PART 1: SOURCE CHARACTERIZATION

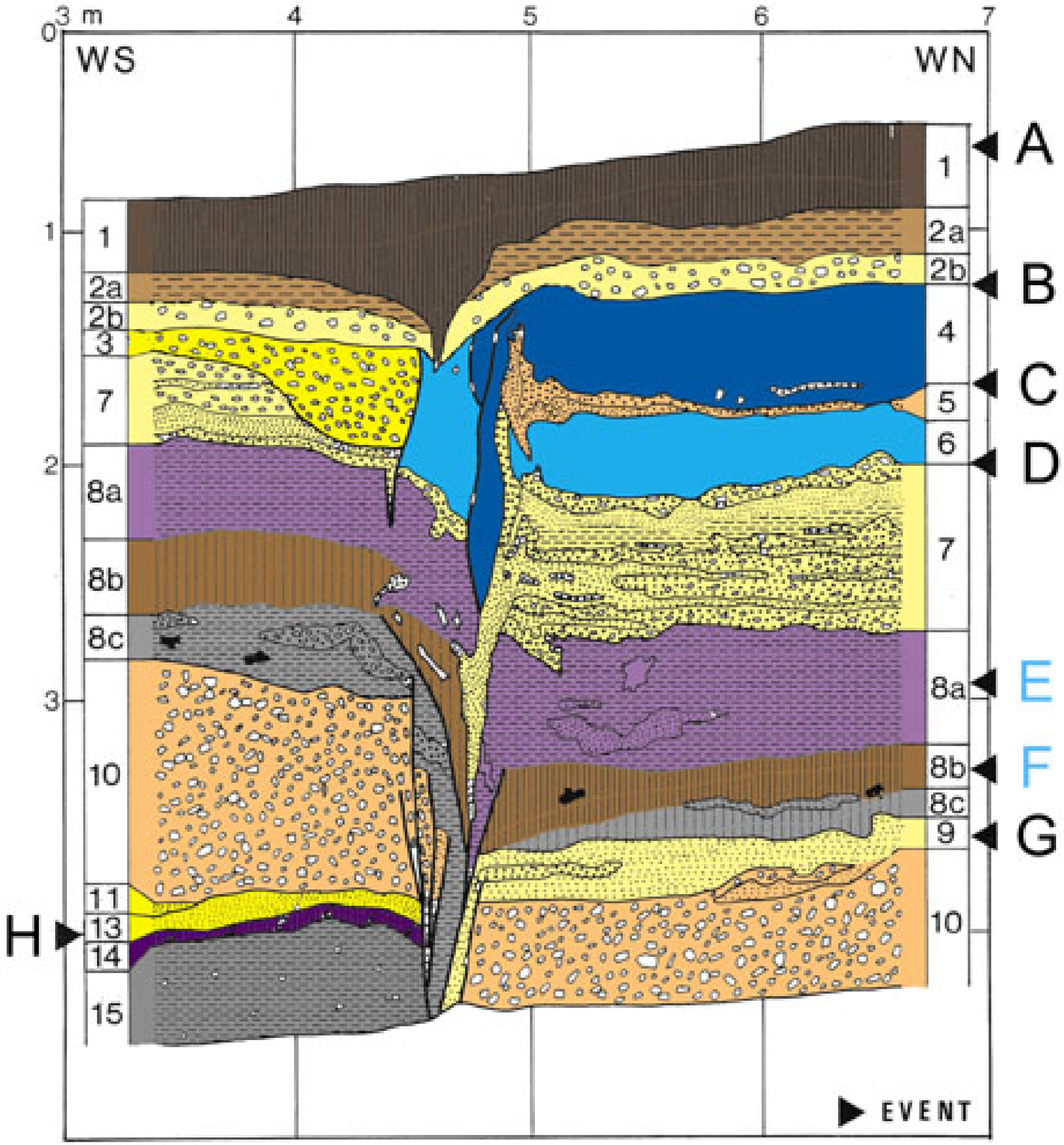
- Fault geology: map 3-d faults, paleoseismic studies to quantify large displacements, slip rate studies (measure displacements and constrain timing), sizes of earthquakes (slip per events)
- Fault geodetic: map strain rates
- Fault seismic: determine sizes of earthquakes,
- Area source seismic: smoothed seismicity
- Magnitude – frequency distribution

GEOLOGIC INPUT

Gerede Site

Oblique view of the Gerede Ardiçili trench site

From Koji Okumura



10 C A.D.

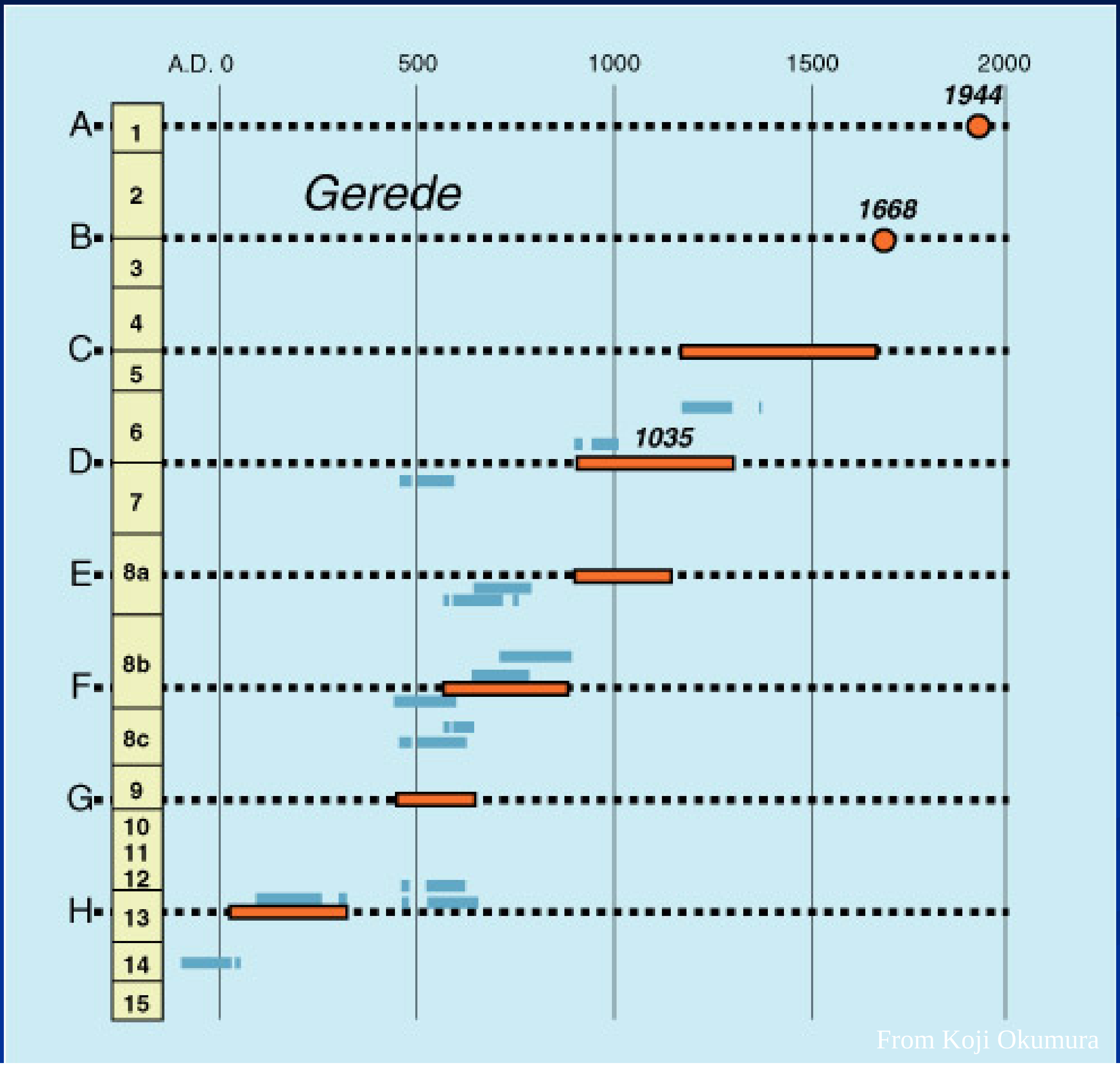
7 C A.D.

6 C A.D.

2 C A.D.

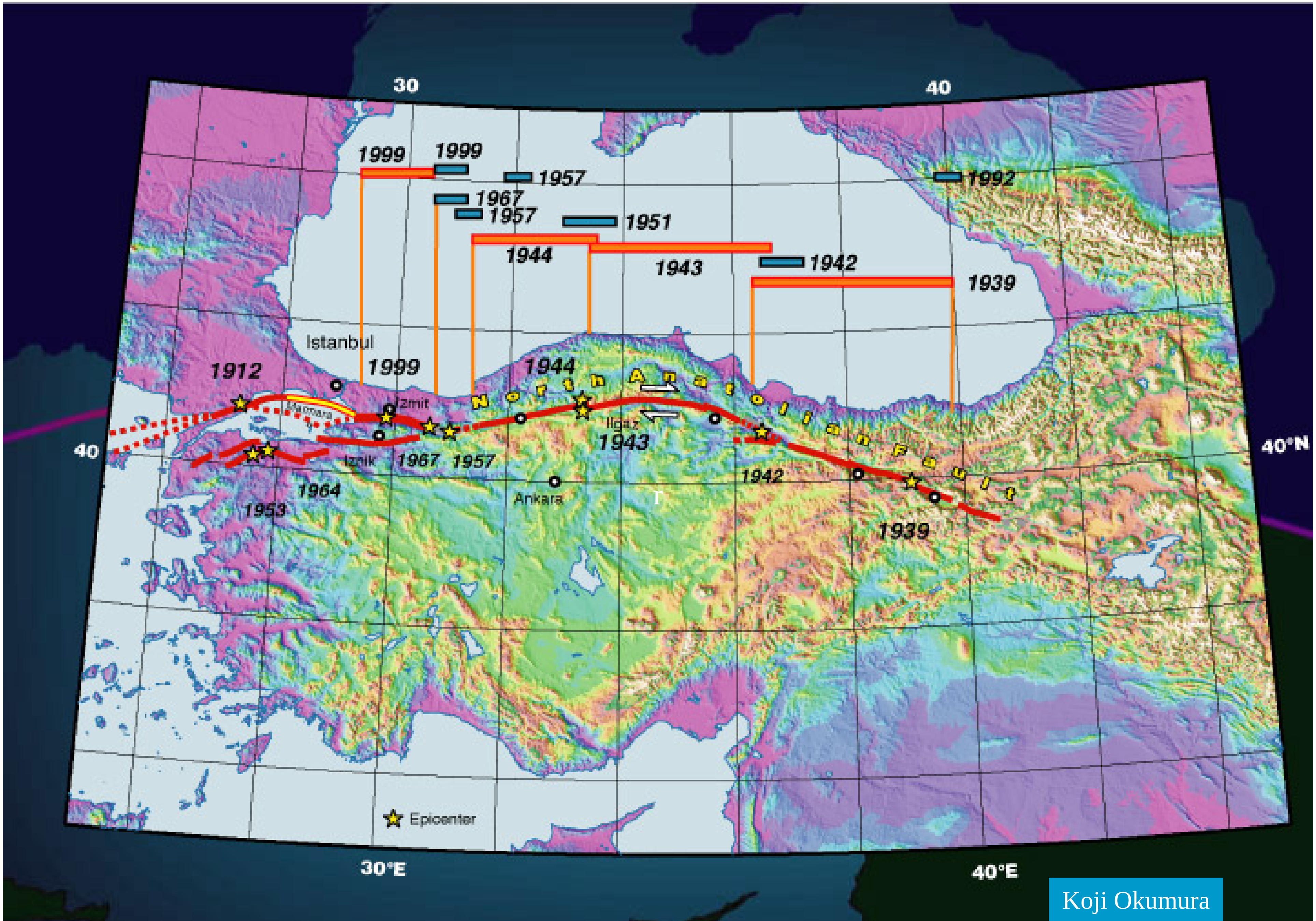
1 C B.C.

timetable

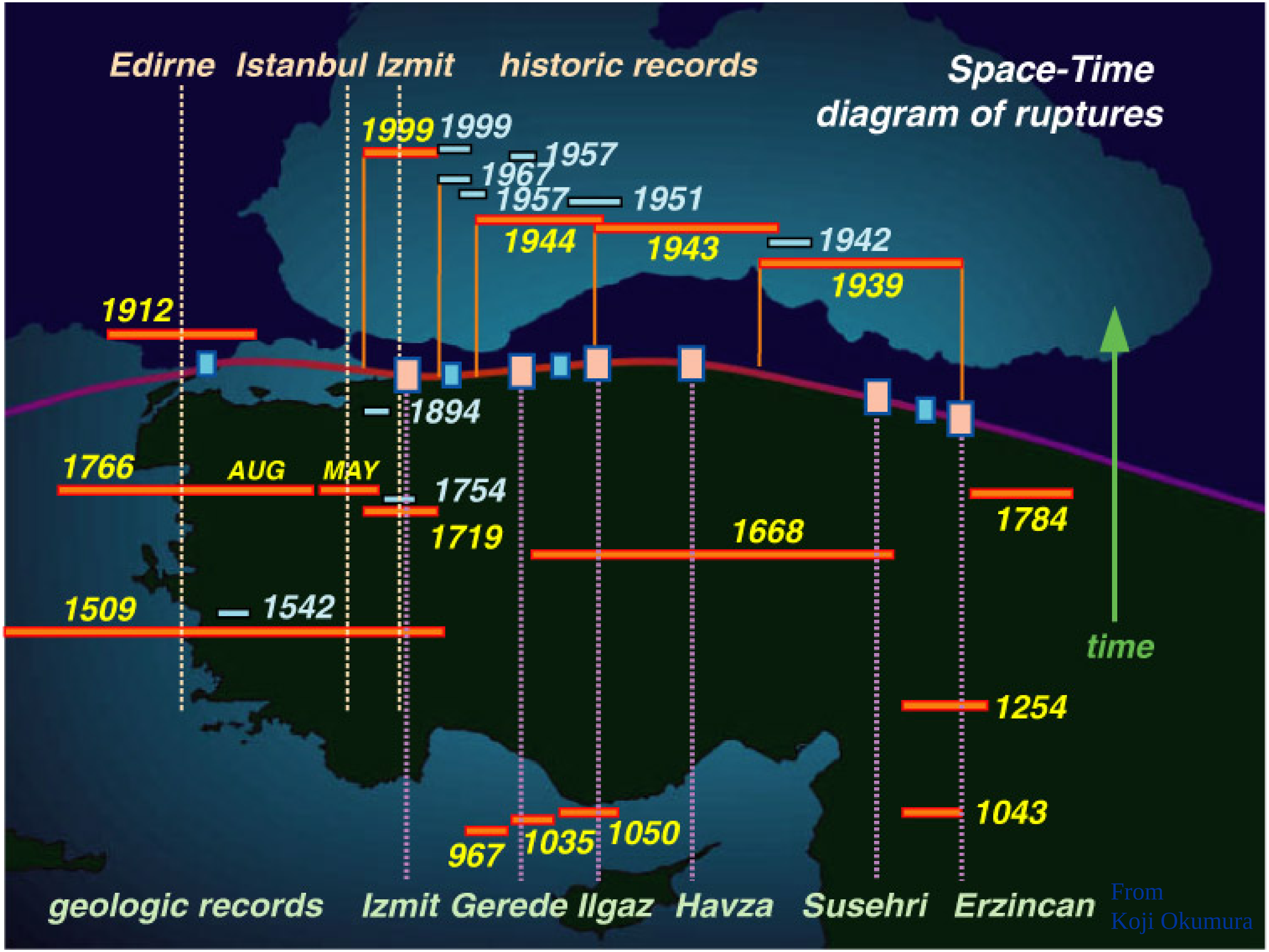


8 events Average Recurrence: 270--230 yr

7 events Average Recurrence: 330--280 yr



Westward migrating sequence in 20th century

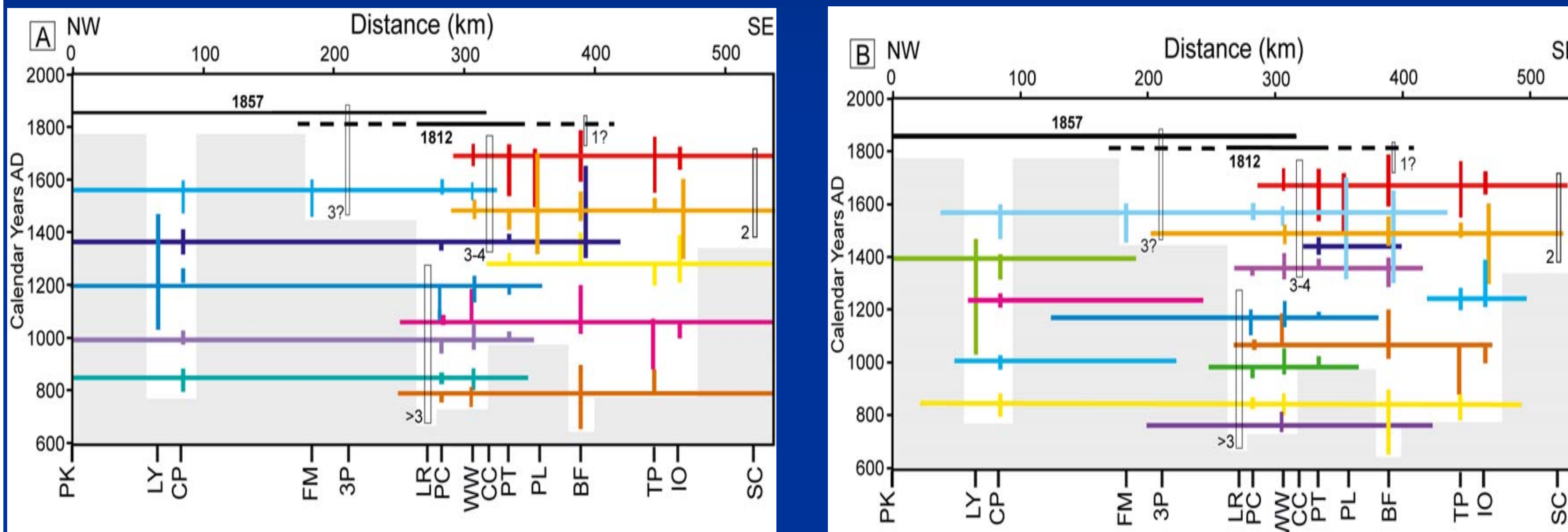


From Koji Okumura

GEOLOGIC DATA

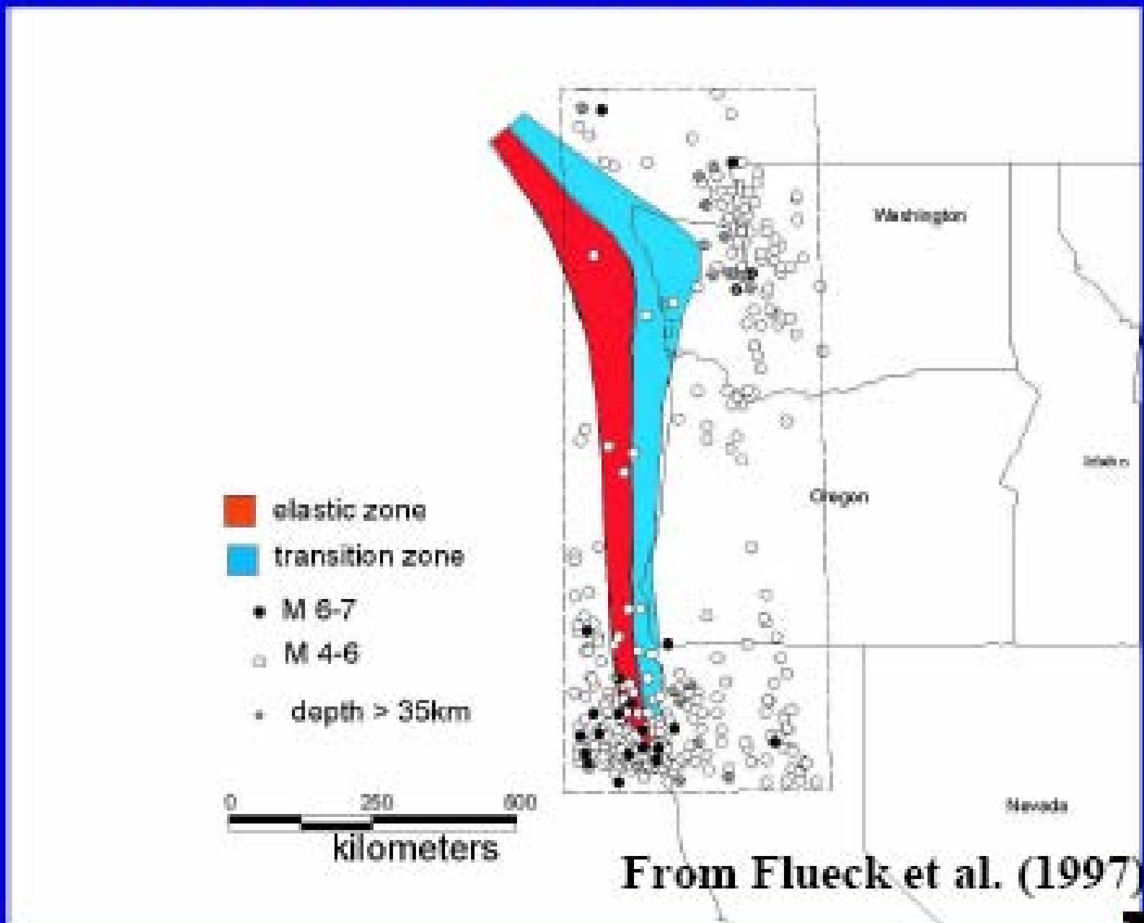
Two multi segment rupture models based on Weldon et al. 2002

From Weldon et al.:



Rupture scenarios for the Southern San Andreas fault. Vertical bars represent the age range of paleoseismic events recognized to date, and horizontal bars represent possible ruptures. Gray shows regions/times without data. In (A) all events seen on the northern 2/3 of the fault are constrained to be as much like the 1857 AD rupture as possible, and all other sites are grouped to produce ruptures that span the southern ½ of the fault; this model is referred to the North Bend/South Bend scenario. In (B) ruptures are constructed to be as varied as possible, while still satisfy the existing age data.

