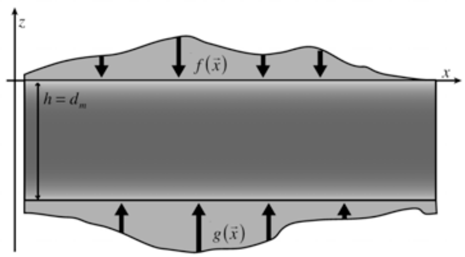
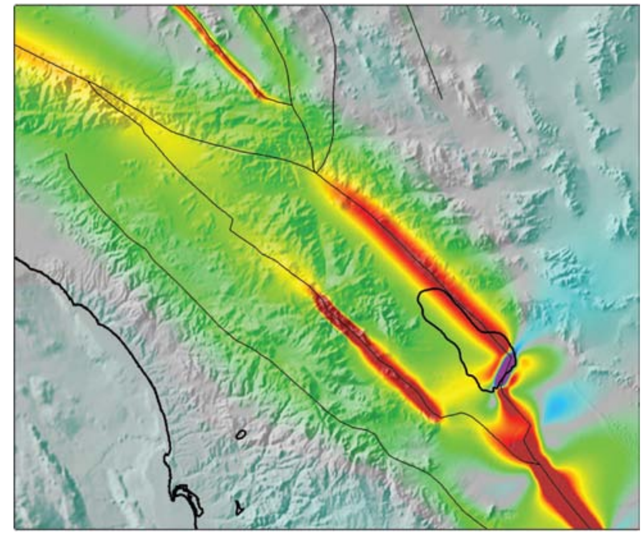


Stress from Topography, Earthquake Cycle, and Tectonics

Karen Luttrell
Bridget Smith-Konter
David Sandwell

CSM Workshop, October 15, 2012

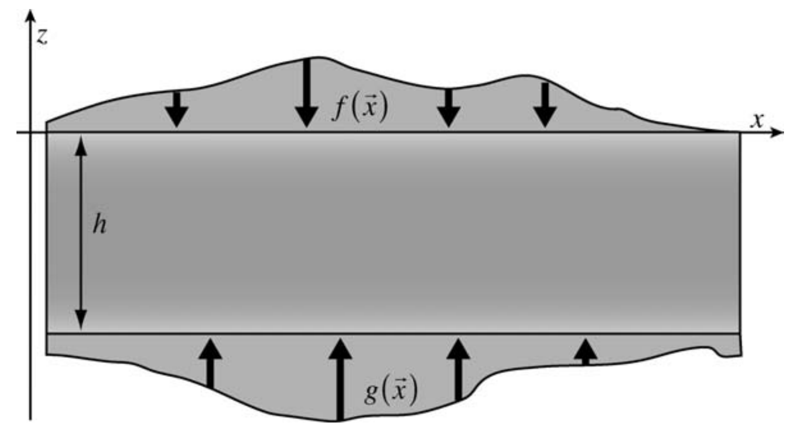


- stress = topographic + eq_cycle * Δt + far_field
- topographic stress = surface + Moho
- earthquake cycle stress rate
- measure of misfit
- tuning the Δt parameters
- what features are required by the data?

topographic component

calculate full stress tensor in a thick elastic plate loaded with surface topography and Moho topography

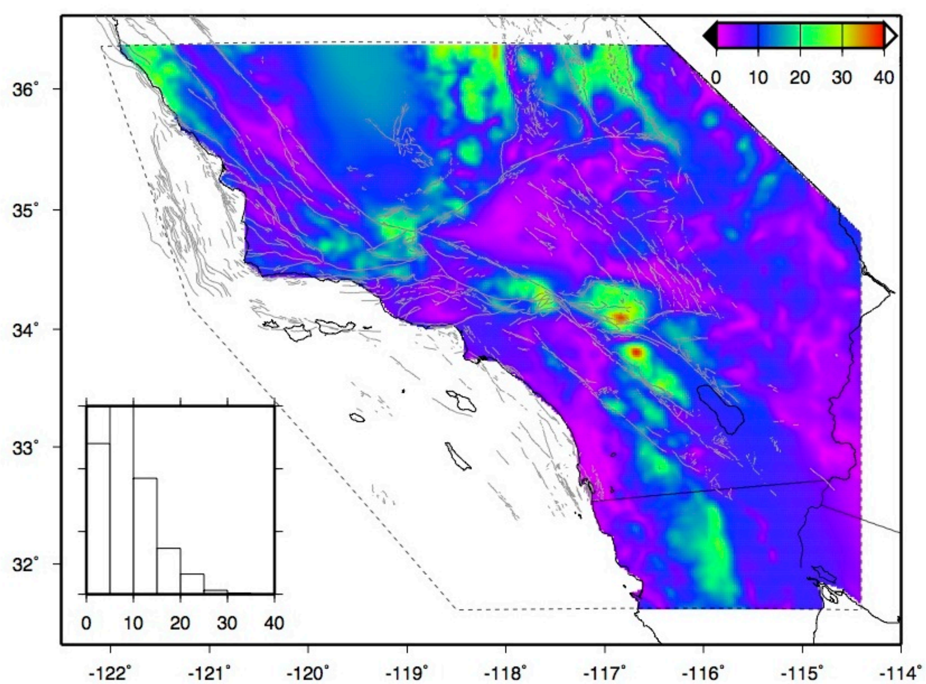
- Use topography $\lambda < 350$ km.
- Moho topography constrained by gravity modeling
- incompressible elastic material has **minimum** stress needed to support topography
- developed Green's function response of a the thick plate to non-identical top and bottom loads
- full stress tensor is calculated at seismogenic depth



