Earthquake forecasting

- observation, modelling and statistics -

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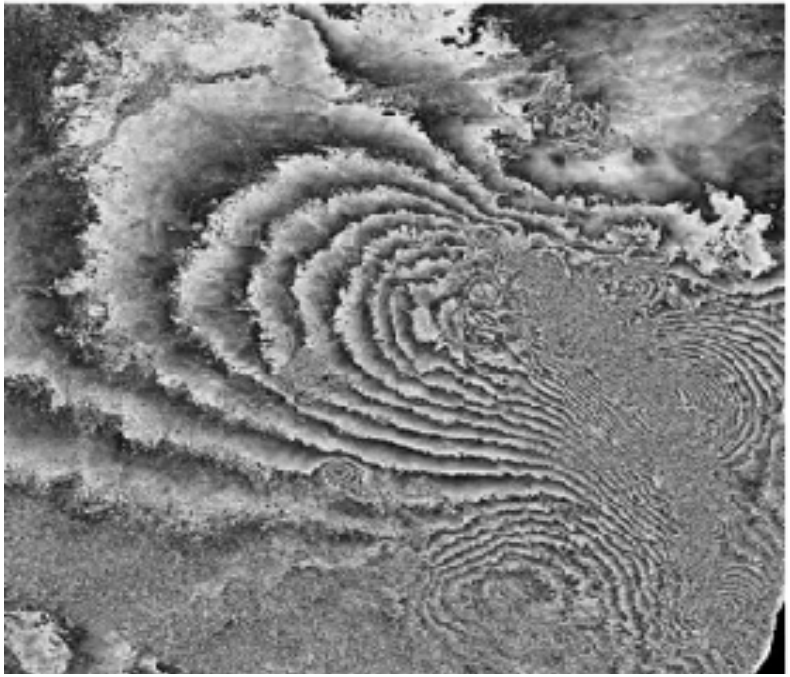
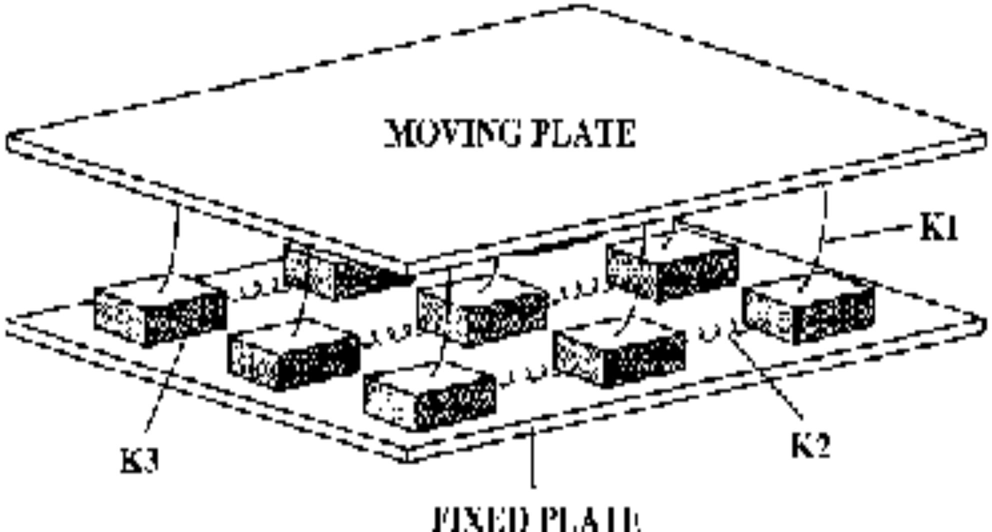
Today's topics

- The seismic cycle
- Geodetic observations
- Strain accumulation models
- Spring block models
- Earthquake statistics
- Seismic gaps and triggering
- Seismic hazard assessment

Figure 4.5-3: SAR interferogram, data and modeling, for the 1992 Landers and Big Bear earthquakes.





Additional material

Stein & Wysession chapter 4.7

Carl Tape’s teaching material https://github.com/uafgeoteach/GEOS626_seis

RichterX Plattform www.richterx.com and Kamer et al., Eur. Phys. J. Special Topics 2020

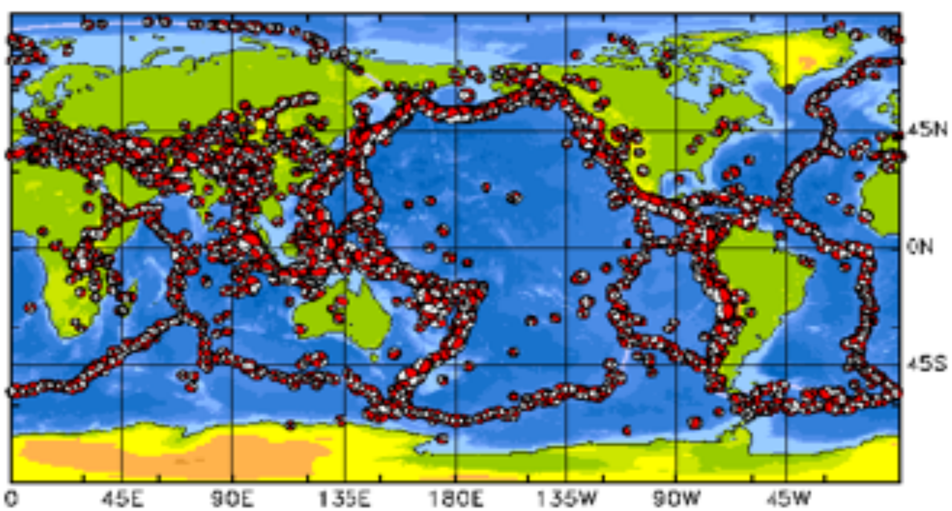
CSEP community https://cseptesting.org and https://github.com/SCECcode/pycsep

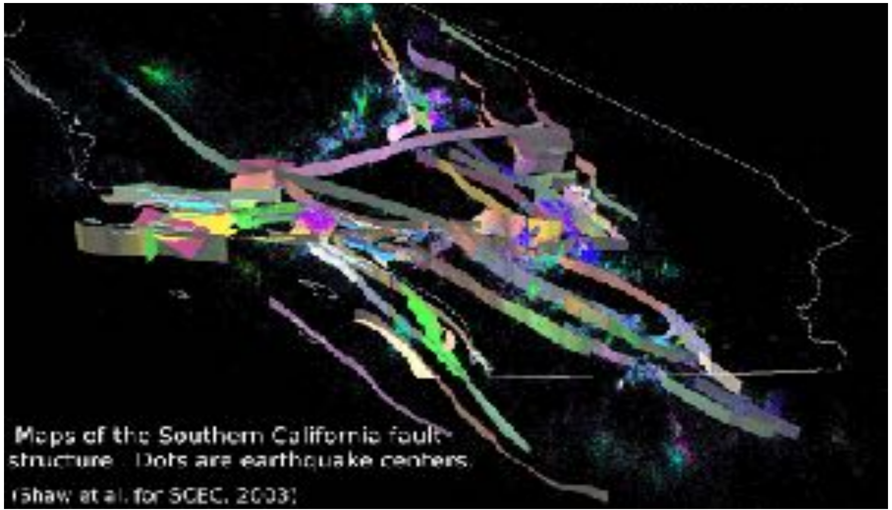
Wiemer & Wyss, BSSA 2000

Taroni, GJI 2020

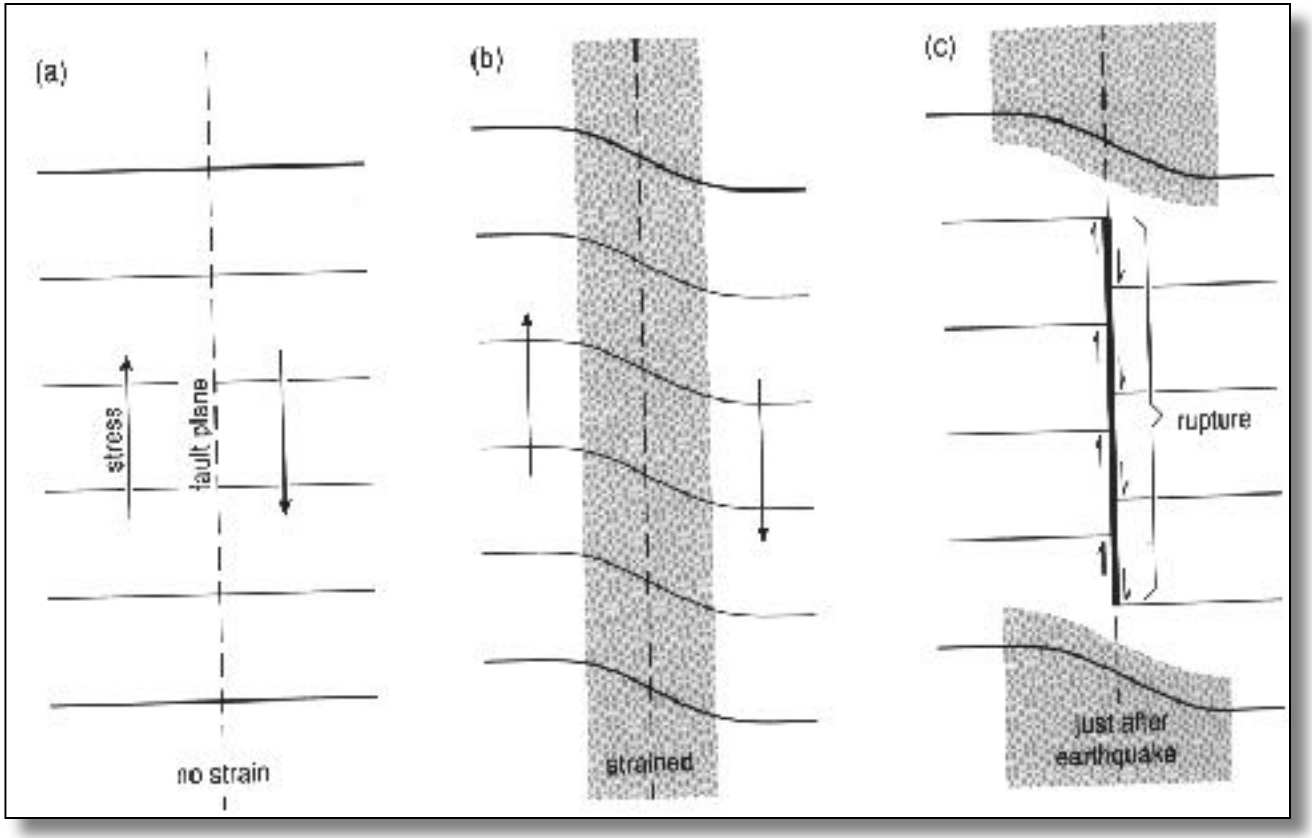
Forecasting earthquakes?

- How does a fault system behave when continuously loaded by tectonic forces?
- How does seismicity evolve?
- When is the recurrence of large earthquakes periodic?
- What is the relation between geometrical and rheological fault properties and the resulting seismic response?
- Under what conditions can low-magnitude conditions be extrapolated to provide explanation of large events?
- **Why is it so difficult to predict major earthquakes?**





The earthquake cycle



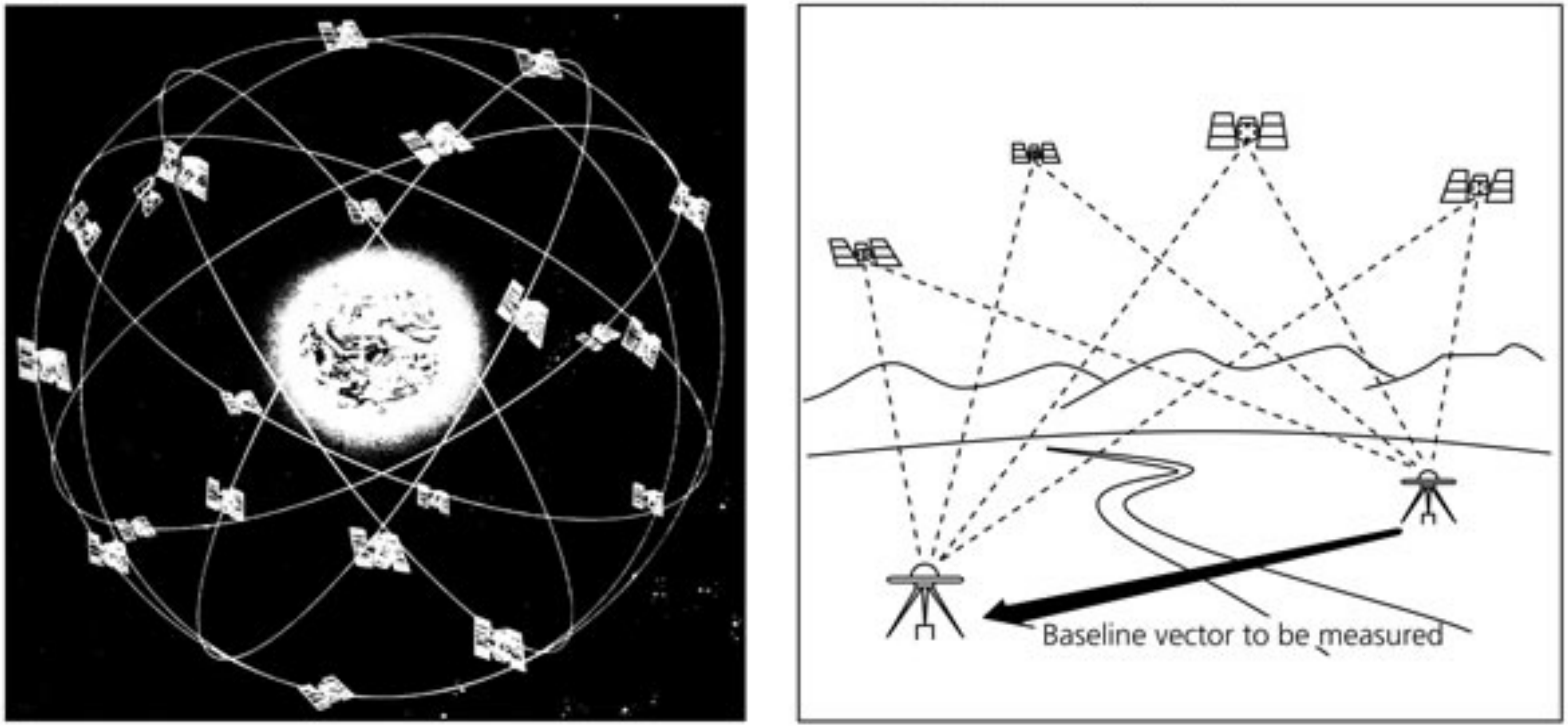
Elastic rebound model of a strike-slip earthquake after Reid (1910)

- Earthquake = sudden release of accumulated stress in the crust
- **Earthquake cycle** follows the **elastic rebound theory** = block offset of the fault

→**Open research questions: WHAT causes faults to fail, and WHEN?**

Geodetic observation

Figure 4.5-1: Cartoon of the Global Positioning System (GPS).



Constellation of GPS satellites

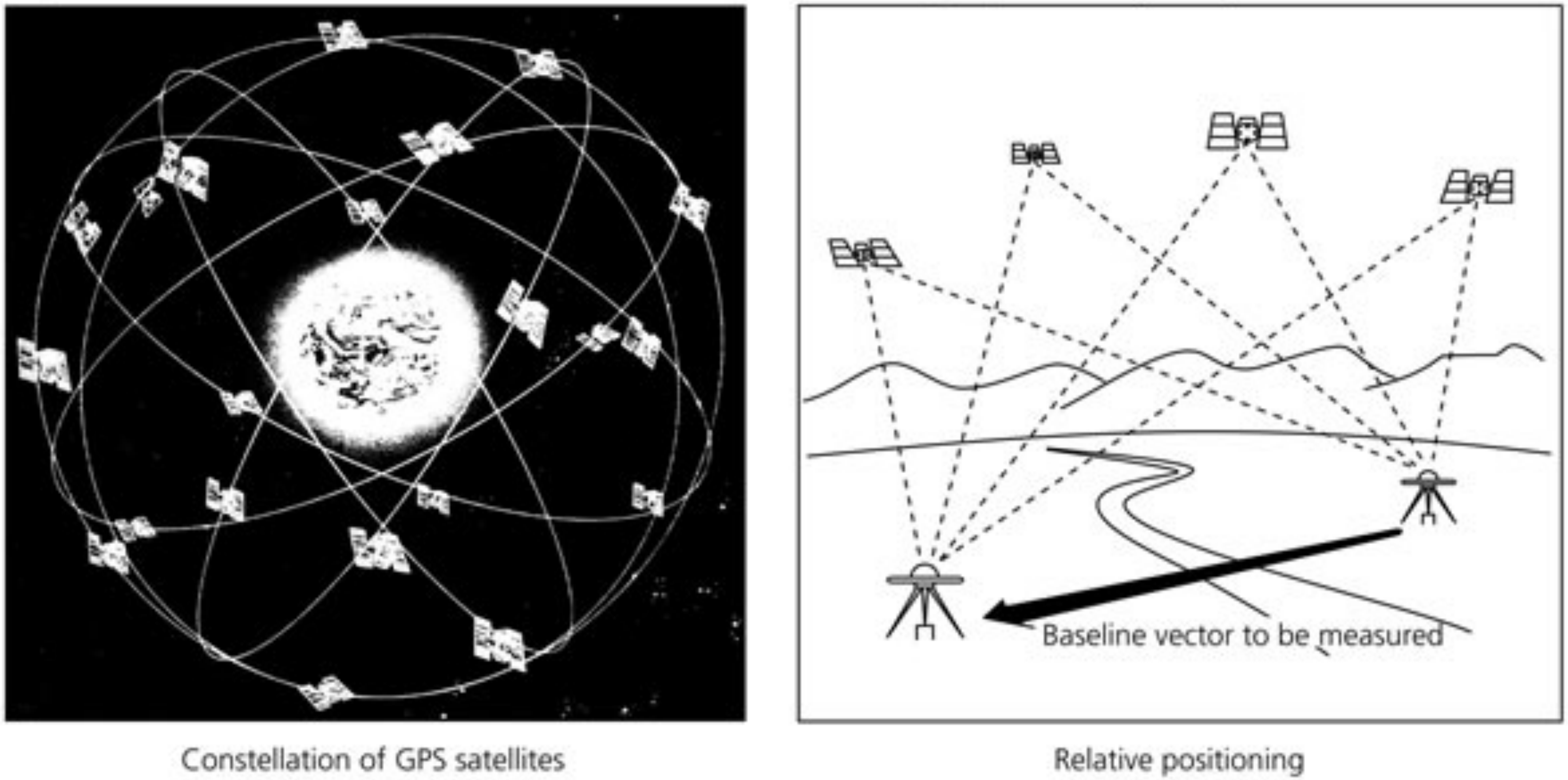
Relative positioning

Observation of surface deformation (I)

- Ground and satellite-based GPS surveys
- Precision of mm/year
- **Limitation?**

Geodetic observation

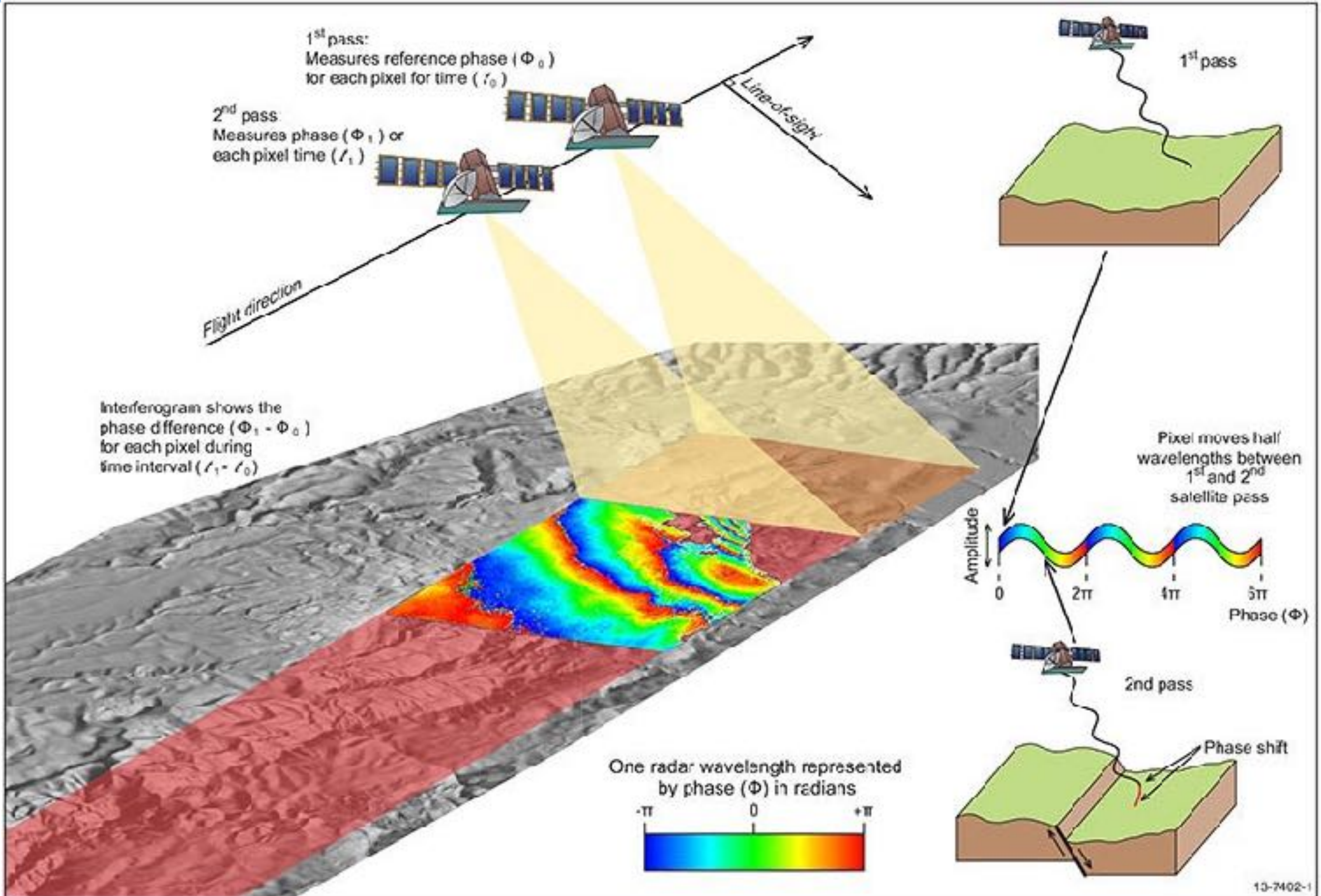
Figure 4.5-1: Cartoon of the Global Positioning System (GPS).



