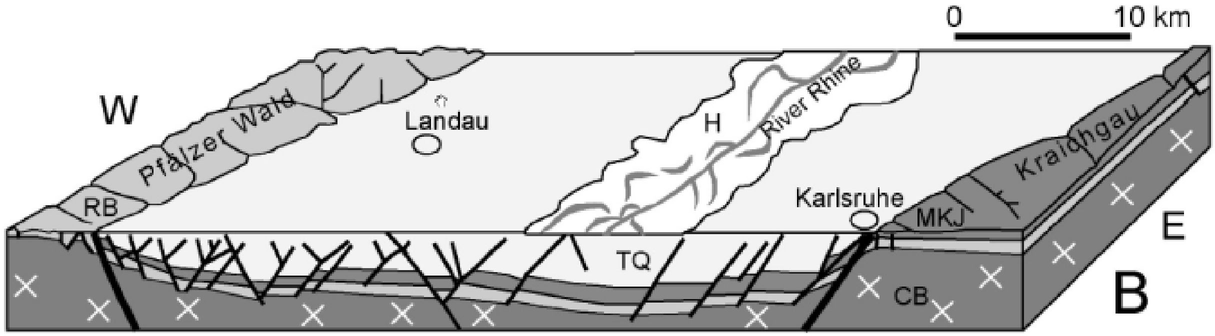


M=7, 70x10 km fault, 1m displacement

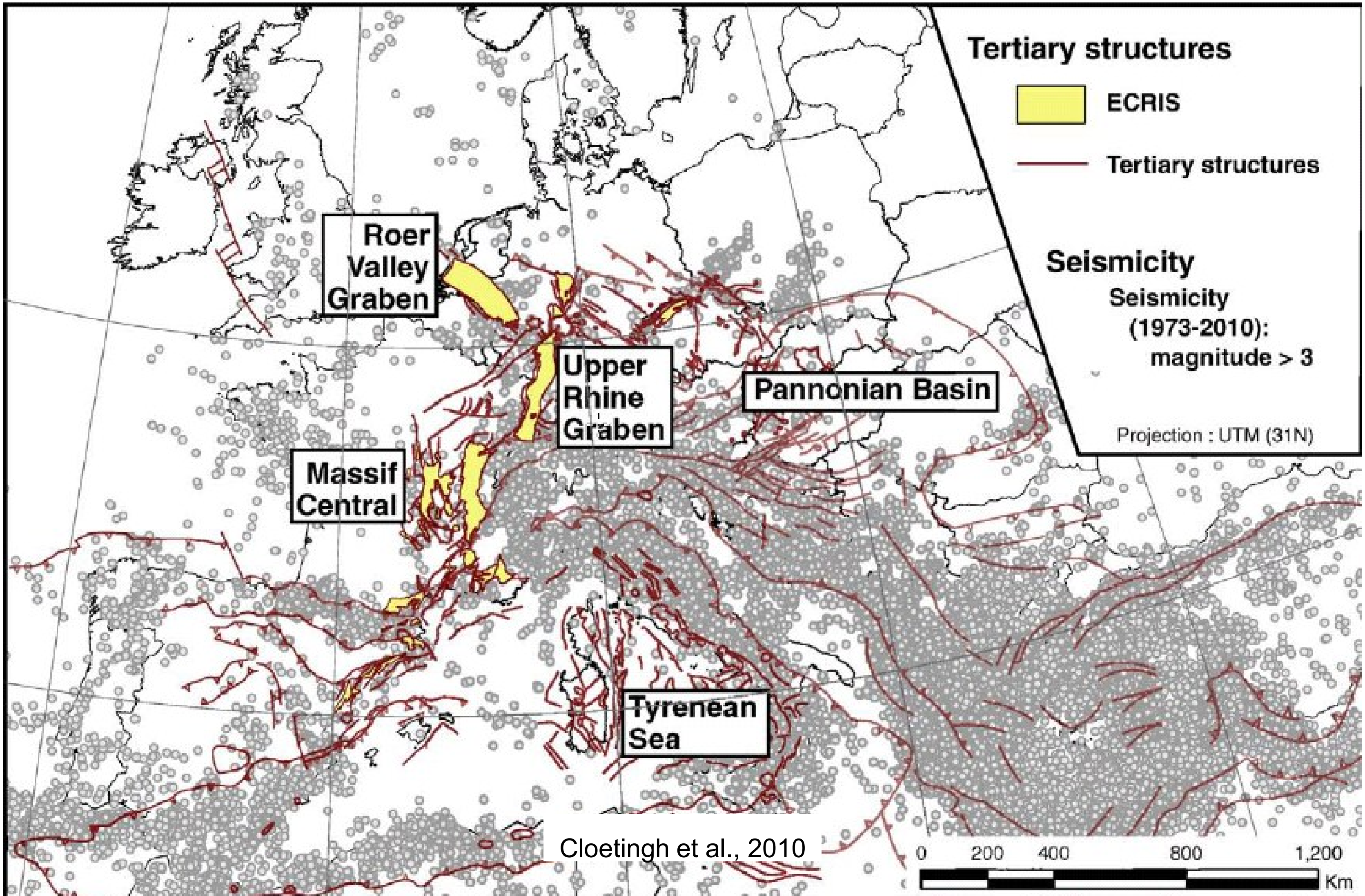
M=6, 30x5 km fault, 0.4m displacement

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

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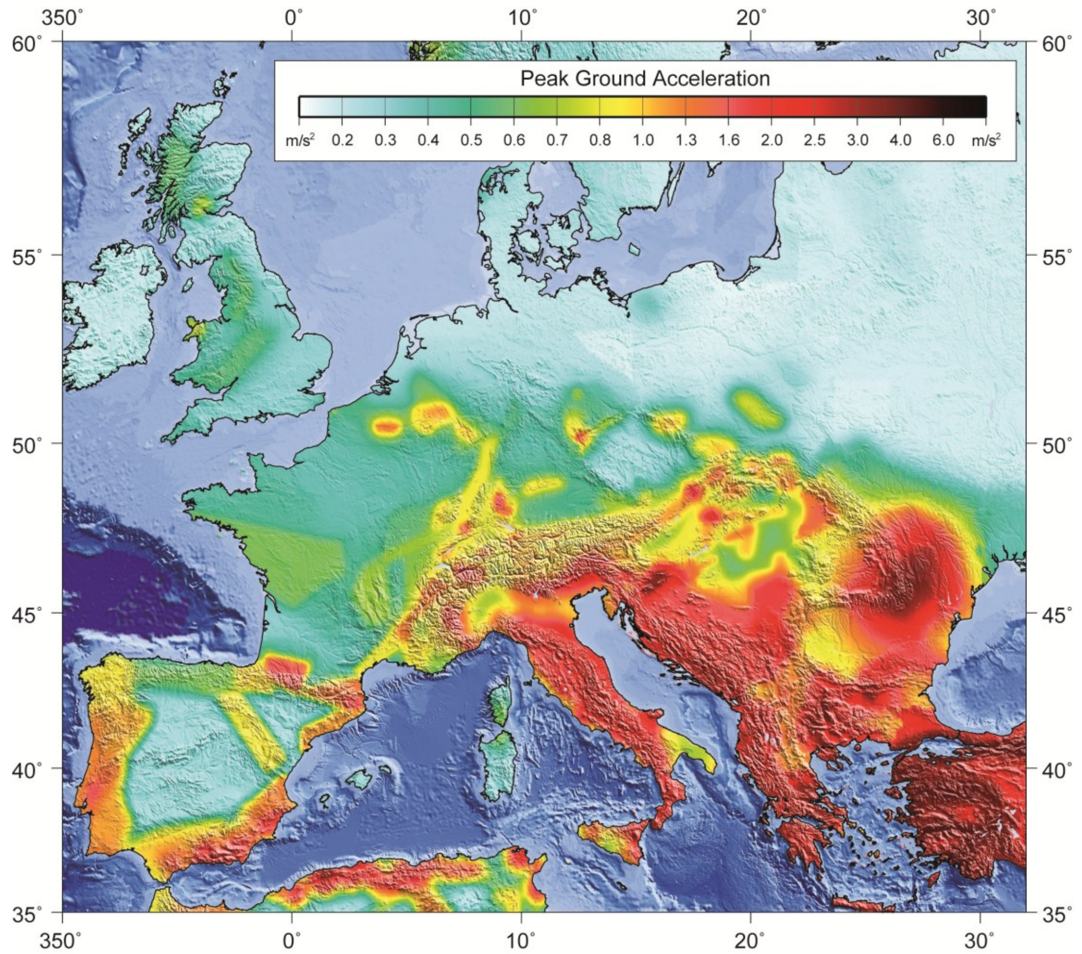
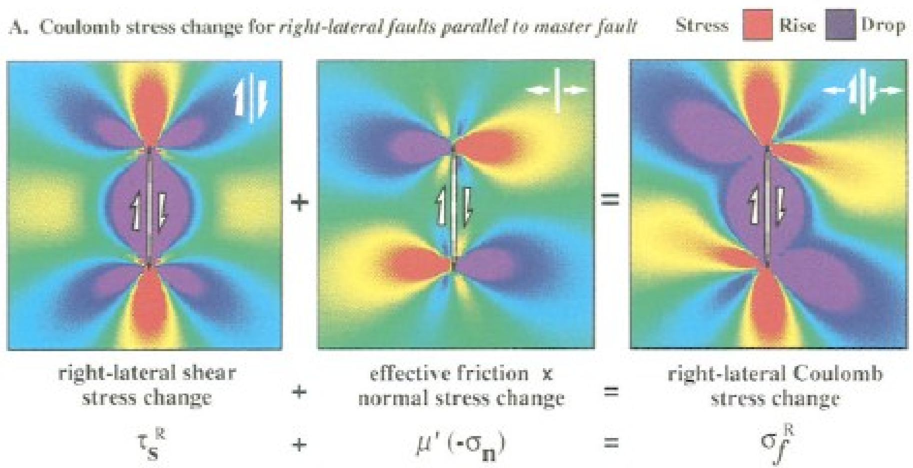
PGA hazard map