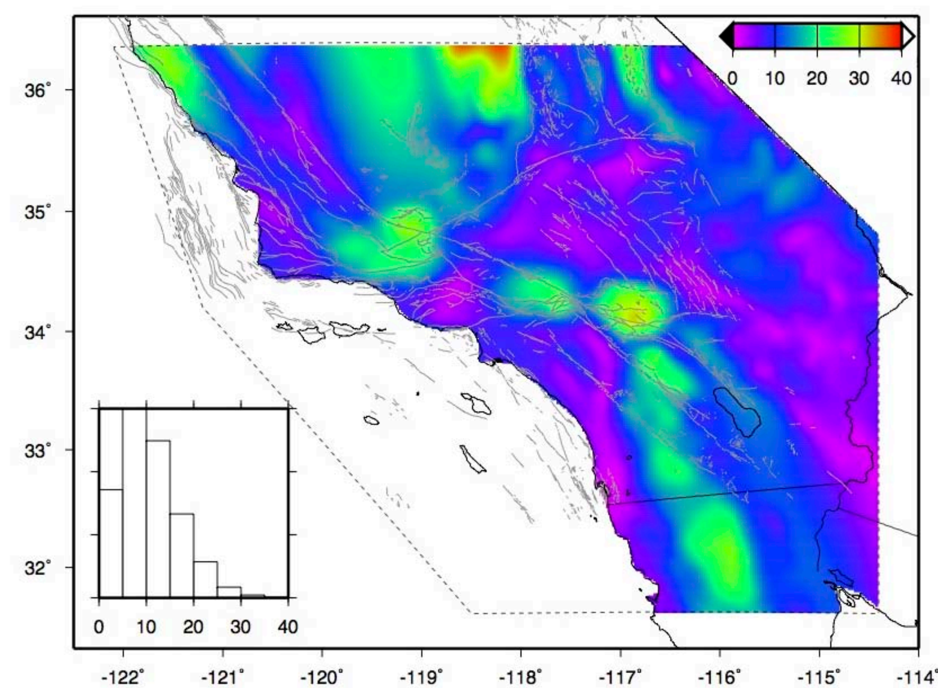
[Luttrell et al., JGR, 2011]

topographic component

differential stress (MPa); depth=5 km



differential stress (MPa); depth=15 km

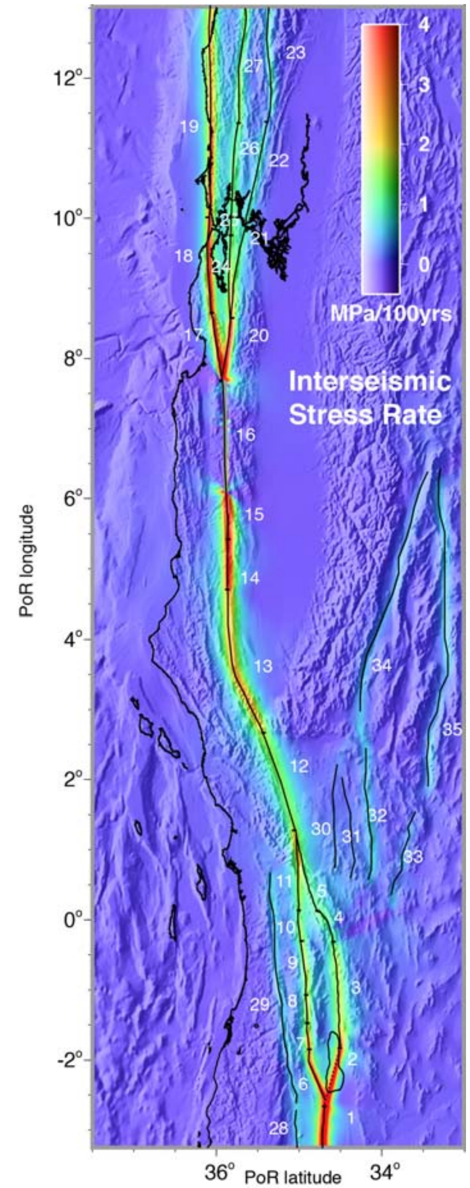


[Luttrell et al., JGR, 2011]

earthquake cycle component

calculate the stress accumulation rate using a 3-D dislocation model

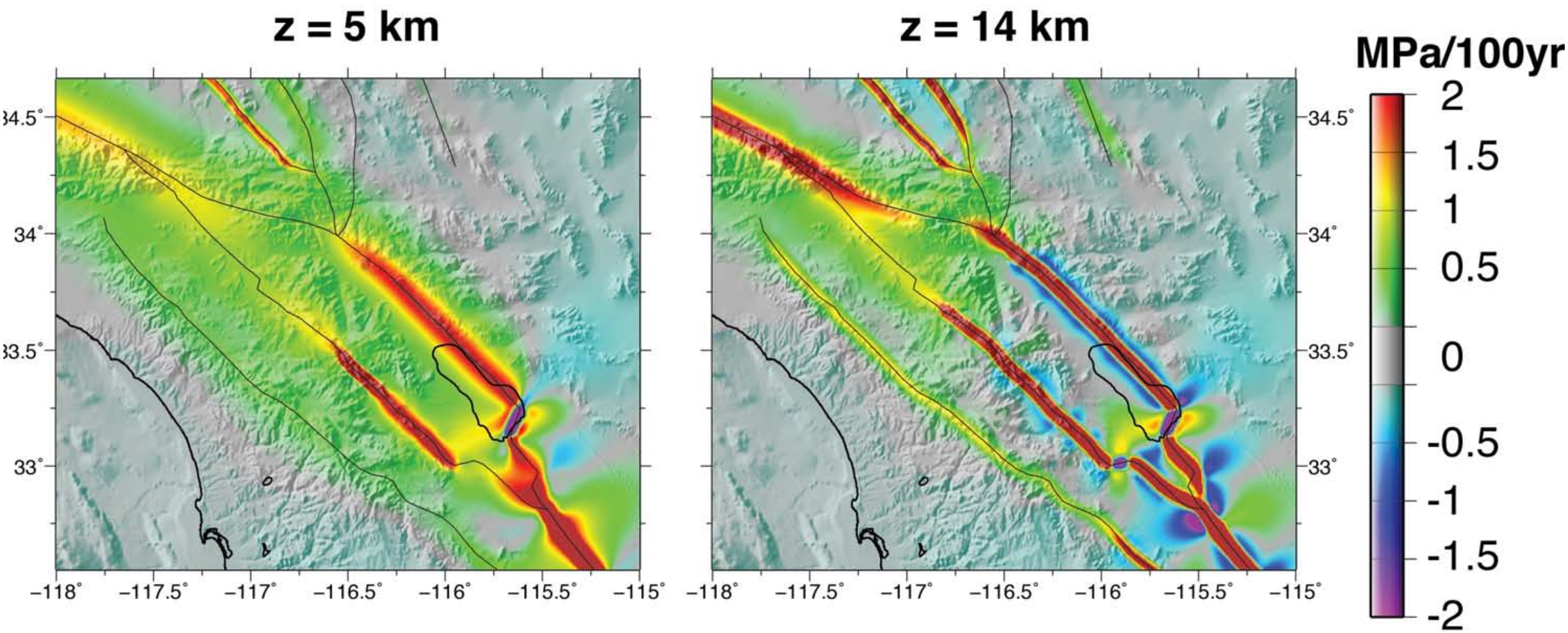
- Use 3-D viscoelastic model. (Note elastic halfspace model provides almost the same stress rate.)
- Vary locking depth and slip rate to match geology and GPS.
- Use uniform rheology so stress rate = strain rate times elastic moduli.
- Can compute stress rate tensor at any depth for each of ~40 fault segments.
- Deeply locked faults have low stress accumulation rate and high recurrence interval.



