How stressed are we really?
Harnessing community models to characterize the crustal stress field in southern California

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All Contributors to the SCEC Community Stress Model
Recall: Why are we doing this?

SCEC4 Community Stress Model (CSM): 2012-2017

• Goal: A set of models of stress and stressing rate in the Southern California lithosphere
• So Far: good representations of
  – \textit{In situ} stress orientation and stress ellipsoid
  – Stress accumulation rate due to major locked faults
  – A few other individual physical processes.

Note:
simulation versus hypothesis testing
Outline

1. Contributions and questions

2. Estimates of stress magnitude

3. Which processes dominate crustal stress heterogeneity?

4. What’s next?
Models of “Stress” in Space and Time

Time scale

(today) (always)

Spatial scale

(local)

EQ local mechanism models
(inversion, relies on recent EQs)

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

(global)

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

Plate driving geodynamic models
(Physics-based forward model, relies on observed plate boundaries and gross plate motions)
Southern California GPS Velocity Field
(stress accumulation rate)
Stress Orientation Model
(assume this is in situ orientation)

- Invert 179,000 FMs
- No depth dependence, all “seismogenic depth”
- 3D stress ellipsoid shape and orientation
- No magnitude

[following work of Hardebeck and Michael 2006 etc.]

[Yang and Hauksson, 2013]
Topography supported within crust (resists tectonic stress)

- Topography contributes to the stress field

- Long-wavelengths (≥~2πh) are supported through isostasy
  - Regionally only contribute to lithostatic stress

- Shorter wavelengths are supported within the crust

[Luttrell and Smith-Konter, 2016, in review]
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 [Dahlen, 1990]

- 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 (< ~ 225 km, SH 160°-200°) topography at surface and Moho
  - Moho depth constrained by receiver functions (h ~ 35 km), shape constrained by gravity (Te ~ 3 km)
  - Convolve in the Fourier domain (numerically efficient)

[Luttrell et al., 2011; Luttrell and Sandwell, 2012]
Stress from Topography at seismogenic depth

- Differential Stress up to 25 MPa, due to roughest topography

- Includes 3D orientation and magnitude

[Luttrell and Smith-Kanter, in progress]
Recall: Why are we doing this?

• The SCEC CSM brings together models of *individual processes*

• What can we learn by *combining specialized models*?

• Questions that remain: *This is not an exhaustive list*
  – What is the magnitude of the deviatoric stress field? (differential stress)
  – What role do each of these individual processes play in the total *in situ* stress field?
  – First Steps toward simulation…
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Simple forward model of stress field

\[ \sigma = T + \text{"Other"} \]

- **Find some indication of this**
- **Calculate this**
- **Figure out some bounding values for this**

**IN SITU STRESS 3D TENSOR (FROM ORIENTATION, Q)**

**TOPOGRAPHY STRESS COMPENSATED IN CRUST**

**FARFIELD PLATE DRIVING STRESS**

**FAULT STRESS ACCUMULATION RATE**
Topography and Regional Stress (megathrust earthquake)

Compare forearc topography with slip direction to constrain driving stress and compare with stress drop

[Luttrell et al., 2011]
Topography and Regional Stress (mid-ocean ridges)

Fitting ridge highs/lows and transform lows/highs simultaneously with a single consistent 2-D stress field

[Luttrell and Sandwell, 2012]
Topography and Regional 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

[Luttrell and Sandwell, 2012]
A challenge: Varied faulting-type plate boundary (Southern California)

[Yang et al. 2012]
A challenge: Varied faulting-type plate boundary (Southern California)

Inverted Focal Mechanism model from Yang and Hauksson [2013]
Simple forward model of stress field

\[ \sigma = T + \text{“Other”} \]

