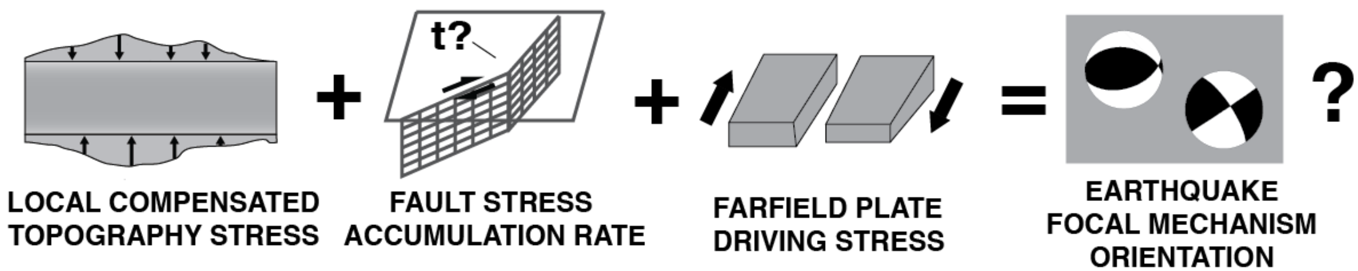
Investigating Absolute Stress in Southern California:

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*]

LSU

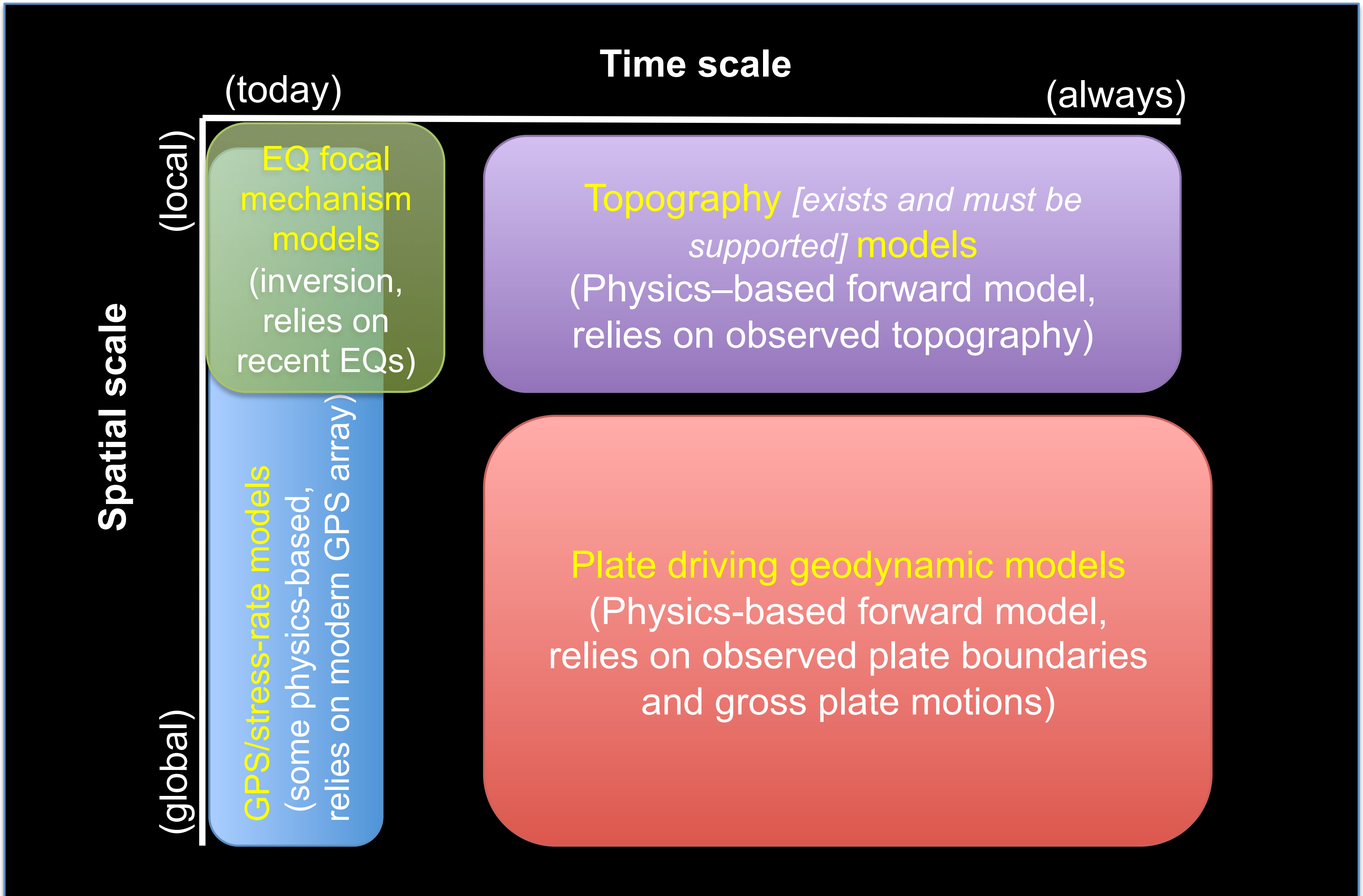
UNIVERSITY of HAWAI'I MĀNOA

SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

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



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

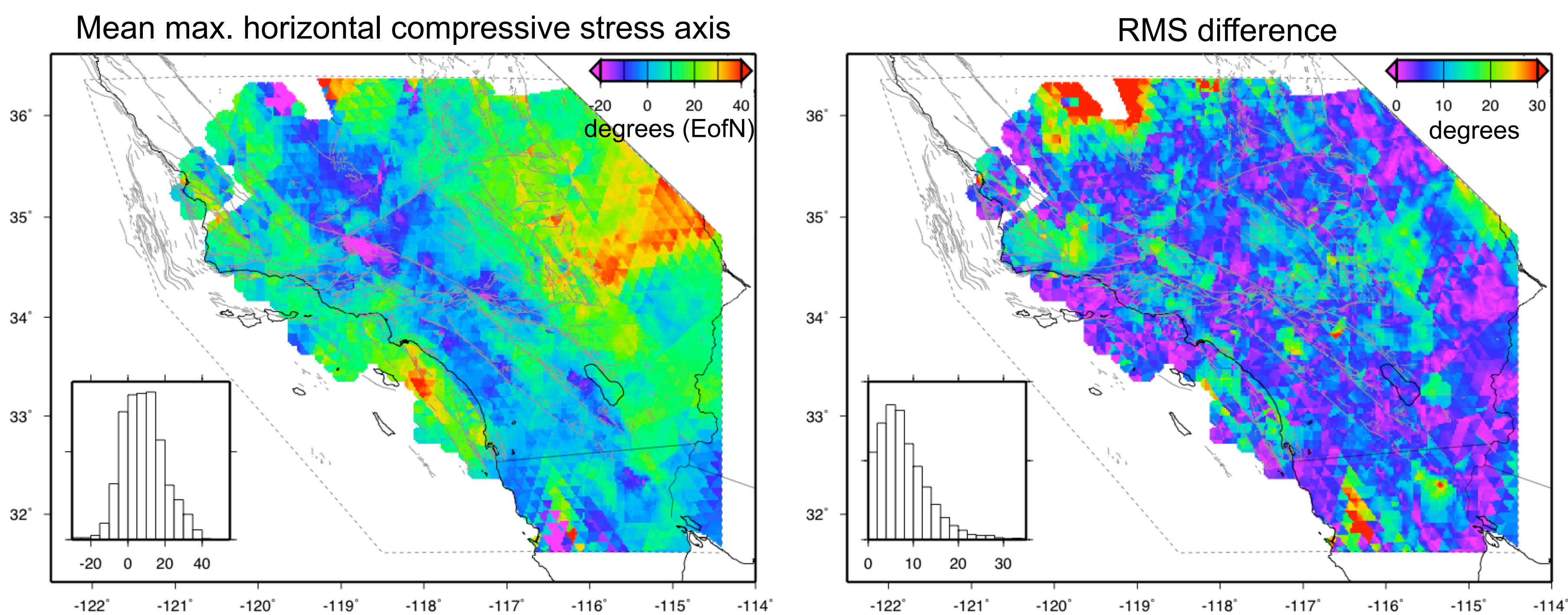
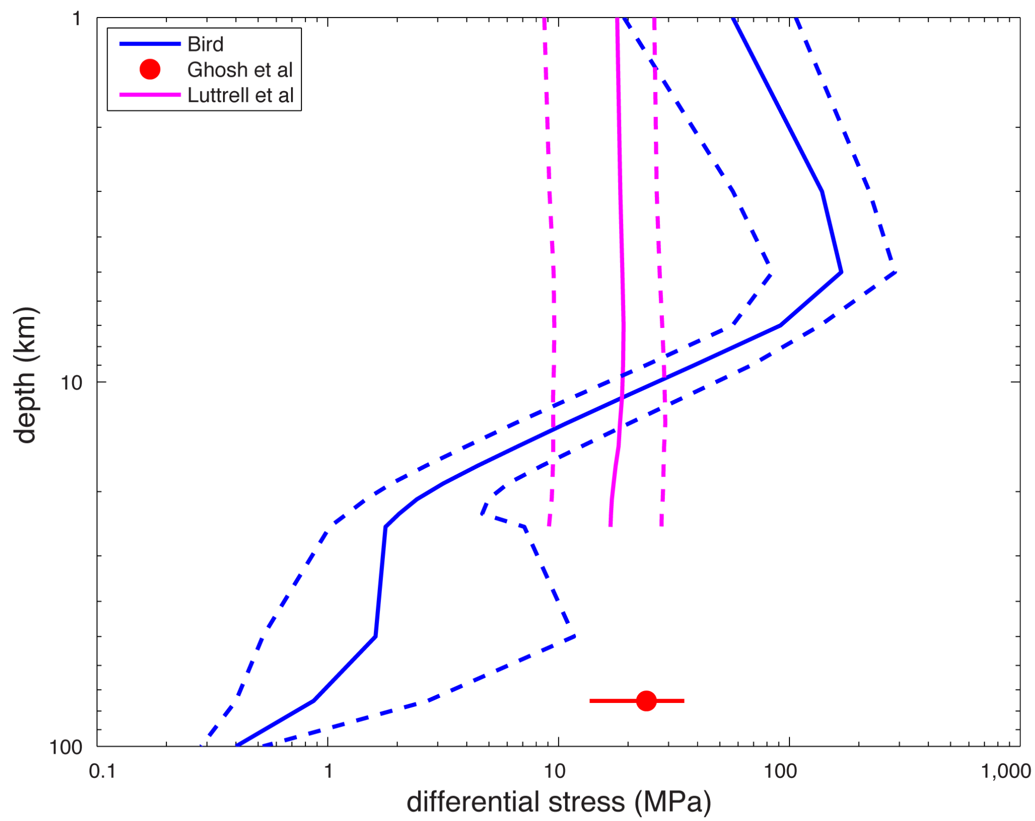


Figure 1. Left: *Maximum horizontal compressive stress axis (SHmax) for an average stress model generated by averaging the normalized stress tensors of the models of Bird; Luttrell, Smith-Konter and Sandwell; and Yang and Hauksson.* ***Right:*** *the RMS difference of the SHmax orientation of the three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

SCEC4 Community Stress Model (CSM)

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



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

[Hardebeck et al., 2012]

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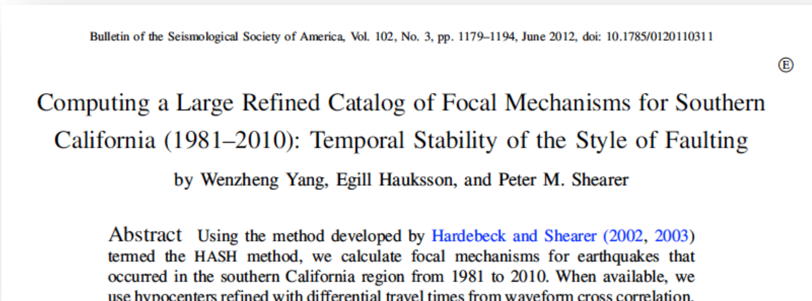
A New Focal Mechanism Catalog for Southern California

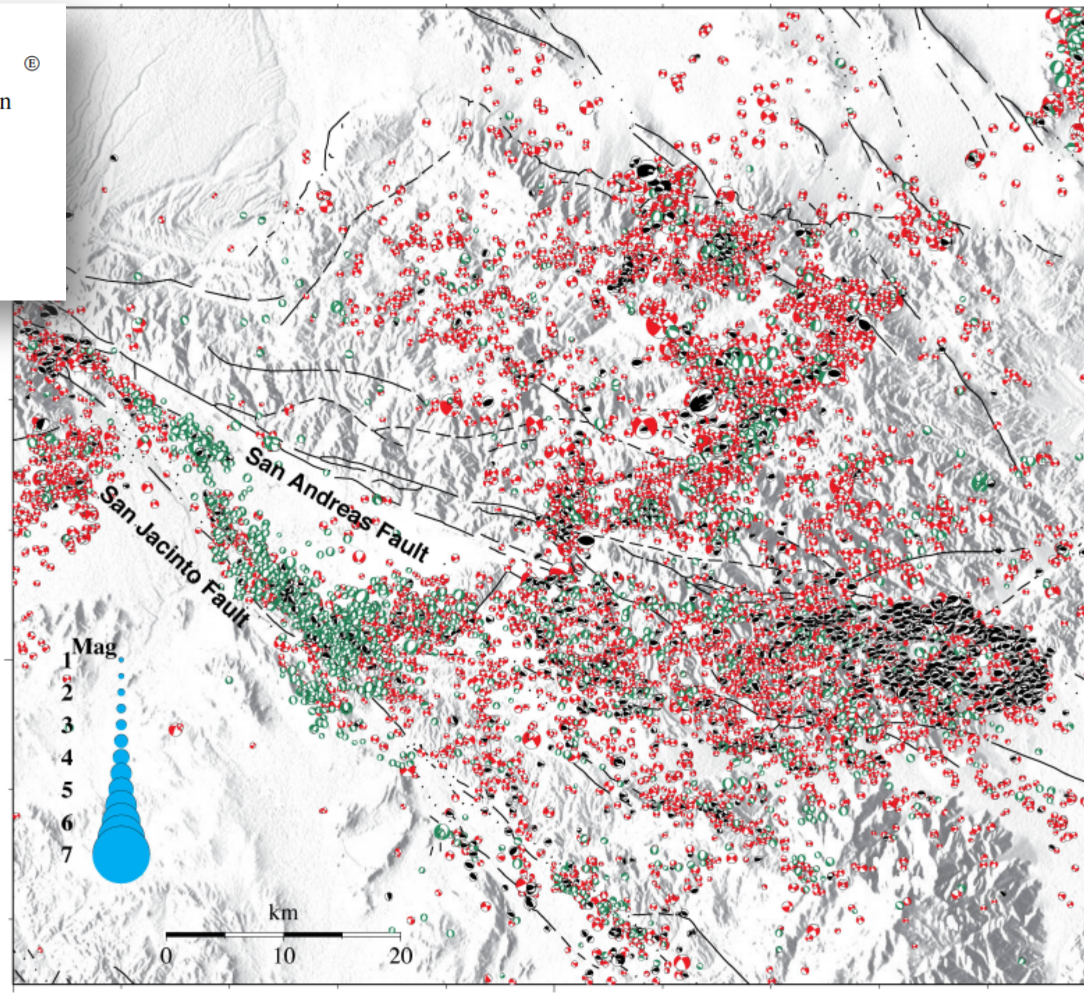


Bulletin of the Seismological Society of America, Vol. 102, No. 3, pp. 1179–1194, June 2012, doi: 10.1785/0120110311

Computing a Large Refined Catalog of Focal Mechanisms for Southern California (1981–2010): Temporal Stability of the Style of Faulting

by Wenzheng Yang, Egill Hauksson, and Peter M. Shearer

Abstract Using the method developed by Hardebeck and Shearer (2002, 2003) termed the HASH method, we calculate focal mechanisms for earthquakes that occurred in the southern California region from 1981 to 2010. When available, we use hypocenters refined with differential travel times from waveform cross correlation.



