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International Centre
for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2464-33

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Velocity Fields and their application to strain rates, fault slip rates, and hazard estimation

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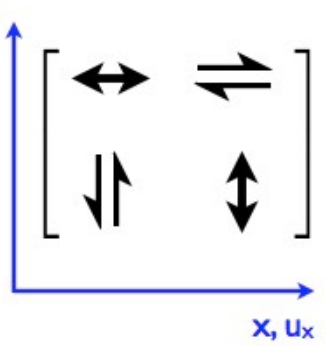
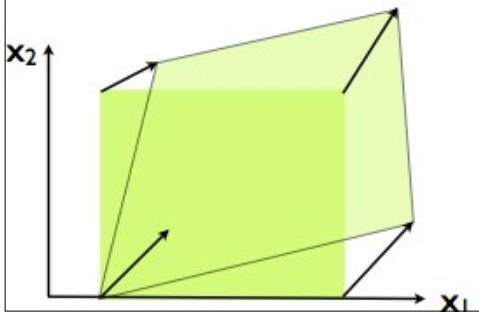
Velocity Gradients

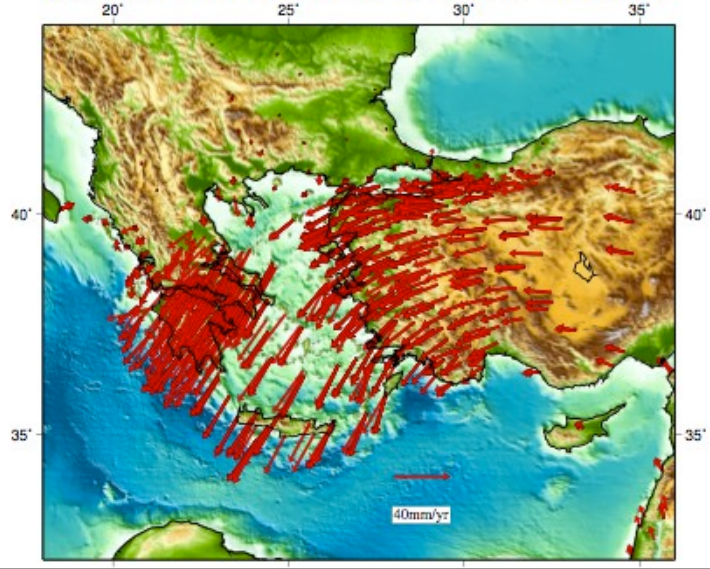
$$\mathbf{L} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} \end{bmatrix} =$$





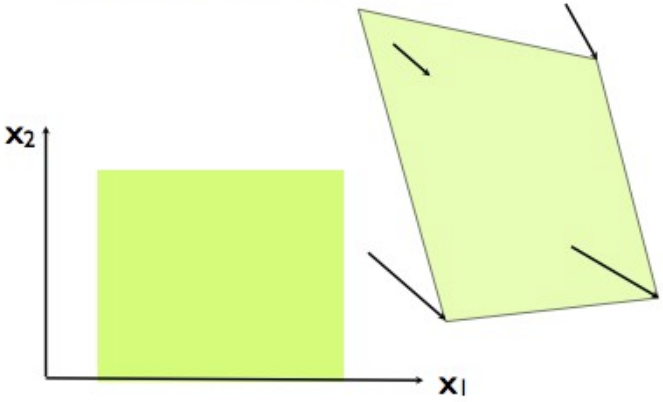
3

From GPS to Tectonic Strain



1

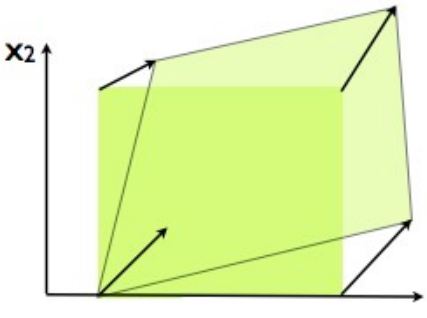
Strains and strain rates do not depend on frame of reference