[Smith-Konter and Sandwell, 2009]

earthquake cycle component

resolved shear stress on vertical strike-slip fault plane
40 unknown parameters

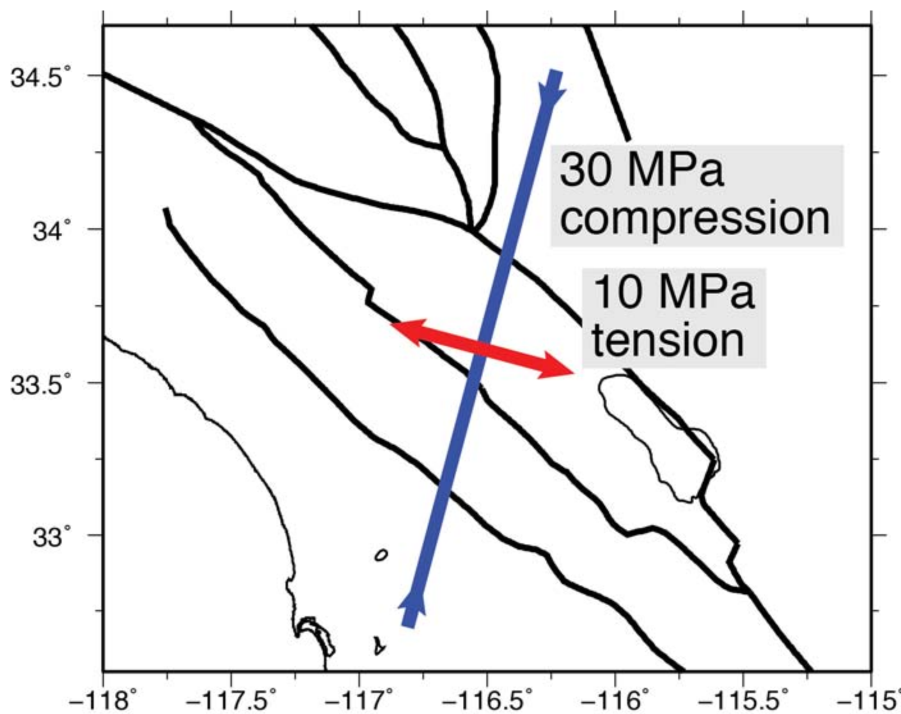


[Smith-Konter and Sandwell, 2009]

“regional” or “far-field” stress component

assume spatially-uniform horizontal stress from tectonics – three unknown parameters

alternatively, let regional stress vary segment by segment

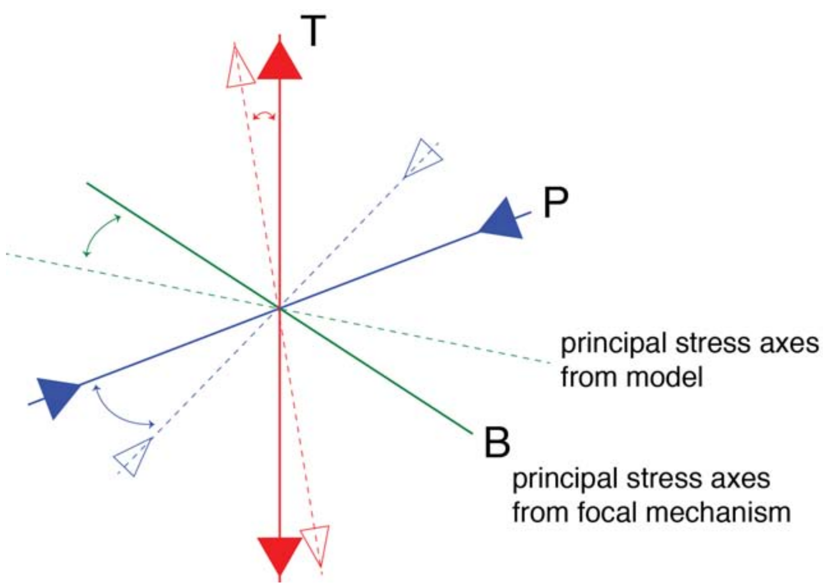


Add these 3 stressfields together

Do they reproduce stress field **orientation** from focal mechanisms?