Observation of surface deformation (I)

- Ground and satellite-based GPS surveys
- Precision of mm/year
- **Limitation?** —> position of geodetic markers has to be set **before** the earthquake

Geodetic observation



Geodetic observation

Observation of surface deformation (II)

Alternative: High resolution Radar mapping from Space by **InSAR** (Synthetic Aperture Radar interferometry)

—> 2 or more SAR images are combined to generate maps of surface elevation or deformation using phase differences in the returning signals to the aircraft or satellite

—> One fringe of phase difference is generated by a ground motion of half the radar wavelength, since this corresponds to a whole wavelength increase in the two-way travel distance.

—> Limitations?

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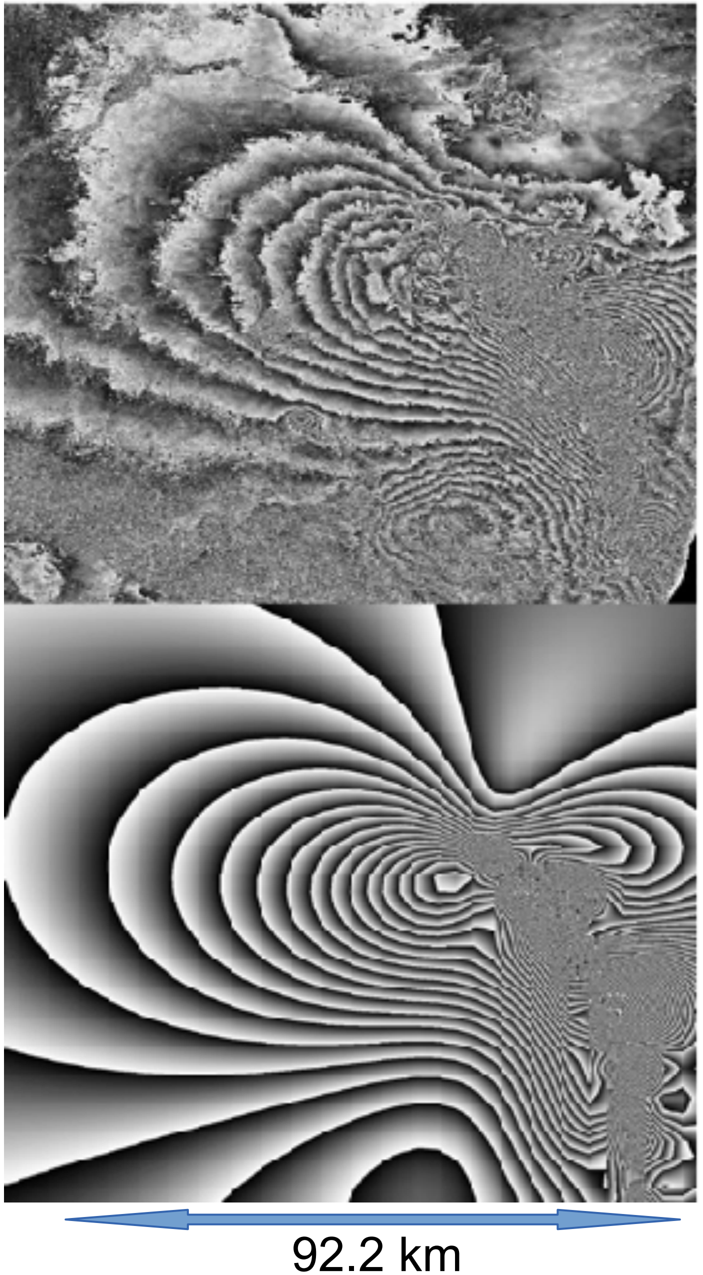
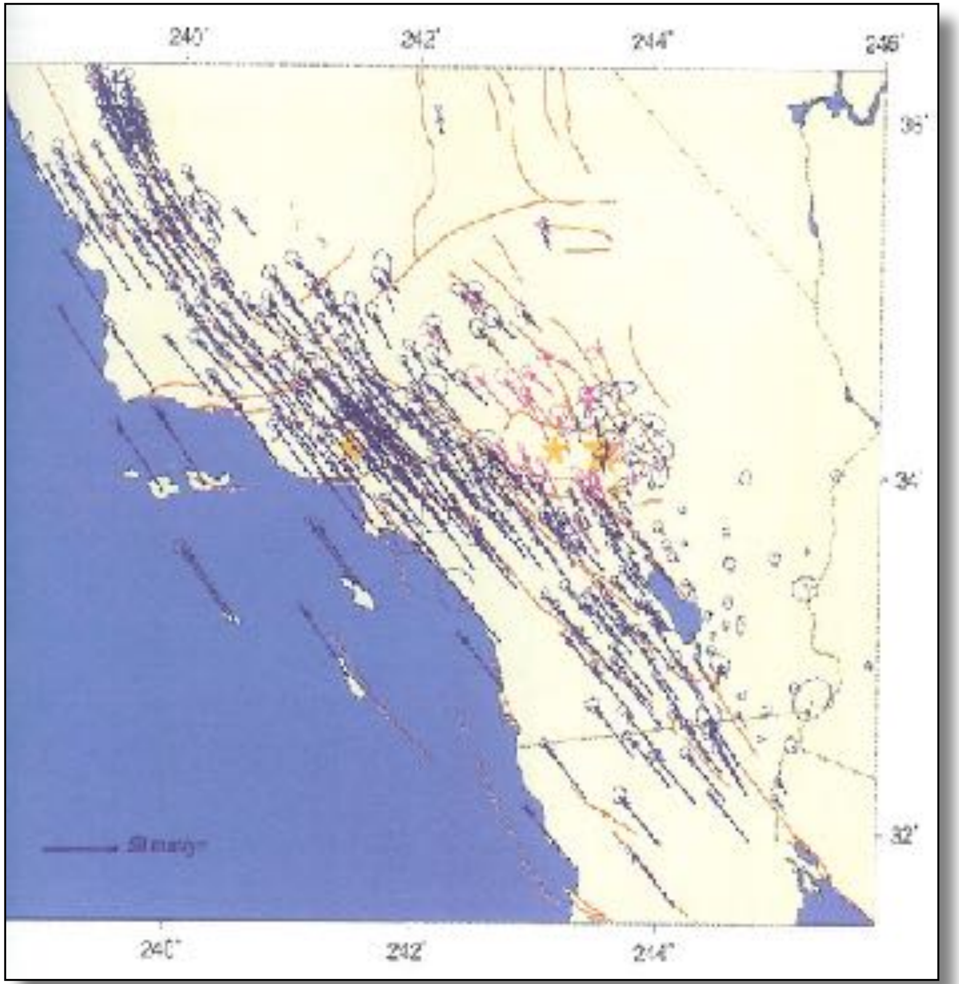


Geodetic observation

Strain accumulation



50mm/yr

Horizontal deformation velocities relative to North-American Plate

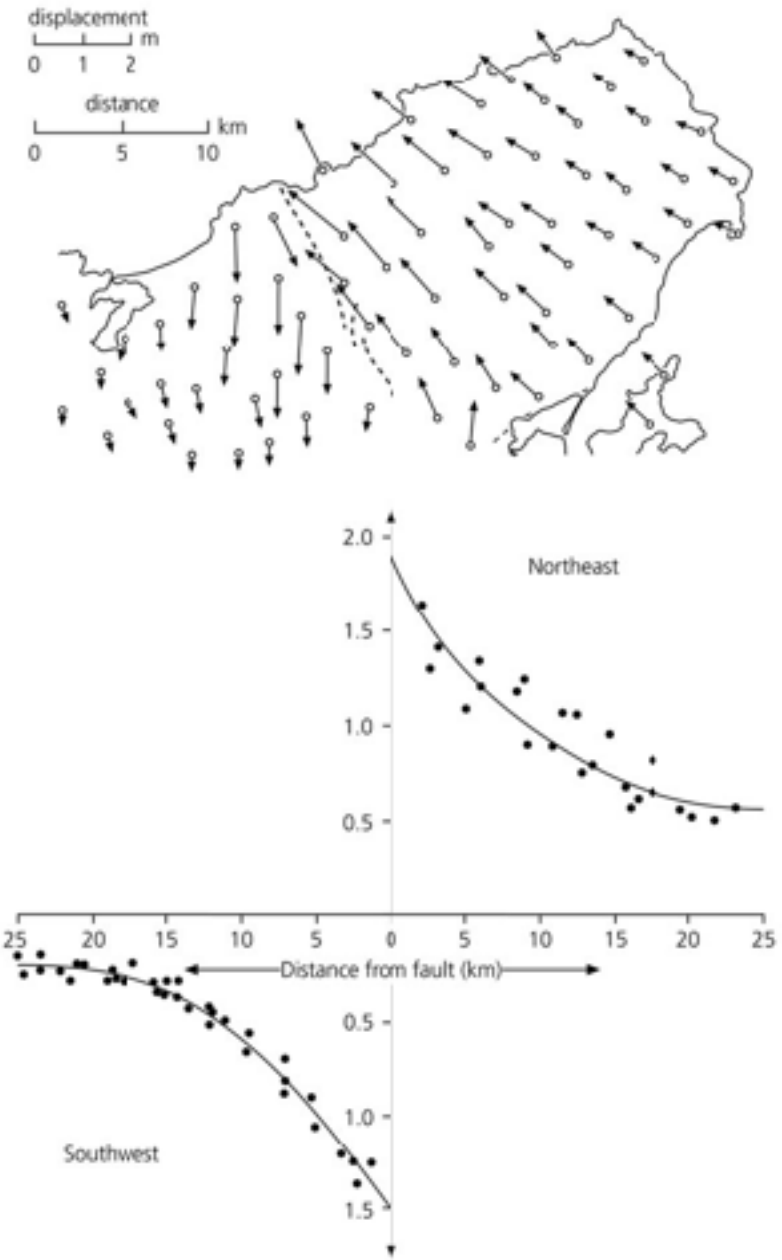
Strain is accumulated by a series of sub-parallel faults over 300km

Geodetic observation

Strain accumulation

- strain accumulation is concentrated near the fault

Figure 4.5-4: Static displacements for the 1927 Tango, Japan, earthquake.

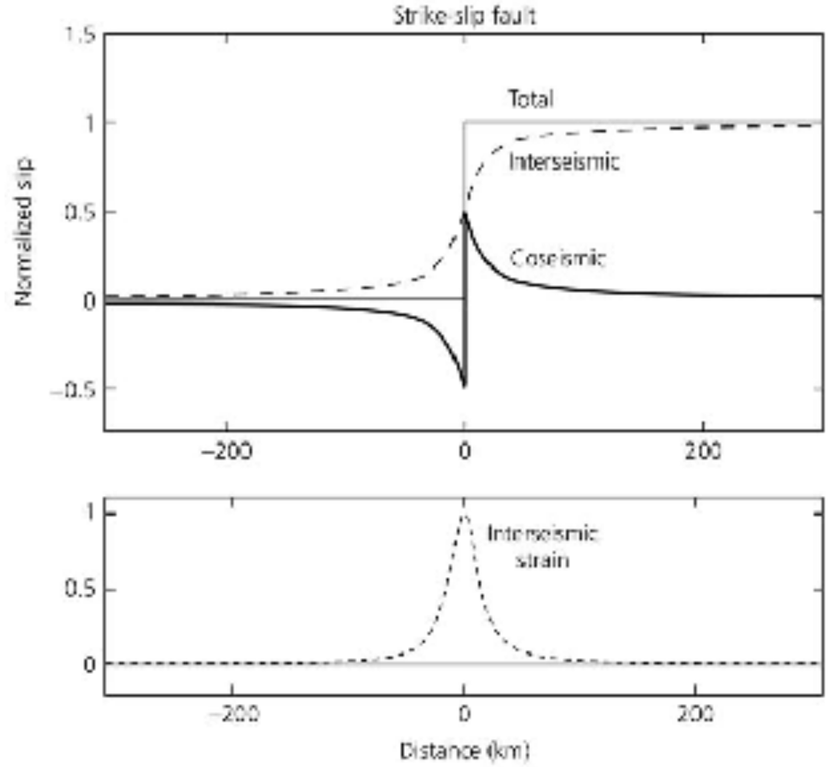


Geodetic observation

Strain accumulation

- strain accumulation is concentrated near the fault
- Inter-seismic slow strain changes
- Pre-seismic strain change just before an earthquake
- Co-seismics (sudden) strain changes (also at considerable distance away from earthquakes)

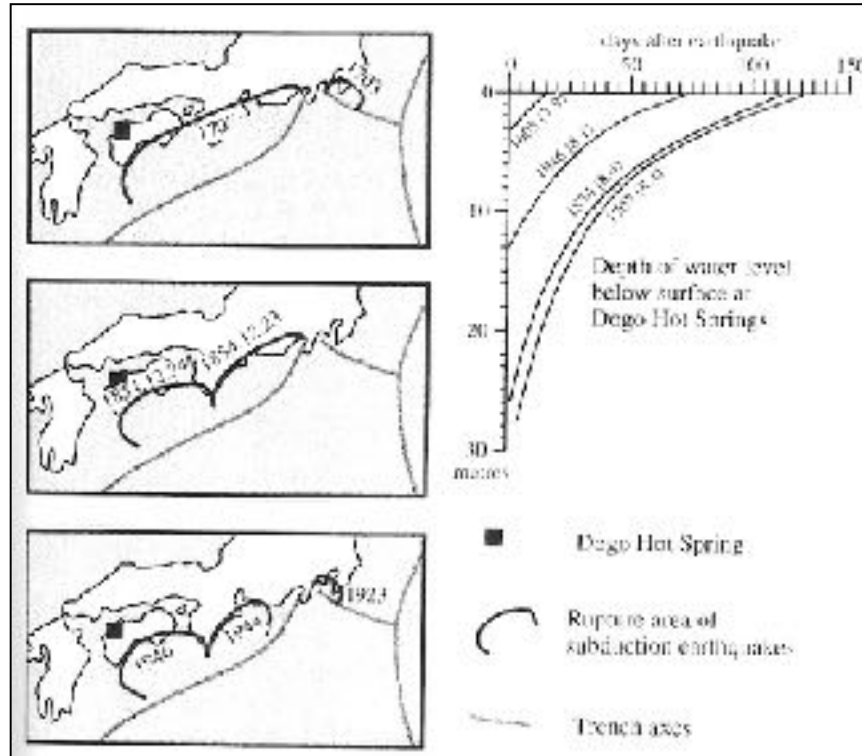
Figure 4.5-12: Coseismic and interseismic slips and strains.



Geodetic observation

Strain accumulation

- strain accumulation is concentrated near the fault
- Inter-seismic slow strain changes
- Pre-seismic strain change just before an earthquake
- Co-seismics (sudden) strain changes (also at considerable distance away from earthquakes)
- Post-seismic deformation (after-slip, poroelastic relaxation and viscoelastic relaxation of lower crust and upper mantle)



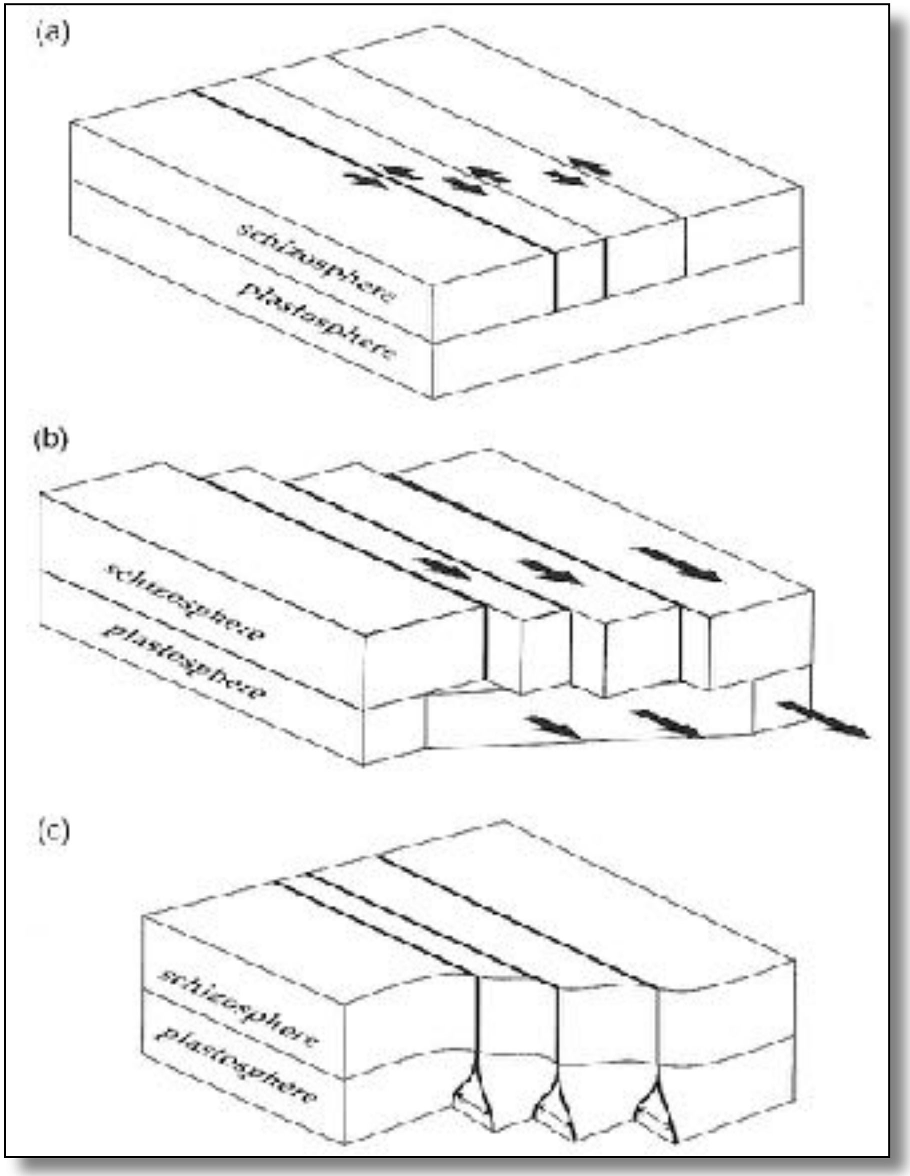
→ **The seismic cycle cannot be explained by a simple elastic system**

Strain accumulation models

- Strong schizosphere underlain by a weak viscous plastosphere

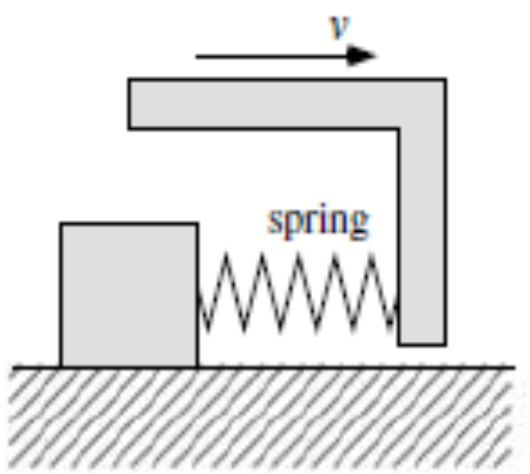
- Shear in strong plastosphere drives slip in weak schizosphere