4

Velocity Gradients

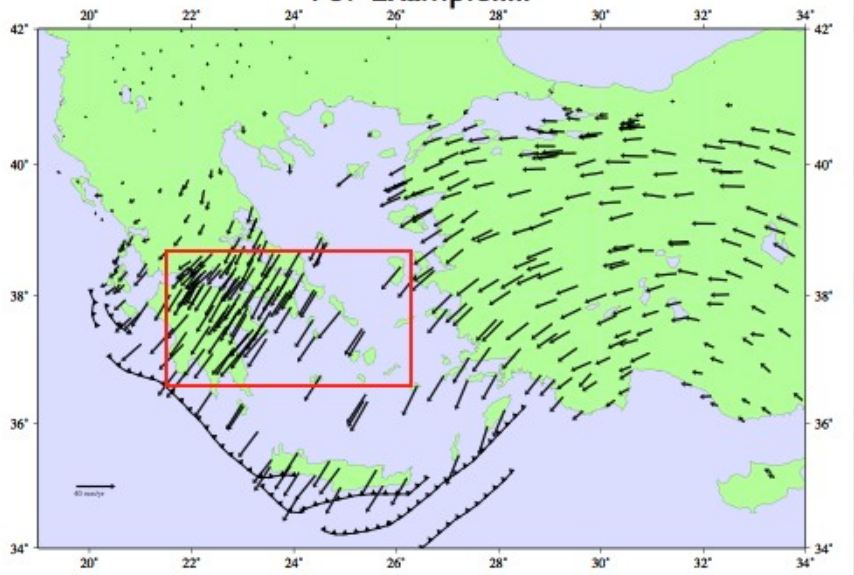
(Remember, we can only interpret the horizontal components of velocity.)



$$\mathbf{L} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} \end{bmatrix}$$

2

For Example.....



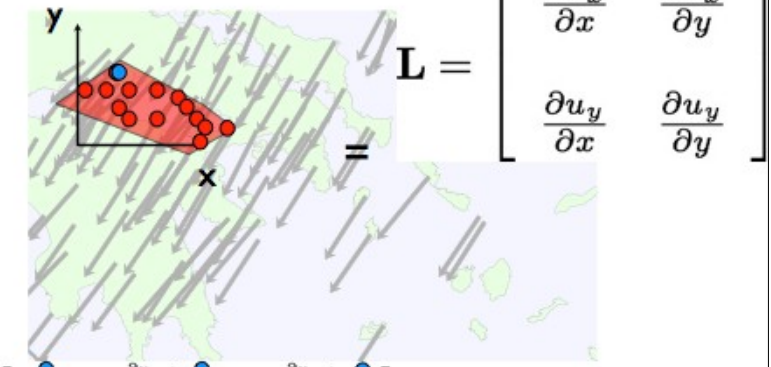
7

$$\mathbf{L} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) & \frac{\partial u_y}{\partial y} \end{bmatrix} \quad \text{Strain}$$

$$+ \begin{bmatrix} 0 & \frac{1}{2}\left(\frac{\partial u_x}{\partial y} - \frac{\partial u_y}{\partial x}\right) \\ -\frac{1}{2}\left(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}\right) & 0 \end{bmatrix} \quad \text{Rotation}$$

5



$$\mathbf{L} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} \end{bmatrix}$$

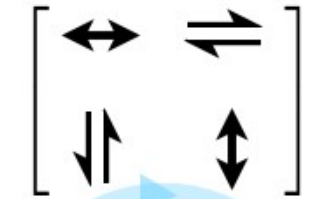
$$\begin{bmatrix} v_x = \frac{\partial v_x}{\partial x}\Delta x + \frac{\partial v_x}{\partial y}\Delta y \\ v_y = \frac{\partial v_y}{\partial x}\Delta x + \frac{\partial v_y}{\partial y}\Delta y \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ v_x^n = \frac{\partial v_x}{\partial x}\Delta x^n + \frac{\partial v_x}{\partial y}\Delta y^n \\ v_y^n = \frac{\partial v_y}{\partial x}\Delta x^n + \frac{\partial v_y}{\partial y}\Delta y^n \end{bmatrix} \equiv \mathbf{b} = \mathbf{A}\mathbf{x}$$

Solve by least squares

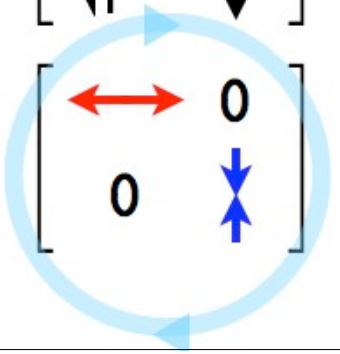
8

Principal Strains + Rotation

$$\mathbf{L} = \begin{bmatrix} \frac{\partial u_x}{\partial x} & \frac{\partial u_x}{\partial y} \\ \frac{\partial u_y}{\partial x} & \frac{\partial u_y}{\partial y} \end{bmatrix} =$$



$$\mathbf{L} = \begin{bmatrix} \frac{\partial u_1}{\partial x_1} & 0 \\ 0 & \frac{\partial u_2}{\partial x_2} \end{bmatrix} =$$