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

[*Yang et al*. 2012]

Stress Orientation Model


Geophysical Journal International

Geophys. J. Int. (2013) **194,** 100–117
Advance Access publication 2013 April 22
doi: 10.1093/gji/ggt113

The tectonic crustal stress field and style of faulting along the Pacific North America Plate boundary in Southern California

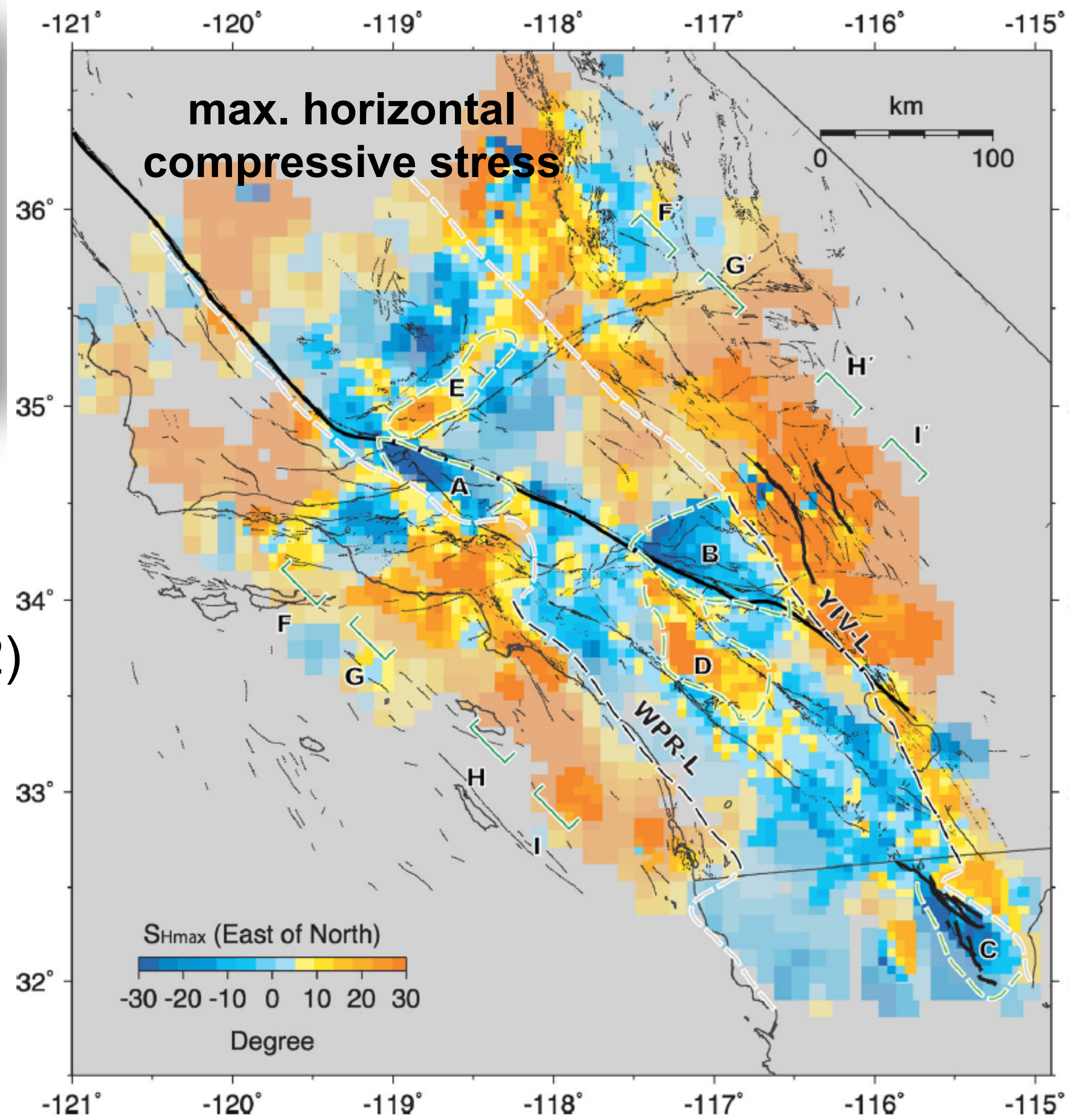
Wenzheng Yang* and Egill Hauksson
Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, CA 91125, USA. E-mail: wenzheng@gps.caltech.edu

Accepted 2013 March 19. Received 2013 March 12; in original form 2012 October 22

SUMMARY
We invert for the state of stress in the southern California crust using a catalogue of high quality earthquake focal mechanisms (1981–2010). The stress field is best resolved where seismicity

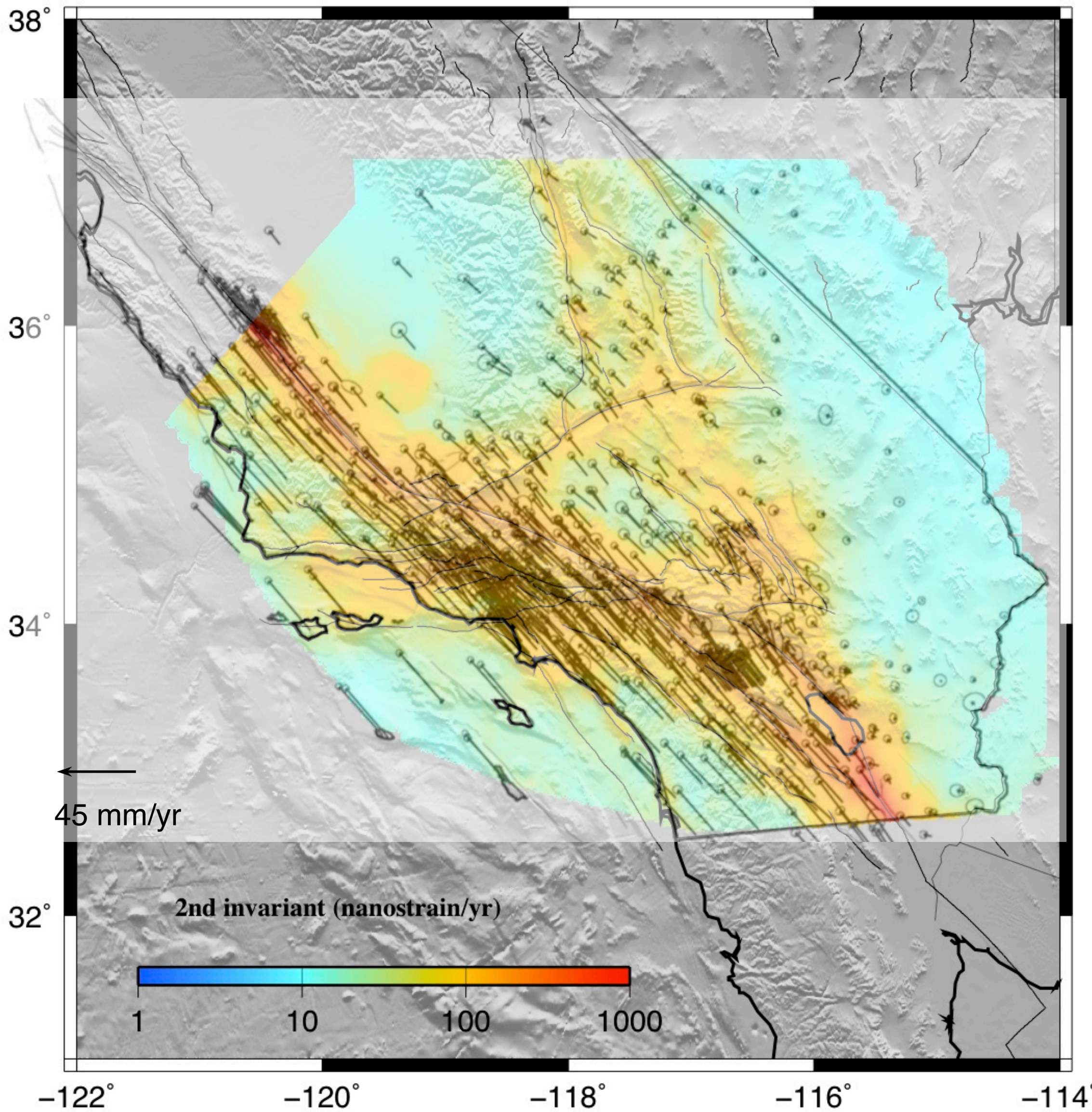
[following work of *Hardebeck and Michael* 2006 etc.]

- Inversion of *Yang et al*. (2012) focal mechanism (FM) catalog to determine crustal stress field and style of faulting



[*Yang and Hauksson, 2013*

Southern California GPS Velocity Field



Velocity to Strain Rate

$v_i\left(x_j^k\right) \pm \sigma_i^k$ vector velocity at point *k*

$i = 1,2,3 \quad j = 1,2 \quad k = 1 - N$

$\Downarrow$ 2-D interpolation and/or dislocation model

$v_i\left(x_j\right)$ - surface vector velocity (0.01˚)

$\Downarrow$ differentiation (GMT grdgradient)

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$ - 2D strain rate

principal strain rate

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

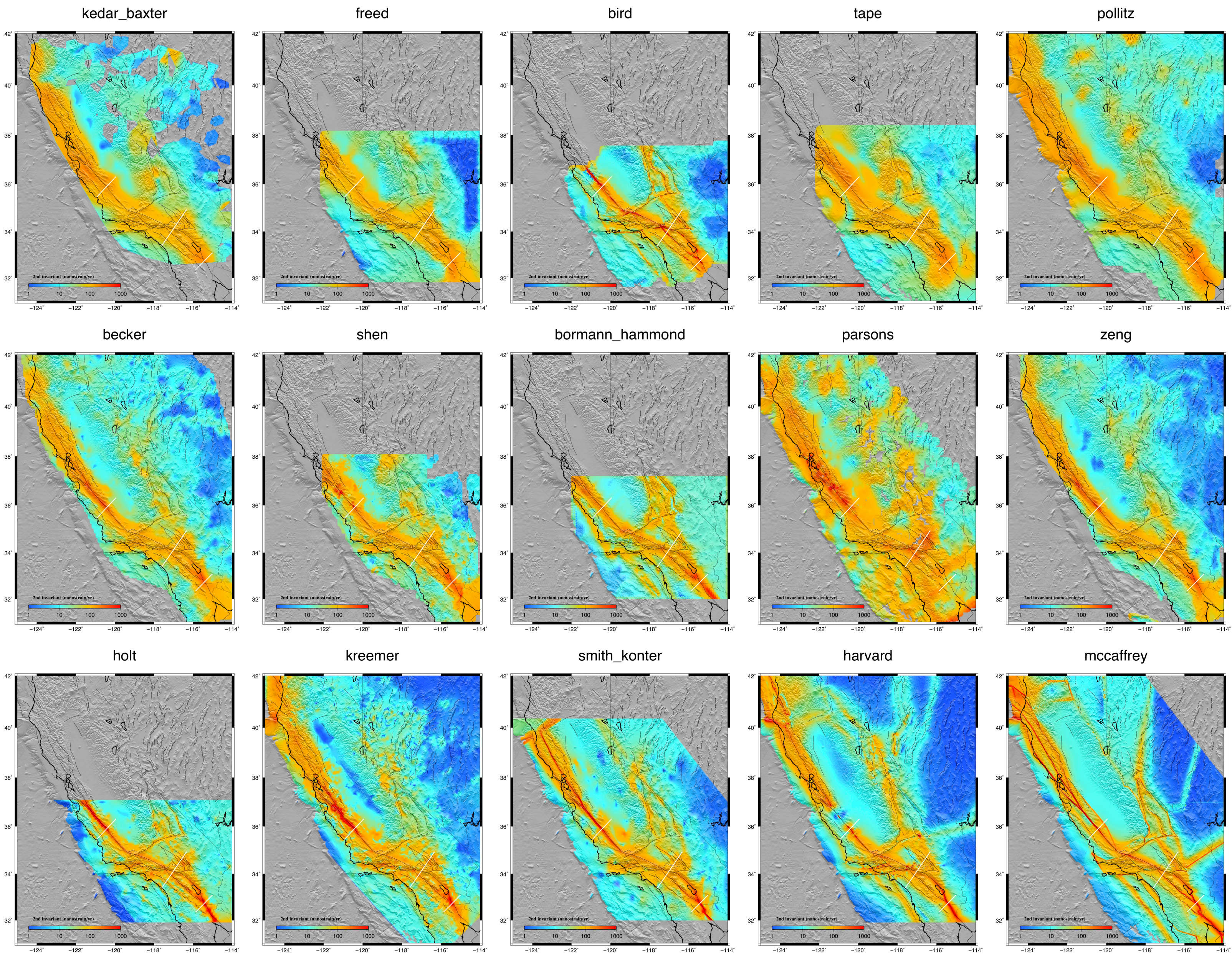
dilatation rate + maximum shear rate

second invariant

$$\dot{\varepsilon}_{II} = \left(\dot{\varepsilon}_{xx}^2 + \dot{\varepsilon}_{yy}^2 + 2\dot{\varepsilon}_{xy}^2\right)^{1/2}$$

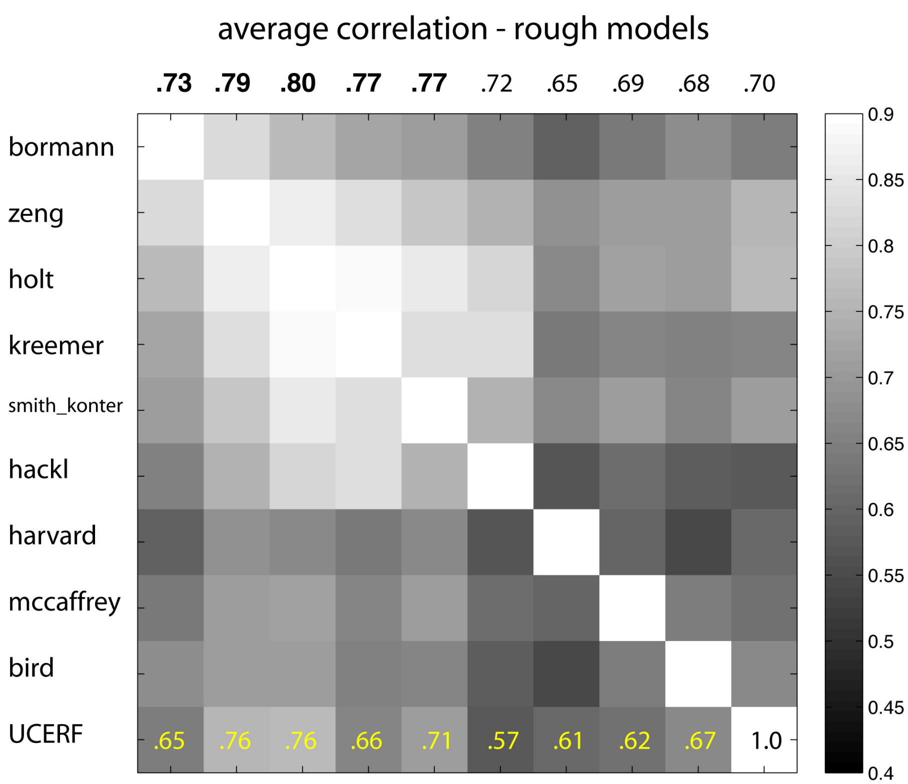
Four approaches are used:
1) isotropic interpolation;
2) interpolation guided by known faults;
3) interpolation of a rheologically-layered lithosphere, and
4) model fitting using deep dislocations in an elastic layer or half space.

