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
  - *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

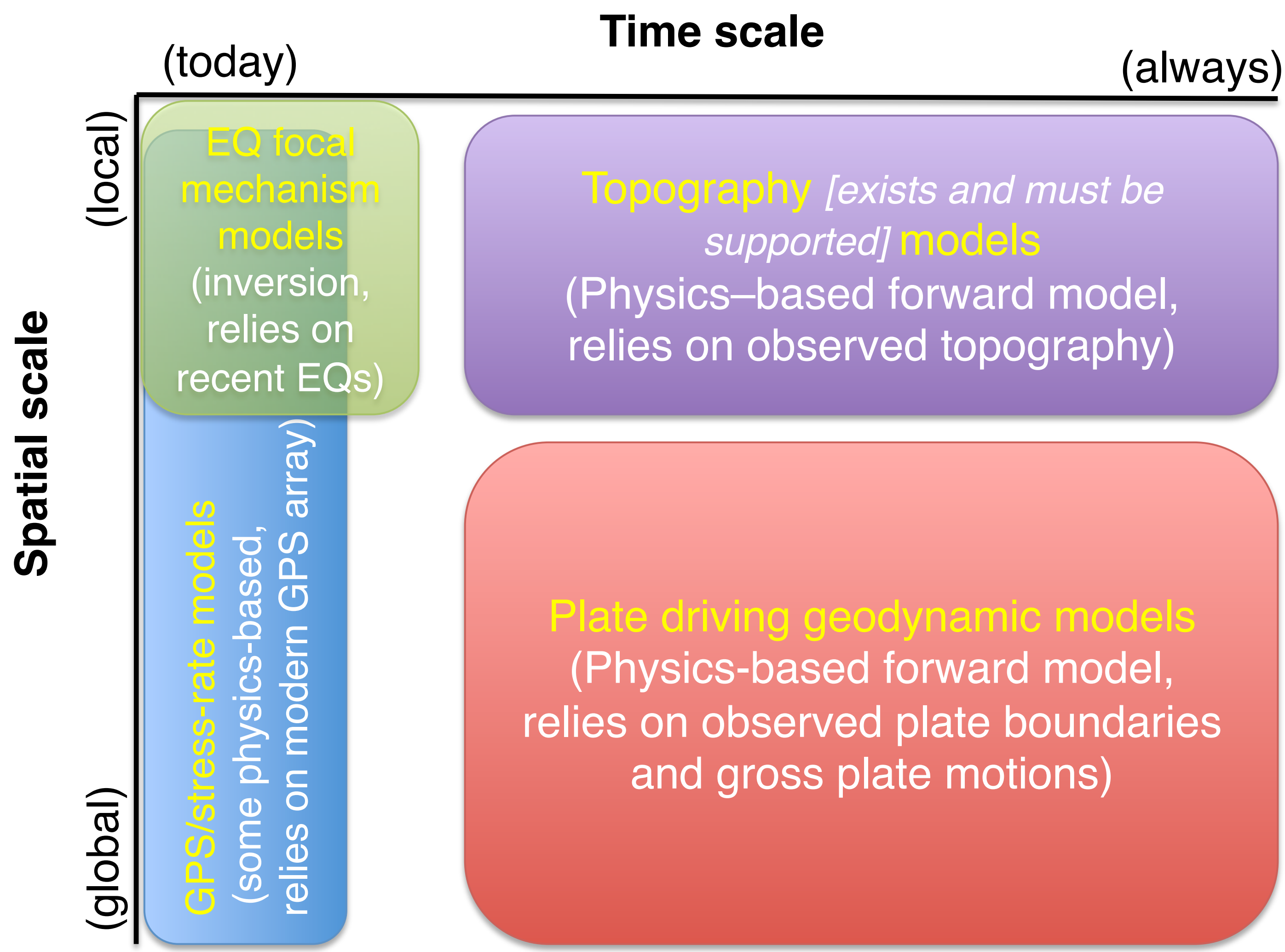
1. Contributions and questions

2. Estimates of stress magnitude

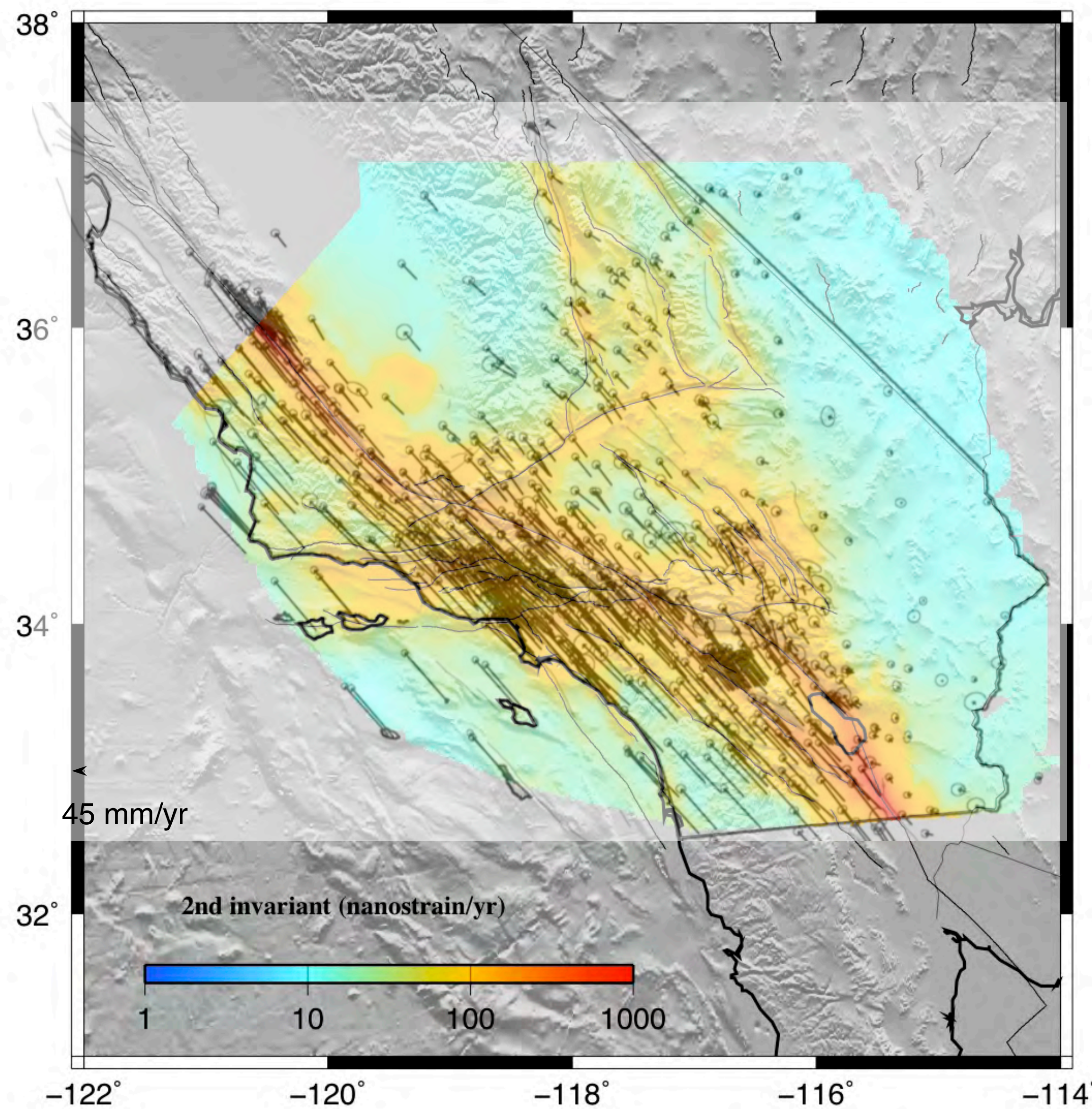
3. Which processes dominate crustal stress heterogeneity?

4. What's next?

Models of "Stress" in Space and Time



Southern California GPS Velocity Field (stress accumulation rate)



Stress Orientation Model (assume this is *in situ* orientation)


Geophysical Journal International

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Advance Access publication 2013 April 22

