The Abdus Salam
International Centre
for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Earthquakes and Strain

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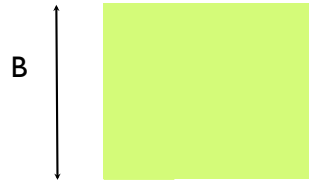
Earthquakes and Strain

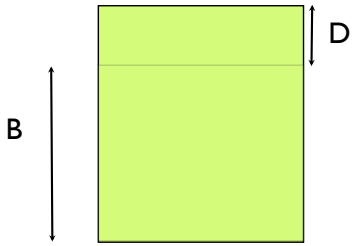
How are they related?

Philip England
ICTP Trieste, 18 June, 2013

Strain

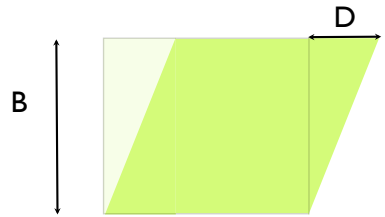


Linear strain



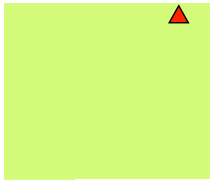
$$\varepsilon = \frac{D}{B}$$

Shear strain

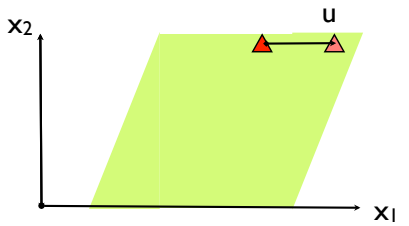


$$\varepsilon = \frac{D}{B}$$

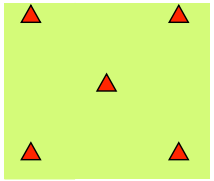
Displacement



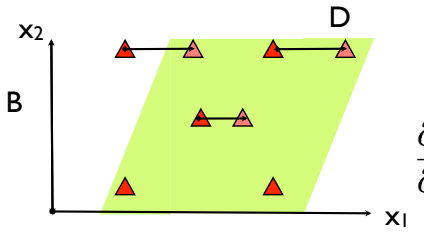
Displacement



Strain

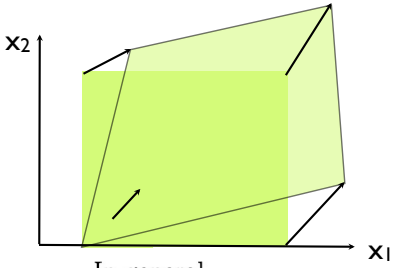


Strain:
Gradients of displacement



$$\frac{\partial u_1}{\partial x_2} = \frac{D}{B}$$

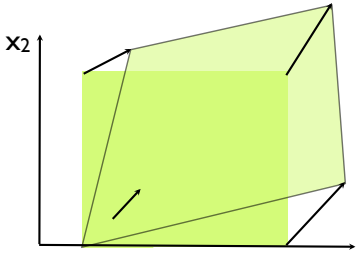
Strain: Gradients of displacement



In general

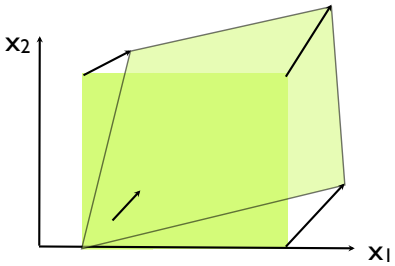
$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Strain Rates: Gradients of velocity

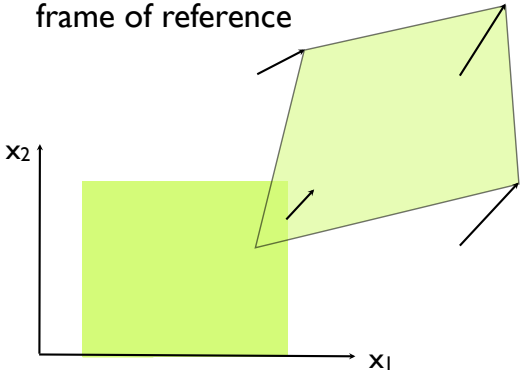


$$\dot{\varepsilon}_{ij} = \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_i}{\partial x_j}\right)$$