- Interseismic slip on ductile shear zones in plastosphere loads the faults



Schizosphere: the part that can break - brittle
Plastosphere: the part that flows - ductile

Spring Block Model



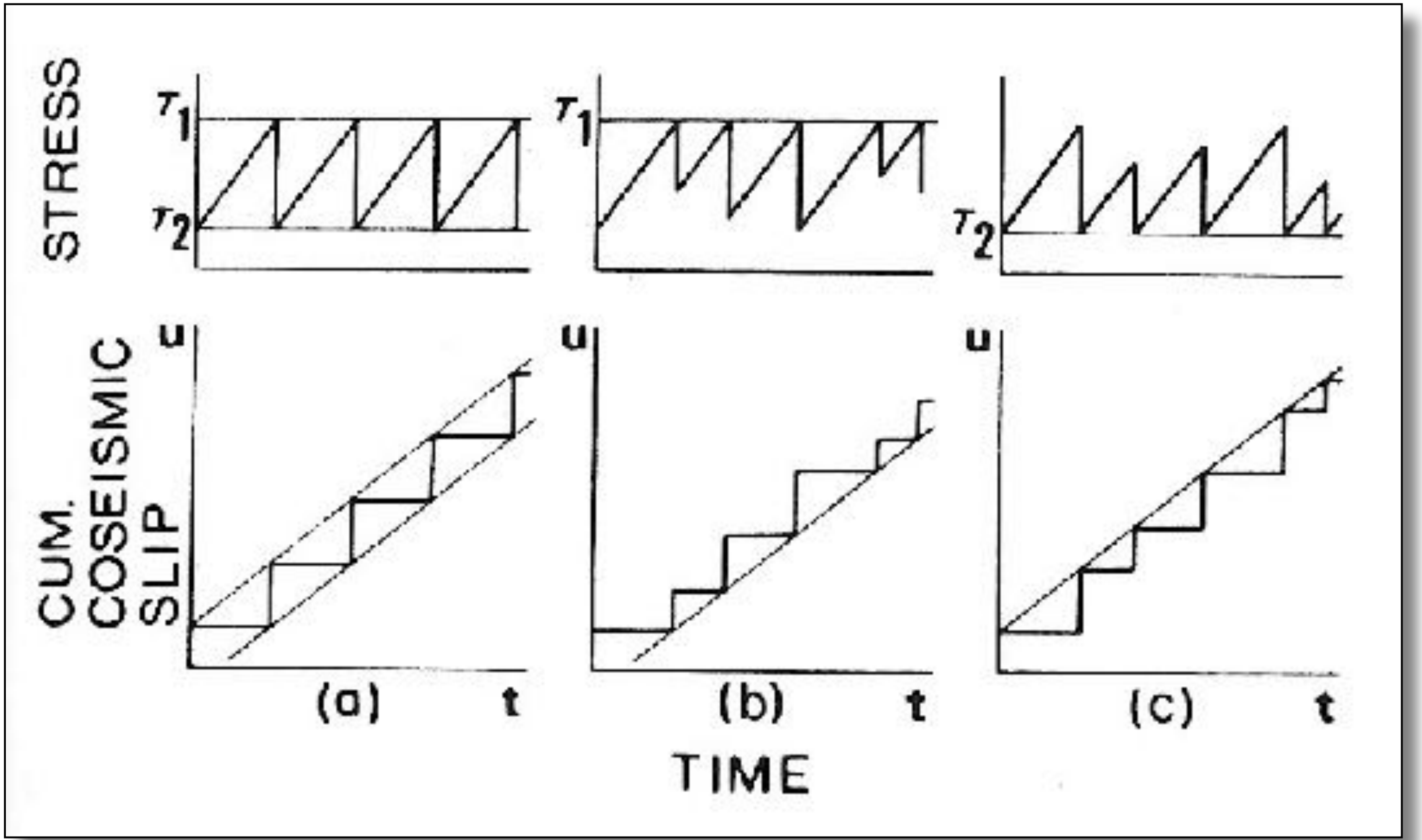
- Parameters: → static friction coefficient
  → dynamic friction coefficient
  → plate pulling rate

→ the block exhibits stick-slip behavior

Spring Block Model

Cyclic, yes, but periodic?

$\mu_d,\ \mu_s,\ v = c$ $\qquad \mu_d \neq c$ $\qquad \mu_s \neq c$



a) Reid‘s model – completely predictable

b) time-predictable model – size of event is not predictable

c) slip-predictable model - occurrence time is not predictable

Spring Block Model

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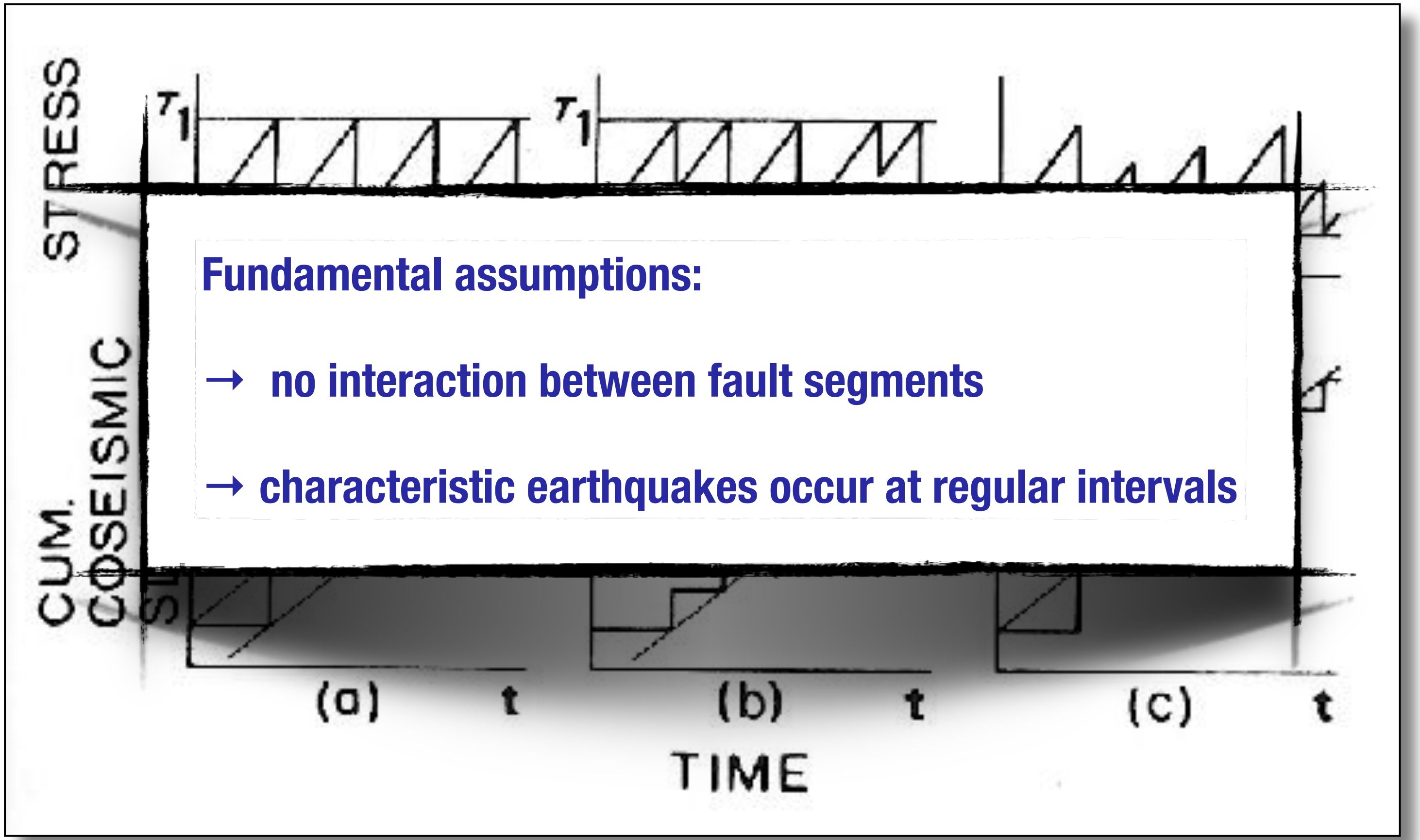

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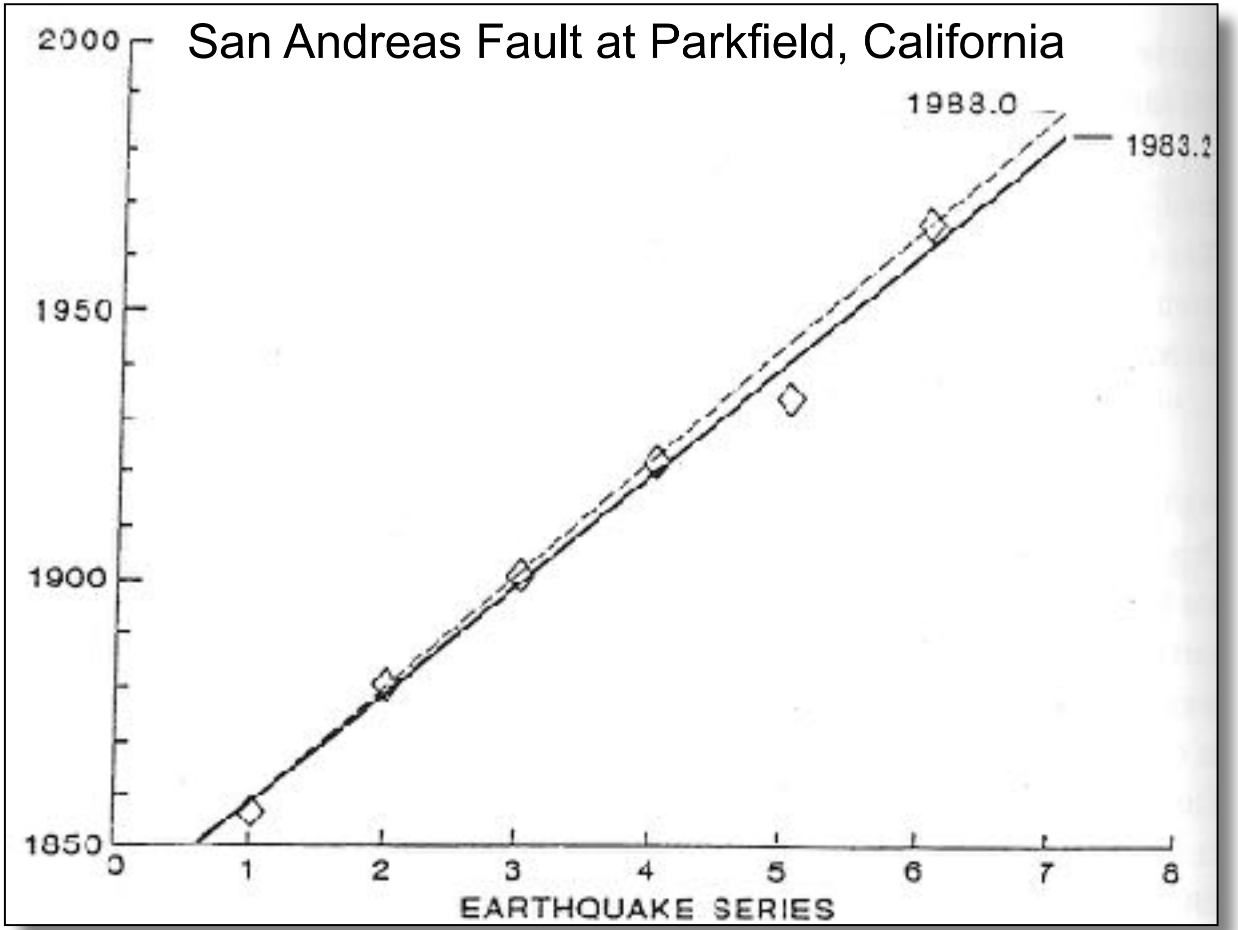
Example: Parkfield



- M_b > 5.5 events occurred 1857, 1881, 1901, 1922, 1934, 1966
- identical waveforms → same fault segement ruptures

→ **“Predicition” of a M_b ~ 6 event in 1984**

Example: Parkfield

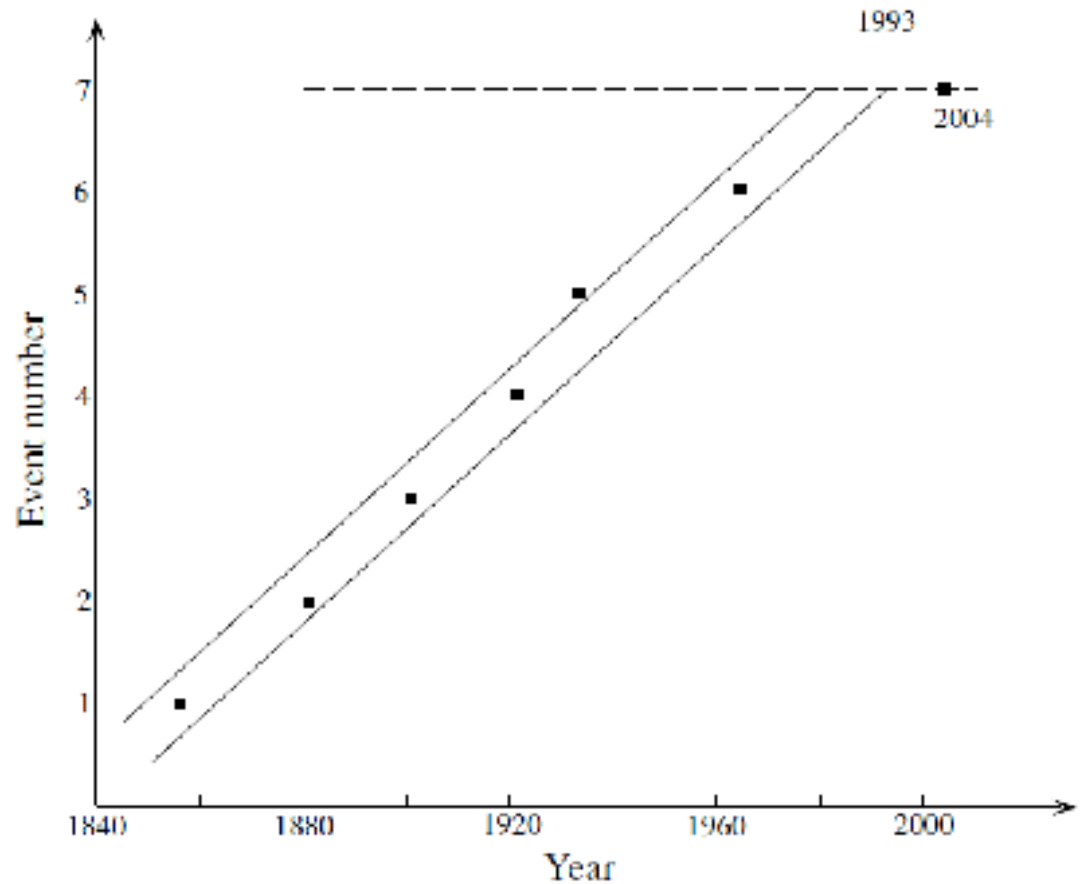


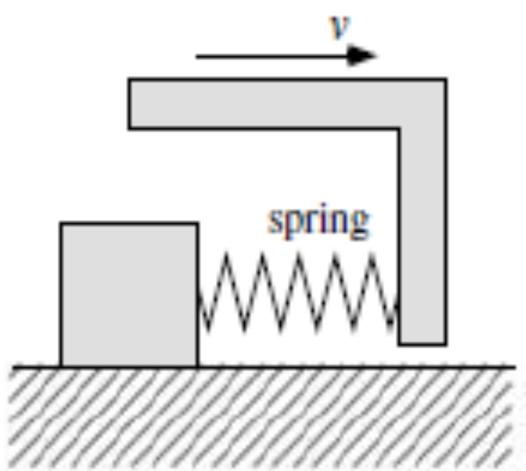
Figure 10.3 Significant earthquakes at Parkfield, California, have repeated at fairly regular intervals since 1850, leading to predictions of another event before 1993. However the earthquake did not occur until 2004.

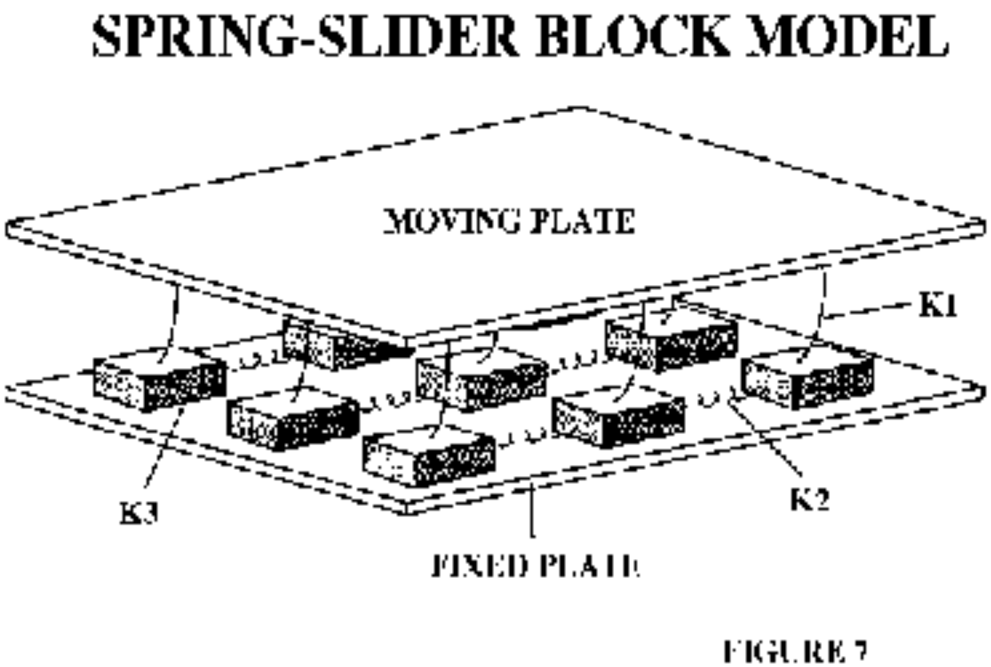
- M_b > 5.5 events occurred 1857, 1881, 1901, 1922, 1934, 1966
- identical waveforms → same fault segement ruptures

→ "Predicition" of a M_b ~ 6 event in 1984, but occurred only in 2004

Spring-slider block model

Spring Block model





- Parameters: → static friction coefficient
  → dynamic friction coefficient
  → plate pulling rate

→ the block exhibits stick-slip behavior

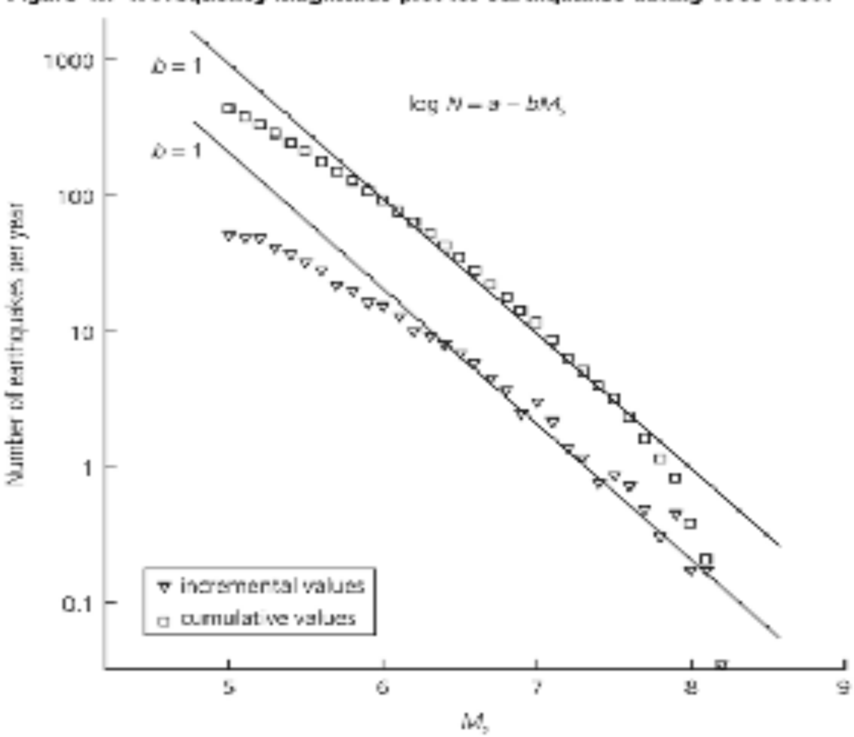
- Parameters: → spring constant
  → friction law
  → individual friction coefficients

→ the blocks can reproduce observed seismicity patterns or chaotic behavior

Earthquake statistics

- Besides aftershock sequences, events in real earthquake catalogs occur at random times (Poisson model)
- Exceptions at small scales: e.g. earthquake swarms
- Small earthquakes are the base of statistical recurrence models
- Some studies (palaeoseismology) indicate that great earthquakes occur at irregular intervales with some tendency to cluster in time

Figure 4.7-1: Frequency-magnitude plot for earthquakes during 1968-1997.