Model orientation is eigenvectors of the 3D stress tensor

goodness-of-fit function: no partial credit if observed and model stress regimes differ



defining a goodness-of-fit parameter $\xi \in [0,1]$, such that

$$\xi = \begin{cases} 0 & \text{if model and event stress regimes differ} \\ \left(\vec{v}_1^{model} \cdot \vec{v}_1^{event} + \vec{v}_2^{model} \cdot \vec{v}_2^{event} + \vec{v}_3^{model} \cdot \vec{v}_3^{event}\right)/3 & \text{else} \end{cases}, \quad (1)$$

inversion method

Start with topostress as baseline: resistive force that must be overcome

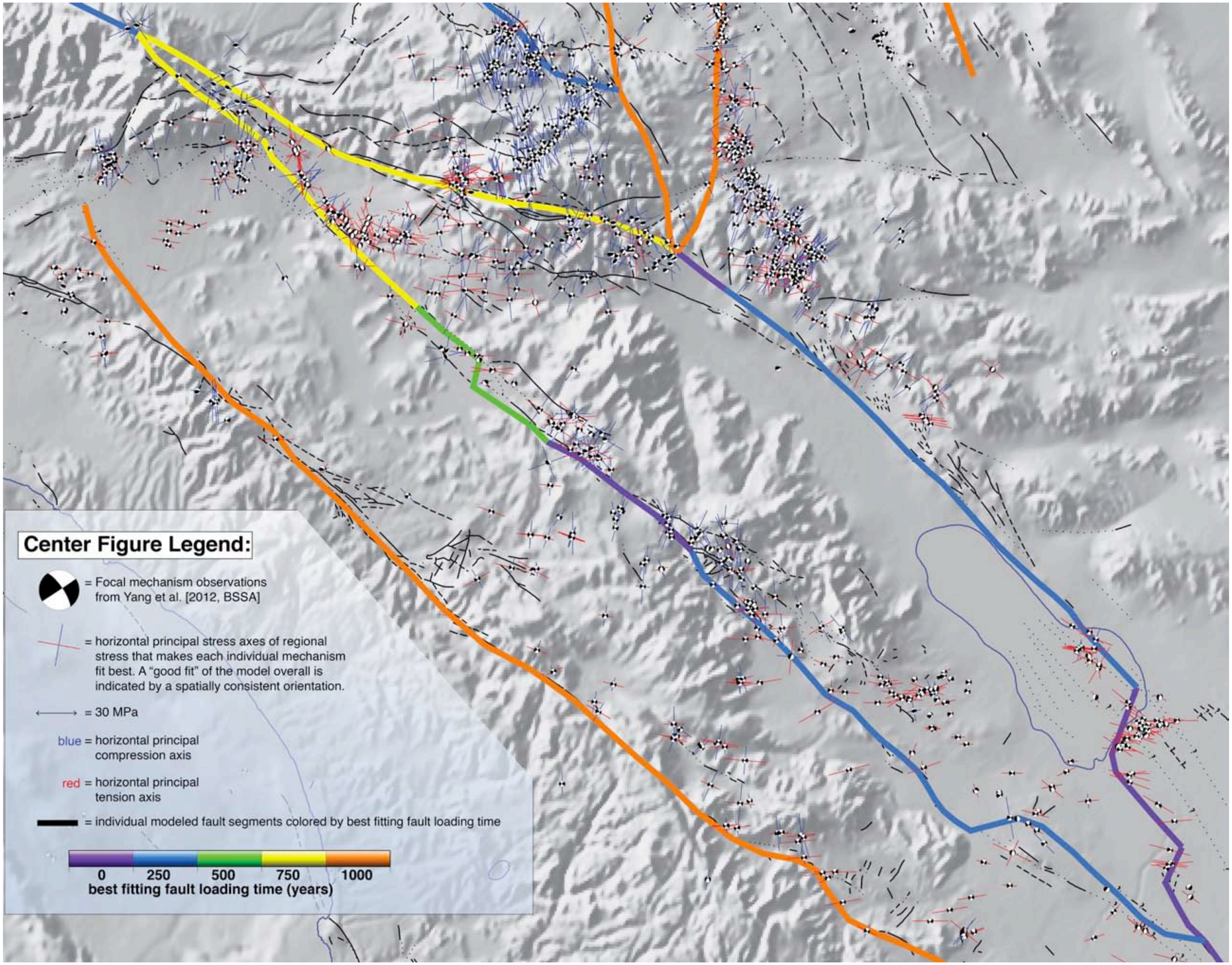
Compute stress rate grids for each of ~40 fault segments.

Add three unknown parameters for regional stress.

Assemble earthquake focal mechanisms from Yang et al., [2012]