Possible configurations for rupture zone of great Cascadia Earthquakes



Working Groups, Downdip width (episodic tremor and slip), deep eqs, recurrence, clusters, magnitudes

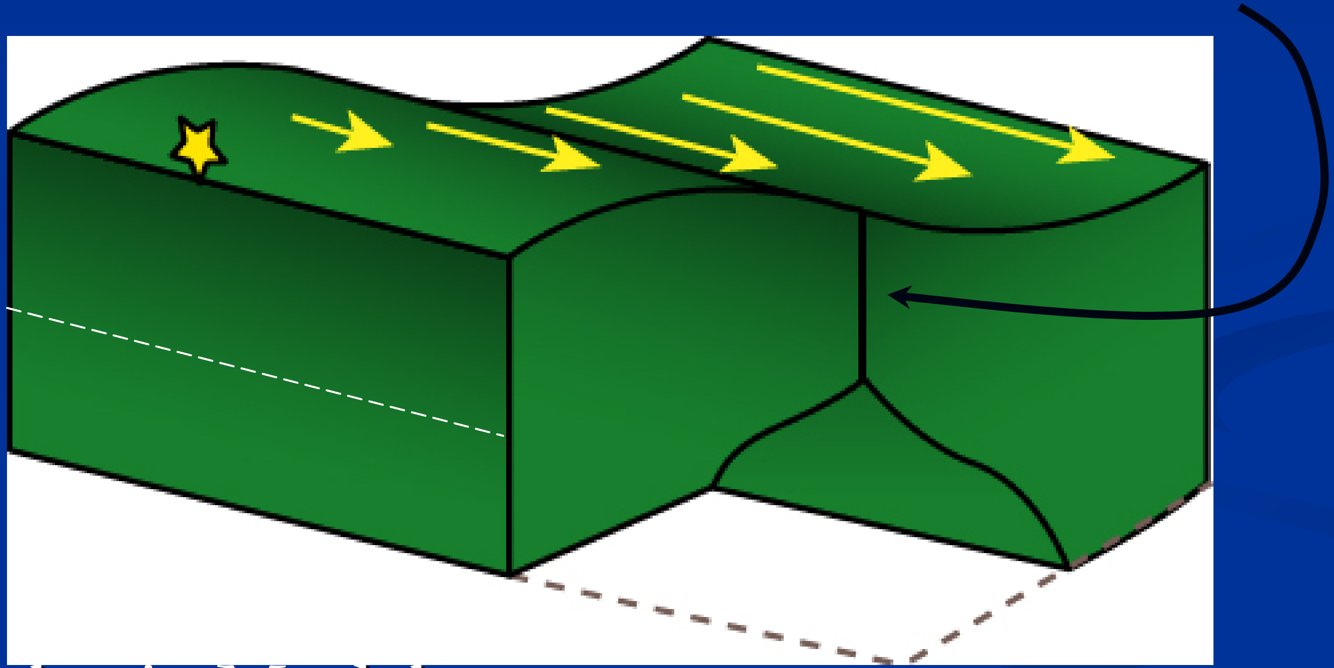
GEODETIC INPUT

DEFORMATION MODELING

- Elastic Models
  - Dislocation theory

Locked near the surface.

Locking Depth



Slip at constant rate below transition depth

- Visco-elastic Models

Geodetic data

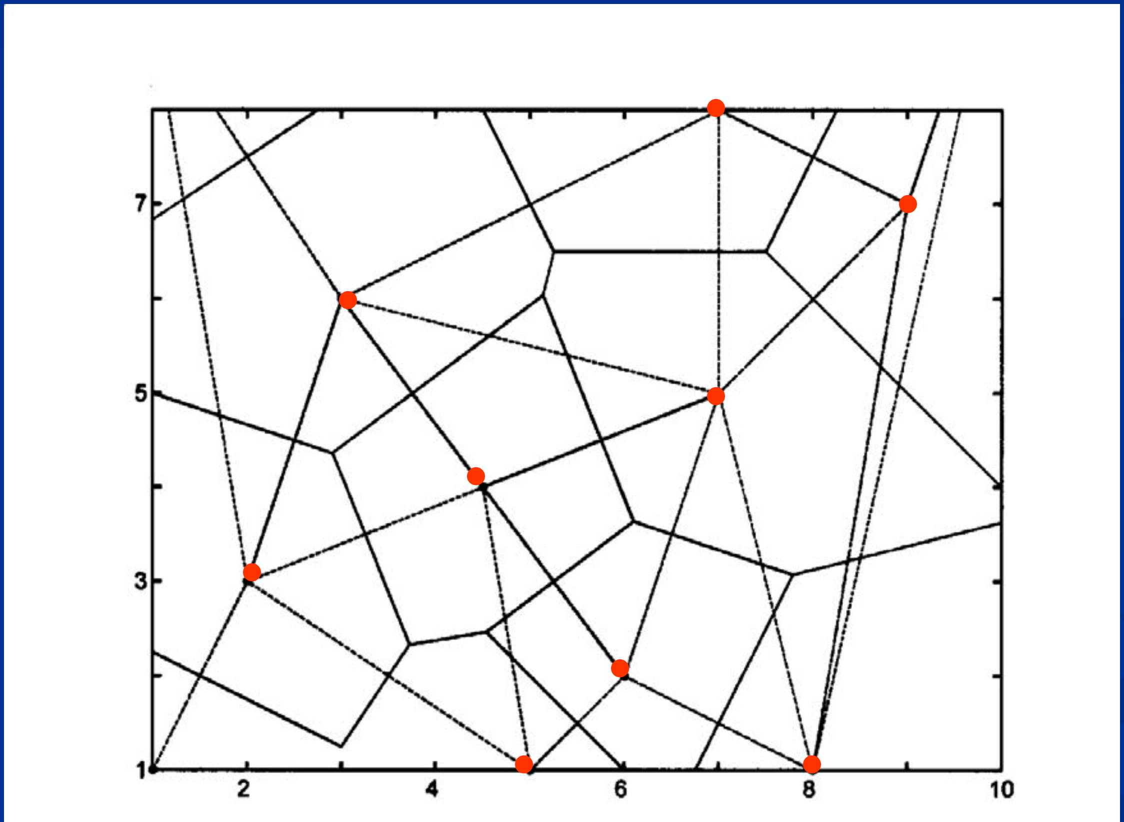
- $V(r) = v(r_0) + (r - r_0) \,.\, \nabla V(r_0)$

Geodetic velocity at r can be expressed by the deformation rate tensor $\nabla V(r_0)$, where v(r0) is the GPS observation at $r_{0;}$

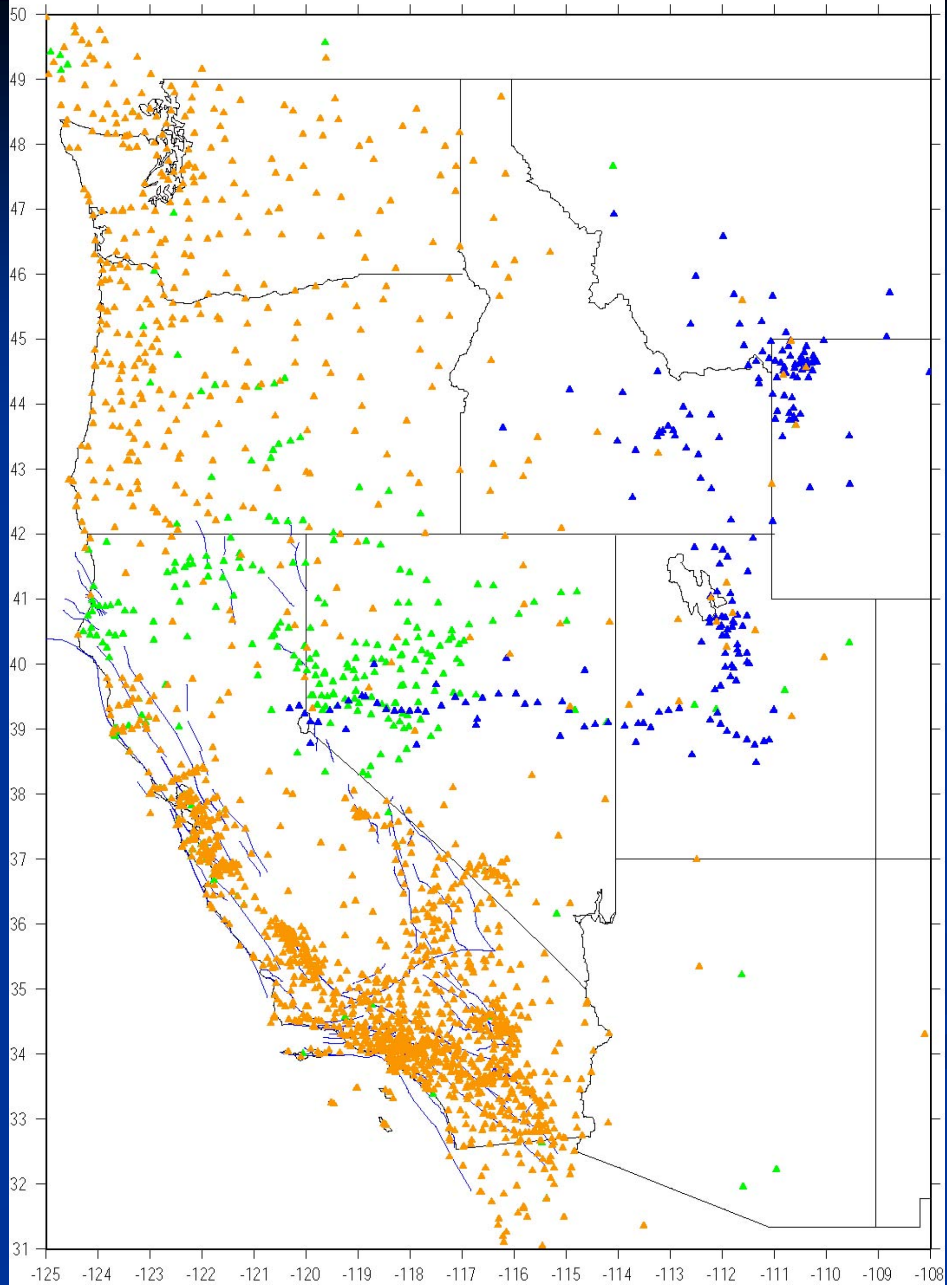
From Steven Ward (1998): Geophys. J. Int. (1998) **134**, 172-186.

Velocity weghting Scheme of the Inversion

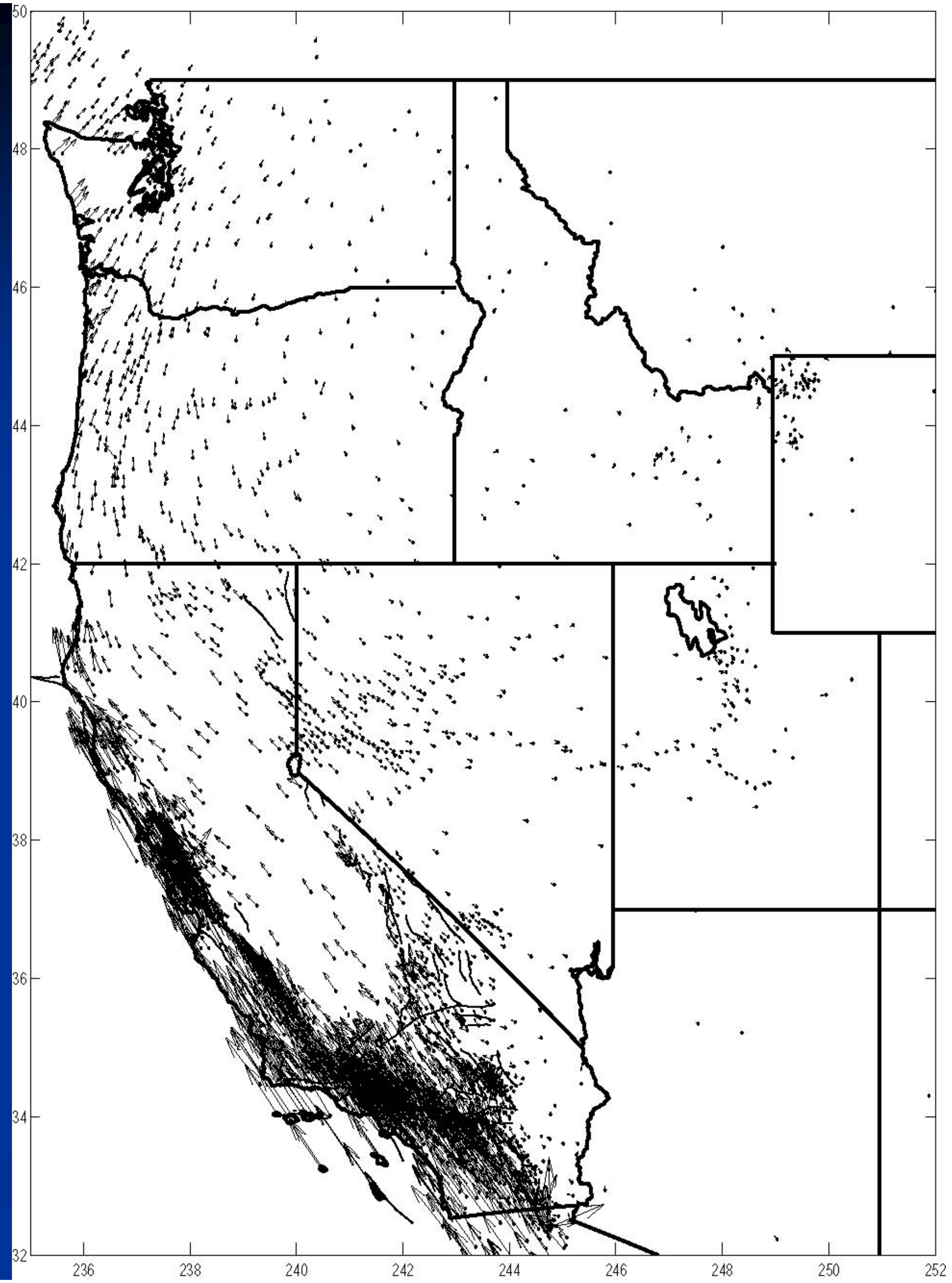
- Distance, azimuth angle, coverage area, etc.
- Voronoi cell



GPS data from different agencies



Velocity data Rotated into same Reference frame



Strain Rates from GPS Velocity measurement (Ward 1998)

$$W\begin{bmatrix} v_n(x_i) \\ v_e(x_i) \end{bmatrix} = WRG(x_i, x_j)\begin{bmatrix} \Omega_n(x_j) \\ \Omega_e(x_j) \\ \Omega_r(x_j) \\ \dot{\varepsilon}^j_{nn} \\ \dot{\varepsilon}^j_{ne} \\ \dot{\varepsilon}^j_{ee} \end{bmatrix}$$

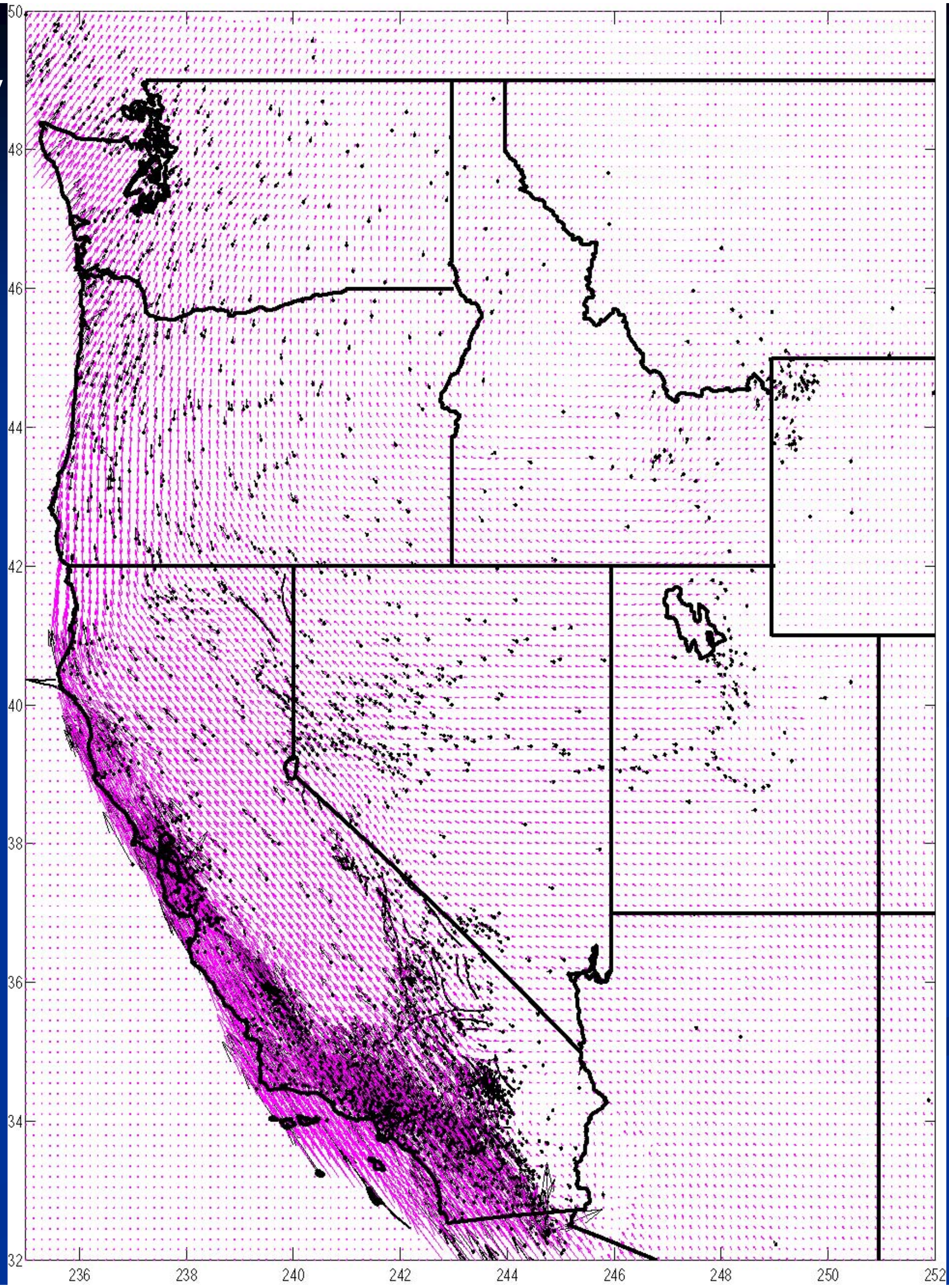
$$G_{11} = -(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{n}}_j) \quad G_{12} = -(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j) \quad G_{13} = -(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{r}}_j) \quad G_{14} = (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{n}}_j)(\hat{\mathbf{n}}_i \cdot \hat{\mathbf{n}}_j)$$

$$G_{15} = (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{e}}_j)(\hat{\mathbf{n}}_i \cdot \hat{\mathbf{n}}_j) + (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{n}}_j)(\hat{\mathbf{n}}_i \cdot \hat{\mathbf{e}}_j) \quad G_{16} = (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{e}}_j)(\hat{\mathbf{n}}_i \cdot \hat{\mathbf{e}}_j)$$

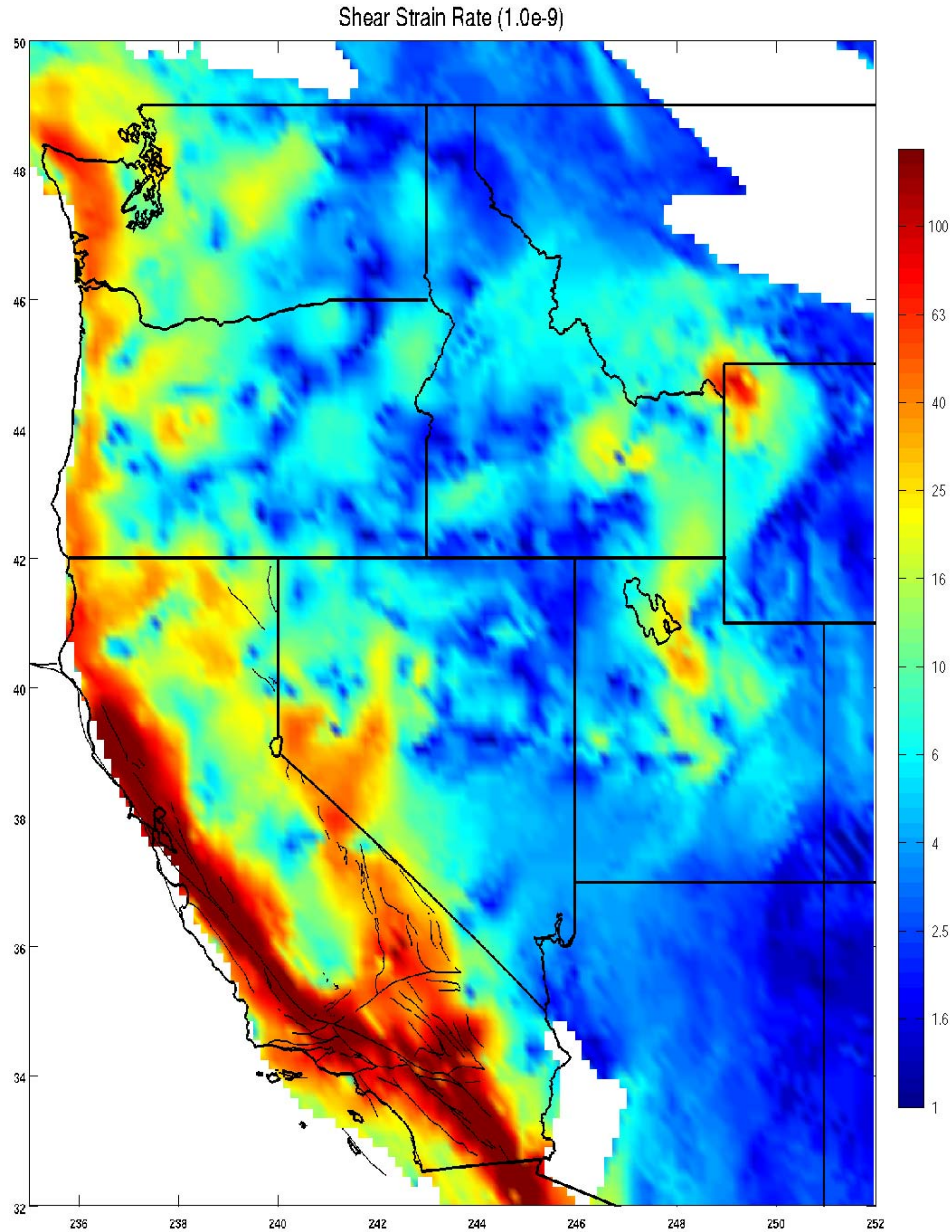
$$G_{21} = (\hat{\mathbf{n}}_i \cdot \hat{\mathbf{n}}_j) \quad G_{22} = (\hat{\mathbf{n}}_i \cdot \hat{\mathbf{e}}_j) \quad G_{23} = (\hat{\mathbf{n}}_i \cdot \hat{\mathbf{r}}_j) \quad G_{24} = (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{n}}_j)(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{n}}_j)$$

$$G_{25} = (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{e}}_j)(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{n}}_j) + (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{n}}_j)(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j) \quad G_{26} = (\hat{\mathbf{r}}_i \cdot \hat{\mathbf{e}}_j)(\hat{\mathbf{e}}_i \cdot \hat{\mathbf{e}}_j)$$

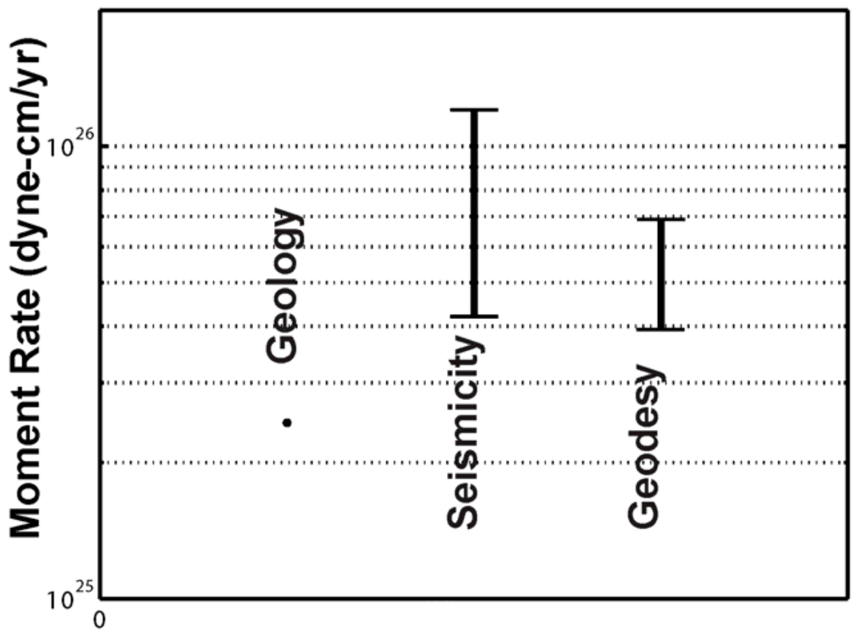
Invert and interpolate velocity data for strain into Uniform grid using Ward (1998) equations.



