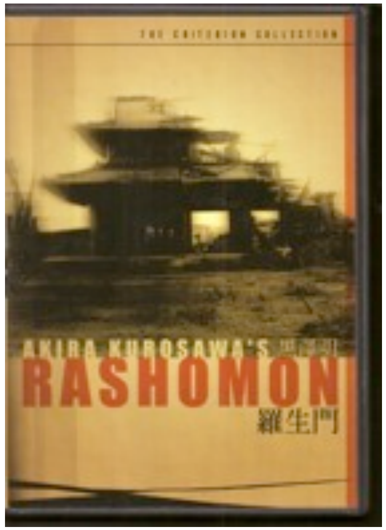
Crash Course in Probabilistic Seismic Hazard Analysis (PSHA)

Part 1

Frank Scherbaum

Content

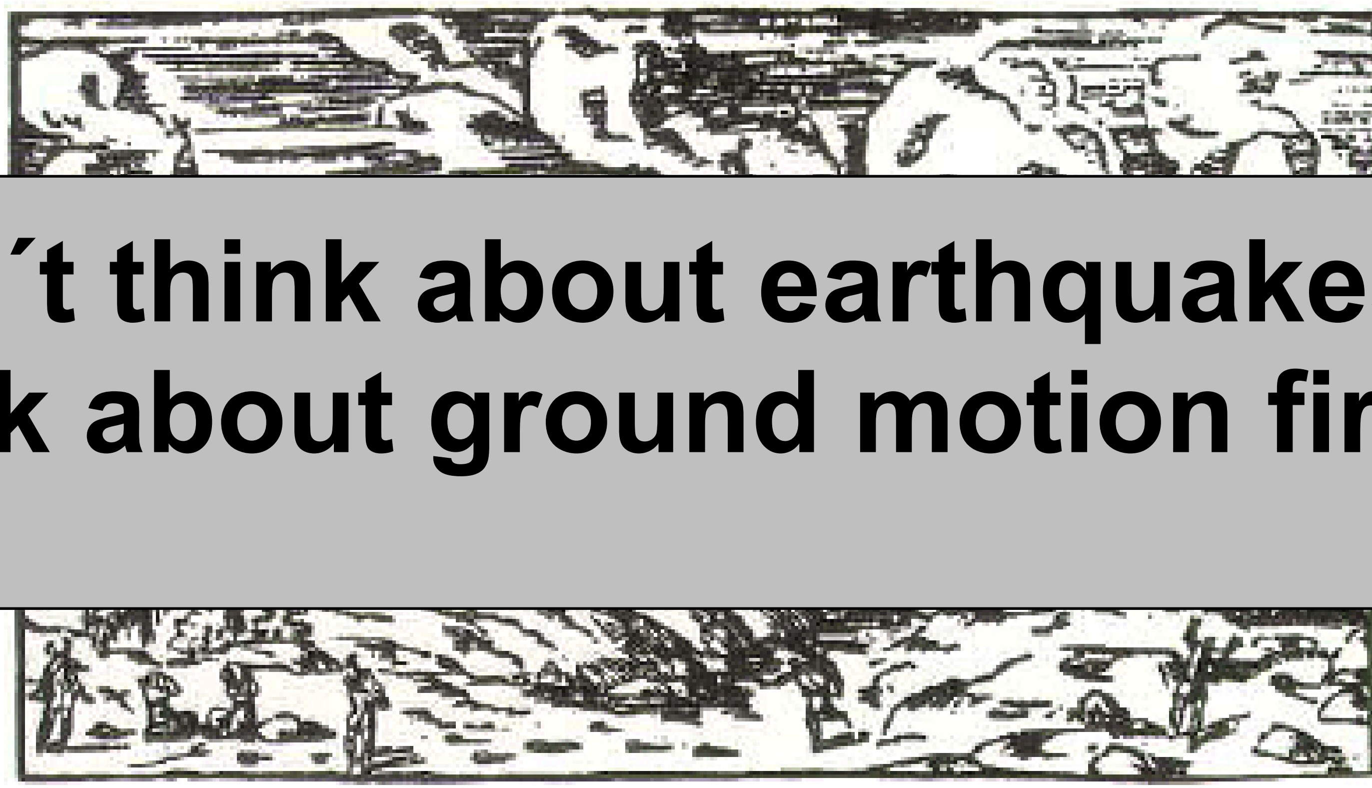


mathSHA

seismic hazard analysis using *Mathematica*

http://www.wolfram.com/products/player/

Seismic hazard is shaking hazard



Don´t think about earthquakes first, think about ground motion first!*

***)But don´t forget the earthquakes**

Key aspects of basic PSHA

PSHA provides models (PSHMs) for shaking hazard in terms of chosen ground motion intensity parameters

PSHMs are probabilistic in nature: ground motion is treated as a **random variable**

Questions that can be addressed with PSHMs are e.g.

- What is the ground motion which is expected to be exceeded with a particular probability at a particular site within a particular time interval?
- What is the probability for a particular ground motion value to be exceeded at a given site of interest within a particular time interval?

PSHA in a nutshell

Modern PSHA deals with probabilistic models for seismically generated ground motion. It combines concepts and methods from seismology, earthquake engineering, and probability theory.

For critical facilities, modern PSHA includes also a systematic assessment of (epistemic) uncertainties.

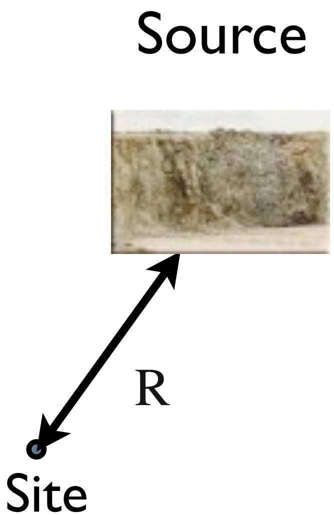
Focus here: **Conceptual understanding**

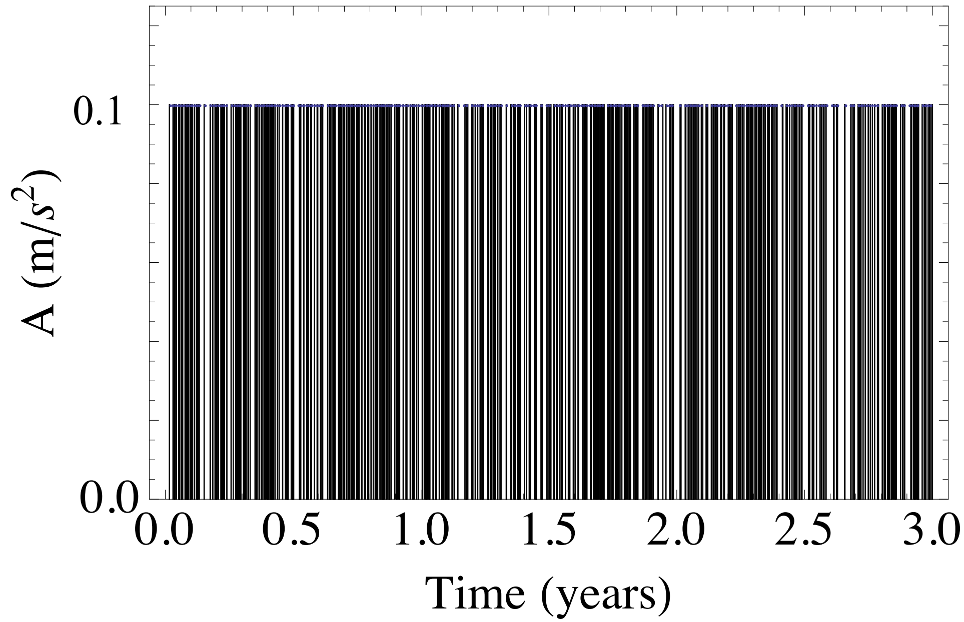
Don´t be afraid to do simple things

\- R. Adams

Single idealized source

$a_i = 0.1 m/s^2$ (for all i)





$\lambda = average\#events/year$ = 200

Exercise 1: What is the expected daily rate at which certain ground motion levels are reached or exceeded?

Exceedance rate & excedance probability

Rate: How often in absolute sense (per chosen time interval)

Probability: How often in relative sense (e. g. in comparizon to a large number of similar cases)

Examples:

How many heads in 500 trials?

$500 \cdot 0.5 = 250$

How many 4s in 600 trials?

$600 \cdot \frac{1}{6} = 100$

Expected number: $\#\,\text{trials} \cdot \text{prob(single event)}$

Single idealized source

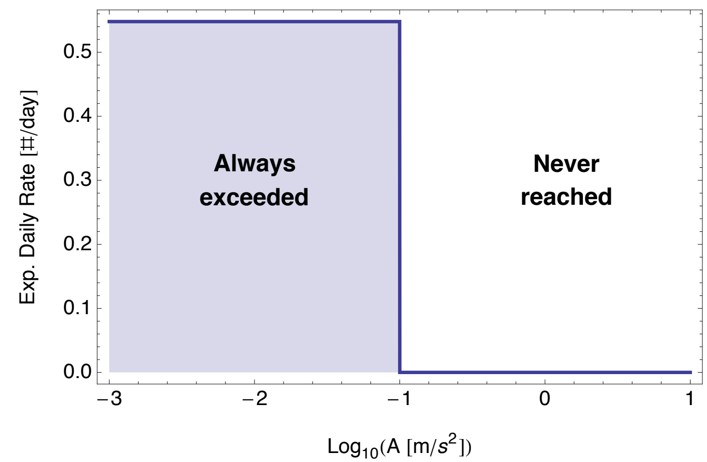
$\lambda = average\#events/year$ = 200 $a_i = 0.1 m/s^2$ (for all i)

What is the expected daily rate at which certain ground motion levels are reached or exceeded?

Expected daily rate of occurrence of blasts is: # blasts/day = 200/365 = 0.55

Each of them generates $0.1 m/s^2$

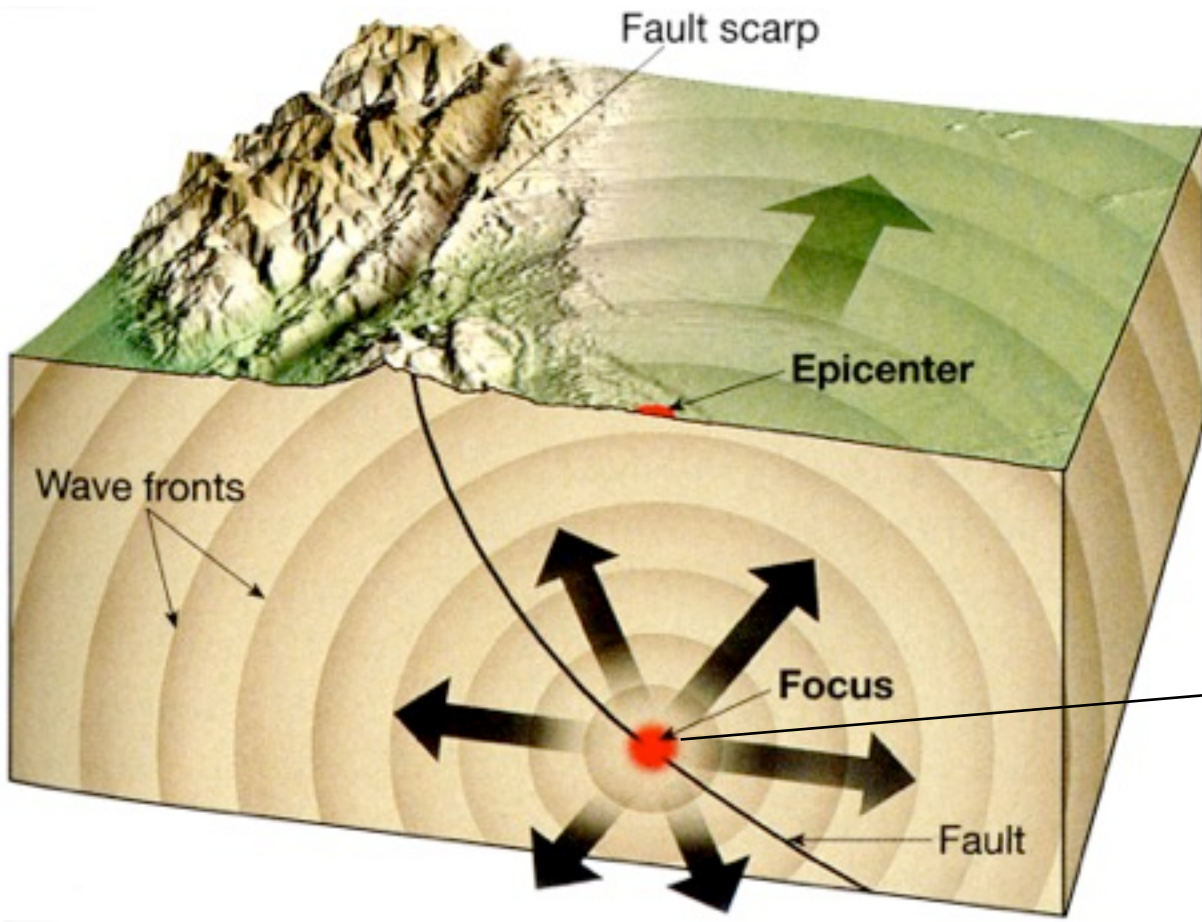
$$P(\text{a is reached or exceeded}) = 1 \ (\text{for all a} \leq 0.1\text{m/s}^2)$$
$$= 0 \ (\text{for all a} > 0.1\text{m/s}^2)$$



$$\text{ExpDailyRate} = 0.55 \cdot 1 = 0.55 \ (\text{for all a} \leq 0.1\text{m/s}^2)$$
$$= 0.55 \cdot 0 = 0 \ (\text{for all a} > 0.1\text{m/s}^2)$$

Single earthquake source

What happens during an earthquake?