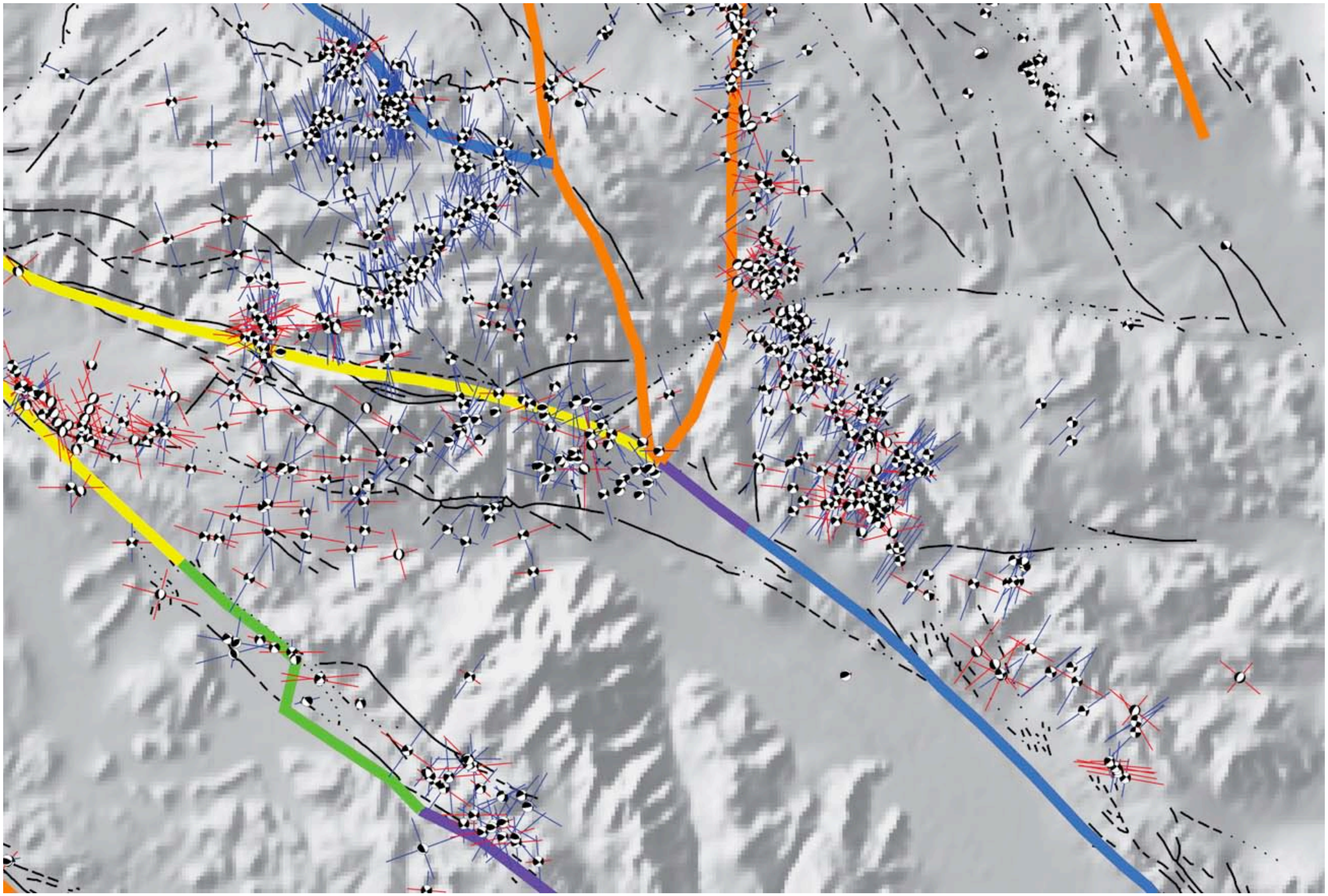
Perform least-squares analysis to solve for the stress accumulation time on each segment and far-field stress.

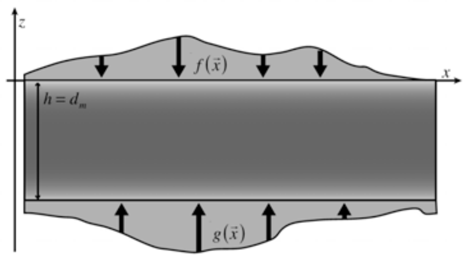
fit to data



Center Figure Legend:
= Focal mechanism observations from Yang et al. [2012, BSSA]
= horizontal principal stress axes of regional stress that makes each individual mechanism fit best. A "good fit" of the model overall is indicated by a spatially consistent orientation.
= 30 MPa
blue = horizontal principal compression axis
red = horizontal principal tension axis
= individual modeled fault segments colored by best fitting fault loading time
0
250
500
750
1000
best fitting fault loading time (years)

fit to data





Conclusions

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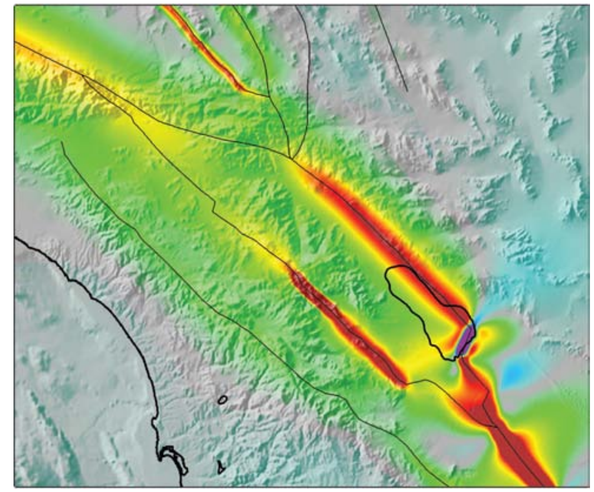


- Topographic stress constrains the magnitude and has few tunable parameters.
- Stress accumulation rate is fairly well resolved by geodesy.
- Principal components of earthquake focal mechanisms are the primary data.
- Invert for loading time of each segment plus far-field stress.
- Loading time generally is longer than recurrence interval so faults carry residual stress?
- This is version 1.0 so we need feedback and refinement.

backup slides

stress decomposition

$$\boldsymbol{\sigma}_t(\mathbf{x}) \quad + \quad \dot{\boldsymbol{\sigma}}_e(\mathbf{x})\Delta t \quad + \quad \sigma_f$$

$\boldsymbol{\sigma}_t(\mathbf{x})$ - local stress from surface and Moho topography, $\lambda < 350$ km

$\dot{\boldsymbol{\sigma}}_e(\mathbf{x}) * \Delta t$ - stress rate for each fault times an unknown time

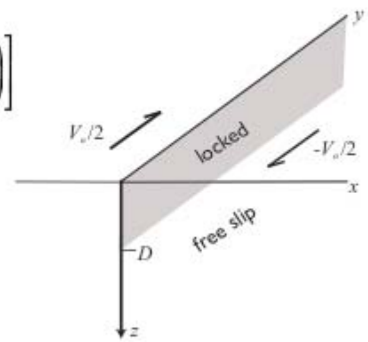
$\boldsymbol{\sigma}_f$ - far field tectonic stress (3-components of tensor)

earthquake cycle component

For an infinitely long strike-slip fault in an elastic half-space (locking depth D = 12 km, slip rate V_o = 40 mm/yr), the 2D analytical solution [1] for interseismic velocity as a function of fault-perpendicular distance (x) is

$$V(x) = \frac{V_o}{2\pi}\left[\tan^{-1}\left(\frac{x}{D-z}\right) + \tan^{-1}\left(\frac{x}{D+z}\right)\right]$$

where z is the observation plane (Fig.1).