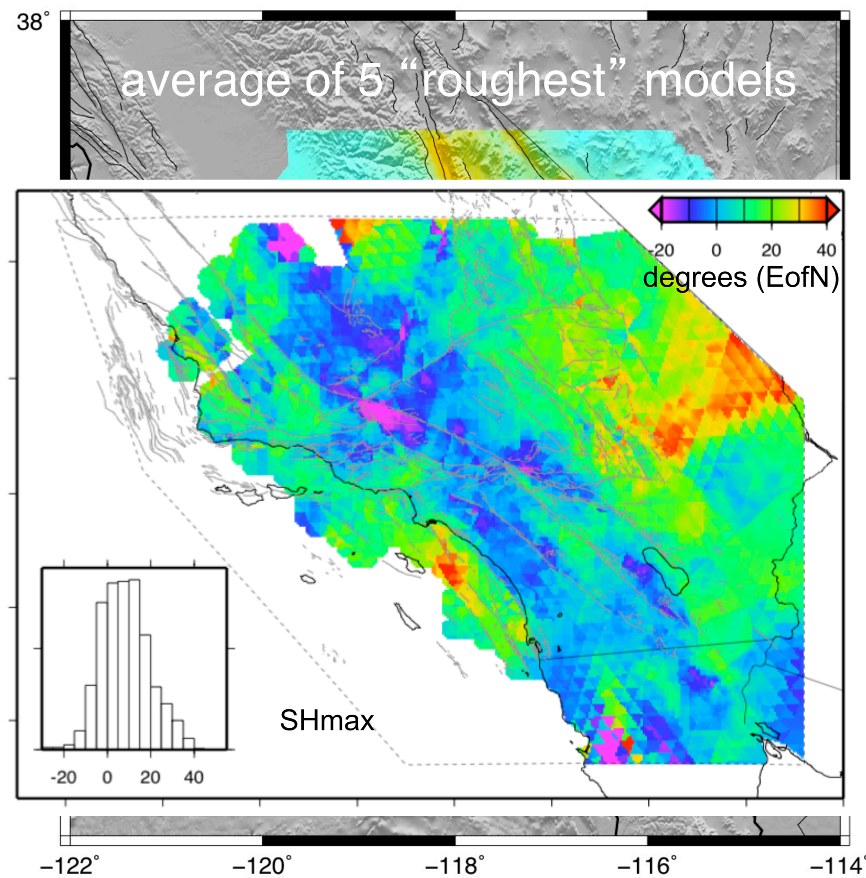
Community Strain Rate Models



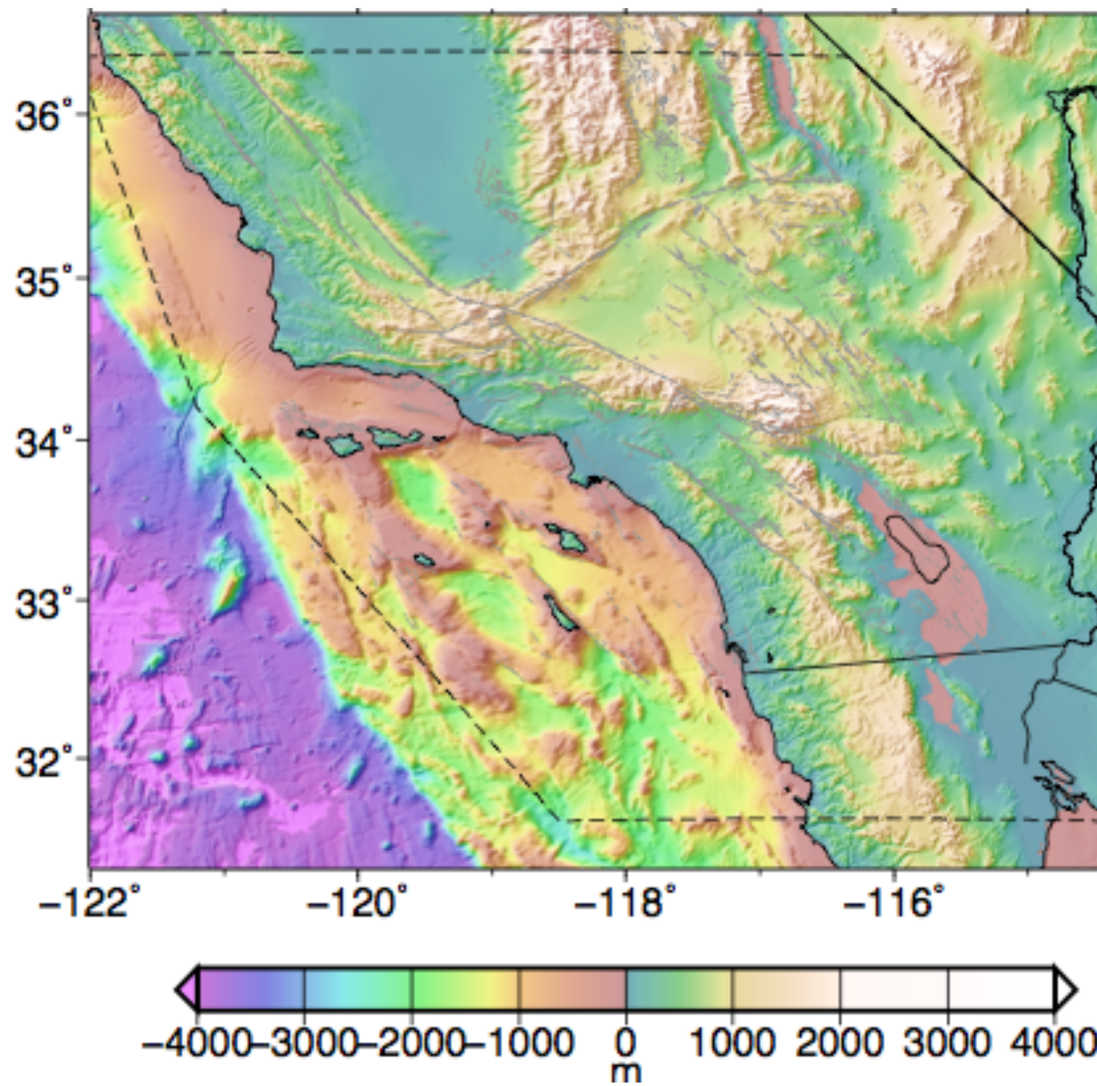
Community Strain/Stress Rate Models

• 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.



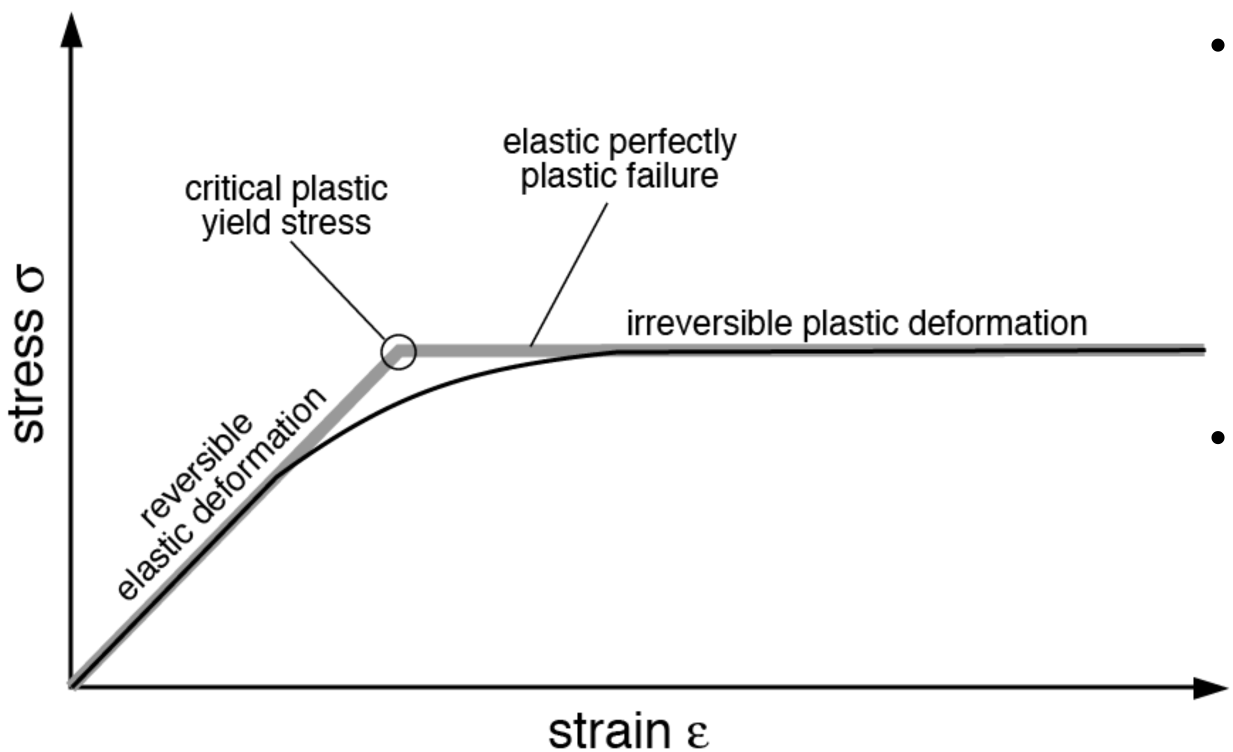


Southern California Topography



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

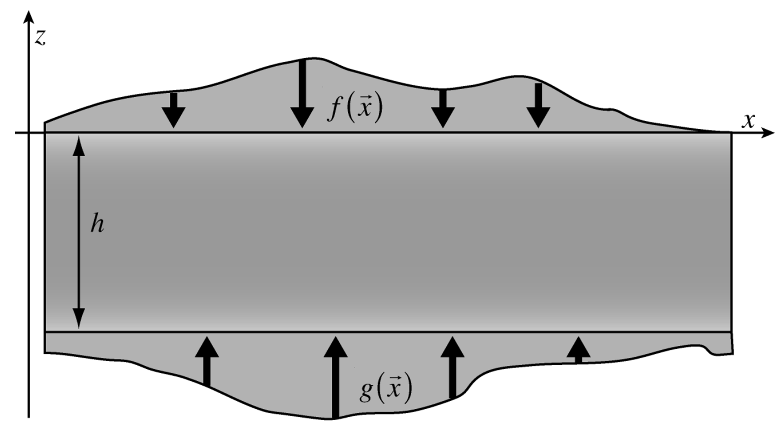


- Stress magnitudes could be higher
  - e.g., if strengthening occurred since topography was built
- Stress magnitudes could not be lower
  - otherwise the existing topography would have relaxed away

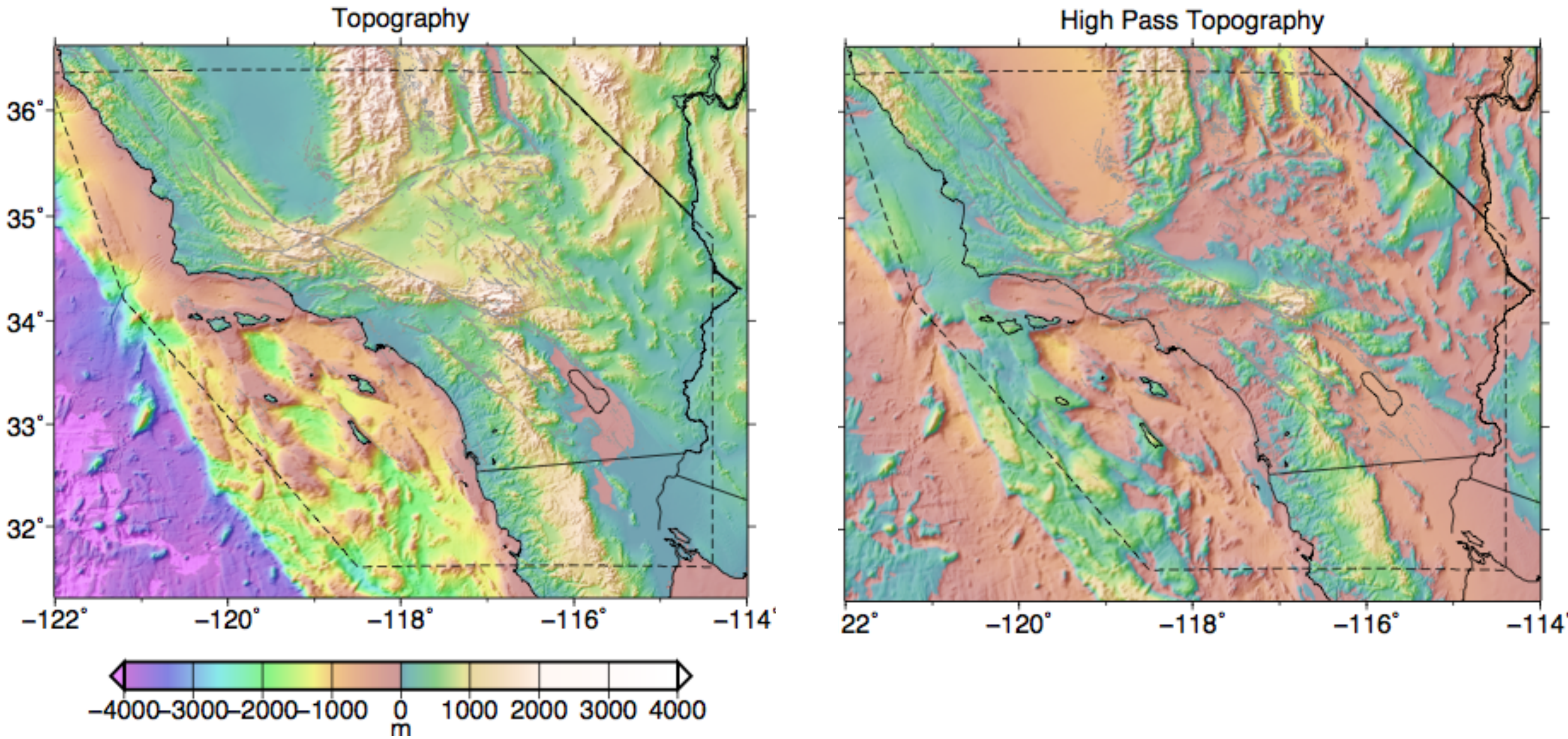
3-D stress within a thick elastic plate

- 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 100º-140º) 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)

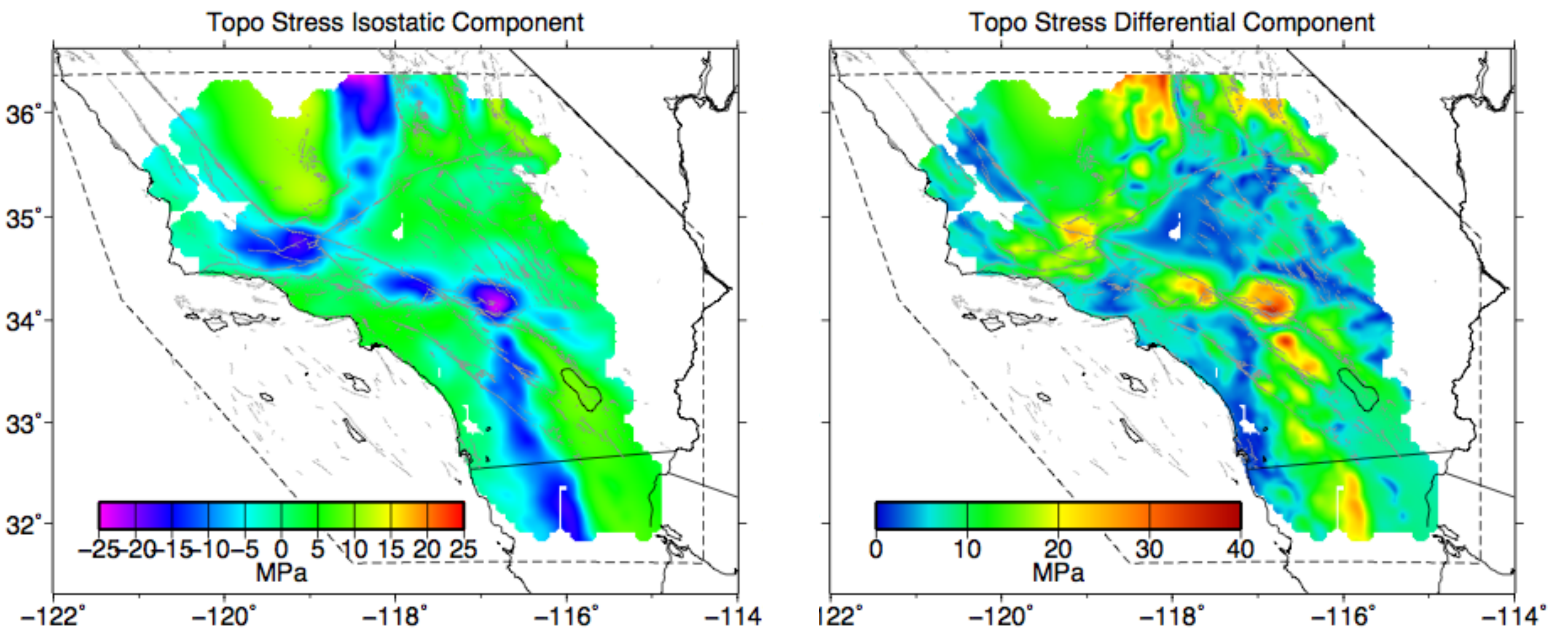


Southern California Topography



- At short wavelengths (< ~350 km), variations in topography are supported by stresses within the crust