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

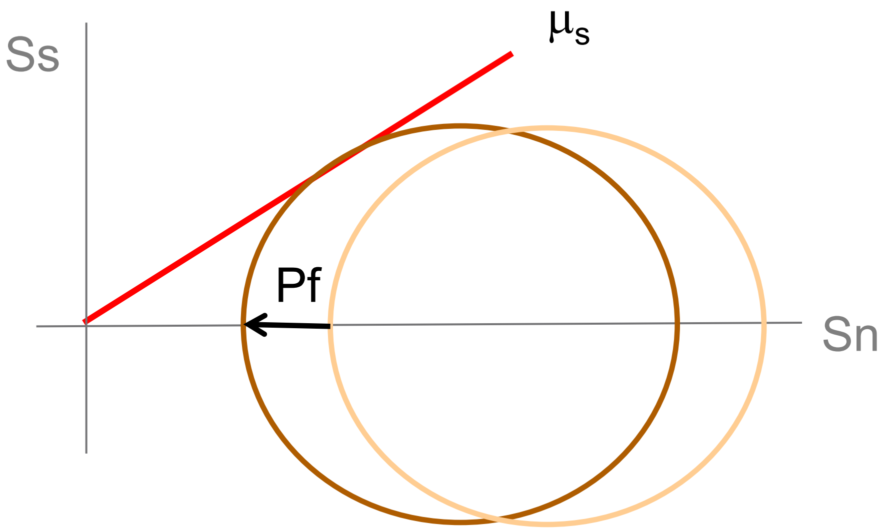
Input parameters

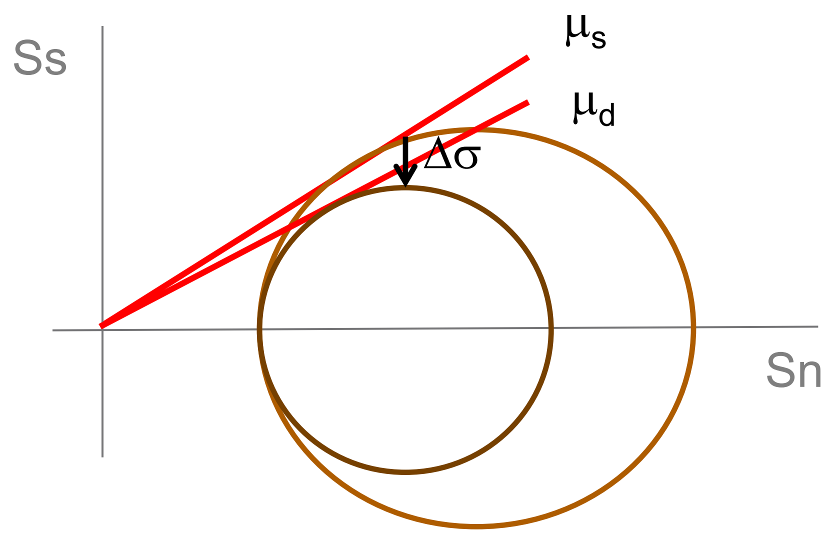
- Young's modulus, Poisson's ratio
- Calculated for a specific orientation of faults
  - Pre-determined
  - Optimally oriented faults
- Slip distribution source fault (often uncertain)

RED is closer to failure, purple away from failure→

Slip only possible if during faulting friction

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>μ_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

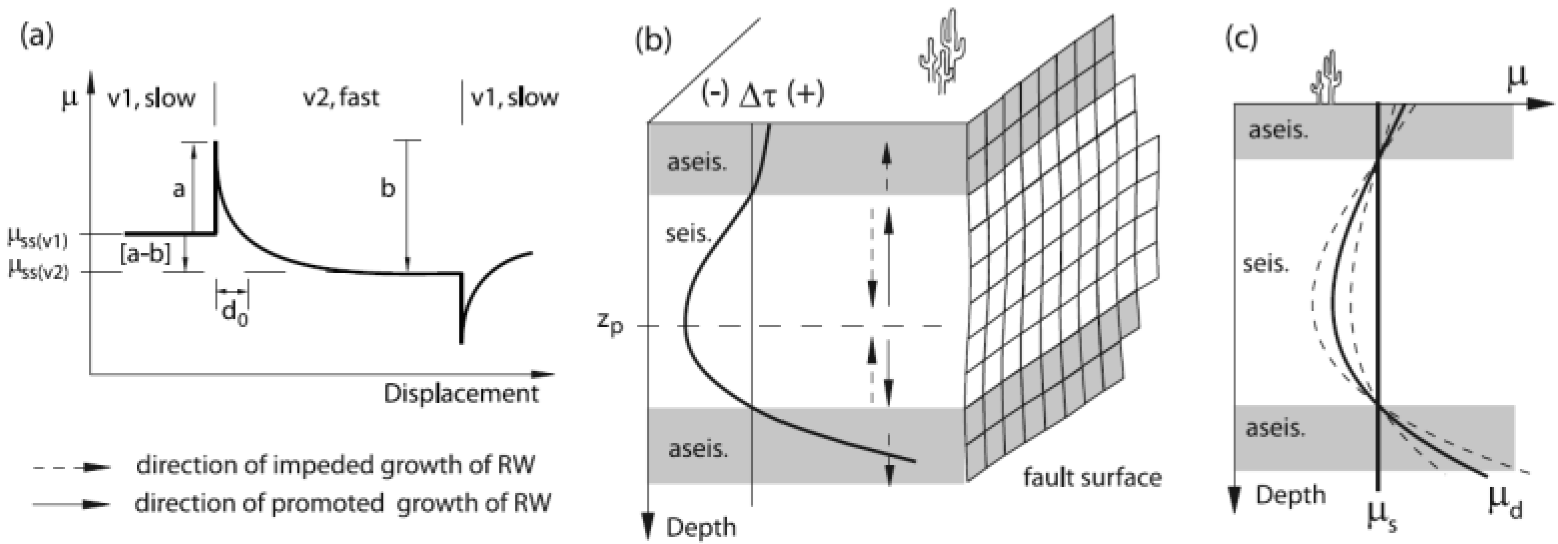


Figure 1. (a) Evolution of friction coefficient μ during a velocity stepping experiment, $v_1 \rightarrow v_2 \rightarrow v_1$). The slip rate dependent change of μ is expressed by $[a-b]$. (b) Depth variation of coseismic stress drop $\Delta\tau$ and inferred non-uniform evolution of rupture width.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