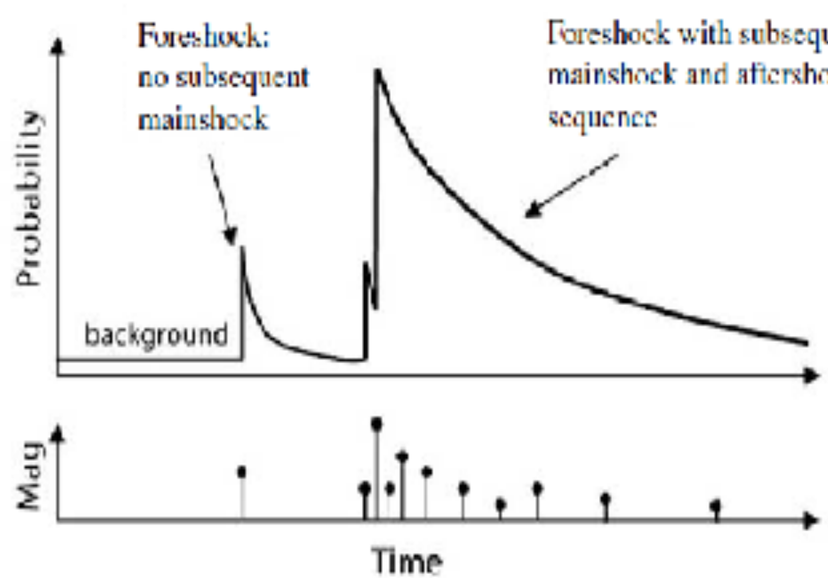


Figure 10.7 A cartoon illustrating how earthquake probability increases immediately after prior events, and then decays back to the background seismicity rate. Figure adapted from web material at: http://pasadena.wr.usgs.gov/step/.

Earthquake statistics

- Real-time predictability programs for ground shaking based on aftershock distributions, earthquake triggering statistics, shaking intensity – magnitude relations, ...

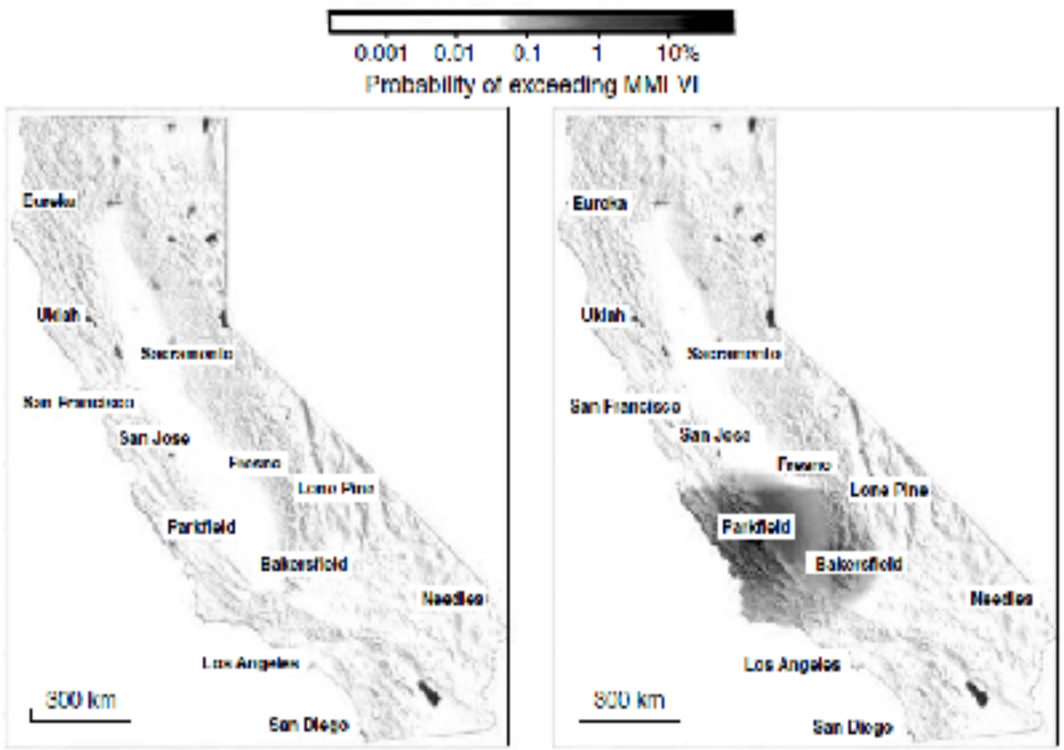
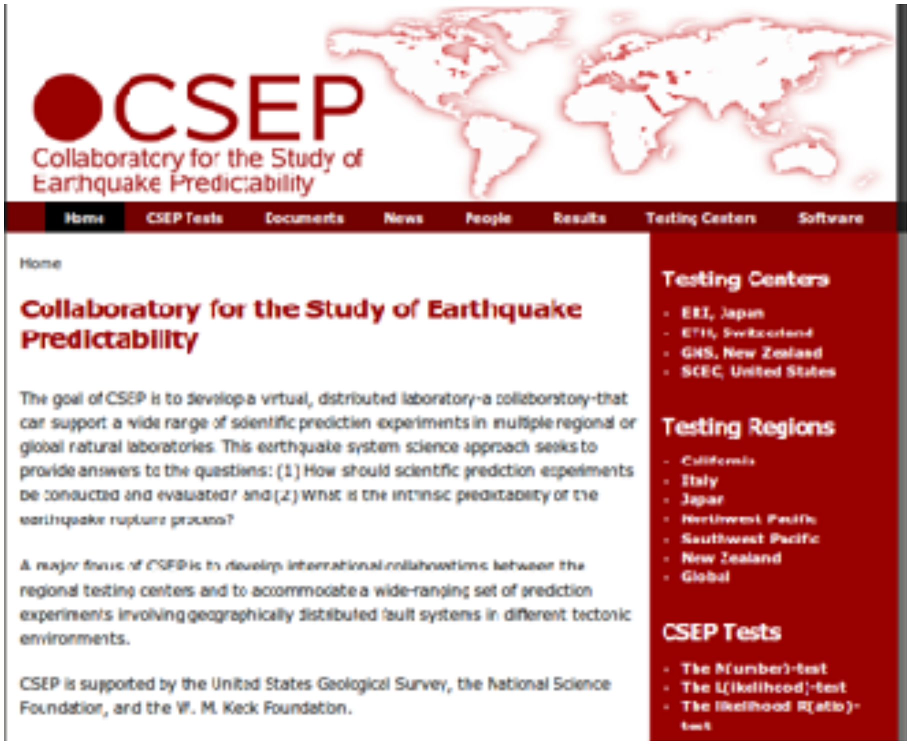


Figure 10.8 The probability of local ground motions of modified Mercalli intensity 6 or greater within a 24-hour period, immediately before and after the 2004 Parkfield earthquake in California. Source: http://pasadena.wr.usgs.gov/step/

http://cseptesting.org/

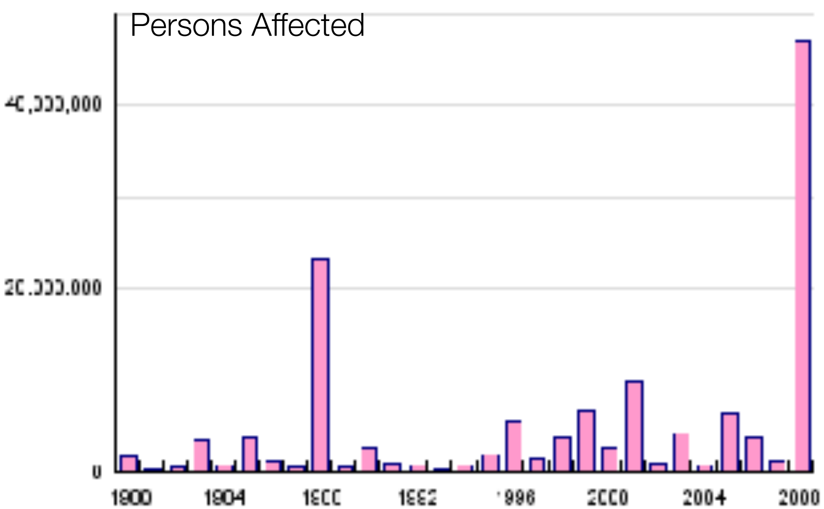


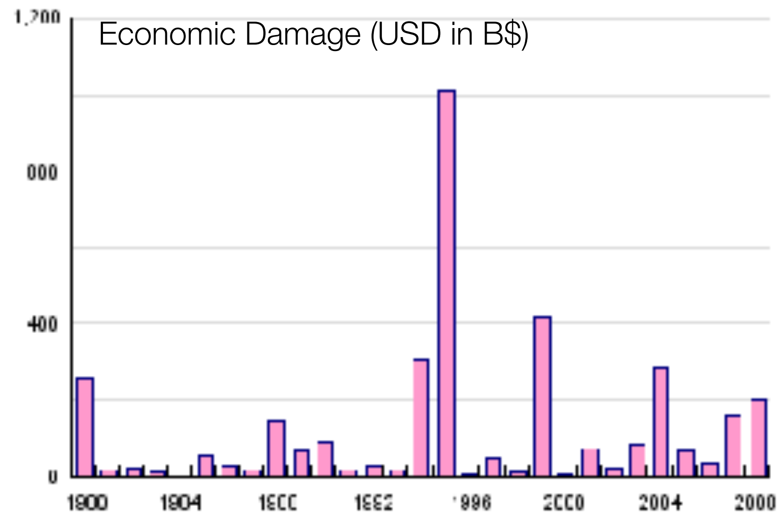
→ the physics behind space-time clustering of earthquakes is not well understood

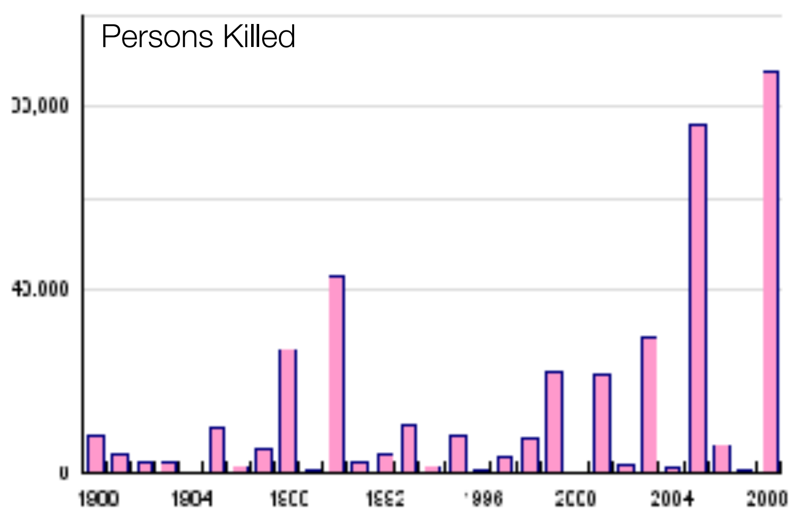
→ earthquake forecasts are easy to make and hard to test (must be validated with data not used in the model development)

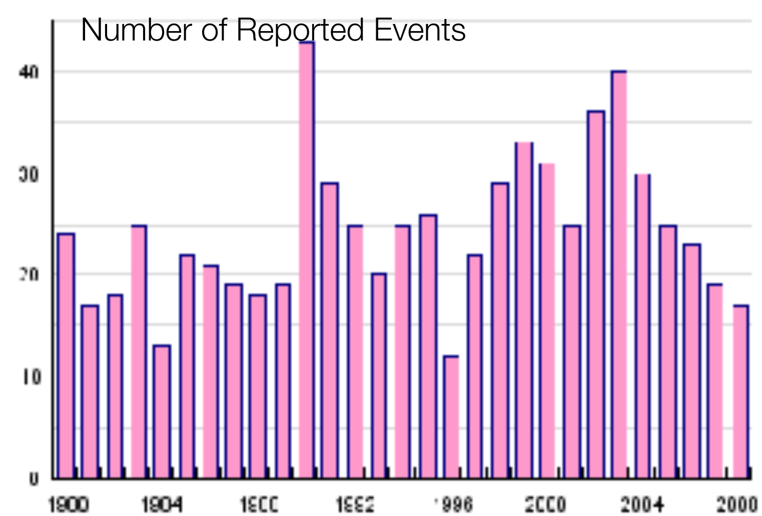
Global Earthquake Statistics, 1980-2008

http://www.preventionweb.net/english/hazards/statistics/?hid=60









Global Earthquakes

Summary Statistics, 1980-2008

http://www.preventionweb.net/english/hazards/statistics/?hid=60

Earthquake disasters from 1980 - 2008

Overview

No of events:	706
No of people killed:	385,630
Average people killed per year:	13,298
No of people affected:	136,333,515
Average people affected per year:	4,701,156
Economic Damage (US$ X 1,000):	351,079,755
Economic Damage per year (US$ X 1,000):	12,106,198

Top 10 Disasters Reported

Affected people

Disaster	Date	Affected	(no. of people)
China P Rep	2008	45,976,596	
India	1988	20,003,766	
India	2001	6,321,812	
Pakistan	2005	5,128,000	
China P Rep	1996	5,077,795	
Indonesia	2006	3,177,923	
China P Rep	1999	3,020,004	
Japan	1983	2,550,028	
Mexico	1985	2,130,204	
China P Rep	2000	1,855,007	

Killed people

Disaster	Date	Killed	(no. of people)
China P Rep	2008	87,476	
Pakistan	2005	73,338	
Iran Islam Rep	1990	40,000	
Iran Islam Rep	2003	26,796	
Soviet Union	1988	25,000	
India	2001	20,005	
Turkey	1999	17,127	
India	1993	9,748	
Mexico	1985	9,500	
Indonesia	2006	5,778	

Economic damages

Disaster	Date	Cost	(US$ X 1,000)
Japan	1995	100,000,000	
United States	1994	30,000,000	
Japan	2004	28,000,000	
China P Rep	2008	20,000,000	
Italy	1980	20,000,000	
Turkey	1999	20,000,000	
Taiwan (China)	1999	14,100,000	
Soviet Union	1988	14,000,000	
Japan	2007	12,500,000	
Iran Islam Rep	1990	8,000,000	

Magnitude and Intensity

- Mercalli Intensity is a measure of ground shaking only
- A small earthquake close by can produce the same PGA (Peak Ground Acceleration) and PGV (Peak Ground Velocity) as a large earthquake far away
- However, the wave characteristics will be different (duration of shaking, frequency content of waves, etc.)
- Note that buildings are sensitive not only to PGA, but shaking duration and frequency
- So we need some more general concepts
- In about 1927, Richter and Gutenberg introduced the concept of earthquake magnitude

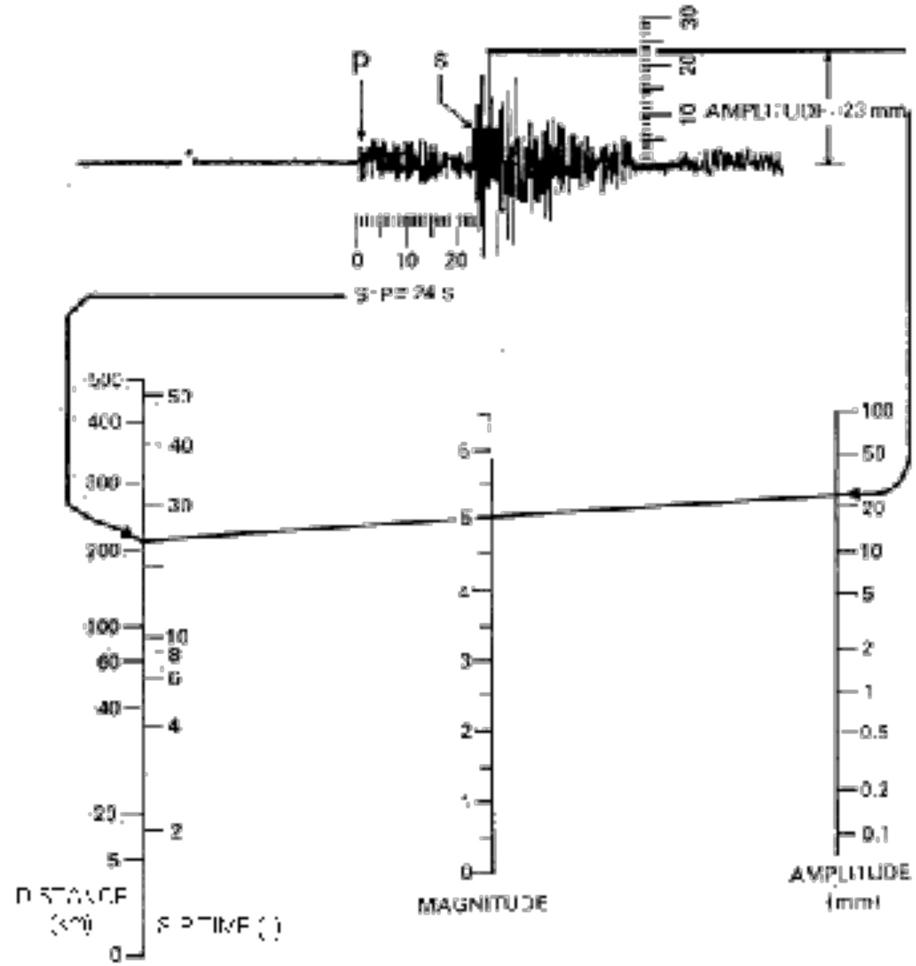
Characteristics of Magnitude

- Gutenberg and Richter had noticed that the amplitude of seismic waves decreases away from the earthquake source position (hypocenter/epicenter) with distance
- The decay in amplitude depends not only on the earth, but also on the observing instrument characteristics
- The sensitivity of the magnitude scale depends on the frequency response of the instrument and its dynamic range (whether waveforms can be "clipped" if the amplitude is too large)
- They adopted a standard instrument, the Wood-Anderson torsional seismometer, and defined an amplitude corresponding to a Magnitude=0 earthquake
- They decided to create a logarithmic scale similar to the magnitude scale of stellar brightness from astronomy
- Strictly speaking, their original scale applies only to earthquakes in southern California, where they were working

Earthquake “Nomogram”

crack.seismo.unr.edu

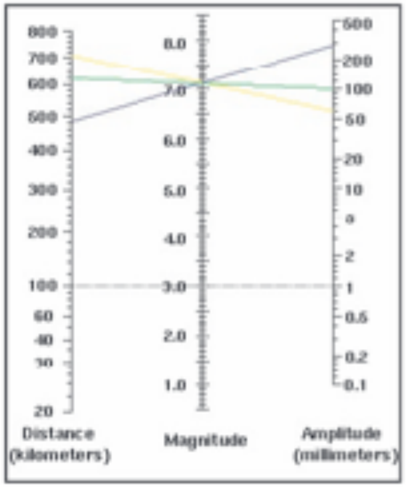
- A version of this earthquake "nomogram" was posted in the recording center of the Caltech seismological laboratory for at least 60 years
- It was used by generations of seismolab students to determine the magnitude from the seismogram
- To apply this, you measure the S-P Time, which gives the Distance in km
- Then you measure the trace Amplitude
- Drawing the straight line intersects the middle scale at the Magnitude value



Determining Earthquake Location

http://academics.concord.edu/sckuehn/VirtualEarthquake.pdf

- To compute the epicenter location of the earthquake, you need to "triangulate" the arrivals
- The epicenter is the horizontal position of the first motion
- The hypocenter is the epicenter + depth information
- You need at least 3 earthquake recording stations
- Draw circles around the 3 stations using distances determined from the S-P times
- Shown here is the form locating the October 17, 1989 Loma Prieta earthquake
- The estimated magnitude is M7.1



Station	S-P Time Interval	Distance from Epicenter	S-wave Amplitude
Eureka, CA	50 seconds	485 Km	285 millimeters
Elko, NV	72 seconds	705 Km	60 millimeters
Las Vegas NV	64 seconds	622 Km	100 millimeters

Epicenter location: about 100 km SSE of San Francisco

Magnitude: about 7.1

Problems with Richter Magnitude

- It applies only to southern California
- It depends on using a certain type of seismometer (Wood Anderson)
- The Wood Anderson instrument is most sensitive to wave periods near 1 sec.
- Wood Anderson is weakly damped, so amplitudes at 1 sec period tend to be very large (resonance!)
- Other types of seismometers, such as the Press-Ewing instrument, are (were) in use, and these are most sensitive to waves at 20s period (surface waves such as Rayleigh and Love waves)
- These different seismometers give different magnitudes for the same earthquake
- In fact, great earthquakes rarely have Wood-Anderson magnitudes larger than 6, whereas the Press-Ewing magnitude might be 8
- Clearly a better means of determining magnitude is needed that does not depend on using a particular seismometer

Seismic Moment

- In order to understand earthquake magnitude, we have to return to energy release
- We define a quantity called "seismic moment" W, which is related to the source parameters of the earthquake:

$$W = \mu S A$$

- Here μ is a (shear) modulus of elasticity, S is the slip in the earthquake, and A is the slipped area of the fault
- It can be shown that W measures the change in stored elastic energy in the earthquake, plus any stored gravitational energy change
- Therefore W is a property of the earthquake source alone

Moment Magnitude Scale

http://en.wikipedia.org/wiki/Moment_magnitude_scale

- The moment magnitude scale (abbreviated as MMS; denoted as M_W or M) is used by seismologists to measure the size of earthquakes in terms of the energy released.
- The magnitude is based on the seismic moment of the earthquake, which is equal to the rigidity of the Earth multiplied by the average amount of slip on the fault and the size of the area that slipped.
- The scale was developed in the 1977 by Hiroo Kanamori and others to succeed the 1930s-era Richter Local magnitude scale (M_L).
- Even though the formulae are different, the new scale retains the familiar continuum of magnitude values defined by the older one.
- The MMS is now the scale used to estimate magnitudes for all modern large earthquakes by the United States Geological Survey.