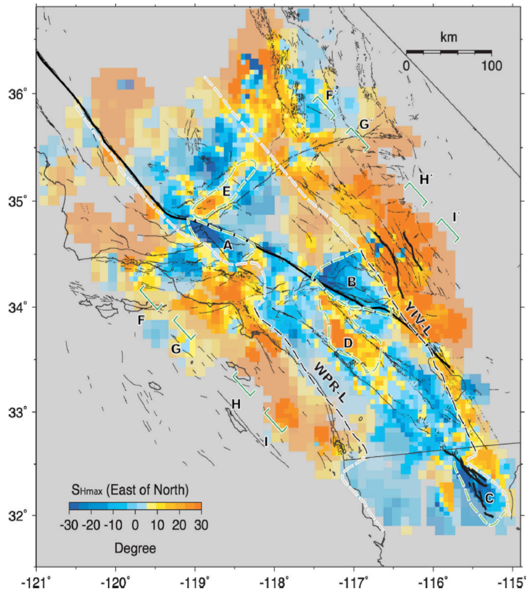
Topography Stress Model



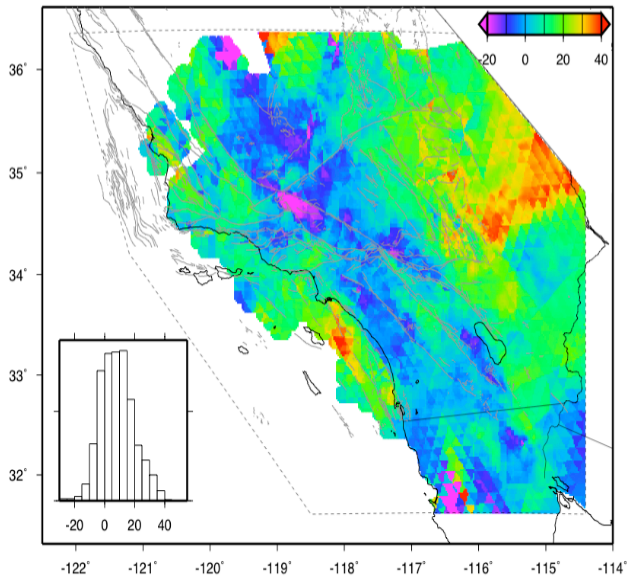
[Lutrell et al. SCEC 2012]

- 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

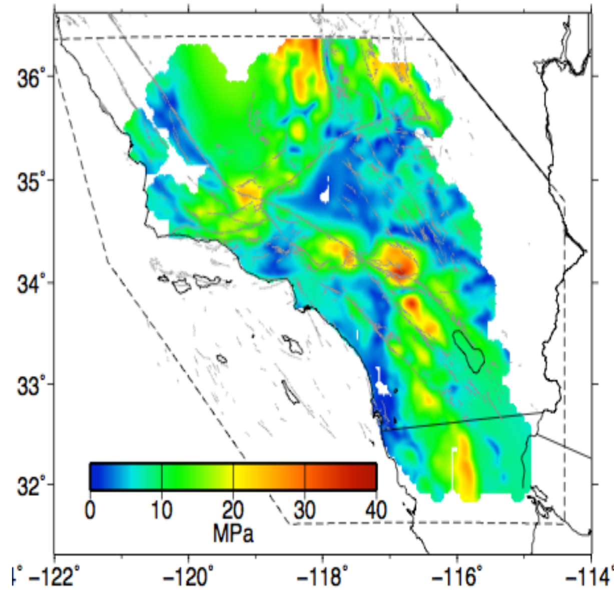
Summary: “Stress” Models



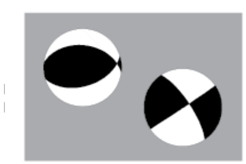
Focal mechanisms,
in situ stress field orientation



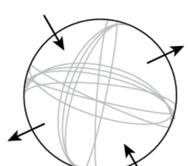
GPS strain rates,
fault stress accumulation rates



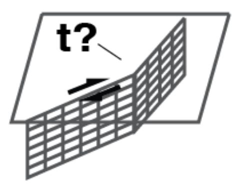
Locally compensated
topography



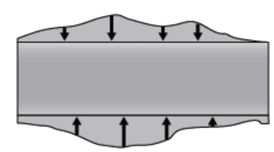
EARTHQUAKE FOCAL MECHANISM ORIENTATION



IN SITU STRESS FIELD ORIENTATION



FAULT STRESS ACCUMULATION RATE



LOCAL COMPENSATED TOPOGRAPHY STRESS

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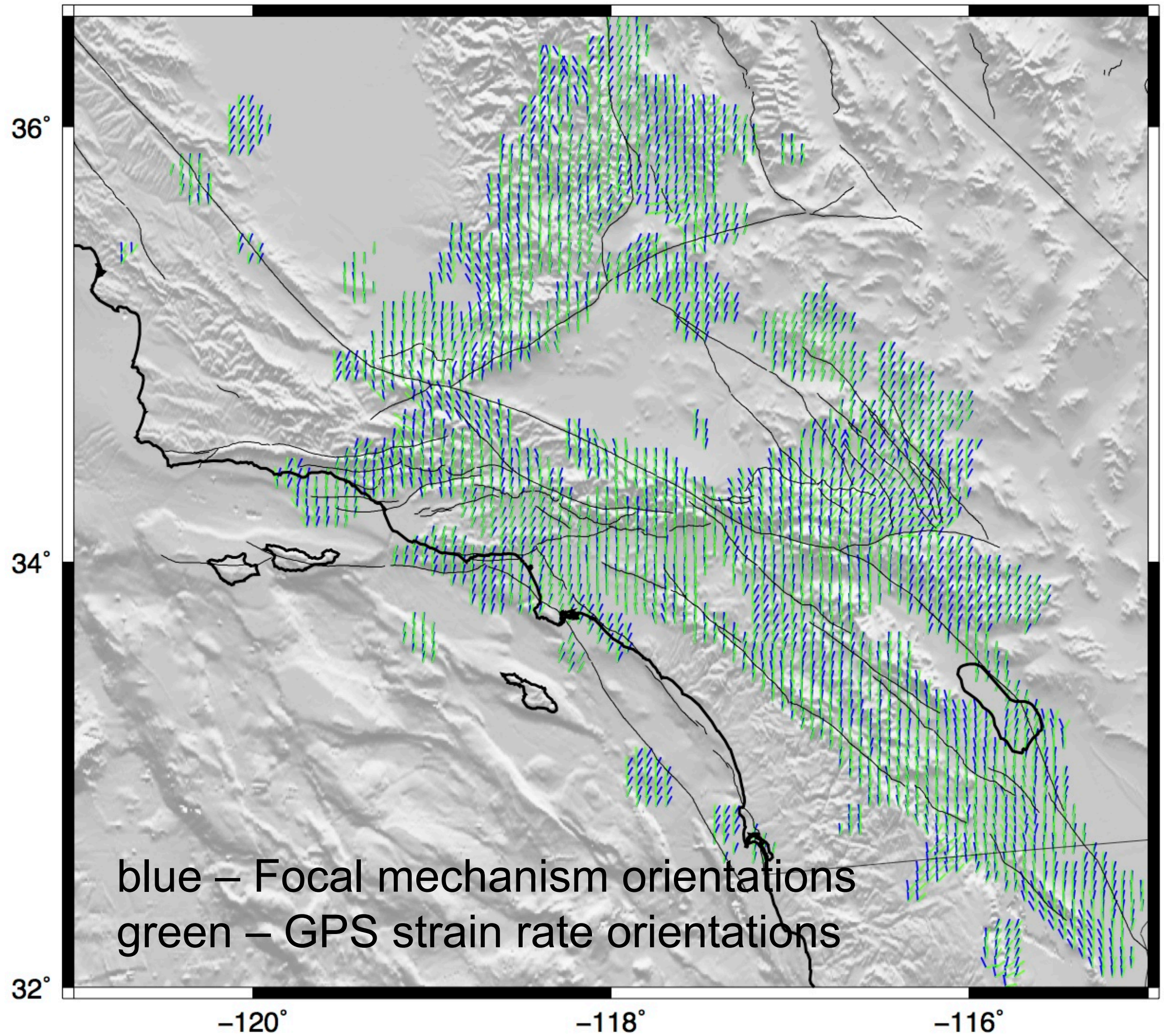
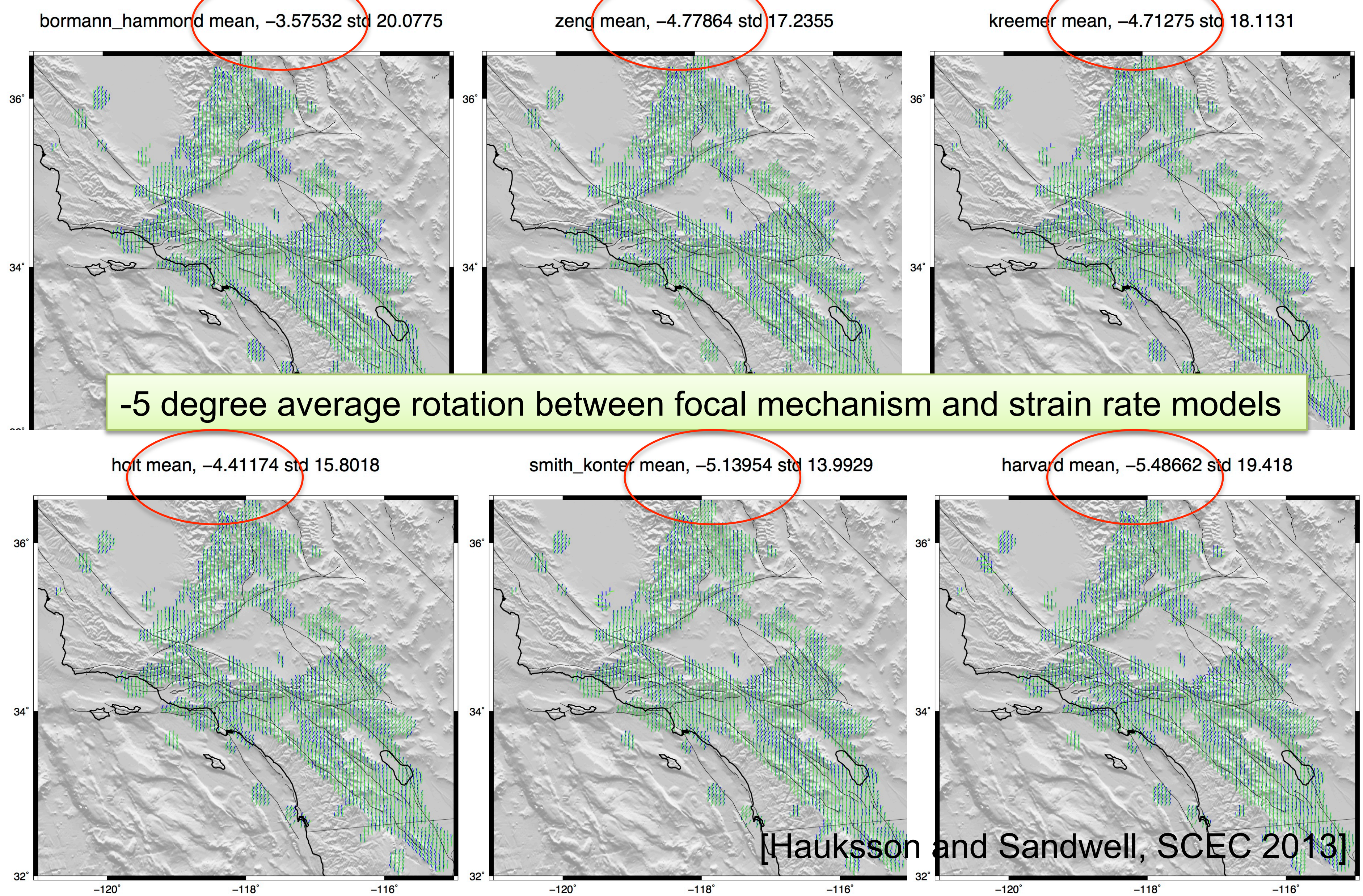
SHmax comparison: Seismology vs. Geodesy



[Hauksson and Sandwell, SCEC 2013]

SHmax Comparison



-5 degree average rotation between focal mechanism and strain rate models

[Hauksson and Sandwell, SCEC 2013]

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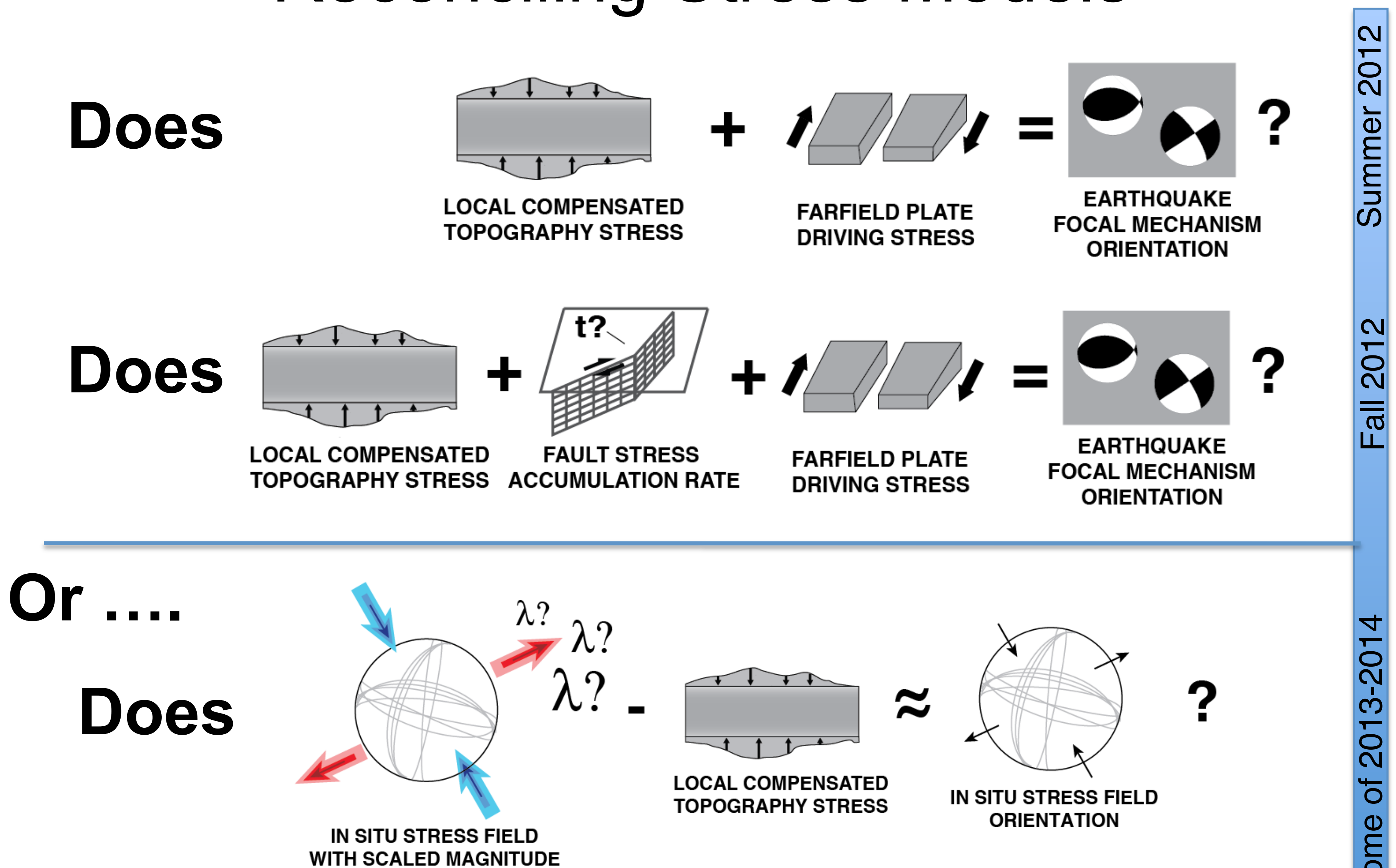
Reconciling Stress Models



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

Topography & regional stress (mid-ocean ridges)

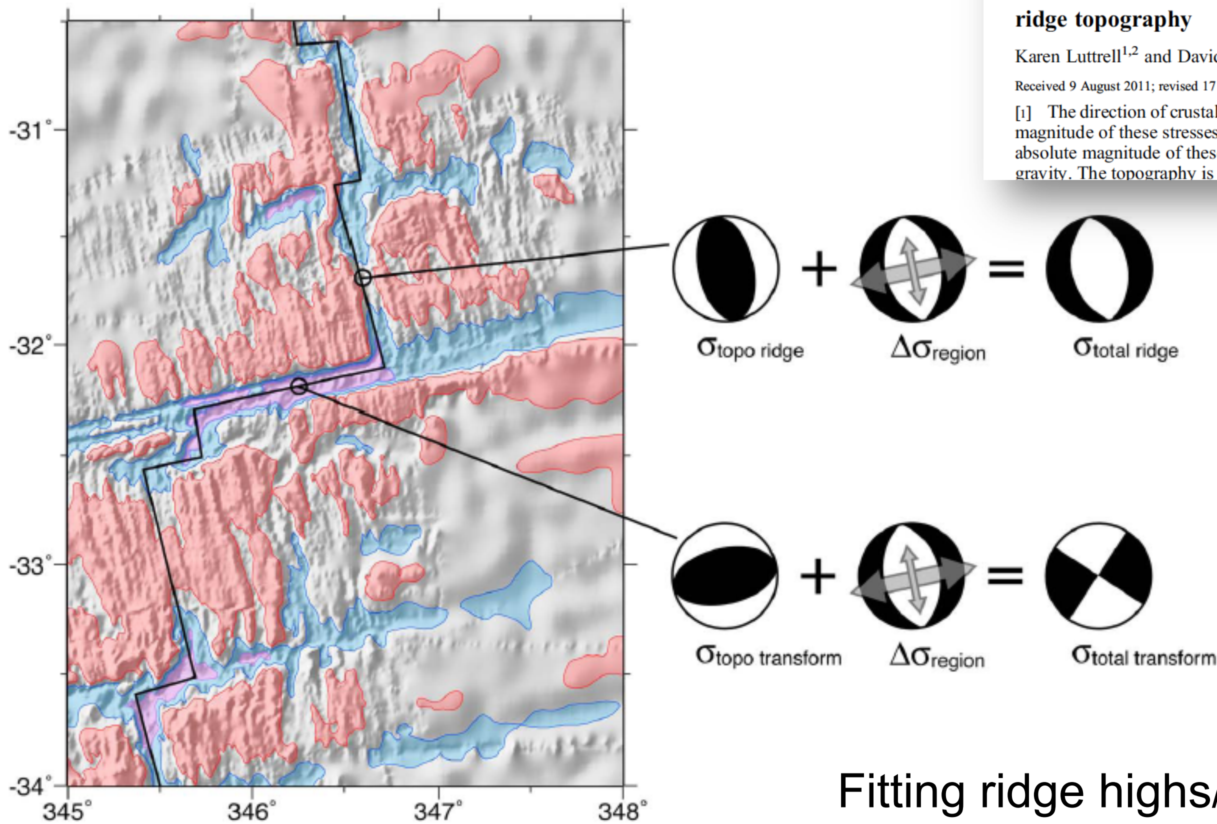
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, B04402, doi:10.1029/2011JB008765, 2012

Constraints on 3-D stress in the crust from support of mid-ocean ridge topography

Karen Luttrell[1,2] and David Sandwell[1]

Received 9 August 2011; revised 17 December 2011; accepted 19 February 2012; published 10 April 2012.