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

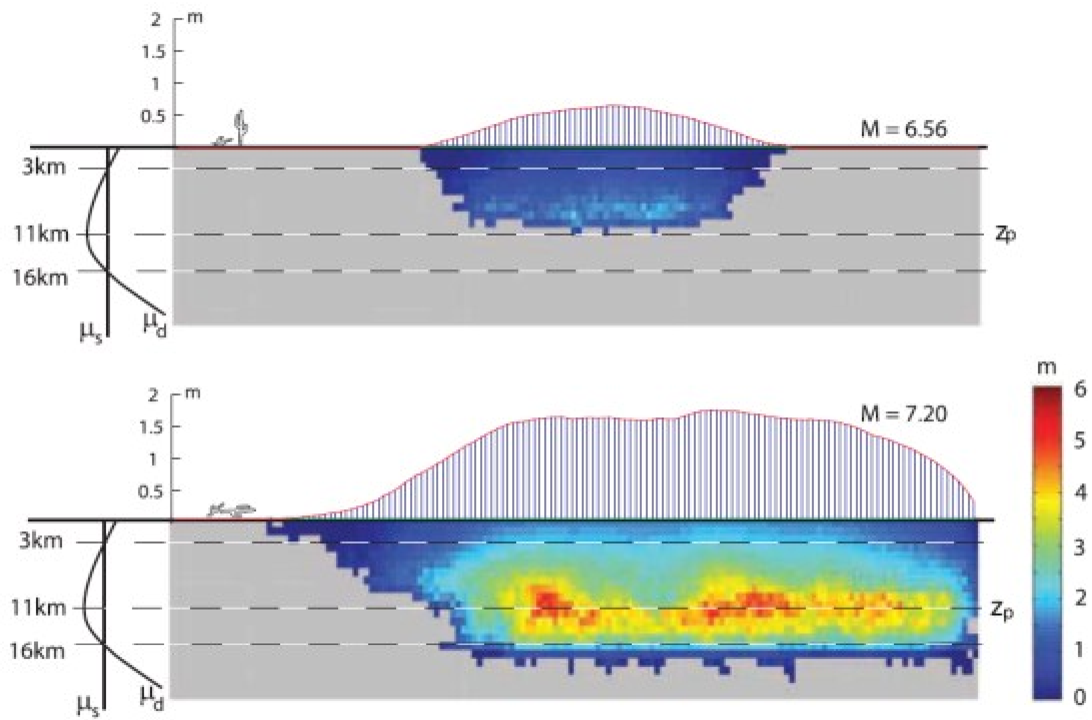
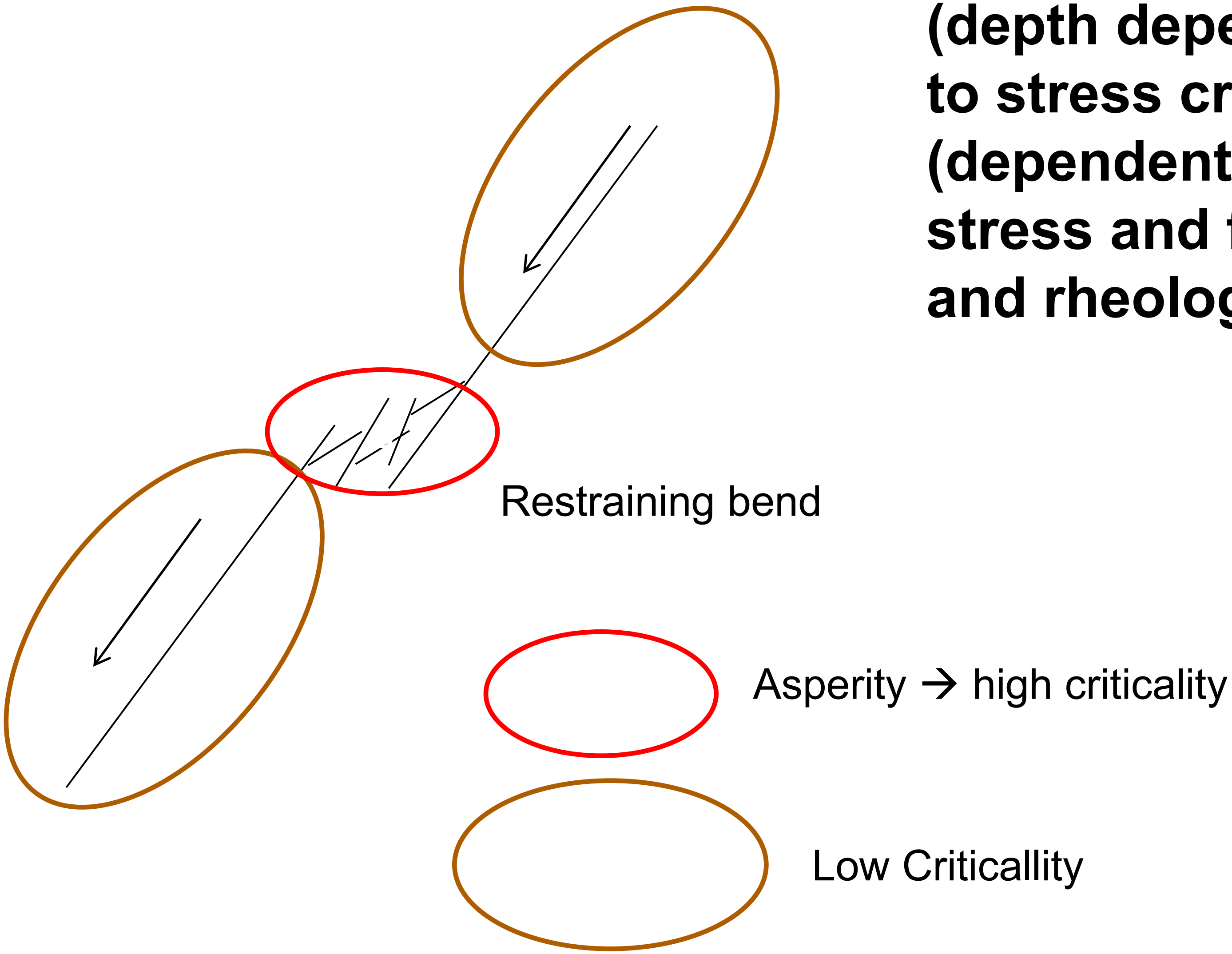


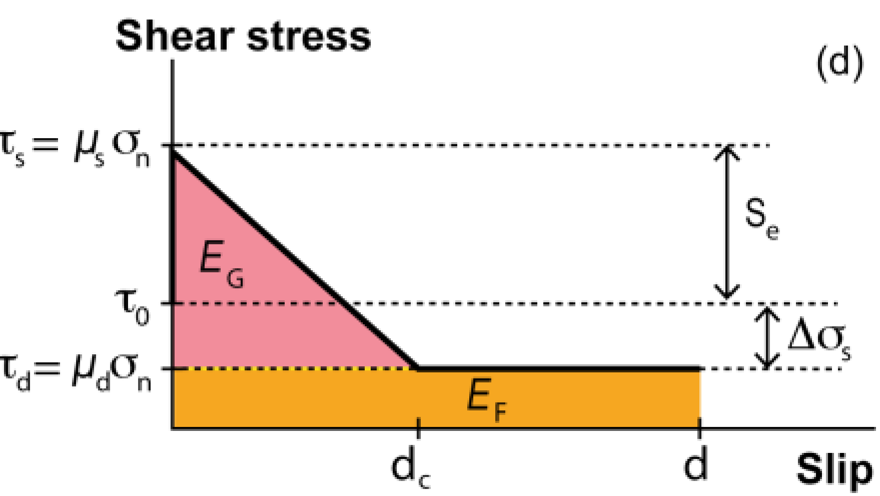
Figure 2. Color-coded amount of slip (22 km wide, 150 km long sub-vertical strike-slip fault with amplitude-wavelength ratio $\lambda = 0.003$) of a typical small and large earthquake. Gray fault patches did not slip in the respective events. Shown above is the respective surface-slip distribution. On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