Resultant
Shear strain
Rate map

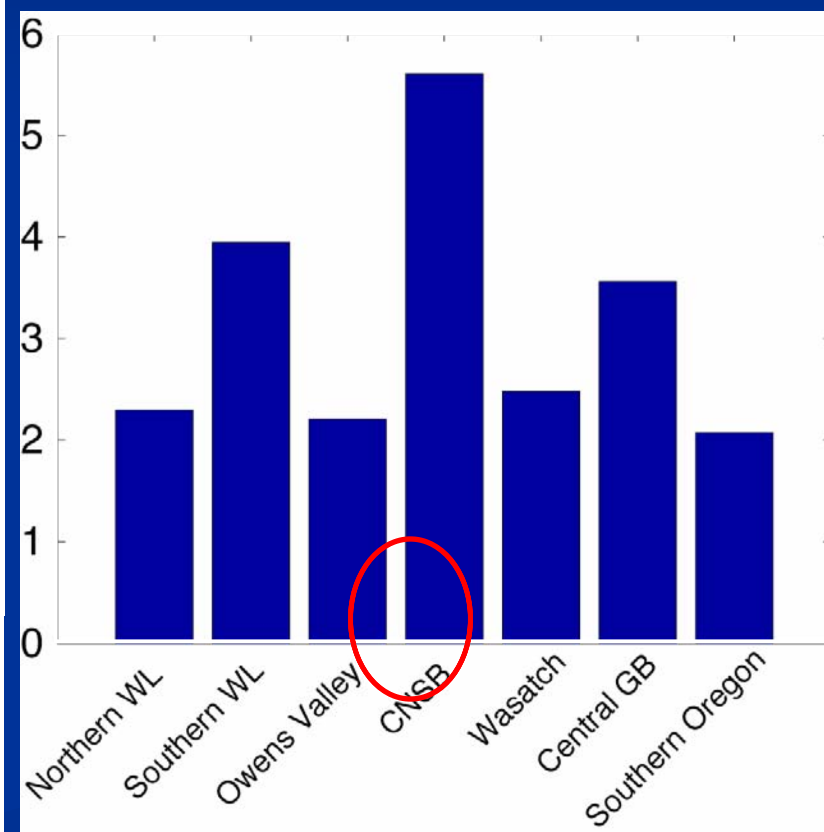


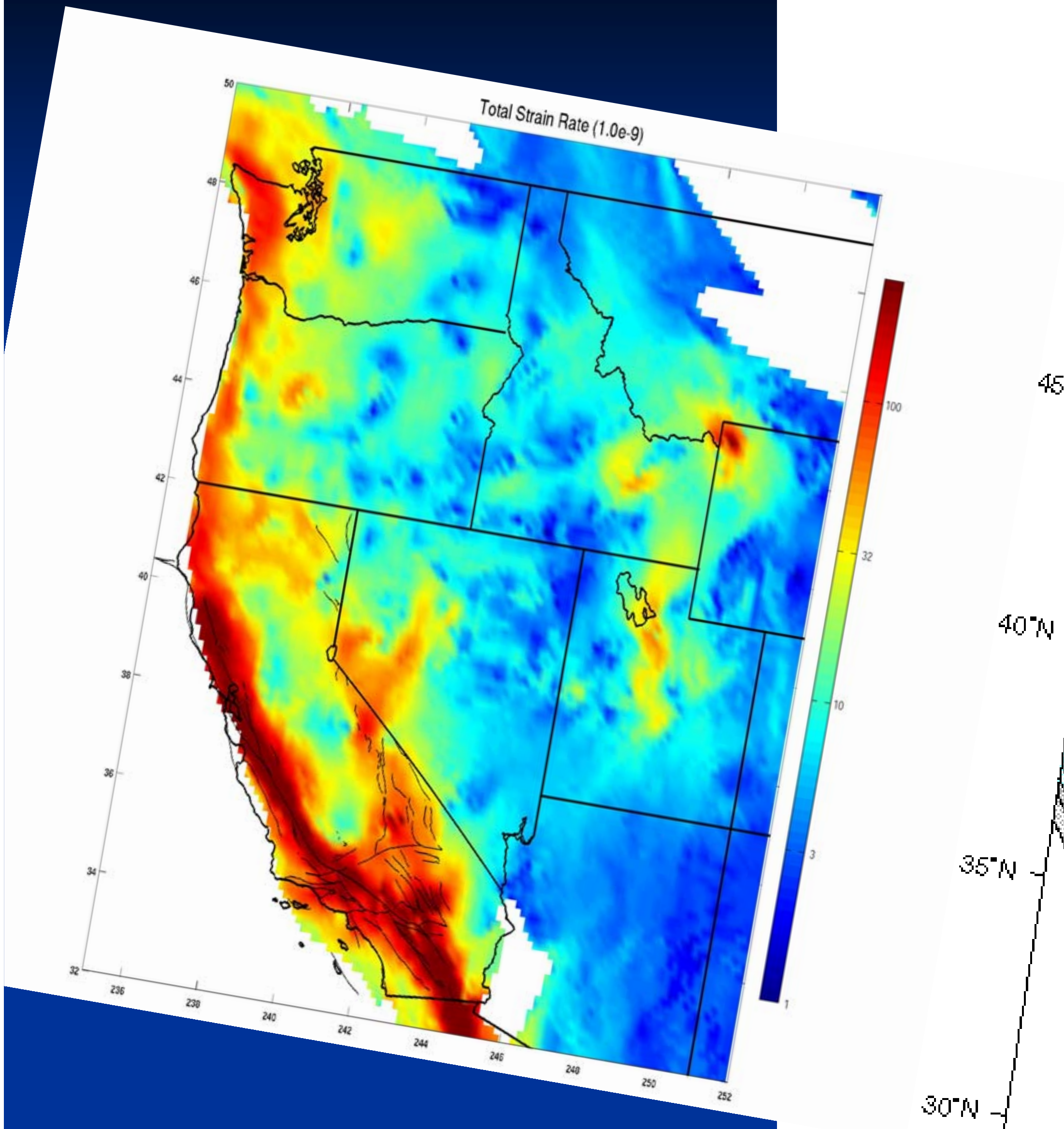
Geodesy Sees More Moment than Geology

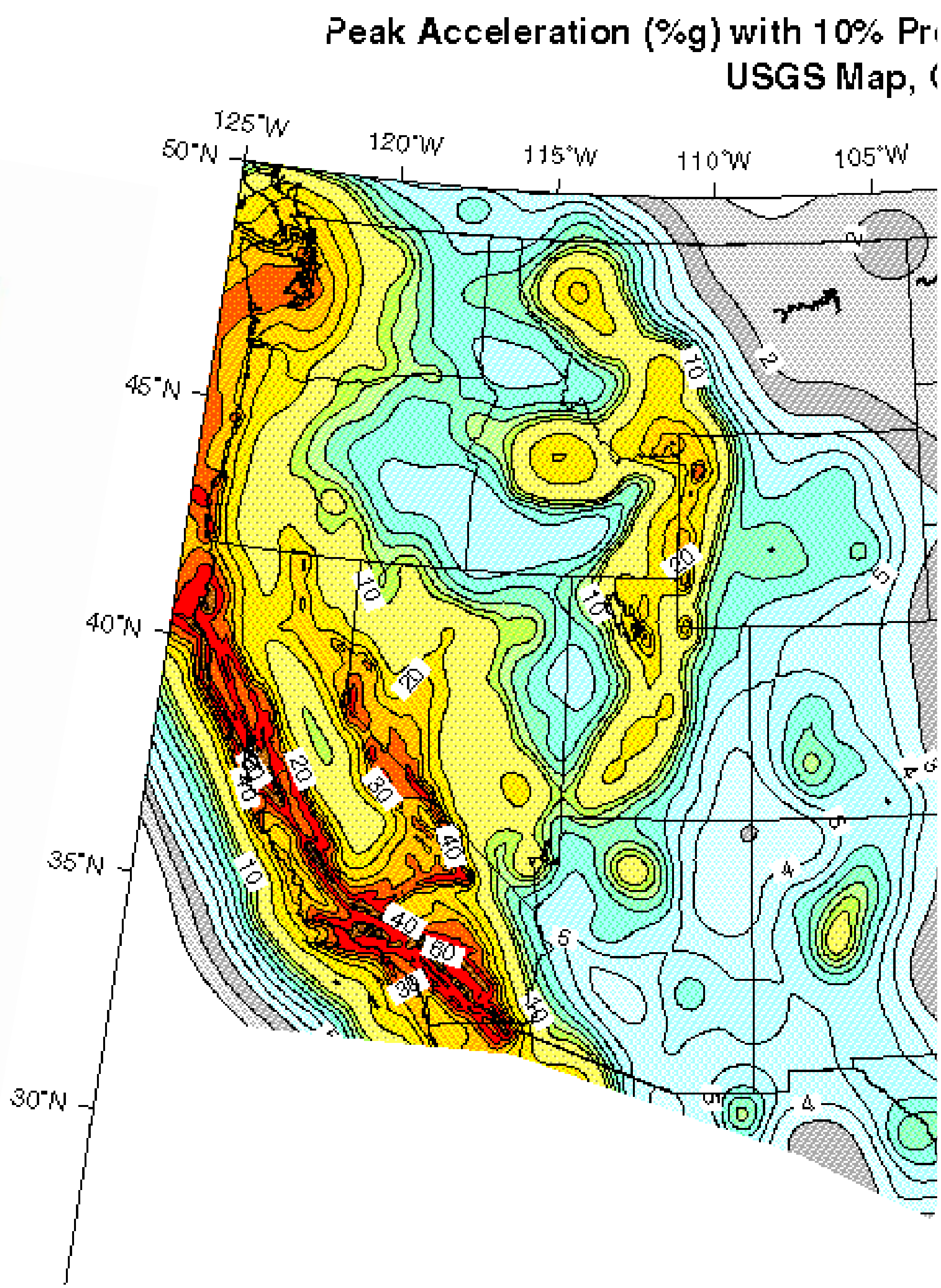


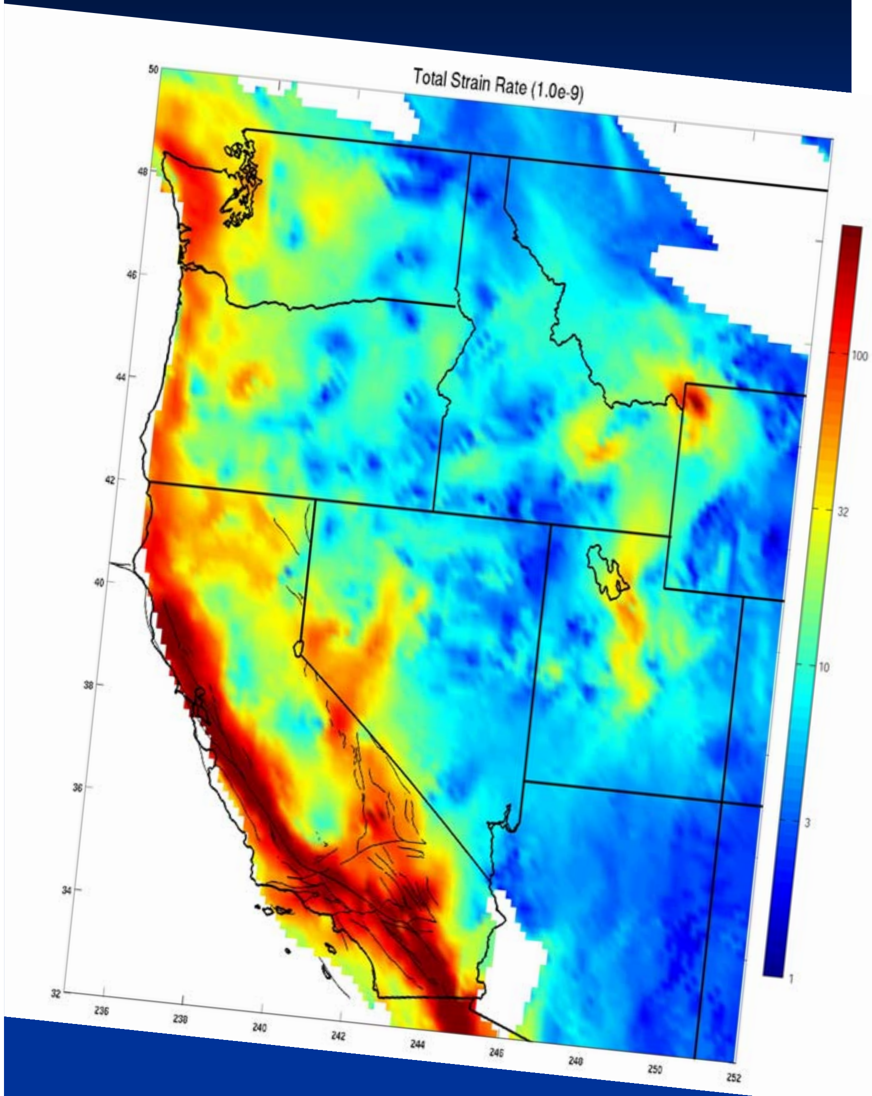
Pancha et al., 2006

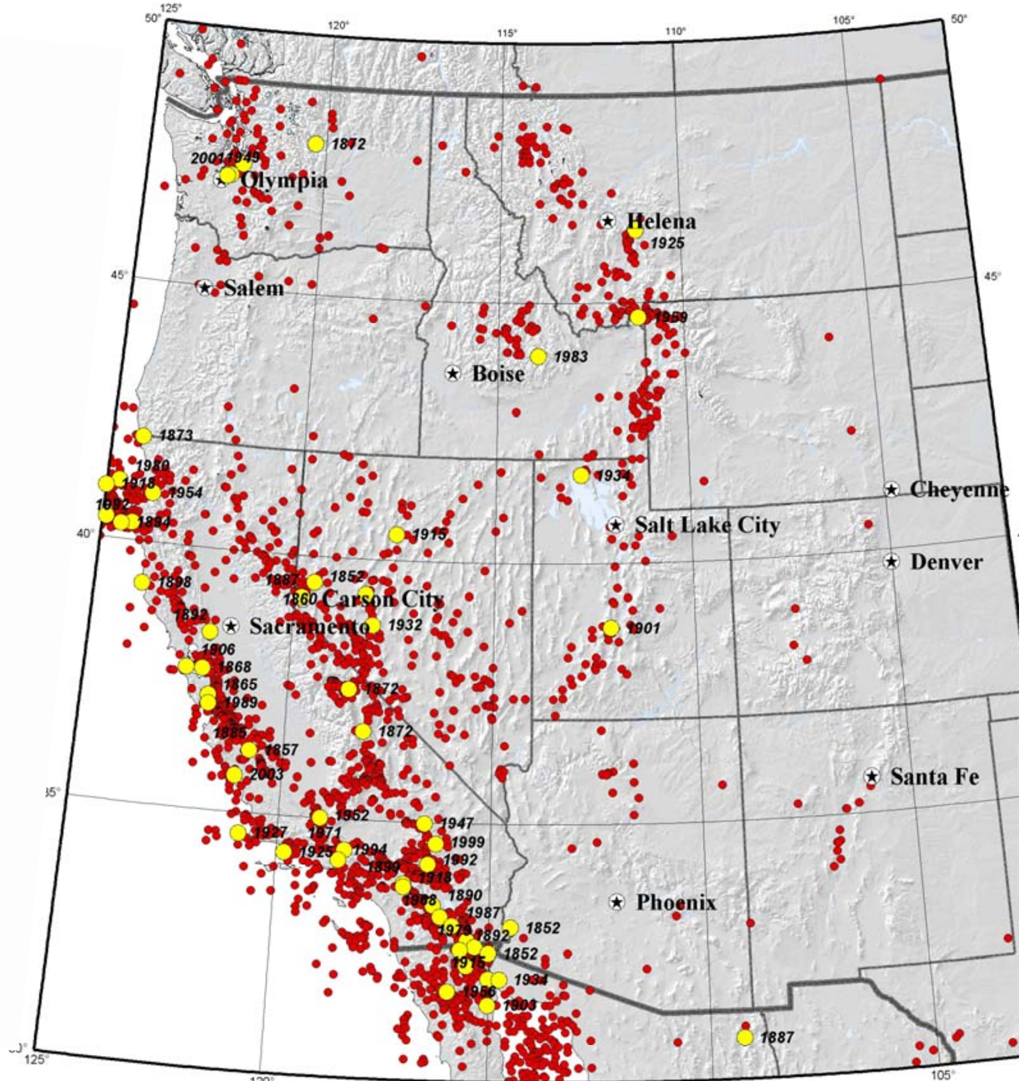
Ratio of Geodetic to Geologic Moment by Sub-Region




Total Strain Rate (1.0e-9)

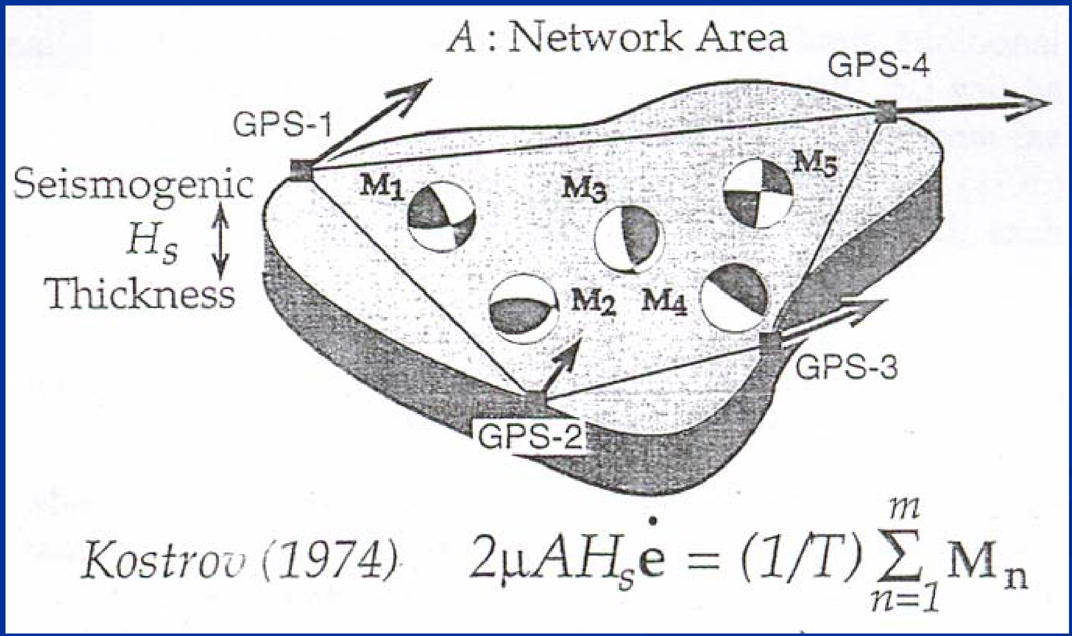

Peak Acceleration (%g) with 10% Pr
USGS Map,
125°W
120°W
115°W
110°W
105°W
50°N
45°N
40°N
35°N
30°N


Total Strain Rate (1.0e-9)
50
48
46
44
42
40
38
36
34
32
236
238
240
242
244
246
248
250
252
100
32
10
3
1