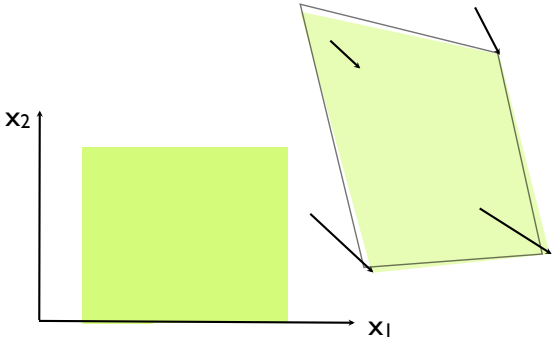
Strains and strain rates do not depend on frame of reference



Strains and strain rates do not depend on frame of reference

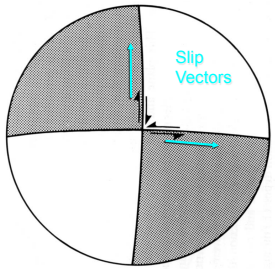


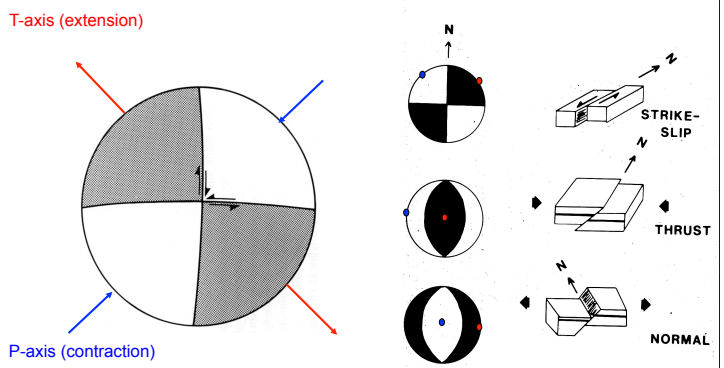
Strains and strain rates do not depend on frame of reference



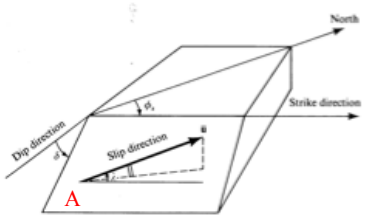
How do Faults Accommodate Strain?

A reminder about Focal Mechanisms





Earthquake Moment Tensor



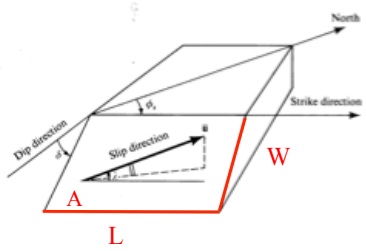
The Moment of an earthquake is the product of the area, A, of a fault that slipped, with the magnitude, s, of the slip, and the shear modulus, μ.

$M_0 = \mu A s$

Moment Tensor

$M_{ij} = M_0 (u_i n_j + u_j n_i)$
Where n is the unit vector normal to the fault

Earthquake Moment Tensor



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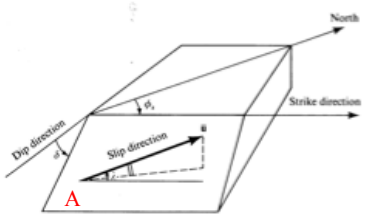
$A = W L$

Earthquake Moment Tensor



$M_0 = \mu A s$

$\mathbf{M} = M_0 \times$ 

$M_{ij} = M_0 (u_i n_j + u_j n_i)$

Measuring Strain

$\underline{\mathbf{M}} = M_0 \times$ 

- Strains associated with three types of faulting.
- Strike-slip on NE-SW or NW-SE planes.

$$= \begin{matrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{matrix}$$

Measuring Strain

$\underline{\mathbf{M}} = M_0 \times$ 

- Strains associated with three types of faulting.
- Strike-slip on NE-SW or NW-SE planes.