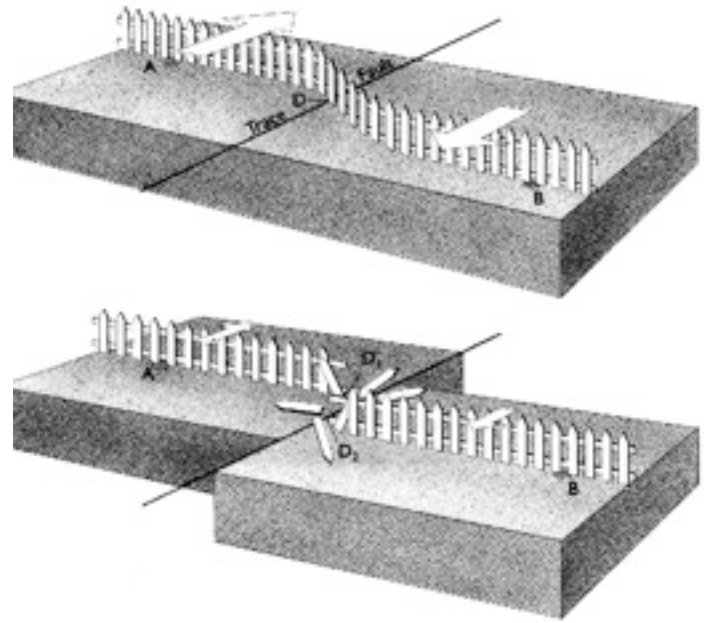


Hypocenter

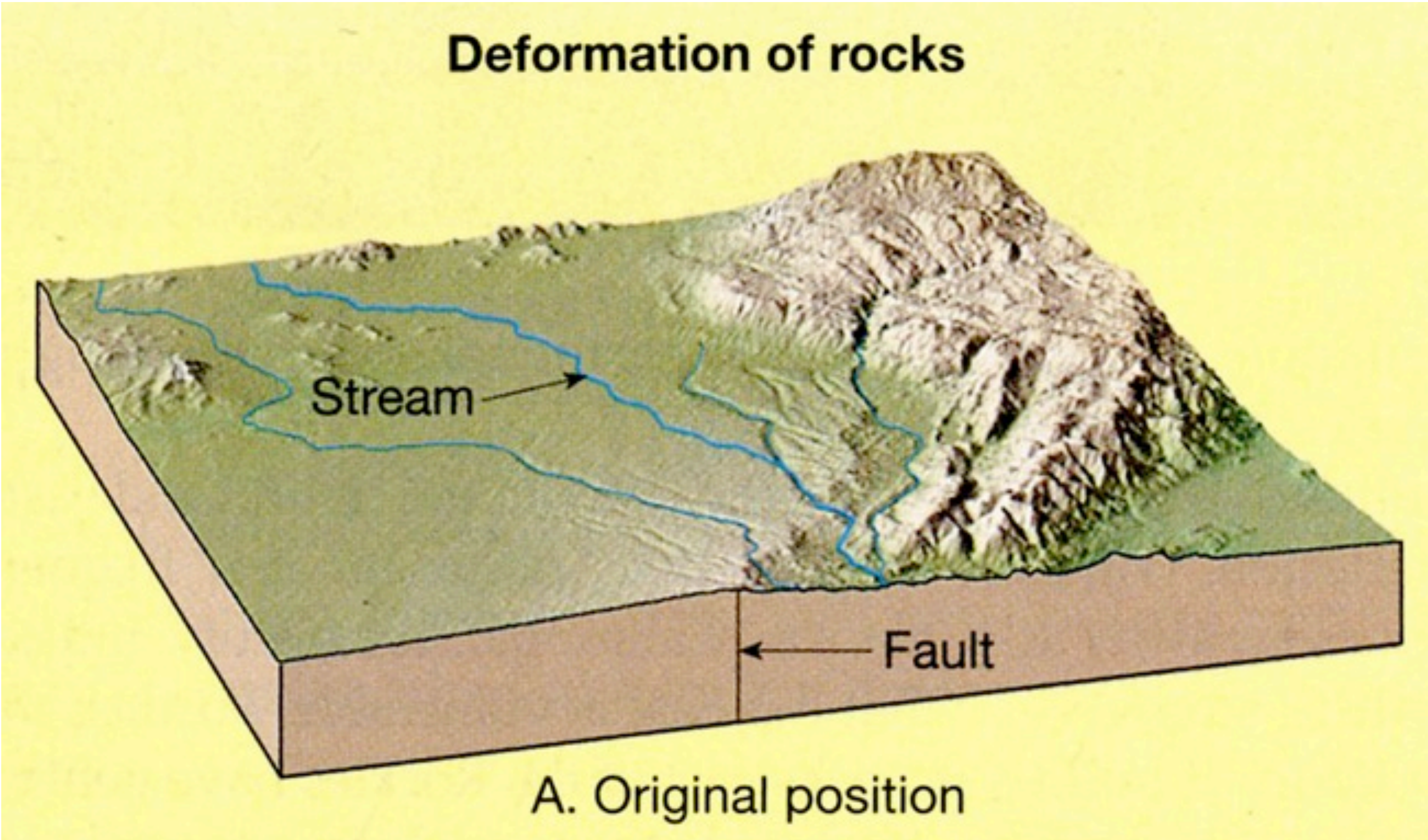
From myths to models

San Francisco earthquake, 18. of April 1906

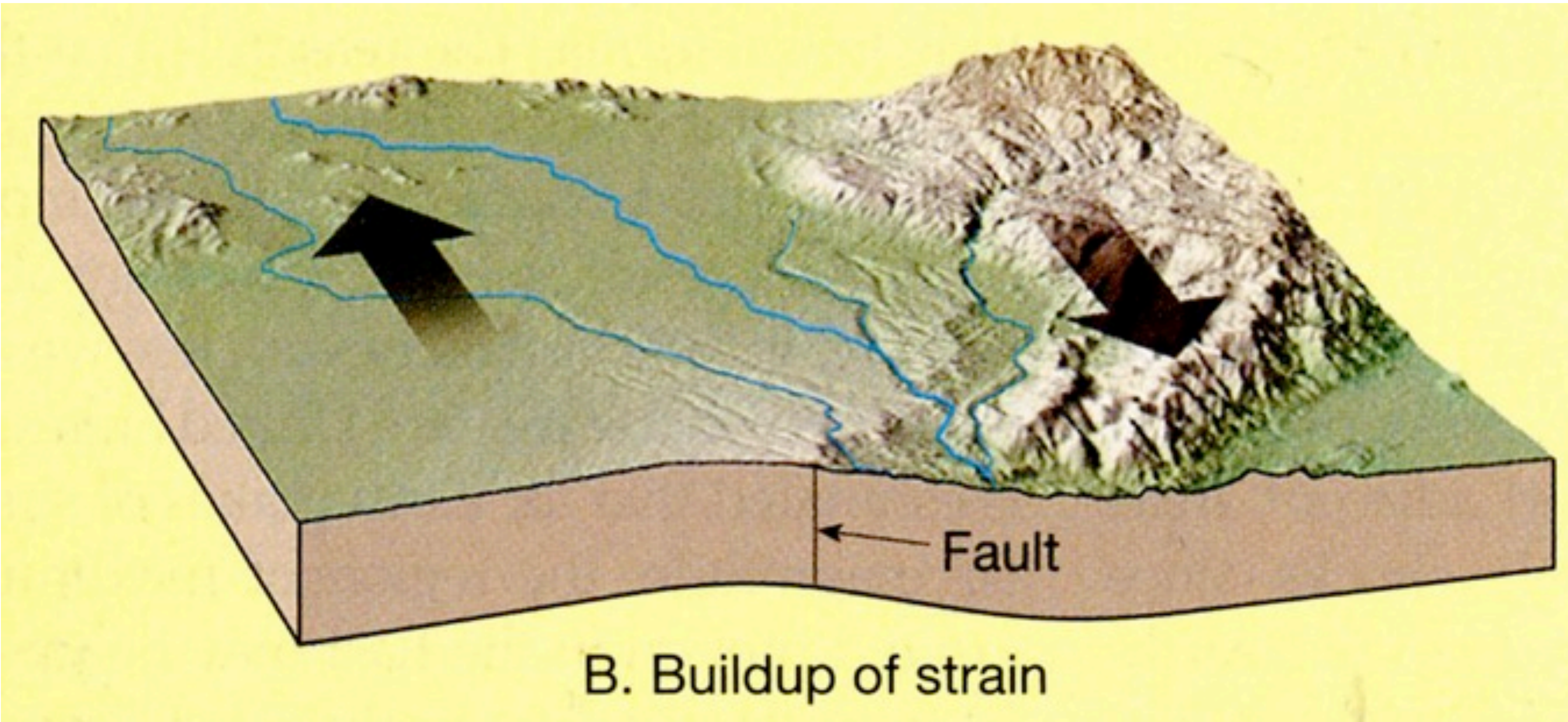
From a shifted fence to the rebound hypothesis