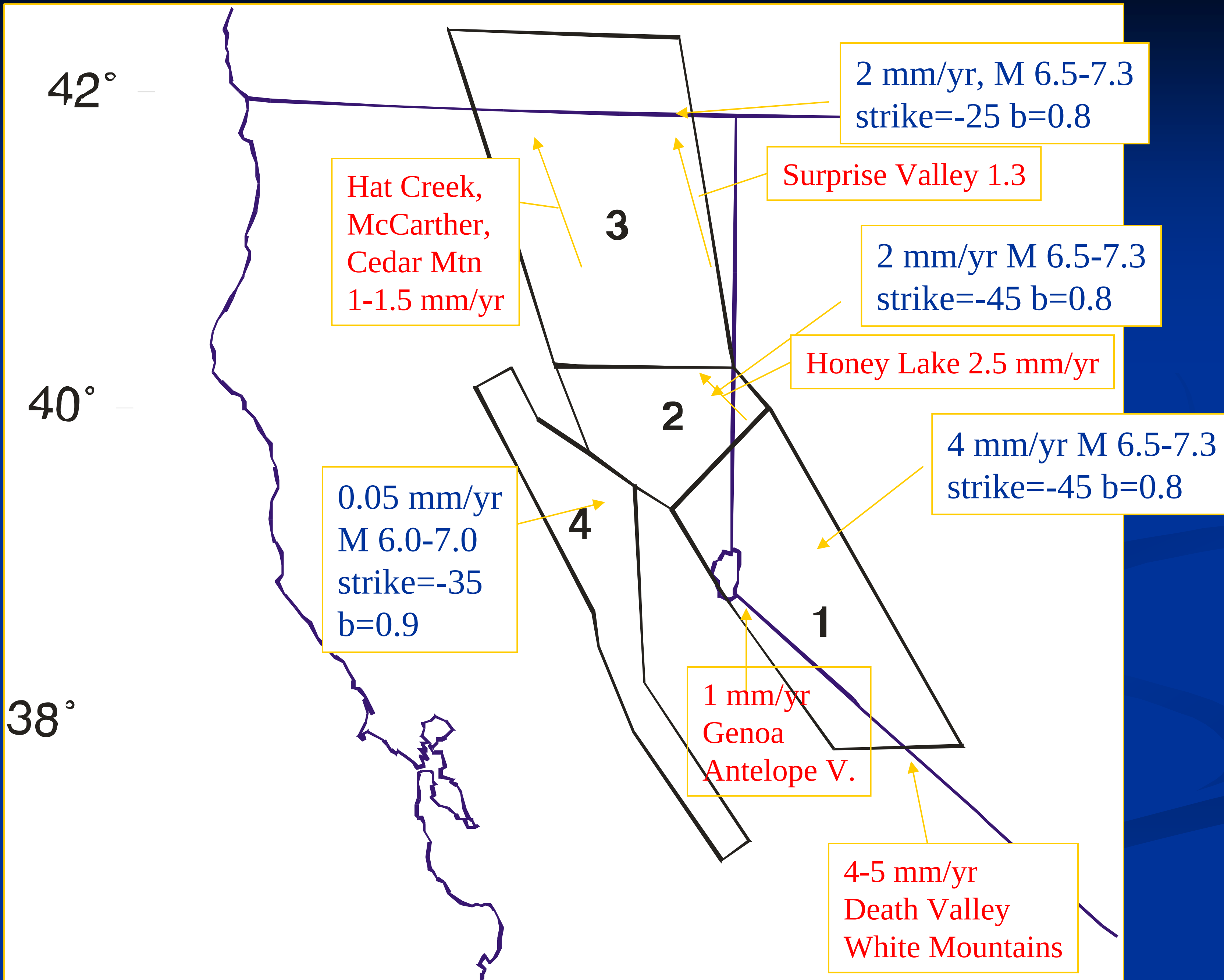

Olympia
Helena
Salem
Boise
Salt Lake City
Cheyenne
Denver
Carson City
Sacramento
Santa Fe
Phoenix
125°
120°
115°
110°
105°
50°
45°
40°
35°

From Geodic Strain Rates to Earthquake Moment Rates

Using Kostrov relation (1974) $\dot{M}_0 = 2\mu H_S \dot{\varepsilon}_{\max}$, we can estimate earthquake moment rate from geodetic strain rate

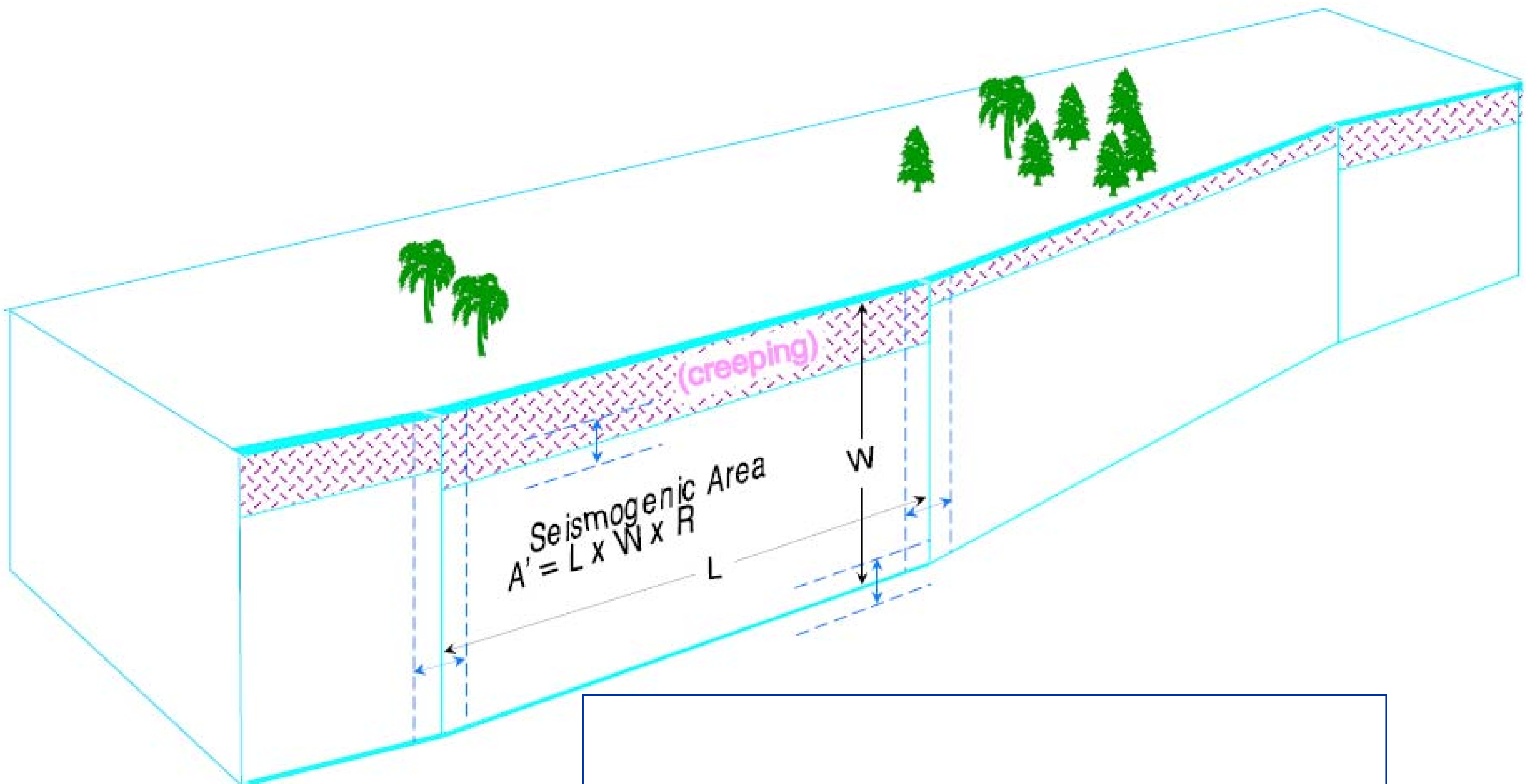


Geodetic based source zones



MAGNITUDE

- Slides contributed by Bill Ellsworth and Paul Somerville



(creeping)
W
Seismogenic Area
A' = L x W x R
L

Magnitude – Area Relations

$M = \log(A) + k$

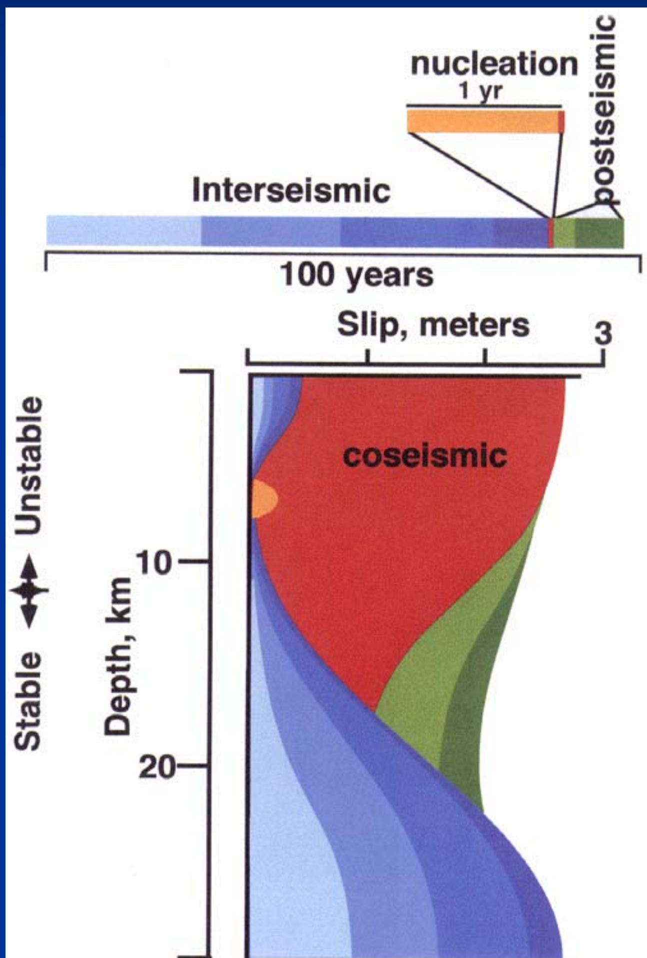
- Wells and Coppersmith (W&C, 1994) widely used in hazard analysis.
- Good agreement between W&C and kinematic rupture models derived from seismic waves.
- Application of W&C to WG02 fault model overpredicts historical seismicity rate.
- WG02 adopted 3 relations for large earthquakes:

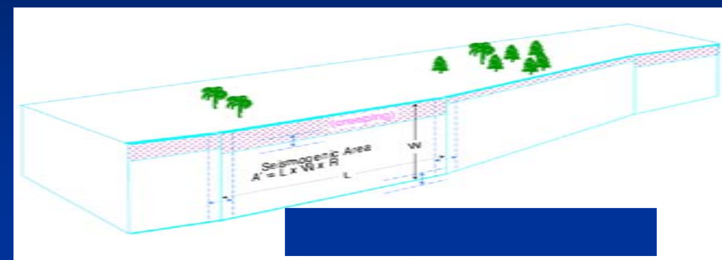
$M = 3.98 + 1.02 \log(A)$	(W&C)
$M = 4.2 + \log(A)$	(Ellsworth)
$M = 3.03 + 4/3 \log(A)$	(Hanks & Bakun)

where A = **L**ength x **W**idth x **R** (seismic coupling factor)

Magnitude – Area Relations

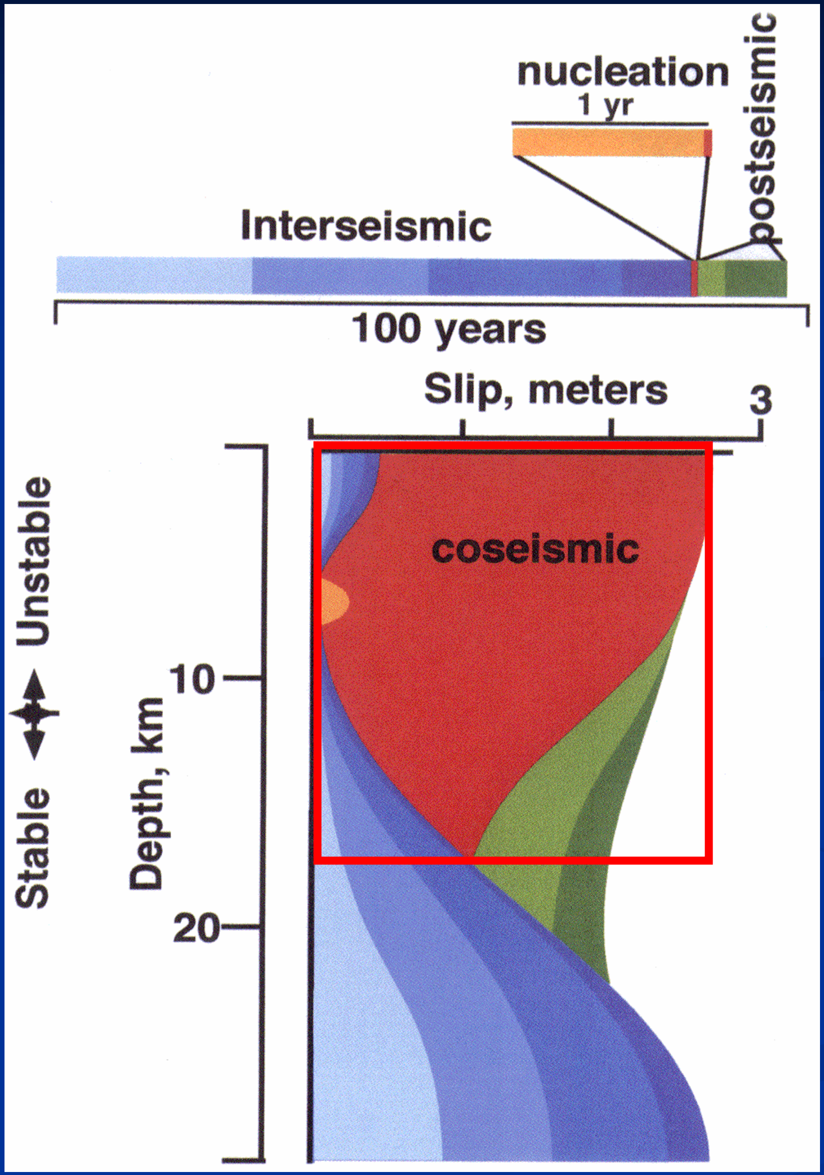
M = log(LWR) + k





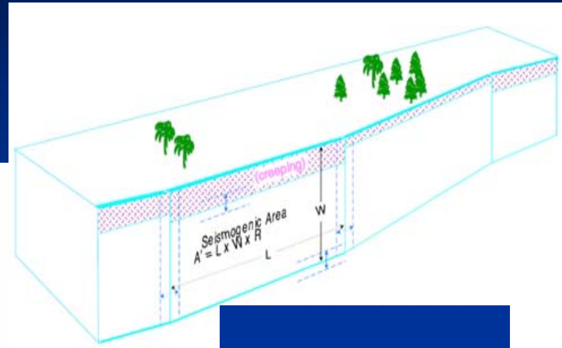
- Length (L):
- Width (W): difficult; disagreement between seismic and geodetic rupture models
- Aseismic slip factor (R): shallow creep – do-able; brittle-ductile transition – hard
- Trade-off between W and R:

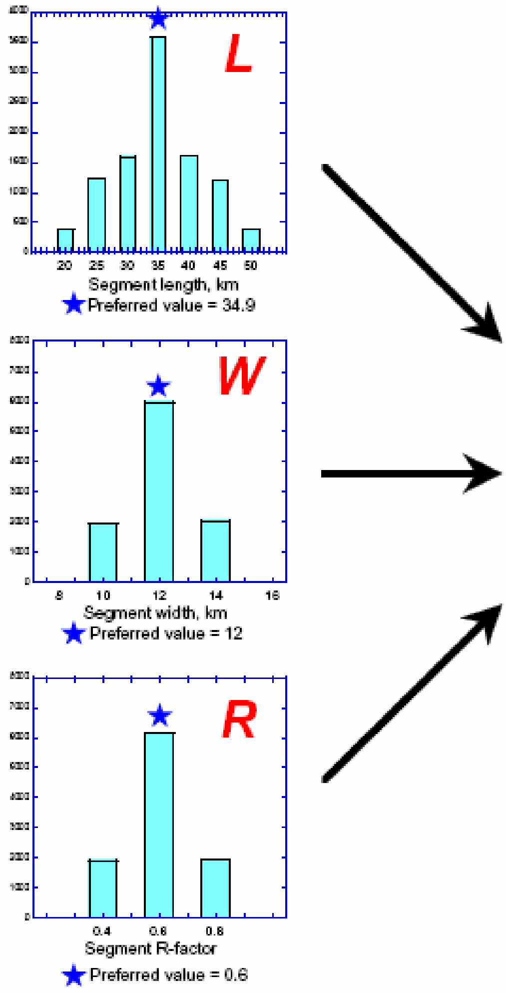
$$M = \log(L) + \log(WR) + k$$

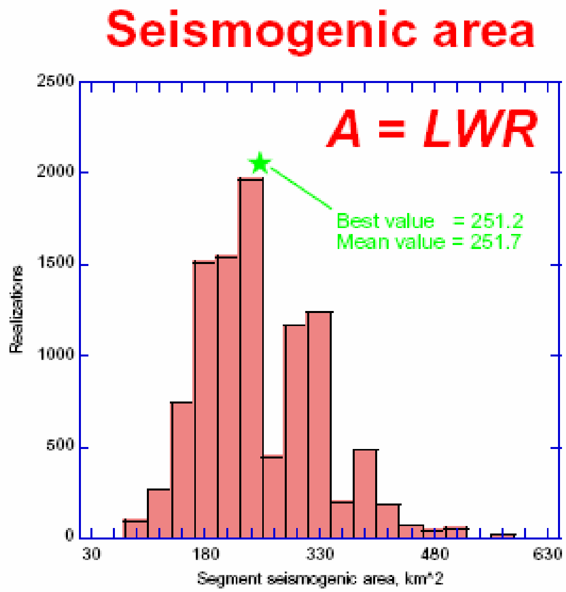


In this example
R = 0.7
or
log(R) = -0.15

WG02 Approach to Determining W and R



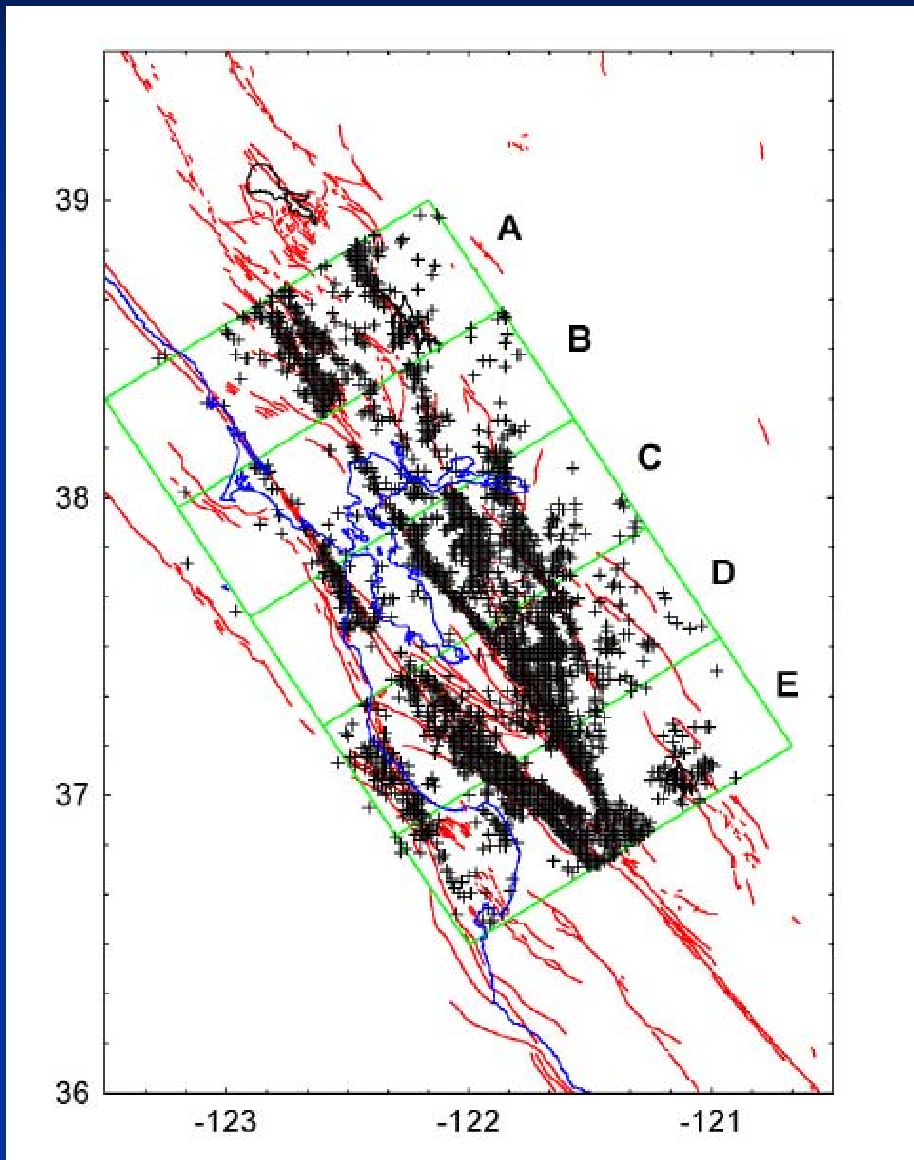


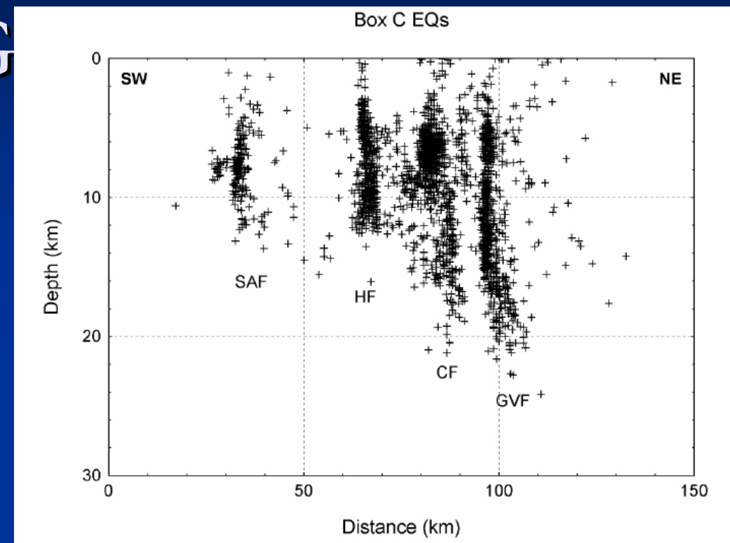


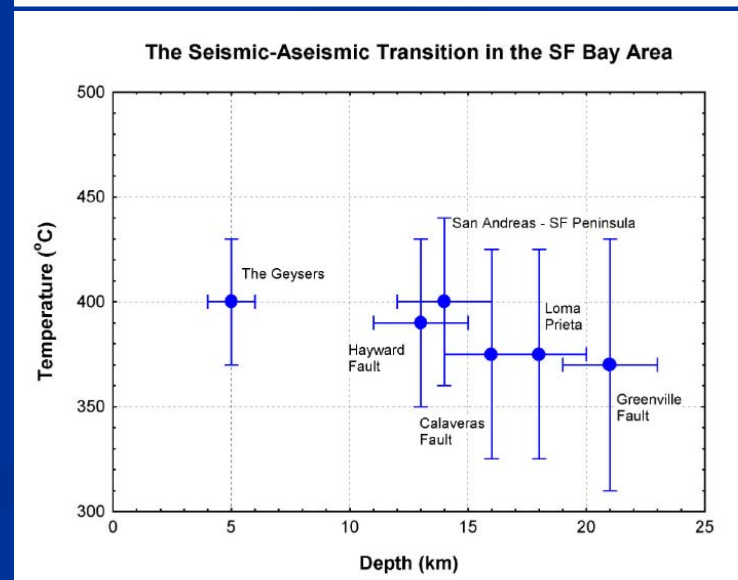
Define W as the depth of the brittle-ductile transition determined from seismicity and thermal data