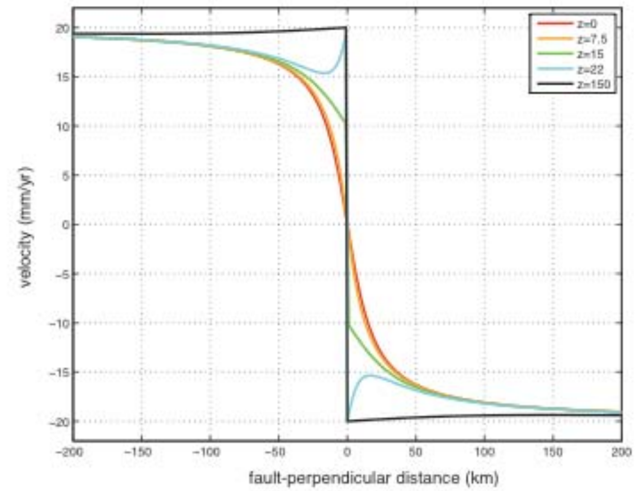


Fig. 1. 2-D interseismic velocity as a function of fault-perpendicular distance (x) and observation plane (z).

Interseismic shear stress rate as a function of observation plane is approximated by taking the fault-perpendicular derivative of the velocity (Fig. 2)

$$\dot{\tau}(x) = \mu\frac{dV}{dx}$$

As z --> D, stress rate is positive and increases. When $z = D$, stress rate remains positive but decreases substantially. For $z > D$, stress rate is negative and approaches zero as $z \rightarrow \infty$.

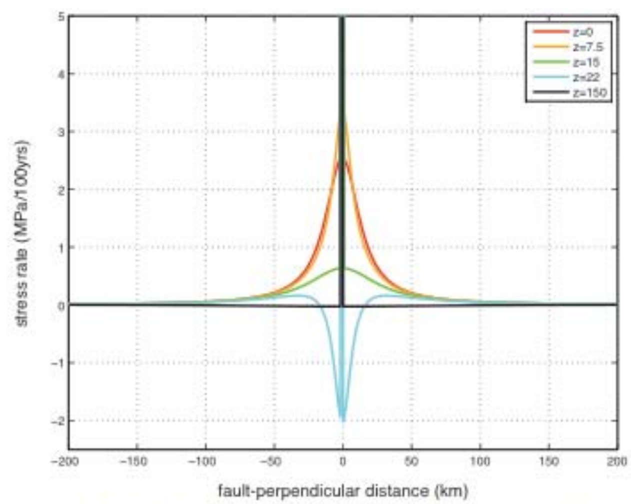
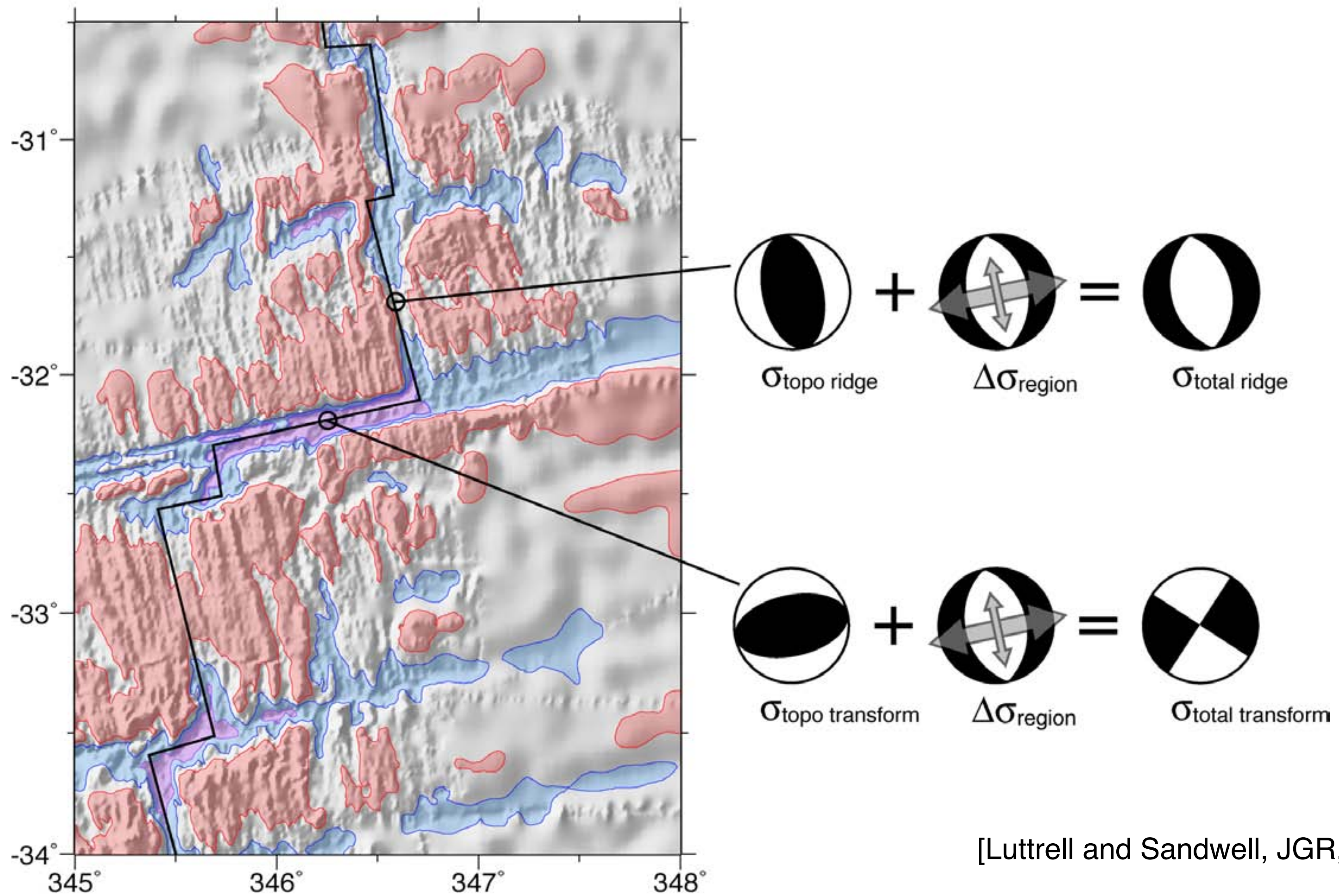