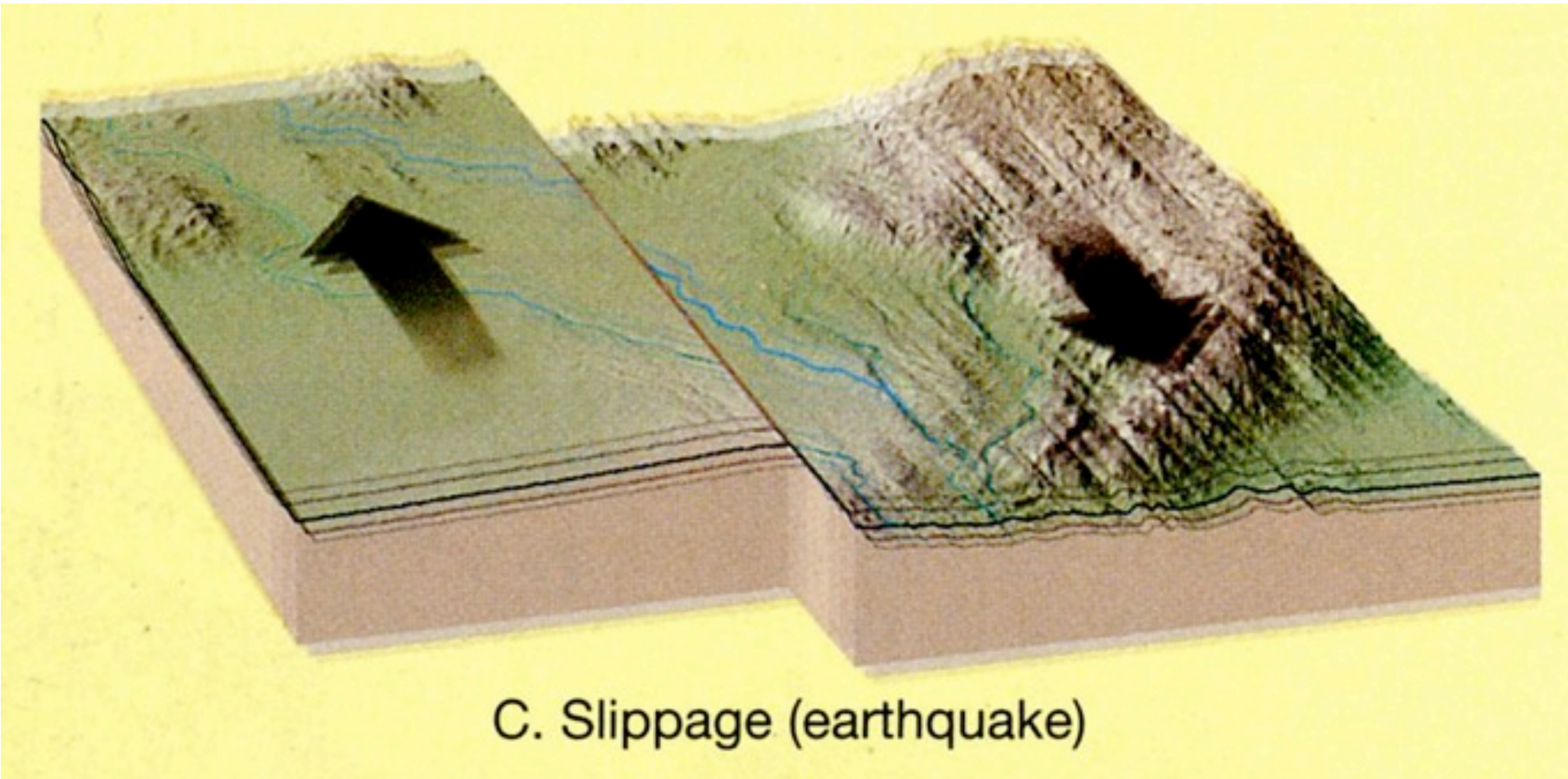
Principle of the rebound hypothesis



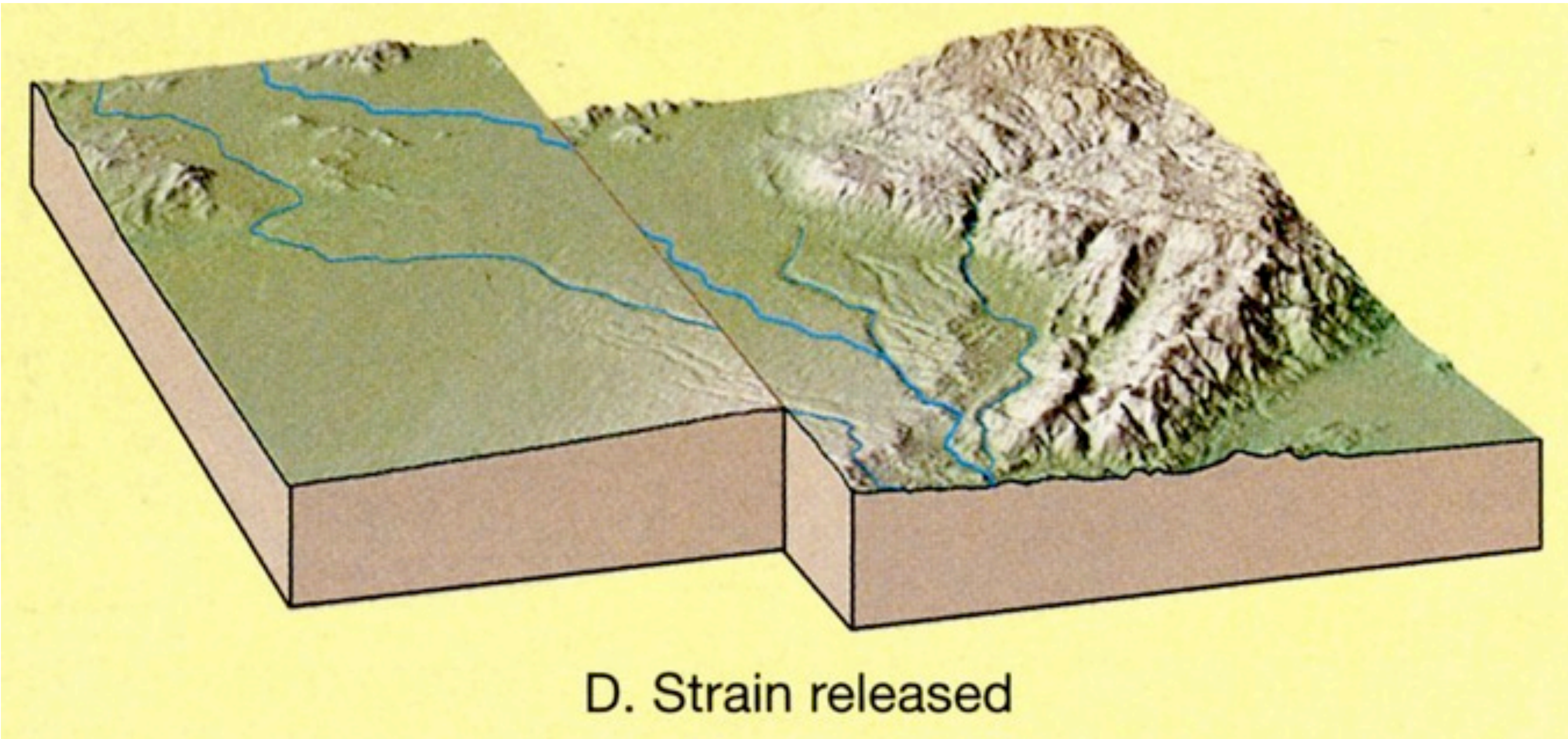
Principle of the rebound hypothesis



Principle of the rebound hypothesis

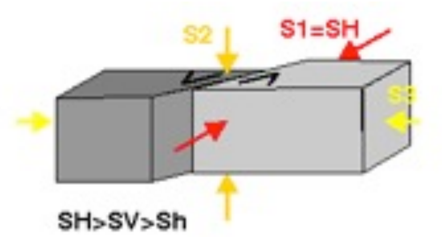


Principle of the rebound hypothesis

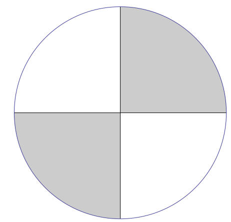


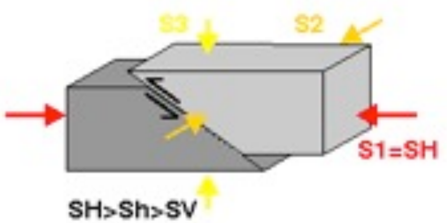
Slip is not only horizontal

Focal mechanism

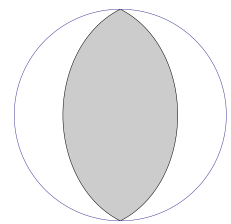


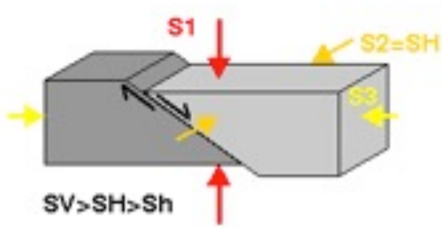
Strike slip



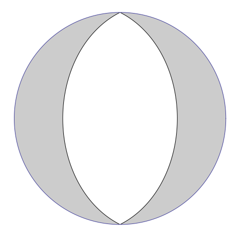


Reverse



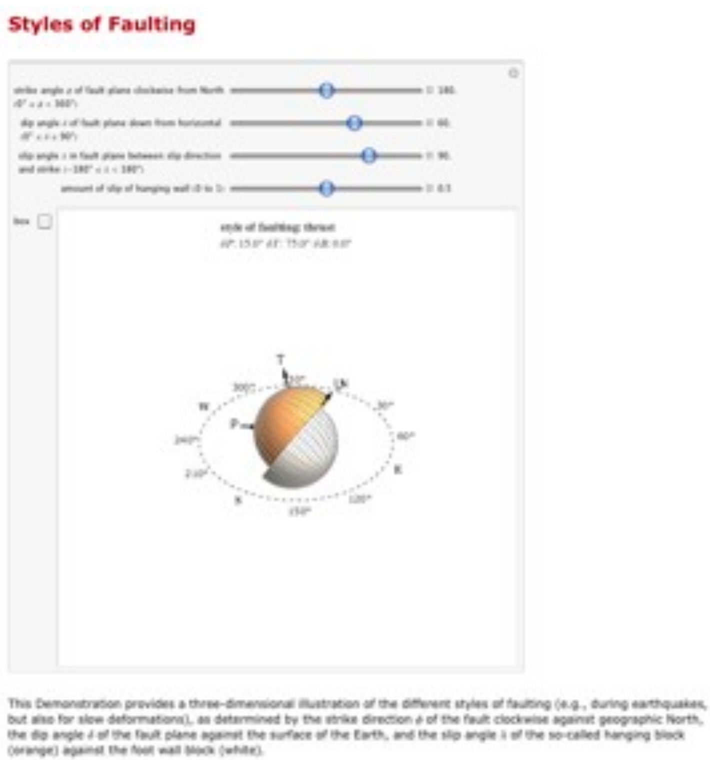


Normal

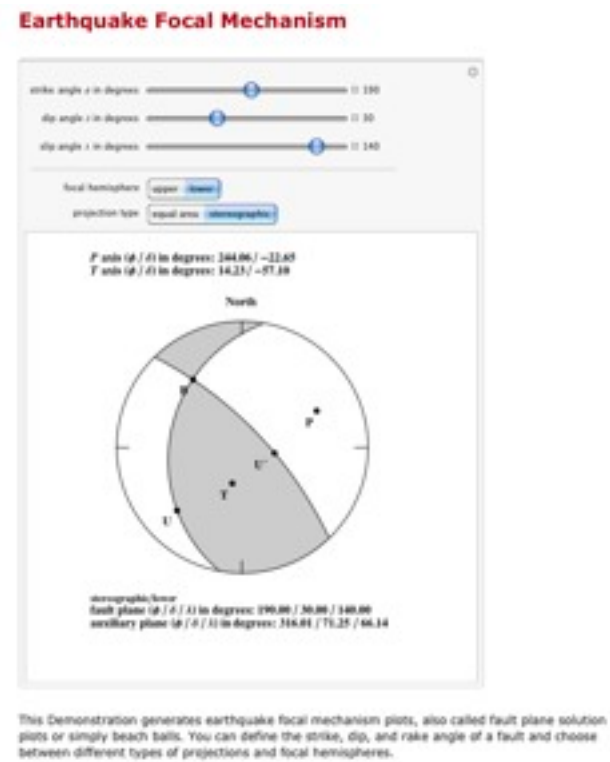


Exercise

StylesOfFaulting.cdf

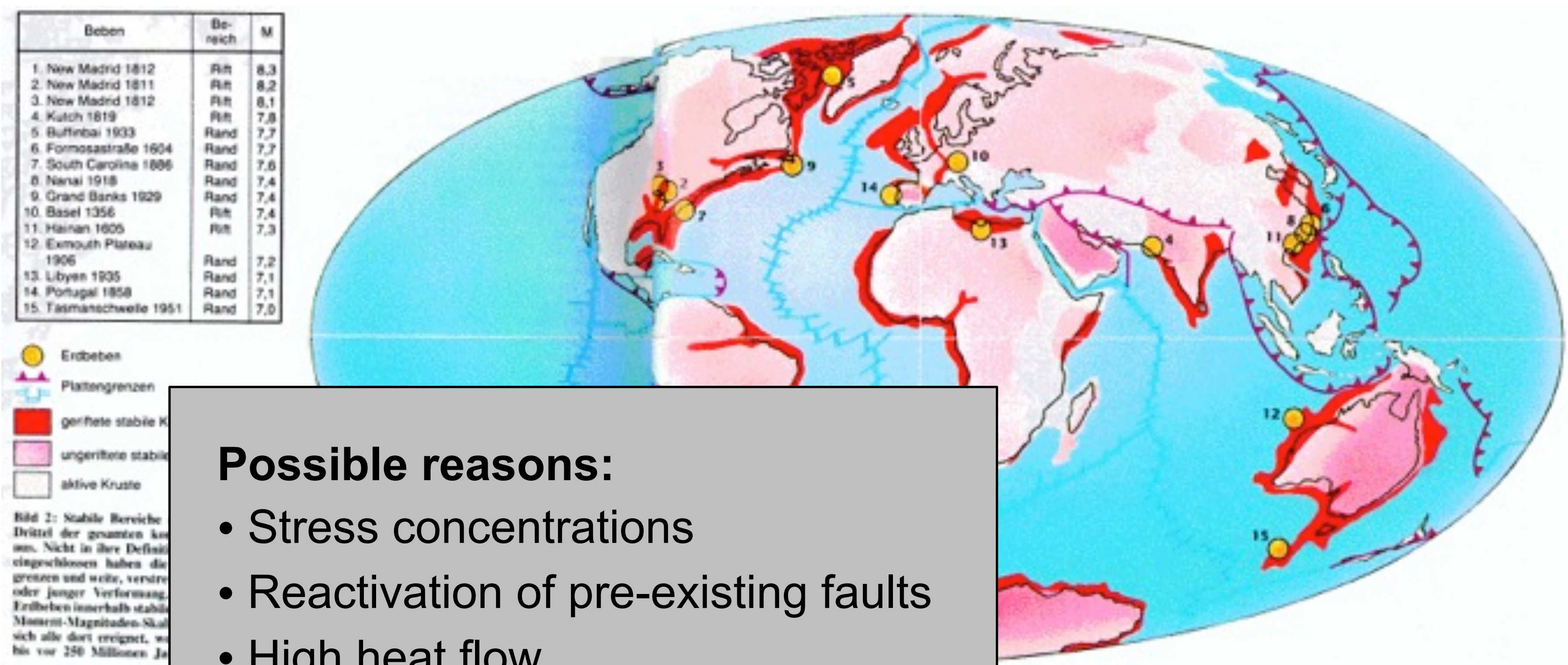


EarthquakeFocalMechanism.cdf



a) What is the style of faulting of an earthquake in which the fault strikes with an angle of 60 degrees NE, dips with 55 degrees to the SE and in which the hanging wall slips at an angle of 45 degrees (counterclockwise against the horizontal in strike direction)?
b) Generate the focal mechanism and discuss the different sections.

Intraplate earthquakes



Beben	Bereich	M
1. New Madrid 1812	Rift	8,3
2. New Madrid 1811	Rift	8,2
3. New Madrid 1812	Rift	8,1
4. Kutch 1819	Rift	7,8
5. Buffinbai 1933	Rand	7,7
6. Formosastraße 1604	Rand	7,7
7. South Carolina 1886	Rand	7,6
8. Nanai 1918	Rand	7,4
9. Grand Banks 1929	Rand	7,4
10. Basel 1356	Rift	7,4
11. Hainan 1605	Rift	7,3
12. Exmouth Plateau 1906	Rand	7,2
13. Libyen 1935	Rand	7,1
14. Portugal 1858	Rand	7,1
15. Tasmanschwelle 1951	Rand	7,0

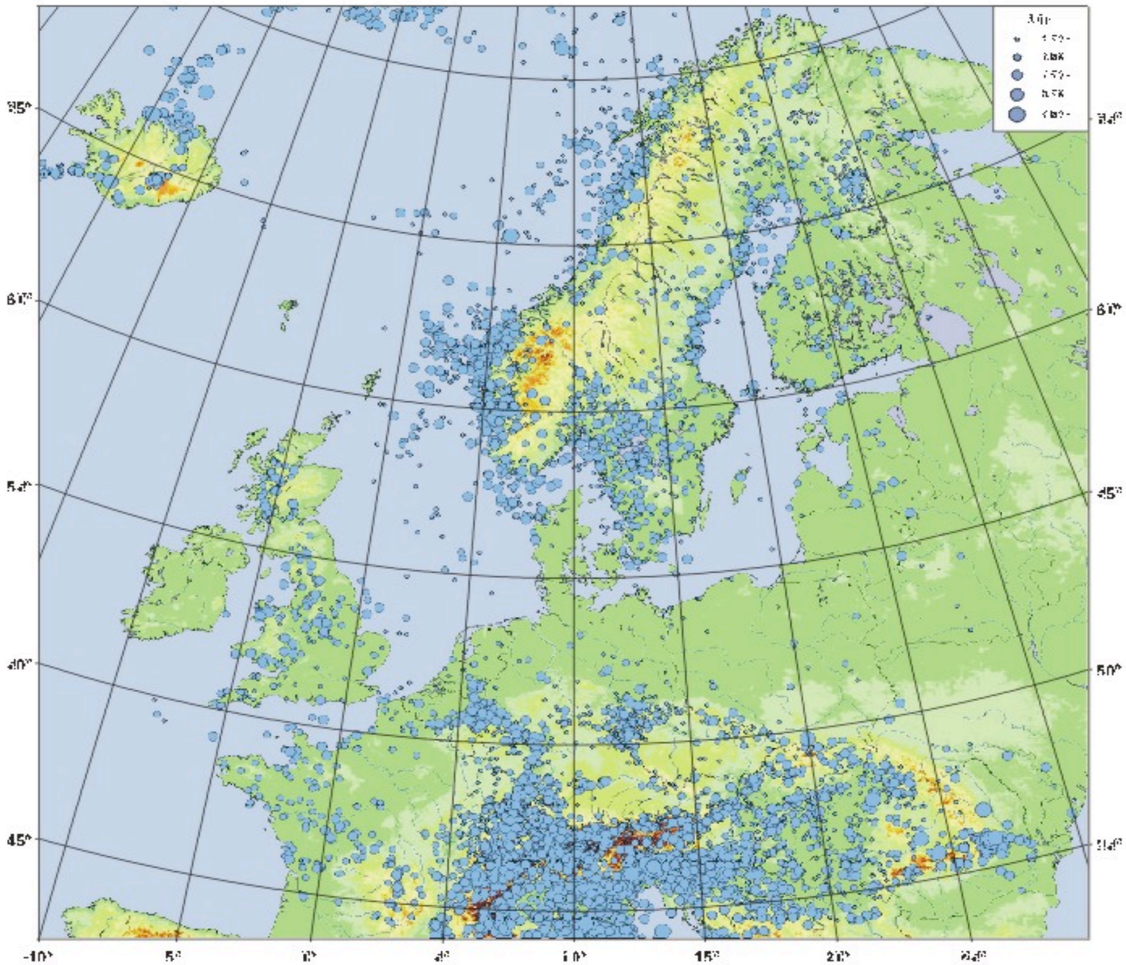
Possible reasons:

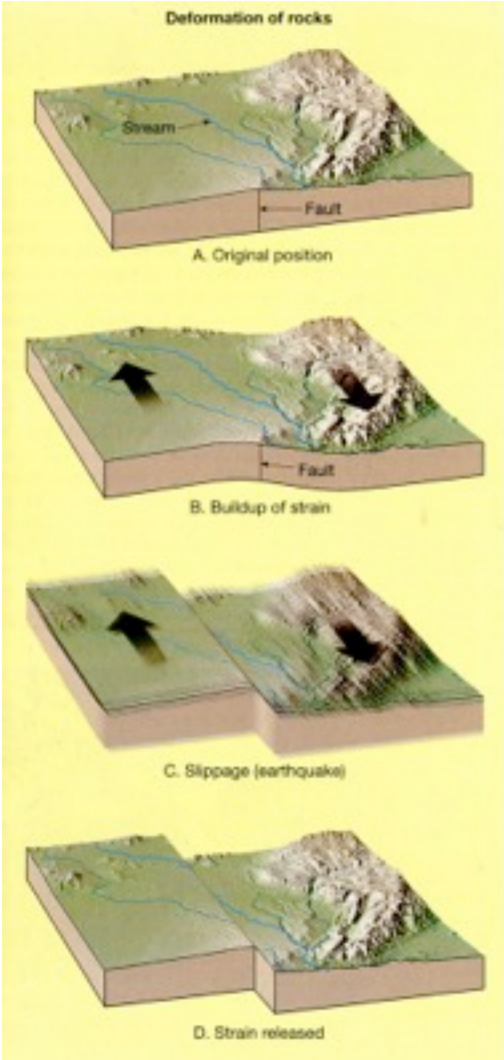
- Stress concentrations
- Reactivation of pre-existing faults
- High heat flow

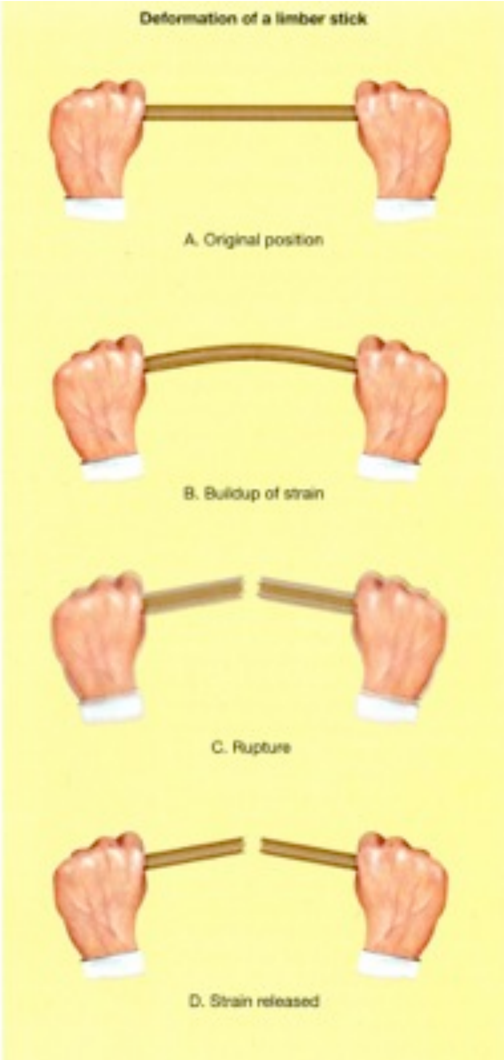
....

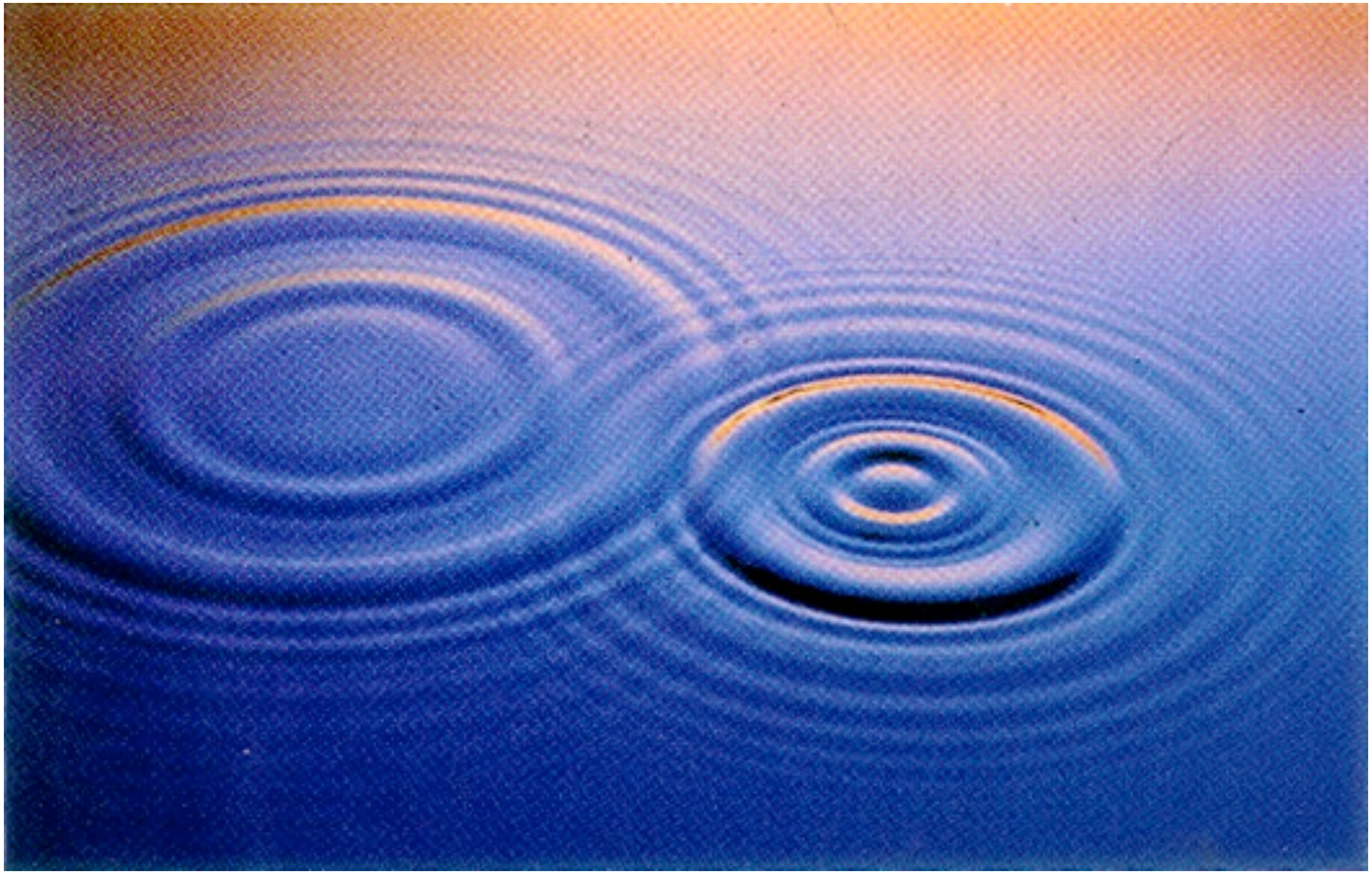
Frank Scherbaum

Seismicity in Europe



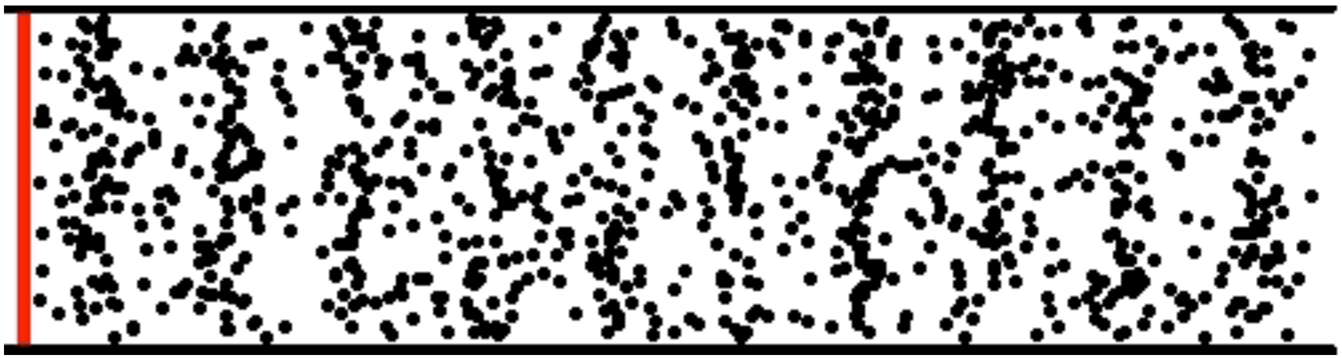

Deformation of rocks
Stream
Fault
A. Original position
Fault
B. Buildup of strain
C. Slippage (earthquake)
D. Strain released


Deformation of a limber stick
A. Original position
B. Buildup of strain
C. Rupture
D. Strain released

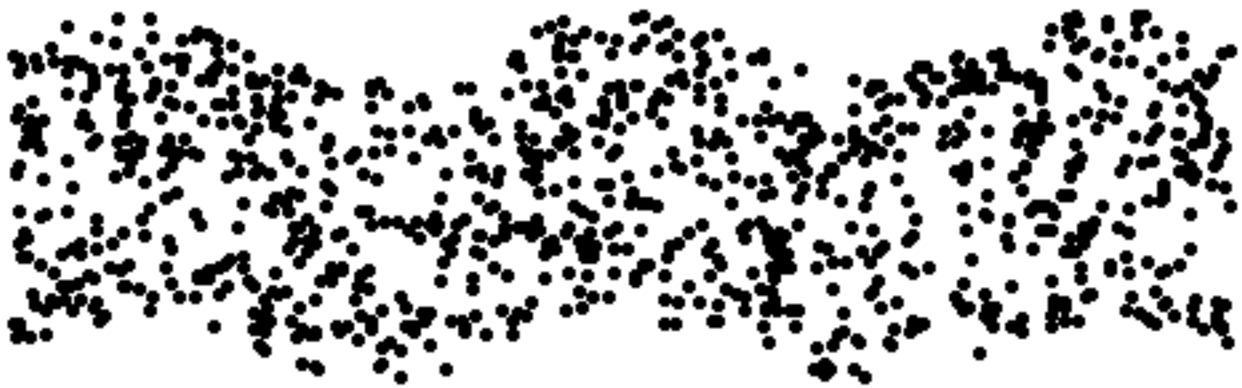


(E. Hecht, 1994)