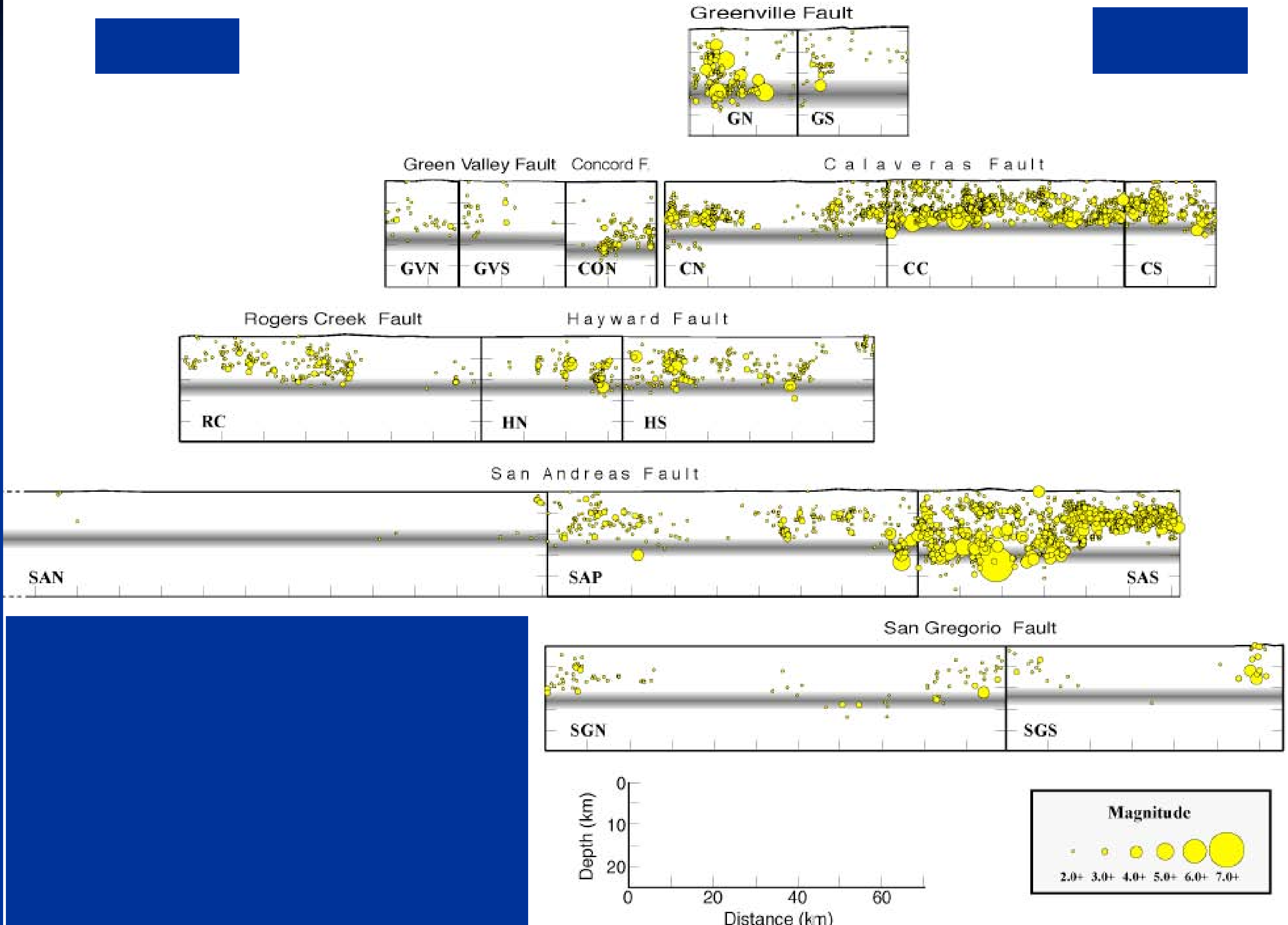
Use geodetic data to determine R given W

Ductile transition in the San Francisco Bay Area

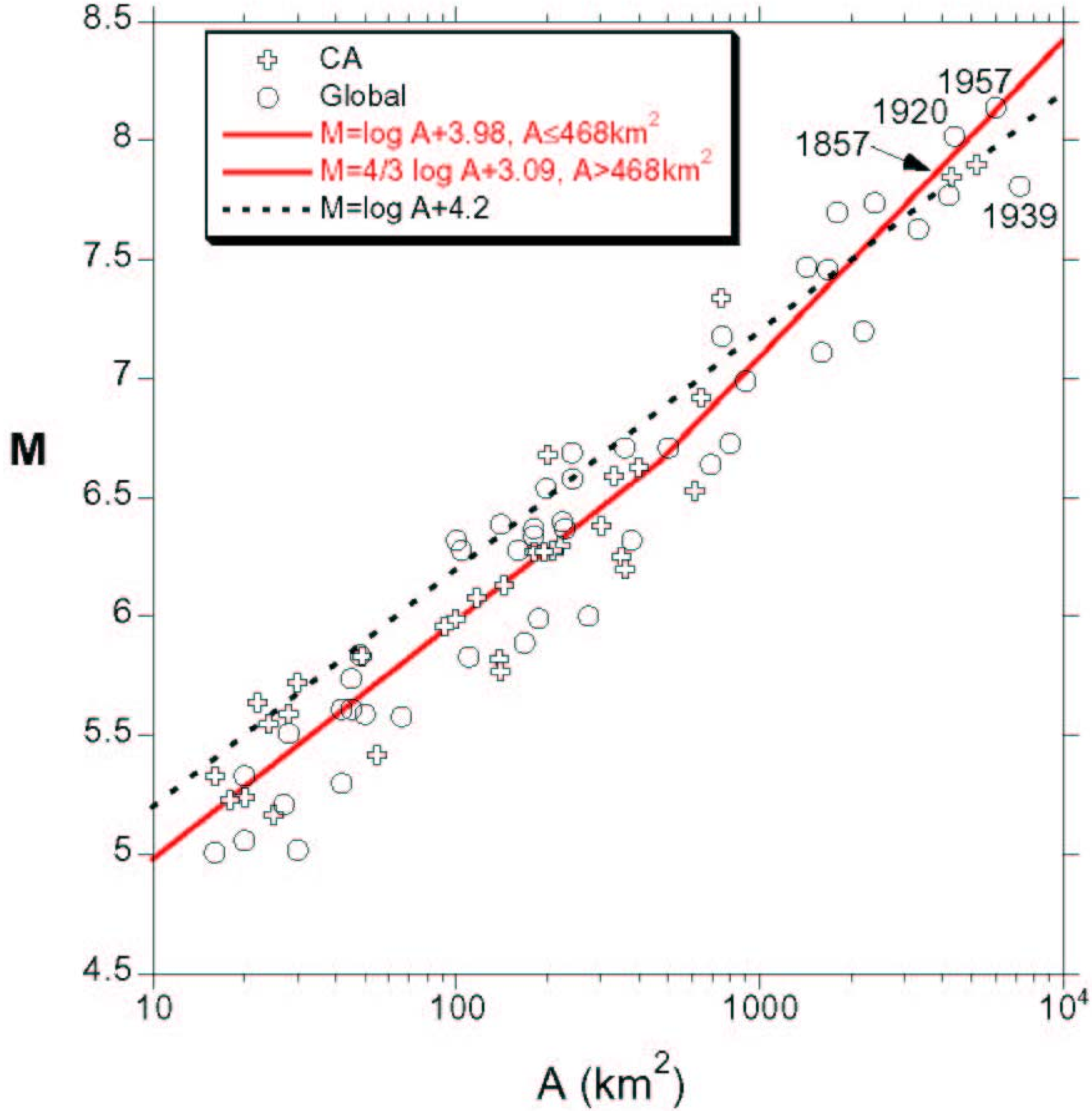








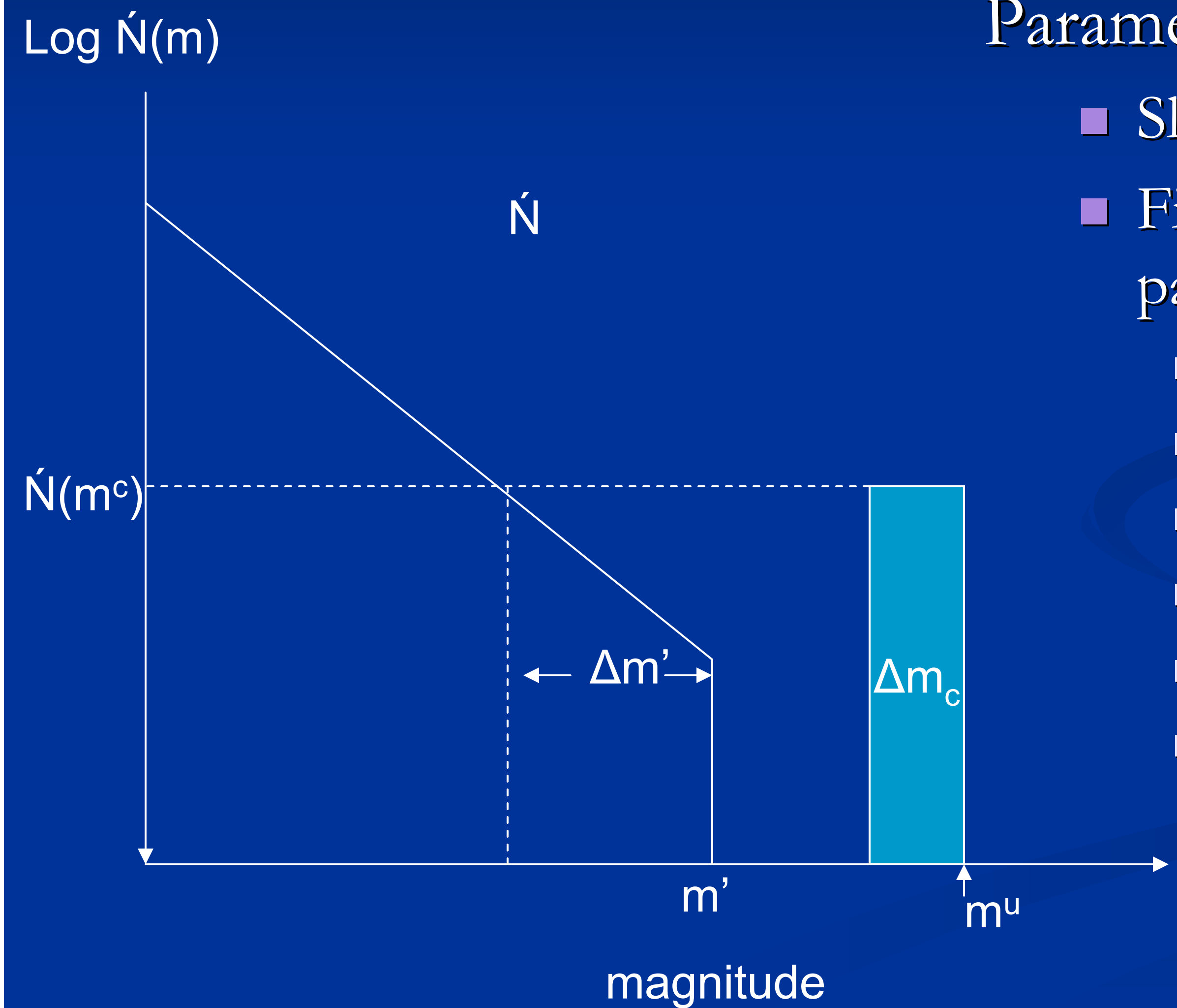
Greenville Fault
GN
GS
Green Valley Fault
Concord F.
Calaveras Fault
GVN
GVS
CON
CN
CC
CS
Rogers Creek Fault
Hayward Fault
RC
HN
HS
San Andreas Fault
SAN
SAP
SAS
San Gregorio Fault
SGN
SGS
Depth (km)
0
10
20
0
20
40
60
Distance (km)
Magnitude
2.0+ 3.0+ 4.0+ 5.0+ 6.0+ 7.0+



CA
Global
M=log A+3.98, A≤468km²
M=4/3 log A+3.09, A>468km²
M=log A+4.2
1957
1920
1857
1939
M
A (km²)
8.5
8
7.5
7
6.5
6
5.5
5
4.5
10
100
1000
10⁴

MAGNITUDE -FREQUENCY

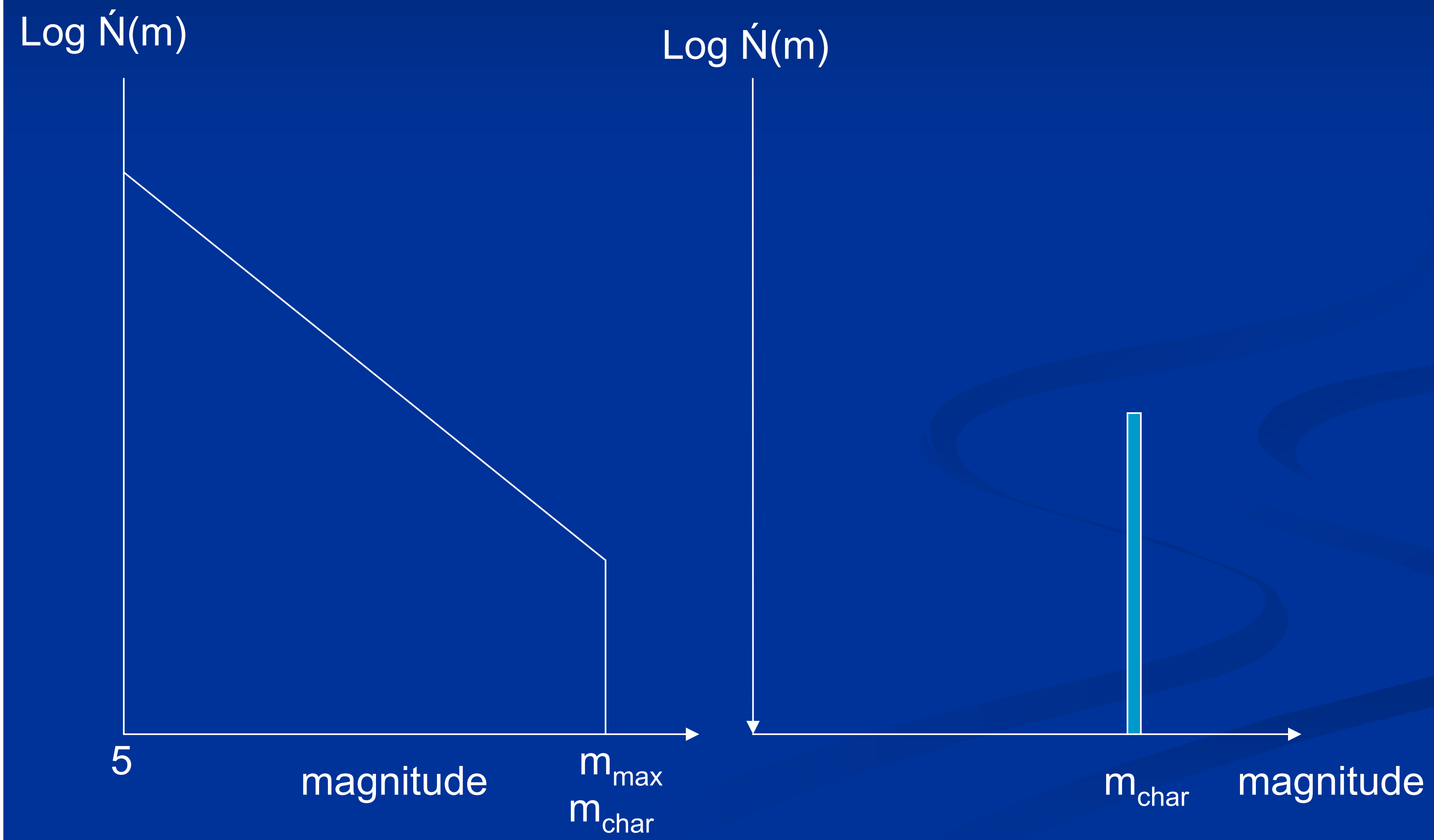
Youngs and Coppersmith (1985) Magnitude-frequency distribution



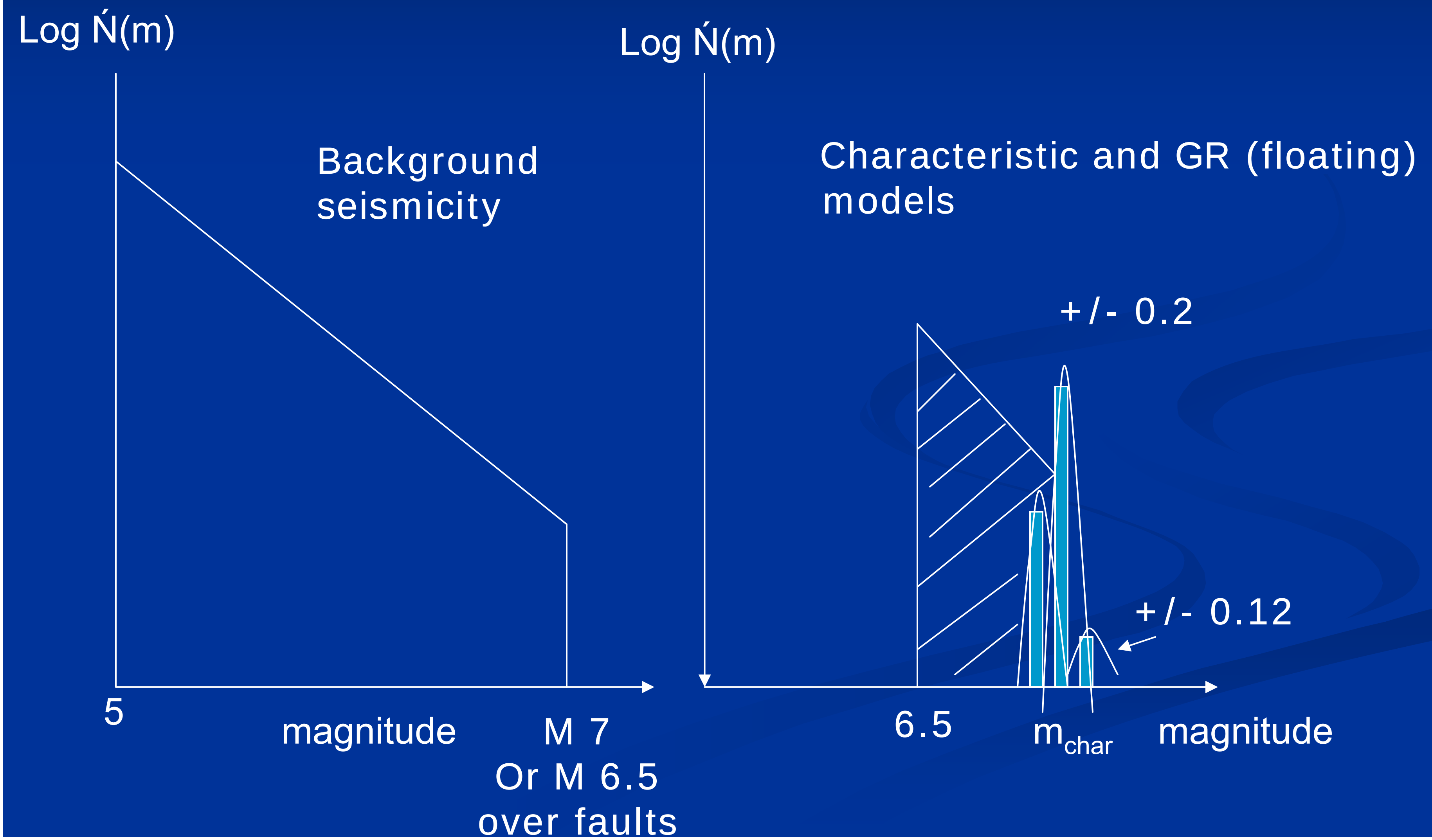
Parameters

- Slip rate
- Five of the following six parameters
  - $\acute{N}(M_0)$
  - b
  - m'
  - m^u
  - Δm_c
  - $\acute{N}(m^c)$

