Investigating Absolute Stress in Southern California:

Constraints from compensated topography, tectonic/fault loading, and earthquake focal mechanisms

Karen Luttrell, Bridget Smith-Konter, David Sandwell

[with guidance from J. Hardebeck, E. Hauksson, and many others]
Outline

• SCEC4 Community Stress Model

• Stress and stress rate “data”
  – Focal mechanisms → in situ stress orientation
  – GPS strain rates → fault loading stress rate
  – Topography → resistive stress

• Stress orientation modeling
  – Focal mechanism vs. GPS strain rates
  – Focal mechanism vs. topography + plate driving stress
  – Focal mechanism vs “ “ + fault loading

• Stress magnitude modeling
  – Absolute stress model that can support topography and match focal mechanism stress orientations
Stress in Space and Time

**Time scale**
- (today)
- (always)

**Spatial scale**
- (local)
- (global)

**GPS/stress-rate models**
(some physics-based, relies on modern GPS array)

**EQ focal mechanism models**
(inversion, relies on recent Eqs)

**Topography** [exists and must be supported] models
(Physics–based forward model, relies on observed topography)

**Plate driving geodynamic models**
(Physics-based forward model, relies on observed plate boundaries and gross plate motions)
Some Different Stress Perspectives

1) Inversion of focal mechanisms for stress orientation. – Wenzheng Yang and Egill Hauksson (Caltech); Jeanne Hardebeck (USGS).

2) Finite element model including topography, depth-dependent rheology, frictional faults, and long-term deformation model. – Peter Bird (UCLA).

3) Inversion for stress field that fits topography, fault loading from dislocation model, tectonic loading, and focal mechanisms. – Karen Luttrell (USGS/LSU), Bridget Smith-Konter (Texas/Hawaii), and David Sandwell (UC San Diego).

4) Smoothing of World Stress Map (mostly focal mechanisms for southern California) – Peter Bird (UCLA); Jeanne Hardebeck (USGS).

5) Global model from density-driven mantle flow, plus lithosphere gravitational potential energy, fit to geoid and global plate motions. – Attreyee Ghosh and Thorsten Becker (USC).
SCEC4 Community Stress Model (CSM)

- **Goal:** A set of models of stress and stressing rate in the S. California lithosphere
- **1st order result:** Orientations of stress contributions agree quite well

**Figure 1.** Left: Maximum horizontal compressive stress axis (SHmax) for an average stress model generated by averaging the normalized stress tensors of the models of Bird; Luttrell, Smith-Koner and Sandwell; and Yang and Hauksson. Right: the RMS difference of the SHmax orientation of the three models relative to the mean. [Hardebeck et al., 2012]
SCEC4 Community Stress Model (CSM)

- 1\textsuperscript{st} order result: Uncertainty in differential stress magnitude & variation with depth over the seismogenic zone

![Graph showing differential stress magnitude and depth](image)

Solid line/symbol: median. Dashed line: middle 68%.

[Hardebeck et al., 2012]
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A New Focal Mechanism Catalog for Southern California

• Very large dataset, 1981-2010
• 480,000 earthquakes

[Yang et al. 2012]
Stress Orientation Model

• Inversion of Yang et al. (2012) focal mechanism (FM) catalog to determine crustal stress field and style of faulting
Southern California GPS Velocity Field

45 mm/yr
Velocity to Strain Rate

\[ \nu_i(x^k_j) \pm \sigma_i^k \text{ vector velocity at point } k \]
\[ i = 1, 2, 3 \quad j = 1, 2 \quad k = 1 - N \]
\[ \downarrow \quad \text{2-D interpolation and/or dislocation model} \]

\[ \nu_i(x^i_j) \quad \text{- surface vector velocity (0.01°)} \]
\[ \downarrow \quad \text{differentiation (GMT grdgradient)} \]

\[ \dot{\varepsilon}_{ij} = \frac{1}{2} \left( \frac{\partial \nu_i}{\partial x_j} + \frac{\partial \nu_j}{\partial x_i} \right) \quad \text{- 2D strain rate} \]