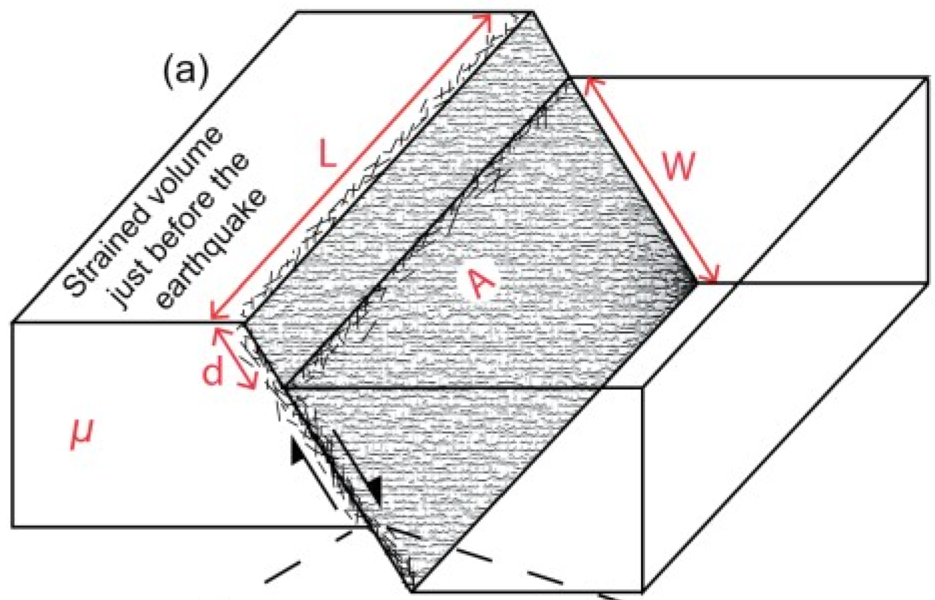


Earth quakes

- 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

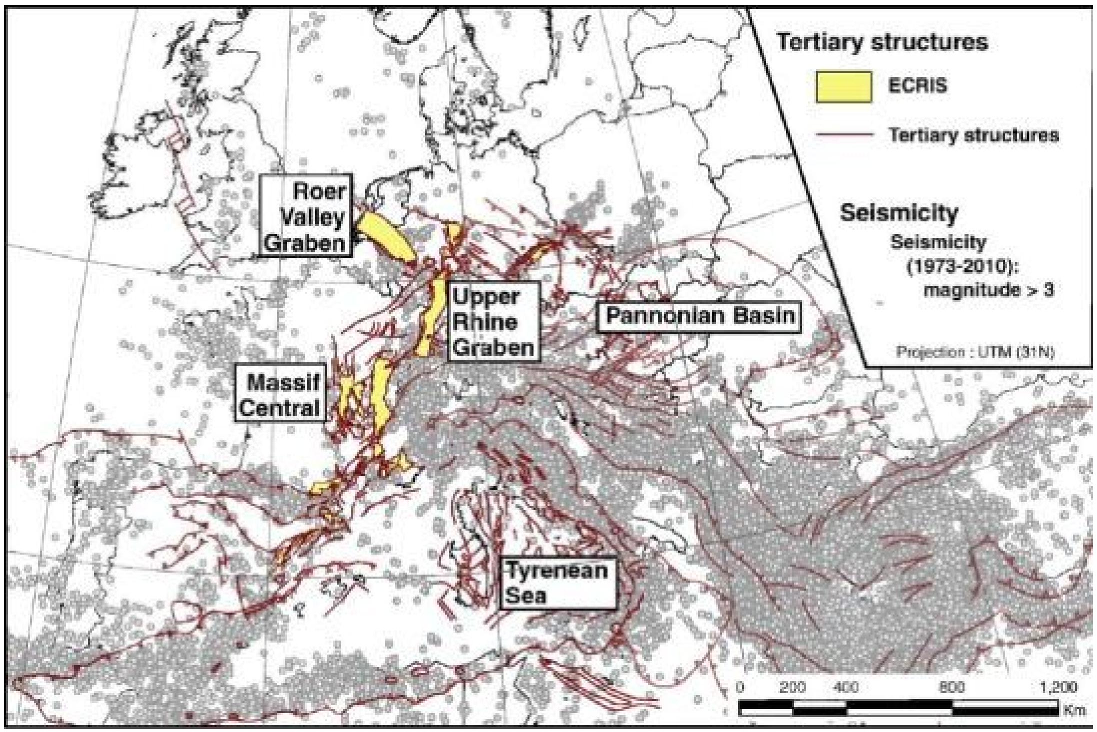


Cappa and Rutquist, 2011



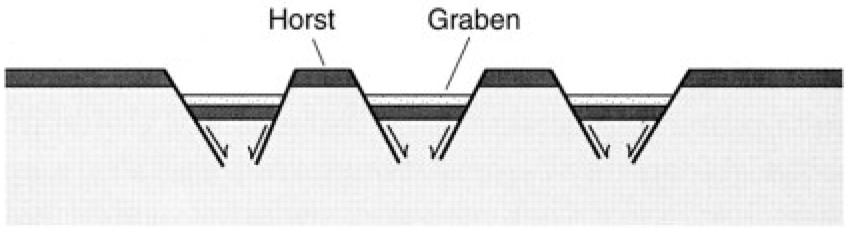
Baseline seismicity in the european central rift