Need some additional information or assumptions

1. Assume topography is **NOT** dominant in Southern California

2. Assume “other” is **dominant** in Southern California
   
i.e., topography is \(~\text{negligible}\)
Simple forward model of stress field

\[ \sigma = T + \text{"Other"} \]

\[ \sigma \approx \sigma^* \Delta \sigma - T \]
Minimum in situ magnitude estimate: $\Delta\sigma_{\text{min}}$

- $\Delta\sigma$ required to maintain *in situ* orientation to within $\pm 15^\circ$, despite resistance from topography
- Across SoCal, ranges from $\sim 10 - 60$ MPa
- This is a lower bound: stress could be arbitrarily higher and fit just as well

[Luttrell and Smith-Konter, in revision]
Minimum in situ magnitude estimate: $\Delta \sigma_{\text{min}}$

- How does min $\Delta \sigma$ estimate vary across region?

- CDF of area able to support existing topography for *in situ* differential stress of a certain magnitude

- Similar result if near-fault areas considered separately

- Most rugged topography requires $\Delta \sigma$ of 62 MPa

[Min. in situ magnitude estimate: $\Delta \sigma_{\text{min}}$ as calculated by Luttrell and Smith-Konter, in revision]
Which estimate should we use for $\Delta \sigma_{\text{min}}$?

Depends on how heterogeneous stress magnitude is…

If variations are large relative to mean…

... this is the best estimate of $\Delta \sigma_{\text{min}}$ at each place

If variations are small relative to mean…

... $\Delta \sigma_{\text{min}}$ everywhere must be large enough to support max
Do these results make sense?

- Compare with estimates from
  - Shallower drilling
  - Deeper exhumed crustal rocks
  - Landers aftershock rotation

- Max required stress is concordant with shallower and deeper estimates

- Landers region is high, but within error bars

- YSE places a lower limit on fault friction and an upper limit on pore pressure

[Luttrell and Smith-Konters, in revision]
Do these results make sense?

- YSE places a lower limit on fault friction and an upper limit on pore pressure
  - At max required stress, 
    - Fault friction can’t be very low \( (\mu_f > 0.3) \)
    - Pore pressure can’t be very high \( (\lambda < 0.7) \)
  
- Heterogeneous stress field more permissive

[Luttrell and Smith-Konters, in revision]
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In Situ Stress Orientation is Heterogeneous.

Why?

Lets assemble some physics-based models and find out…

Inverted Focal Mechanism model from *Yang and Hauksson* [2013]
Simple forward model of stress field

\[ \sigma = G + T + \dot{\sigma}_{t_{load}} \]

- **\( \sigma \)**: In situ stress 3D tensor (from \( \mathbf{Q} \) orientation).
- **\( G \)**: Farfield plate driving stress.
- **\( T \)**: Topography stress compensated in crust.
- **\( \dot{\sigma}_{t_{load}} \)**: Fault stress accumulation rate.
Independently calculated model components

- **Q**: In situ stress orientation from earthquake focal mechanisms, but **no magnitude**
  - [Yang and Hauksson, 2013]
Independently calculated model components

• **Q**: In situ stress orientation from earthquake focal mechanisms, but **no magnitude**
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• **L**: Stress accumulation rate on locked faults from buried dislocation, constrained by geodesy, but **need to know time**
  – e.g. [Smith-Konter et al., 2011]

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Independently calculated model components

- **Q**: In situ stress orientation from earthquake focal mechanisms, but no magnitude
  - [Yang and Hauksson, 2013]

- **L**: Stress accumulation rate on locked faults from buried dislocation, constrained by geodesy, but need to know time
  - e.g. [Smith-Konter et al., 2011]

- **T**: Crustal stress from Topography assuming critical stress state, constrained by gravity, but minimum estimate of magnitude
  - e.g. [Luttrell and Sandwell, 2012]

[Luttrell and Smith-Konter, 2016, in review]
What about the driving stress (G) ?

- If stress variation (Q) is due to fault loading processes (L) or topography (T), then driving stress (G) should have homogeneous orientation.
- If stress variation (Q) is dominated by more localized processes, then driving stress (G) should be \( \sim \)uniformly distributed about mean SHmax.
What about the driving stress (G)?