$$= \begin{matrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{matrix}$$

- Reverse faulting on NS planes

$$= \begin{matrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{matrix}$$

Measuring Strain

$\underline{\mathbf{M}} = M_0 \times$ 

- Strains associated with three types of faulting.
- Strike-slip on NE-SW or NW-SE planes.

$$= \begin{matrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{matrix}$$

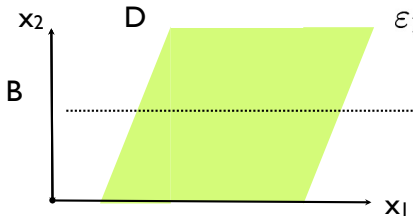
- Reverse faulting on NS planes

$$= \begin{matrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{matrix}$$

- Reverse faulting on EW planes.

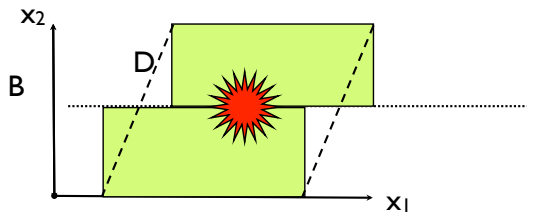
$$= \begin{matrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{matrix}$$

How do Faults Accommodate Strain?

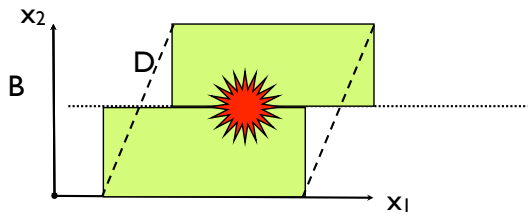


$$\varepsilon_{12} = \frac{1}{2}\frac{D}{B}$$

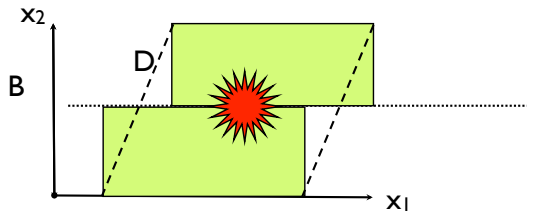
$$\varepsilon_{12} \sim \frac{1}{2}\frac{D}{B}$$



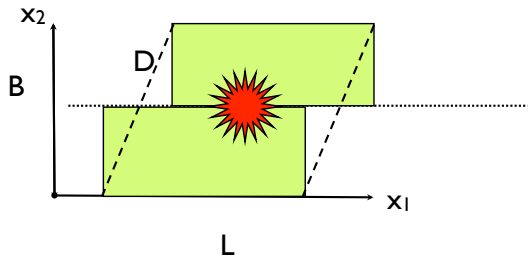
Moment of this earthquake
$M_0 = \mu A D$
where A is area of fault.



$M_0 = \mu L W D$
where W is width (down-dip extent) of the fault.

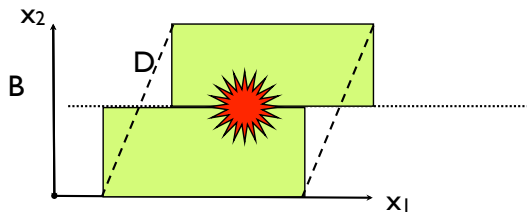


$M_0 = \mu L W D$
where W is width (down-dip extent) of the fault.
But
$\varepsilon_{12} \sim \frac{1}{2}\frac{D}{B} = \frac{1}{2}\frac{M_0/(\mu L W)}{B}$



$$\varepsilon_{12} \sim \frac{1}{2}\frac{D}{B} = \frac{1}{2}\frac{M_0/(\mu LW)}{B}$$

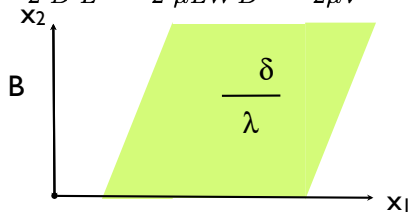
$$\varepsilon_{12} \sim \frac{M_0}{2\mu V}$$