- Extensional and strike slip setting



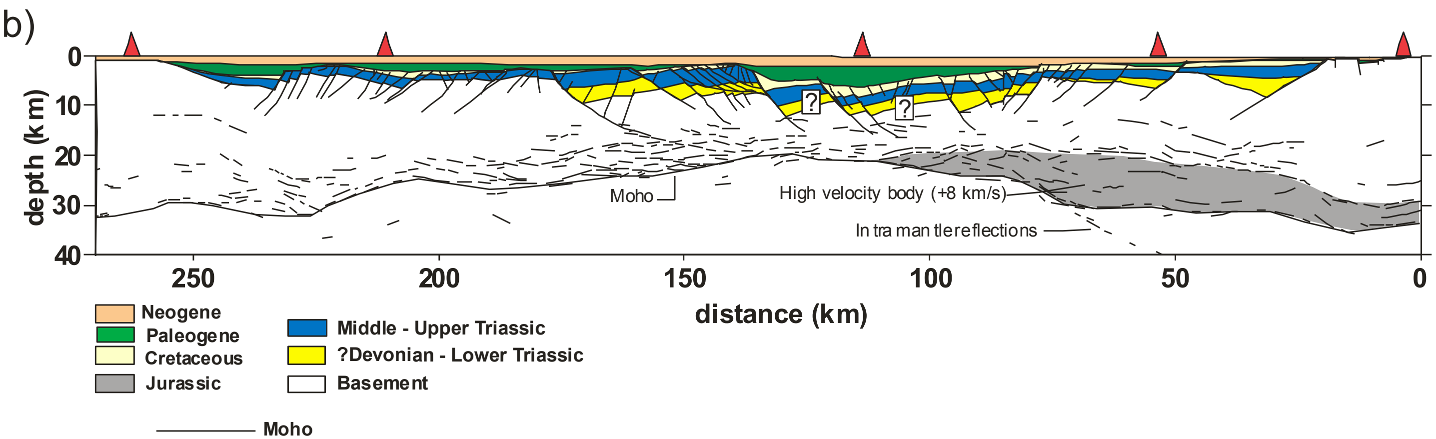
rate (depth dependency and spatial

FAULT SYSTEMS

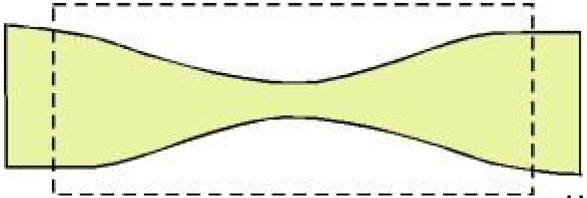


Assemblage of planar faults

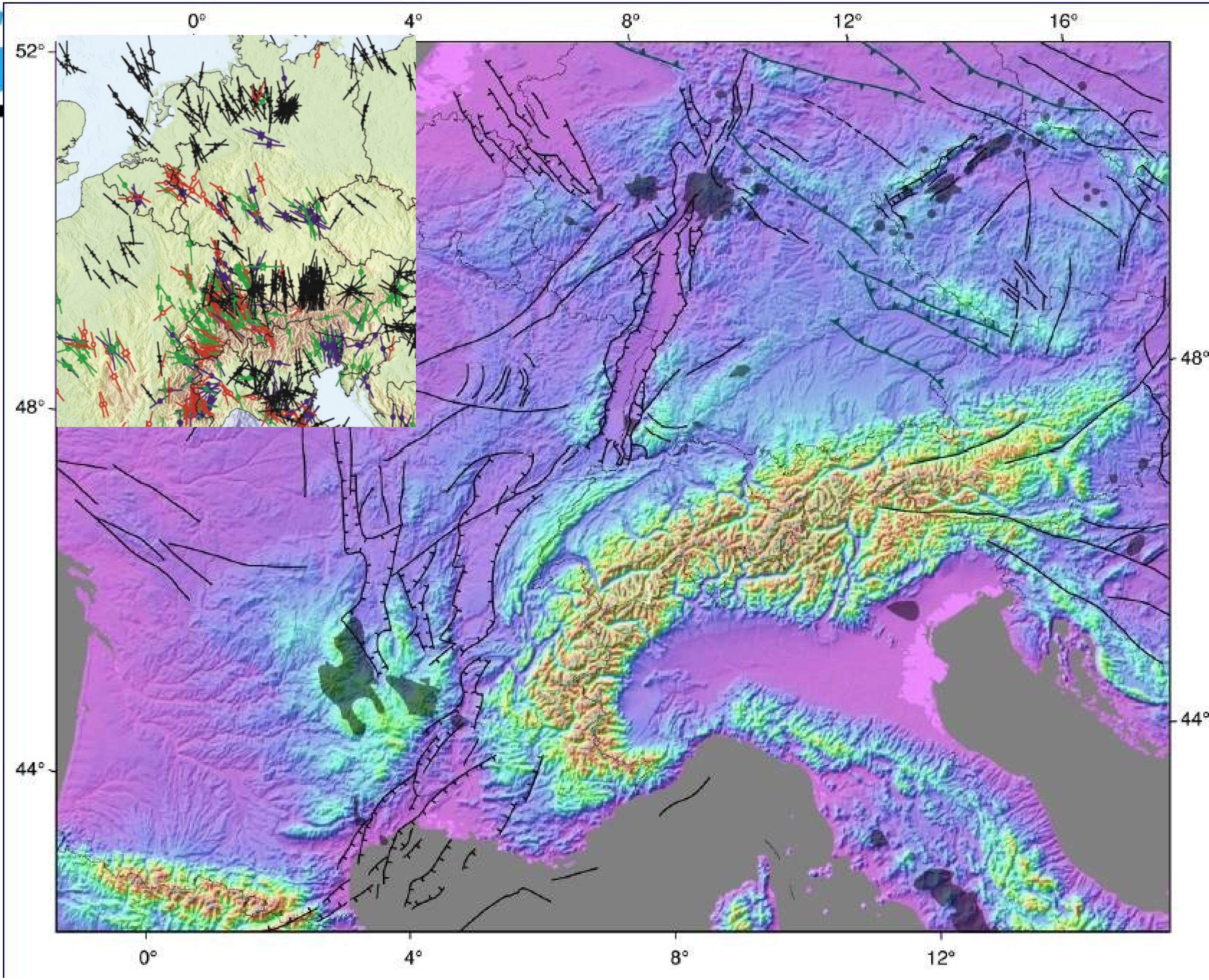
Assemblage of listric faults



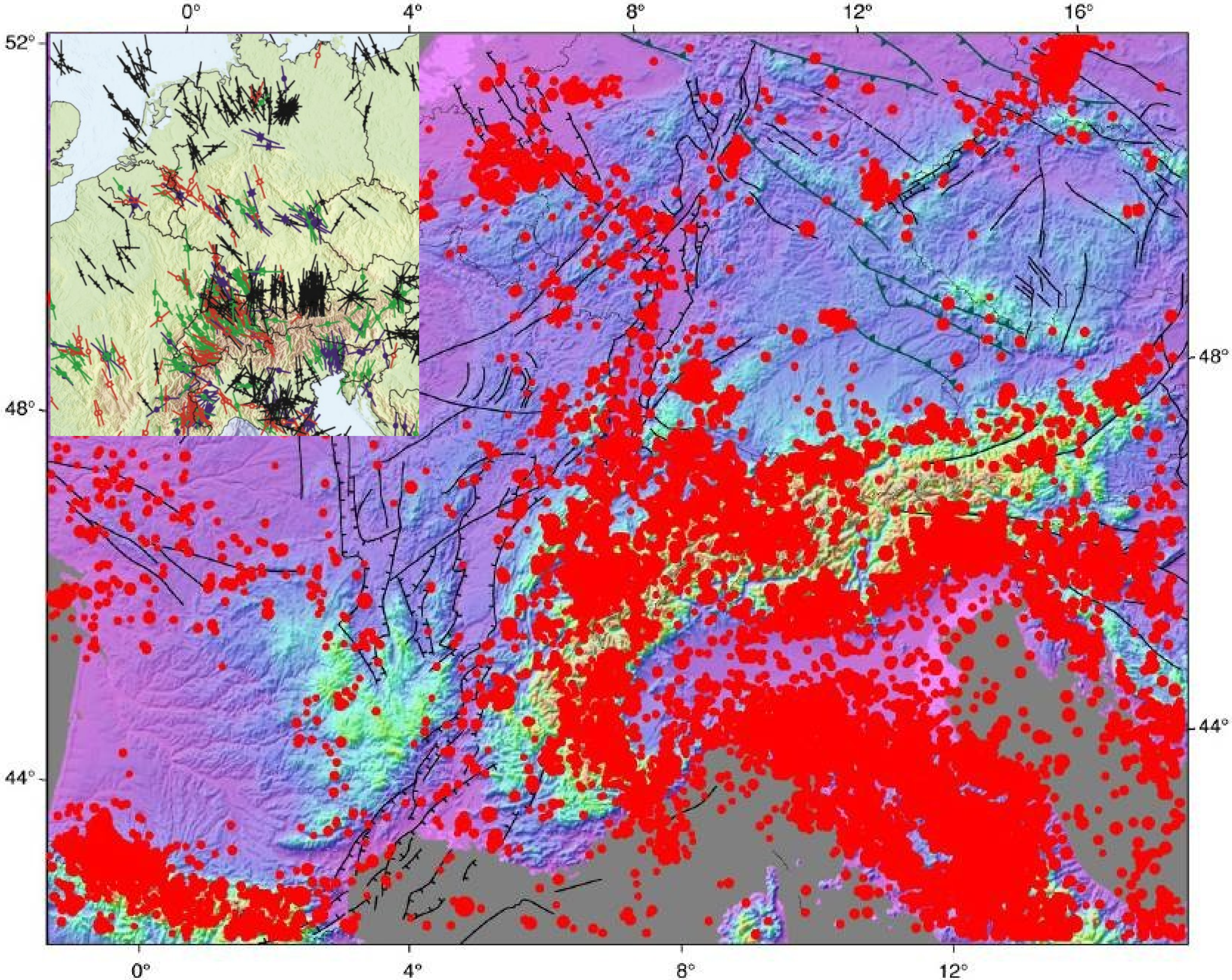
Note: these faults accommodate a **pure shear** **deformation (also called non rotational**



G FZ



Ziegler and Dezes, 2008



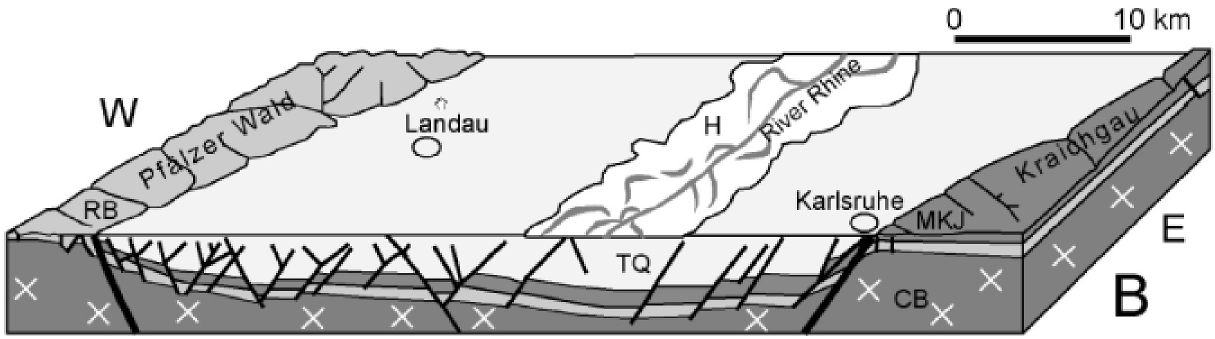
NOAA NEIC EPIC earthquake catalogue 1900 - 2003 (Mag > 3.0)