Moment Magnitude

- Moment magnitude M_w is defined by:

$$M_w = (2/3) \, Log_{10} W - 6.0$$

- Here seismic moment W is defined in MKS (SI) units (meters-seconds-kg)
- By using moment magnitude, Kanamori was able to unify all measures of earthquake magnitude
- Both Richter magnitude and surface wave magnitude, determined using Press-Ewing seismometers, fit smoothly onto the same scale

Comparing Magnitude Calculations

http://en.wikipedia.org/wiki/Moment_magnitude_scale

The following table compares magnitudes towards the upper end of the Richter Scale for major Californian earthquakes.[1]

Date	Seismic moment $M_0 \times 10^{25}$ (dyne-cm)	Richter scale M_L	Moment magnitude M_w
1933-03-11	2	6.3	6.2
1940-05-19	30	6.4	7.0
1941-07-01	0.9	5.9	6.0
1942-10-21	9	6.5	6.6
1946-03-15	1	6.3	6.0
1947-04-10	7	6.2	6.5
1948-12-04	1	6.5	6.0
1952-07-21	200	7.2	7.5
1954-03-19	4	6.2	6.4

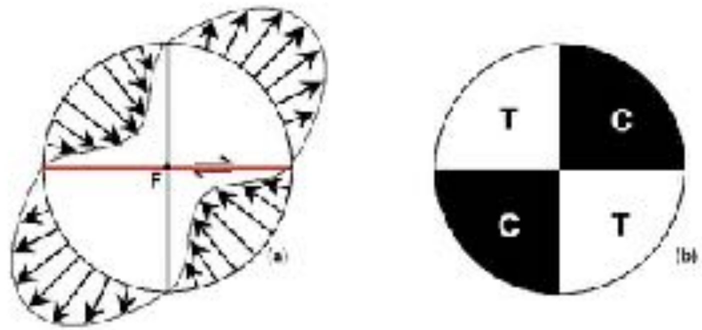
Next Question:

How is seismic moment determined?

- First, it is important to use a class of broad band, high-dynamic range seismometer to record the waves so that no distortions are produced
- Then we need at least a dozen or more seismometers, spread out over a variety of directions and distances to adequately sample the waves
- We then use computer programs to fit a source model to the actual waveforms
- The source model involves both the type of fault, as well as the time-dependence of slip on the fault
- We also need an earth model that represents how the seismic waves propagate through the earth
- The final result is a complete description of the earthquake source

Determination of Focal Mechanism

- Simplest method is to use first motion data (up or down, in or out, etc.)
- Plot these on focal sphere for various stations
- Then choose best fitting "nodal planes"
- Either of the nodal planes can represent the actual fault
- The most probable fault plane is usually chosen either by reference to local tectonics, or by observing the pattern of aftershocks
- Geologists plot fault planes on a "stereonet" in a similar way



Schematic diagram showing the direction of initial movement of particles around the focus (F) of an earthquake on a W-E dextral strike-slip fault, viewed from above (a) and the equivalent zones of compressional (C) and tensional (T) sense first motion in the seismic waves radiating outward (b).

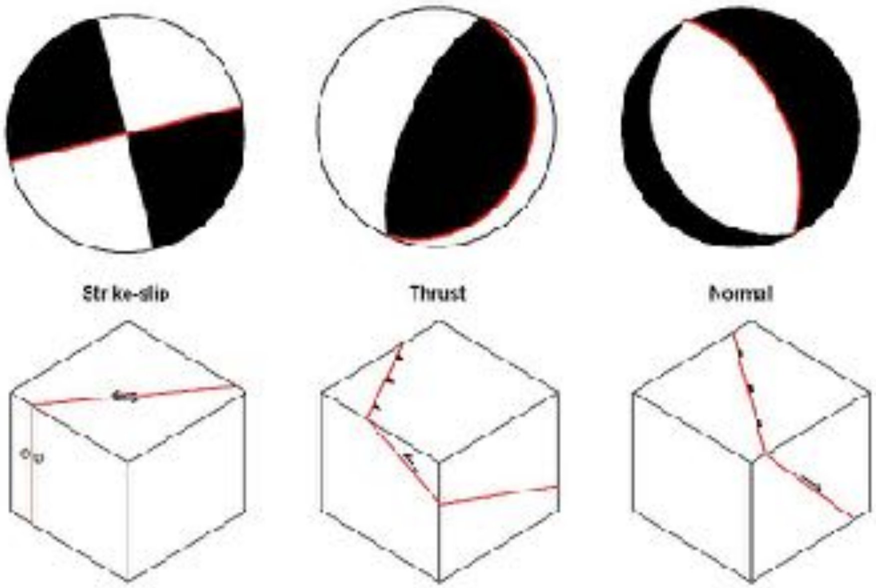
Note that due to the symmetry, an identical pattern would result from movement on an N-S sinistral strike-slip fault passing through the focus.

https://www.youtube.com/watch?v=JJAMAcf_BEc

Type of Earthquake Focal Mechanisms

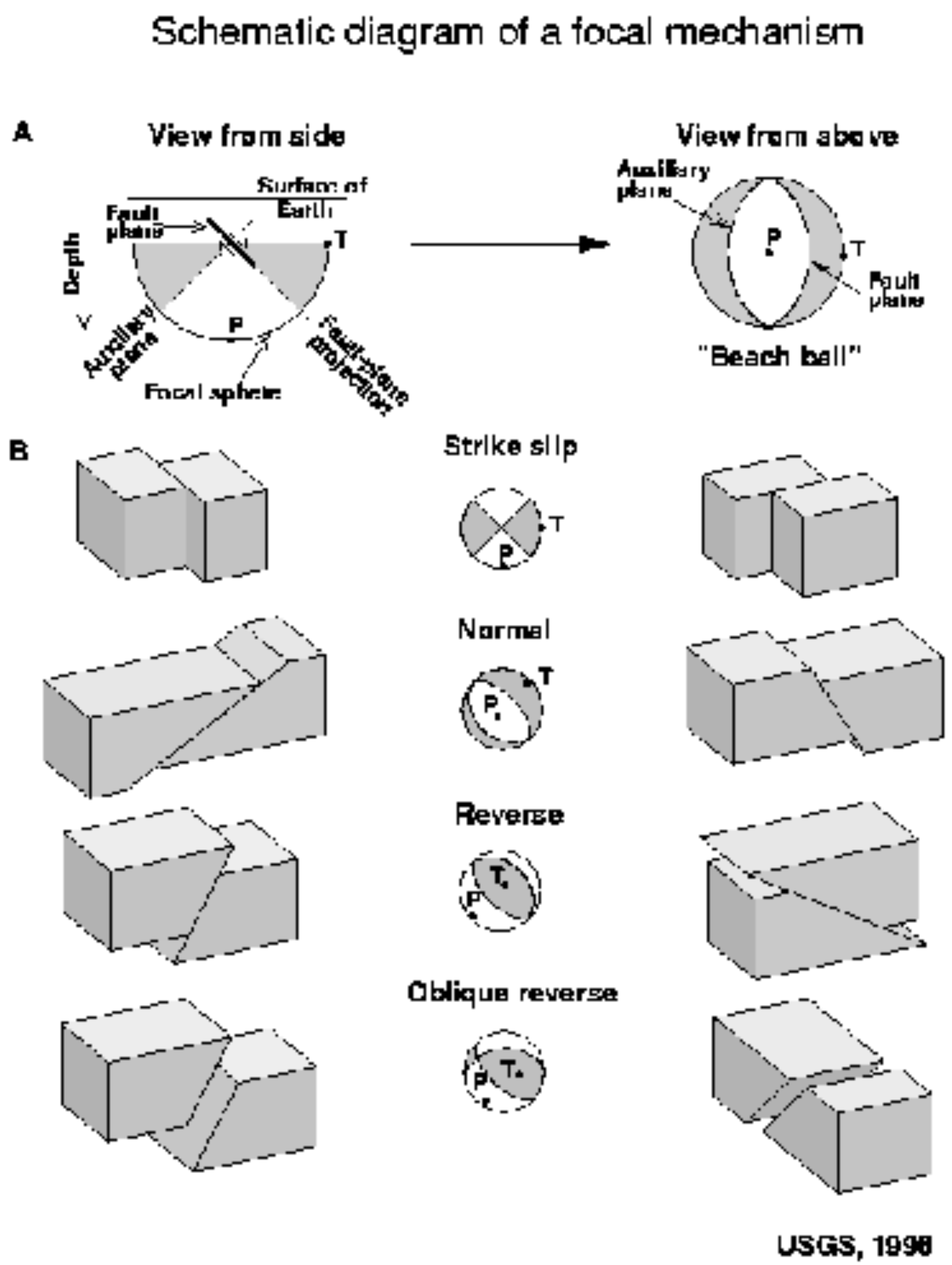
http://en.wikipedia.org/wiki/Focal_mechanism

- Earthquake source mechanisms
- Strike-slip, thrust, and normal faults
- As determined by analysis of the radiation pattern
- Simplest method is to use local first motions



Types of 'beachball plot' associated with different fault end-members
(nodal plane in red parallel to fault)

Focal Sphere: Another View



Great Global Earthquakes

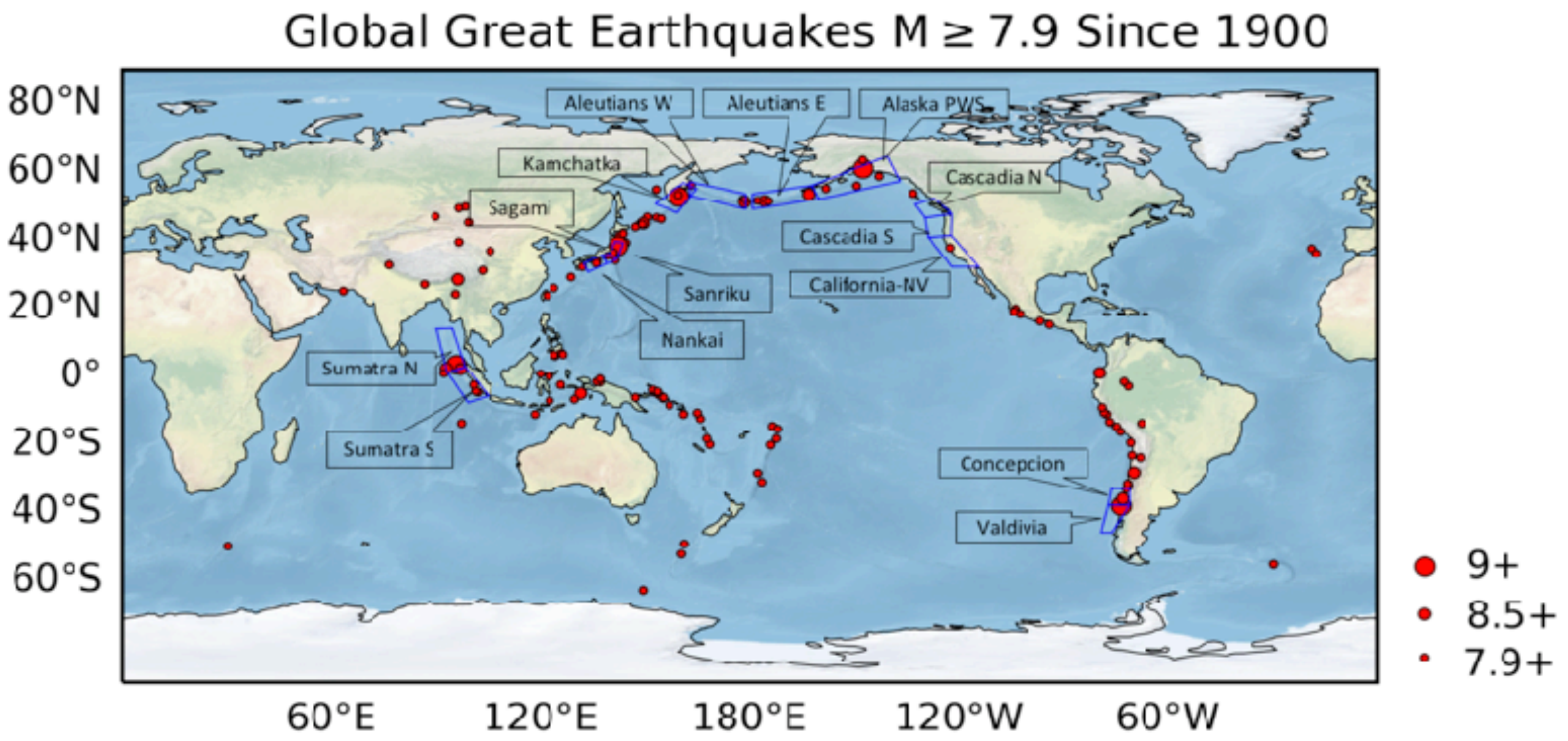


Figure 1. Map with polygons used to define source regions of great earthquakes used in the analysis. Of interest here is the source polygon for the M9.0 Kamchatka earthquake on 11/04/1952. The great earthquakes having $M \geq 7.9$ are shown as red circles. These are used to define the histogram of small earthquakes used to compute the Earthquake Potential Score.

Beno Gutenberg

http://en.wikipedia.org/wiki/Beno_Gutenberg

- Born June 4, 1889, Darmstadt, German Empire
- Died January 25, 1960, Pasadena, CA
- Graduated from the University of Gottingen

Beno Gutenberg

http://en.wikipedia.org/wiki/Beno_Gutenberg

- Gutenberg, especially in his collaboration with Charles Francis Richter, made the Caltech Seismological Laboratory the leading seismological institute worldwide.
- Collaborating with Richter, Gutenberg developed a relationship between seismic magnitude and energy
- They also developed a relationship between seismic magnitude and frequency of occurrence.
- This relationship is commonly referred to as the “Gutenberg-Richter Magnitude-Frequency Relation”

Earthquake Statistics:
Gutenberg-Richter Relation

- In 1942, G&R discovered that earthquake occurrence follows a specific type of law
- They observed that the number of small magnitude earthquakes is much larger than the number of large magnitude earthquakes and follows a well-determined relation
- The Gutenberg-Richter law is then:

$$N = 10^{a}\, 10^{-bM}$$

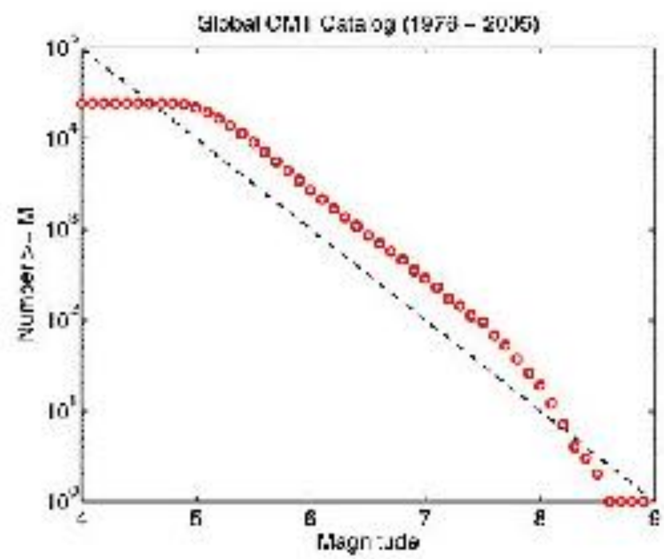
- Here N is the cumulative number of earthquakes larger than Magnitude M, and a and b are constants
- Also, a represents the level of seismicity, and b ~1 (by observation)

Data from the Global Centroid Moment Catalog of Global Earthquakes

(Morgan Page: earthquake.usgs.gov)

- A plot of the cumulative number of earthquakes larger than M vs. M shows this characteristic form
- The flattening at small magnitudes (M≤5) is due to lack of small earthquakes in the catalog
- At the large magnitude end, is often presumed that the catalog is incomplete due to sampling statistics
- However, the changes at large magnitude may be real...

The Gutenberg-Richter Magnitude Distribution

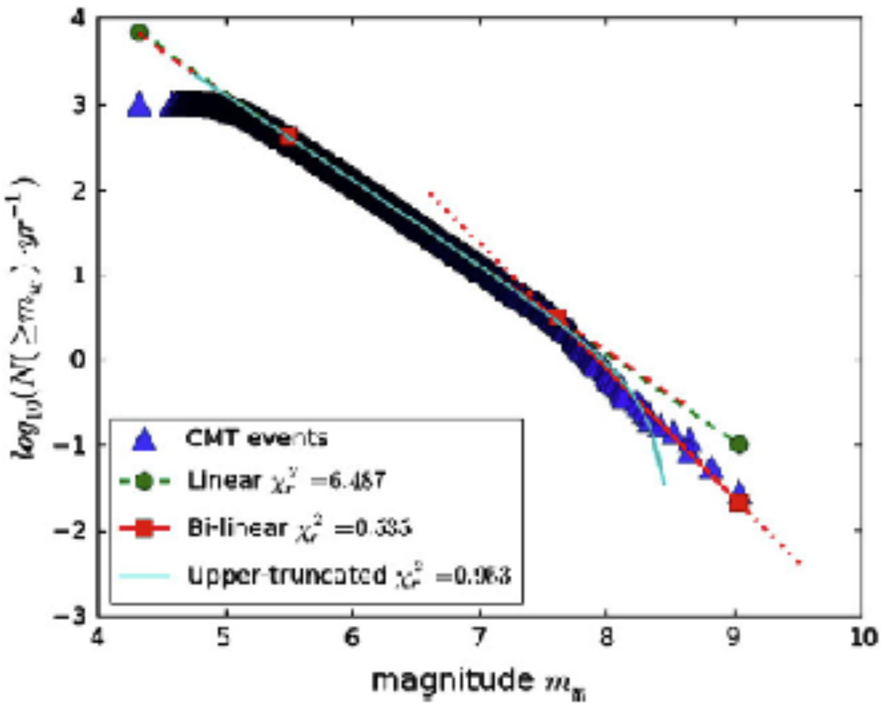


For any randomly chosen collection of earthquakes,
$\log(N \geq M) = a - bM$

Deviations at Large Magnitude

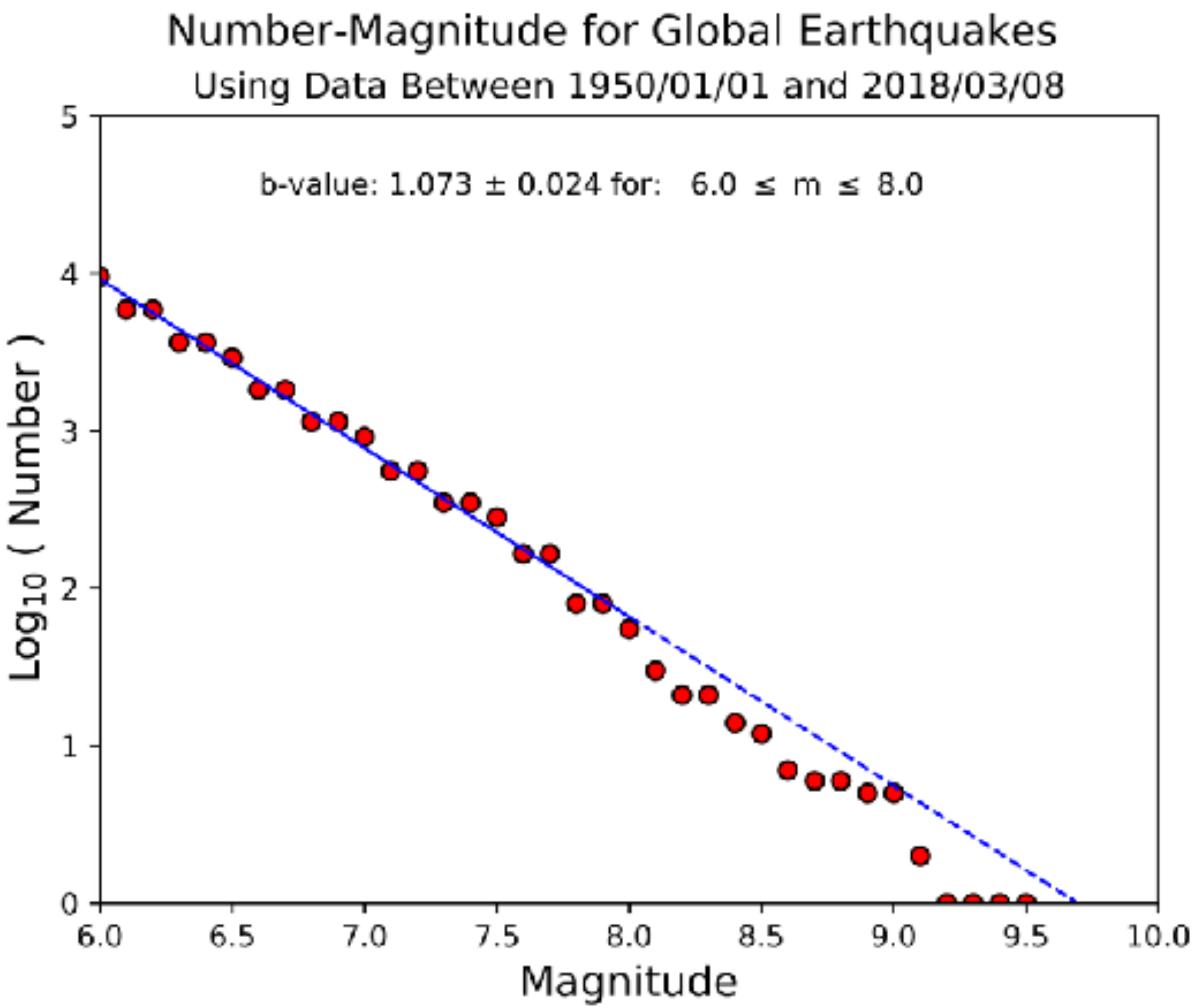
(Yoder et al. Tectonophysics, 2012)