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

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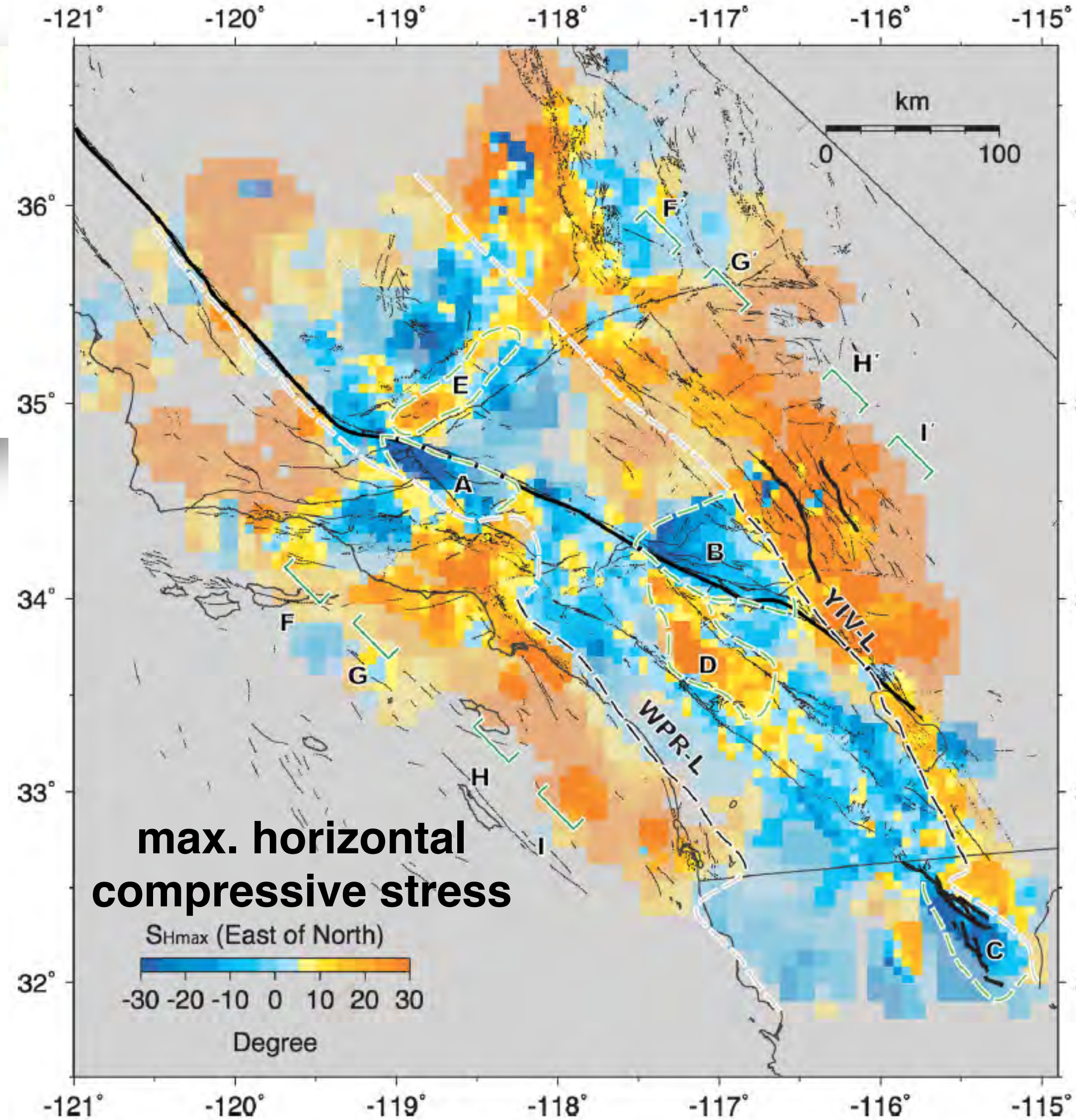
SUMMARY

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.]

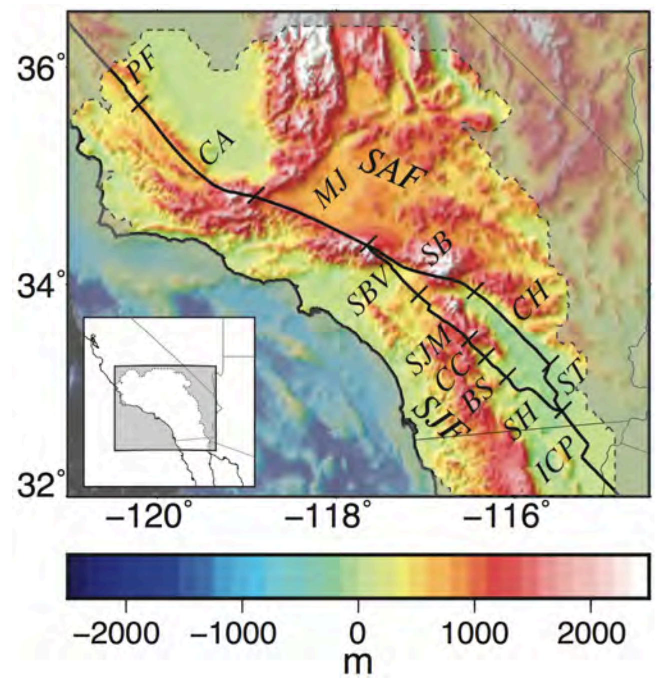
- Invert 179,000 FMs
- No depth dependence, all "seismogenic depth"
- 3D stress elipsoid shape and orientation
- **No magnitude**

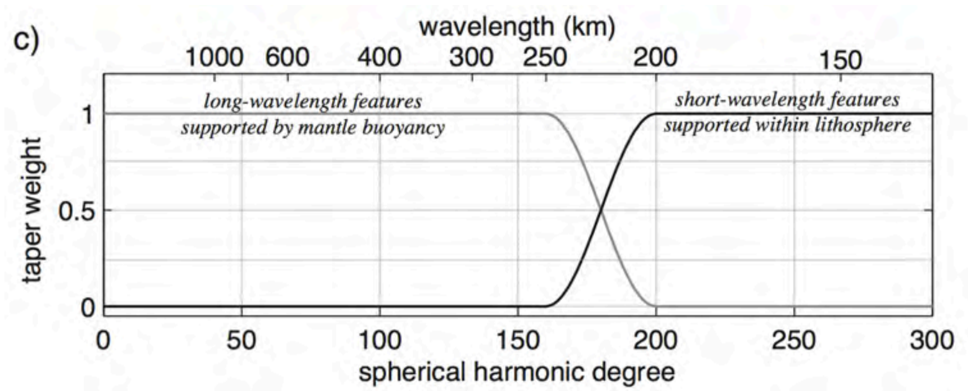


[*Yang and Hauksson, 2013*]

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

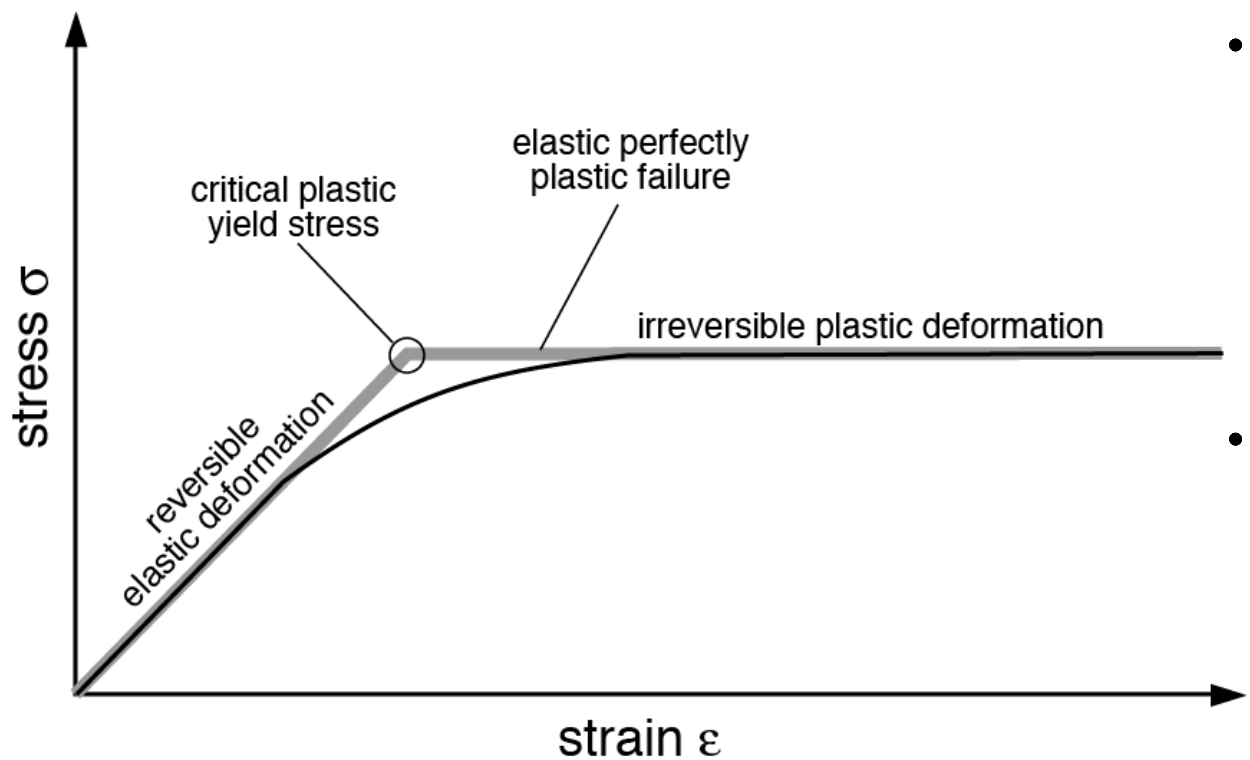




[Luttrell and Smith-Konter, 2016, in review]

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

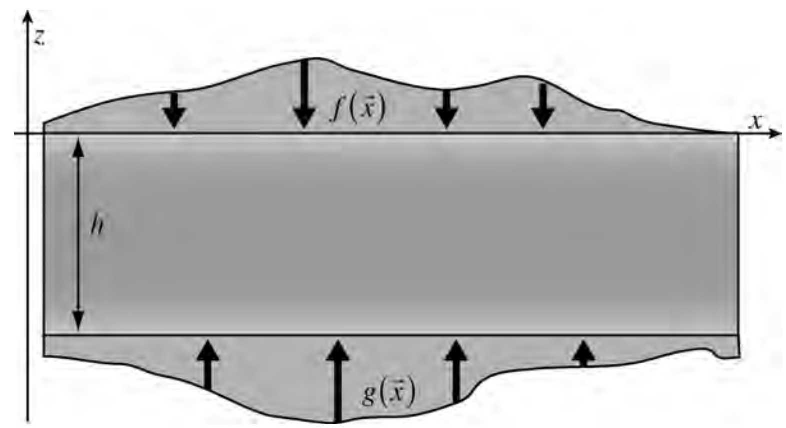


- Stress magnitudes could be higher
  - e.g., if strengthening occurred since topography was built
- Stress magnitudes could not be lower
  - otherwise the existing topography would have relaxed away