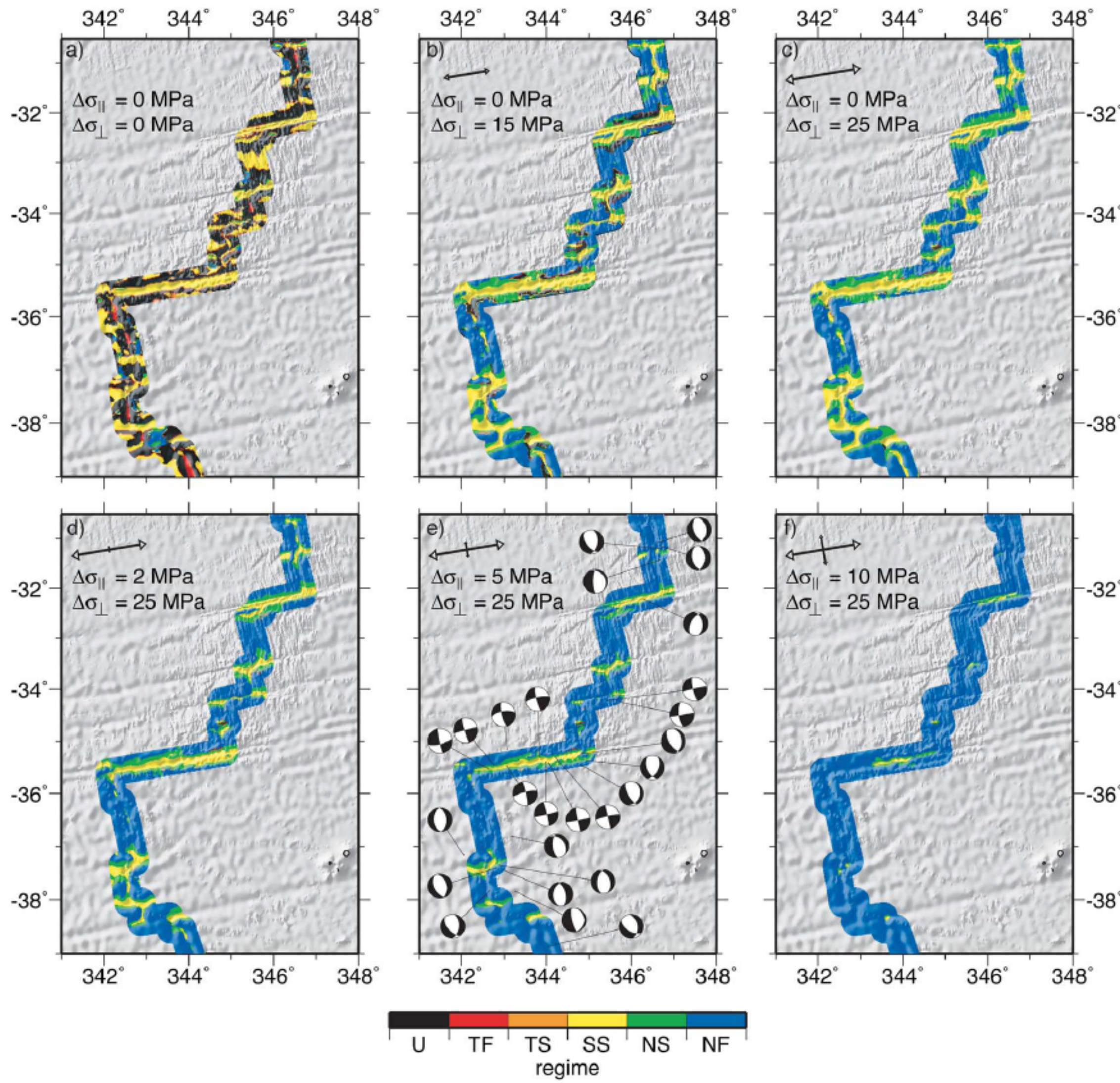
[1] The direction of crustal stresses acting at mid-ocean ridges is well characterized, but the magnitude of these stresses is poorly constrained. We present a method by which the absolute magnitude of these stresses may be constrained using seafloor topography and gravity. The topography is divided into a short-wavelength portion, created by rifting,



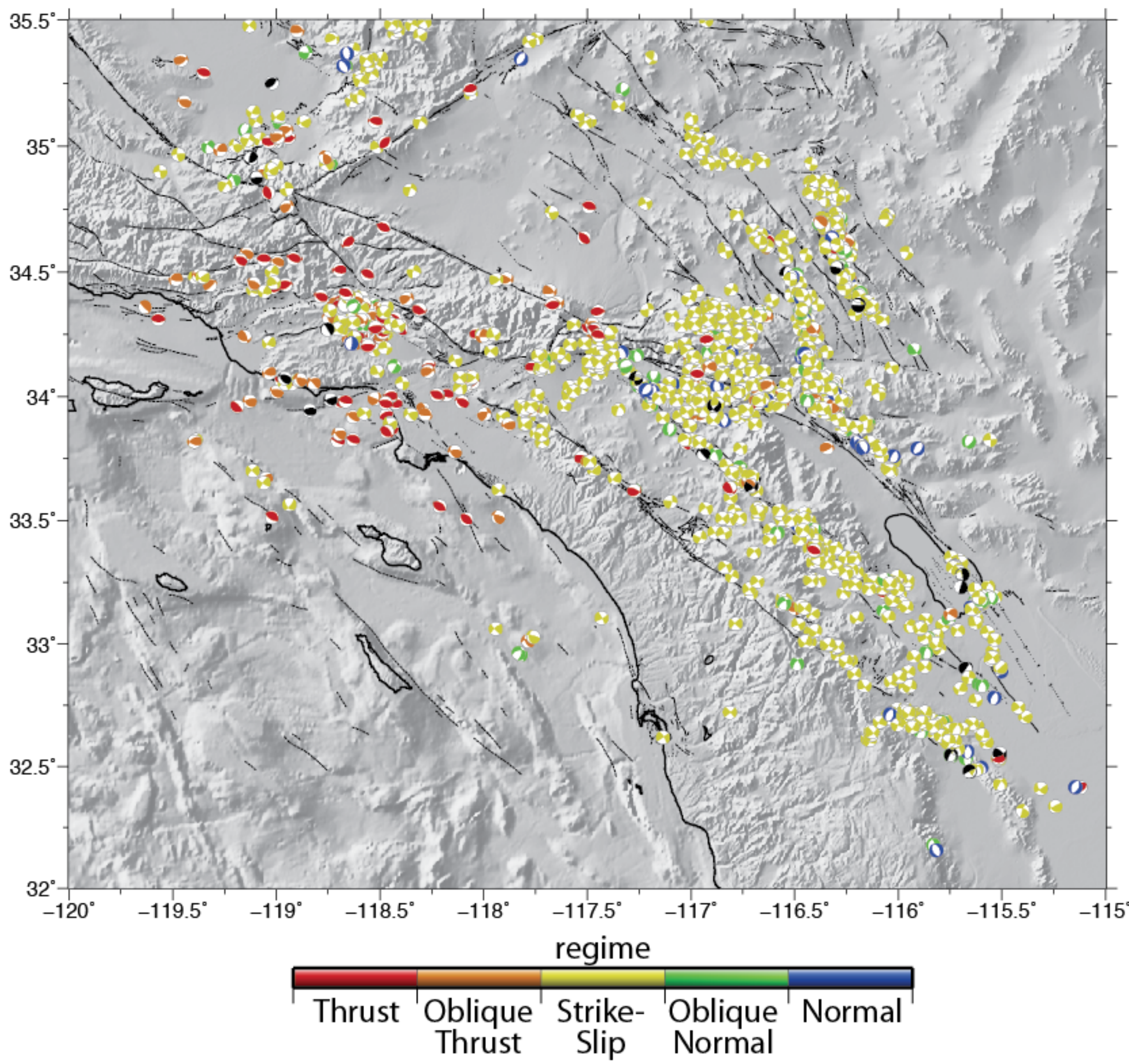
Fitting ridge highs/lows and transform lows/highs simultaneously with a single consistent 2-D stress field

Topography & Plate Driving Stress (mid-ocean ridges)

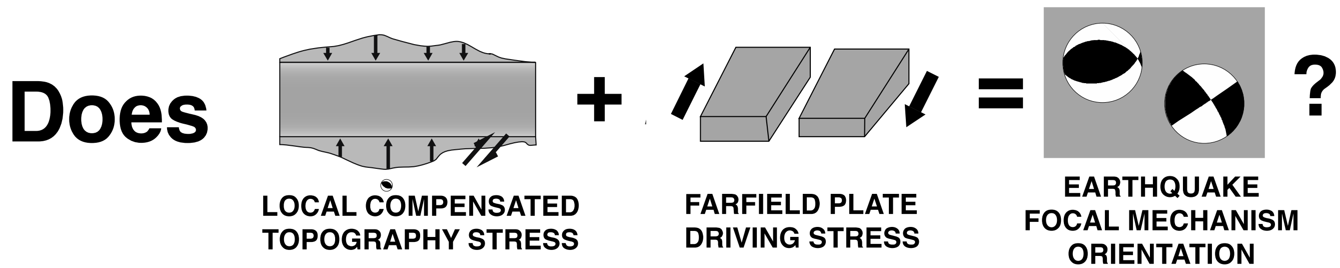
- Stress from topography alone is in the completely wrong regime
- Adding a regional “plate driving” stress brings the “total” stress into the correct regime
- → Normal faulting along ridges and strike-slip faulting along transforms



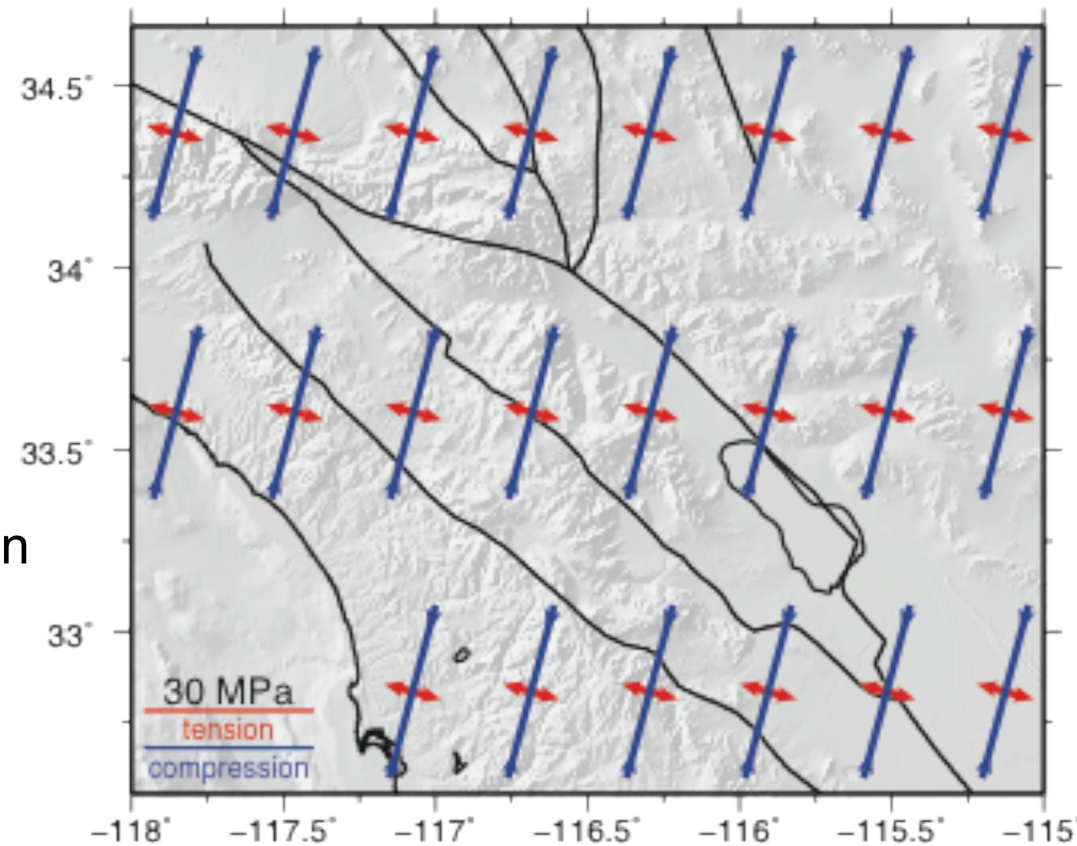
A challenge: Varied faulting-type plate boundary (Southern California)



Best-fitting plate driving stress?