- If we look at the large magnitude end, we see an interesting deviation beyond M>7.5
- The GR b-value changes from ~1 to ~1.5
- This implies that large and great earthquakes have lower frequency of occurrence than what would be expected for b~1
- The magnitude M~7.5 corresponds to a lithospheric thickness of about 30 km



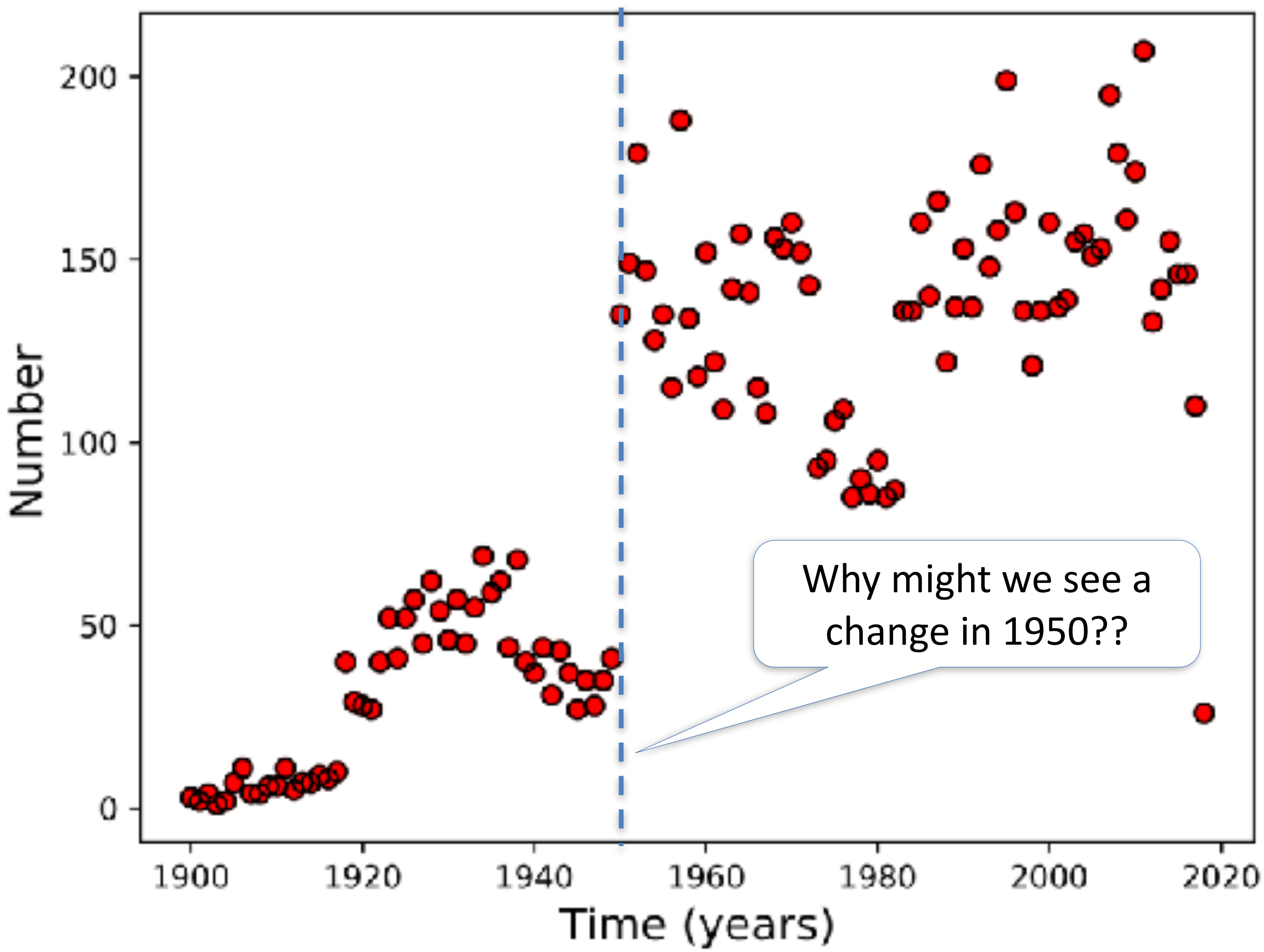
Global Magnitude-Frequency Relation

A long term look with the USGS global catalog



But…Data is Incomplete at Early Times

Global Earthquake Numbers vs. Time for M ≥ 6.0
Between 1900 and 2018



Earthquake Statistics can Vary in Time

Before the M9.1 Tohoku Japan Earthquake

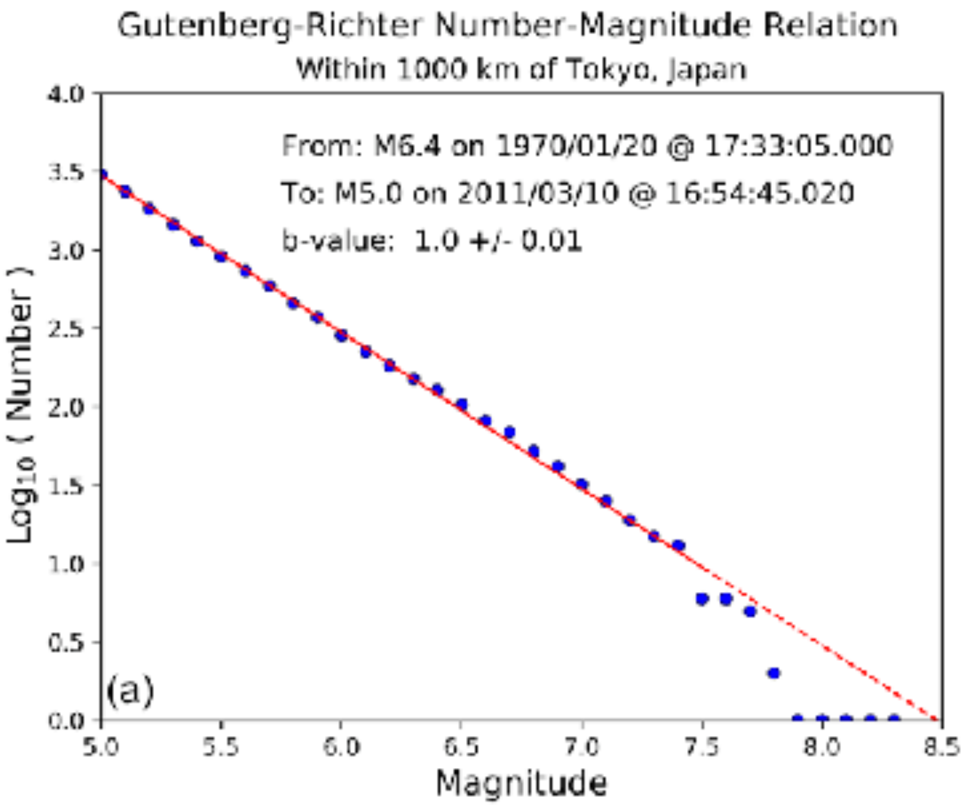


Figure 4(a). Magnitude-frequency data for the spatial region within 1000 km of Tokyo, Japan, prior to the M9.1 mainshock on March 11, 2011. Solid red line indicates the magnitude range fit by the scaling line, from M5.0 to M7.5.

After the M9.1 Tohoku Japan Earthquake

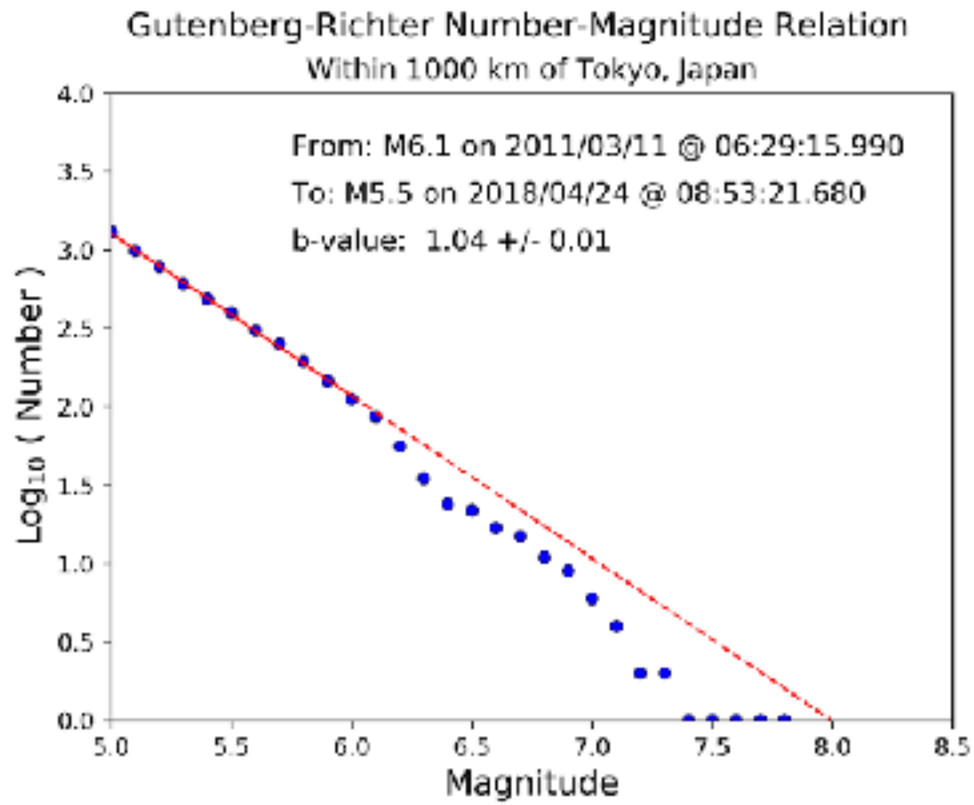


Figure 4(b). Magnitude-frequency data for the spatial region within 1000 km of Tokyo, Japan, following the M7.7 aftershock on March 11, 2011. Solid red line indicates the magnitude range fit by the scaling line, from M5.0 to M6.0.

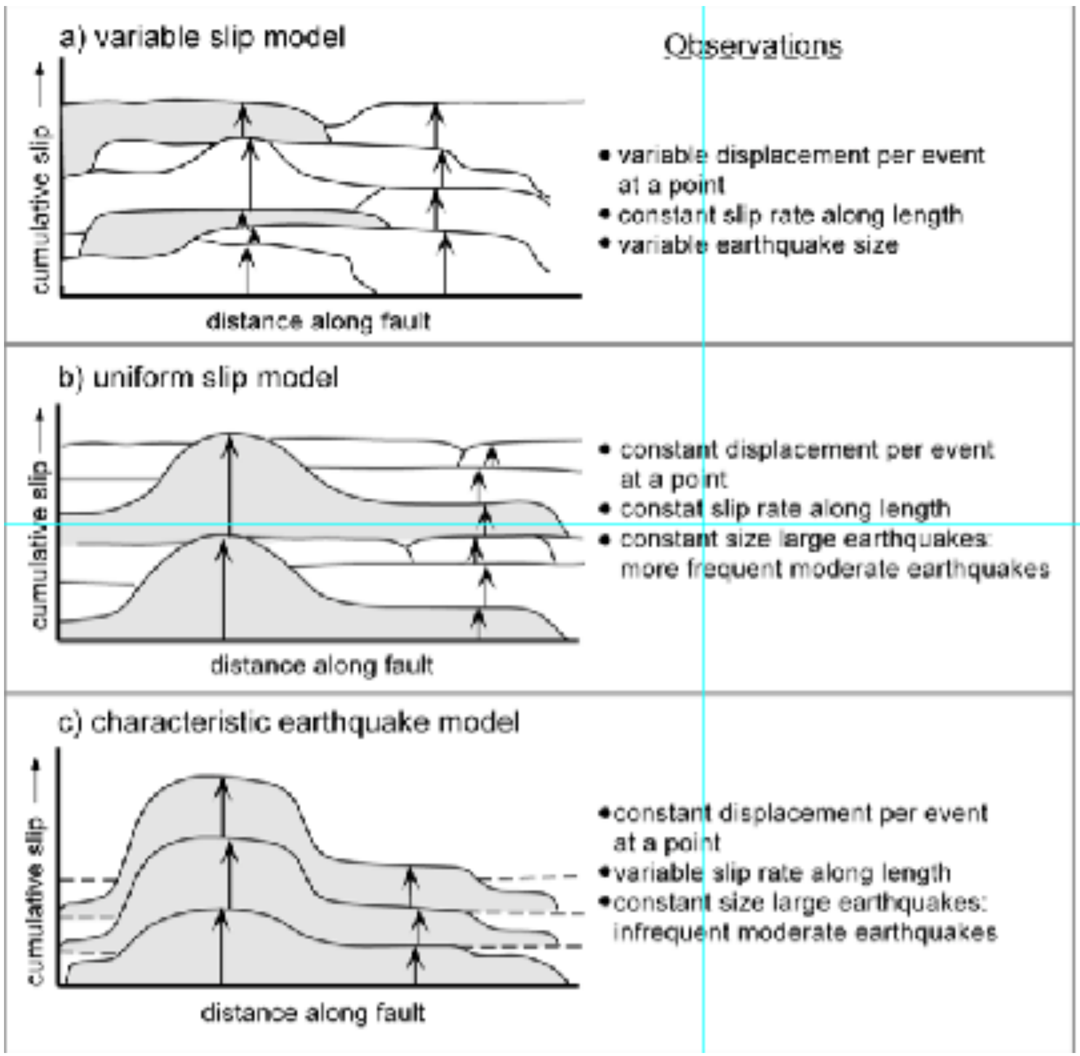
Characteristic Earthquakes

whipple_arrowsmith598.asu.edu/

- The break in slope of Gutenberg-Richter that we observe globally represents a violation of the simple b =1 GR model
- If we could simply extrapolate the GR law to higher magnitudes, we would have a simple way to forecast large damaging earthquakes as we will see
- However another problem is that large earthquakes are sometimes observed to occur more often than they should on a fault
- In this case, there is a either a change in slope, or in fact a "bump" at the large magnitude end
- This has been modeled with the "characteristic earthquake" idea
- In this idea, the largest earthquakes recur relatively regularly (~periodic?) but the smaller events are represented by Gutenberg-Richter

Characteristic Earthquakes

whipple_arrowsmith598.asu.edu/



If we know slip rate du/dt

And we assume u(x) per event

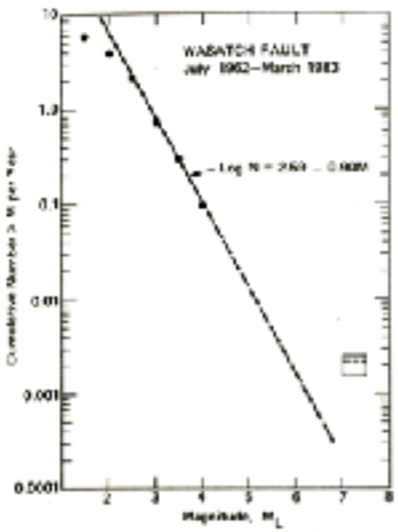
We can get recurrence time

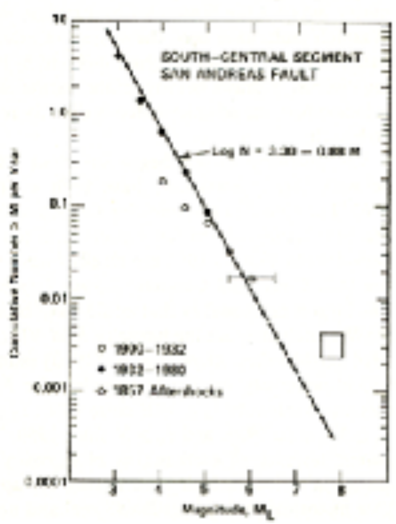
u_{ave} or u_{max} per event should also imply length and M

Burbank and Anderson

Characteristic Earthquakes

whipple_arrowsmith598.asu.edu/





1984

SCHWARTZ AND COPPERSMITH: CHARACTERISTIC EARTHQUAKES

FAULT–SPECIFIC RECURRENCE

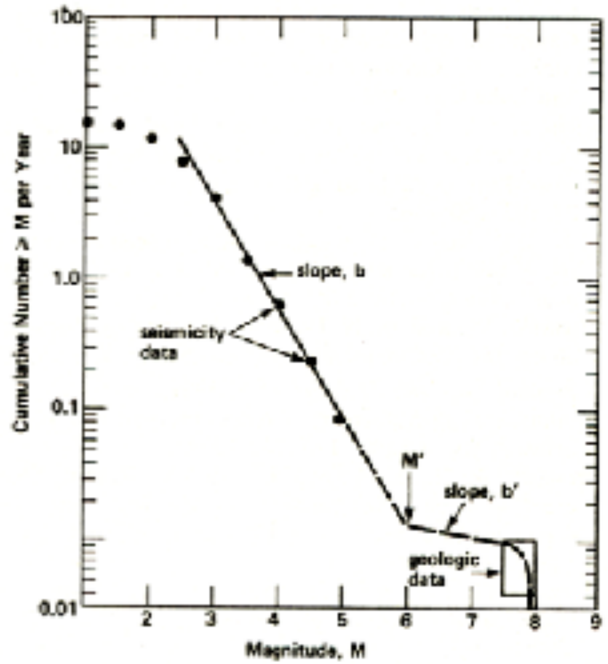


Fig. 15. Diagrammatic cumulative frequency-magnitude recurrence relationship for an individual fault or fault segment. Above magnitude M' a low b value (b') is required to reconcile the small-magnitude recurrence with geologic recurrence, which is represented by the box.

"...individual faults and fault segments tend to generate essentially the same size *or characteristic* earthquakes having a relatively narrow range of magnitudes near the maximum."