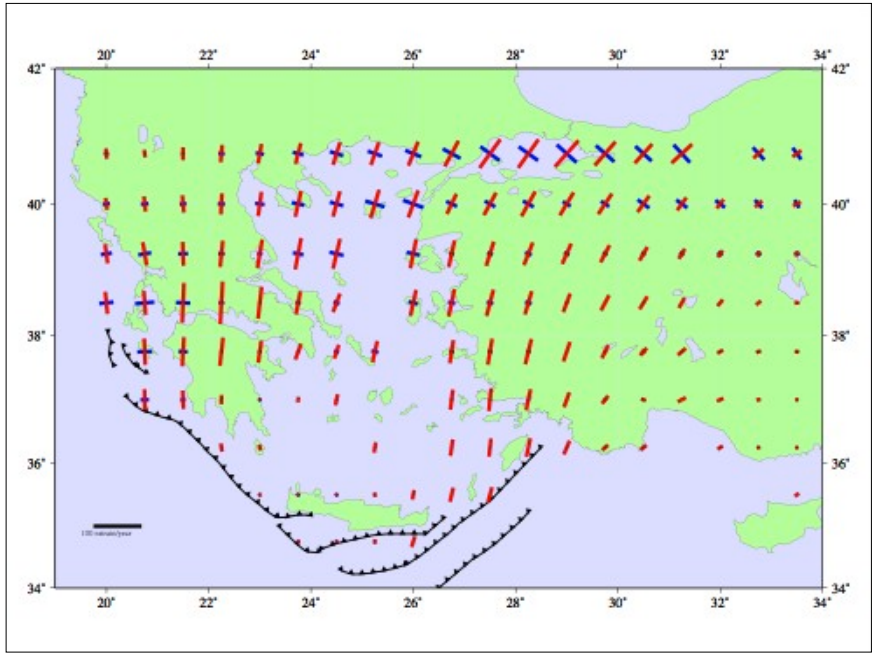
6

Principal Strains + Rotation

$$\begin{bmatrix} \frac{\partial u_1}{\partial x_1} & 0 \\ 0 & \frac{\partial u_2}{\partial x_2} \end{bmatrix} = \begin{bmatrix} \leftrightarrow & 0 \\ 0 & \updownarrow \end{bmatrix}$$

What Types of faulting ought we to expect?