A small fault, length λ, slip δ:

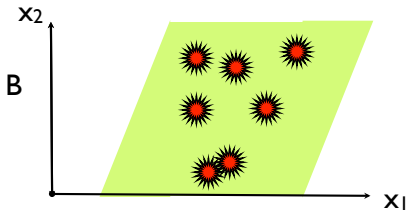
$$M_0 = \mu W \lambda \delta$$

$$\varepsilon_{12} \sim \frac{1}{2}\frac{\delta}{B}\frac{\lambda}{L} = \frac{1}{2}\frac{M_0}{\mu LWB} = \frac{M_0}{2\mu V}$$

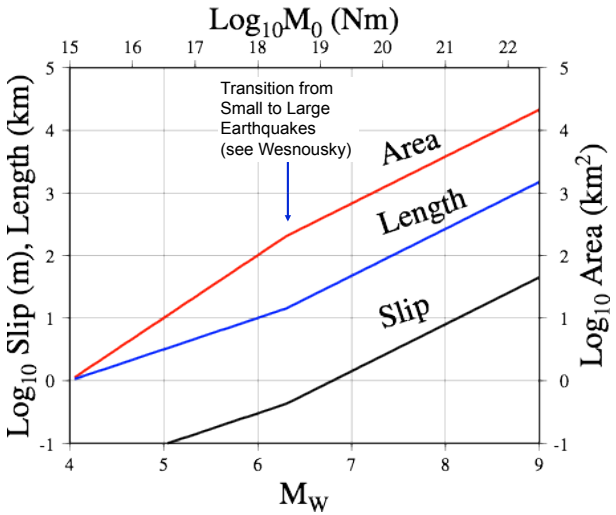


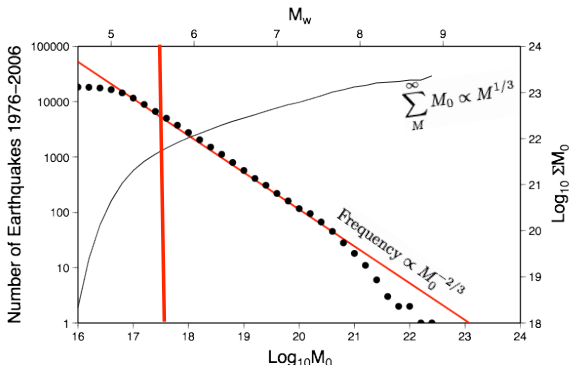
Kostrov 1974

Many earthquakes, n, in a volume V



$$\varepsilon_{ij} = \frac{\sum_n M_{ij}^n}{2\mu V} \qquad \underline{\mathbf{M}} = \mathrm{M}_0 \times$$





- Global relation between moment and frequency.

$$N(M_0) = aM_0^{-b}$$

$$N(M_0) = \int_{M_0}^{M_{\max}} n(M)dM$$

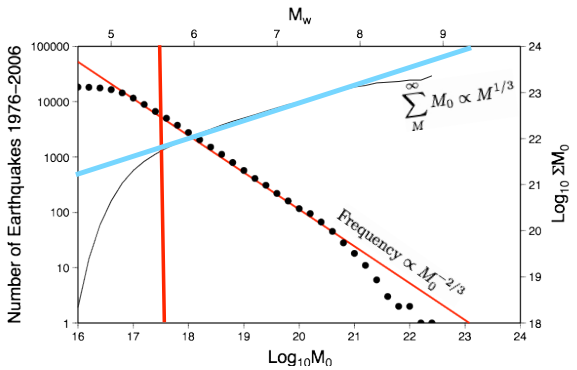
$$M_{\text{Total}} = \int_{0}^{M_{\max}} n(M)\, M\, dM$$

$$M_{\text{Obs}} = \int_{M_{\text{Min}}}^{M_{\max}} n(M)\, M\, dM$$

$$= M_{\text{Tot}} \left[1 - \left(\frac{M_{\text{Min}}}{M_{\max}}\right)^{(1-b)}\right]$$