- 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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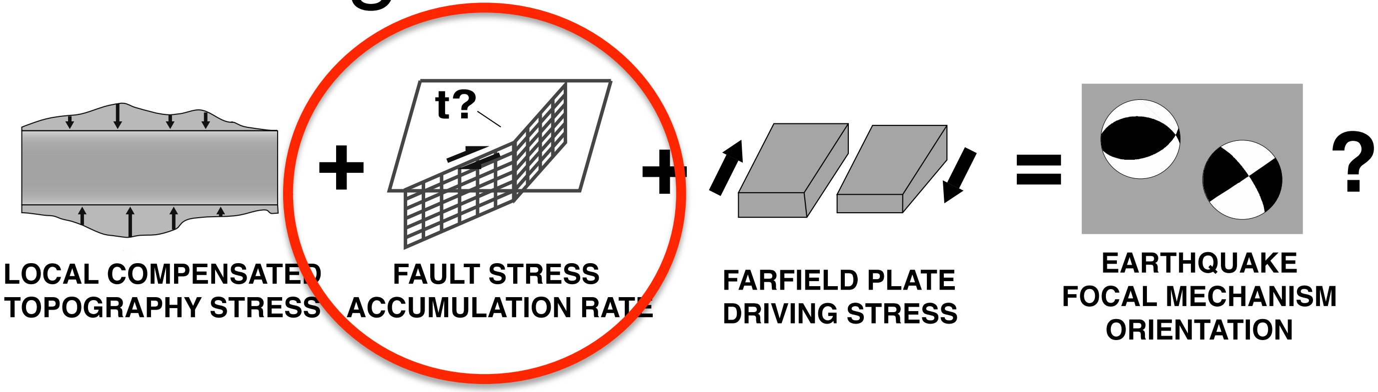
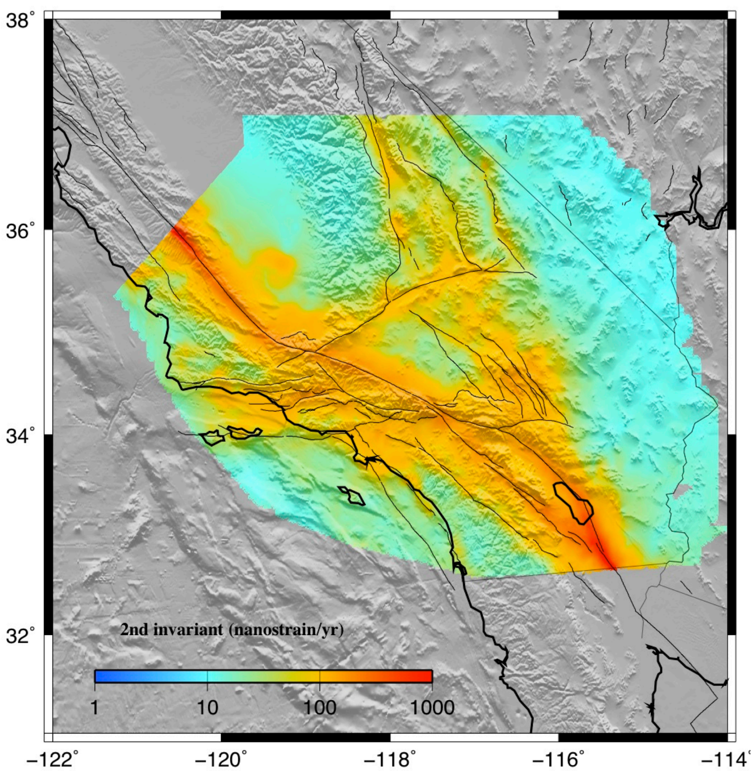
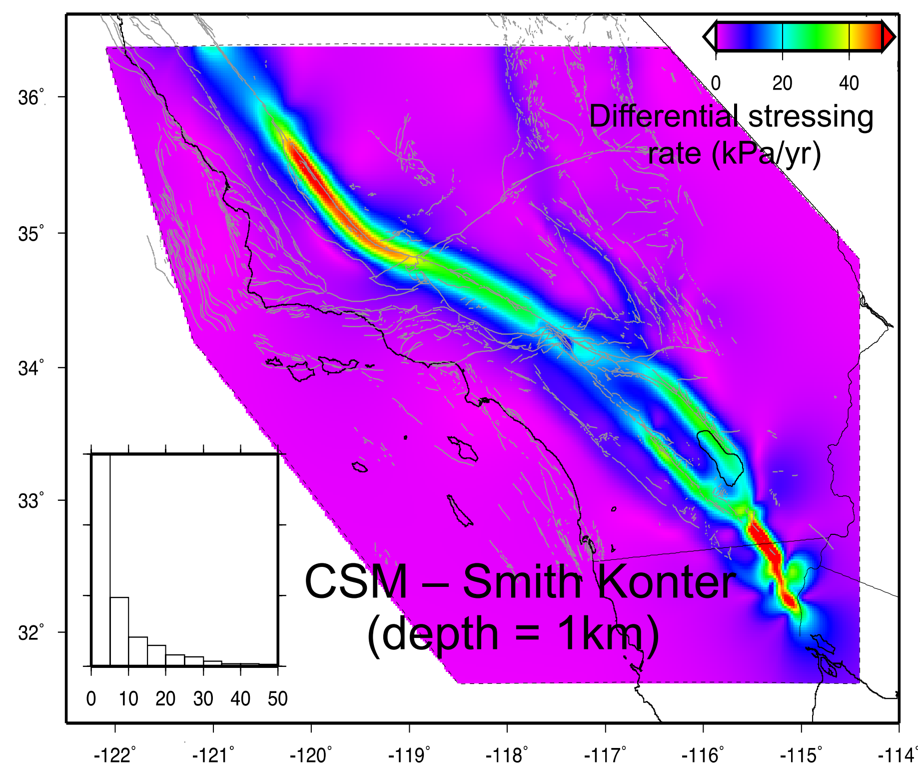
Fault loading stress contributions?

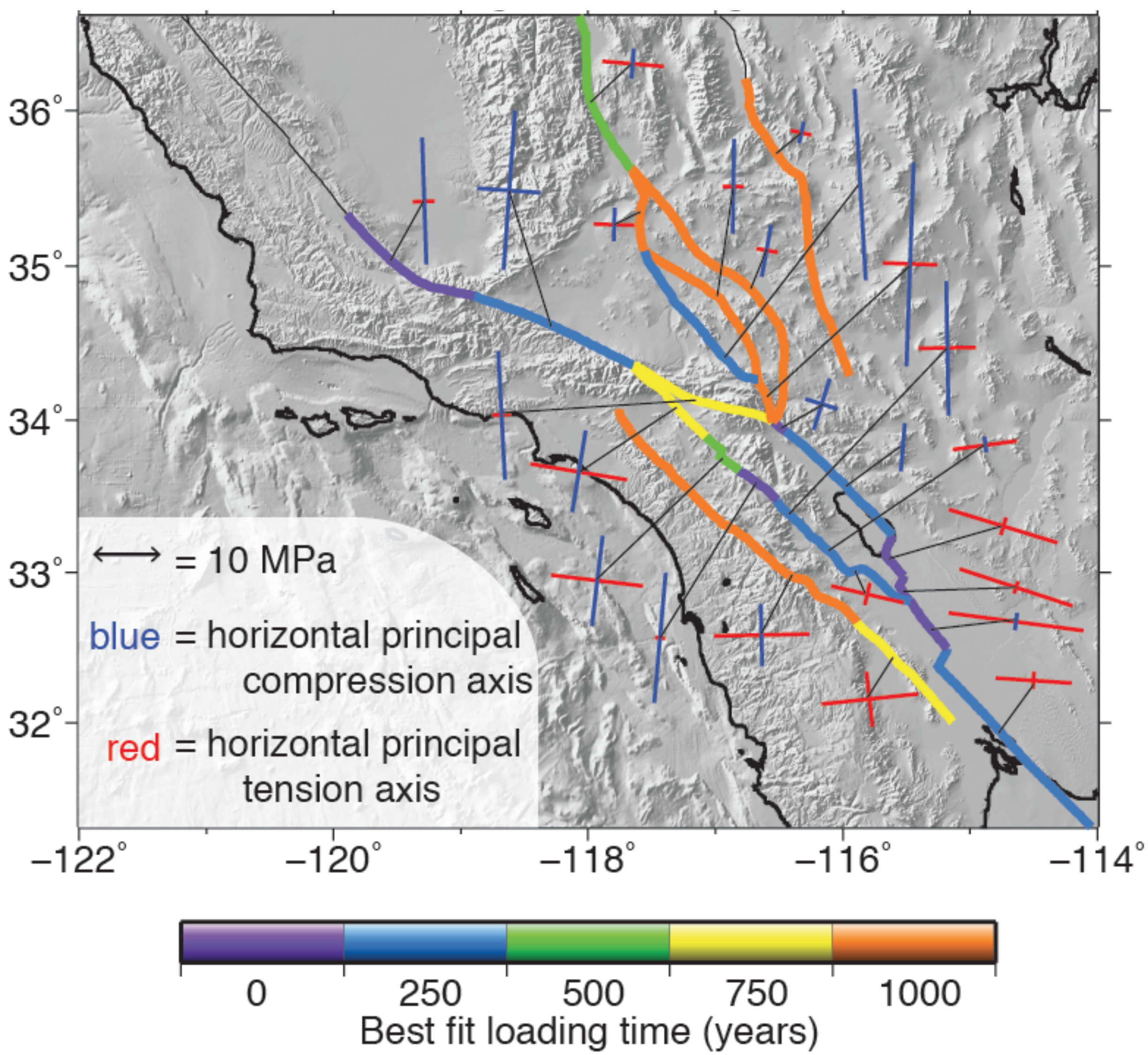
Does







Best-Fitting Stress Loading Times



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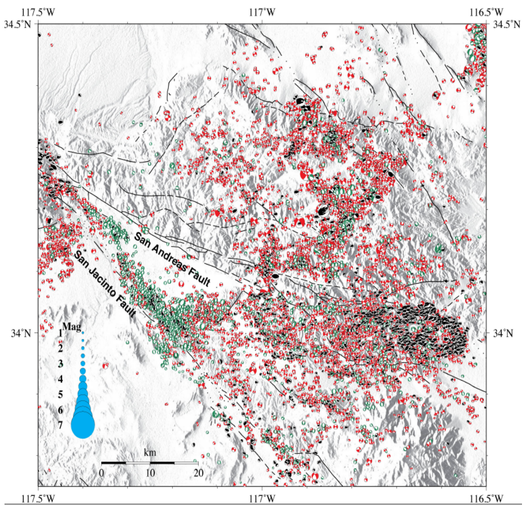
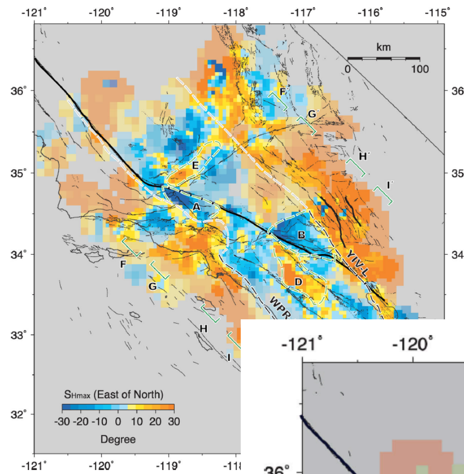
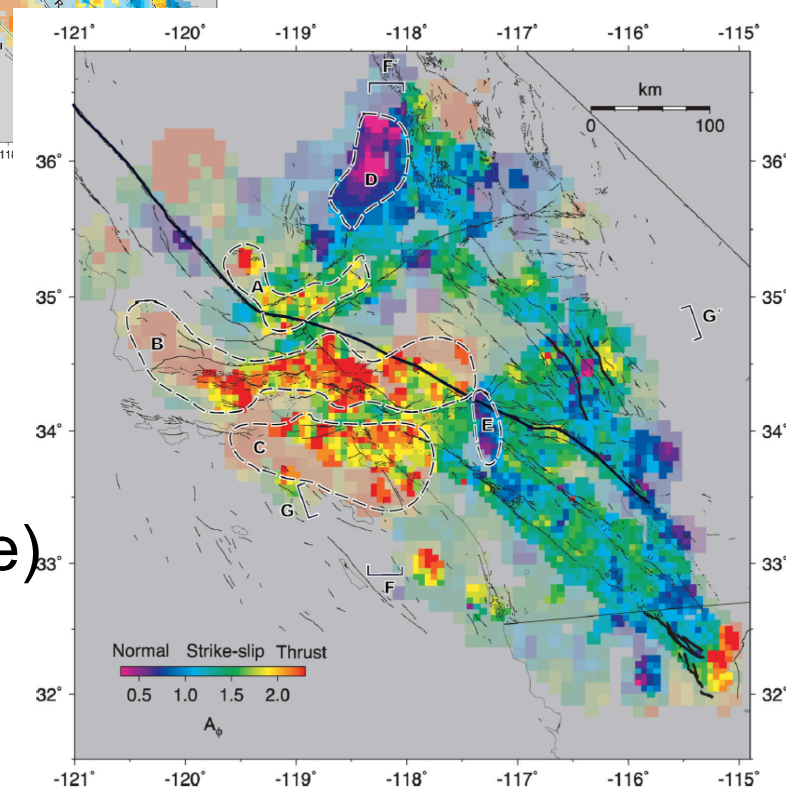
Revisiting the Focal Mechanism (FM) Stress Model



[Yang and Haukkson, 2013]



max. horizontal compressive stress



"Aphi"
(faulting style)

Understanding stress field orientation & faulting regime

phi (stress ratio)

$$= \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$

Aphi (style of faulting)

$$= \begin{cases} phi & \text{if } \sigma_3 \text{ is most vertical (normal)} \\ 2 - phi & \text{if } \sigma_2 \text{ is most vertical (strike-slip)} \\ 2 + phi & \text{if } \sigma_1 \text{ is most vertical (thrust)} \end{cases}$$

Normal [0-1] Strike-slip [1-2] Thrust [2-3]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, B11310, doi:10.1029/2005JB004144, 2006

Damped regional-scale stress inversions: Methodology and examples for southern California and the Coalinga aftershock sequence

Jeanne L. Hardebeck[1] and Andrew J. Michael[1]

Received 3 November 2005; revised 29 June 2006; accepted 26 July 2006; published 29 November 2006.

[1] We present a new focal mechanism stress inversion technique to produce regional-scale models of stress orientation containing the minimum complexity necessary to fit the data. Current practice is to divide a region into small subareas and to independently fit a

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. B13, PAGES 11,517–11,526, DECEMBER 10, 1984

Determination Of Stress From Slip Data: Faults And Folds

ANDREW J. MICHAEL

Geophysics Department, Stanford University, California

A new technique is derived to invert slickenside data for the stress field that caused the faulting episode. This inversion is simplified by the assumption that the magnitude of the tangential traction on the various fault planes, at the time of rupture, is similar. Study of three normal faulting regimes

Tectonophysics, 56 (1979) T17—T26 T17

Letter Section

Determination of the mean principal directions of stresses for a given fault population

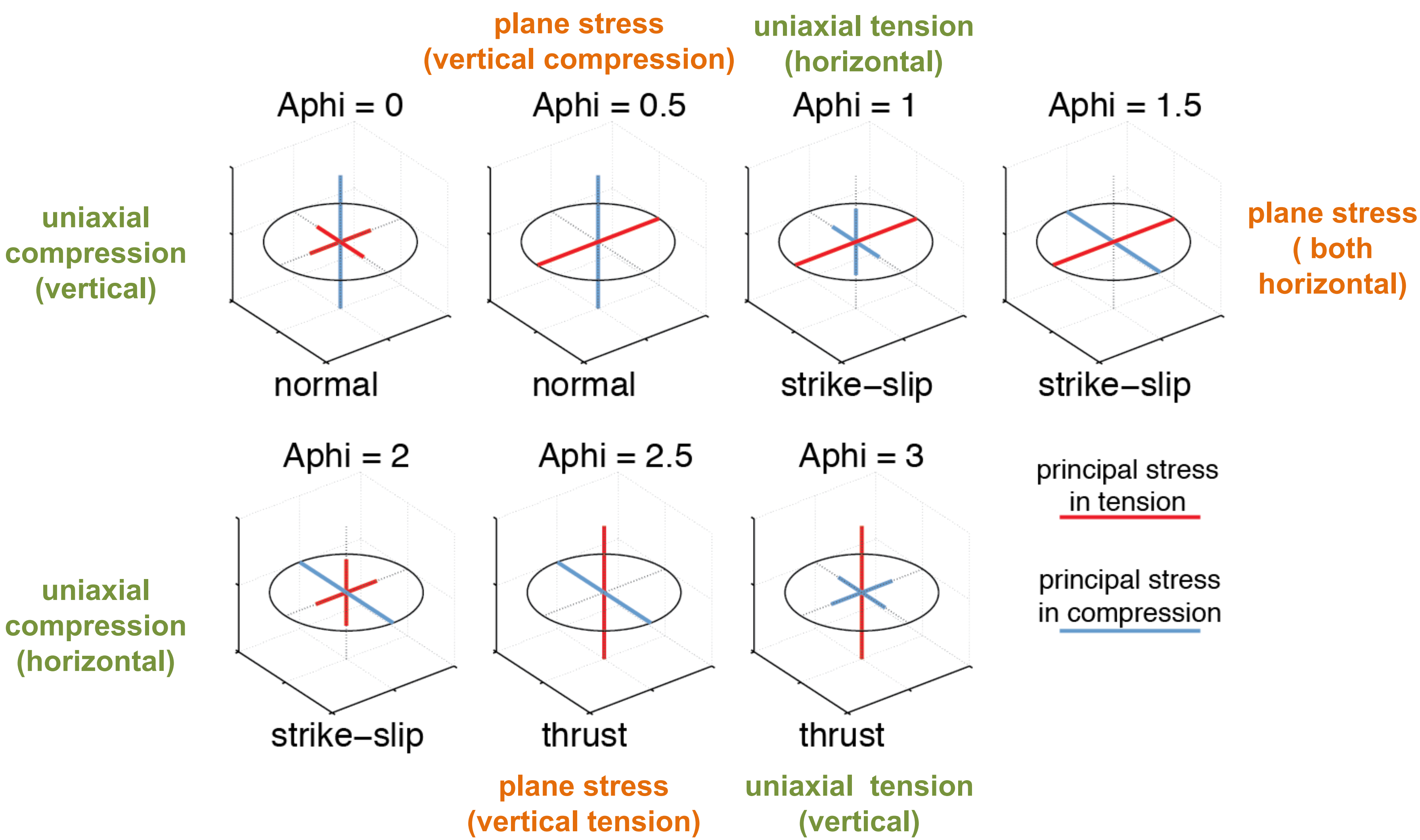
JACQUES ANGELIER

Laboratoire de Géodynamique, Département de Géotectonique, Université de Paris VI, 75230 Paris, Cédex 05 (France)

(Received February 9, 1979; revised edition accepted April 19, 1979)