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

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

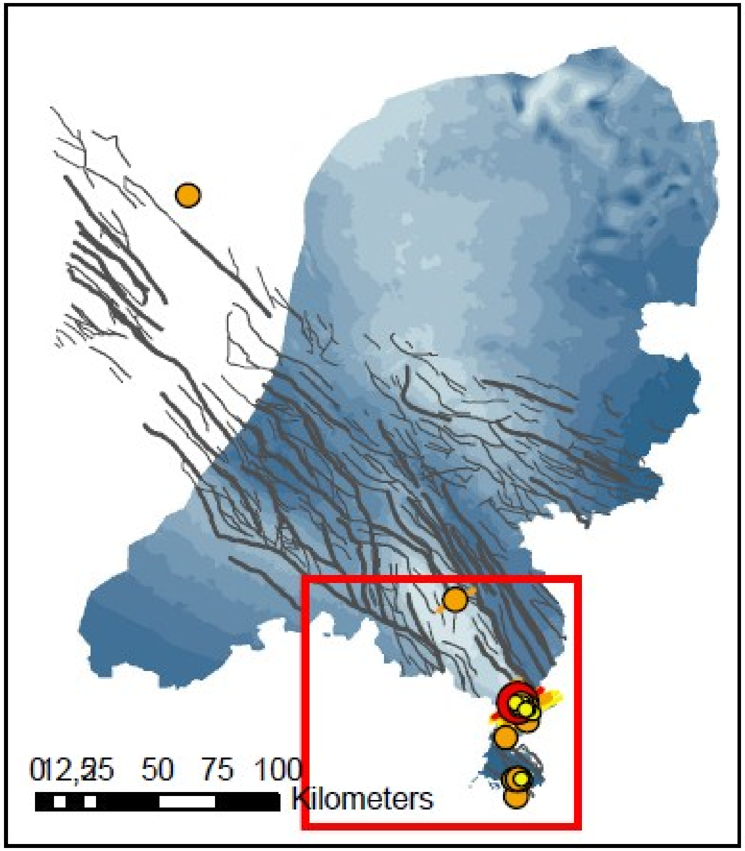
M=5, 15x5 km fault, 0.15m displacement

Big earth quakes
Located at
Mapped Major faults

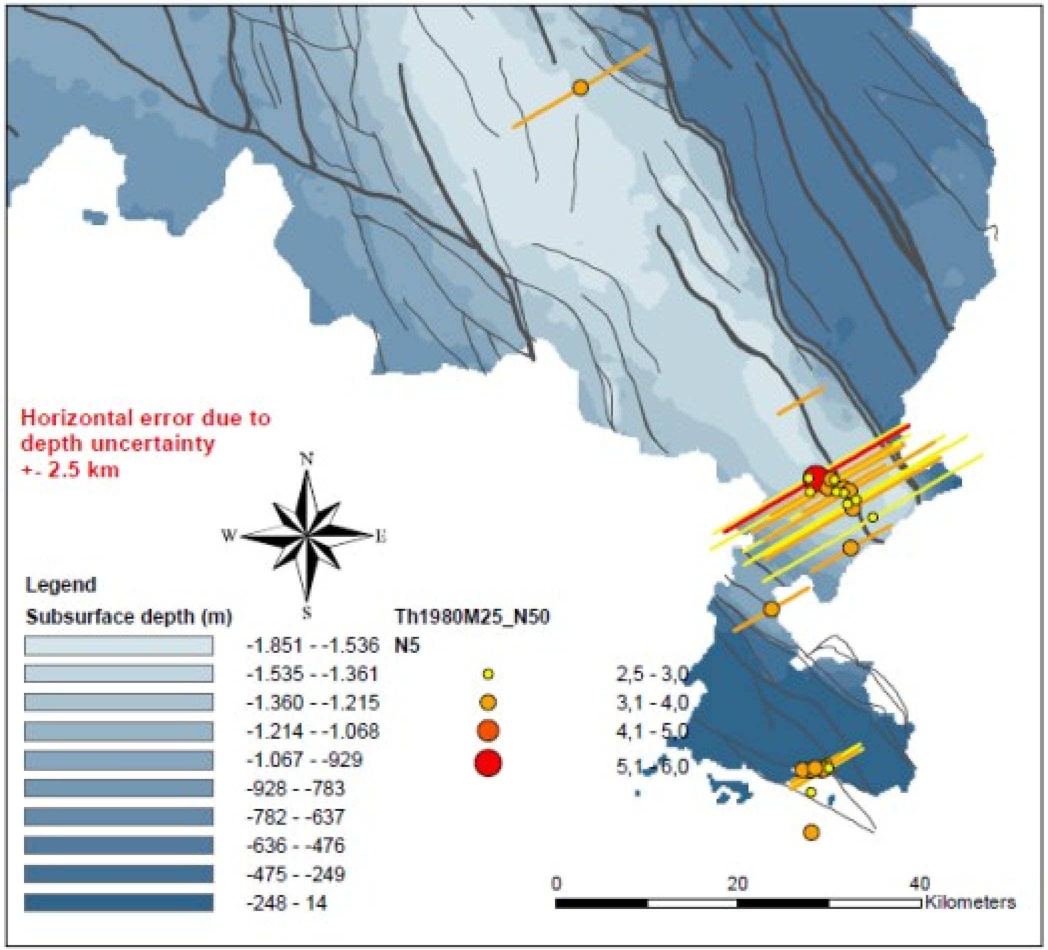


→ Lesson: stay away from seismically active faults

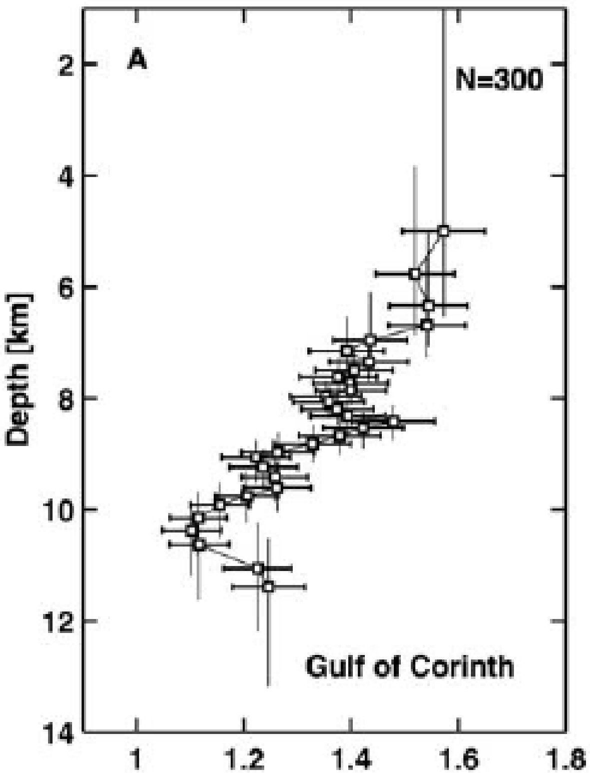
Can we identify M7-M5 faults prior to stimulation: most say yes - some say no