11

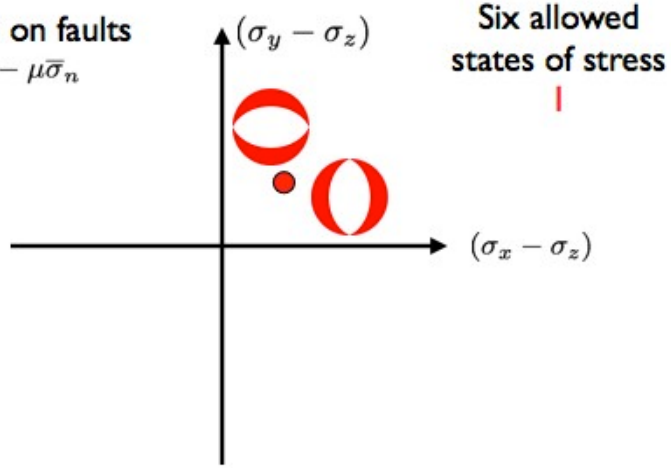


9

Allowed States of Stress

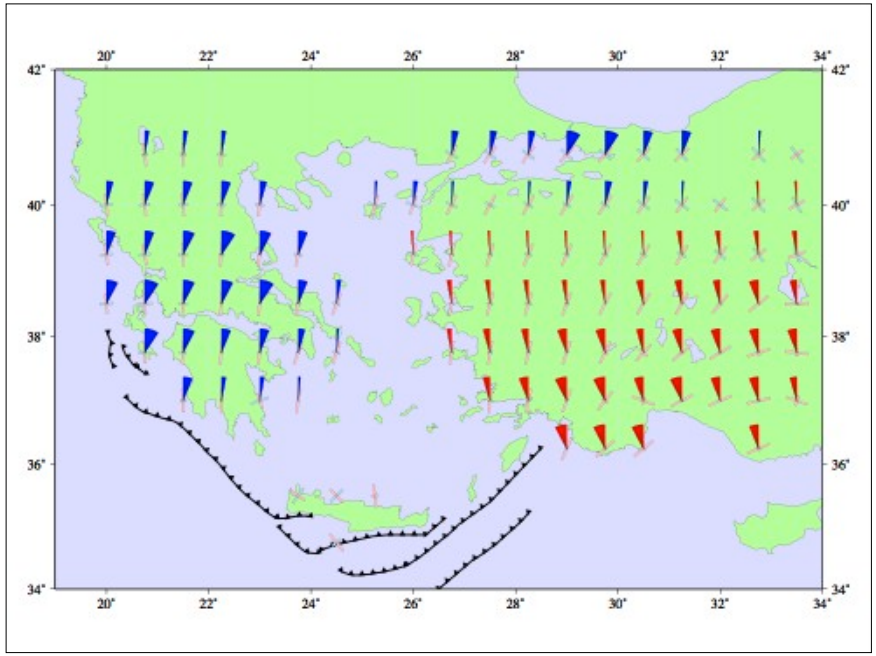
Friction on faults

$|\sigma_s| = c - \mu\bar{\sigma}_n$



Six allowed states of stress

12

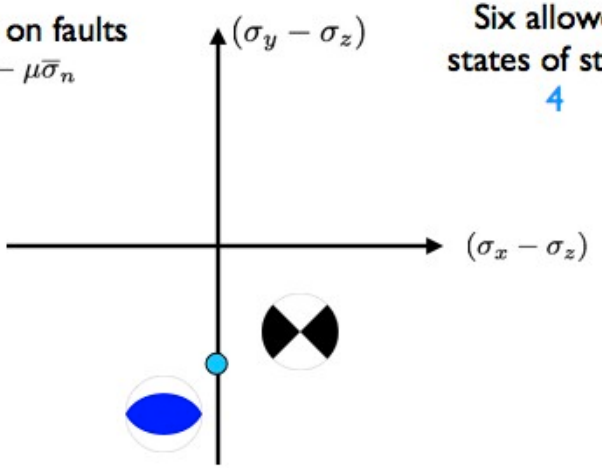


10

Allowed States of Stress

Friction on faults
$|\sigma_s| = c - \mu\overline{\sigma}_n$

Six allowed states of stress
4



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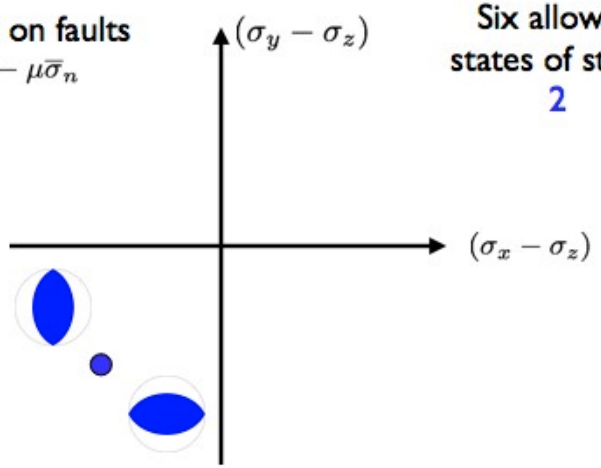