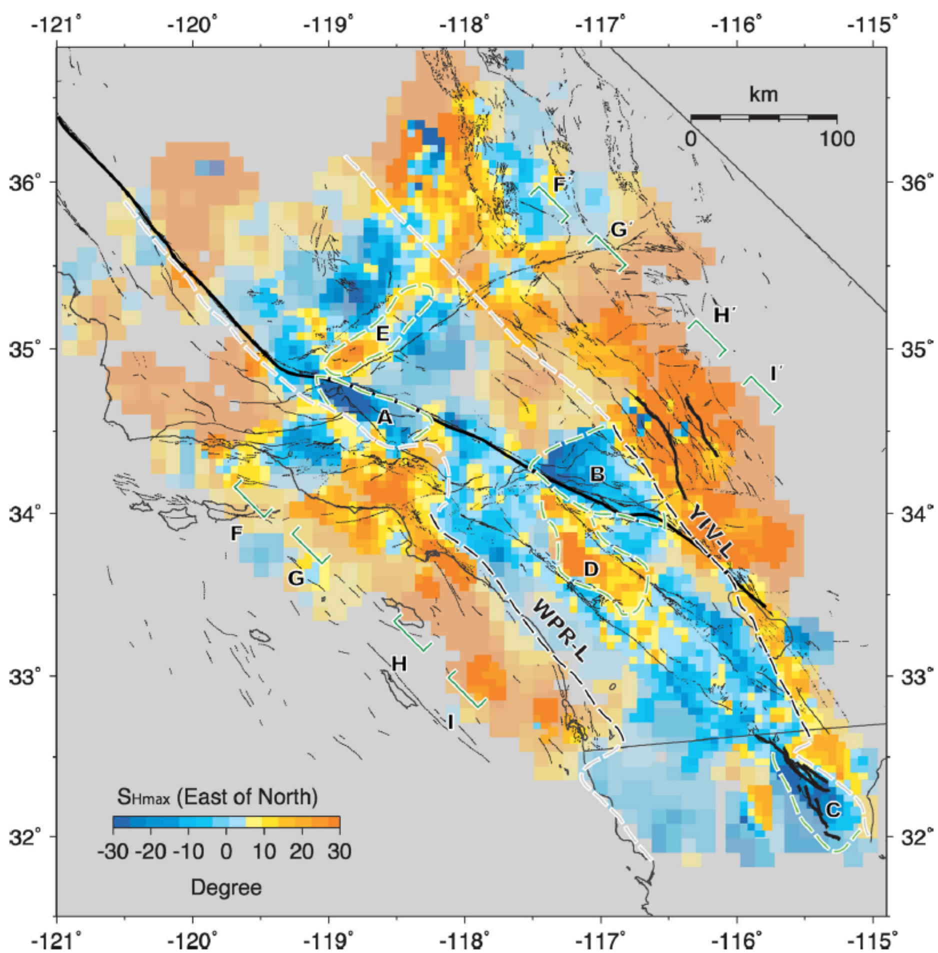
Aphi

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

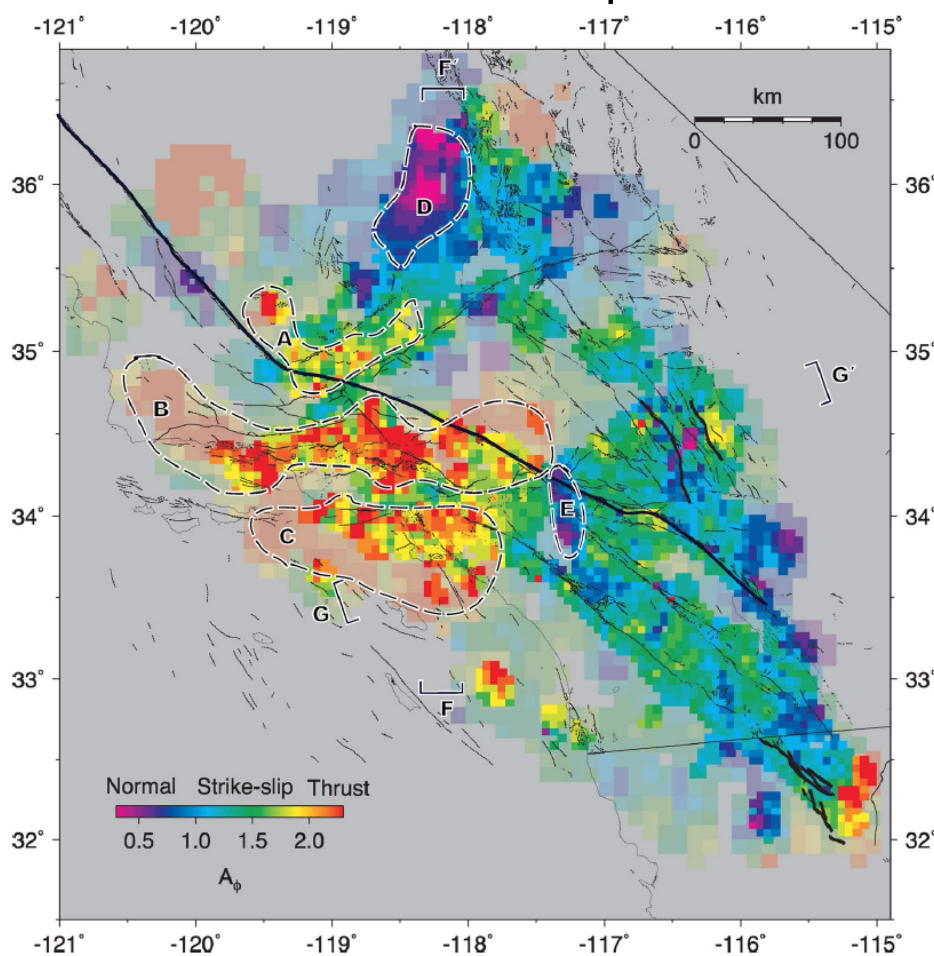


3D in situ stress orientation model
(from focal mechanisms -- FM)

Inverted Model: SHmax

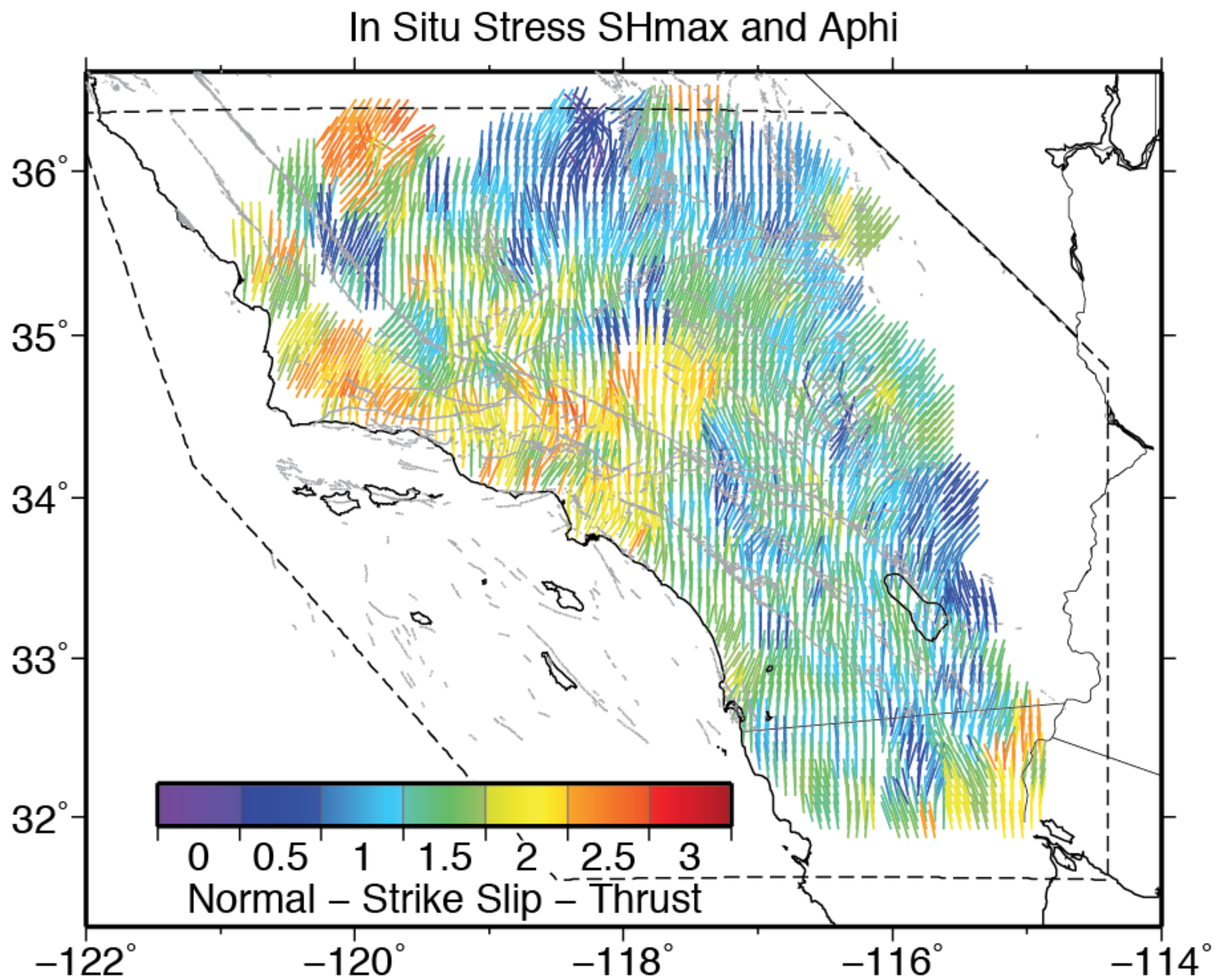


Inverted Model: Aphi

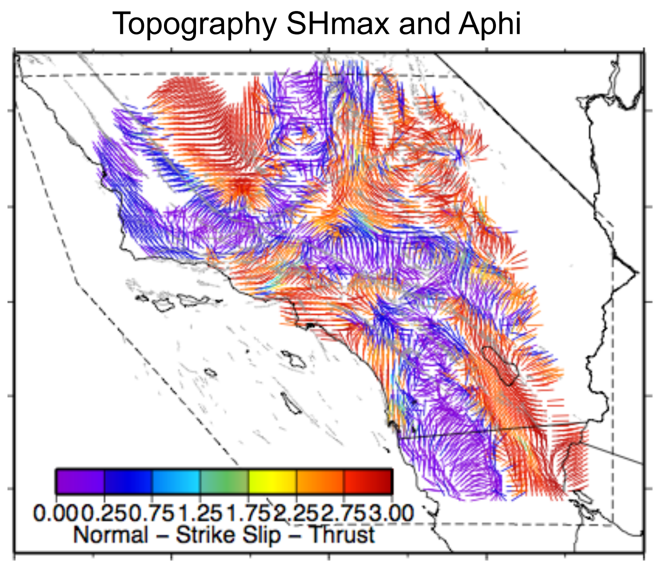


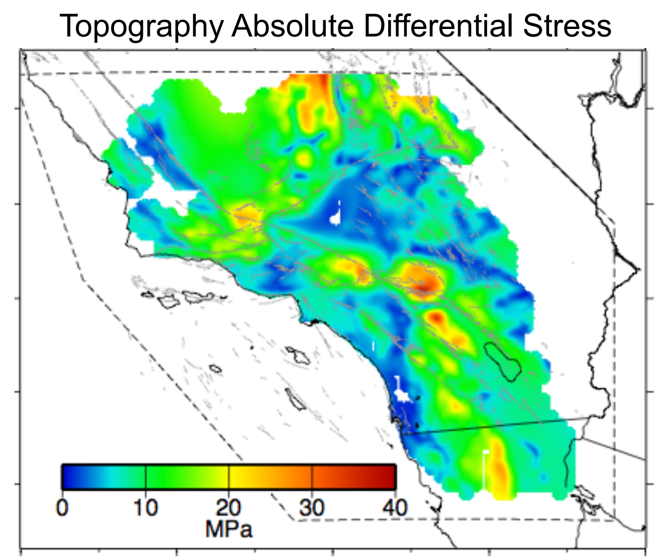
[Yang and Haukson, 2013]

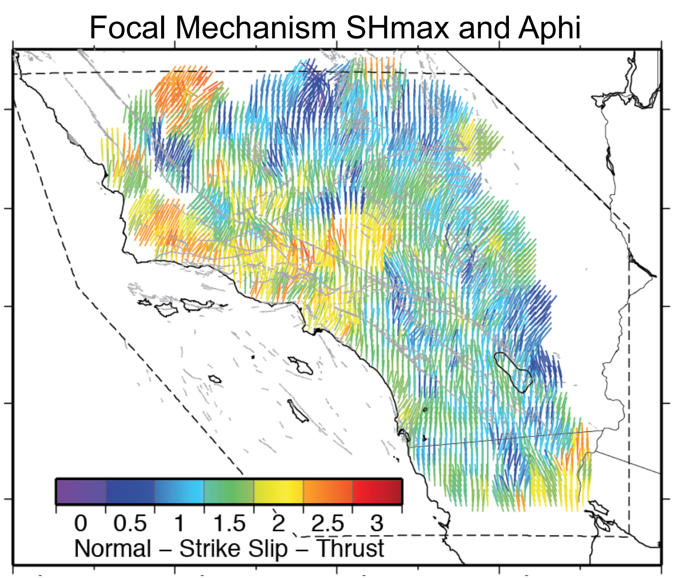
3D in situ stress orientation model
(from focal mechanisms -- FM)

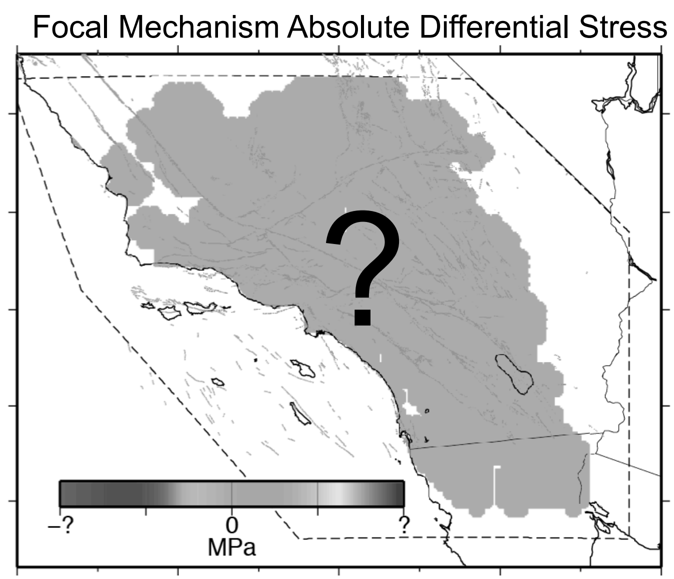


Topo & Focal Mechanism Stress Models



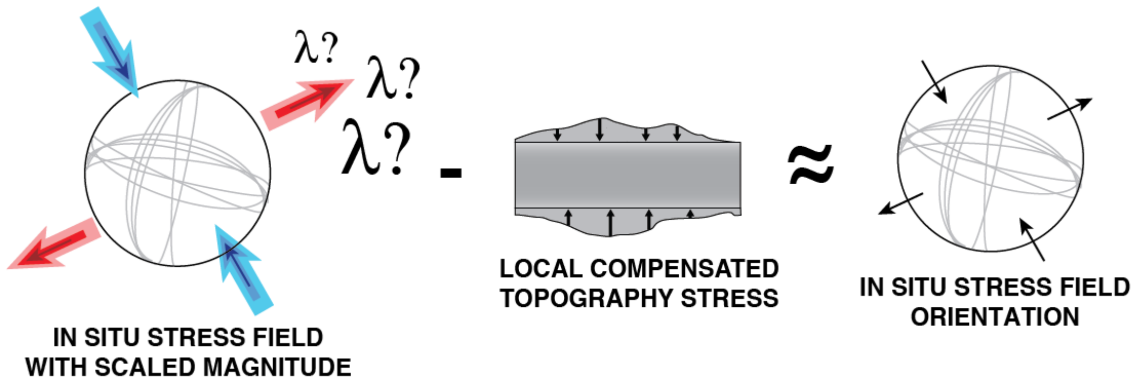






Using Topographic Stress to Estimate Minimum In Situ Stress Magnitude

Does



?

$$[\ \lambda\ FMij - Tij\ ]_{orientation} \approx [\ FMij\ ]_{orientation}$$

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

Ways to assess goodness-of-fit of 3D tensor orientations (A,B)