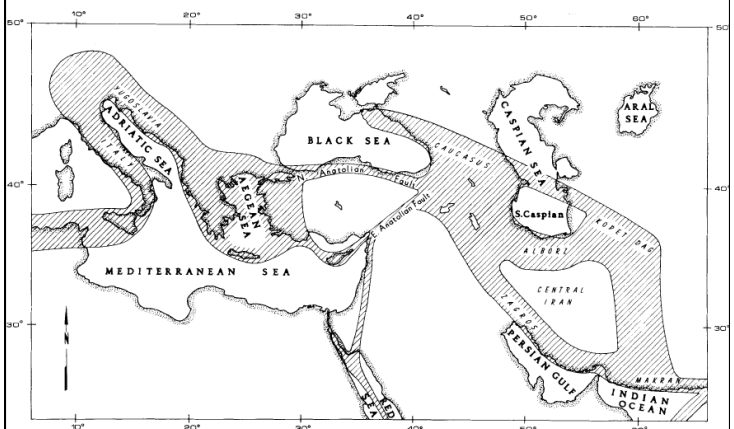
$$b \sim 2/3$$

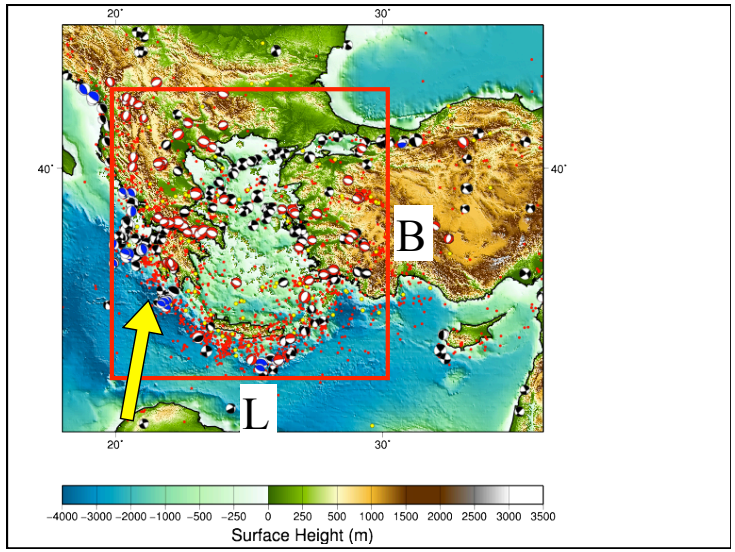
Read England Handout

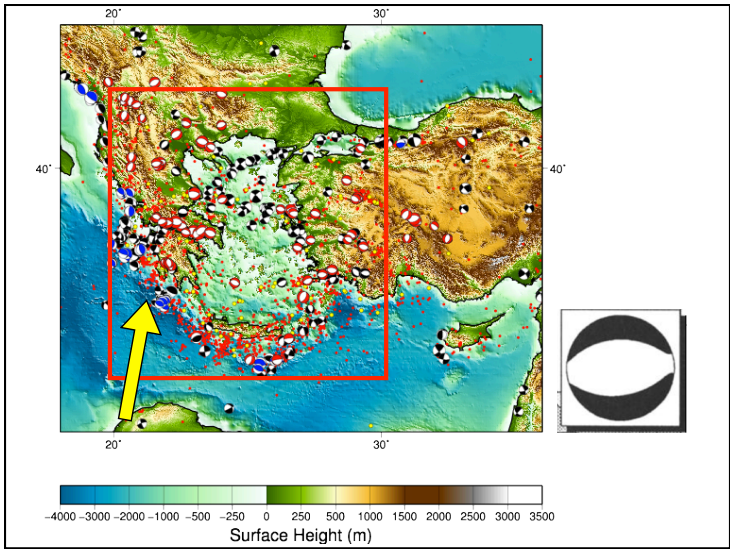


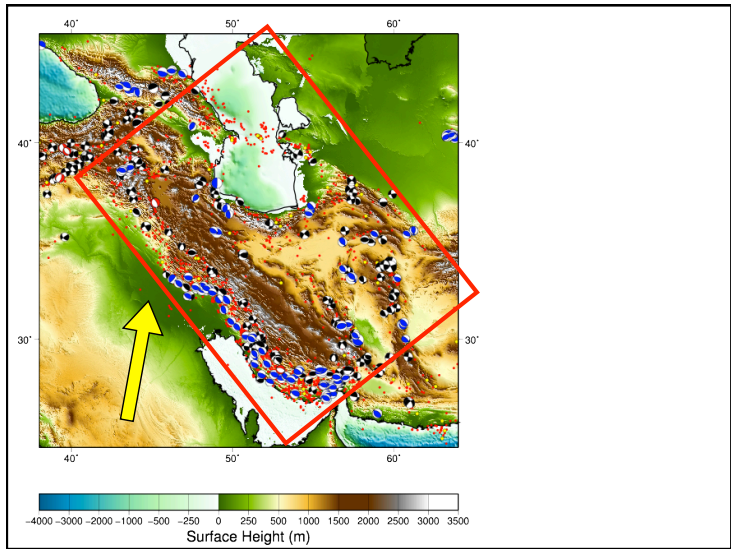