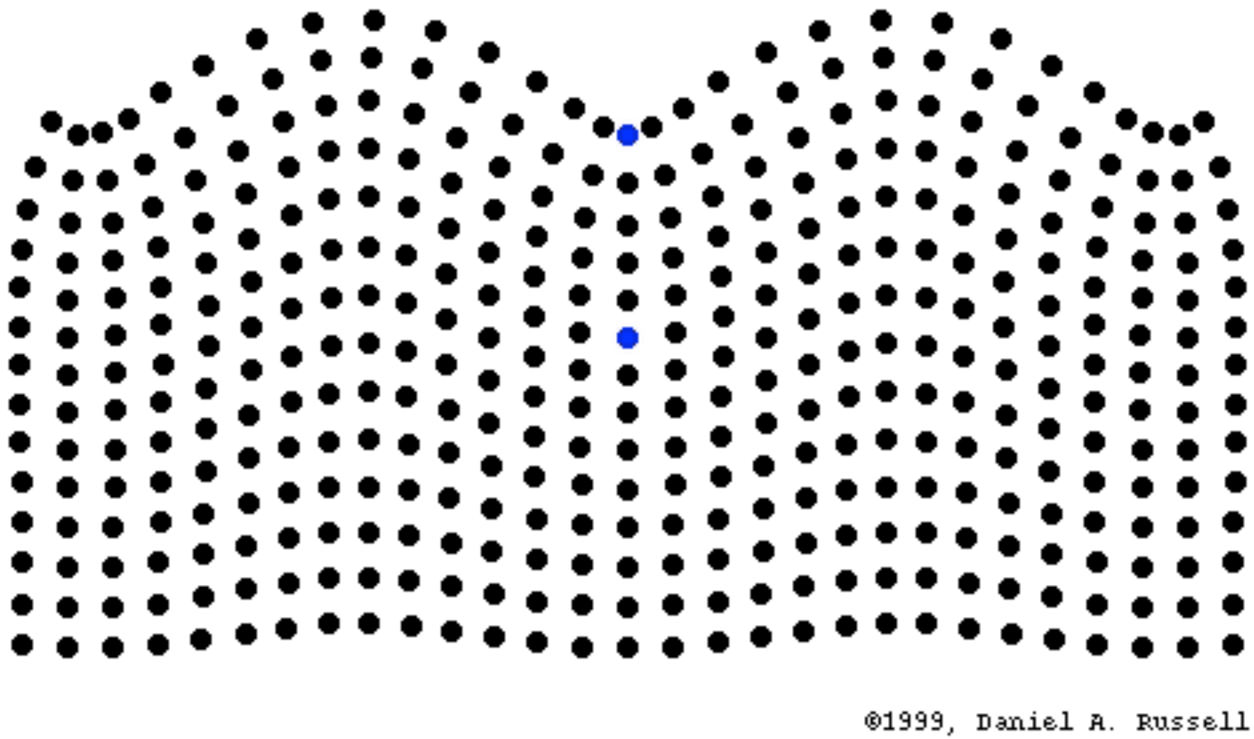
P wave



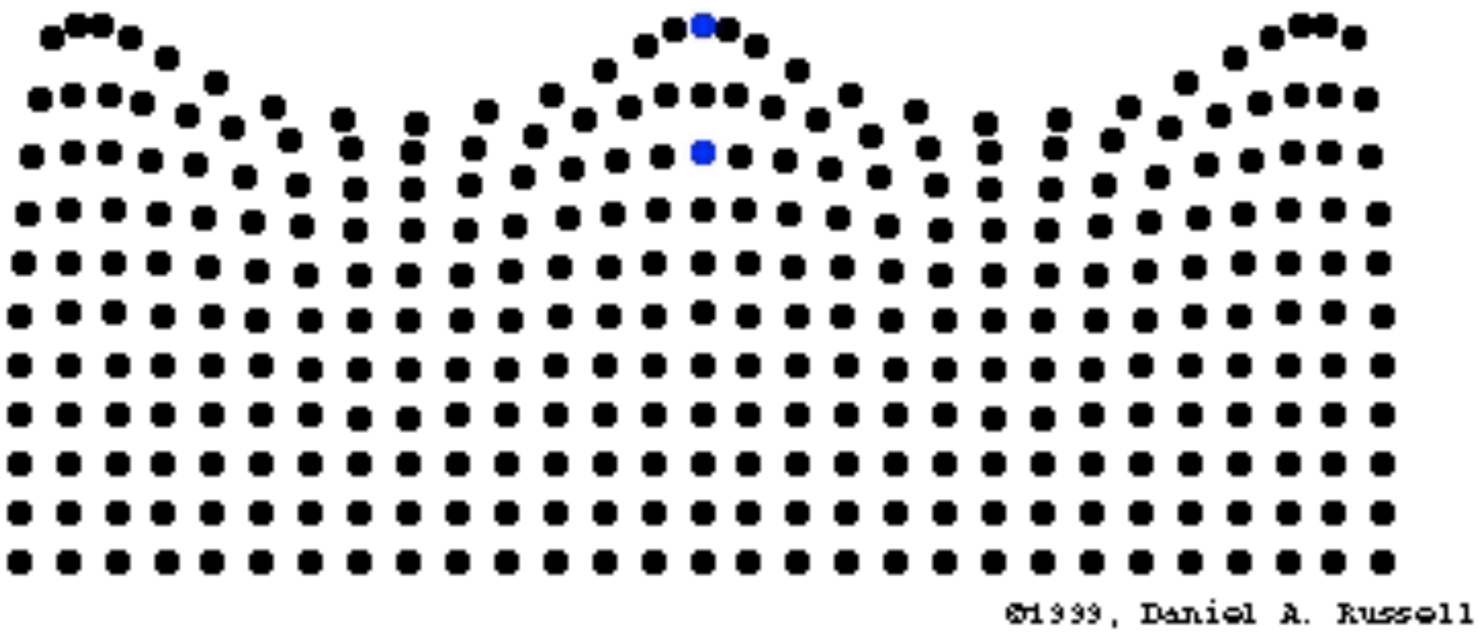
S wave



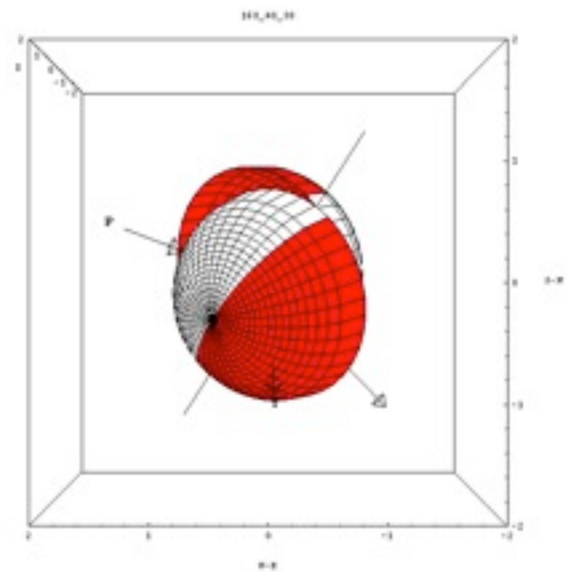
Rayleigh wave



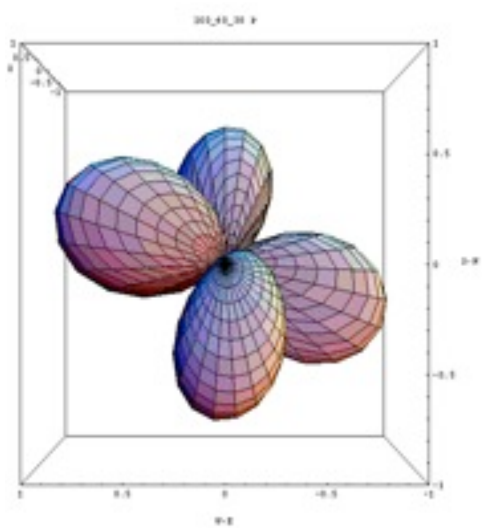
Water wave



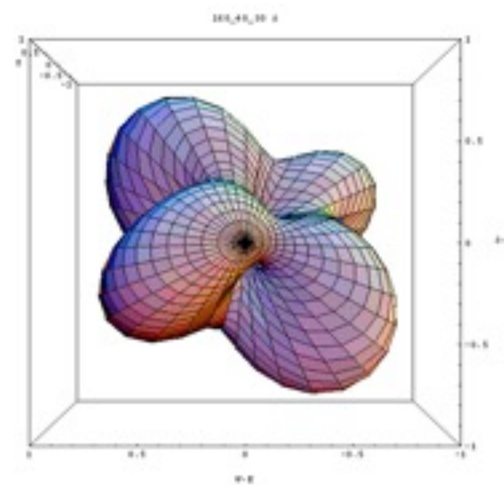
Radiation from an earthquake source



P waves

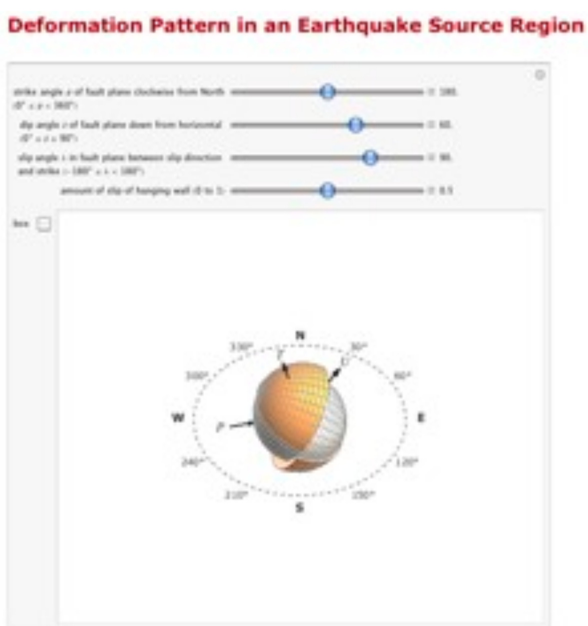


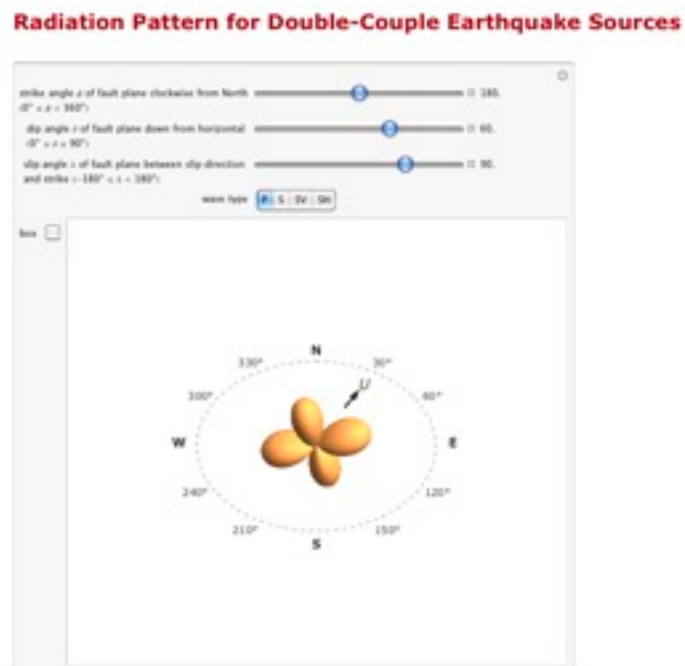
S waves



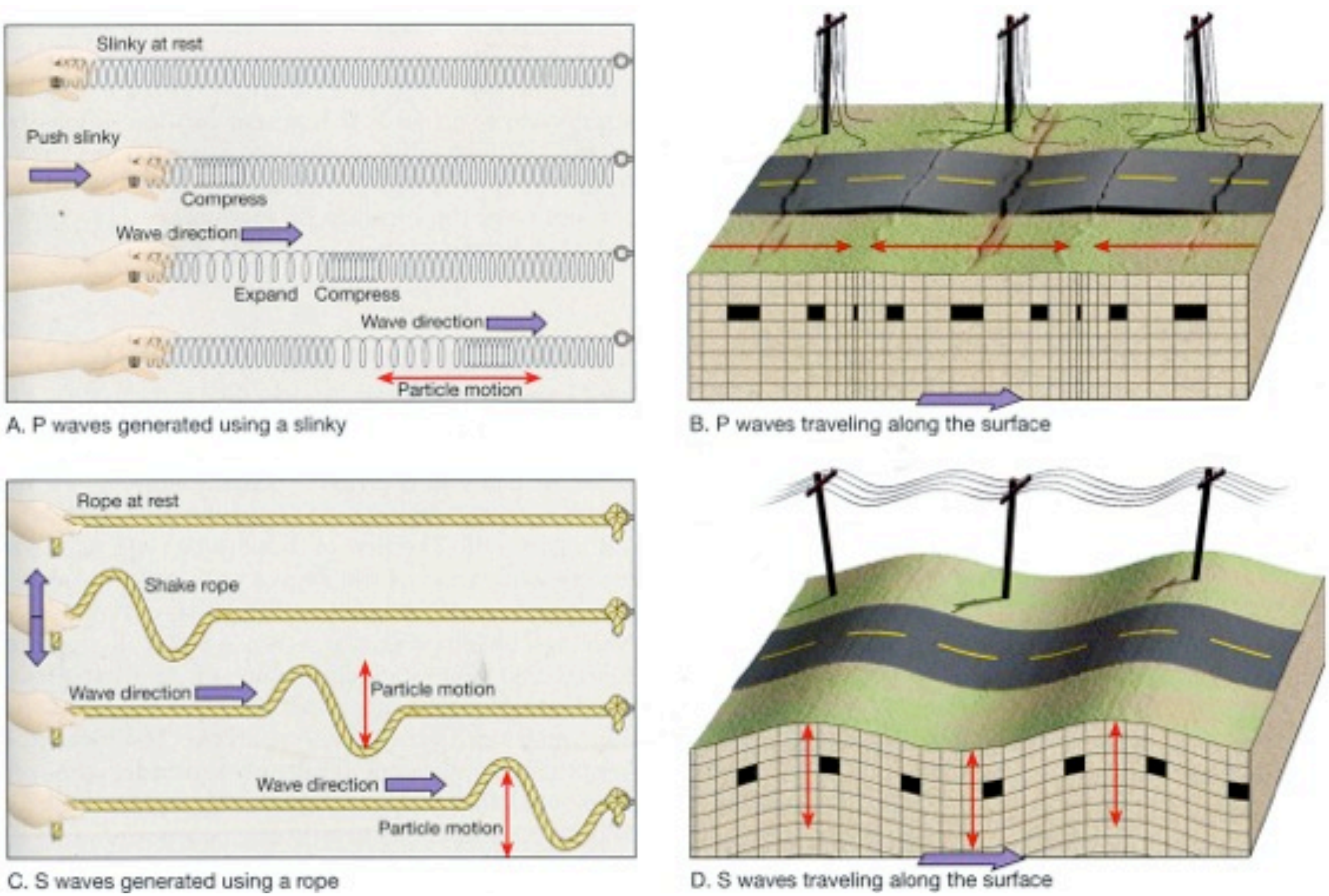
Exercise

DeformationPatternInAnEarthquakeSourceRegion.cdf
RadiationPatternForDoubleCoupleEarthquakeSources.cdf





a) What is the deformation pattern of an earthquake in which the fault strikes with an angle of 60 degrees NE, dips with 55 degrees to the SE and in which the hanging wall slips at an angle of 45 degrees (counterclockwise against the horizontal in strike direction)?
b) Generate the corresponding readiation pattern and discuss the different sections.



A. P waves generated using a slinky

B. P waves traveling along the surface

C. S waves generated using a rope

D. S waves traveling along the surface

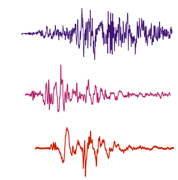

5
14
Autos

Loma Prieta, 1989

Mexico City, 1985

Earthquake ground motion in a nutshell

Source → Crustal propagation → Site effects →



- rupture propagation effects (directivity)
- source heterogenity effects (asperities, barriers)
- source extension effects (interference)
- hanging wall /foot wall

- geometrical spreading,
- scattering
- anelastic attenuation
- reflection (e. g. Moho bounce),
- refraction
- focusing, defocusing

- reverbaration
- basin effects
- non-linear damping
- kappa- effect

Seismic moment M_0

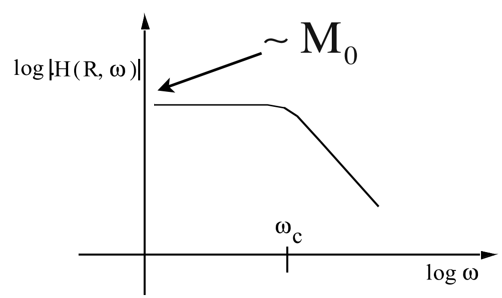
mean dislocation [m]

$$M_0 = \mu \cdot d_0 \cdot A \quad [\mathrm{N\ m}]$$

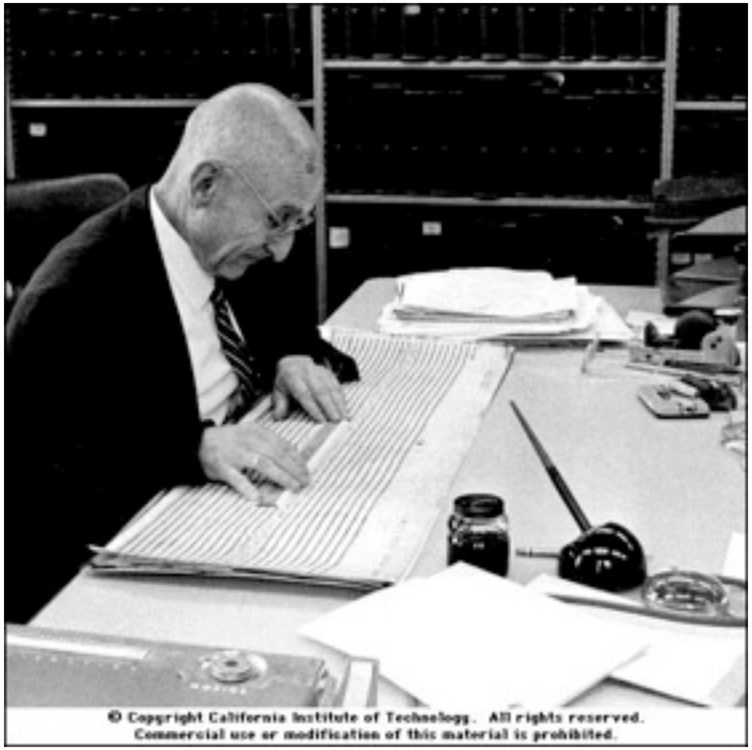
shear modulus [N/m^2]

rupture plane area [m^2]