Fig. 2. 2-D shear stress rate as a function of fault-perpendicular distance (x) and observation plane (z).

For the case of an elastic plate overlying a viscoelastic half-space (full relaxation), shear stress rate as a function of observation plane is nearly identical to the behavior of Fig. 2, except with slightly larger peak magnitudes.

constrain the magnitude of the far-field tectonic stress

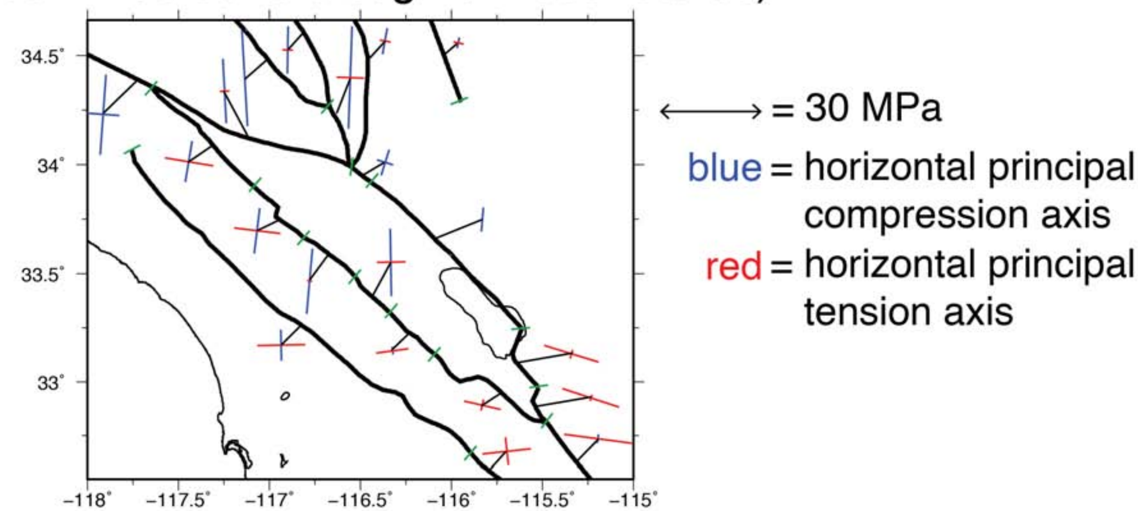
- calculate topographic stress for wavelength < 350 km
- add to this a regional horizontal stress field
- adjust 3 components of regional stress to match style of faulting



[Luttrell and Sandwell, JGR, 2012]

Best fitting regional stress field for each modeled fault segment:

(green lines denote segment boundaries)



Segment-scale regional stress patterns:

west SAF: North-South compression is dominant (~30 MPa)
with small East-West tension (~0 MPa)

east SAF: East West tension is dominant (~20 MPa)
with small North-South compression (~0 MPa)

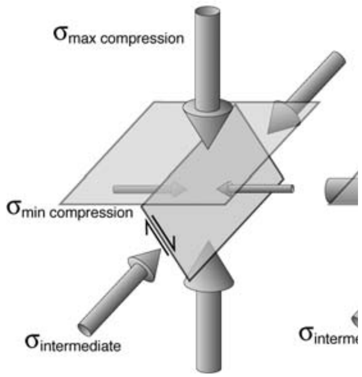
SJF: North-South compression and
East-West tension are balanced (~20 MPa)

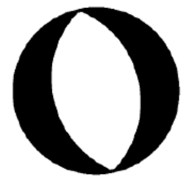
Elsinore: North-South compression and
East-West tension are balanced (~10 MPa)

ECSZ: regional stress field is very small (~0 MPa)

stress and focal mechanisms

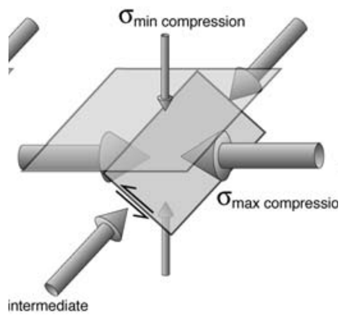
topo
high

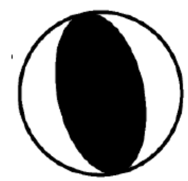




normal fault

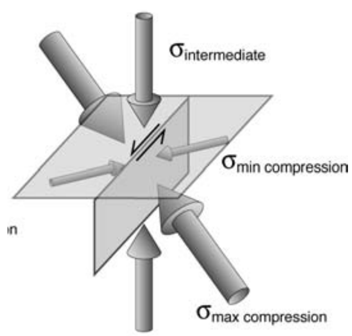
topo
low

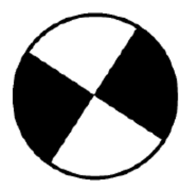




reverse fault

topo
flat





strike-slip
fault

[Luttrell and Sandwell, JGR, 2012]