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 160º-200º) 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)

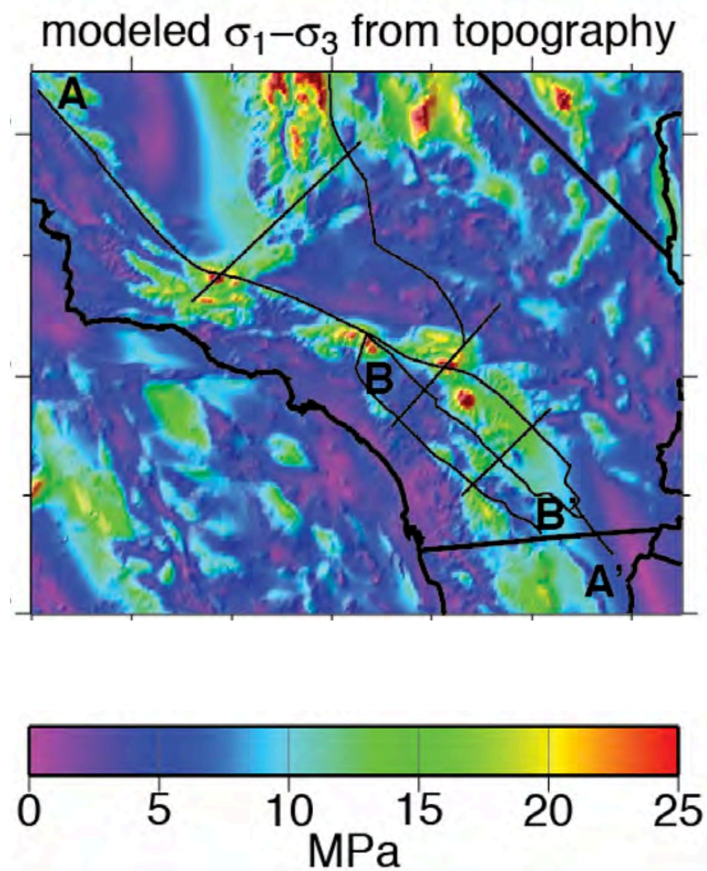


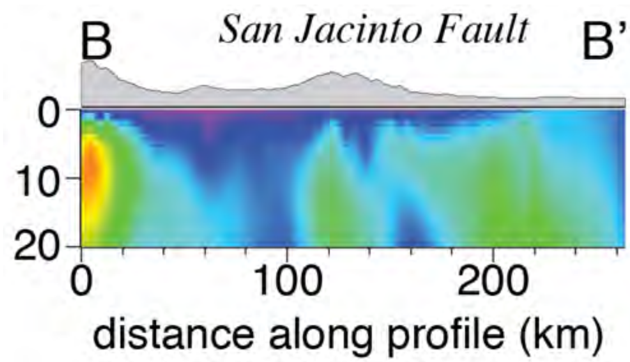
[*Luttrell et al.*, 2011;
Luttrell and Sandwell, 2012]

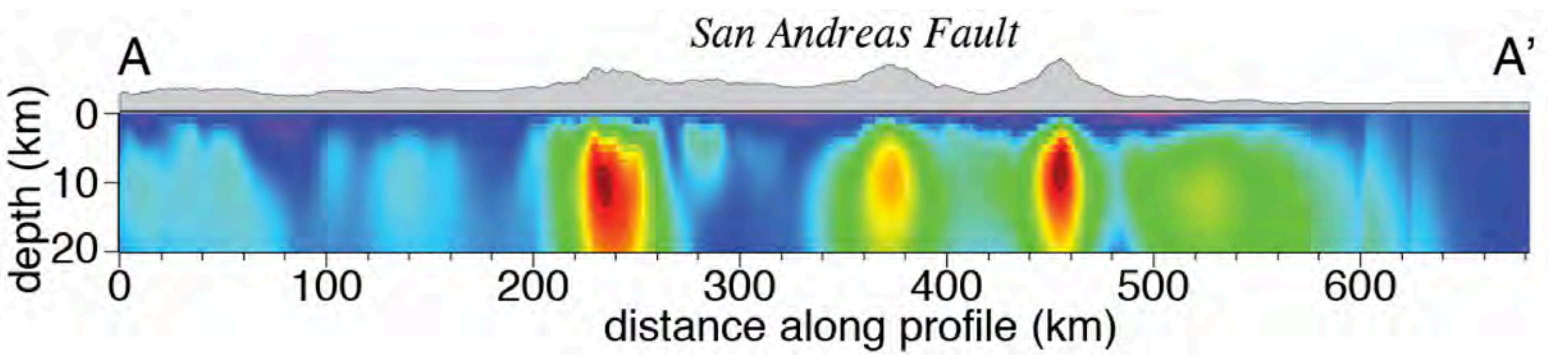
Stress from Topography at seismogenic depth

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

- Includes 3D **orientation and magnitude**







[*Luttrell and Smith-Konter, 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…

Outline

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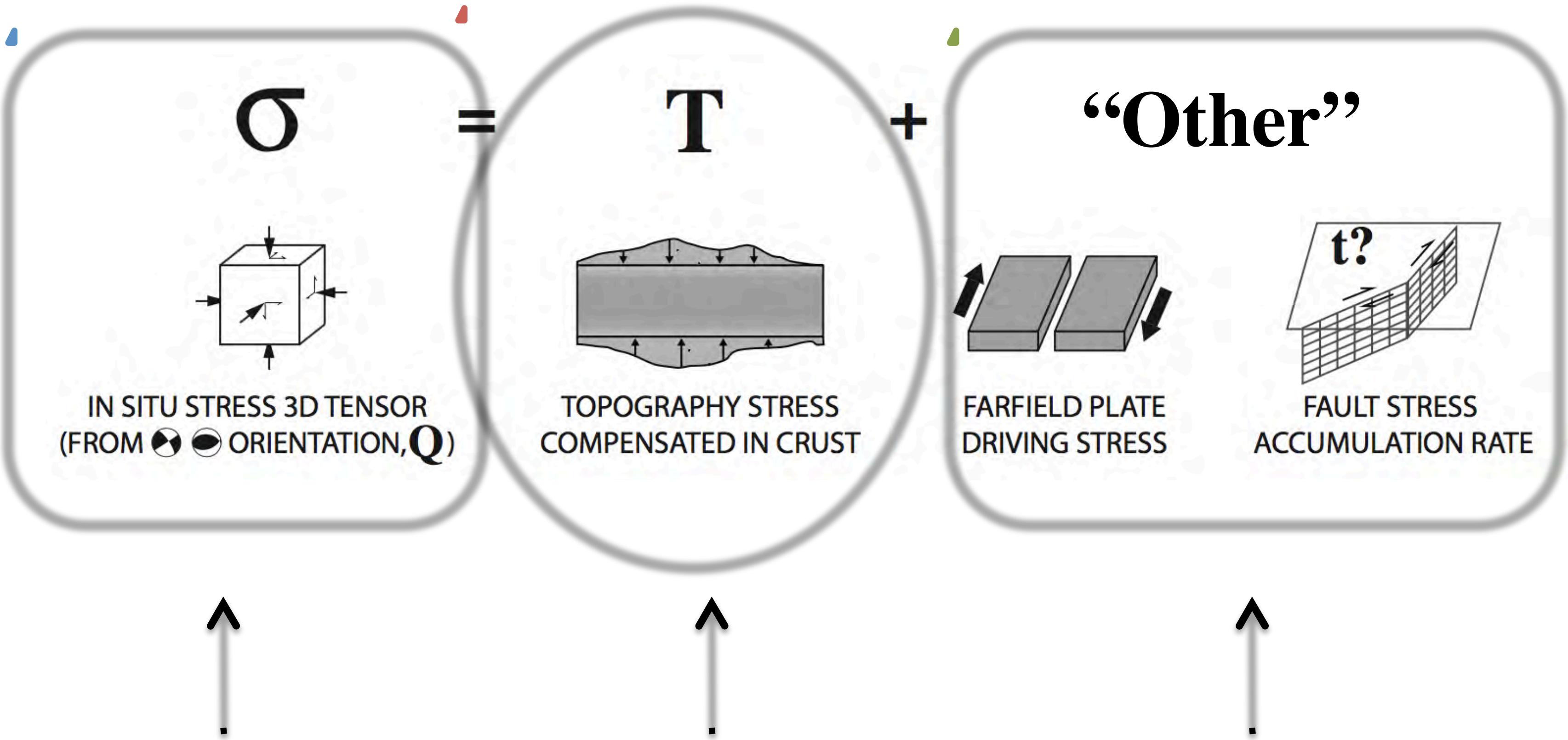
Simple forward model of stress field