principal strain rate

\[ \dot{\varepsilon}_{1,2} = \frac{\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy}}{2} \pm \frac{1}{2} \left\{ \left( \dot{\varepsilon}_{xx} - \dot{\varepsilon}_{yy} \right)^2 + 4 \dot{\varepsilon}_{xy}^2 \right\}^{1/2} \]

dilatation rate + maximum shear rate

second invariant

\[ \dot{\varepsilon}_{\Pi} = \left( \dot{\varepsilon}_{xx}^2 + \dot{\varepsilon}_{yy}^2 + 2 \dot{\varepsilon}_{xy}^2 \right)^{1/2} \]

Four approaches are used:
1) isotropic interpolation;
2) interpolation guided by known faults;
3) interpolation of a rheologically-layered lithosphere, and
4) model fitting using deep dislocations in an elastic layer or half space.
Community Strain Rate Models
Community Strain/Stress Rate Models

- Models are well-correlated, some more “rough” than others
- When multiplied by shear modulus, models provide a good representation regional **crustal stress rates** from GPS strain field.
Southern California Topography
Estimating the stress from topography

- How does topography form?
  - Cumulative result of inelastic deformation
  - Deformation brings the stress back down to the level of the critical yield stress

- Assume elastic-perfectly-plastic rheology
  - Critical failure stress is an end-member of elastic deformation

- Stress magnitudes could be higher
  - e.g., if strengthening occurred since topography was built

- Stress magnitudes could not be lower
  - otherwise the existing topography would have relaxed away
3-D stress within a thick elastic plate

- Calculate critical failure stress in crust in a thick elastic plate loaded with surface topography and Moho topography

- Semi-analytic (pseudo-spectral)
  - Green’s function for elastic plate loaded with non-identical point loads
  - Convolve with short-wavelength (< ~ 350 km, SH 100°-140°) topography at surface and Moho
  - Moho depth constrained by receiver functions (h ~ 35 km), shape constrained by gravity (~ 5 km)
  - Convolve in the Fourier domain (numerically efficient)
• At short wavelengths (< ~350 km), variations in topography are supported by stresses within the crust
Topography Stress Model

- Spatial variations in the absolute stress field exerted by static topography over the last $>10^4$ years
- High topography typically predicts normal faulting, low predicts thrust

[Lutrell et al. SCEC 2012]
Summary: “Stress” Models

Focal mechanisms, in situ stress field orientation

GPS strain rates, fault stress accumulation rates

Locally compensated topography

EARTHQUAKE FOCAL MECHANISM ORIENTATION

IN SITU STRESS FIELD ORIENTATION

FAULT STRESS ACCUMULATION RATE

LOCAL COMPENSATED TOPOGRAPHY STRESS
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SHmax comparison: Seismology vs. Geodesy

- blue – Focal mechanism orientations
- green – GPS strain rate orientations

[Hauksson and Sandwell, SCEC 2013]
-5 degree average rotation between focal mechanism and strain rate models

[Hauksson and Sandwell, SCEC 2013]
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Reconciling Stress Models

Does

\[ \begin{align*}
\text{LOCAL COMPENSATED TOPOGRAPHY STRESS} & \quad + \\
\text{FAREIELD PLATE DRIVING STRESS} & \quad = \\
\text{EARTHQUAKE FOCAL MECHANISM ORIENTATION} & \quad ?
\end{align*} \]

Does

\[ \begin{align*}
\text{LOCAL COMPENSATED TOPOGRAPHY STRESS} & \quad + \\
\text{FAULT STRESS ACCUMULATION RATE} & \quad + \\
\text{FAREIELD PLATE DRIVING STRESS} & \quad = \\
\text{EARTHQUAKE FOCAL MECHANISM ORIENTATION} & \quad ?
\end{align*} \]

Or ….