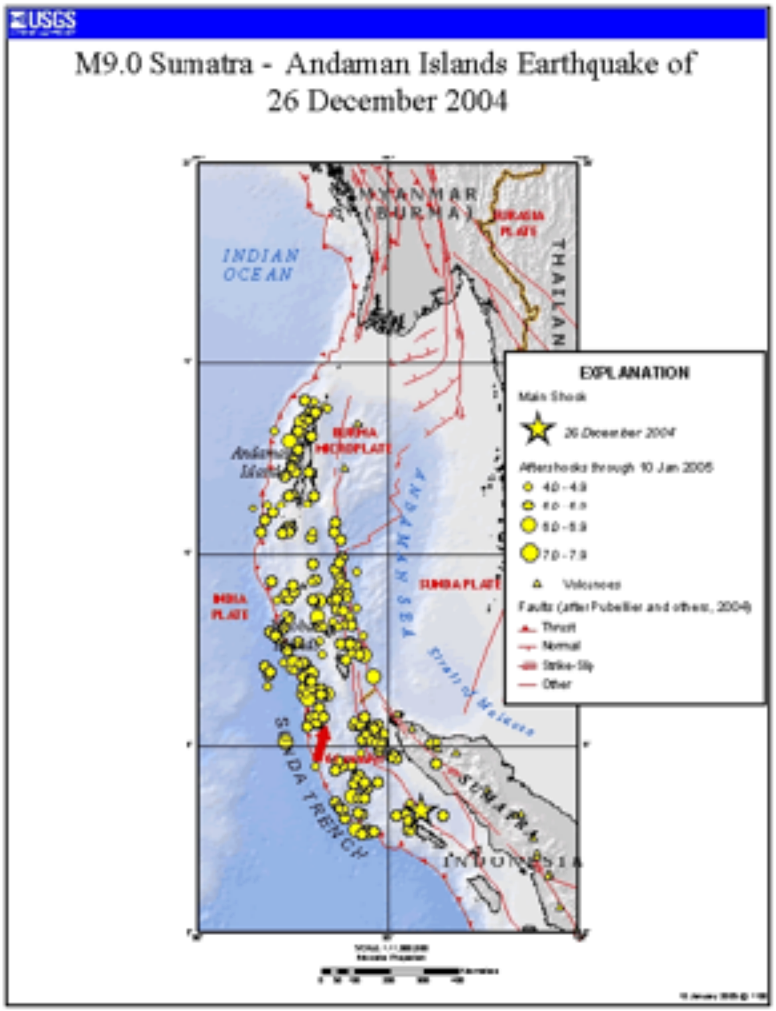
Aftershocks

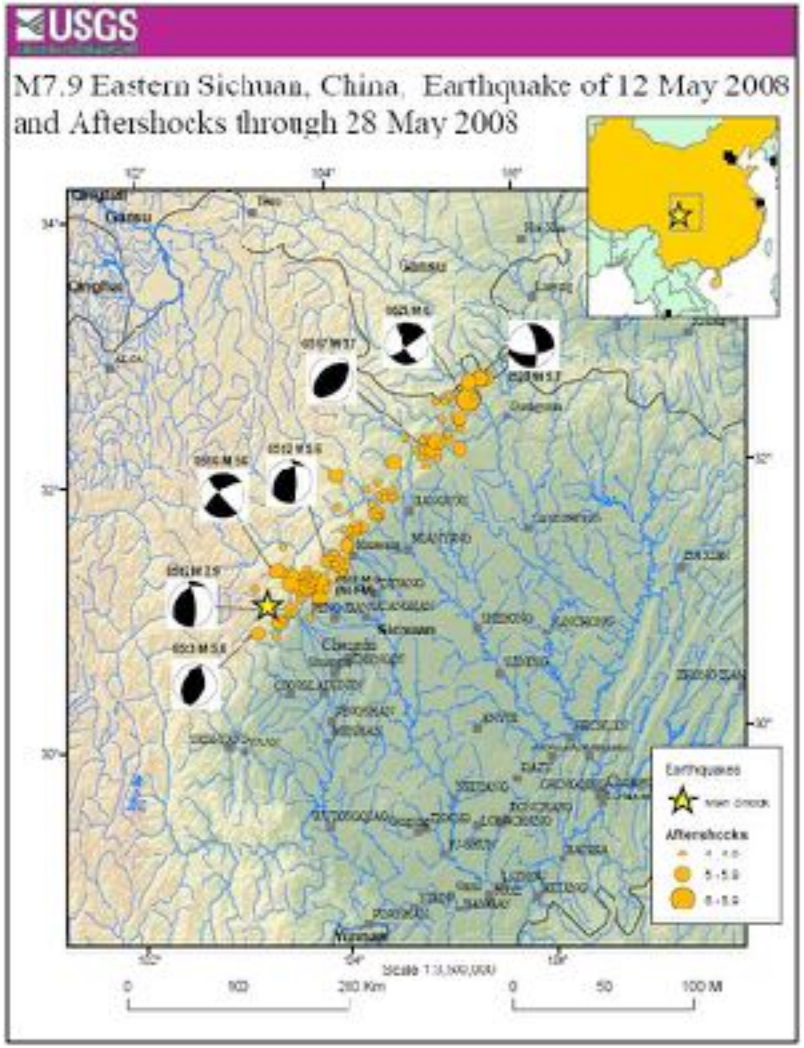
http://en.wikipedia.org/wiki/Fusakichi_Omori

- Large shallow earthquakes (in fact mostly all earthquakes) are usually followed by a sequence of smaller earthquakes called "aftershocks"
- The aftershocks themselves follow the Gutenberg-Richter scaling relation
- The aftershocks die away with time, in a process that is observed to obey "Omori's Law of Aftershock Decay"

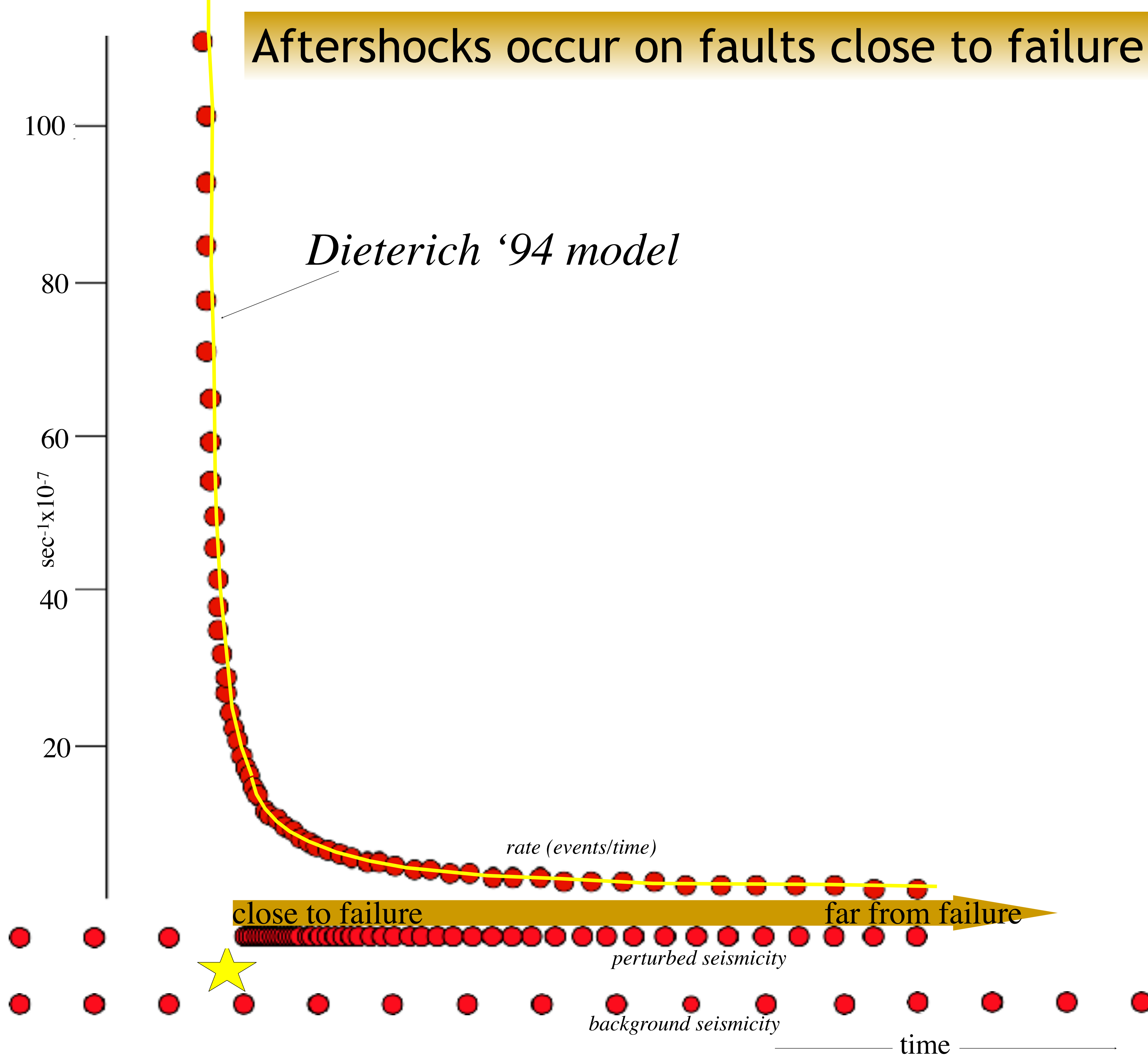
Examples of Aftershock Patterns

http://en.wikipedia.org/wiki/Aftershock





Aftershocks occur on faults close to failure.



Utsu (1961)

The Omori-Utsu formula for aftershock decay rate

$$v(t) = K(t + c)^{-p}$$

t : Elapsed time from the mainshock

K , c , p : constant parameters

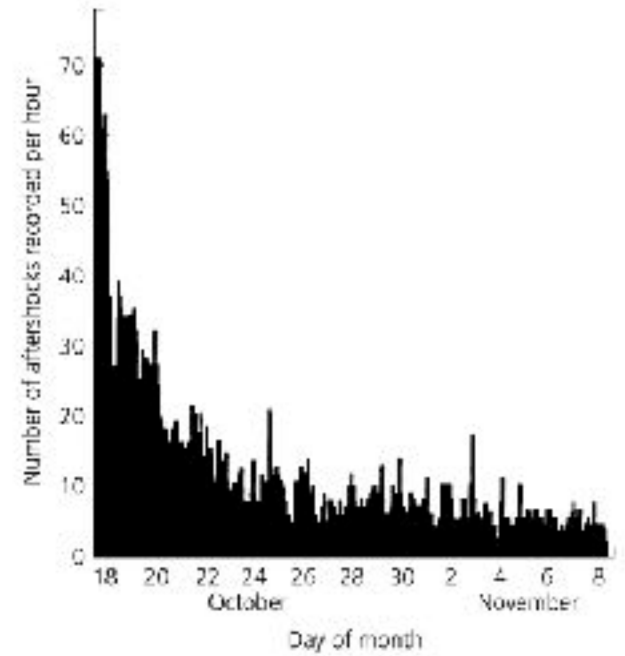
Aftershocks

Aftershock decay rate follows the OMORI law

Figure 4.7-8: Aftershocks following the 1989 Loma Prieta earthquake.

Magnitude	Number	Effect
5	2	Damaging
4	20	Strong
3	65	Perceptible
2	384	Not felt
1	1855	Not felt
<1	2434	Not felt
Total	4760	

4760 aftershocks of the Loma Prieta earthquake had been recorded by noon on November 7, 1989. The diminishing number of aftershocks with time is typical for large California earthquakes.

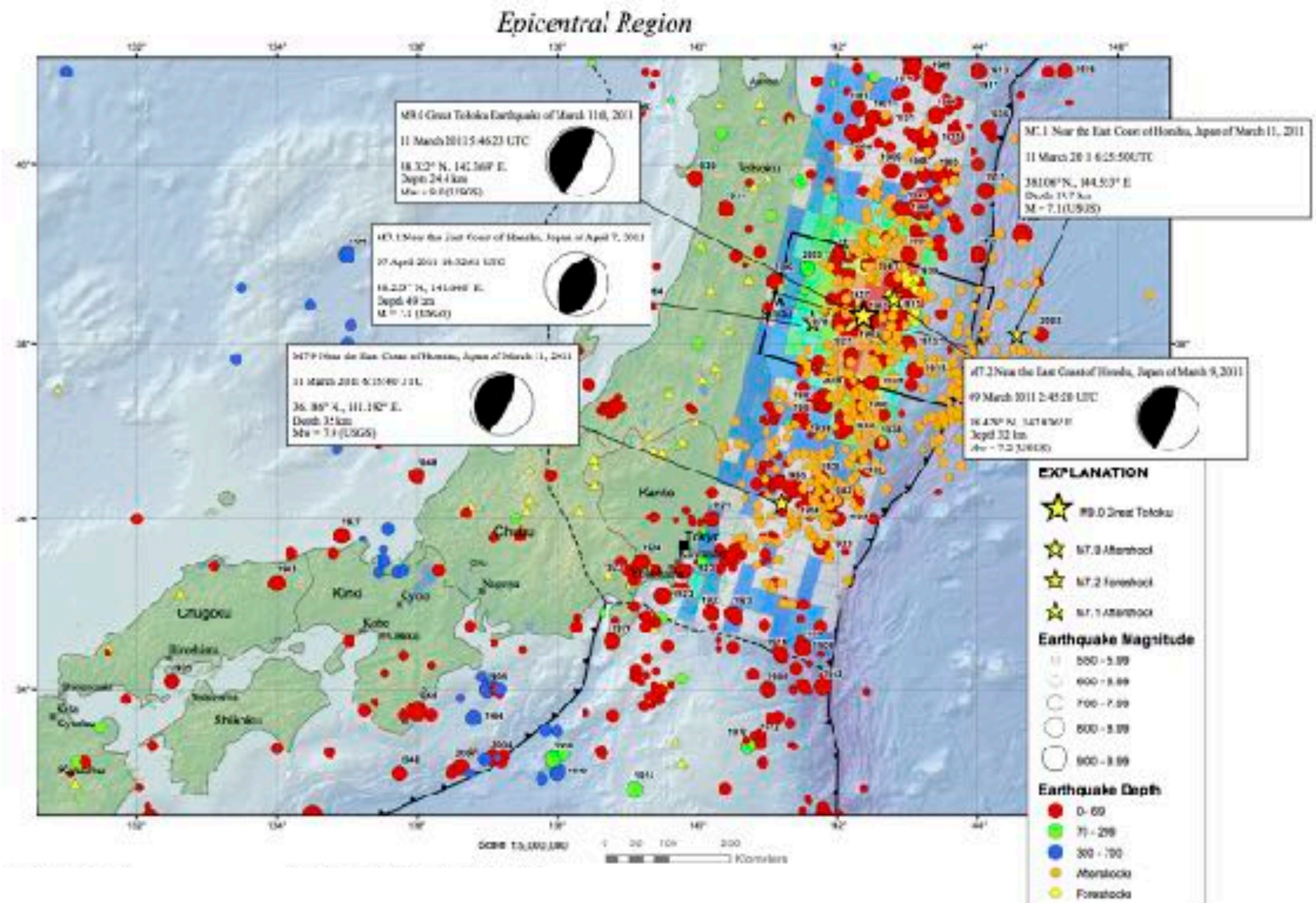


K is the productivity

p is close to 1

c account for magnitude completness

Tohoku, Japan Earthquake 3/11/2011



Omori's Law

- Original Omori Law (1894):

$$n(t) = \frac{K}{c + t}$$

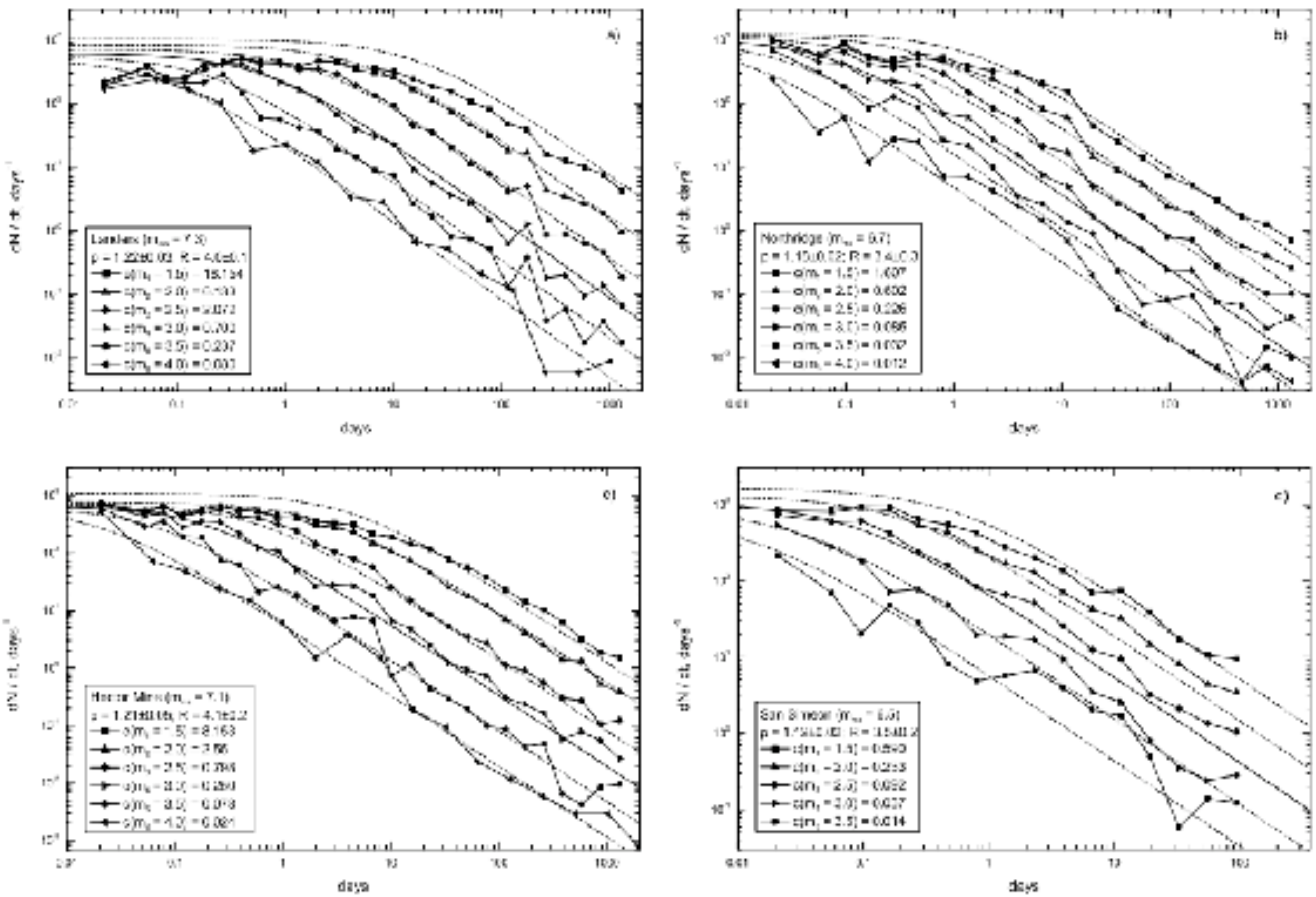
- Modified Omori Law (Utsu, 1961):