Allowed States of Stress

Friction on faults
$|\sigma_s| = c - \mu\overline{\sigma}_n$

Six allowed states of stress
2

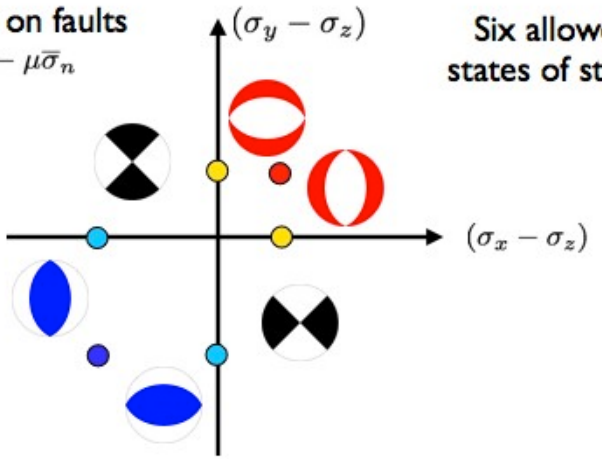


13

Allowed States of Stress

Friction on faults
$|\sigma_s| = c - \mu\overline{\sigma}_n$

Six allowed states of stress



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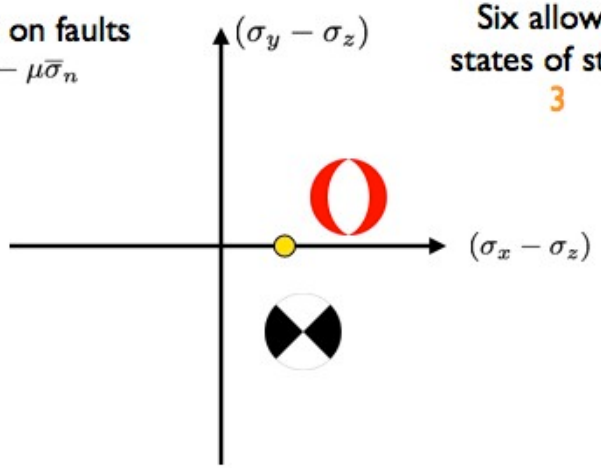
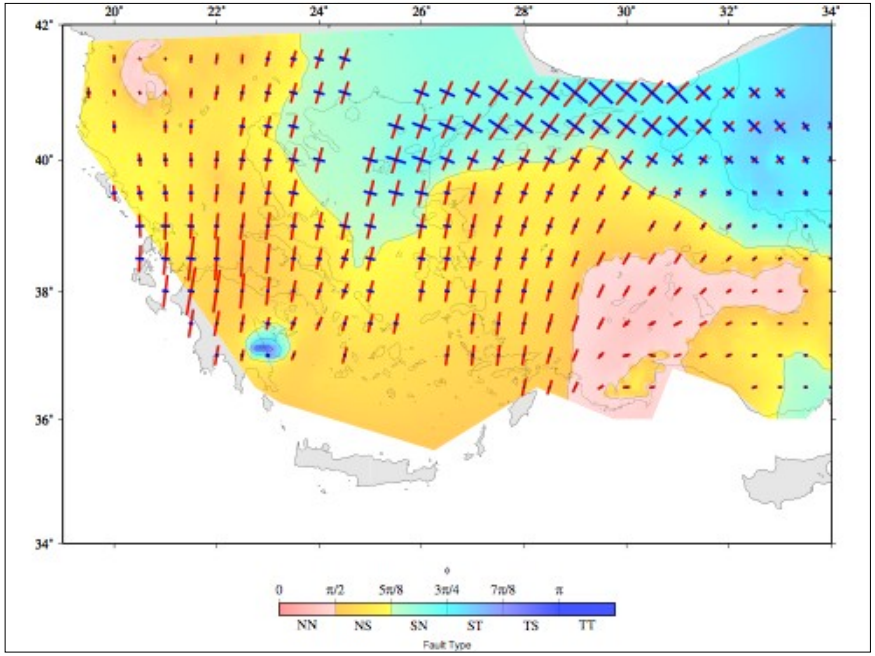
Allowed States of Stress