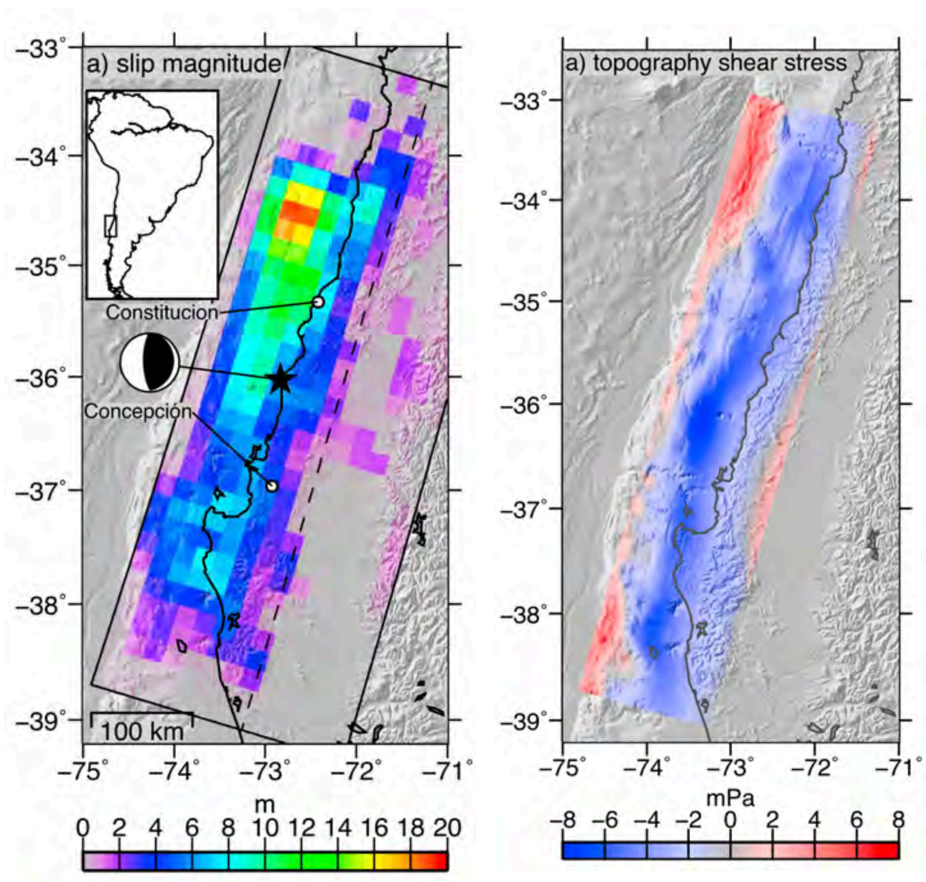


Find some indication of this

Calculate this

Figure out some bounding values for this

Topography and Regional Stress (megathrust earthquake)



[*Luttrell et al.*, 2011]

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, B11401, doi:10.1029/2011JB008509, 2011

Estimates of stress drop and crustal tectonic stress from the 27 February 2010 Maule, Chile, earthquake: Implications for fault strength

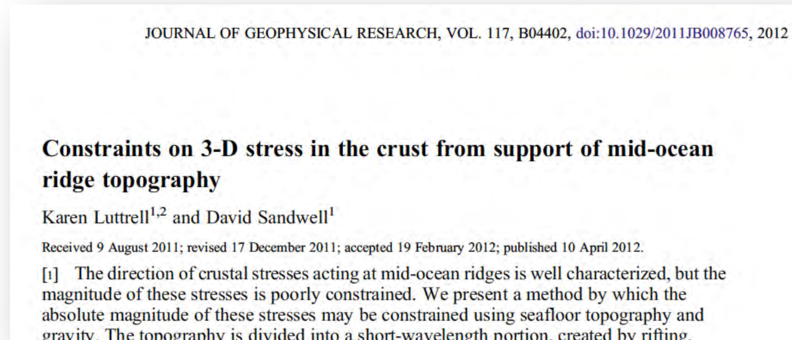
Karen M. Luttrell,[1,2] Xiaopeng Tong,[1] David T. Sandwell,[1] Benjamin A. Brooks,[3] and Michael G. Bevis[4]

Received 3 May 2011; revised 8 August 2011; accepted 20 August 2011; published 3 November 2011.

[1] The great 27 February 2010 M_w 8.8 earthquake off the coast of southern Chile ruptured a ~600 km length of subduction zone. In this paper, we make two independent

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

Topography and Regional Stress (mid-ocean ridges)



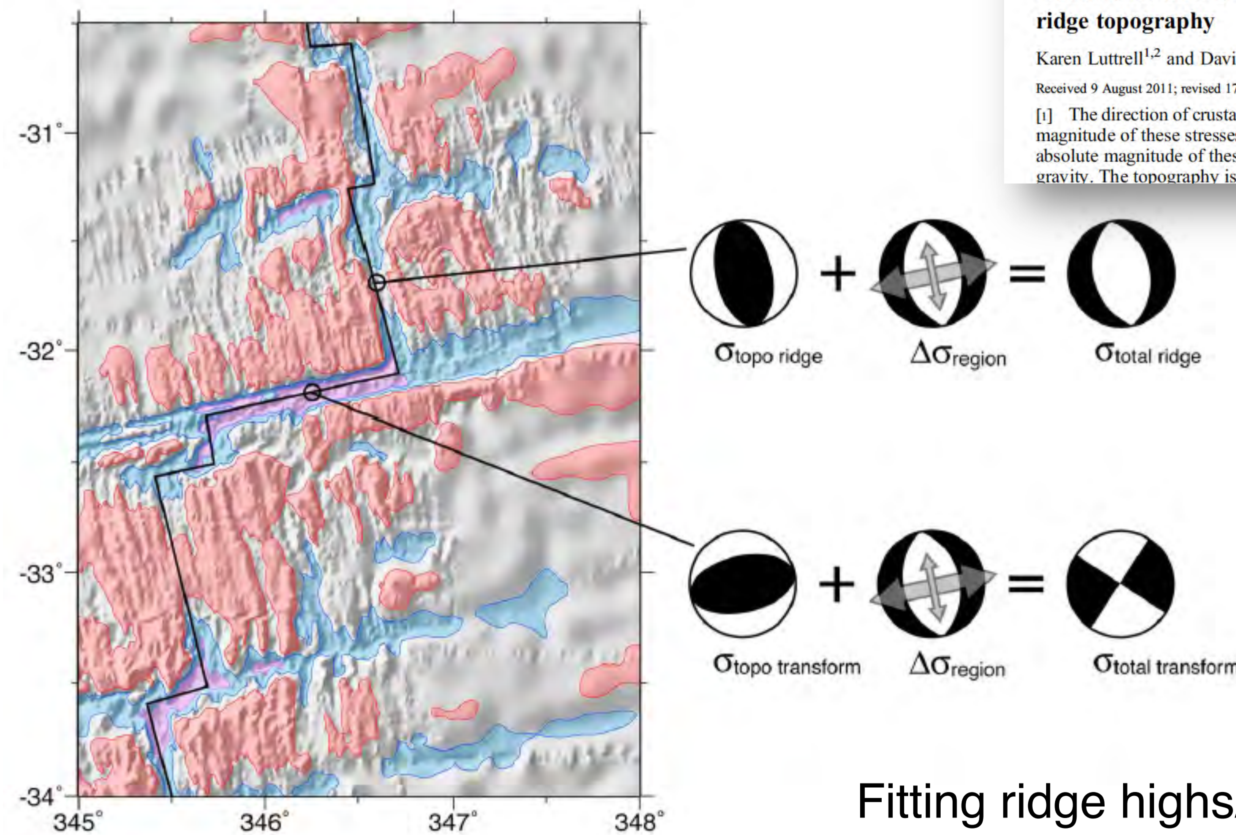
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 117, B04402, doi:10.1029/2011JB008765, 2012