Moment determination e. g.:



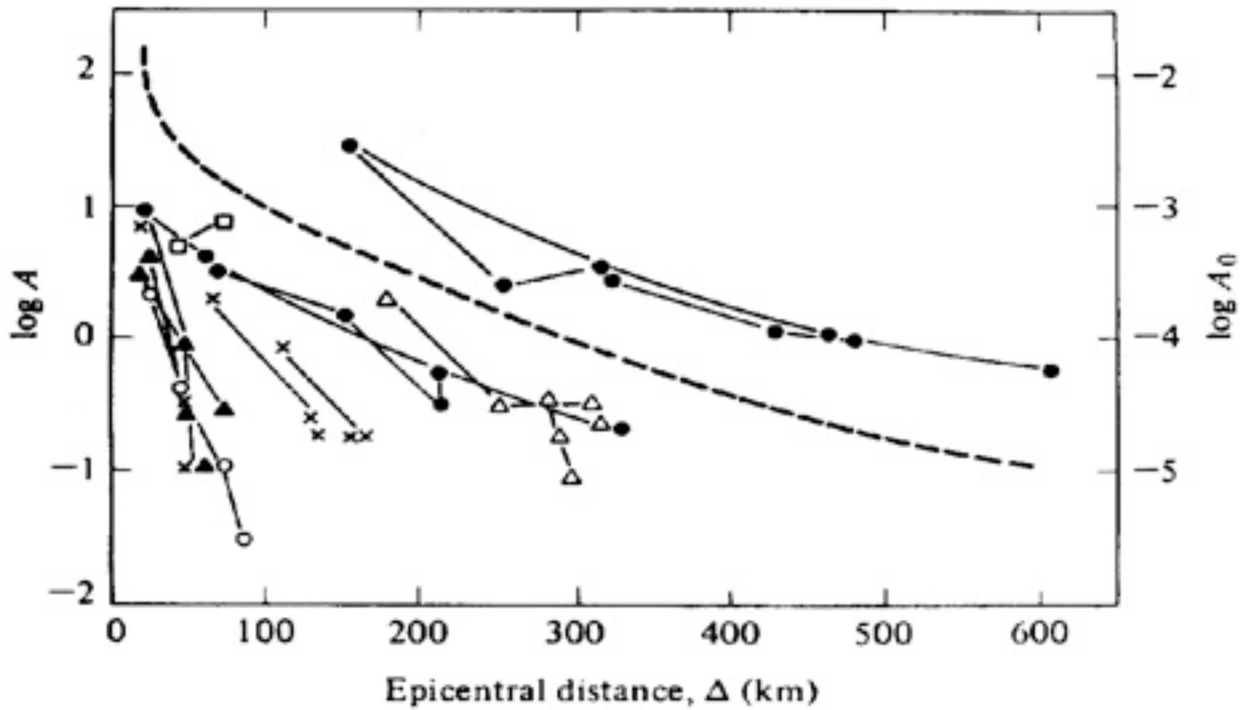
Earthquake strength: magnitudes



B. Gutenberg

C. F. Richter

Magnitude



Amplitude - distance relations for Southern California earthquakes

- Amplitude ratios widely independent of measurement site

Frank Scherbaum

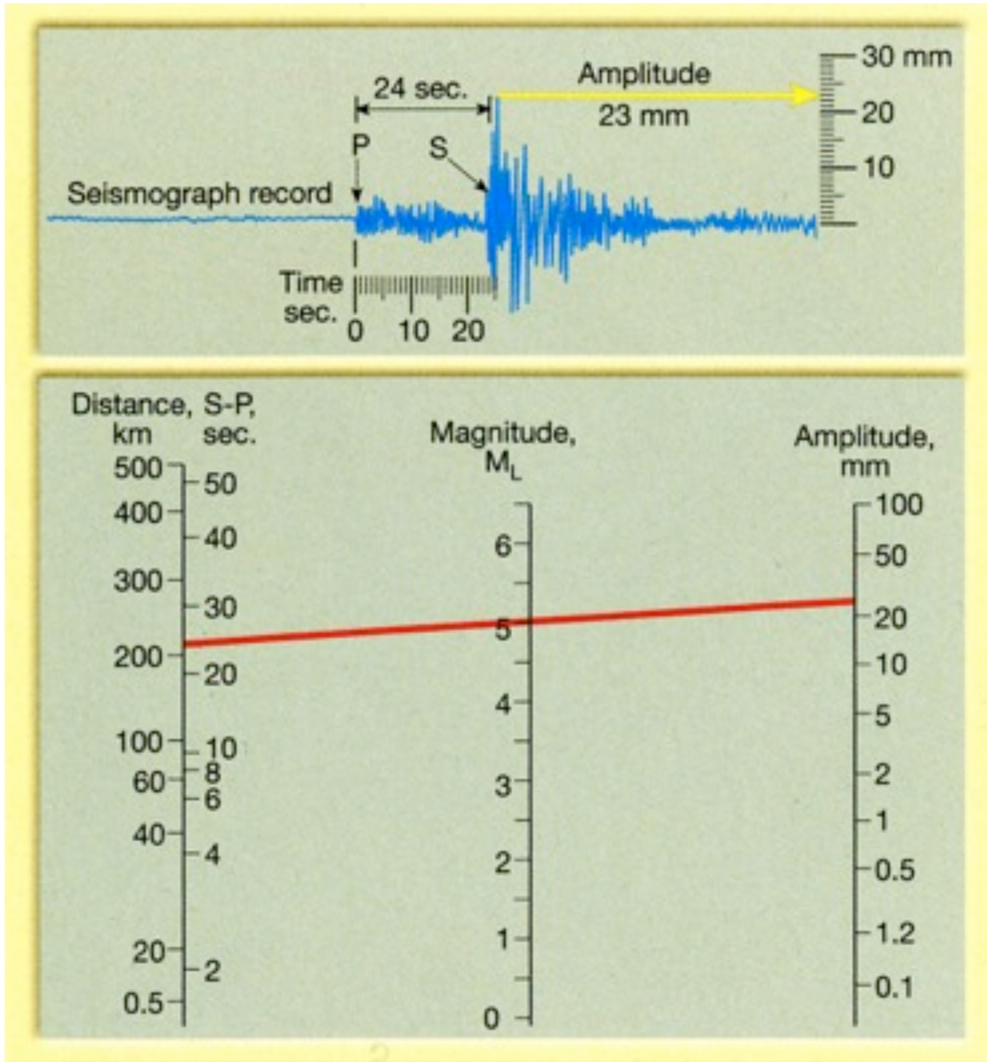
First magnitude definition 1935, C.F. Richter
„Richter-, Wood-Anderson-, local magnitude“

- Amplitude measurement on Wood Anderson displacement seismometer (T_0 = 0.8 s, h = 0.8, V= 2800)
- Comparison to expected amplitude of reference earthquake

$$M_{WA} = \log A(\Delta) - \log A_{ref}(\Delta)$$

- Δ = epicentral distance
- $\log A_{ref}(\Delta)$ = amplitude of $M_{WA} = 0$ quake at the site
- Definition of reference amplitude: half PP-amplitude of $M_{WA} = 3$ quake at 100 km distance is 1 mm

Graphical Richter magnitude determination



Other magnitude definitions

Body wave magnitude M_b

Surface wave magnitude M_S

~ Energy

Moment magnitude $$M_W = \frac{\log 10(M_0)}{1,5} - 10,73$$

$$\longrightarrow \quad \Delta M_W = 1 \Rightarrow \Delta \log 10(E) = 1.5 \Rightarrow \text{Energy ratio} = 10^{1.5} \approx 32$$

- Most magnitude scales not valid for all distance/depth ranges
- Other problems e. g.: saturation, determination effort
- In the context of SHA: M_W least problematic (no saturation)

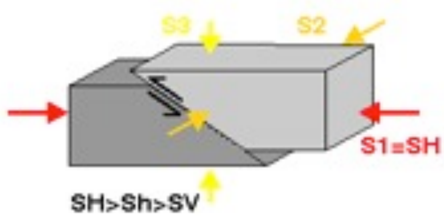
Some dimensions

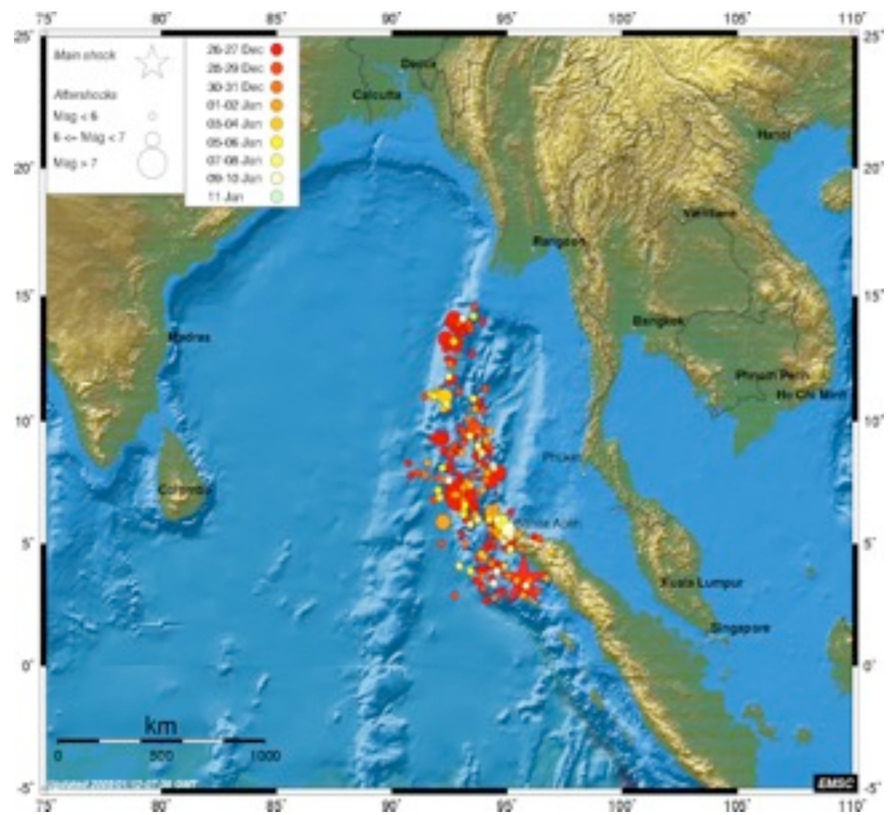
Magnitude M_W	Length (km)
4	< 1
5	≈ 2
6	≈ 10
7	≈ 50
8	≈ 250

Take with many grains of salt.....

Example: Sumatra earthquake

- **26.12.2004, 00:58:53 UTC, MW 9**
- **Rupture length > 1000 km**
- **Displacement up to 20 m**
- **Energy: 3 month Europe**





Macroseismic Intensities

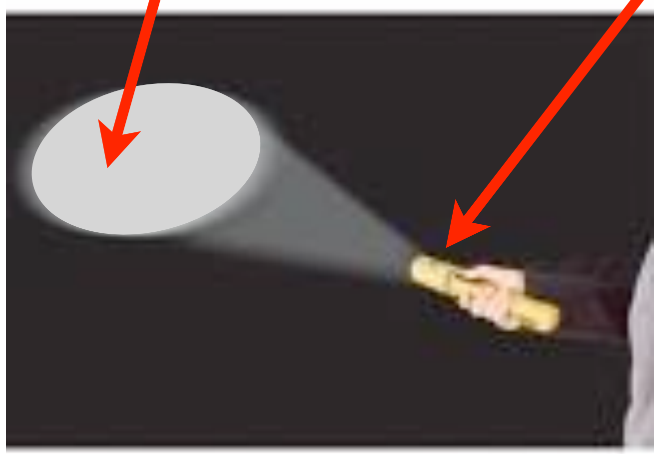
TABLE 7.1 Modified Mercalli Intensity Scale.

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake.
IV	During the day felt indoors by many, outdoors by few. Sensation like heavy truck striking building.
V	Felt by nearly everyone, many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight-to-moderate in well-built ordinary structures; considerable in poorly built or badly designed structures.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. (Fall of chimneys, factory stacks, columns, monuments, walls.)
IX	Damage considerable in specially designed structures. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed. Most masonry and frame structures destroyed. Ground badly cracked.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces. Objects thrown upward into air.

Differences between magnitude and intensity

intensity

magnitude



CDFs related to the seismology part

UnderstandingEarthquakes.cdf (Wolfram Research CDF Demo)
EarthquakeFocalMechanism.cdf
DeformationPatternInAnEarthquakeSourceRegion.cdf
RadiationPatternForDoubleCoupleEarthquakeSources.cdf
StylesOfFaulting.cdf
VerticalPendulumSeismometer.cdf

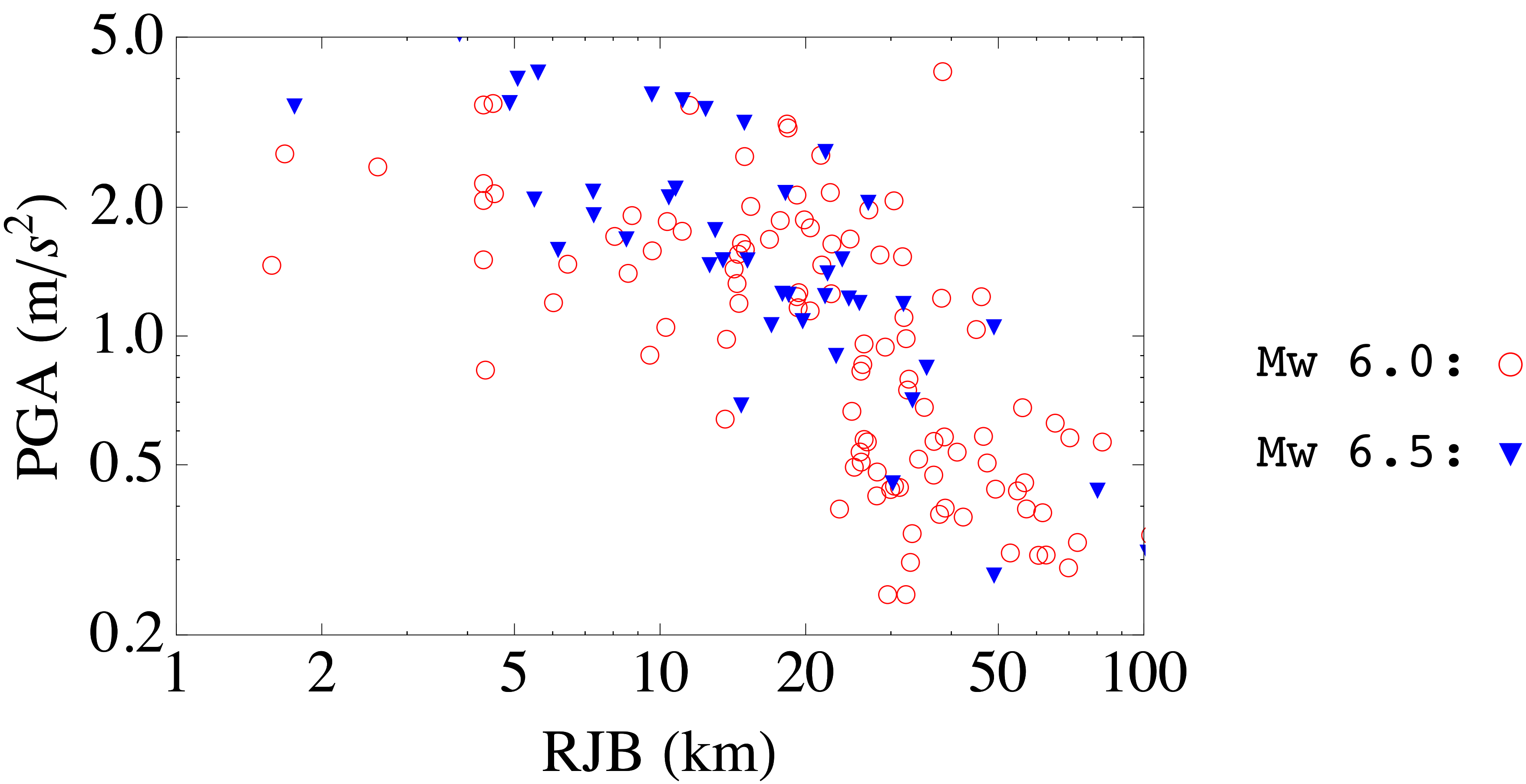
For now enough seismology, back on the main road