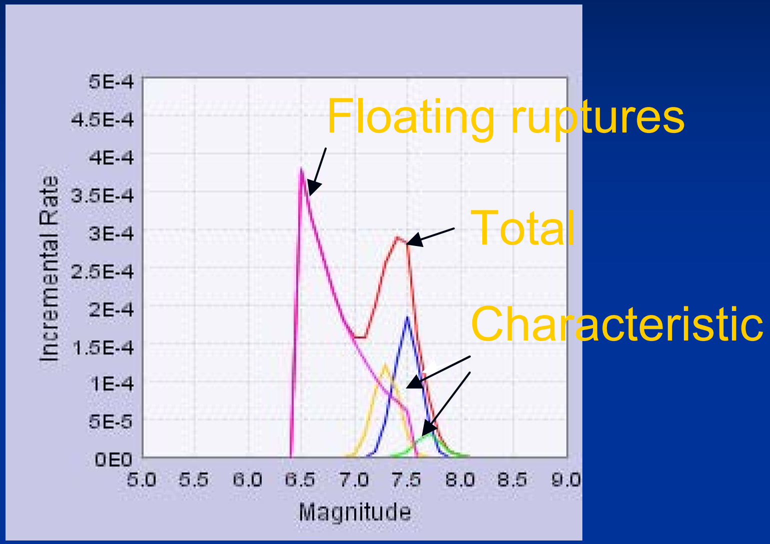
Characteristic and GR to describe M-f distribution on a fault

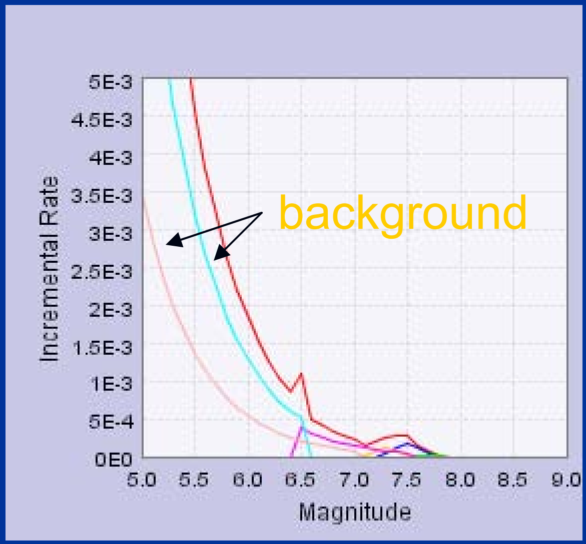


Background seismic and fault magnitude-frequency distributions



USGS Magnitude-frequency model

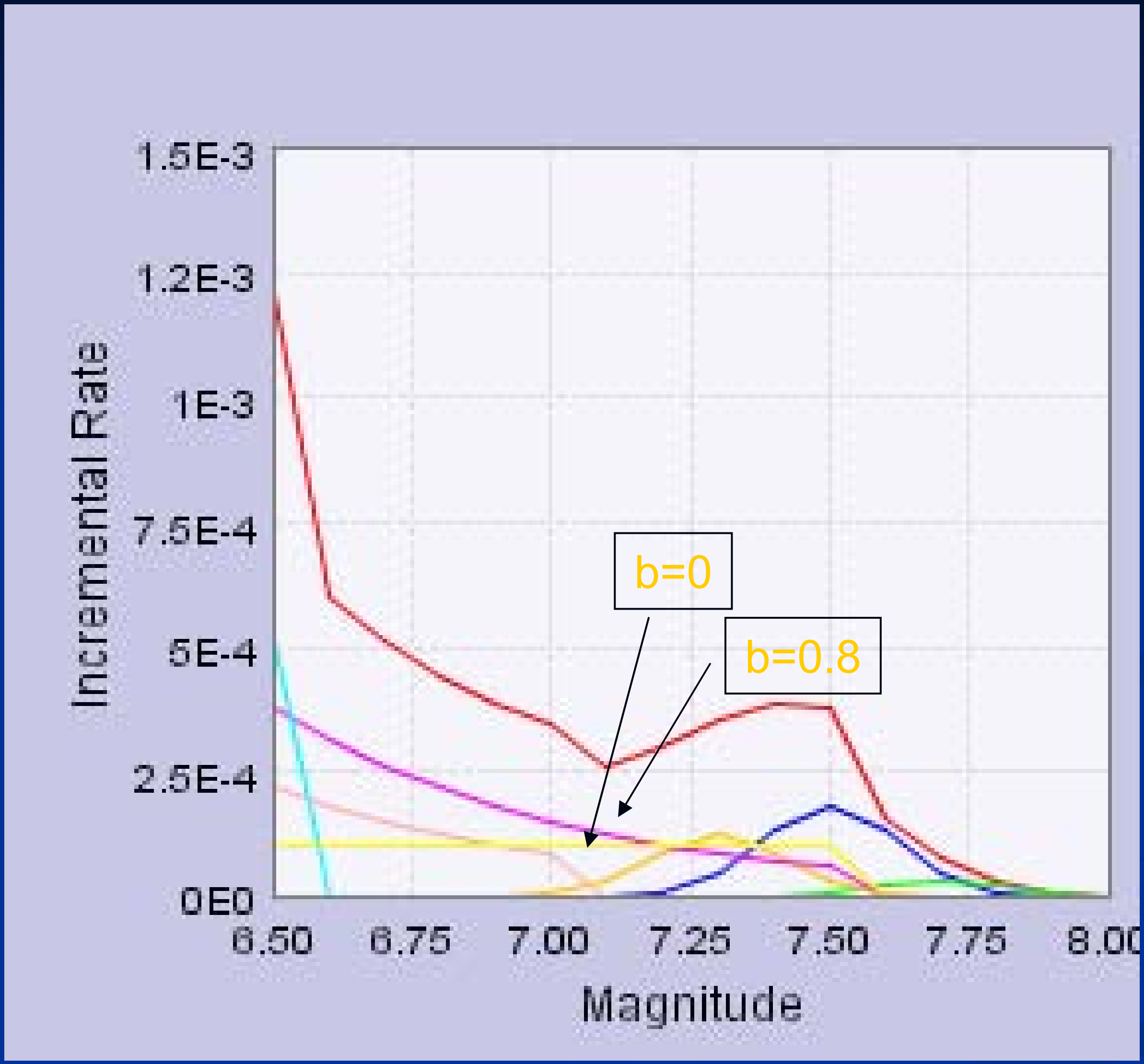




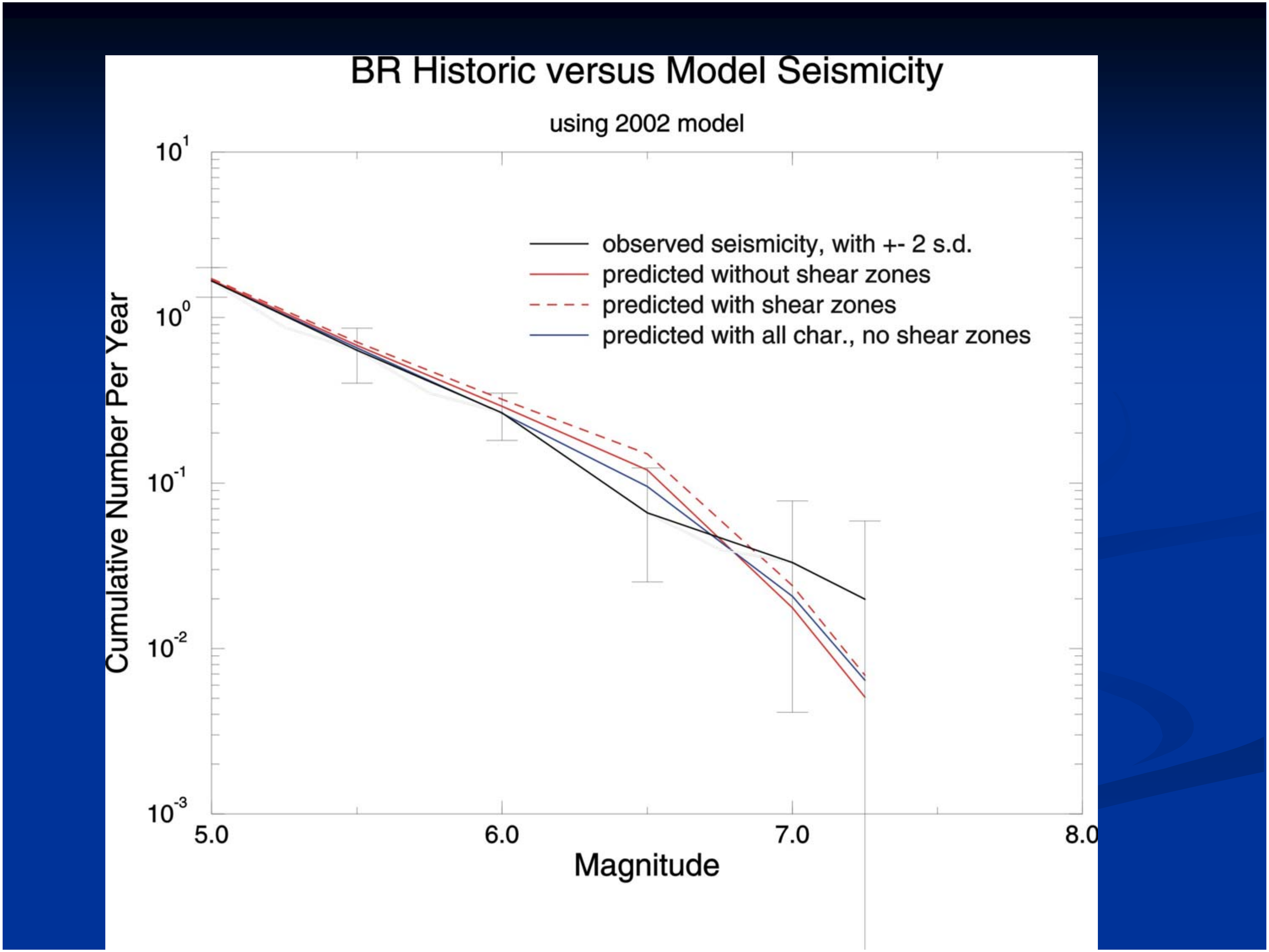
Parameters

- Slip rate
- Characteristic or maximum magnitude
- Epistemic and aleatory uncertainty
- Ratio of Characteristic to Floating Rupture moment rate
- Minimum magnitude
- b-value

Moment rate 2E17/yr (2/3) split into three magnitudes
Moment rate 6.7E16/yr (1/3) used for floating ruptures (GR)
Moment rate 2E16/yr used for background earthquakes



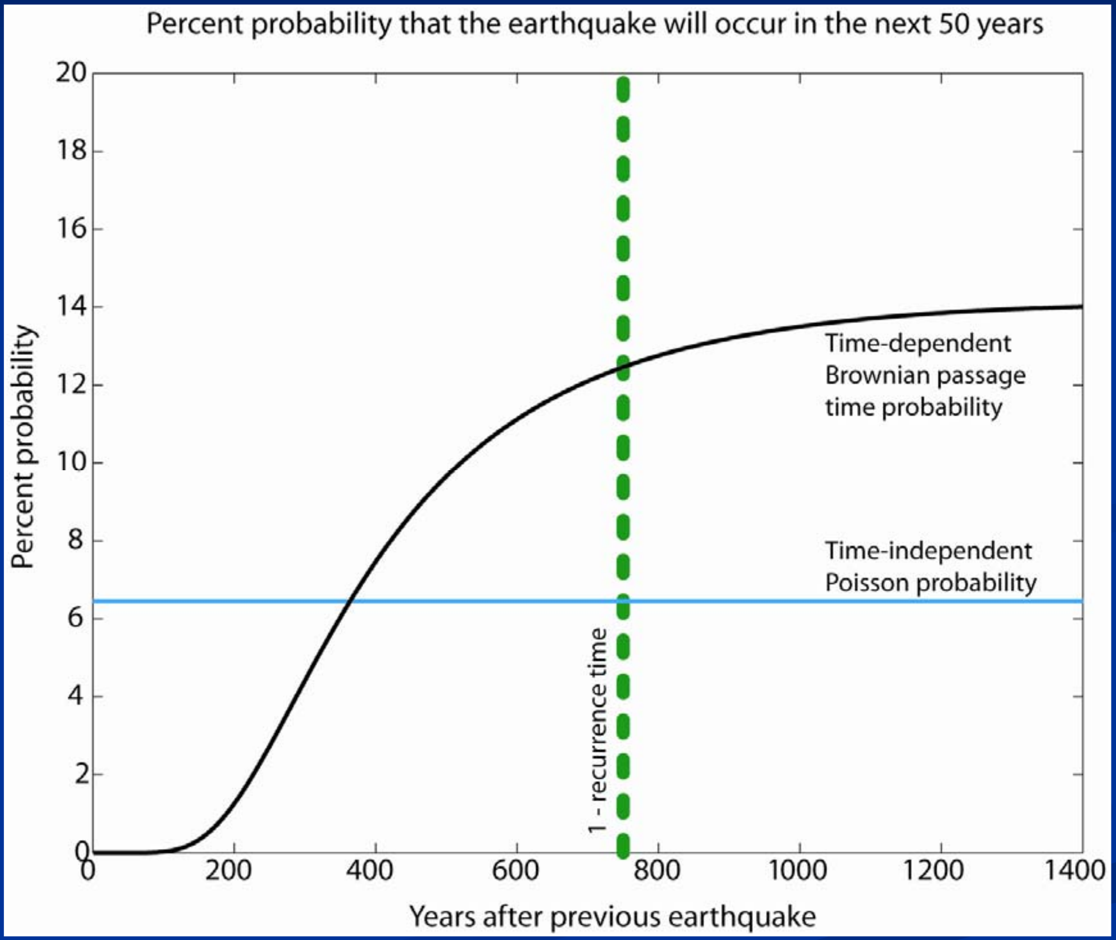
1.5E-3
1.2E-3
1E-3
7.5E-4
5E-4
2.5E-4
0E0
Incremental Rate
6.50
6.75
7.00
7.25
7.50
7.75
8.00
Magnitude
b=0
b=0.8


BR Historic versus Model Seismicity
using 2002 model
observed seismicity, with +- 2 s.d.
predicted without shear zones
predicted with shear zones
predicted with all char., no shear zones
Cumulative Number Per Year
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
5.0
6.0
7.0
8.0
Magnitude

TIME-DEPENDENCE

What are time-dependent earthquake probabilities?

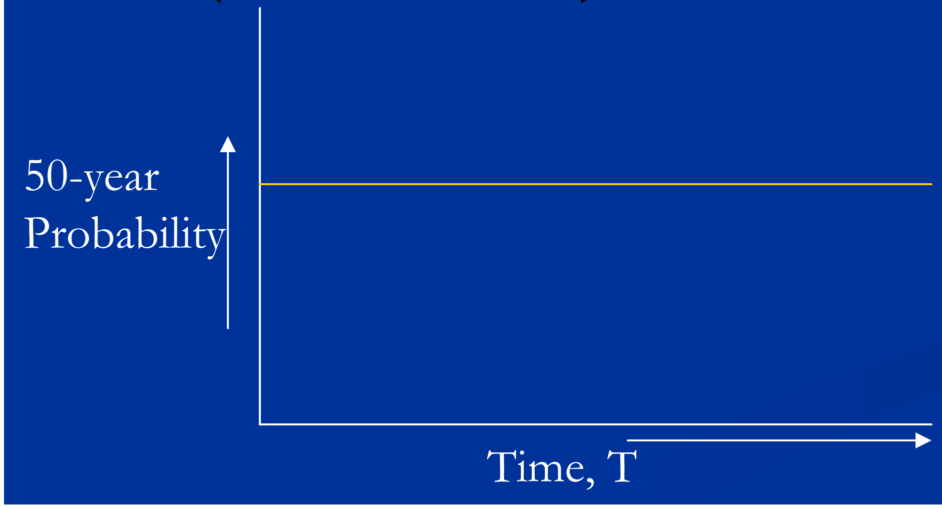
- Time-dependent conditional probability



Oliver Boyd

Poisson Process

- $P(N>0)=1-e^{(-annual\ rate*t)}$ expresses the probability of no events occurring in a fixed time (e.g., t=50 years) if these events occur with a known average rate, and are independent of the time since the last event.
- Simple model, only one parameter needed (annual rate)

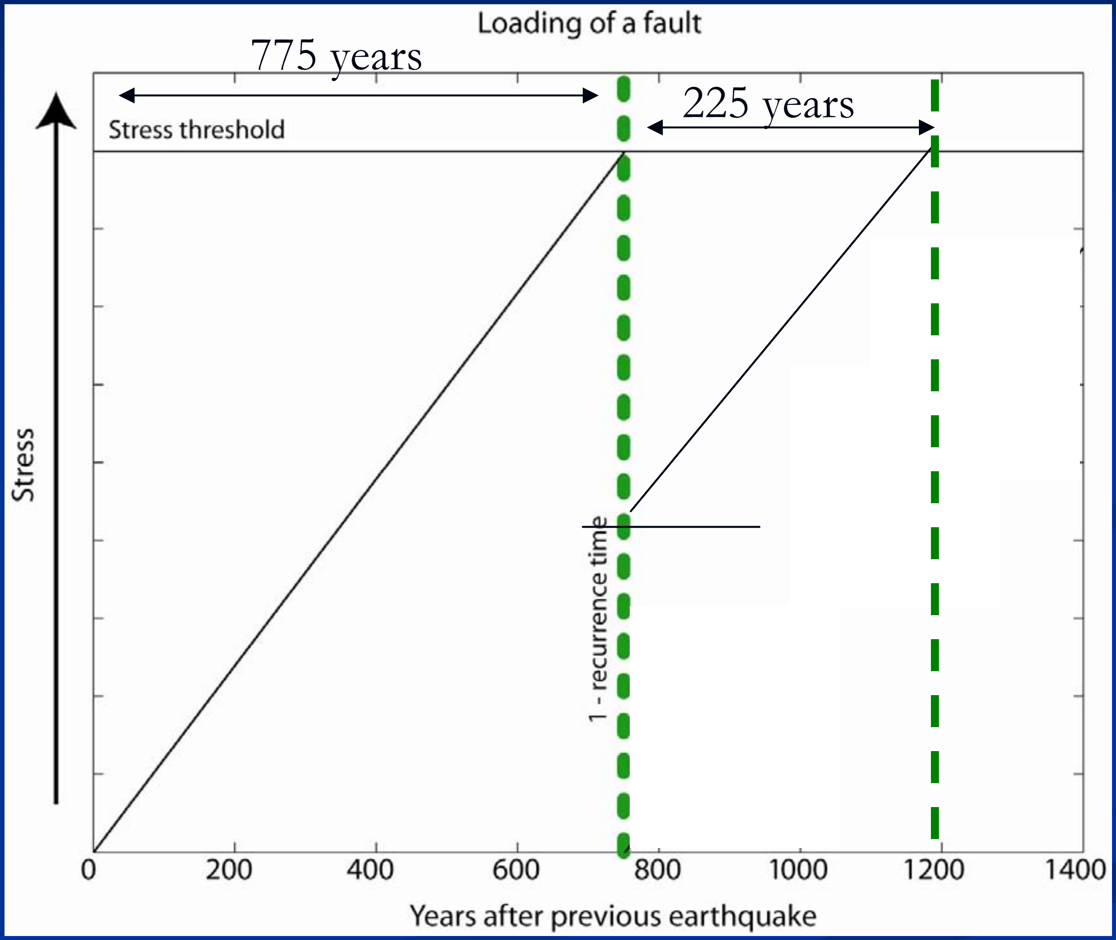


Empirical model

- To account for stress shadow following the 1906 earthquake
- Uses observed seismicity rates since 1906 as proxy for stress shadow
- Scales rates by factor (0.4, 0.5, 0.7) and then computes Poisson probabilities using these updated rates

Time-predictable model

- Linear loading
- Time-predictable model: size (slip) in last event and strain accumulation rate predicts the time of next event.