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,

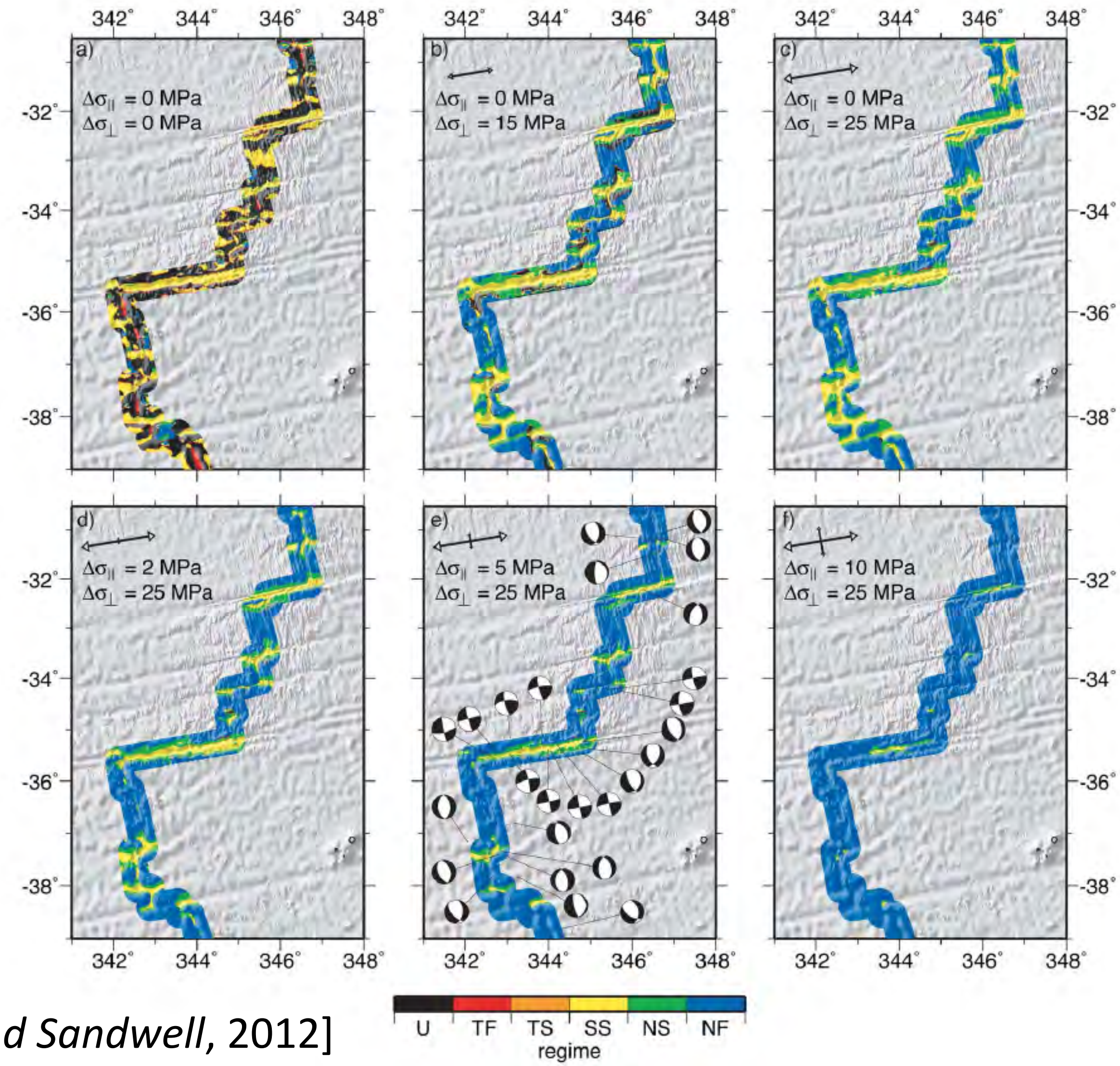


[*Luttrell and Sandwell*, 2012]

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

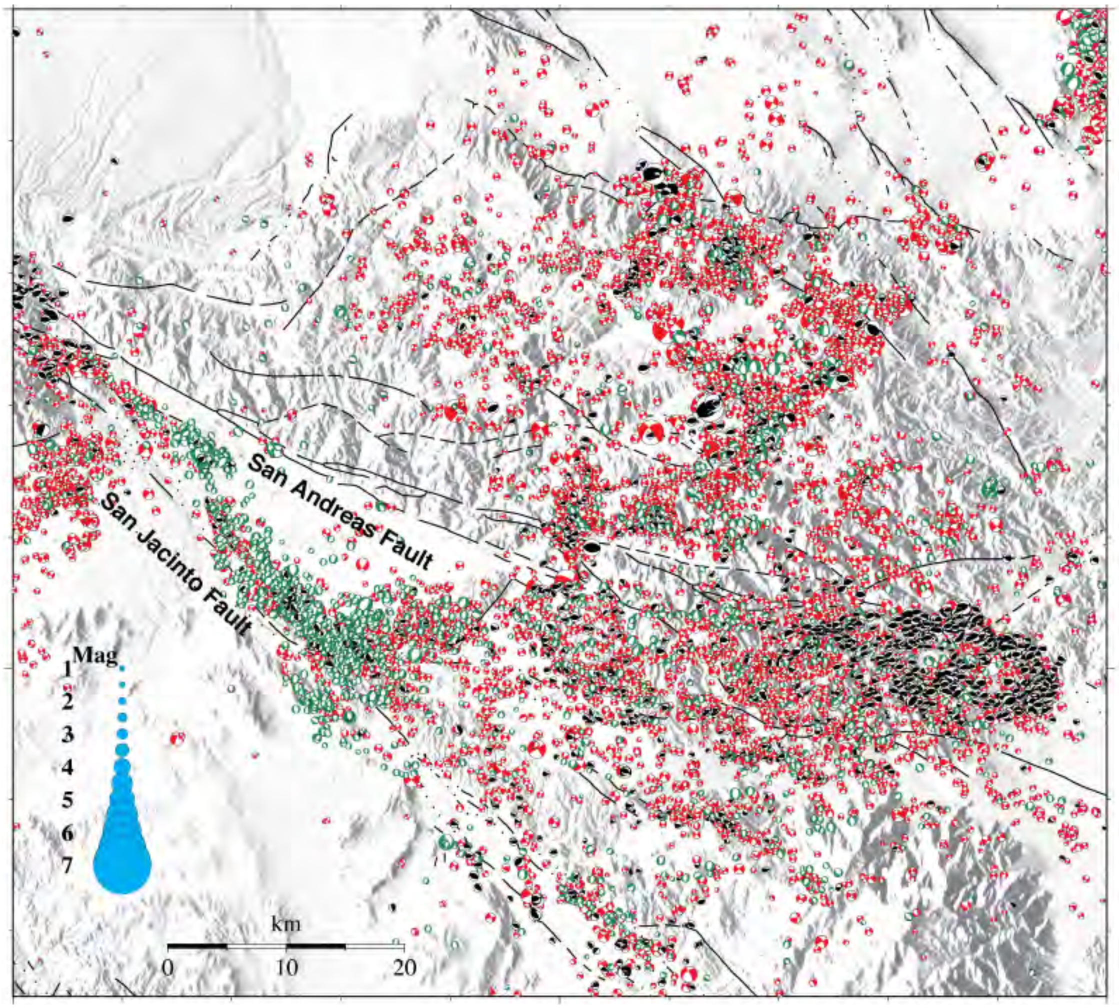
Topography and Regional Stress (mid-ocean ridges)

- 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]

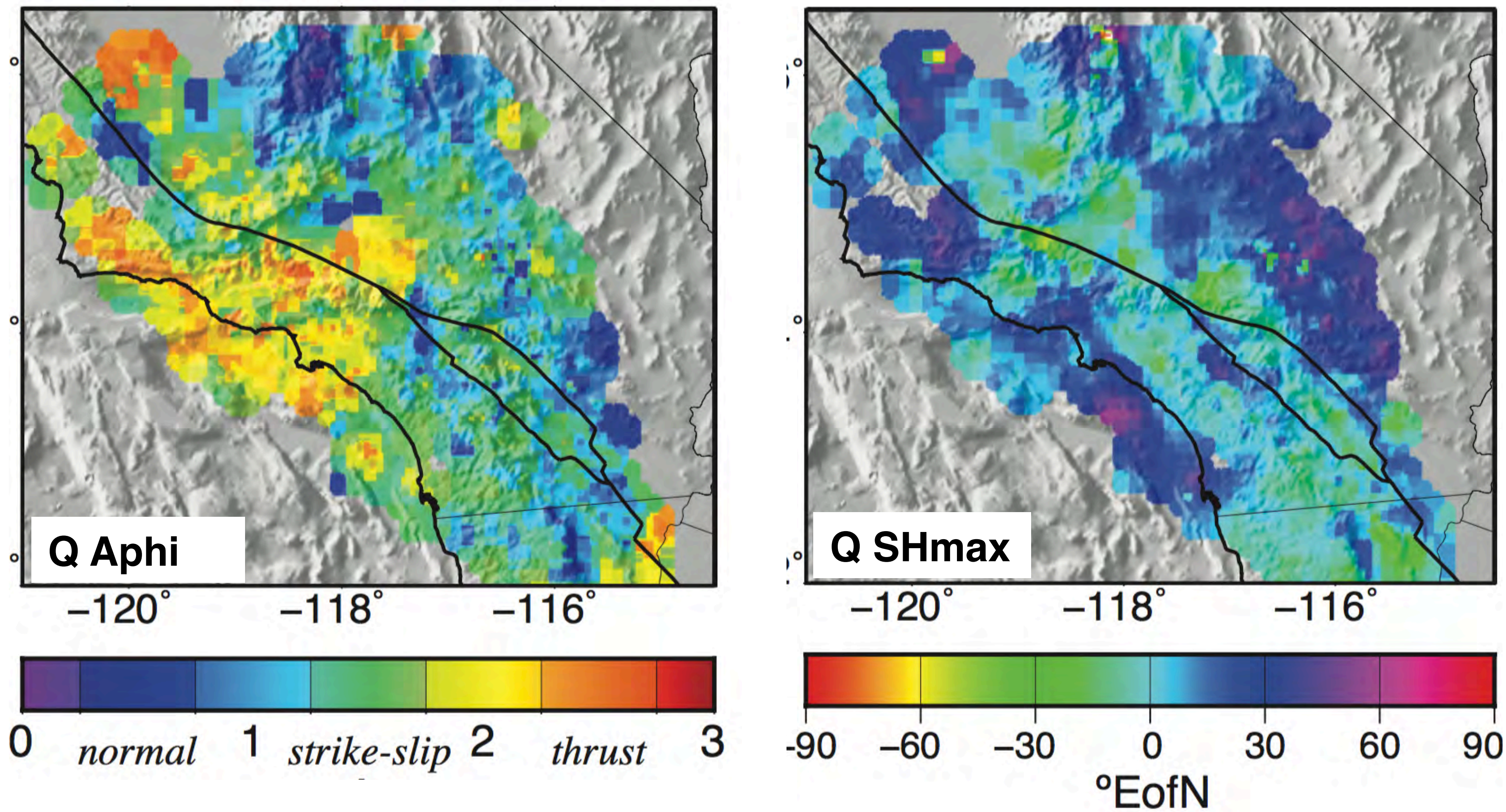
A challenge: Varied faulting-type plate boundary (Southern California)