Earthquake ground motion models

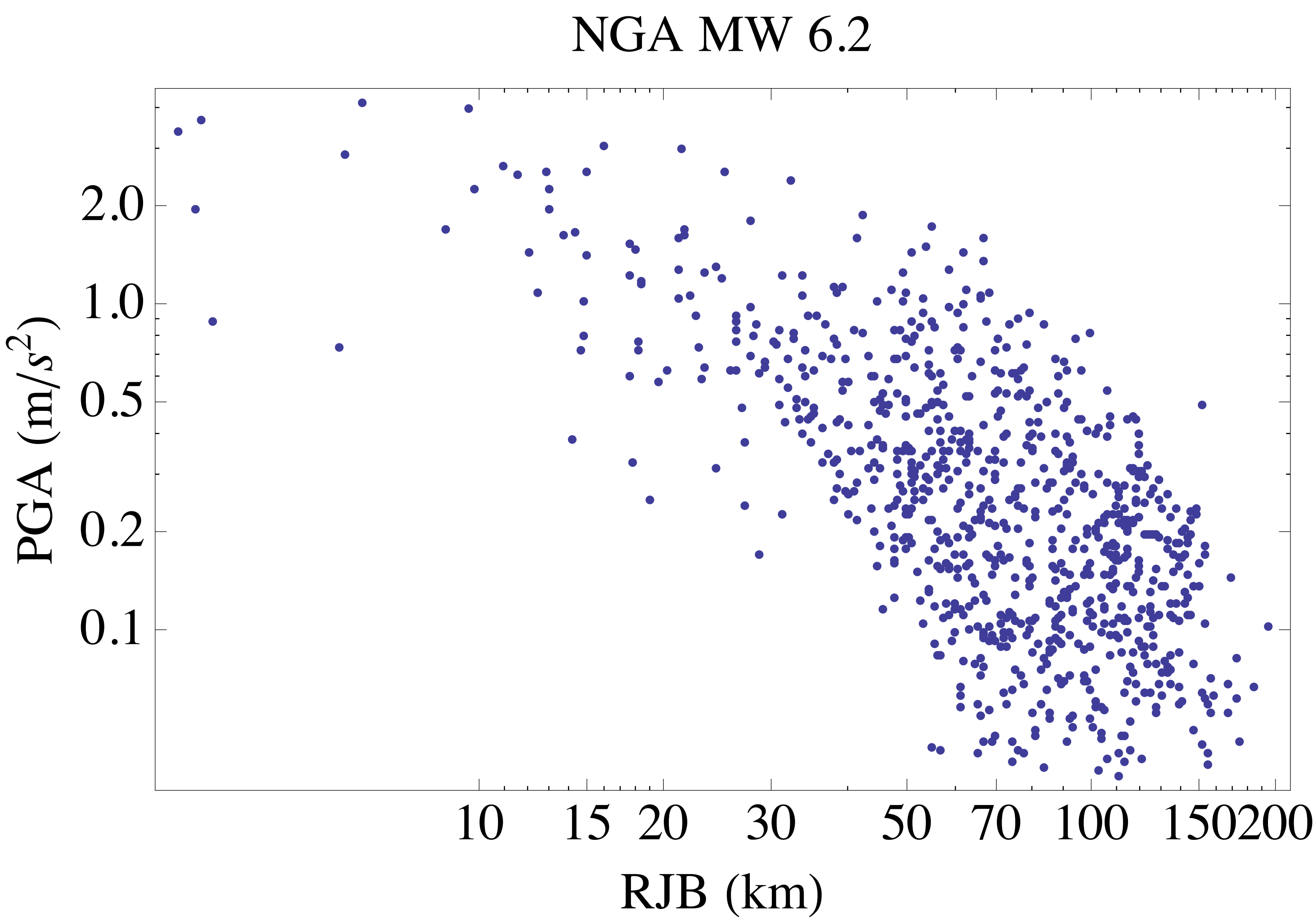
Options

- complete models (e. g. 3D spectral elements)
- simplified models (e. g. stochastic models)
- empirical regression models (GMPE)

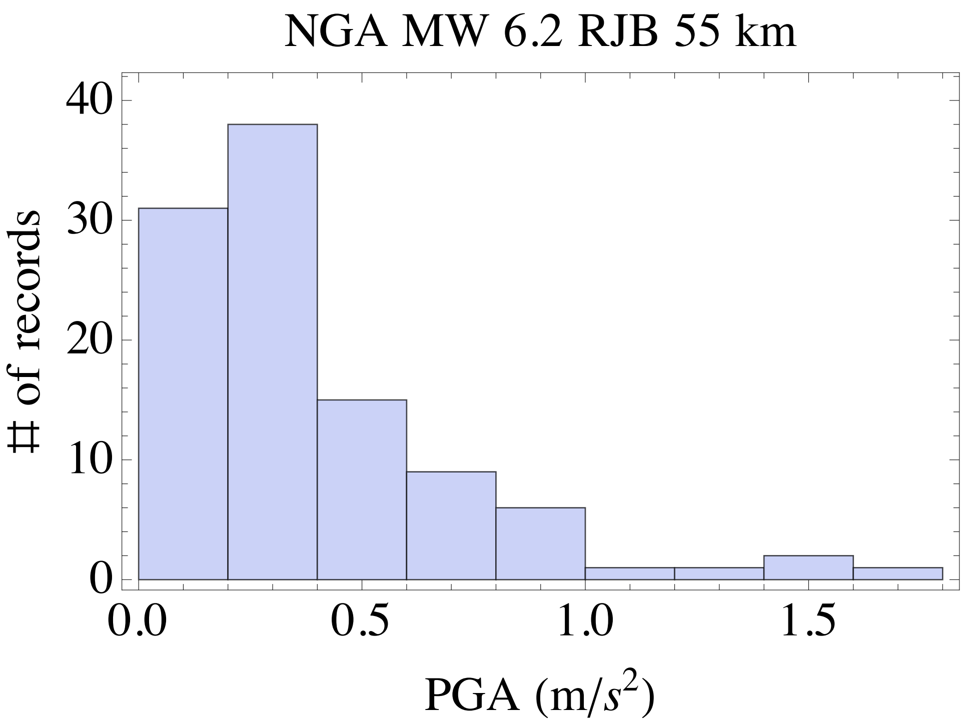
Empirical data (NGA)

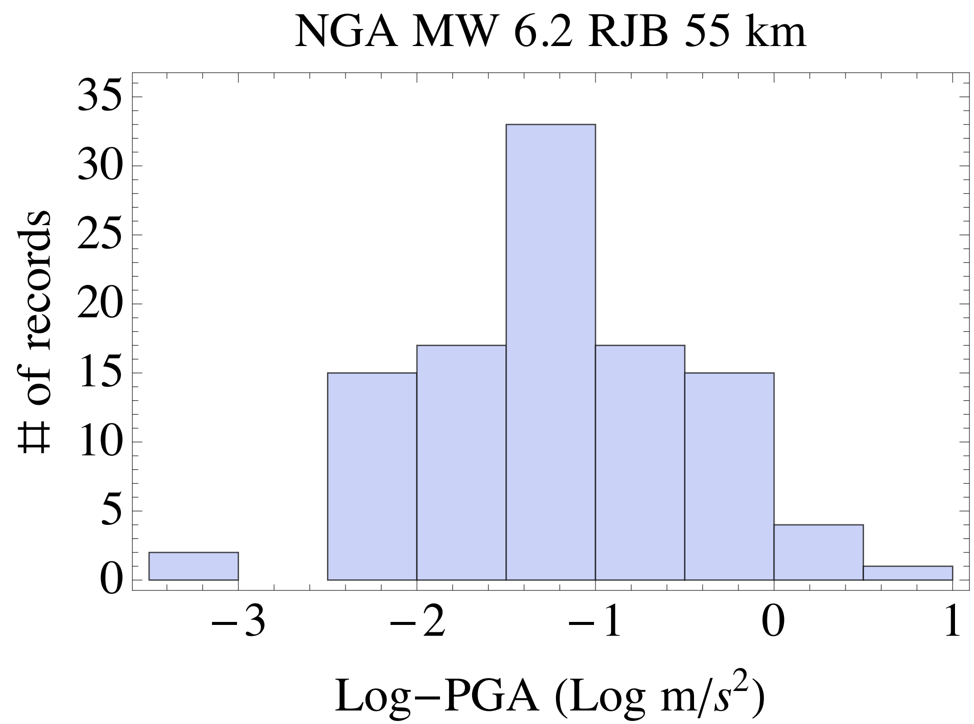


Distance dependence



PGA distribution





Principle: Empirical Ground Motion Models

Probabilistic model

Typical form:

$$Y = c_1 e^{c_2 M} R^{-c_3} e^{-c_4 r} e^{-c_5 F} e^{-c_6 S} e^{\varepsilon \cdot \sigma}$$

or:

$$\ln Y = \underbrace{c_1 + c_2 M - c_3 \ln R - c_4 r + c_5 F + c_6 S}_{\text{median}} + \varepsilon \cdot \sigma$$

magnitude

composite distance term

Source-to-site distance measure

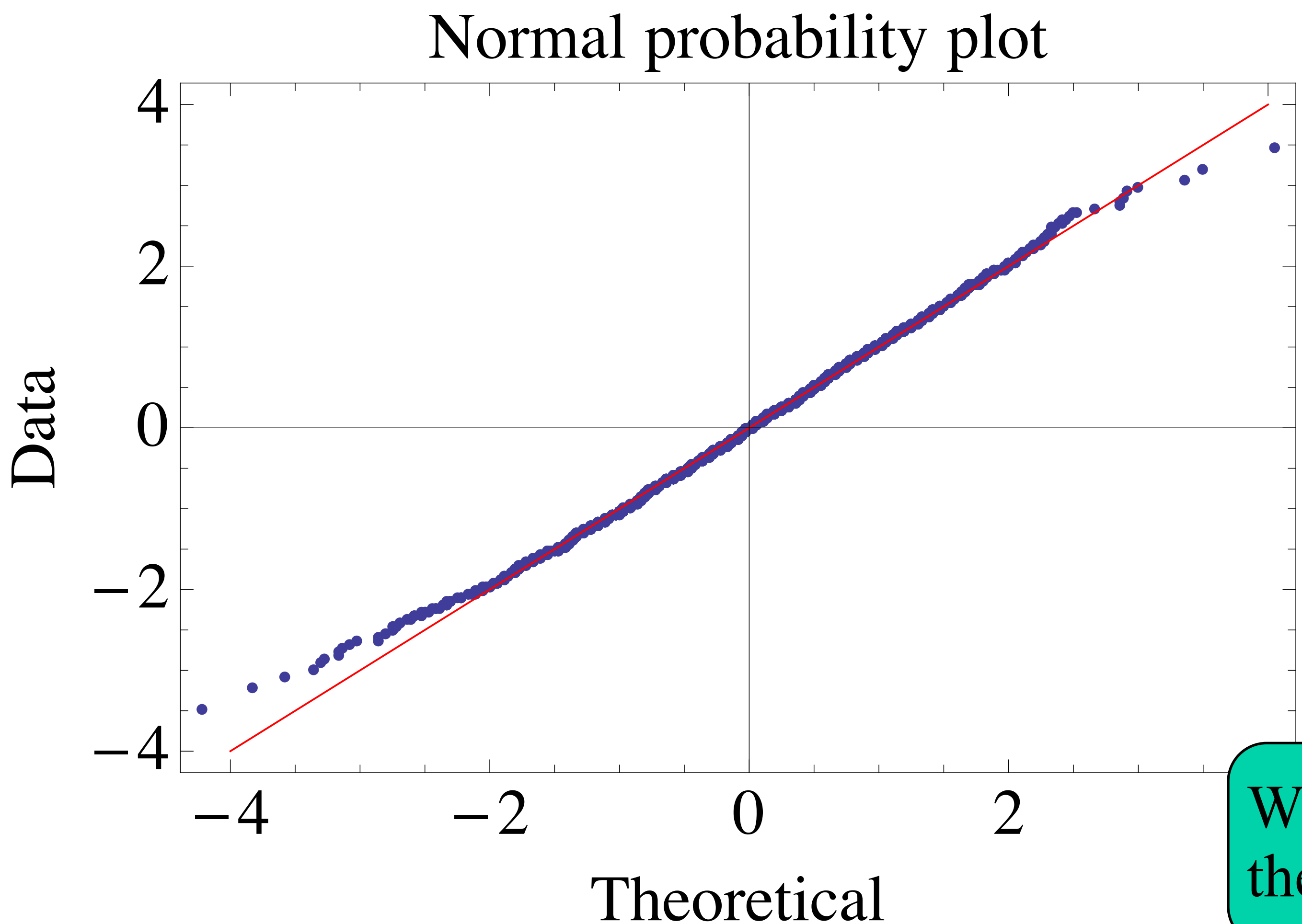
Site condition

Style of faulting

Residual in terms of σ

median

lnY-residual distribution NGA data



What causes the residuals ?

One contribution: variability in the earthquake process

Example: What´s represented by magnitude (Mw)...

$$M_W = 2/3 \cdot (\log M_0 - 9.1)$$

$$M_0 = \mu \cdot d_0 \cdot A$$

area

Shear modulus

Dislocation

Mw 5.5:

Radius [km]	**Dislocation [cm]**
8.4	**3**
6.5	**5**
4.6	**10**
....	**....**

- relative dislocation controls stress drop
- stress drop controls HF ground motion
- **earthquakes of same magnitude can produce very different ground motion**

Consequences

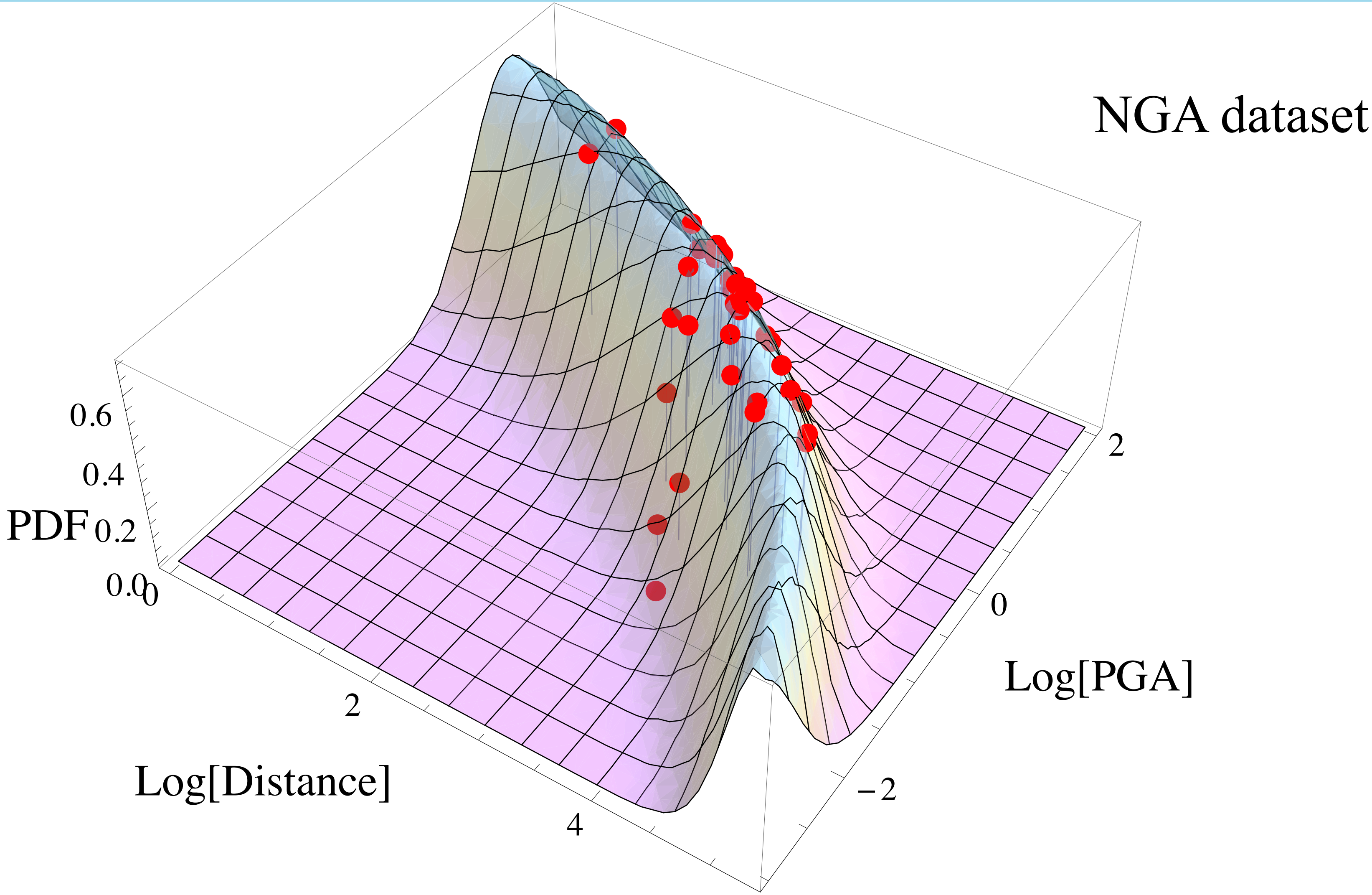
For an earthquake of a particular magnitude in a particular distance at a particular site:

• there is no single „true“ ground motion value for an EQ of fixed magnitude at fixed distance !