Friction on faults
$|\sigma_s| = c - \mu\overline{\sigma}_n$

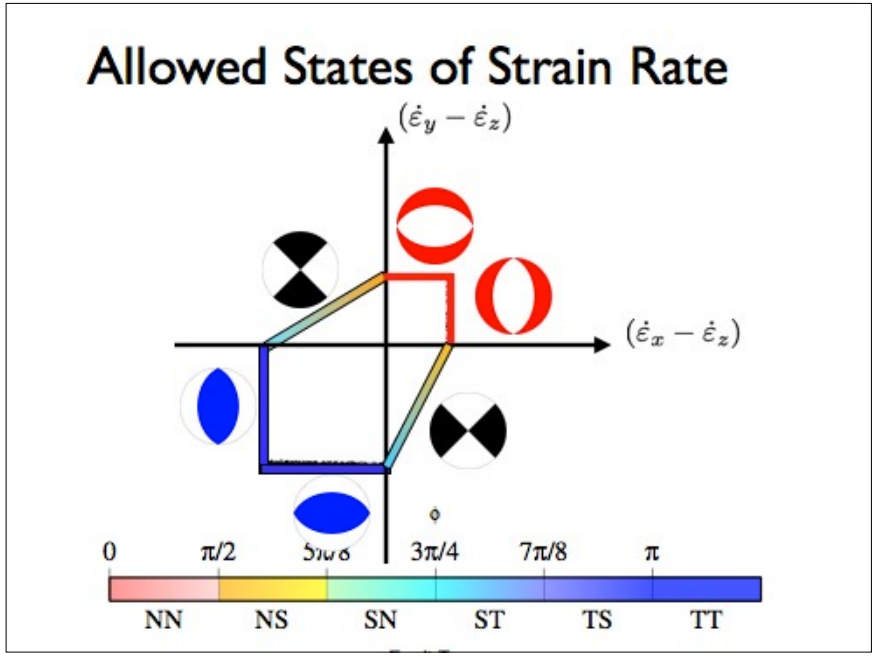
Six allowed states of stress
3



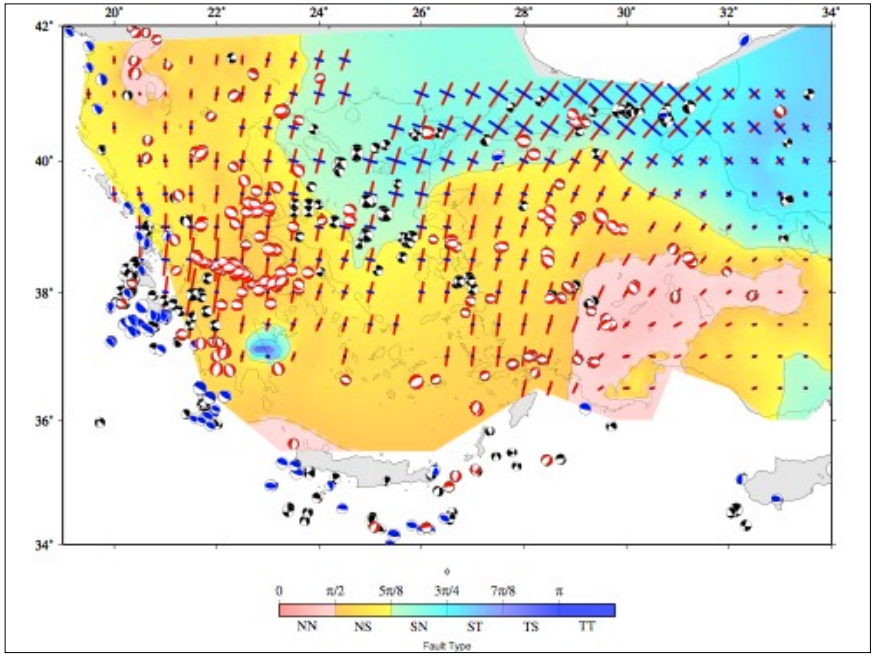
14


20°
22°
24°
26°
28°
30°
32°
34°
42°
40°
38°
36°
34°
ϕ
0
π/2
5π/8
3π/4
7π/8
π
NN
NS
SN
ST
TS
TT
Fault Type

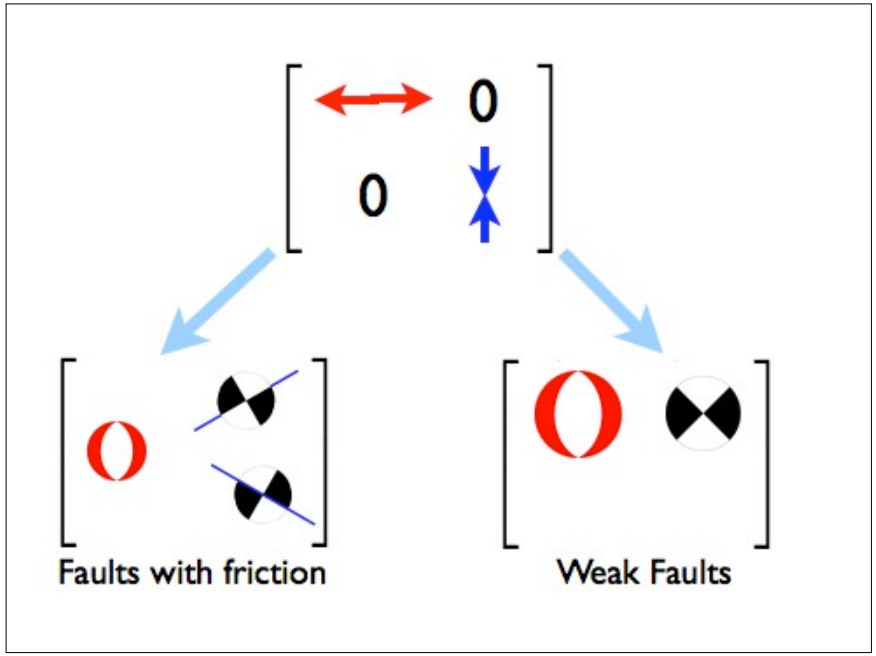
19


Allowed States of Strain Rate
$(\dot{\epsilon}_y - \dot{\epsilon}_z)$
$(\dot{\epsilon}_x - \dot{\epsilon}_z)$
ϕ
0
π/2
5π/8
3π/4
7π/8
π
NN
NS
SN
ST
TS
TT

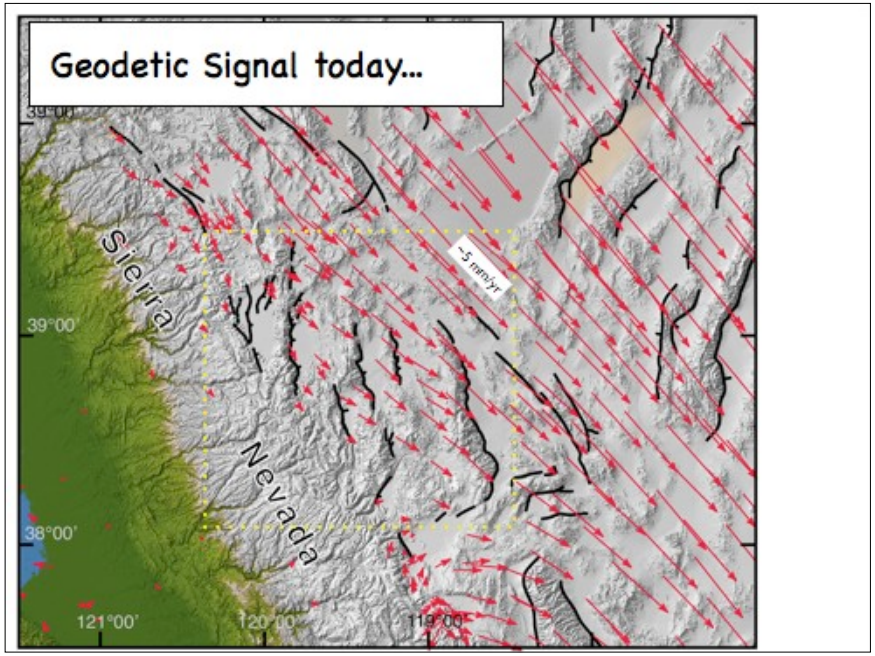
17


20°
22°
24°
26°
28°
30°
32°
34°
42°
40°
38°
36°
34°
ϕ
0
π/2
5π/8
3π/4
7π/8
π
NN
NS
SN
ST
TS
TT
Fault Type