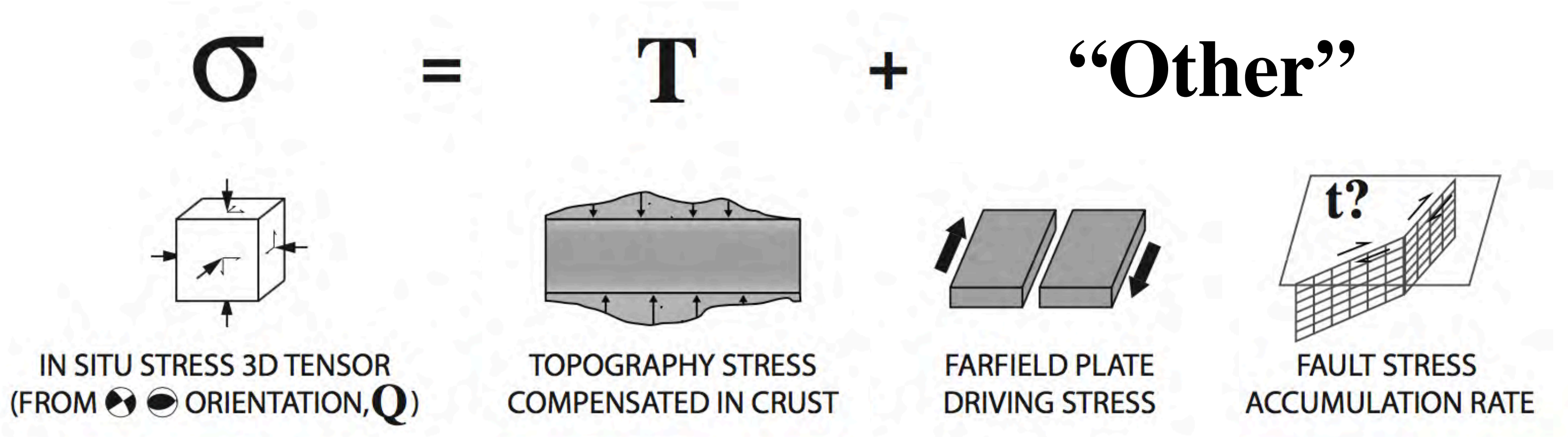
[*Yang et al*. 2012]

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

Inverted Focal Mechanism model from *Yang and Hauksson* [2013]



Simple forward model of stress field



Need some additional information or assumptions

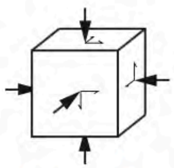
1. **Assume topography is NOT dominant in Southern California**

2. **Assume "other" is dominant in Southern California**

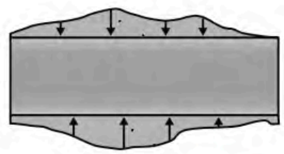
   i.e., topography is ~negligible

Simple forward model of stress field

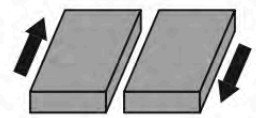
σ = **T** + **"Other"**



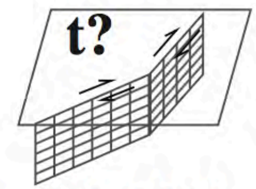
IN SITU STRESS 3D TENSOR
(FROM ORIENTATION, **Q**)



TOPOGRAPHY STRESS
COMPENSATED IN CRUST

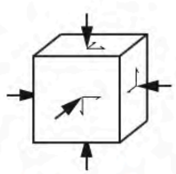


FARFIELD PLATE
DRIVING STRESS



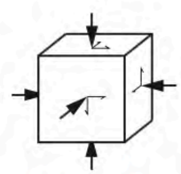
FAULT STRESS
ACCUMULATION RATE

$\sigma \approx \sigma^{*} \Delta\sigma$ - **T**



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

orientation



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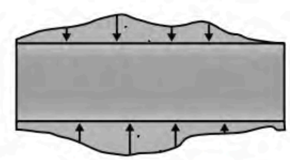
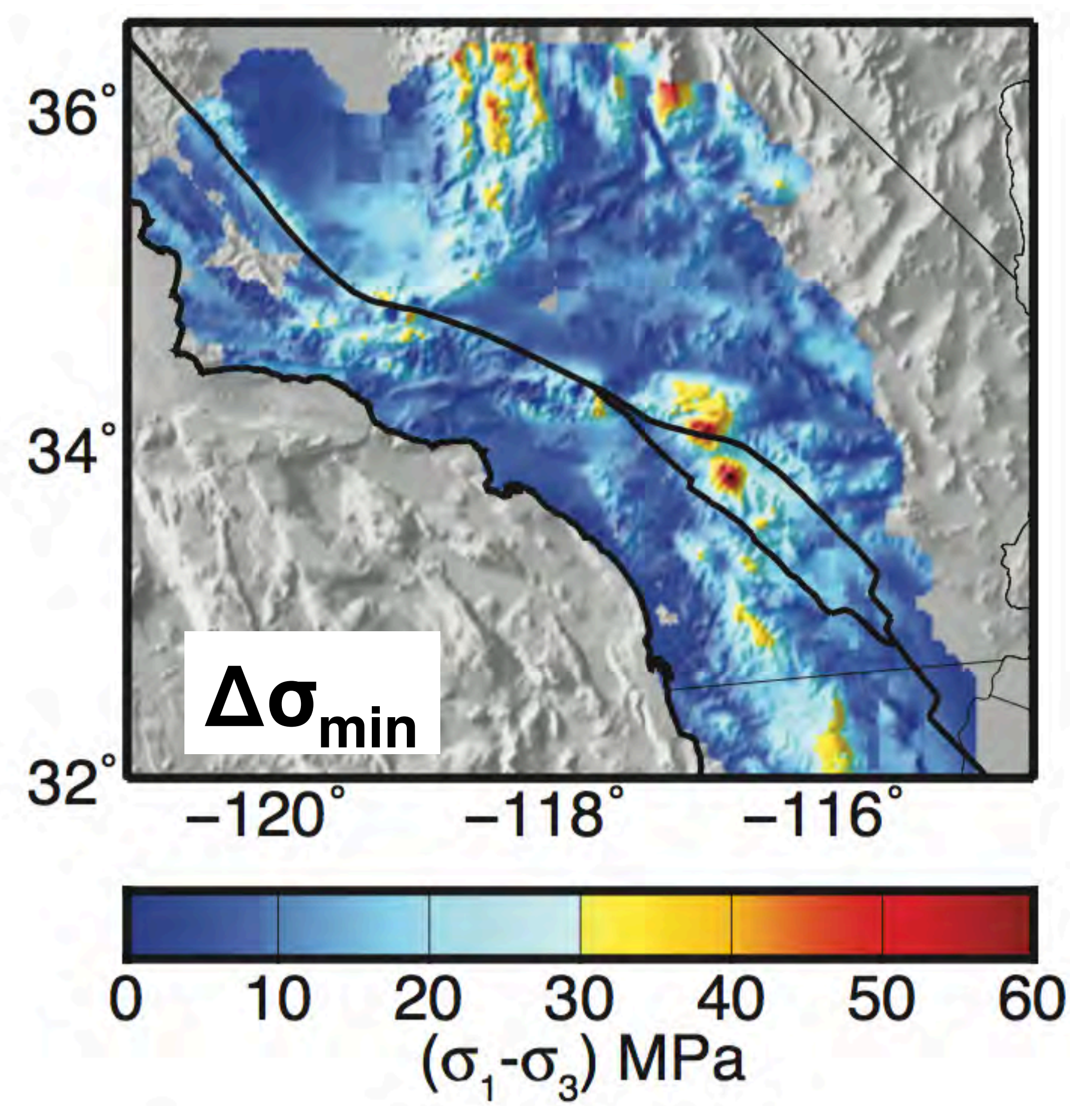


TOPOGRAPHY STRESS
COMPENSATED IN CRUST

orientation

Minimum in situ magnitude estimate: $\Delta\sigma_{min}$

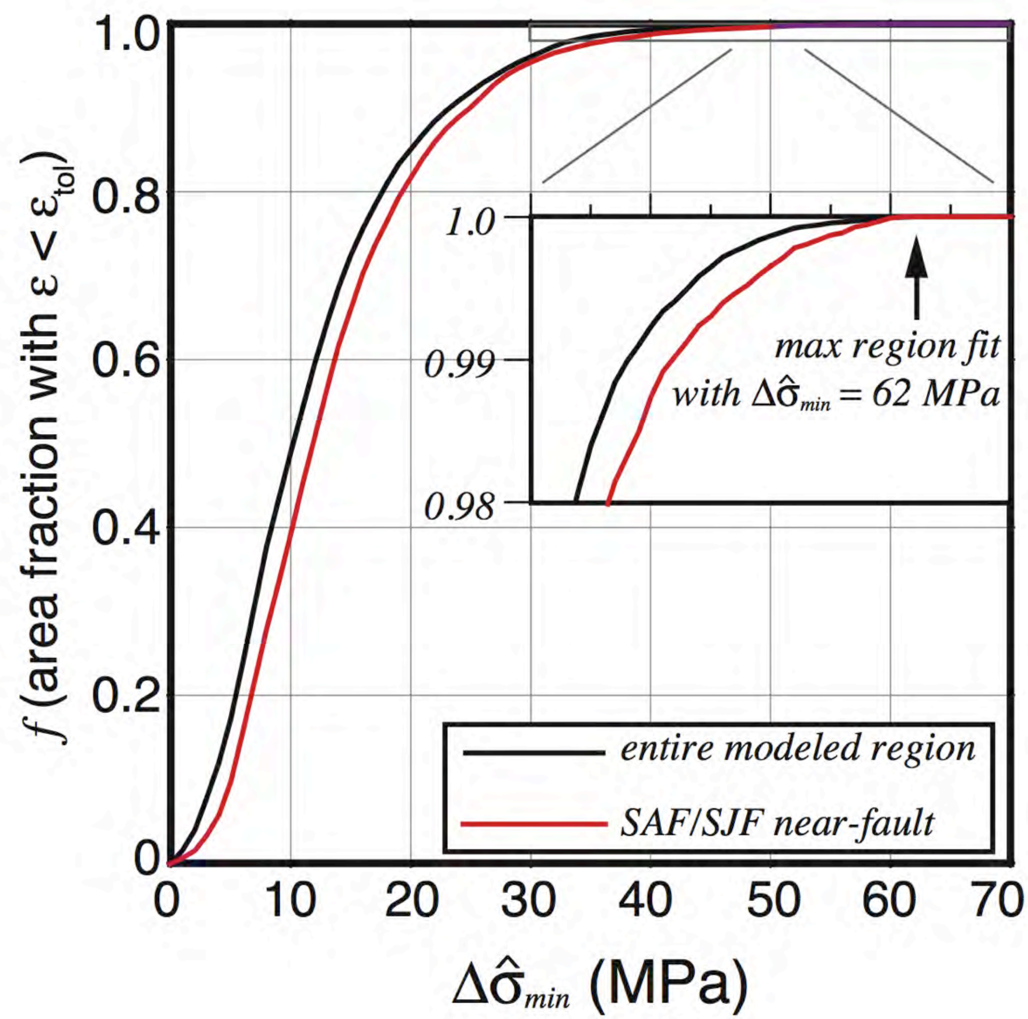
- $\Delta\sigma$ required to maintain *in situ* orientation to within ±15º, despite resistance from topography
- Across SoCal, ranges from ~10 – 60 MPa
- This is a lower bound: stress could be arbitrarily higher and fit just as well