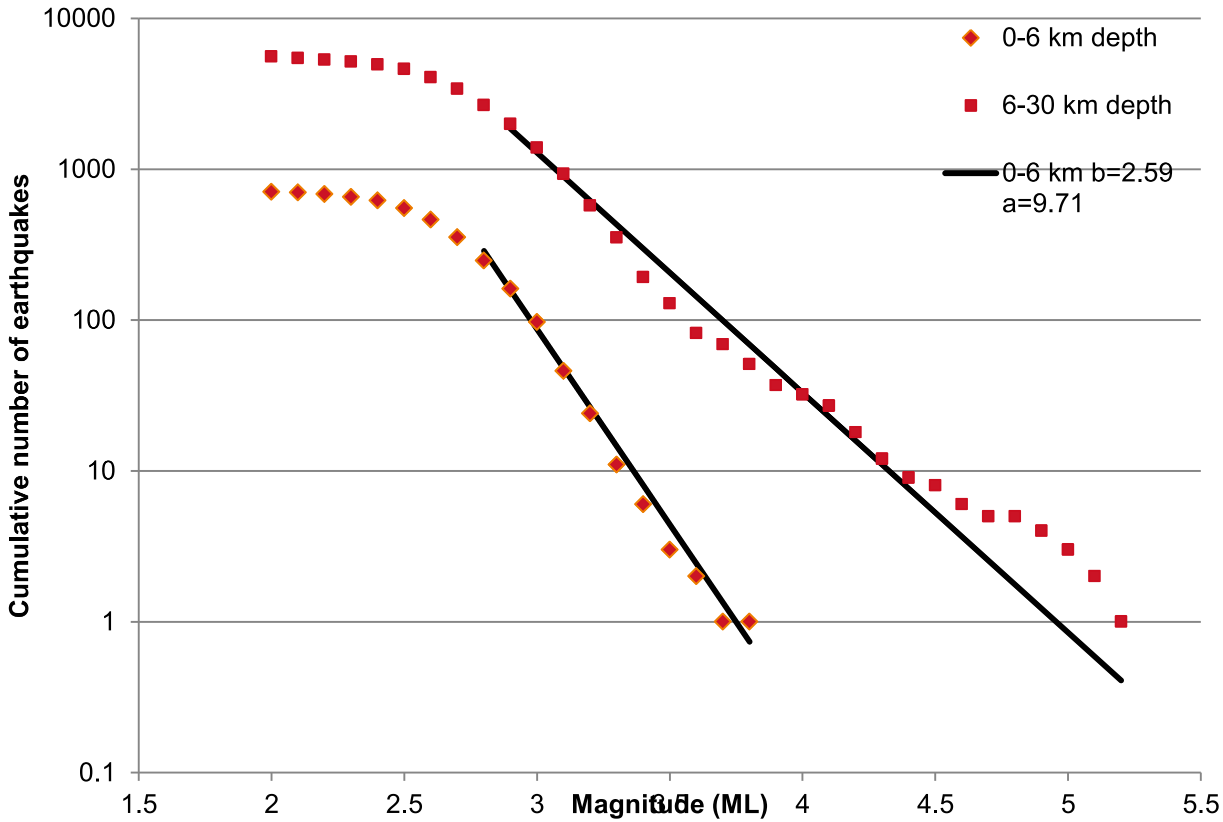
EQ after 1980



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



Wyss et al., 2008



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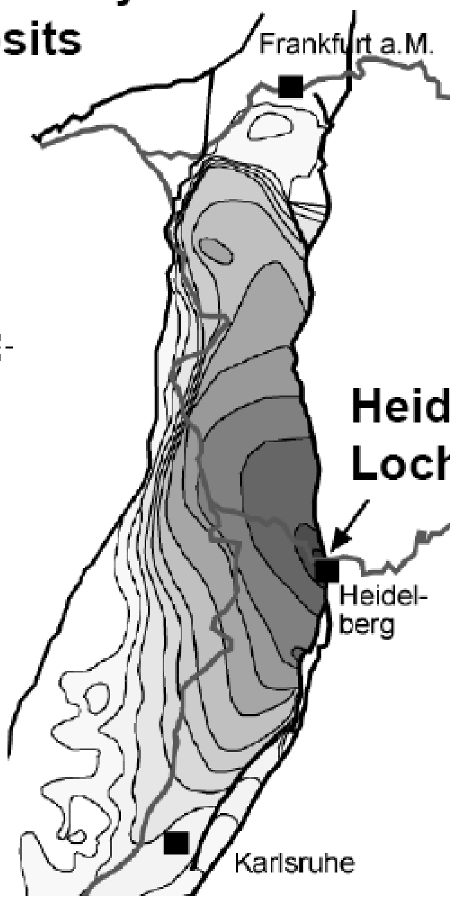
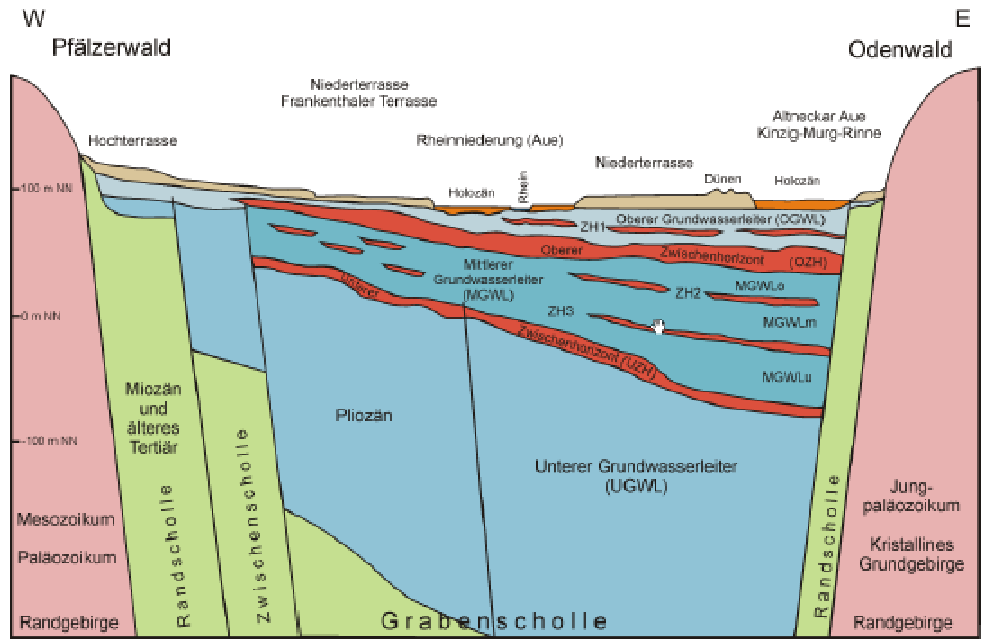
Peters and Van Balen, 2008

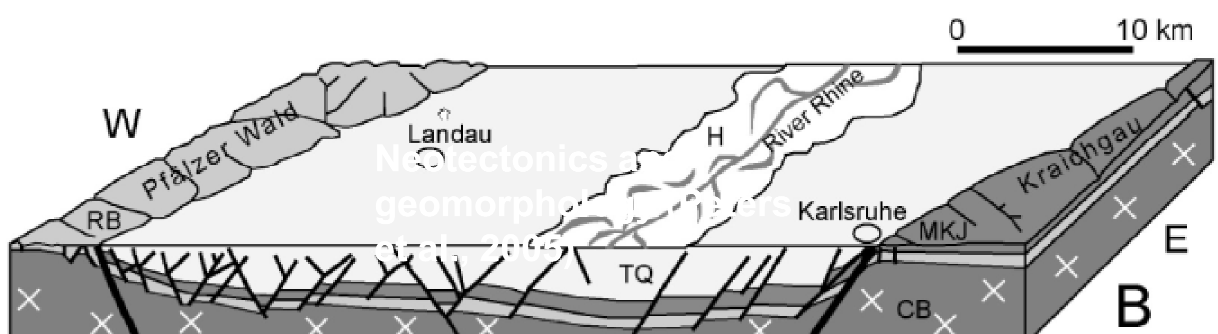
Asymmetry of the northern URG

Quaternary deposits



Heidelberger Loch

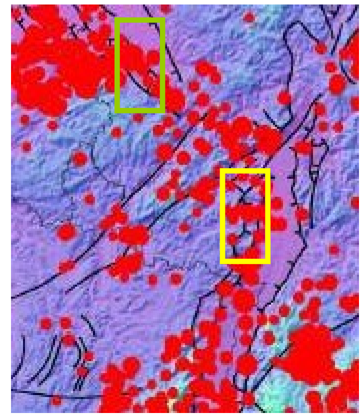




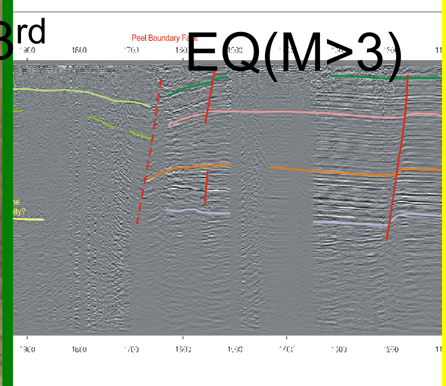
Strain at neotectonic timescales Trenching 10^4 years