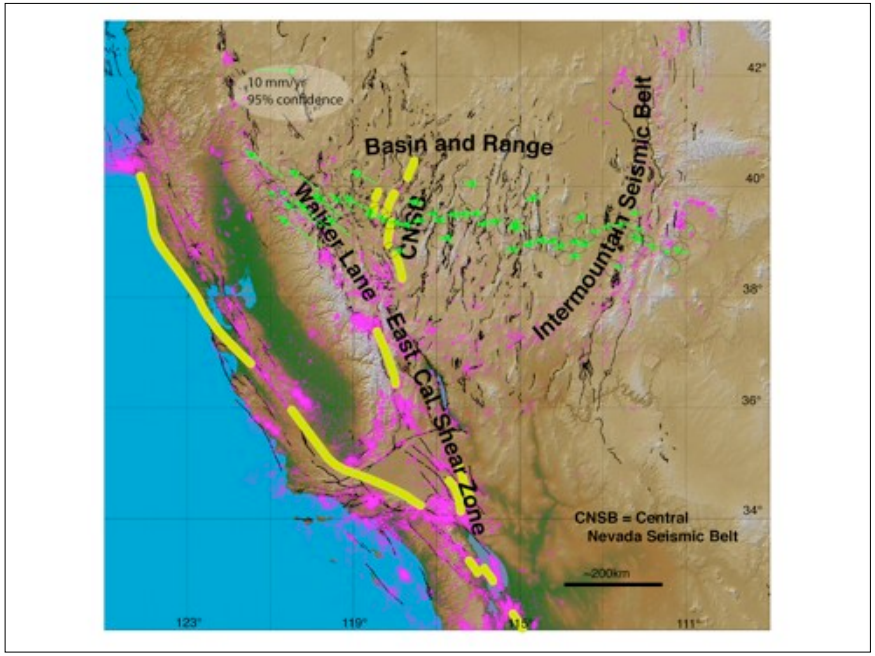
20


0
0
Faults with friction
Weak Faults

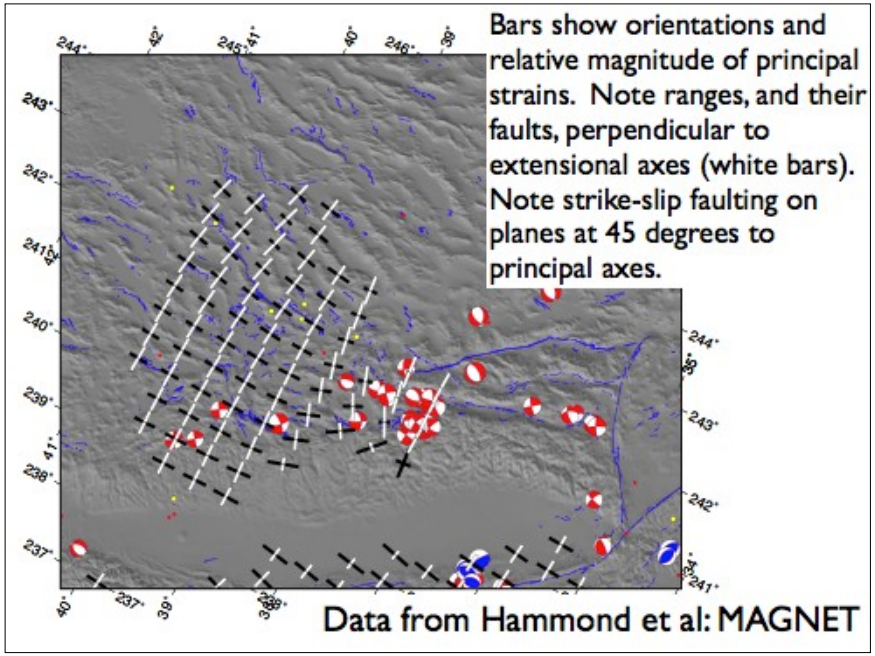
18


Geodetic Signal today...
Sierra
Nevada
~5 mm/yr
39°00'
38°00'
121°00'
120°00'
119°00'

23


10 mm/yr
95% confidence
Basin and Range
Walker Lane
CNSB
East Cal. Shear Zone
Intermountain Seismic Belt
CNSB = Central
Nevada Seismic Belt
~200km
42°
40°
38°
36°
34°
123°
119°
115°
111°

21


Bars show orientations and relative magnitude of principal strains. Note ranges, and their faults, perpendicular to extensional axes (white bars). Note strike-slip faulting on planes at 45 degrees to principal axes.
Data from Hammond et al: MAGNET