[*Luttrell and Smith-Konter, in revision*]

<u>Minimum in situ magnitude estimate</u>: $\Delta\sigma_{min}$

- How does min Δσ 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 seperately
- Most rugged topography requires Δσ of 62 MPa



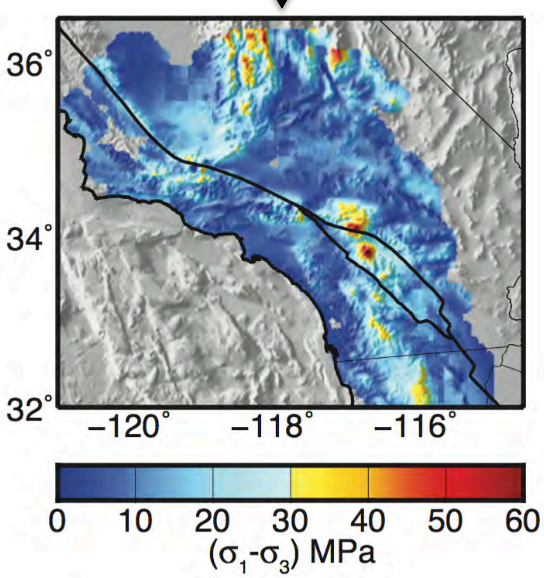
[*Luttrell and Smith-Konter, in revision*]

Which estimate should we use for $\Delta\sigma_{min}$?

Depends on how heterogeneous stress magnitude is…

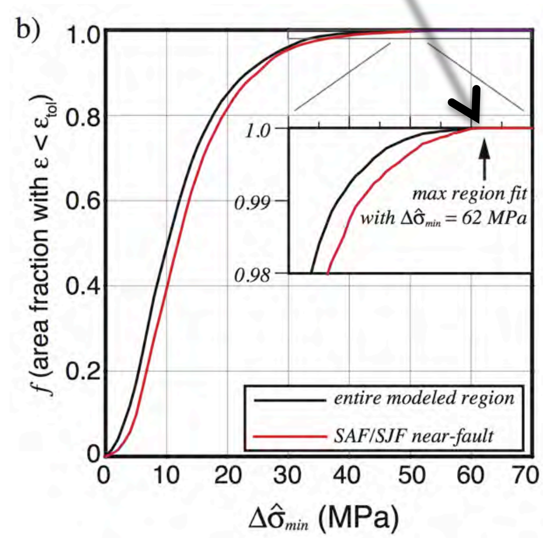
If variations are large relative to mean…

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



If variations are small relative to mean…

… $\Delta\sigma_{min}$ everywhere must be large enough to support max



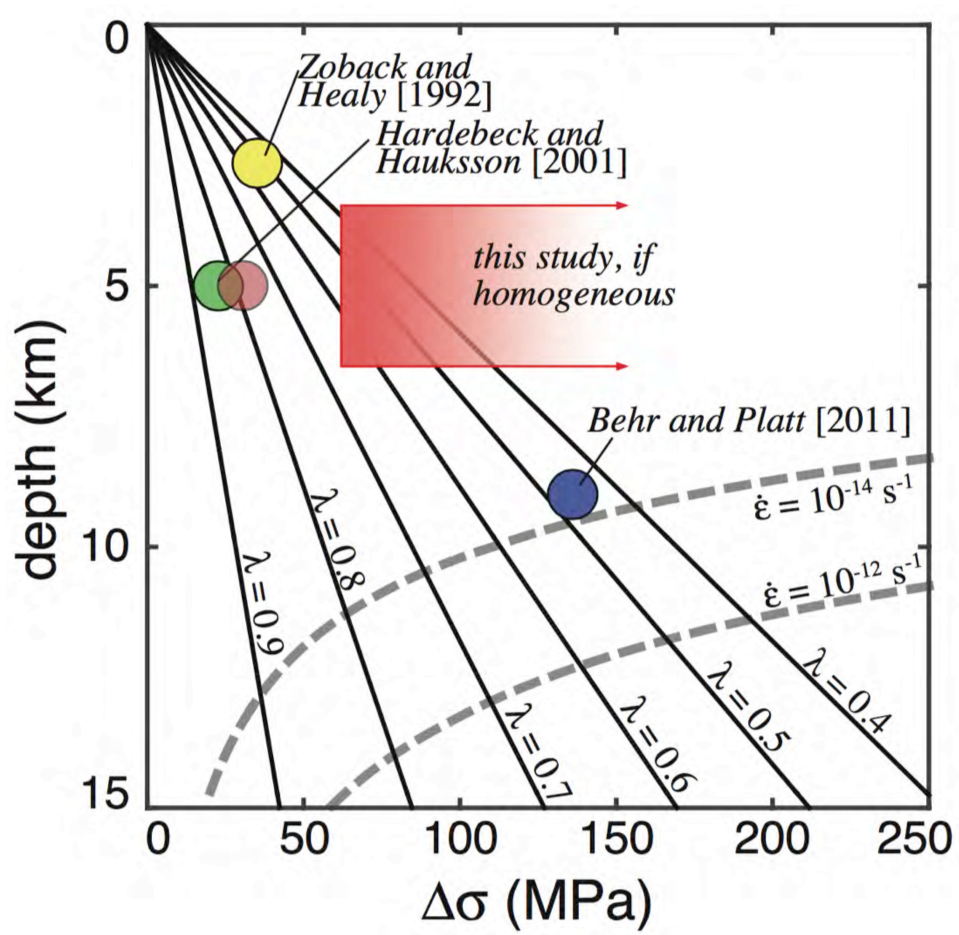
Do these results make sense?

- 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

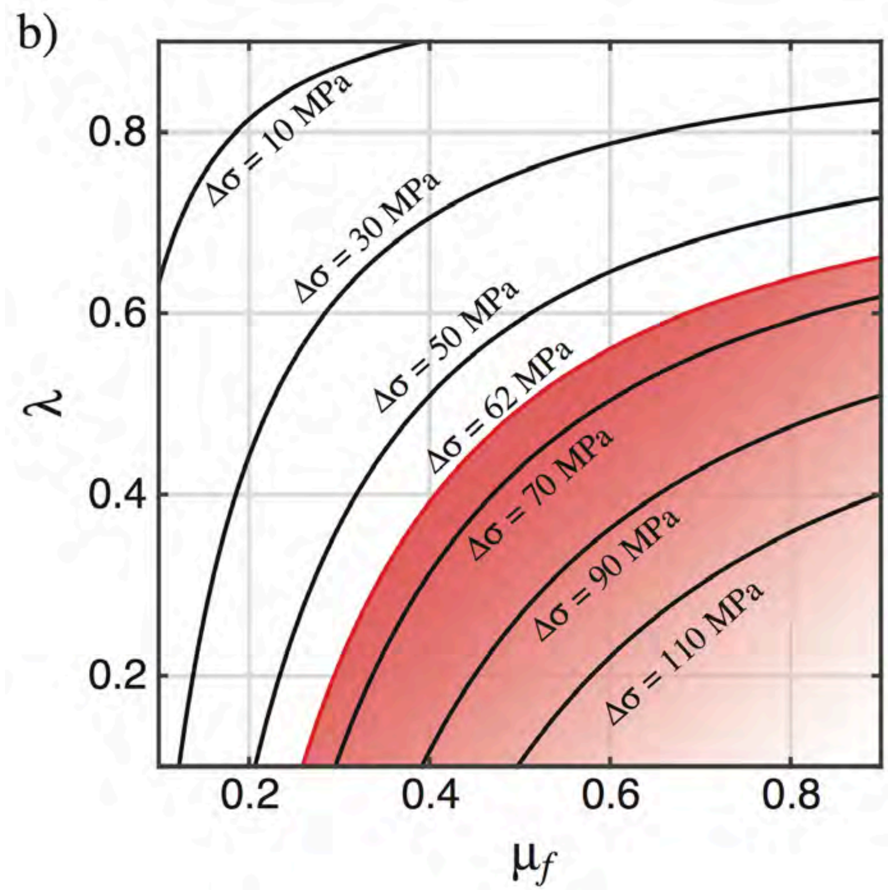
- YSE places a lower limit on fault friction and an upper limit on pore pressure