Efficient calculation of the short wavelength 3-D stress

$$T_{ij} = f\left(\vec{k}\right)G_{ij}\left(\vec{k}\right)$$

$$T_{xx} = f\left(\vec{k}\right)\left[\frac{k_x^{\ 2}}{\left|\vec{k}\right|^2}\left(C_f - S_f\right) - 2\nu S_f\frac{k_y^{\ 2}}{\left|\vec{k}\right|^2}\right] + g\left(\vec{k}\right)\left[\frac{k_x^{\ 2}}{\left|\vec{k}\right|^2}\left(C_g - S_g\right) - 2\nu S_g\frac{k_y^{\ 2}}{\left|\vec{k}\right|^2}\right]$$

$$T_{yy} = f\left(\vec{k}\right)\left[\frac{k_y^{\ 2}}{\left|\vec{k}\right|^2}\left(C_f - S_f\right) - 2\nu S_f\frac{k_x^{\ 2}}{\left|\vec{k}\right|^2}\right] + g\left(\vec{k}\right)\left[\frac{k_y^{\ 2}}{\left|\vec{k}\right|^2}\left(C_g - S_g\right) - 2\nu S_g\frac{k_x^{\ 2}}{\left|\vec{k}\right|^2}\right]$$

$$T_{zz} = f\left(\vec{k}\right)\left[-C_f - S_f\right] + g\left(\vec{k}\right)\left[-C_g - S_g\right]$$

$$T_{xy} = \frac{k_x k_y}{\left|\vec{k}\right|^2}\left\{\begin{matrix} f\left(\vec{k}\right)\left[C_f - S_f + 2\nu S_f\right] \\ +g\left(\vec{k}\right)\left[C_g - S_g + 2\nu S_g\right]\end{matrix}\right\}$$

$$T_{xz} = \frac{ik_x}{\left|\vec{k}\right|}\left[f\left(\vec{k}\right)S_f' + g\left(\vec{k}\right)S_g'\right]$$

$$T_{yz} = \frac{ik_y}{\left|\vec{k}\right|}\left[f\left(\vec{k}\right)S_f' + g\left(\vec{k}\right)S_g'\right]$$

$$u = \frac{-ik_x}{\left|\vec{k}\right|}\frac{1}{2\mu\beta}\left[f\left(\vec{k}\right)\left(C_f - S_f + 2\nu S_f\right) + g\left(\vec{k}\right)\left(C_g - S_g + 2\nu S_g\right)\right]$$

$$v = \frac{-ik_y}{\left|\vec{k}\right|}\frac{1}{2\mu\beta}\left[f\left(\vec{k}\right)\left(C_f - S_f + 2\nu S_f\right) + g\left(\vec{k}\right)\left(C_g - S_g + 2\nu S_g\right)\right]$$

$$w = \frac{1}{2\mu\beta}\left[f\left(\vec{k}\right)\left(S_f' + 2(1-\nu)C_f'\right) + g\left(\vec{k}\right)\left(S_g' + 2(1-\nu)C_g'\right)\right]$$

$$C_f = \frac{2\beta^2 h(h-z)\cosh\beta z - \beta z\sinh\beta z - \beta z\sinh\beta(2h-z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$S_f = \frac{2\beta h\sinh\beta z + \cosh\beta z - \cosh\beta(2h-z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$C_g = \frac{2\beta^2 hz\cosh\beta(h-z) - \beta(h-z)\sinh\beta(h-z) - \beta(h-z)\sinh\beta(h+z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$S_g = \frac{2\beta h\sinh\beta(h-z) + \cosh\beta(h-z) - \cosh\beta(h+z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$C_f' = \frac{-2\beta h\cosh\beta z - \sinh\beta z - \sinh\beta(2h-z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$S_f' = \frac{-2\beta^2 h(h-z)\sinh\beta z + \beta z\cosh\beta z - \beta z\cosh\beta(2h-z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$C_g' = \frac{2\beta h\cosh\beta(h-z) + \sinh\beta(h-z) + \sinh\beta(h+z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

$$S_g' = \frac{2\beta^2 hz\sinh\beta(h-z) - \beta(h-z)\cosh\beta(h-z) + \beta(h-z)\cosh\beta(h+z)}{1 + 2\beta^2h^2 - \cosh(2\beta h)}$$

Second invariant of deviatoric stress is **minimized** when ν = 0.5 (incompressible)

$$\mathbf{T}_{II} = \frac{1}{6}\left[\left(T_{xx}-T_{yy}\right)^2+\left(T_{xx}-T_{zz}\right)^2+\left(T_{yy}-T_{zz}\right)^2\right]+T_{xy}{}^2+T_{xz}{}^2+T_{yz}{}^2$$

$$= f\left(\vec{k}\right)^2\left[\begin{array}{l}\frac{1}{6}\left(\frac{k_x{}^2-k_y{}^2}{\left|\vec{k}\right|^2}\left[C-S\right]+2\nu S\frac{k_x{}^2-k_y{}^2}{\left|\vec{k}\right|^2}\right)^2+\frac{1}{6}\left(\frac{k_x{}^2}{\left|\vec{k}\right|^2}\left[C-S\right]-2\nu S\frac{k_y{}^2}{\left|\vec{k}\right|^2}+C+S\right)^2+ \\ \frac{1}{6}\left(\frac{k_y{}^2}{\left|\vec{k}\right|^2}\left[C-S\right]-2\nu S\frac{k_x{}^2}{\left|\vec{k}\right|^2}+C+S\right)^2+\left(\frac{k_x{}^2k_y{}^2}{\left|\vec{k}\right|^4}\left(C-S+2\nu S\right)^2-S'^2\right)\end{array}\right]$$

$$\frac{\partial \mathbf{T}_{II}}{\partial \nu} = \frac{4S^2 f\left(\vec{k}\right)^2}{3}\left[2\nu-1\right]=0$$

$$\nu = \frac{1}{2}$$