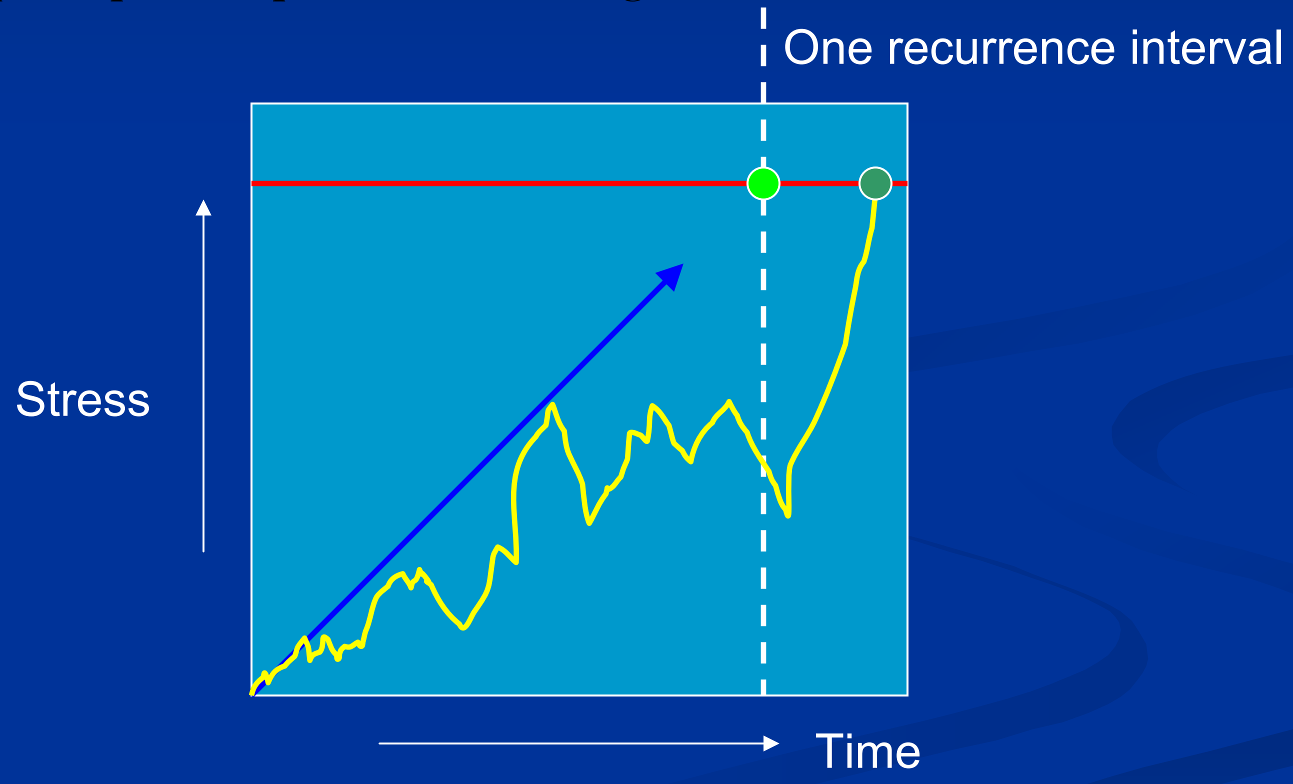


Shimazaki and Nakata (1980), Murray and Segall (2002)

Oliver Boyd

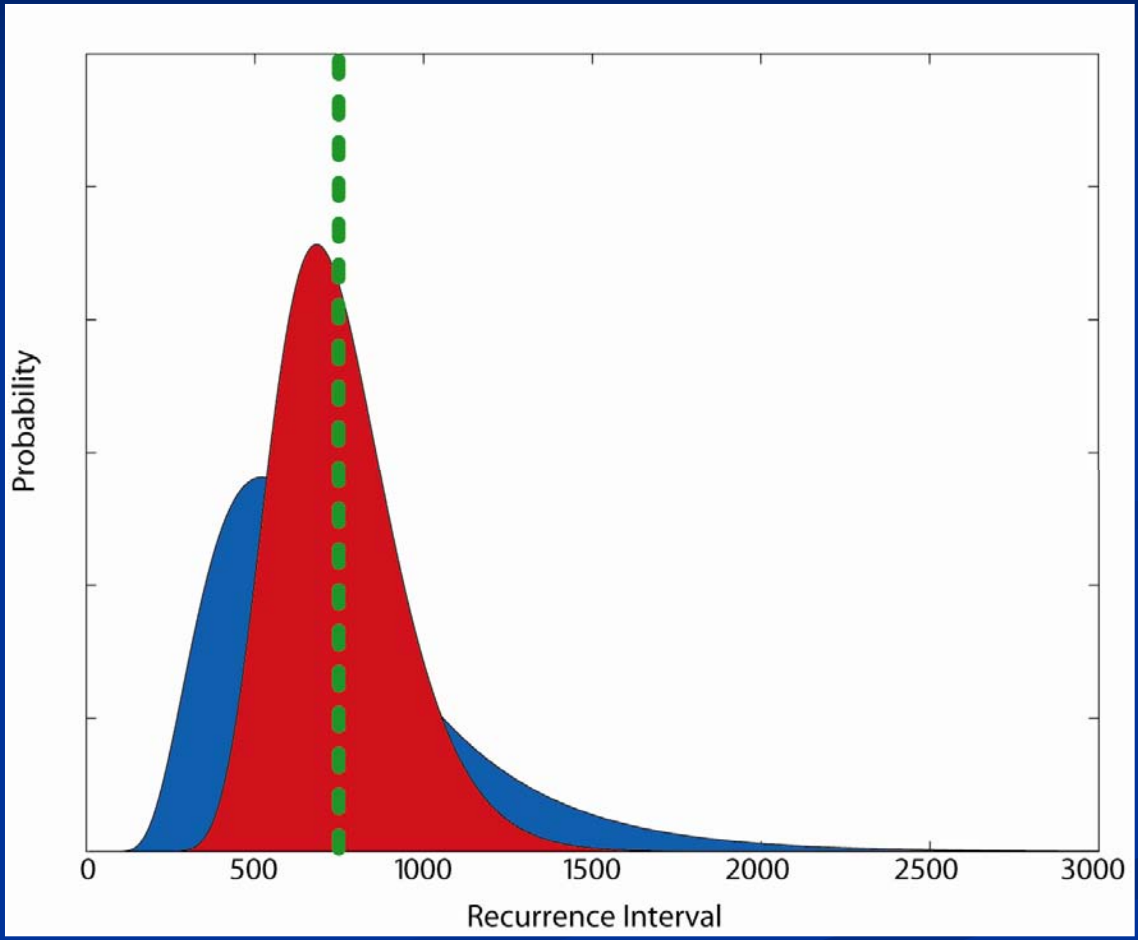
Brownian Passage Time

- Brownian passage time (BPT) loading on a fault – random fluctuations of stress superimposed upon linear loading of a fault.



What are time-dependent earthquake probabilities?

- Linear loading with Brownian motion



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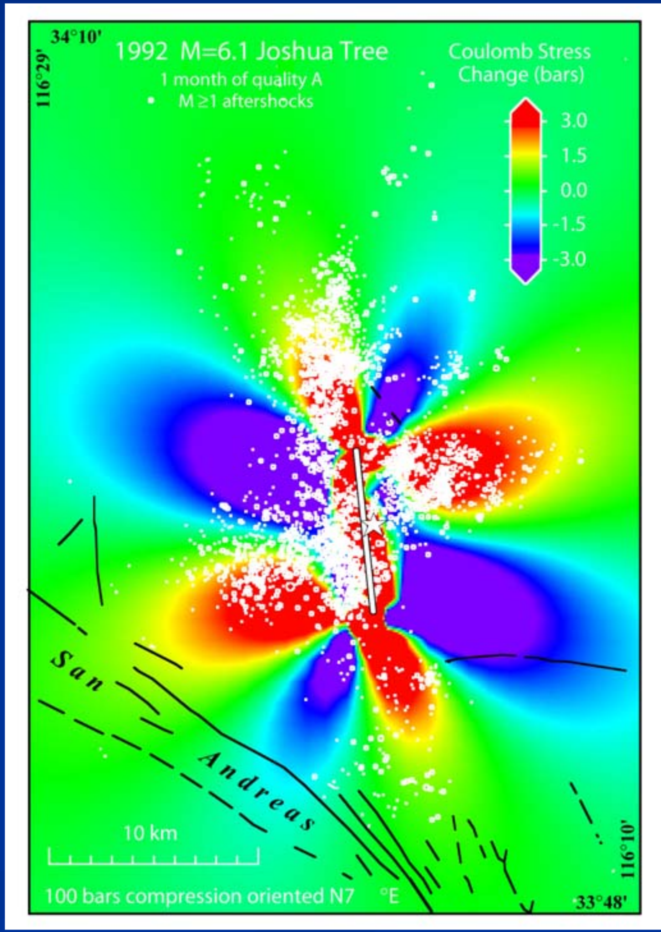
How do stress changes influence time-dependent earthquake probabilities?

- Coulomb stress change for optimally oriented faults

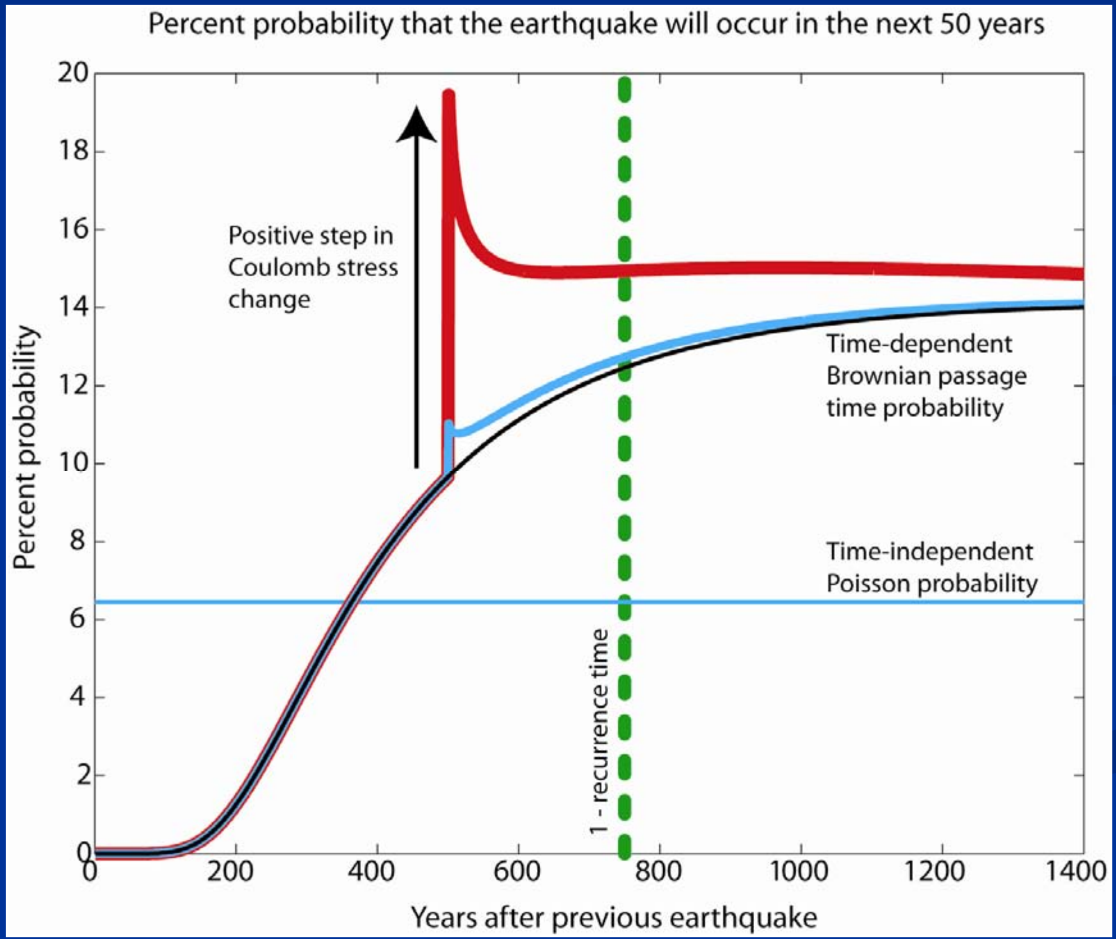
$$\Delta CS = \sigma_S + \mu' \sigma_N$$



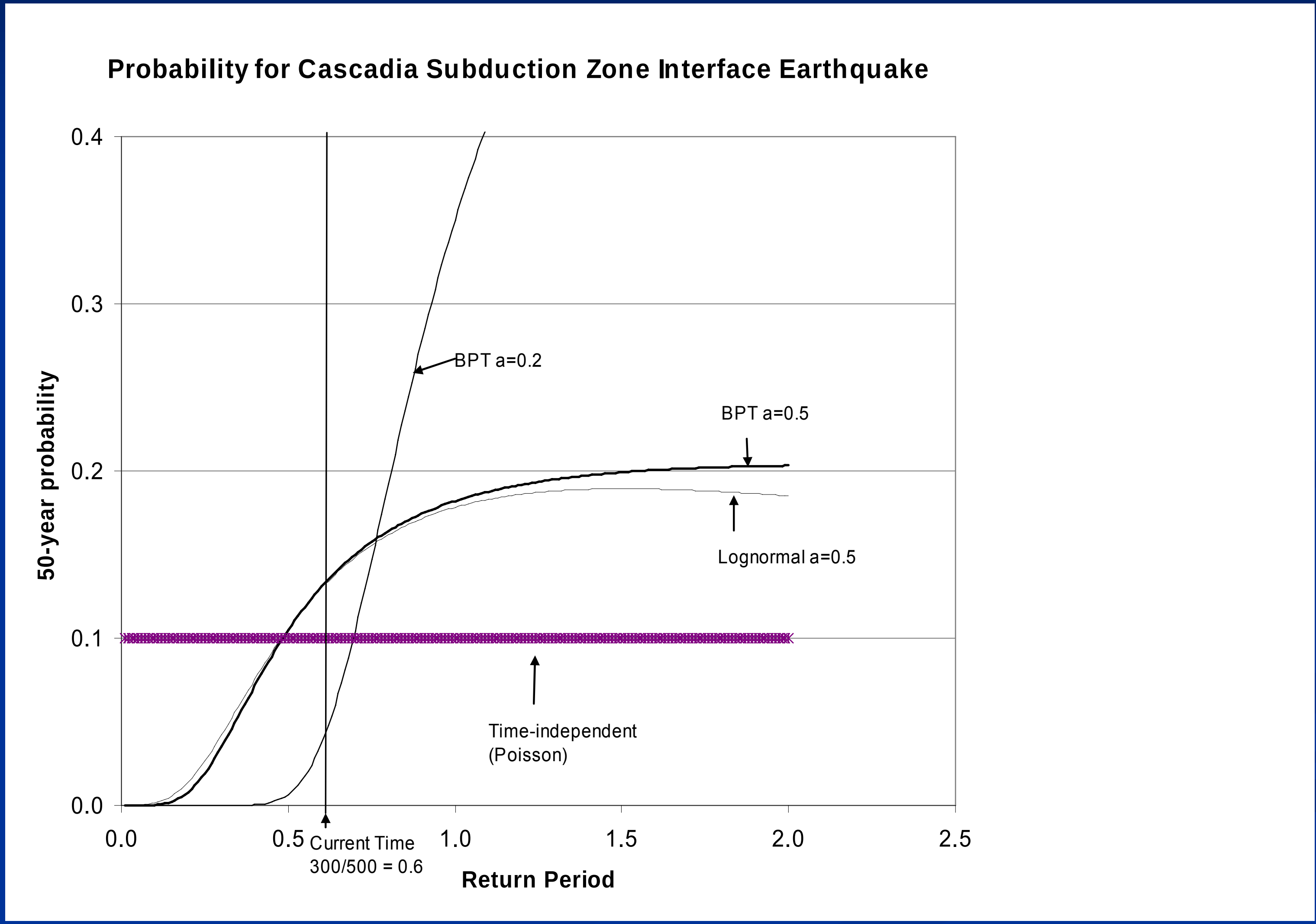
King et al., BSSA 1994

How do stress changes influence time-dependent earthquake probabilities?

- Time-dependent conditional probability *with stress changes*



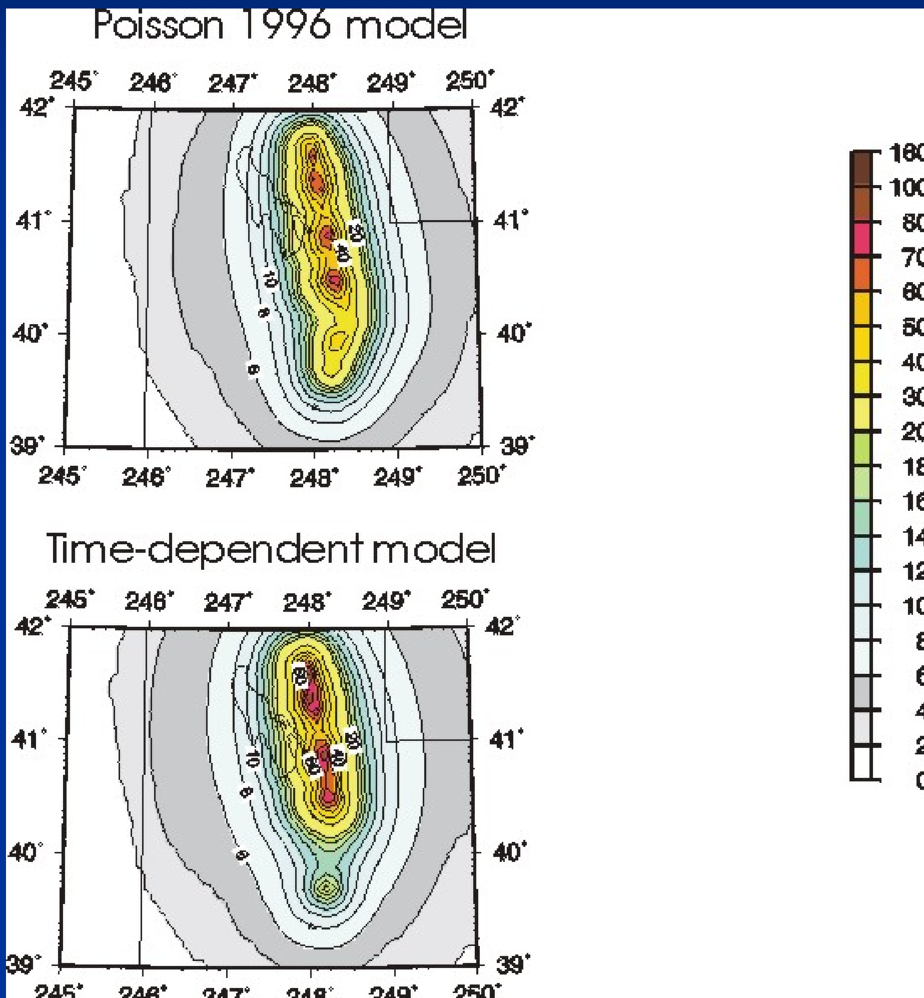
Time-dependent hazard maps

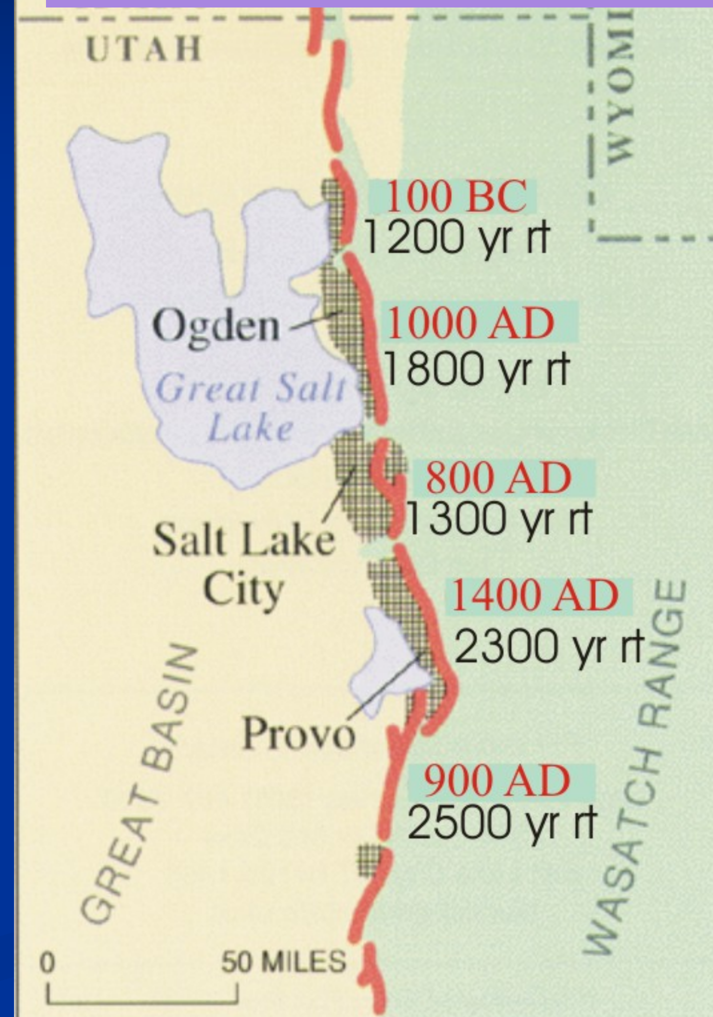


Source characterization

Time-dependent models

	Med. Rec.	Elapsed time	50-year prob
Brigham City:	1230	2175	8%
Weber:	1674	1066	3%
Salt Lake:	1367	1280	6%
Provo:	2413	668	0.1%
Nephi:	2706	1198	0.8%





SEISMIC: SOURCE ZONES

Earthquake Catalogs

Magnitude scales:

- Body wave magnitude (Mb)
- Richter magnitude (ML)
- Surface wave magnitude (Ms)
- Moment magnitude (Mw)

Catalogs:

- Preliminary Determination of Earthquakes (PDE)
- International Seismic Centre (ISC)
- Local catalogs (Ambraseys)

Magnitude Saturation

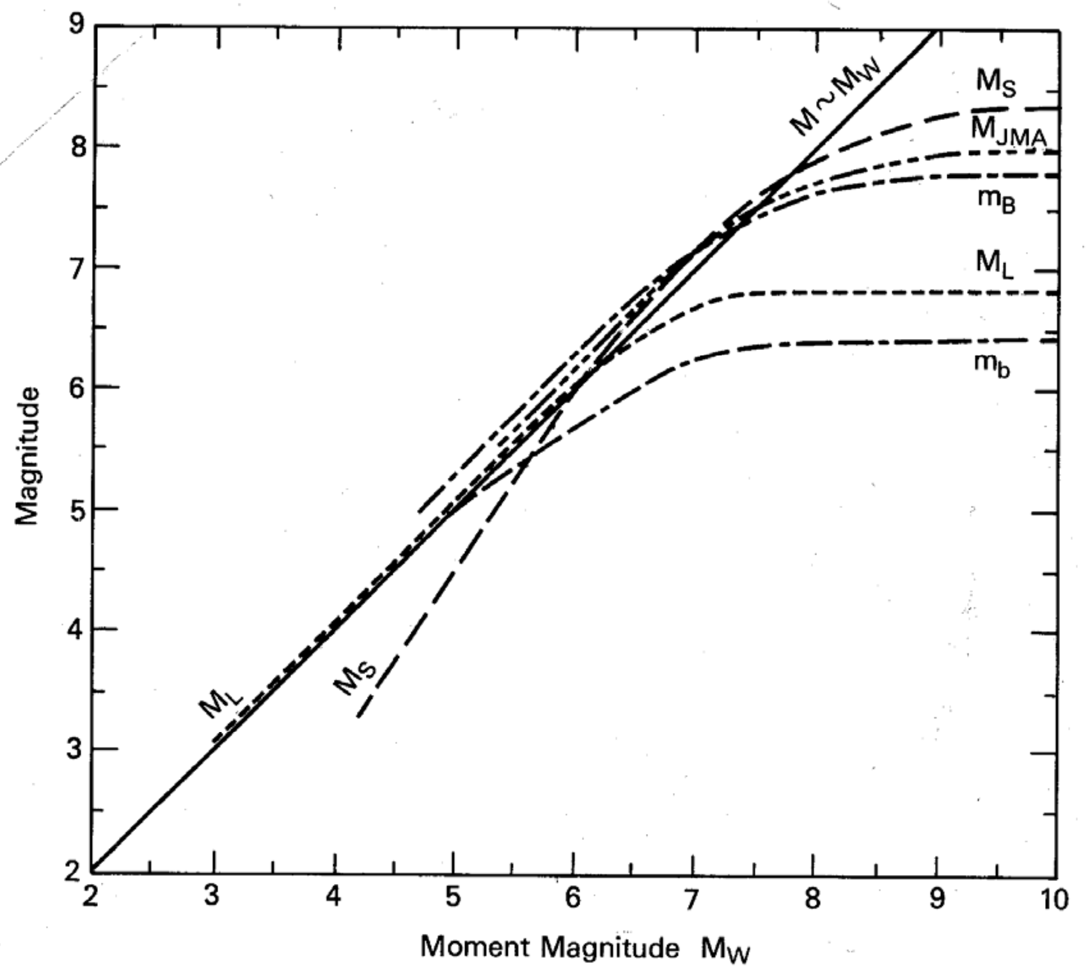


FIGURE 2.4 A comparison of moment magnitude with other magnitude scales (after Heaton, Tajima and Mori 1986).