\[ \begin{align*}
\lambda ? & - \\
\lambda ? & \approx \\
\text{IN SITU STRESS FIELD WITH SCALED MAGNITUDE} & \quad \text{LOCAL COMPENSATED TOPOGRAPHY STRESS} \\
\text{IN SITU STRESS FIELD ORIENTATION} & \quad ?
\end{align*} \]

How large must in situ stress be to overcome the resistive forces of topography?
Topography & regional stress (mid-ocean ridges)

Fitting ridge highs/lows and transform lows/highs simultaneously with a single consistent 2-D stress field
Topography & Plate Driving Stress (mid-ocean ridges)

- Stress from topography alone is in the completely wrong regime.

- Adding a regional “plate driving” stress brings the “total” stress into the correct regime.

- Normal faulting along ridges and strike-slip faulting along transforms.
A challenge: Varied faulting-type plate boundary (Southern California)
Best-fitting plate driving stress?

Does \[ \text{LOCAL COMPENSATED TOPOGRAPHY STRESS} + \text{FARFIELD PLATE DRIVING STRESS} = \text{EARTHQUAKE FOCAL MECHANISM ORIENTATION} \]?

- Determine magnitude & orientation of 2-D horizontal stress field
- Absolute lower bound estimate:
  - 30 MPa NNE compression
  - 10 MPa ESE tension
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Fault loading stress contributions?

Does

LOCAL COMPENSATED TOPOGRAPHY STRESS + FAULT STRESS ACCUMULATION RATE + FARFIELD PLATE DRIVING STRESS = EARTHQUAKE FOCAL MECHANISM ORIENTATION

Differential stressing rate (kPa/yr)

CSM – Smith Konter (depth = 1km)
Best-Fitting Stress Loading Times

- **blue** = horizontal principal compression axis
- **red** = horizontal principal tension axis

- **$\leftarrow$** = 10 MPa

Best fit loading time (years)
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Revisiting the Focal Mechanism (FM) Stress Model

max. horizontal compressive stress

[Yang and Haukkson, 2013]

“Aphi” (faulting style)
Understanding stress field orientation & faulting regime

\( \phi \)  
(stress ratio)

\[
\phi = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}
\]

\( \phi \)

(style of faulting)

\[
\begin{align*}
\phi & \quad \text{if } \sigma_3 \text{ is most vertical (normal)} \\
2 - \phi & \quad \text{if } \sigma_2 \text{ is most vertical (strike-slip)} \\
2 + \phi & \quad \text{if } \sigma_1 \text{ is most vertical (thrust)}
\end{align*}
\]

Aphi

- Describes the “shape” of stress tensor (i.e., uniaxial vs. plane stress) and stress regime simultaneously

uniaxial compression (vertical)

- Aphi = 0.5: plane stress (vertical compression)
- Aphi = 1: uniaxial tension (horizontal)
- Aphi = 1.5: plane stress (both horizontal)

uniaxial compression (horizontal)

- Aphi = 2: strike-slip
- Aphi = 2.5: thrust
- Aphi = 3: principal stress in tension
- Aphi = 3: uniaxial tension (vertical)

plane stress (vertical tension)
3D in situ stress orientation model
(from focal mechanisms -- FM)

Inverted Model: SHmax

Inverted Model: Aphi

[Yang and Haukson, 2013]
3D in situ stress orientation model
(from focal mechanisms -- FM)
Topo & Focal Mechanism Stress Models

Topography SHmax and Aphi

Focal Mechanism SHmax and Aphi

Topography Absolute Differential Stress

Focal Mechanism Absolute Differential Stress
Using Topographic Stress to Estimate Minimum In Situ Stress Magnitude

How large must in situ stress be to overcome the resistive forces of topography?

\[
[\lambda \left\{ FM_{ij} - T_{ij}\right\}_{\text{orientation}} \approx [FM_{ij}]_{\text{orientation}}
\]
Ways to assess goodness-of-fit of 3D tensor orientations (A,B)