SHdot

$$= \vec{v}_{SH\max_A} \cdot \vec{v}_{SH\max_B}$$

Range [0,1], 1 indicates perfect fit

dAphi

$$= Aphi_A - Aphi_B$$

Range [-3,3], 0 indicates perfect fit

Tdot

$$= \frac{A:B}{\sqrt{A:A}\sqrt{B:B}}$$

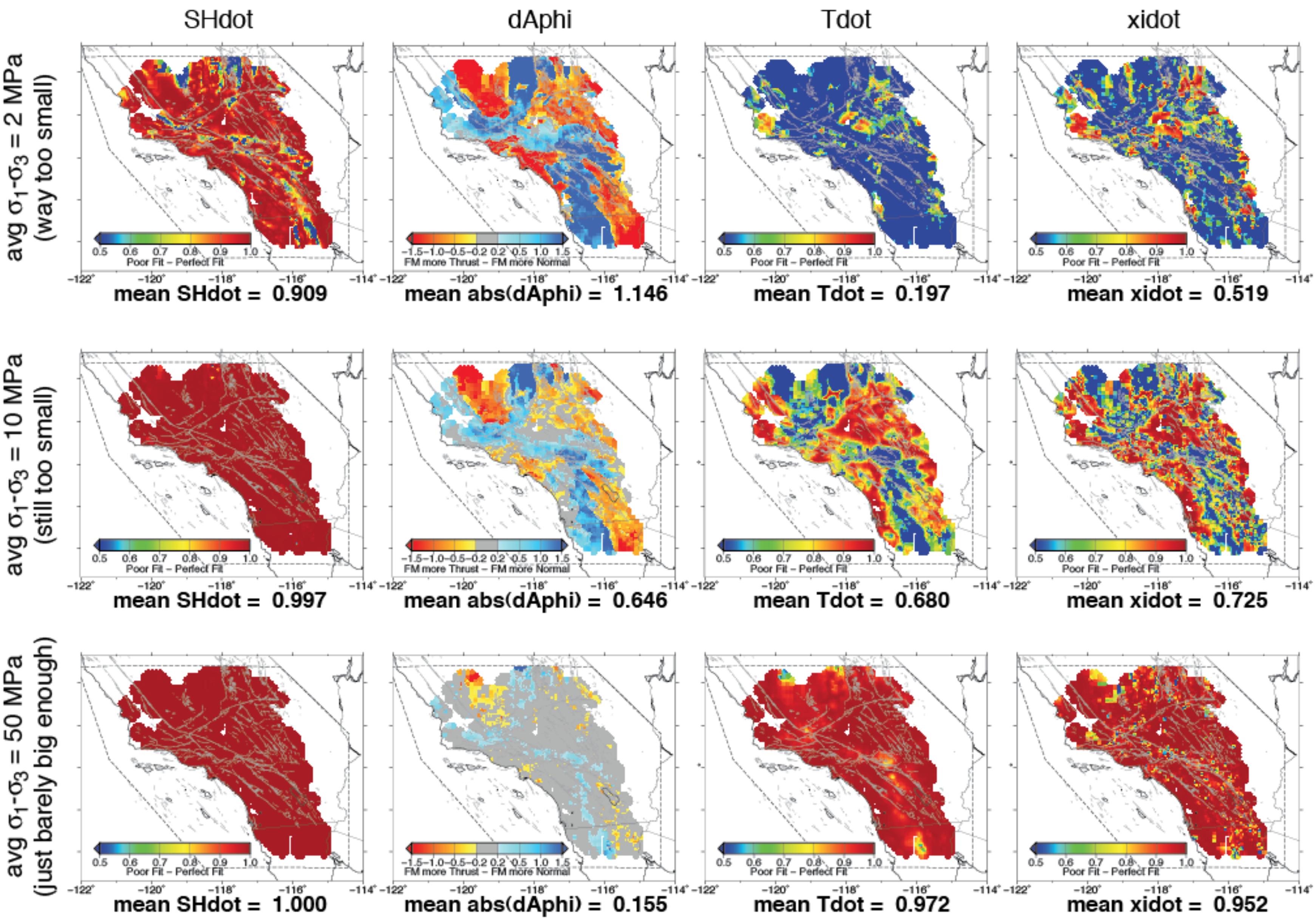
Range [-1,1], 1 indicates perfect fit

xidot

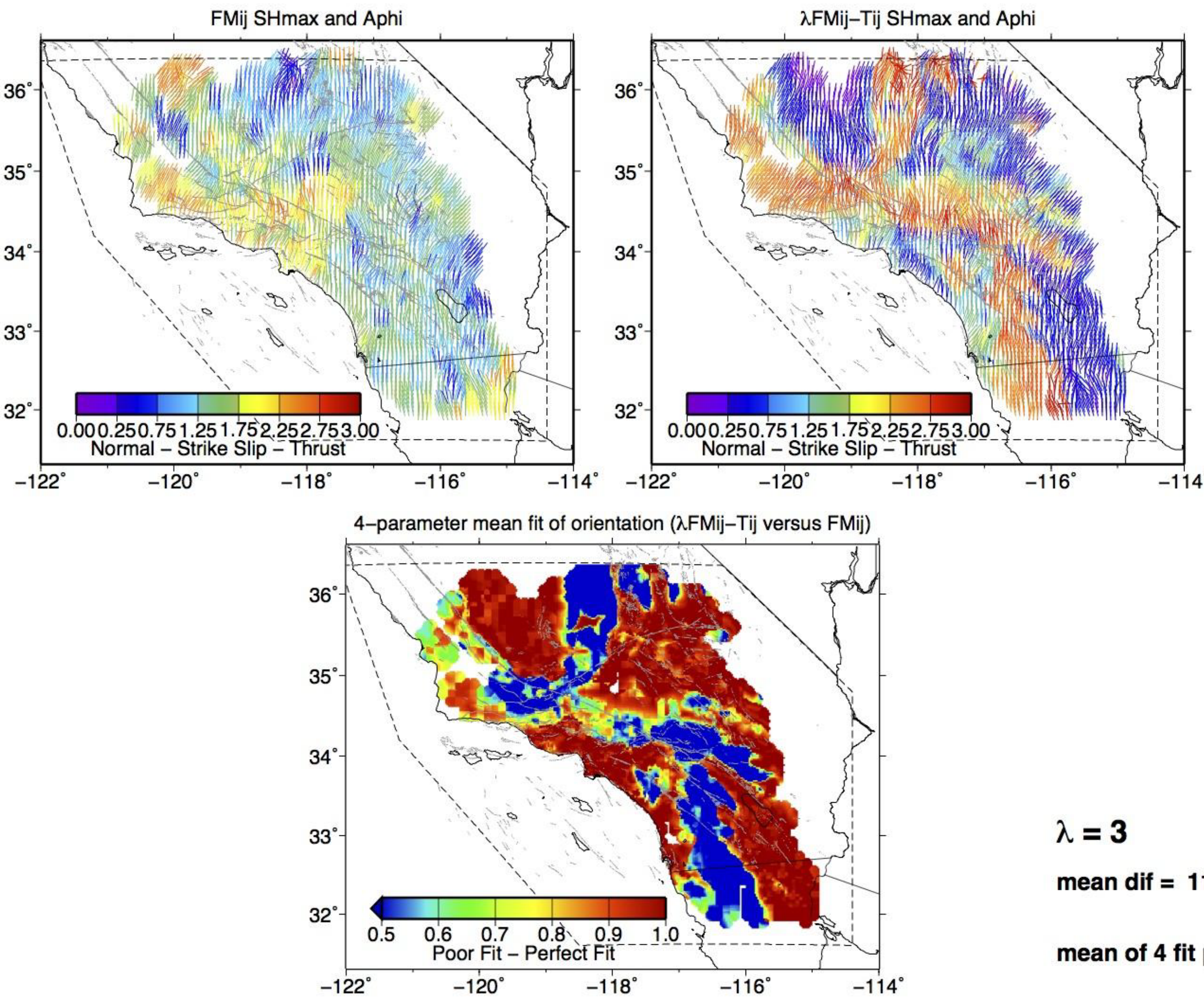
$$= \left(\vec{v}_{1A} \cdot \vec{v}_{1B} + \vec{v}_{2A} \cdot \vec{v}_{2B} + \vec{v}_{3A} \cdot \vec{v}_{3B}\right)/3$$

Range [0,1], 1 indicates perfect fit

Stress Tensor Comparisons



Does Scaled FM Stress Overcome Topographic Stress?

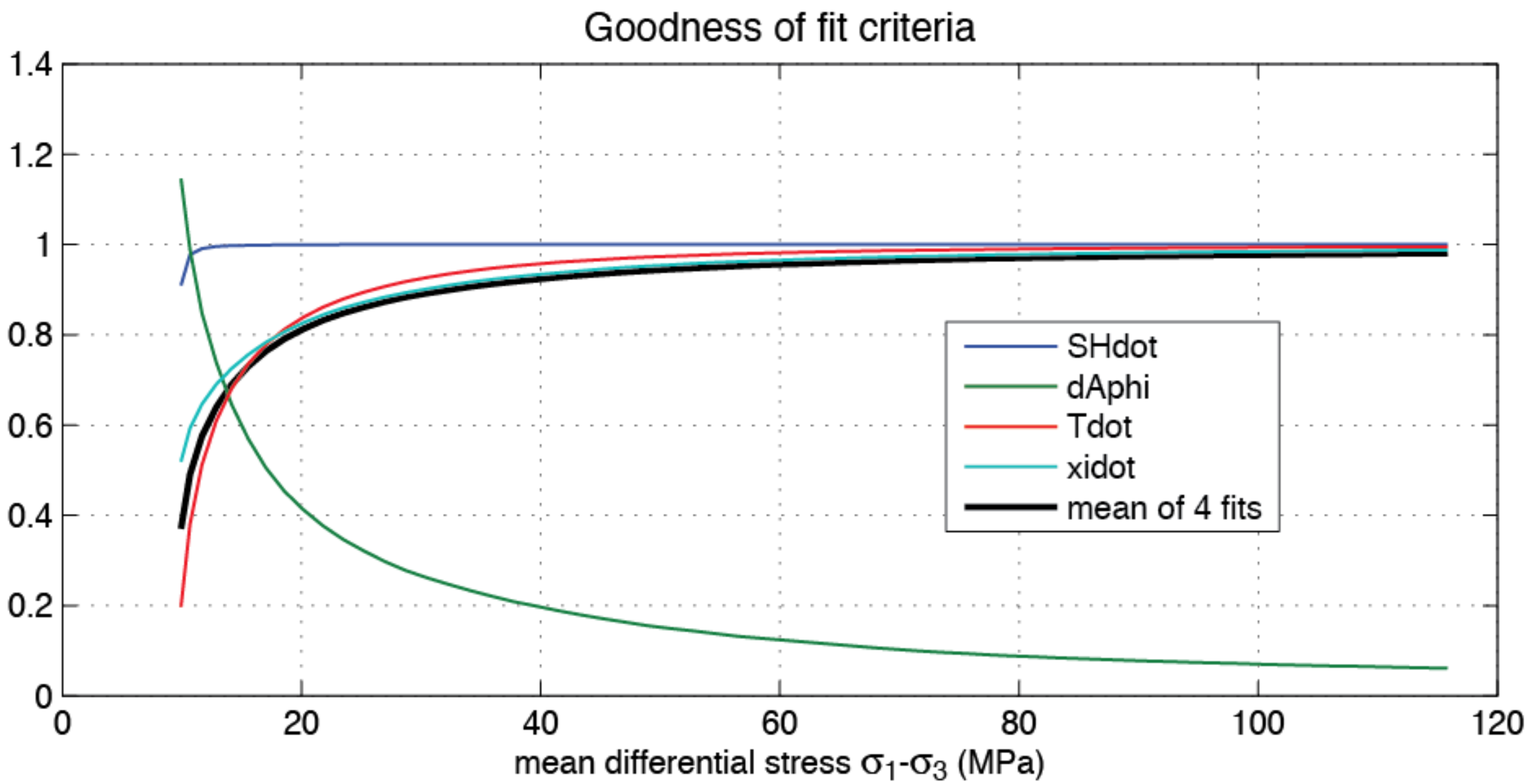


λ = 3

mean dif = 11.681

mean of 4 fit parameters = 0.777

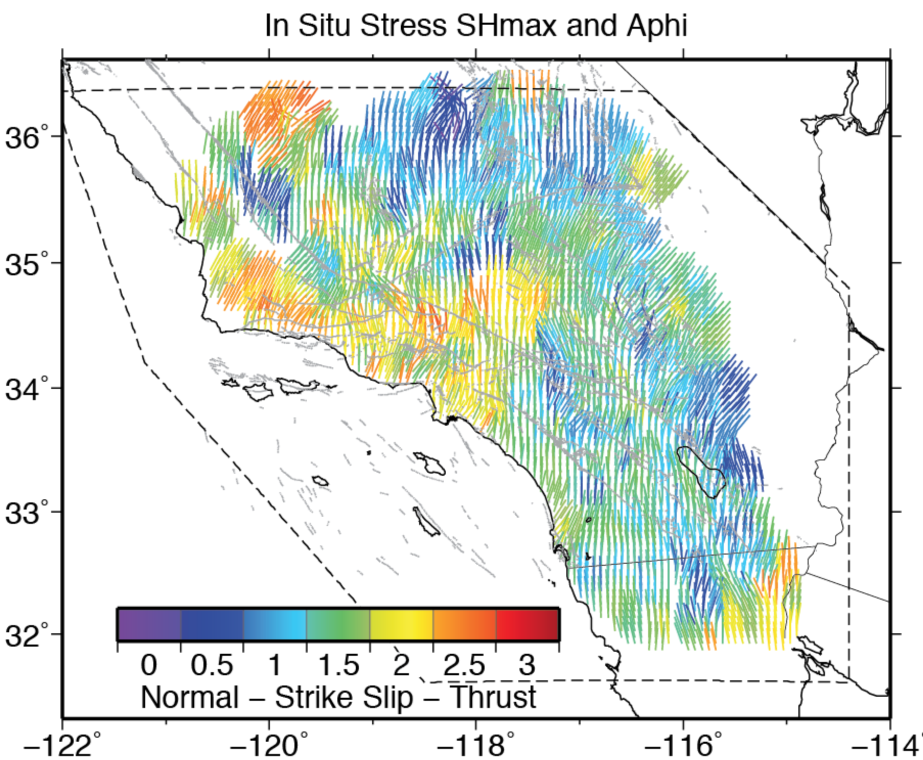
Mean fit of orientation

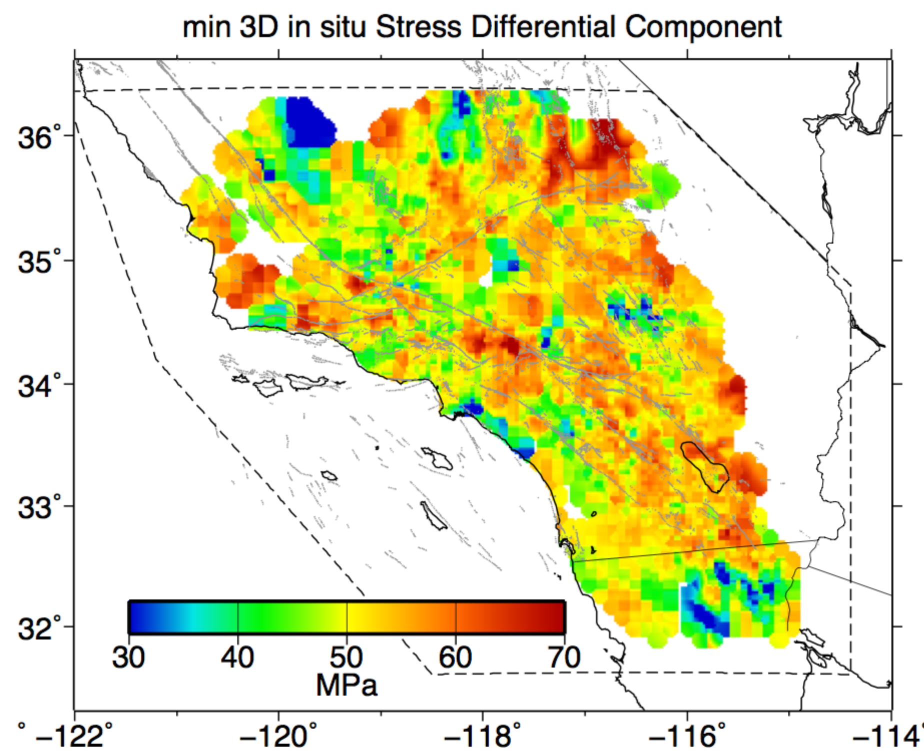


- Mean fit of orientation FMij stress to orientation of "total stress" (λFMij-Tij) for entire S. Califorina region
- When $\sigma_1 - \sigma_3$ is large enough, $[\ \lambda\ FMij - Tij\ ]_{orientation} \approx [\ FMij\ ]_{orientation}$

Differential Stress Magnitude

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





mean $\sigma_1 - \sigma_3$ = 51 MPa

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?
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