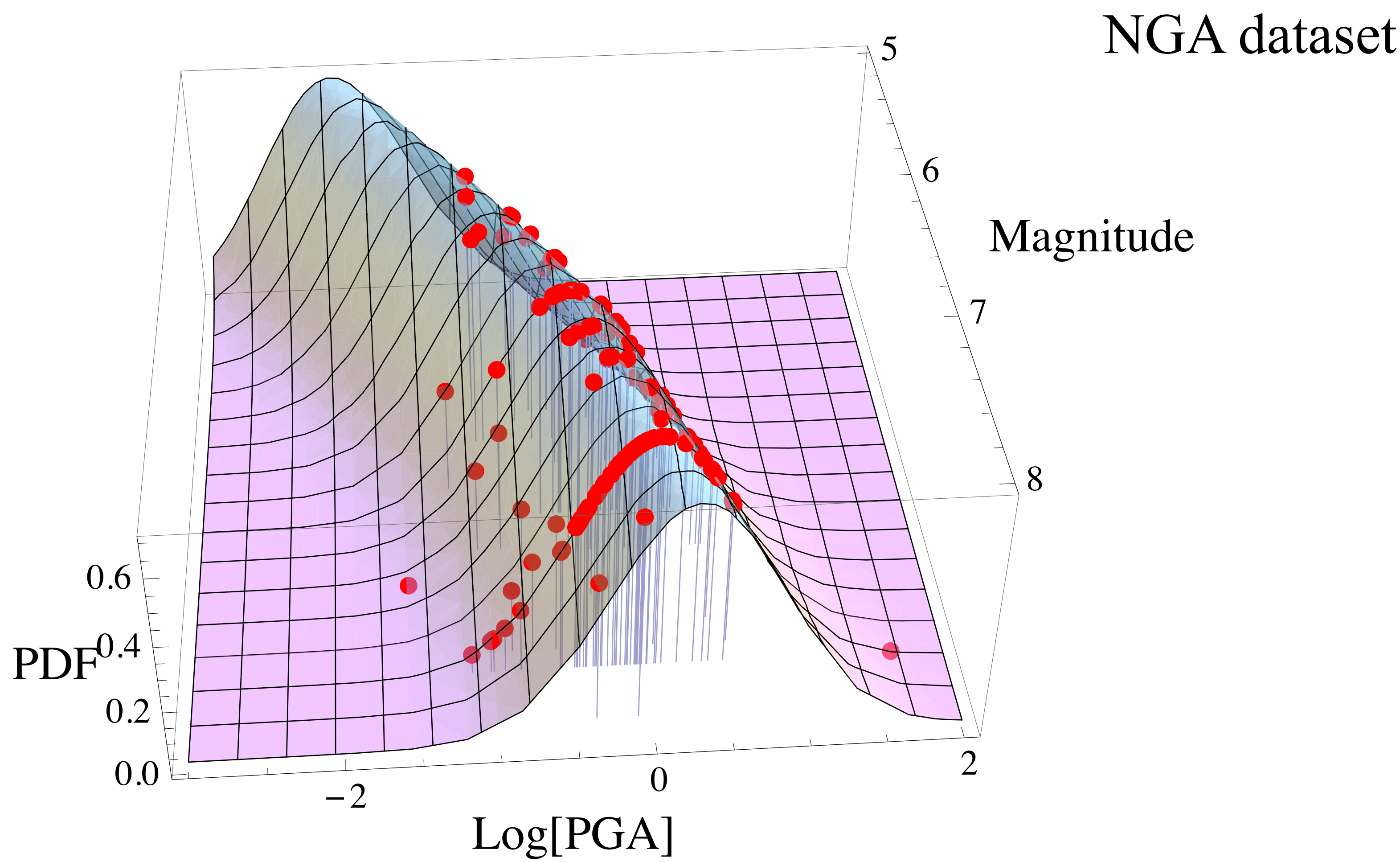
• ground-motion must be treated as **random variable** reflecting the intrinsic randomness of the earthquake process (aleatory uncertainty).

• assumption (based on data) log-normal distribution

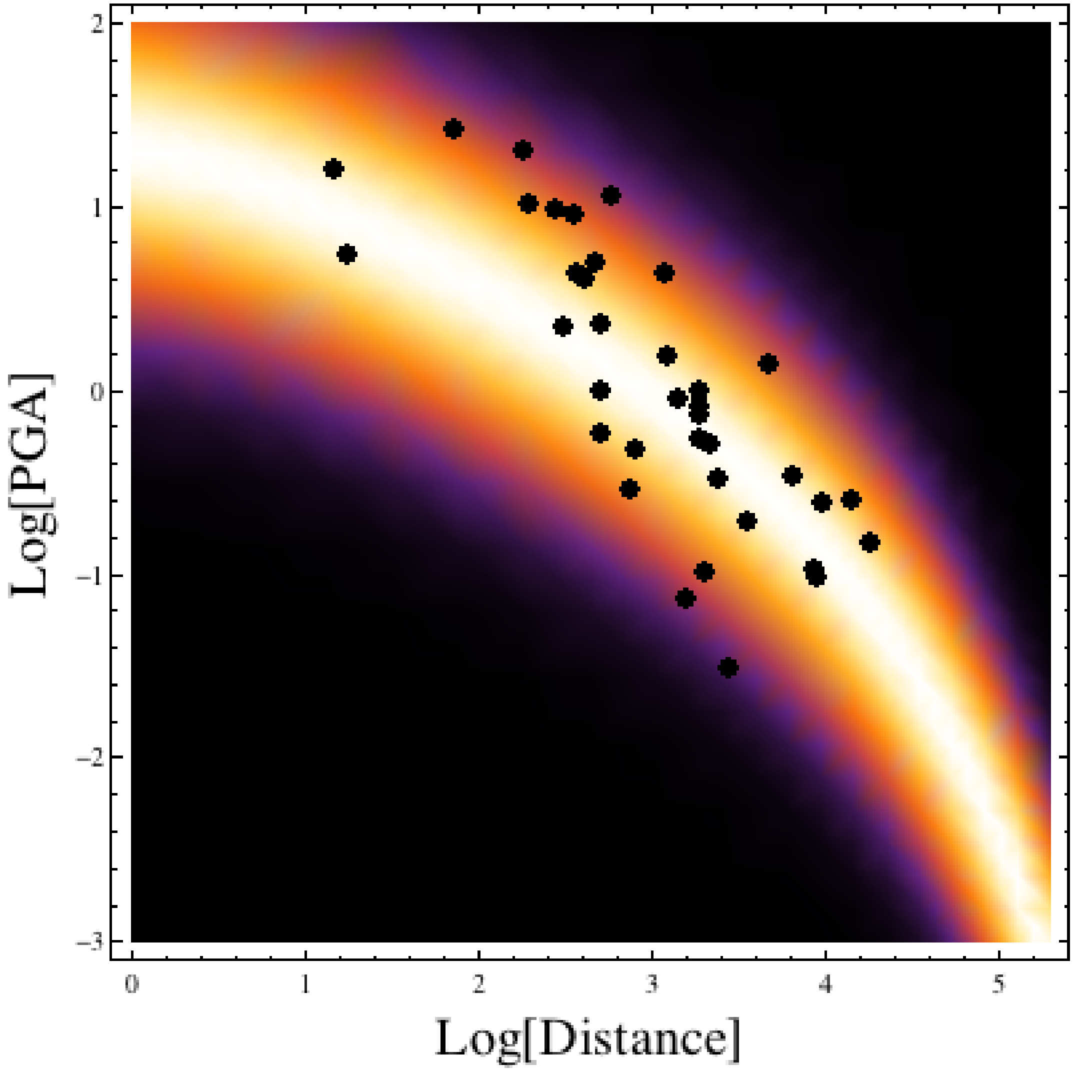
Distance scaling: Mw 6.2



Magnitude scaling: RJB 45-55 km



GMPEs are probabilistic models!!!



NGA dataset

Mw 6.2

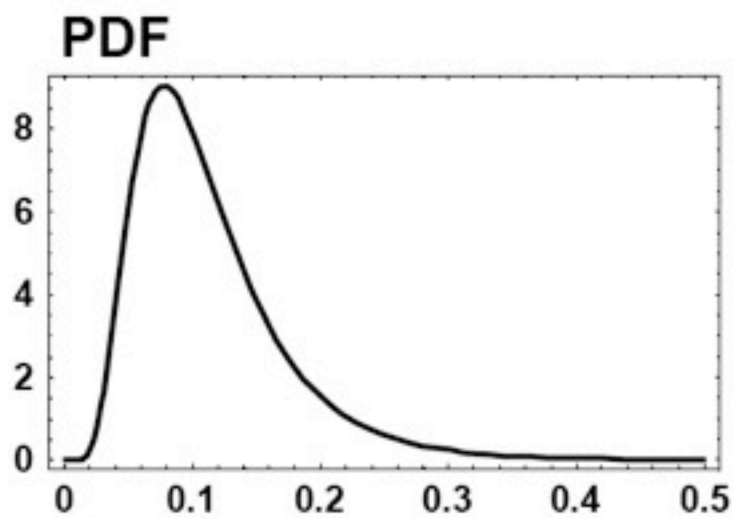
Single earthquake source

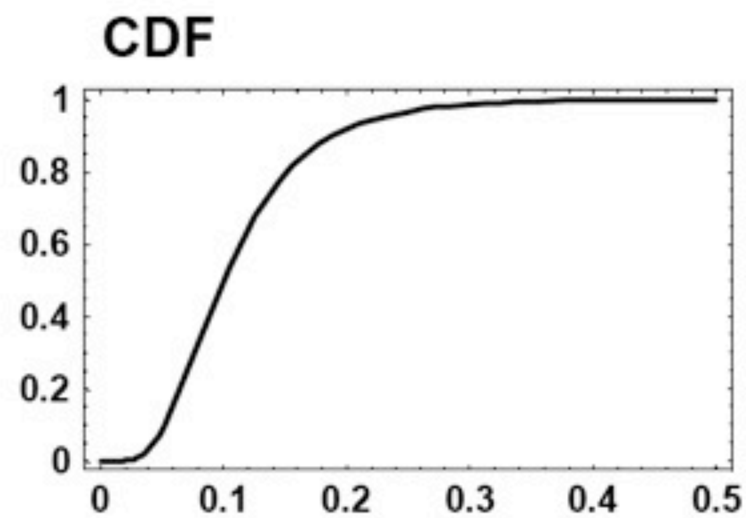
Single source producing variable ground motion levels (RV)

Let us assume *a* is log-normally distributed $f(x) = \frac{1}{\sigma\sqrt{2\pi}\cdot x} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$

$\lambda = average\#events/year$ = 200

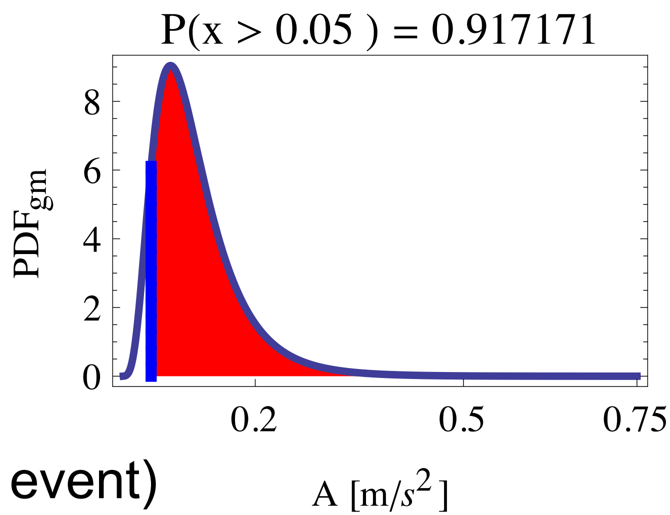
$\mu = \ln(0.1); \sigma = 0.5$

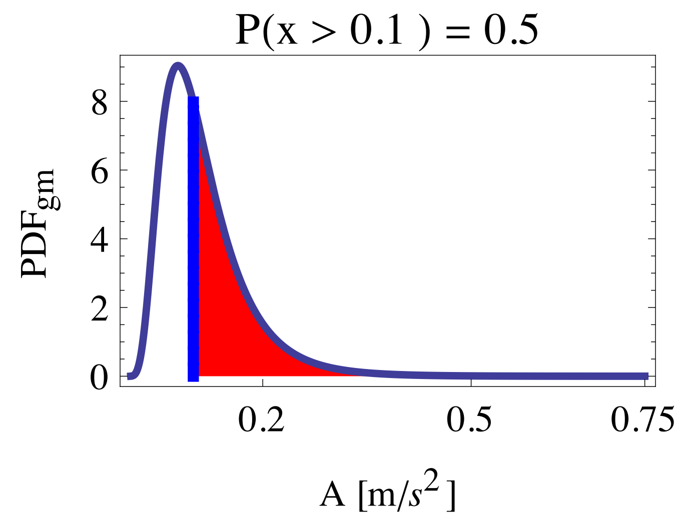




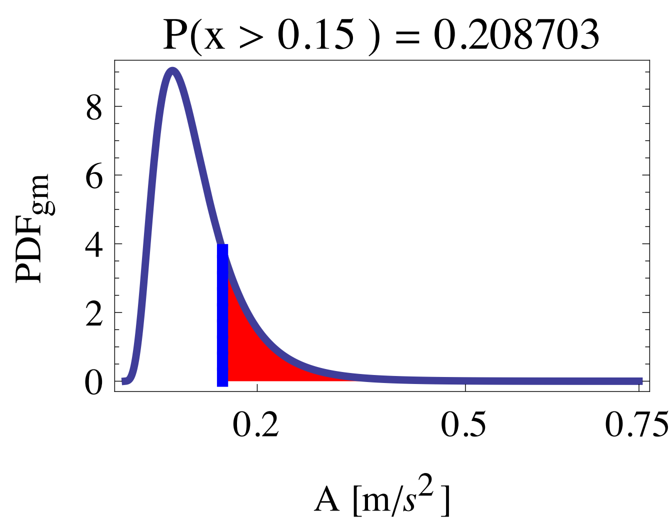
$$\text{Expected daily rate of exceedance of } x_{test} = \begin{array}{l}\text{Expected daily rate of}\\ \text{occurrence of events}\\ (200/365 = 0.55)\end{array} \times \underbrace{P(x > x_{test} \mid \text{seismic event})}_{\text{conditional probability from GMM}}$$

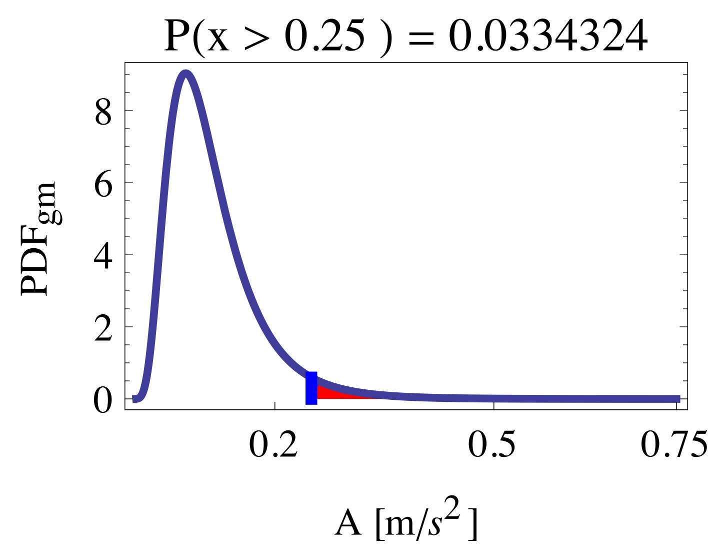
Conditional exceedance probability for different ground motion levels





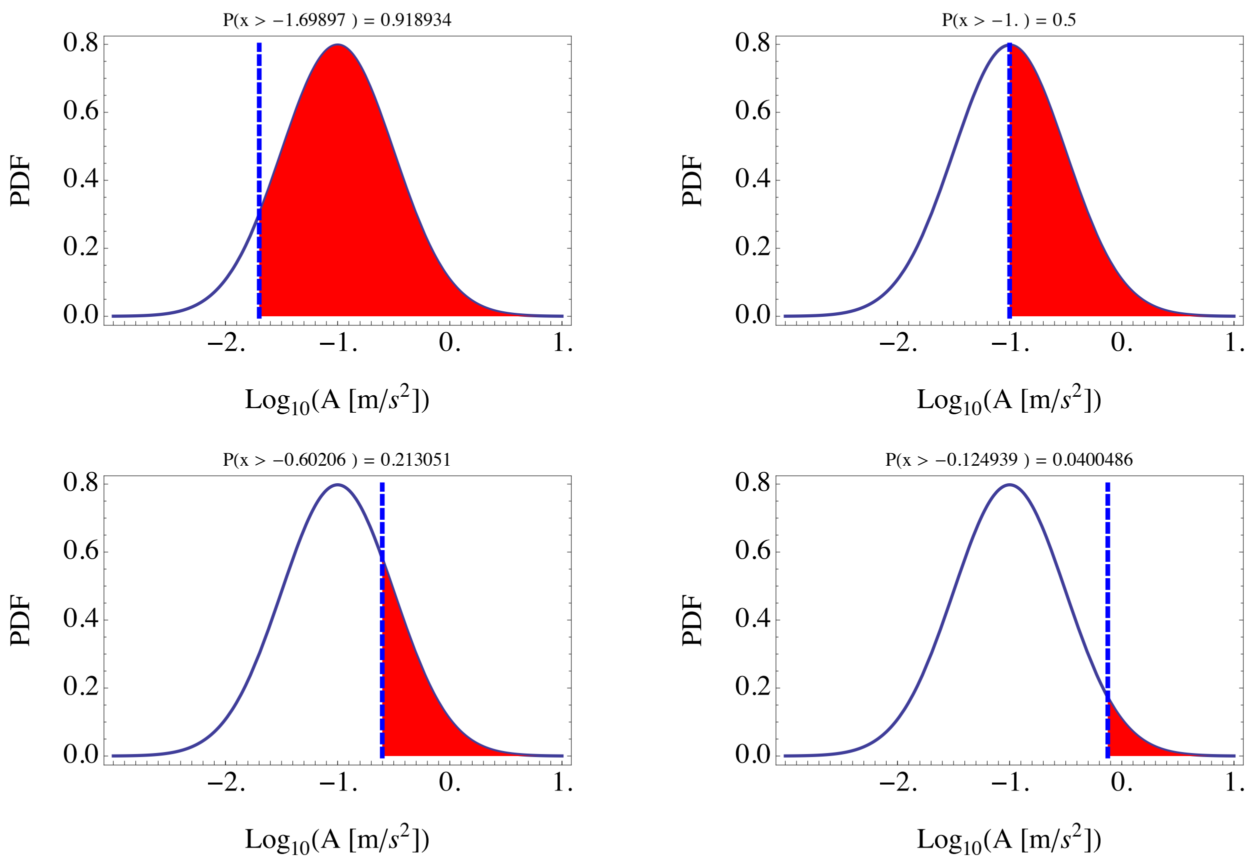
$P(x>x_{test}$ | seismic event)