<table>
<thead>
<tr>
<th>Formula</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>$S_{Hdot}$</strong></td>
<td>$= \vec{v}<em>{SH</em>{max}}<em>A \cdot \vec{v}</em>{SH_{max}}_B$</td>
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<tr>
<td><strong>Range</strong></td>
<td>$[0,1]$, 1 indicates perfect fit</td>
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<tr>
<td><strong>$dAphi$</strong></td>
<td>$= Aphi_A - Aphi_B$</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>$[-3,3]$, 0 indicates perfect fit</td>
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<tr>
<td><strong>$T_{dot}$</strong></td>
<td>$= \frac{A : B}{\sqrt{A : A \sqrt{B : B}}}$</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>$[-1,1]$, 1 indicates perfect fit</td>
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<tr>
<td><strong>$x_{idot}$</strong></td>
<td>$= \left( \vec{v}<em>{1A} \cdot \vec{v}</em>{1B} + \vec{v}<em>{2A} \cdot \vec{v}</em>{2B} + \vec{v}<em>{3A} \cdot \vec{v}</em>{3B} \right) / 3$</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>$[0,1]$, 1 indicates perfect fit</td>
</tr>
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Stress Tensor Comparisons

- **SHdot**: avg $\sigma_1-\sigma_3 = 2$ MPa (way too small)
  - mean $\text{SHdot} = 0.909$

- **dAphl**: avg $\sigma_1-\sigma_3 = 10$ MPa (still too small)
  - mean $\text{abs(dAphl)} = 1.146$

- **Tdot**: avg $\sigma_1-\sigma_3 = 50$ MPa (just barely big enough)
  - mean $\text{Tdot} = 0.197$

- **xldot**: avg $\sigma_1-\sigma_3 = 50$ MPa (just barely big enough)
  - mean $\text{xldot} = 0.519$

- **SHdot**
  - mean $\text{SHdot} = 0.997$

- **dAphl**
  - mean $\text{abs(dAphl)} = 0.646$

- **Tdot**
  - mean $\text{Tdot} = 0.680$

- **xldot**
  - mean $\text{xldot} = 0.725$

- **SHdot**
  - mean $\text{SHdot} = 1.000$

- **dAphl**
  - mean $\text{abs(dAphl)} = 0.155$

- **Tdot**
  - mean $\text{Tdot} = 0.972$

- **xldot**
  - mean $\text{xldot} = 0.952$
Does Scaled FM Stress Overcome Topographic Stress?

\[
\lambda = 3 \\
\text{mean dif} = 11.681 \\
\text{mean of 4 fit parameters} = 0.777
\]
• Mean fit of orientation FMij stress to orientation of "total stress" ($\lambda FMij - Tij$) for entire S. California region

• When $\sigma_1 - \sigma_3$ is large enough, $[\lambda FMij - Tij]_{\text{orientation}} \approx [FMij]_{\text{orientation}}$
Differential Stress Magnitude

- Mean differential stress should be at least 40-60 MPa
- Preliminary attempt at CSM v0.1a?
Conclusions

• Stress rates:
  – Best strain rate models predict stress rates with SHmax very similar to each other and to the SHmax from focal mechanisms
  – Preliminary fault loading time estimates are consistent with recurrence intervals, refined analysis forthcoming

• Absolute stress (preliminary):
  – FM model by itself provides crustal stress orientation, but together with the topography model we can upgrade to orientation + absolute magnitude lower bound
  – Spatial variations in differential stress magnitude across S. California?
Outstanding Questions/Thoughts

• Why does SHmax from focal mechanisms agree with stress rate orientations but not so much with absolute stress?
  – Is the crust critically stressed such that the incremental stress rate is relieved by small earthquakes?

• A 5 degree misfit exists between strain rate and focal mechanism orientation – where does this come from?

• Could integrating far-field stress from geodynamic models with stress from local models reconcile some of the differences?

• So far we have used the mean differential stress as a tuning parameter, perhaps we should use the maximum differential stress?

• Where is our simple topography model deficient?