- Global relation between moment and frequency. Large earthquakes are much rarer than small ones, but they account for most of the strain.
- most of the strain

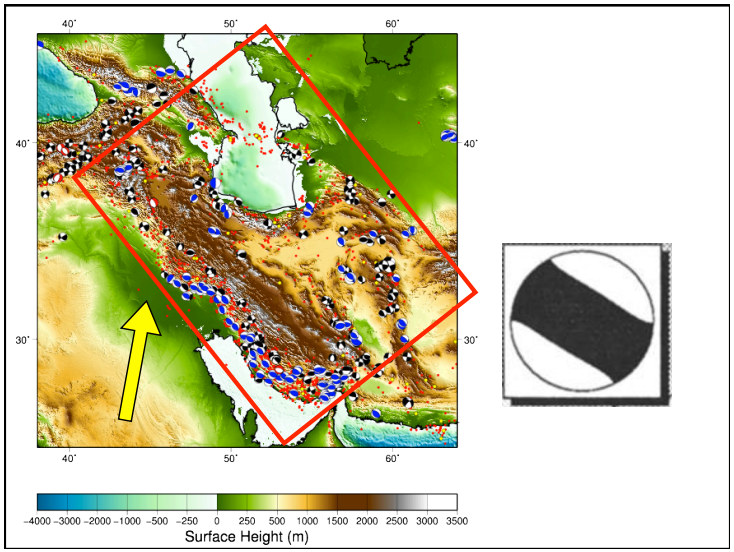
Jackson and McKenzie, 1988, Geophys. J. Int