Switching scales

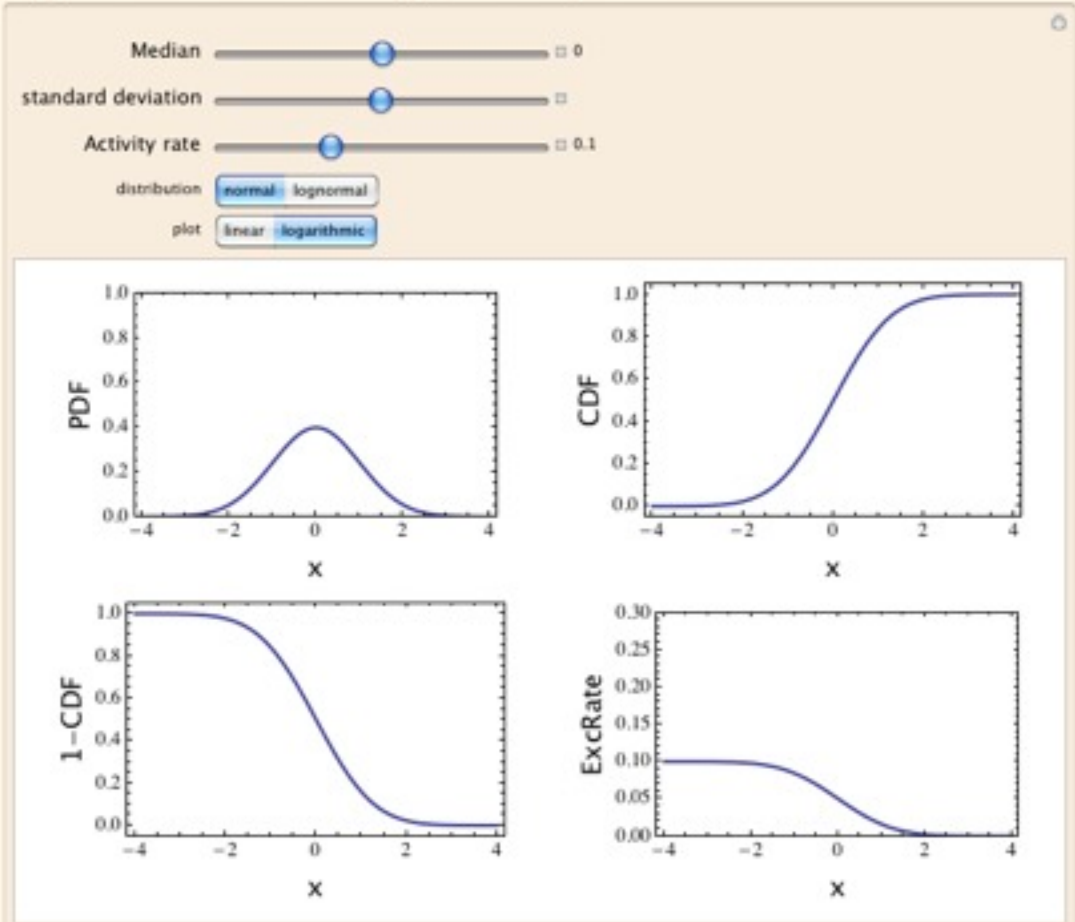
$P(x > x_{tes}$ | seismic event)



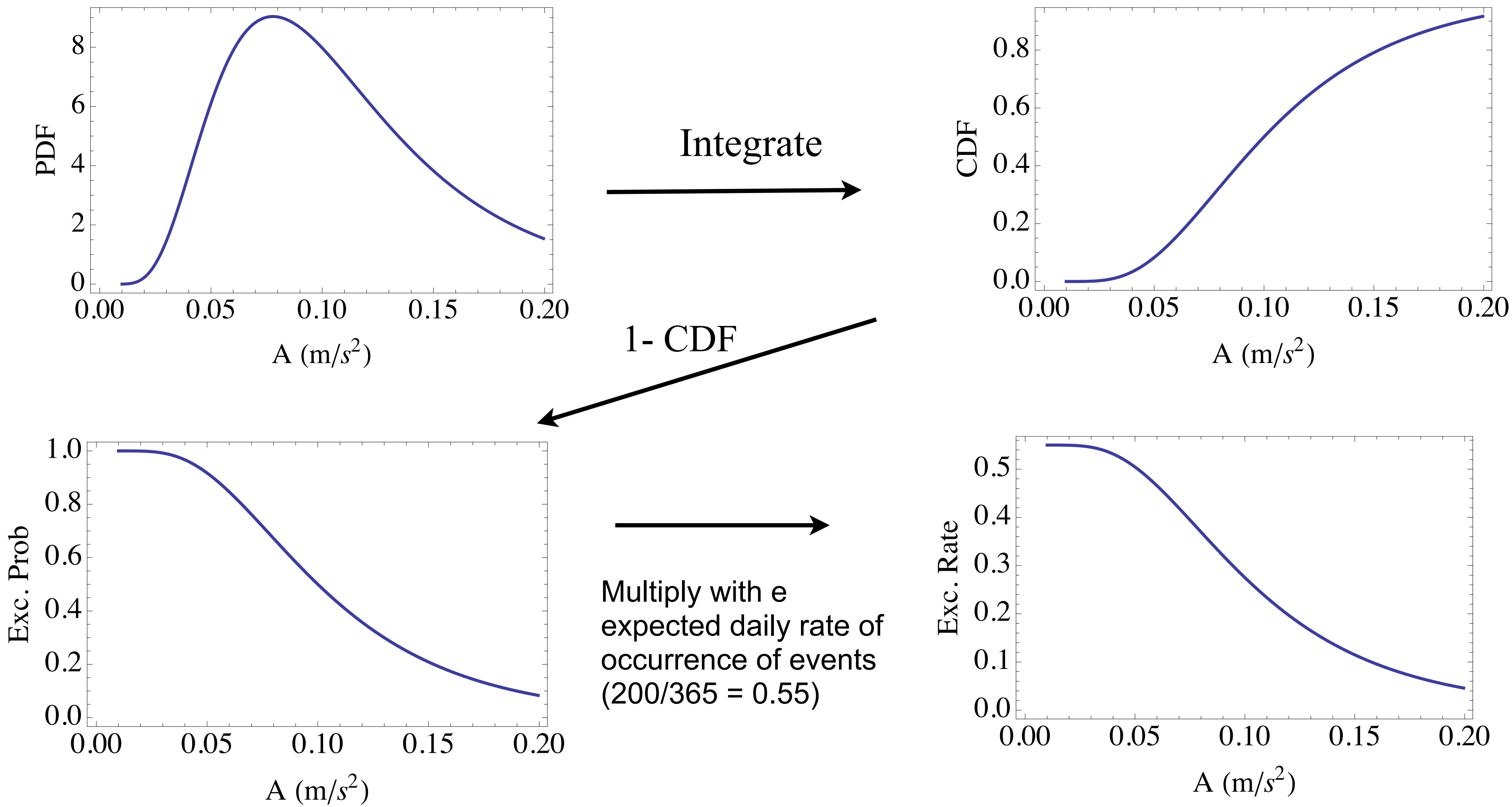
Note: x-axis now logarithmic

FromPDF2ExcRate

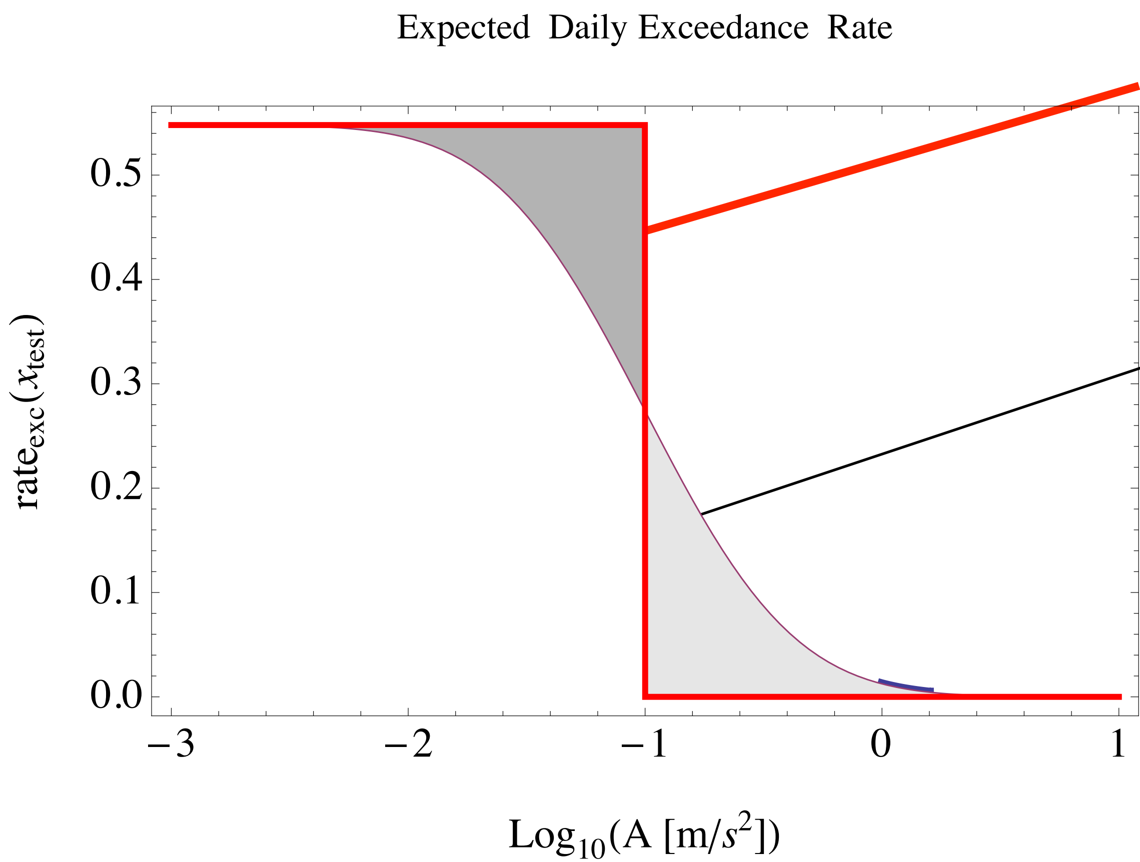
The purpose of this manipulet is to illustrate the relationships between the probability density function (PDF), the cumulativ distribution function (CDF), the exceedance probability function (1-CDF) and the exceedance rate for normal and log-normally distributed random variables of varying median and sigma values.



PDF, CDF, Exceedance Probability (Rate)



Expected daily rate of exceedance of x_{test}



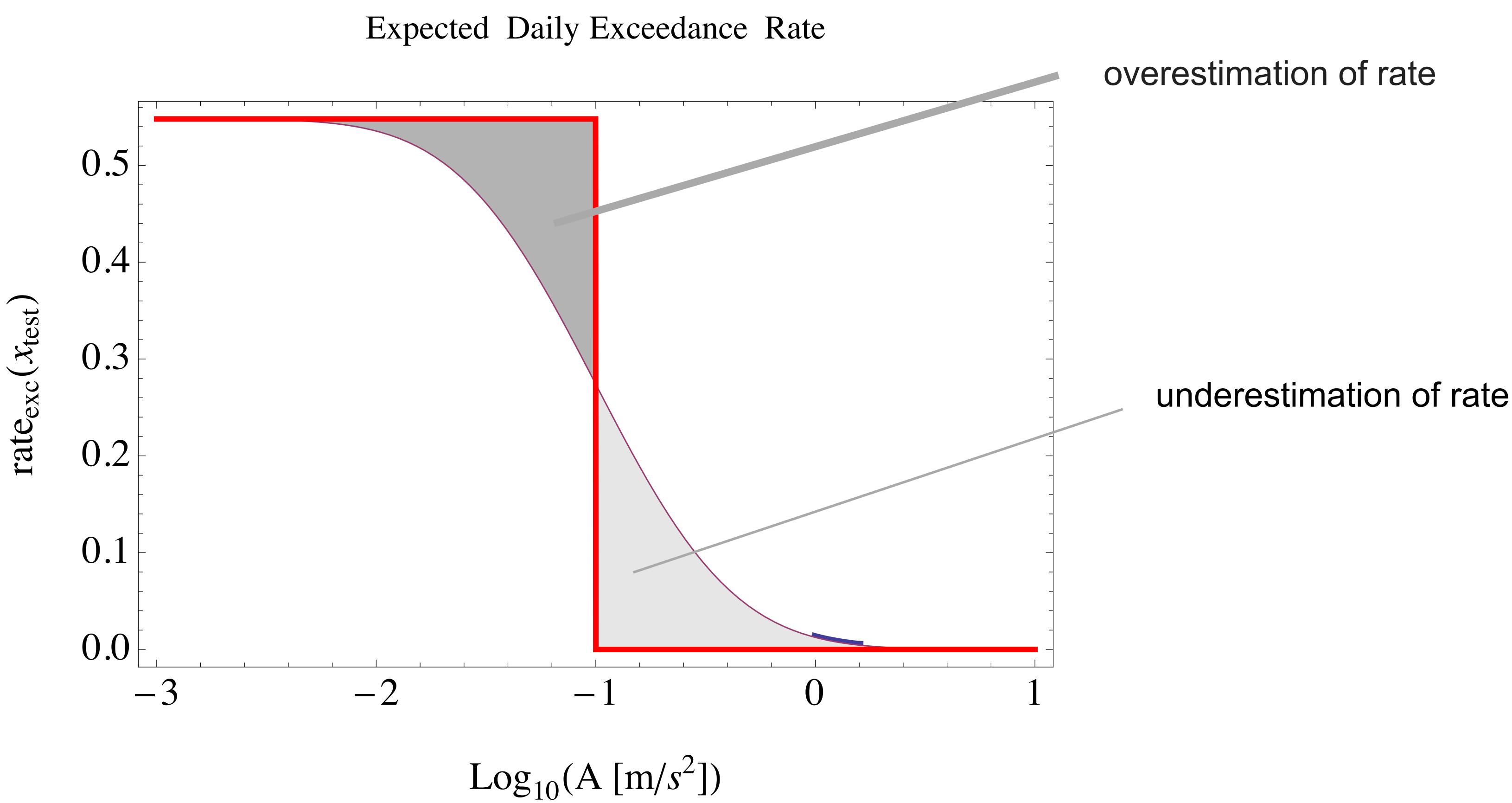
constant ground motion (exceedance rate depends only on occurrence rate of events = 0.55 or 0)

variable ground motion (exceedance rate depends on occurrence rate of events AND conditional probability of ground motion exceedance)

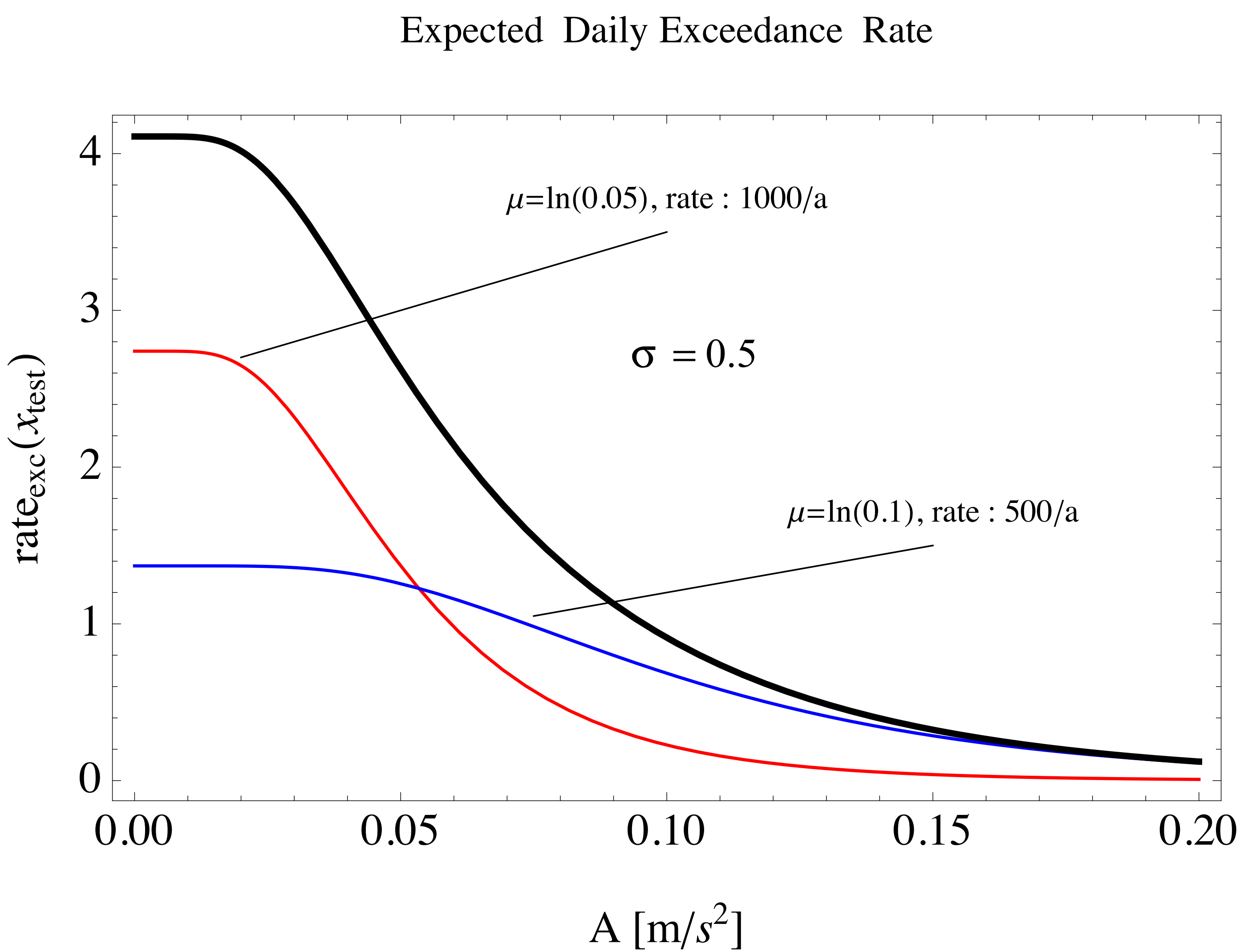
Expected daily rate of exceedance of x_{test} = Expected daily rate of occurrence of events (200/365 = 0.55) x $P(x > x_{test}$ | seismic event)

A note on the side

Approximating ground motion by a deterministic model will lead to overestimation of exceedance rates for low values and underestimation of high values.



Two seismic sources with different occurrence rates



TwoSources

The purpose of this manipulet is to illustrate the superposition of two seismic sources with different activity rate and different probability density functions for their ground motion, each of which is assumed by log - normally distributed. The yellow curve represents the overall ground motion exceedance rate.