Implementing Earthquake Catalogs

Developing uniform catalog:

- Development of one catalog from several catalogs
- Declustering

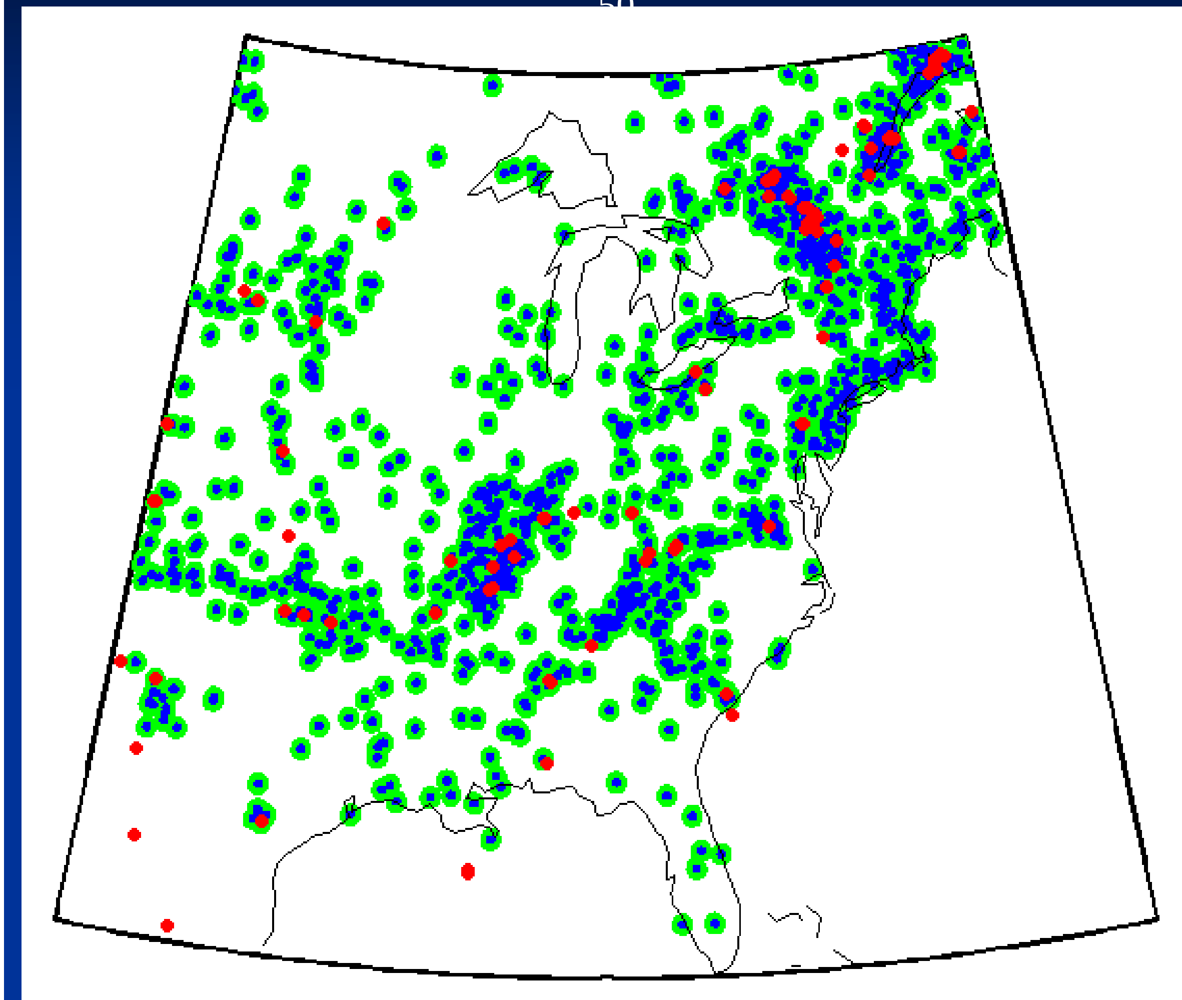
Use of Catalog

- Calculation of Gutenberg-Richter a and b-values
- Smooth seismicity model (background)
- Comparison with model rates of seismicity

Smoothed Seismicity

- Assumes that where smaller magnitude earthquakes have occurred in the past is where larger earthquakes will occur in the future.
- Gaussian smoothing function, correlation distance=50km
- Anisotropic smoothing

Central and Eastern United States



green zones = 36 km radius = 33% map area

Future large earthquakes in the CEUS have about 86% probability of occurring within 36 km of past earthquakes, and about 60% probability of occurring within 14 km of past earthquakes.

- Kafka (2005)

$$\hat{\rho}(0.33)=0.86$$
$$0.79\leq\rho(0.33)\leq0.93$$

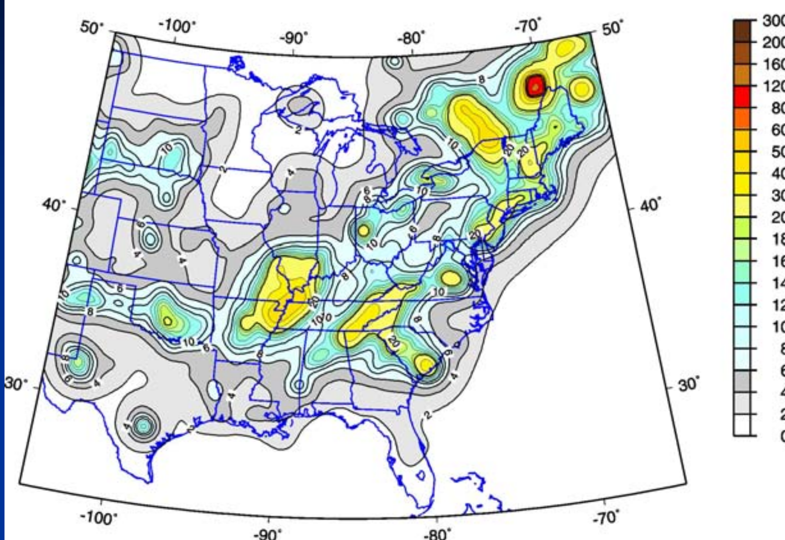
$$\hat{\rho}(0.10)=0.60$$
$$0.50\leq\rho(0.10)\leq0.70$$

Eastern U.S. Background seismicity

- Seismicity Models: b=0.95;
  - 1. Smoothed Mb ≥3 since 1924 (wt=0.4)
  - 2. Smoothed Mb ≥4 since 1860 (wt=0.2)
  - 3. Smoothed Mb ≥5 since 1700 (wt=0.2)
  - 4. background zone- craton (Mmax7.0) and extended crust (Mmax7.5), Adaptive weighting avoids lower hazard in higher seismicity areas -wt=0.2 (low) or 0.0 (high seismicity)

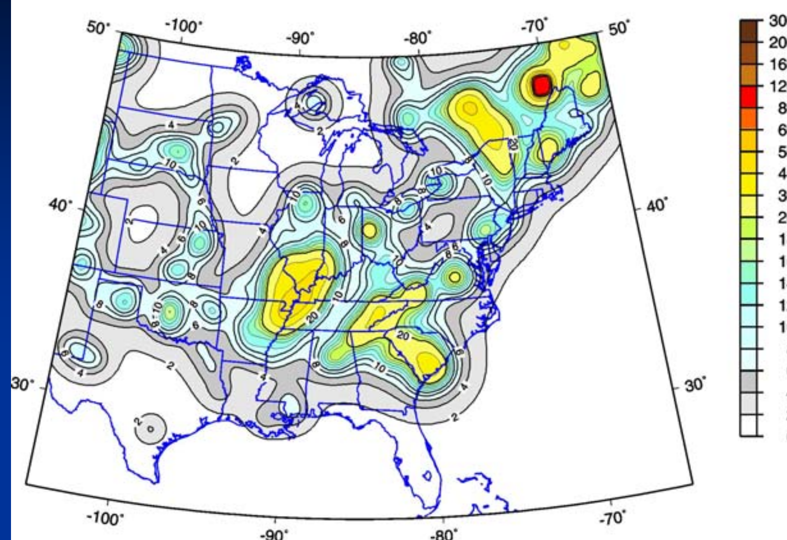
MODEL 1

Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
from M3+ since 1924



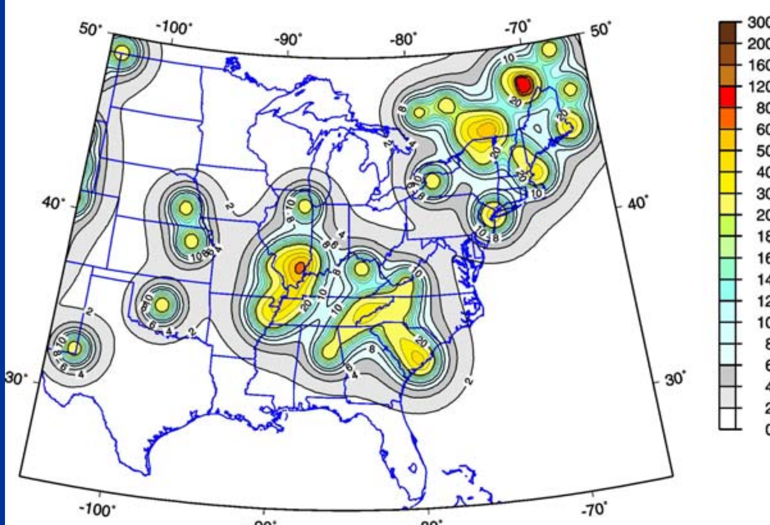
MODEL 2

Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
from M4+ since 1860



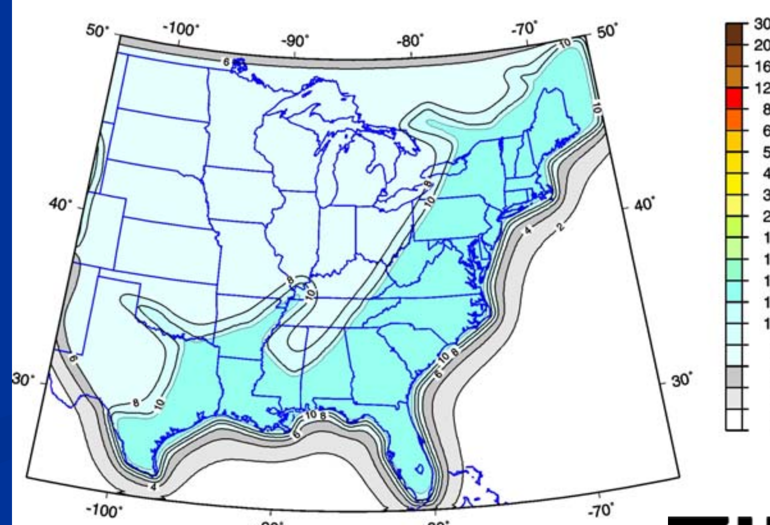
MODEL 3

Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
from M5+ since 1700



MODEL 4

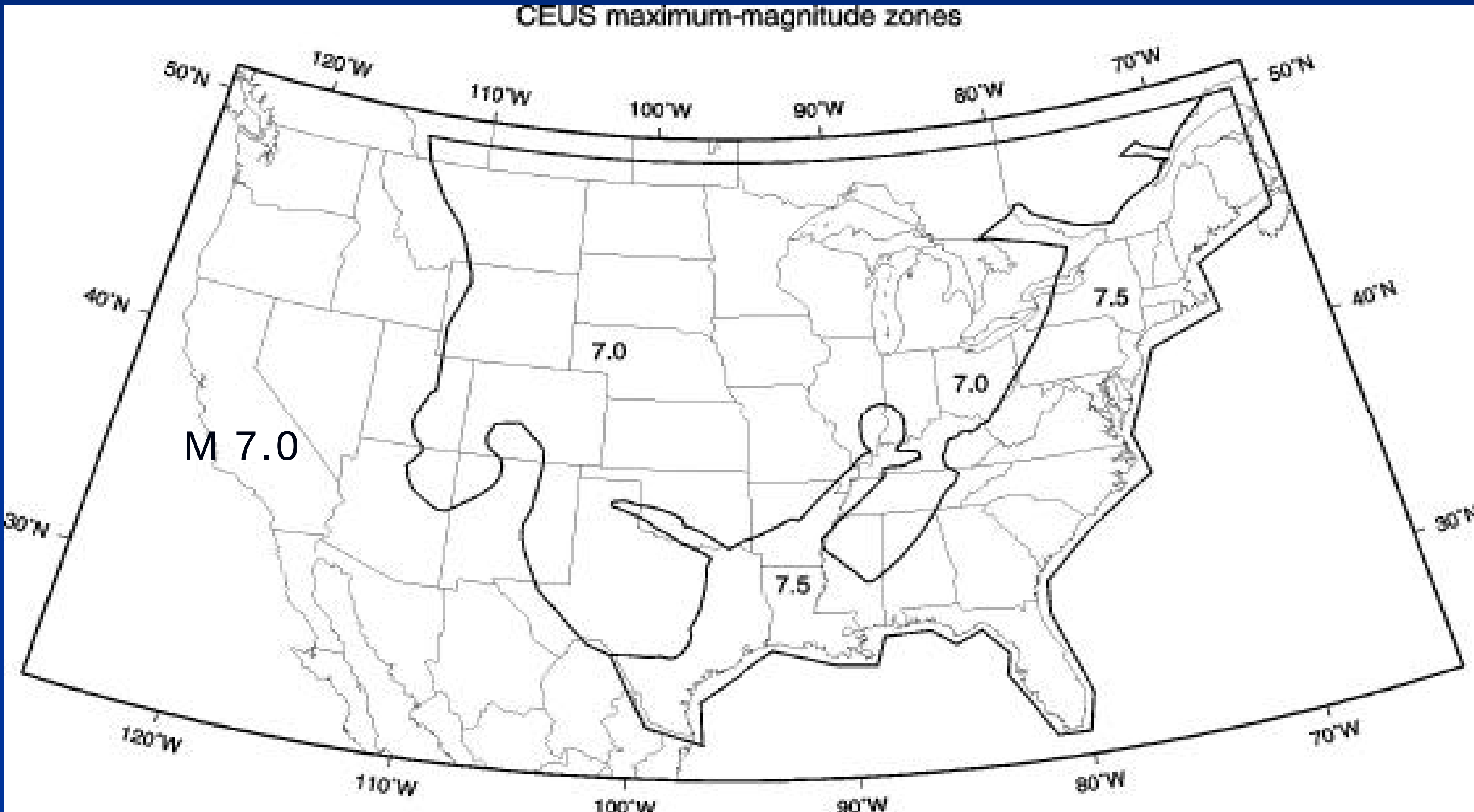
Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
from background zones

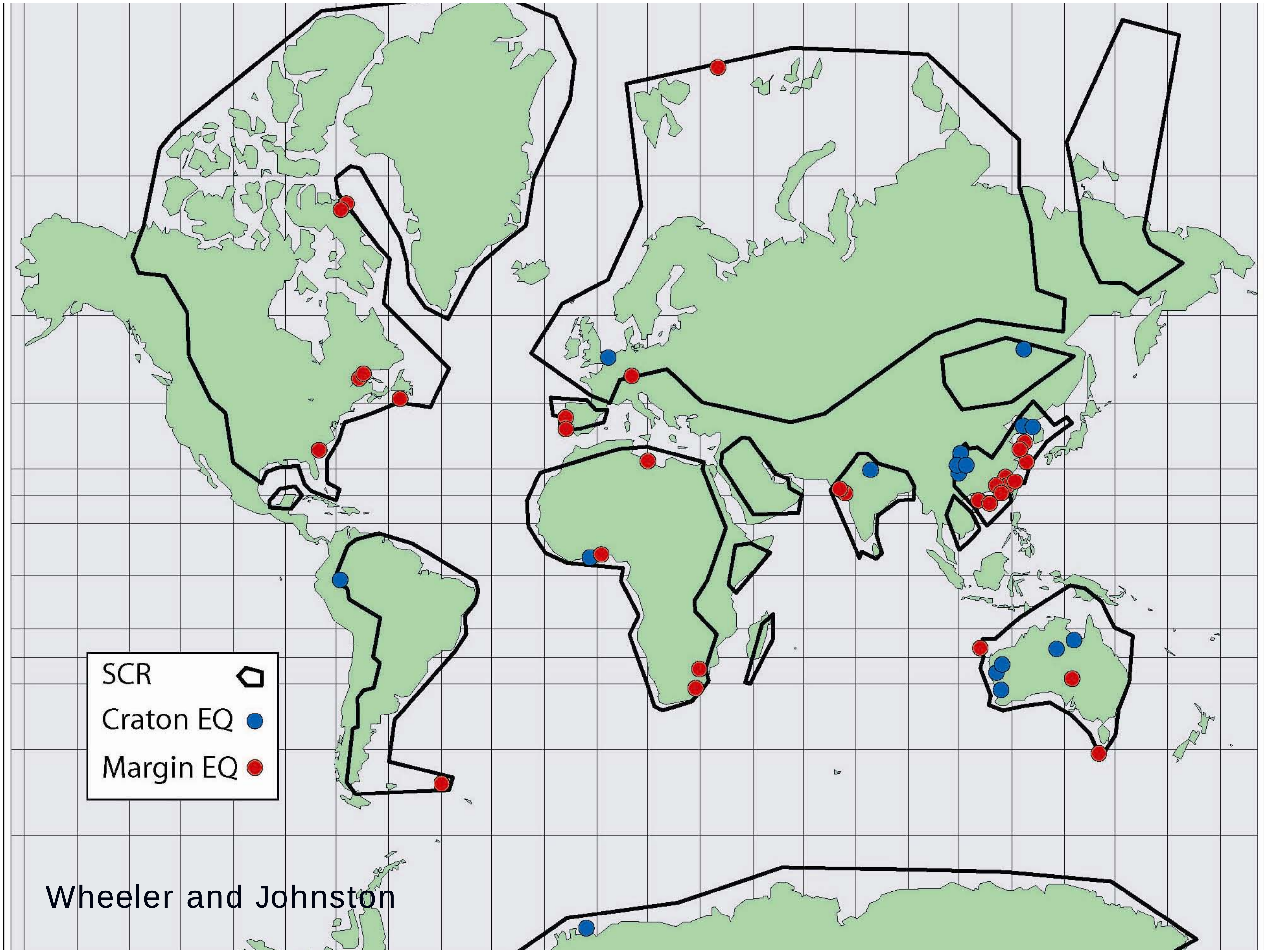


From Art Frankel

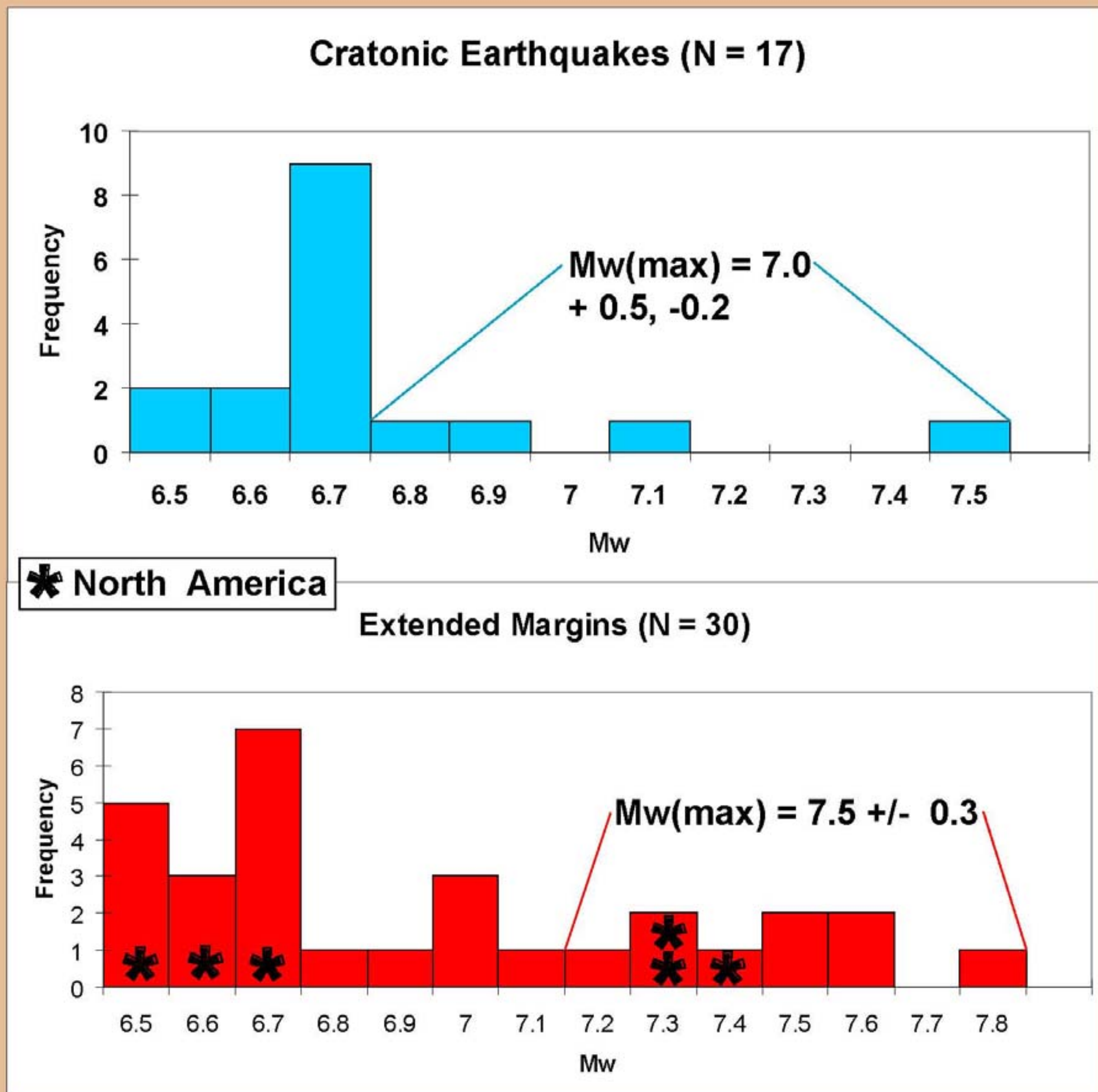
USGS
science for a changing world

BACKGROUND SOURCE ZONES




SCR
Craton EQ
Margin EQ
Wheeler and Johnston

Mw(max) for Tectonic Analogs of Central and Eastern U.S.



Wheeler and Johnston