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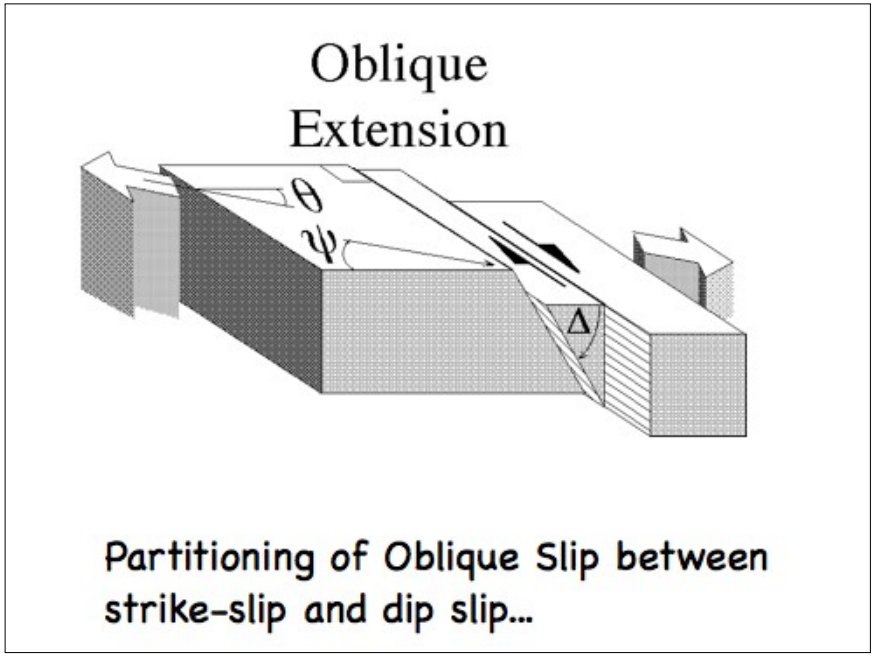
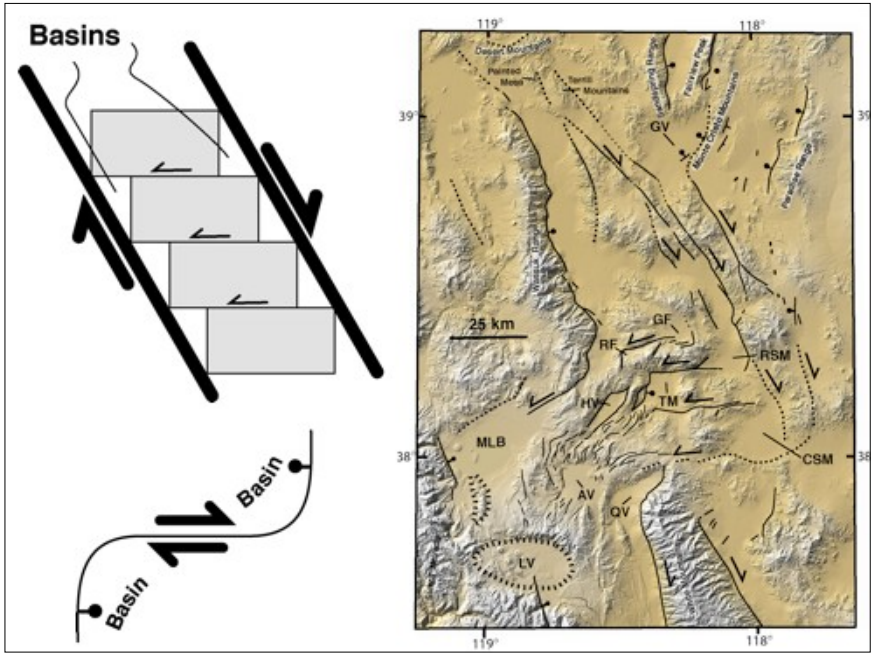
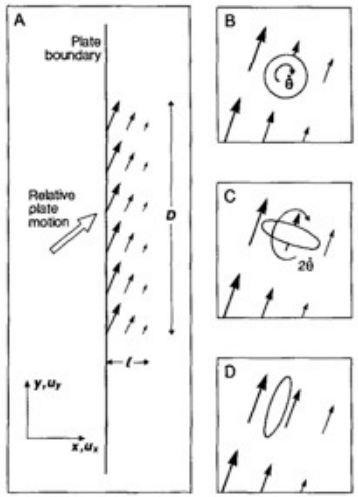

Oblique
Extension
θ
ψ
Δ
Partitioning of Oblique Slip between strike-slip and dip slip...

22



25



If there exist strong blocks, they will rotate in ways that depend upon the velocity gradients, and upon the shapes of the blocks.

(McKenzie and Jackson, *EPSL*, 1983)

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