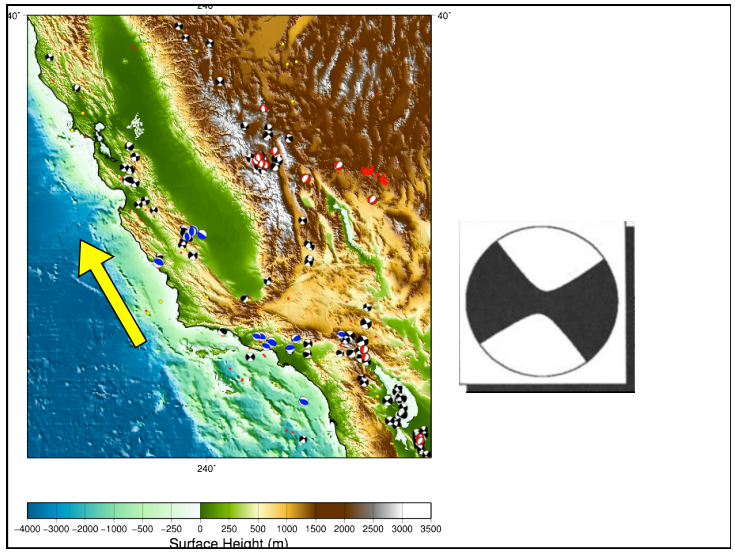


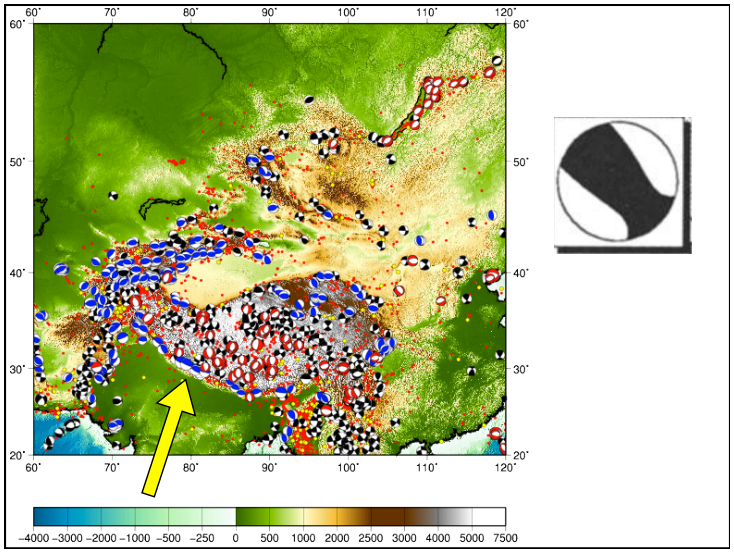

20°
30°
40°
B
L
−4000 −3000 −2000 −1000 −500 −250 0 250 500 1000 1500 2000 2500 3000 3500
Surface Height (m)

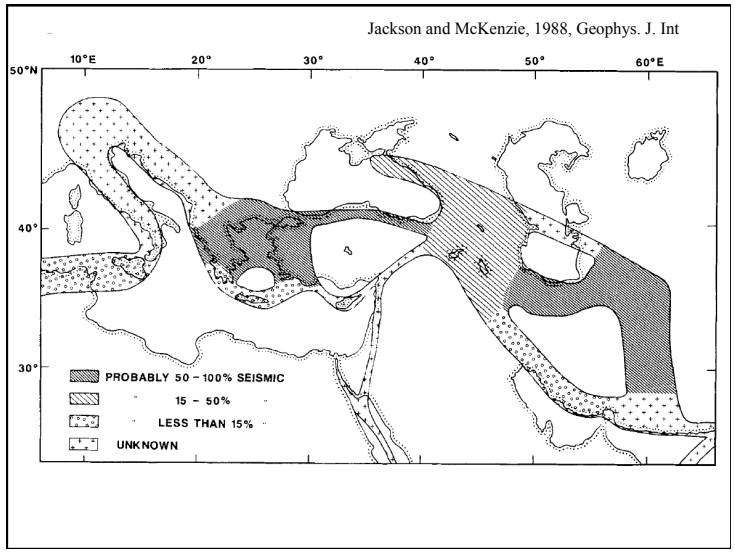

20°
30°
40°
−4000 −3000 −2000 −1000 −500 −250 0 250 500 1000 1500 2000 2500 3000 3500
Surface Height (m)


40°
50°
60°
30°
−4000 −3000 −2000 −1000 −500 −250 0 250 500 1000 1500 2000 2500 3000 3500
Surface Height (m)


40°
50°
60°
30°
−4000 −3000 −2000 −1000 −500 −250 0 250 500 1000 1500 2000 2500 3000 3500
Surface Height (m)


40°
240°
−4000 −3000 −2000 −1000 −500 −250 0 250 500 1000 1500 2000 2500 3000 3500
Surface Height (m)


60° 70° 80° 90° 100° 110° 120°
60°
50°
40°
30°
20°
−4000 −3000 −2000 −1000 −500 −250 0 500 1000 2000 2500 3000 4000 5000 7500


Jackson and McKenzie, 1988, Geophys. J. Int
10°E 20° 30° 40° 50° 60°E
50°N
40°
30°
PROBABLY 50 – 100% SEISMIC
15 – 50%
LESS THAN 15%
UNKNOWN