- **Caveat**: fault loading model based on horizontal GPS and major faults
  - Therefore limited to regions that are near-fault and strike slip
What about the driving stress (G)?

- Let driving stress $G$ be 2D horizontal strike-slip
  - Let magnitude $\Delta \sigma_G = 62$ MPa (sufficient to support near fault topography, [Luttrell and Smith-Konter, in revision])
  - Let orientation $\theta_G$ vary between 12 individual SAF/SJF fault segments
  - Let loading time $t_{load}$ vary between 12 individual SAF/SJF fault segments

- Calculate best $t_{load}$ and $\theta_G$ for each fault segment

\[
\sigma = G + T + \dot{L} t_{load}
\]
Results for one segment

- Fraction (f) of segment area fit by forward model with parameters loading time ($t_{load}$) and driving stress orientation ($\theta_G$)

- Tradeoff between $t_{load}$ and $\theta_G$ (less sensitive to $t_{load}$)
Results for all the segments

- Best fit lines for 7 SAF segments and 5 SJF/SH segments

- SAF rotates CCW from south to north, ~14° jump at Coachella

- SJF gradually rotates CW from south to north, ~14° total

- Phase within earthquake cycle ($t_{load}$) makes a small difference
Compare total model to in situ orientation

- Simple model captures the first order features
  - >90% of region fits to better than ±30°, ~60% fits to better than ±15°
- Along-fault driving stress rotations are required (can’t be homogeneous)
What does this mean?

• If stress variation (Q) is due to fault loading processes (L) or topography (T), then driving stress (G) should have homogeneous orientation.
• If stress variation (Q) is dominated by more localized processes, then driving stress (G) should be ~uniformly distributed about mean SHmax.

• **Observations:** driving stress (G) is ~bimodal,
• **Loading of major faults is not sufficient** to explain the gross heterogeneities of the *in situ* stress field, despite matching the surface geodetic observations very well.

• If these heterogeneities of stress orientation are, in fact, external to fault processes, then they are *expected to be long lived*, relative to the earthquake cycle on these faults (hundreds of years).
How does this compare?

- Geodynamic forward models of stress in lithosphere globally
- Global model, but SoCal has a few pixels...
- Along SAF, stress rotates CCW then CW from south to north

[Predicted deviatoric stress]

[Ghosh and Holt, 2012]
Side by side

[Ghosh and Holt, 2012]
Conclusions so far...

• Lower-bound estimate on differential stress magnitude

• Simple forward model **fits pretty well**
  – Corroborates individual model components

• Plate driving stress has rotations *(not homogeneous)*
  – Sudden ~14° CCW rotation along sSAF, between Coachella and San Bernardino segments
  – Gradual ~14° CW rotation along SJF and SH

• Regional stress field is strongly influenced by processes **external to the earthquake cycle on major faults**
  – If so, then they should be long lived, relative to the earthquake cycle on these faults (hundreds of years).

• **What is** causing rotations? Possible suspects:
  – Differences in fault strength and friction?
  – Differences in connecting segments?
  – Differences in underlying rheology / crustal blocks?
  – ??????
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4. **What’s next?**
What’s Next? More Observations

- Finding more borehole observations

- Incorporating the borehole observations we already have

Persaud et al., 2015 AGU

Phoenix Harris, LSU undergrad

Joel Spansel, LSU undergrad
What’s Next? Incorporating Depth

- Depth Dependent observations
  - e.g., borehole observations in same well/area, emerging FM results

- Depth dependent component models
  - e.g., topography and fault loading
What’s Next?  Incorporating Time

Smith-Konter et. al, Poster #010

San Andreas Fault System Stress Accumulation

1800 MPa
What’s Next? Bridging Processes

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(local) (global)

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??? (your model here) ???

??? (your model here) ???
Thanks!