$$n(t) = \frac{k}{(c + t)^p}$$

- p typically in the range of 0.7 – 1.3

A More Recent Model for Aftershocks

Shcherbakov et al., Geophys. Res. Lett., 2004



Here the c-parameter is a function of magnitude

Seismic gap theory

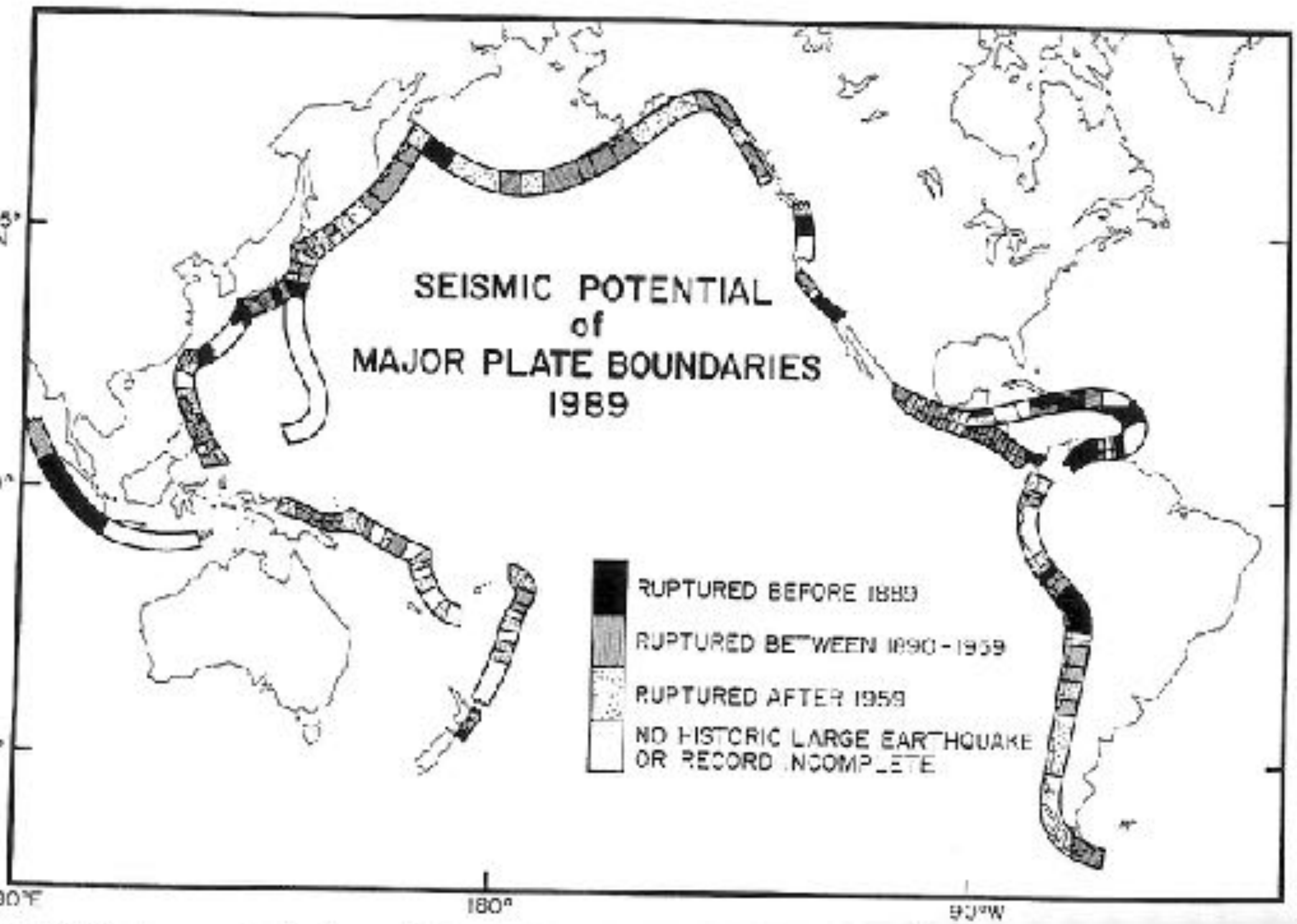
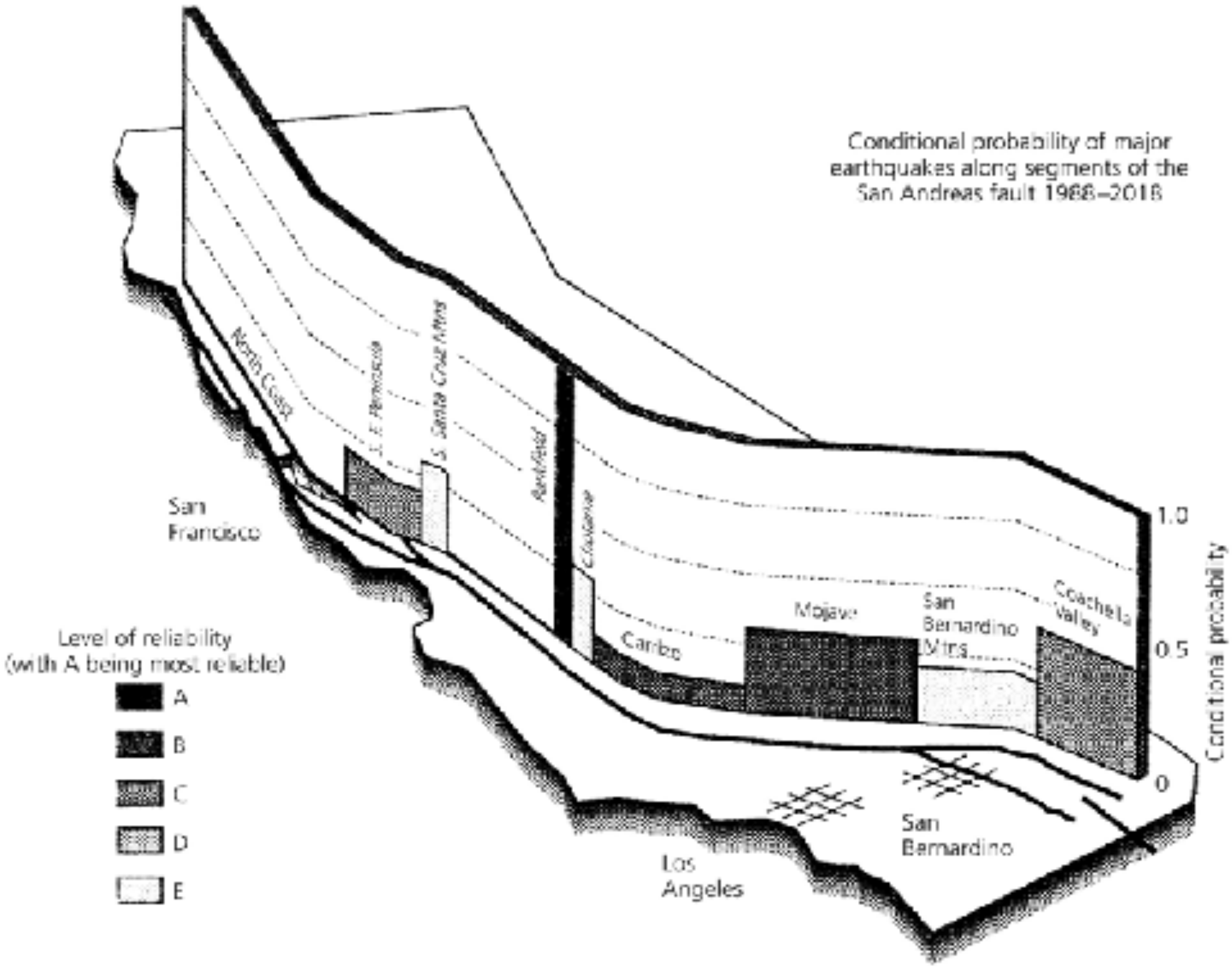


Fig. 5.28 Seismic gaps and seismic potential for the Circumpacific region. (Data courtesy of S. Nishenko, FEMA.)

"The probability of a large earthquake on an individual fault segment is greater for those segments which did not fail in a long time "

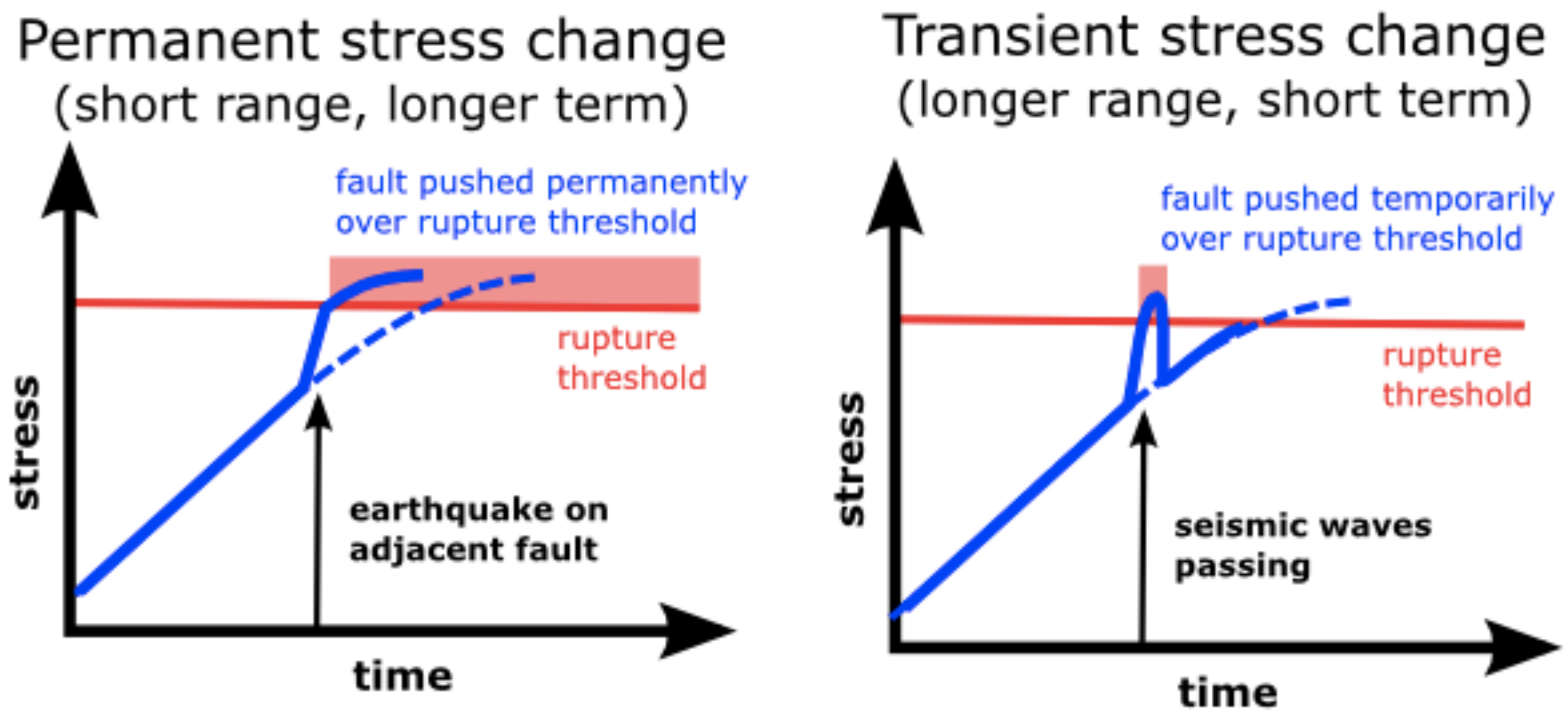
Seismic gap theory

Figure 4.7-12: Conditional probabilities for various San Andreas fault segments.



- In the “stress shadow” relieved by a large earthquake no major earthquakes are likely to occur

Seismic gap theory



→ Global models forecast the location of major earthquakes **not better than random guesses**

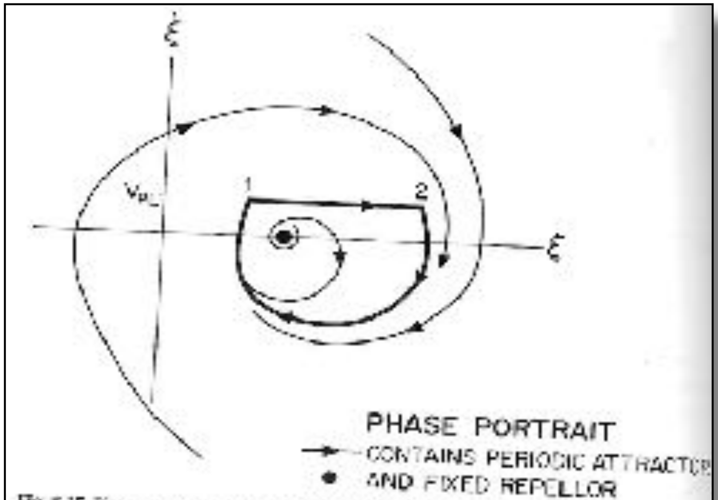
→ Contrarian idea: probability of an event is highest in the vicinity of recent earthquakes (**earthquake triggering**)

Are earthquakes unpredictable?

- Simple block-slider models exhibit **chaotic behavior**, thus also more complex fault systems? In that case:

→ **long – term earthquake prediction is impossible**

→ but chaotic behavior does not prevent short-term prediction



Are earthquakes unpredictable?

- Simple block-slider models exhibit **chaotic behavior**, thus also more complex fault systems? In that case:

→ **long – term earthquake prediction is impossible**

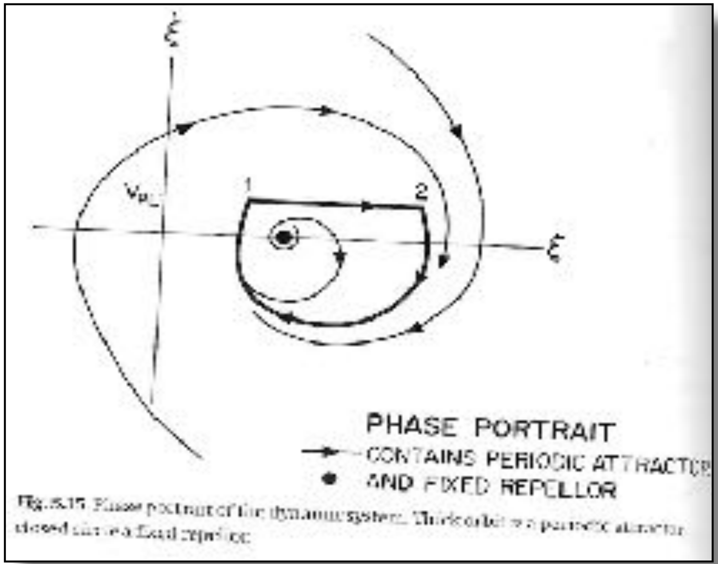
→ but chaotic behavior does not prevent short-term prediction

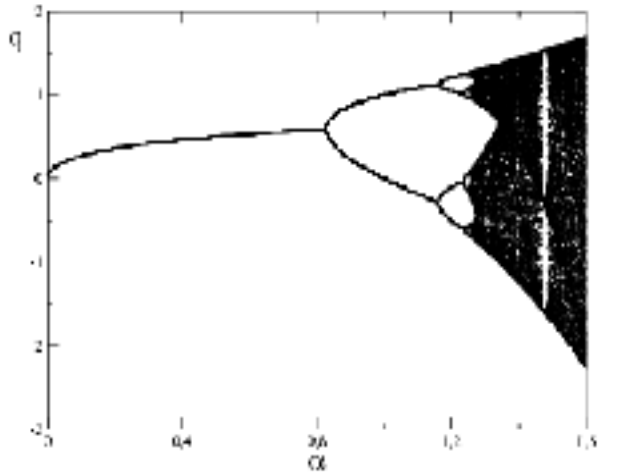
- **No clear precursors** have been observed (so far), thus do also large earthquakes start as small earthquakes (cascade earthquake nucleation) ? In that case:

→ no detectable precursory phenomena

→ supported by observations and **self-organized criticality** models (faults may be in a stress state such that even small events can initiate long-distance rupture)

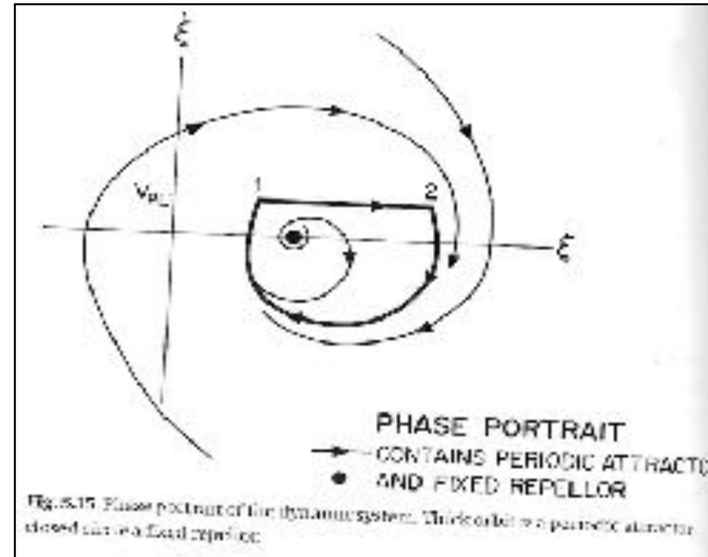
→ **short-term prediction may be inherently very difficult (impossible)**





Bifurcation diagram of mean-field solution map (Lippiello et al. 2006)

Are earthquakes unpredictable?



- Simple block-slider models exhibit **chaotic behavior**, thus also more complex fault systems? In that case:

→ **long – term earthquake prediction is impossible**

→ but chaotic behavior does not prevent short-term prediction

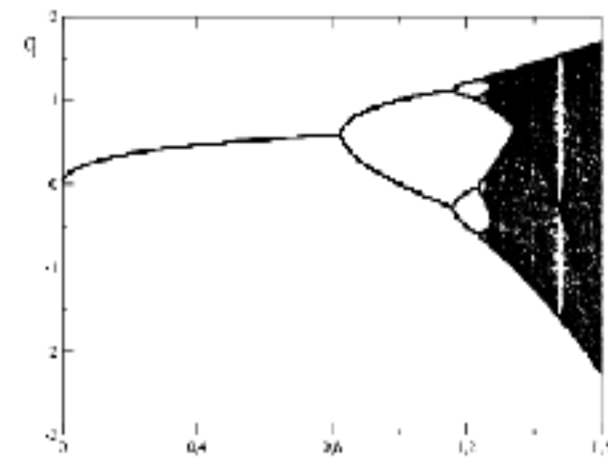
us

Seismology's direct benefits: identifying regions at risk, enforcing building codes

→ no detectable precursory phenomena

→ supported by observations and **self-organized criticality** models (faults may be in a stress state such that even small events can initiate long-distance rupture)

→ **short-term prediction may be inherently very difficult (impossible)**



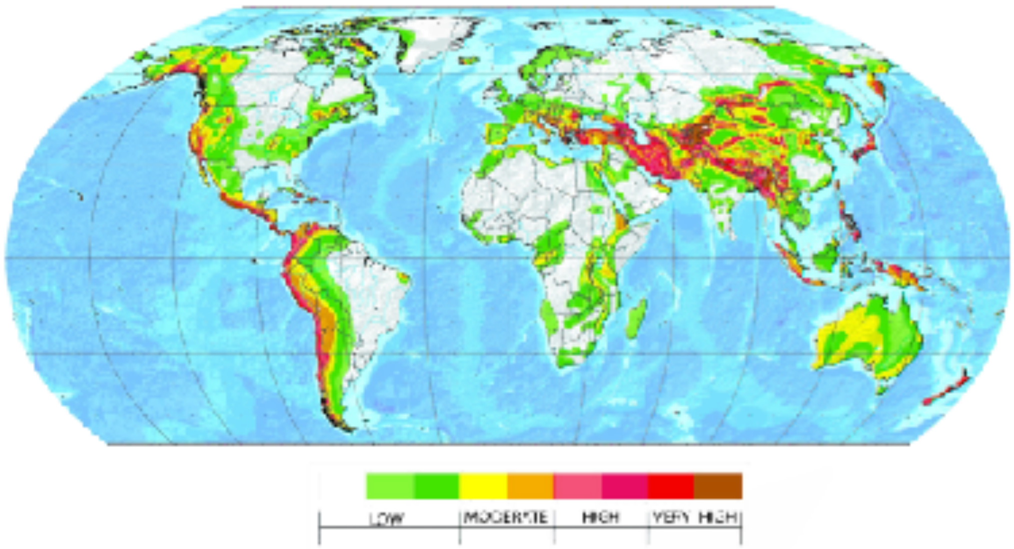
Bifurcation diagram of mean-field solution map (Lippiello et al. 2006)

Seismic hazard assessment

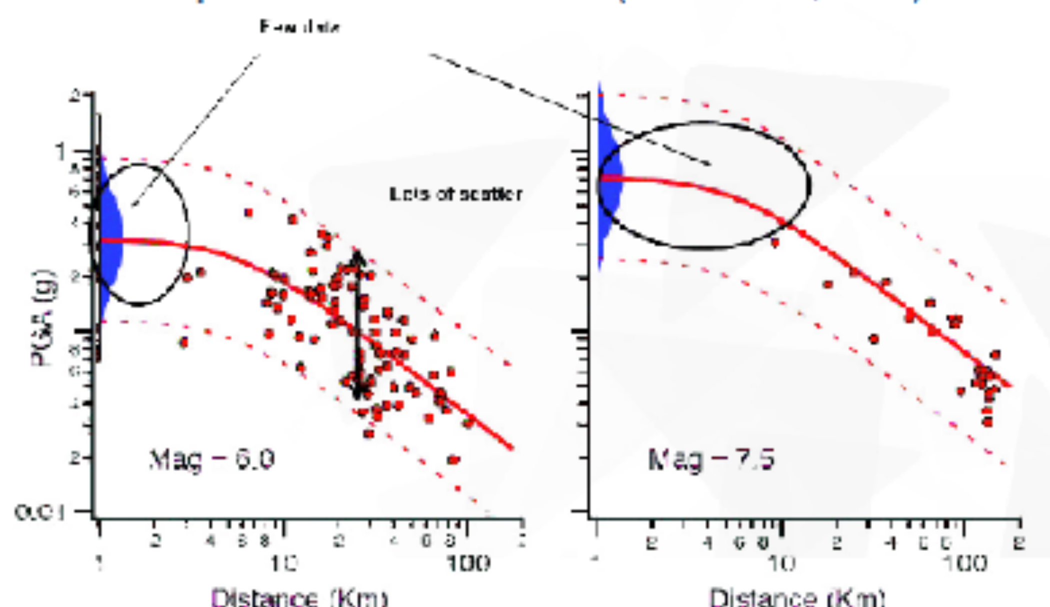
- Empirical approaches
  - Seismicity records
  - Ground motion prediction equations
  - Empirical Green's functions

- Limitations
  - Data coverage
  - Shaking duration
  - Variability of earthquakes

Global seismic hazard map (GSHAP, 1999)



Empirical attenuation relation (Boore et al., 1997)



Summary

- Geodetic observations allow insight in strain accumulation and release of fault systems
- The earthquake cycle loading behaviour cannot be explained by a simple elastic model
- Theoretical models for the earthquake cycle range from simple spring block models, over combined spring-slider models to complex models including friction laws and strain accumulation theory
- Earthquake statistics and probabilities mainly base on empirical (non-physical) models, are hard to validate and have large uncertainties
- The seismic gap theory is not supported by statistical tests of its global significance
- Barring dramatic new developments, an earthquake prediction program promising timely, accurate warnings of future events with a minimal number of false alarms is unlikely to be achieved
- Seismic hazard analysis currently uses empirical earthquake models to provide ground shaking probabilities for earthquake engineering purposes