Roer Valley Graben

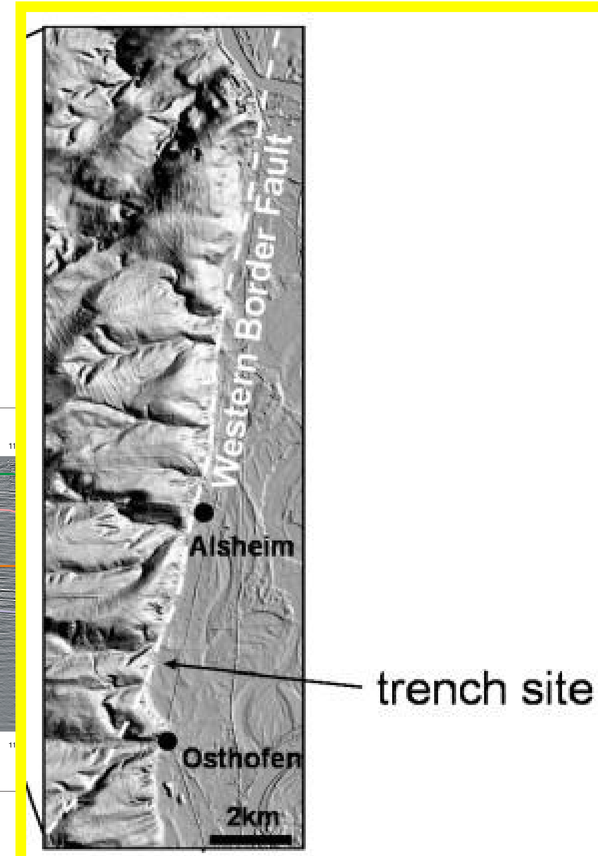
Houtgast et al., 2002



3rd EQ(M>3)



Upper Rhine Graben



Peters et al., 2005

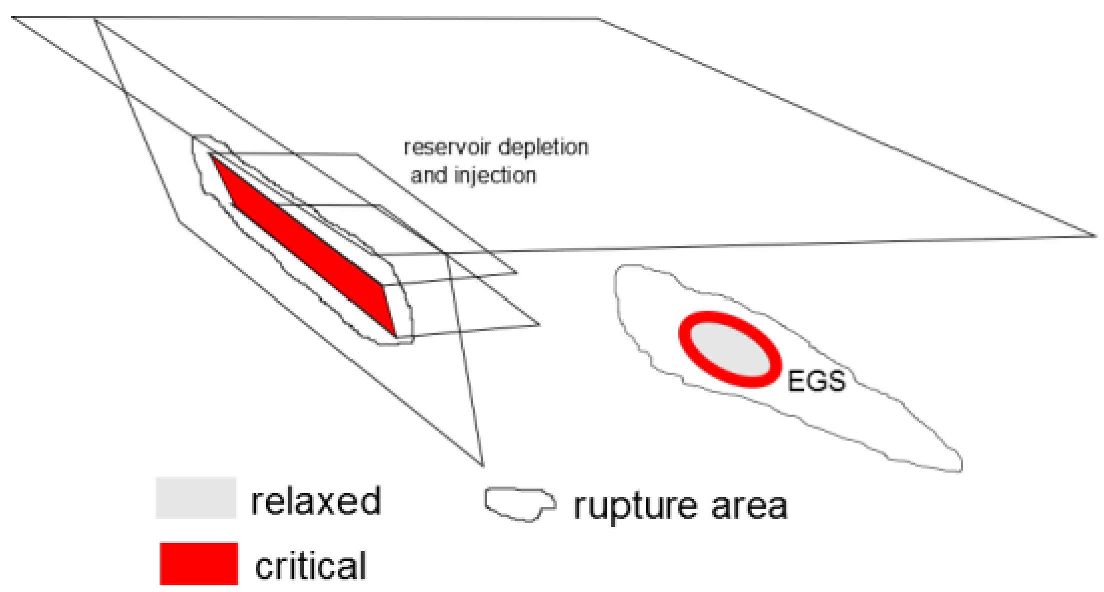
M =7 highly unlikely, it would require a rupture area of 70x10km and 1 meter slip

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

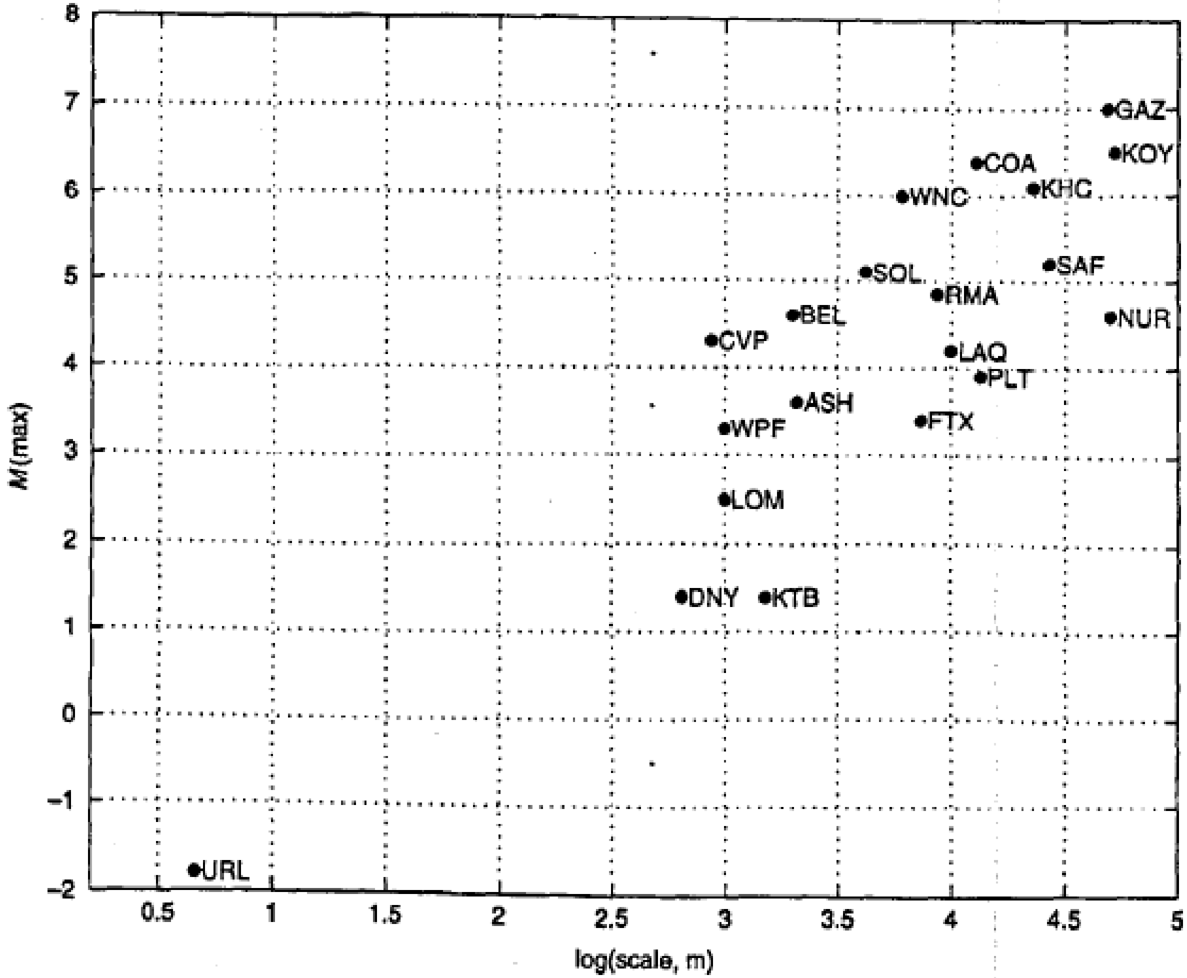


FIGURE 3 Maximum magnitude as a function of scale for 20 case histories. The scale is the maximum dimension of the causative activity as explained in the text. The letter identifications for the case histories, in the same order as they appear in the text, are: underground mining: SAF, deep gold mines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