[*Luttrell and Smith-Konter, 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-Konter, in revision*]

Outline

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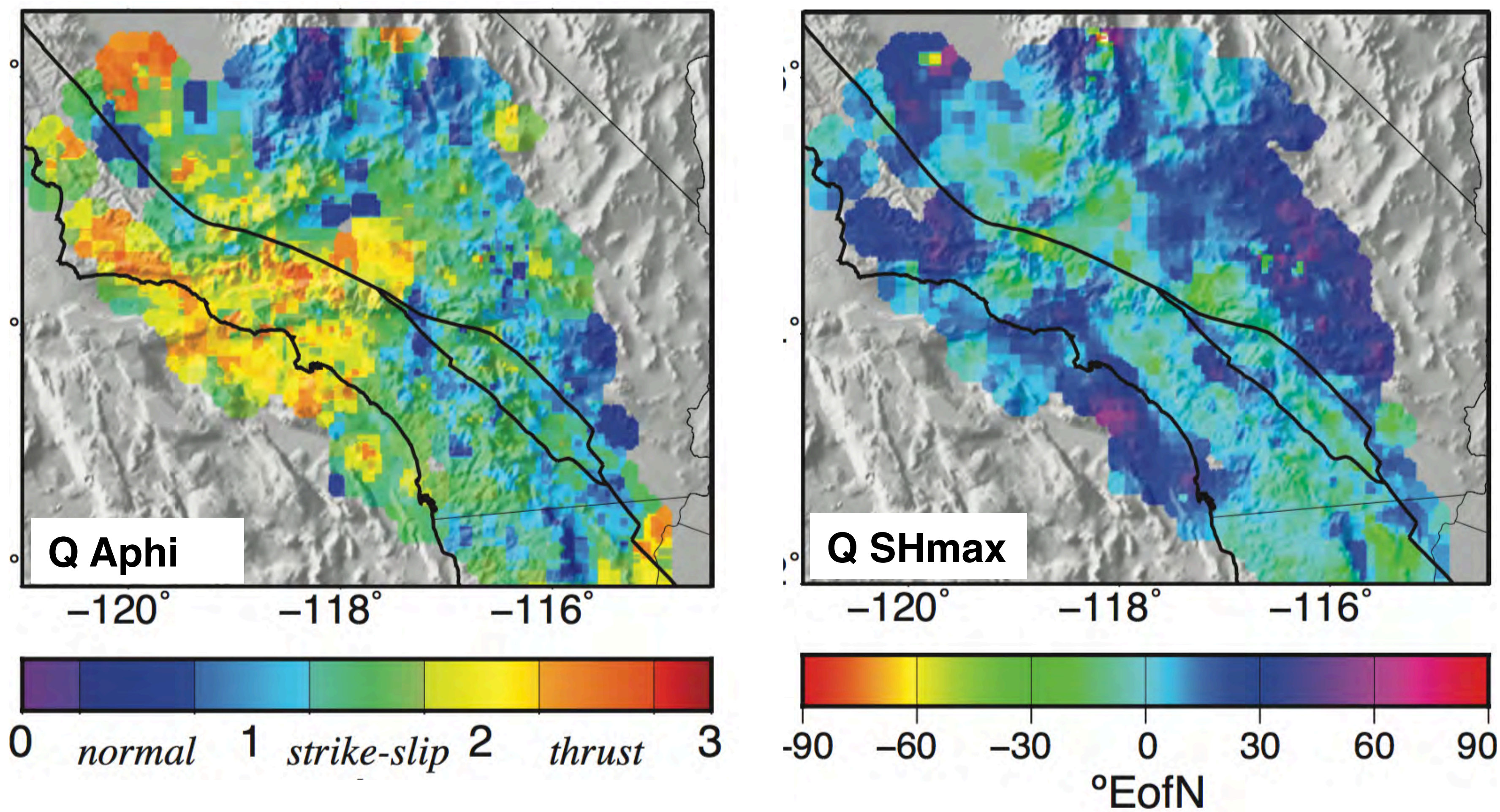
In Situ Stress Orientation is Heterogeneous.

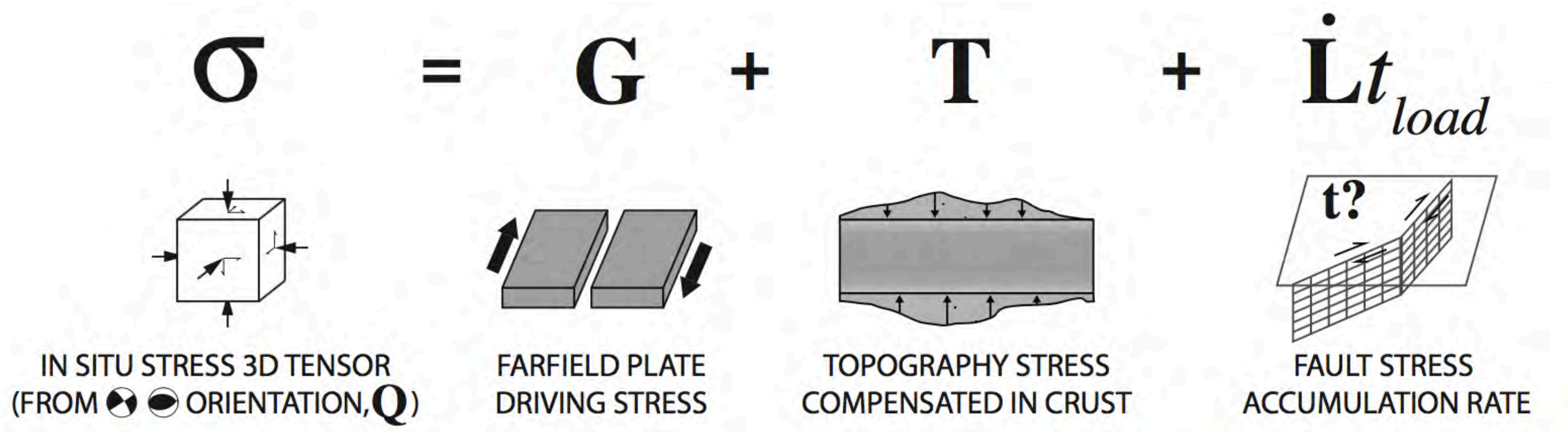
Why?

Lets assemble some physics-based models and find out…

Inverted Focal Mechanism model from *Yang and Hauksson* [2013]

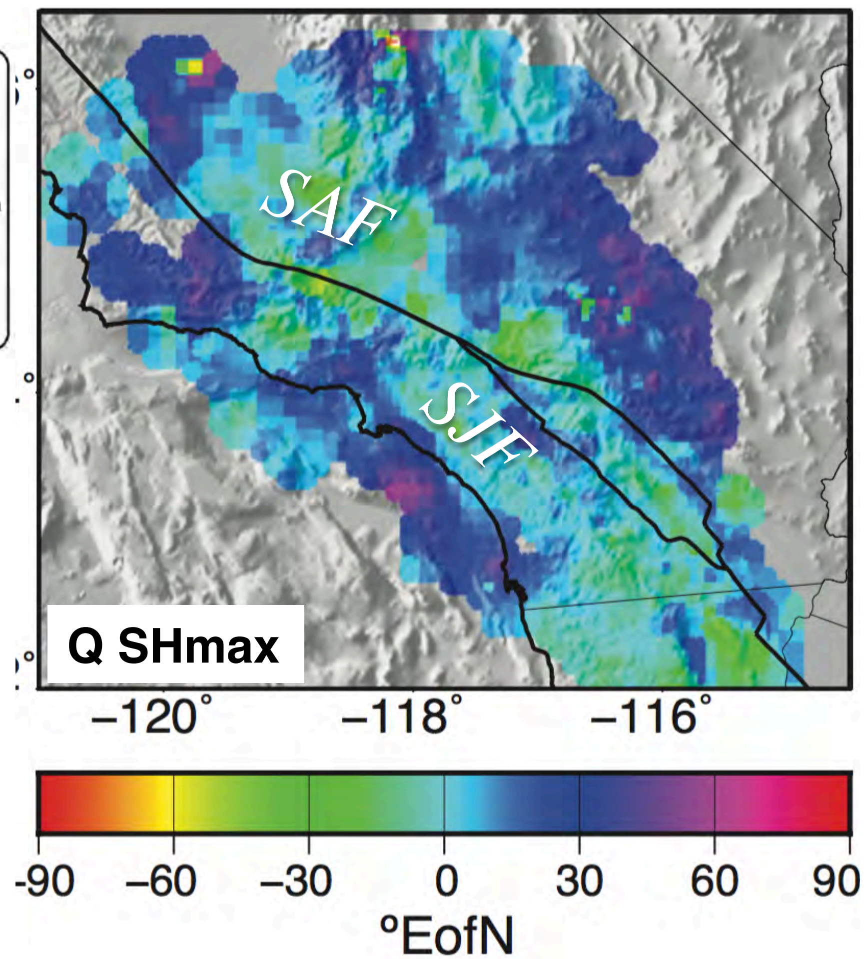


Simple forward model of stress field



Independently calculated model components

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



[Yang and Hauksson, 2013]

Independently calculated model components

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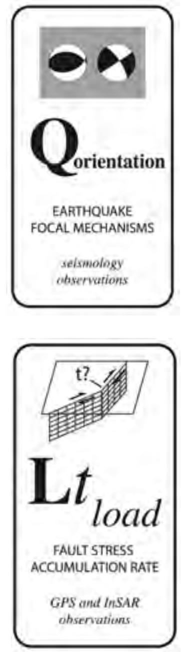
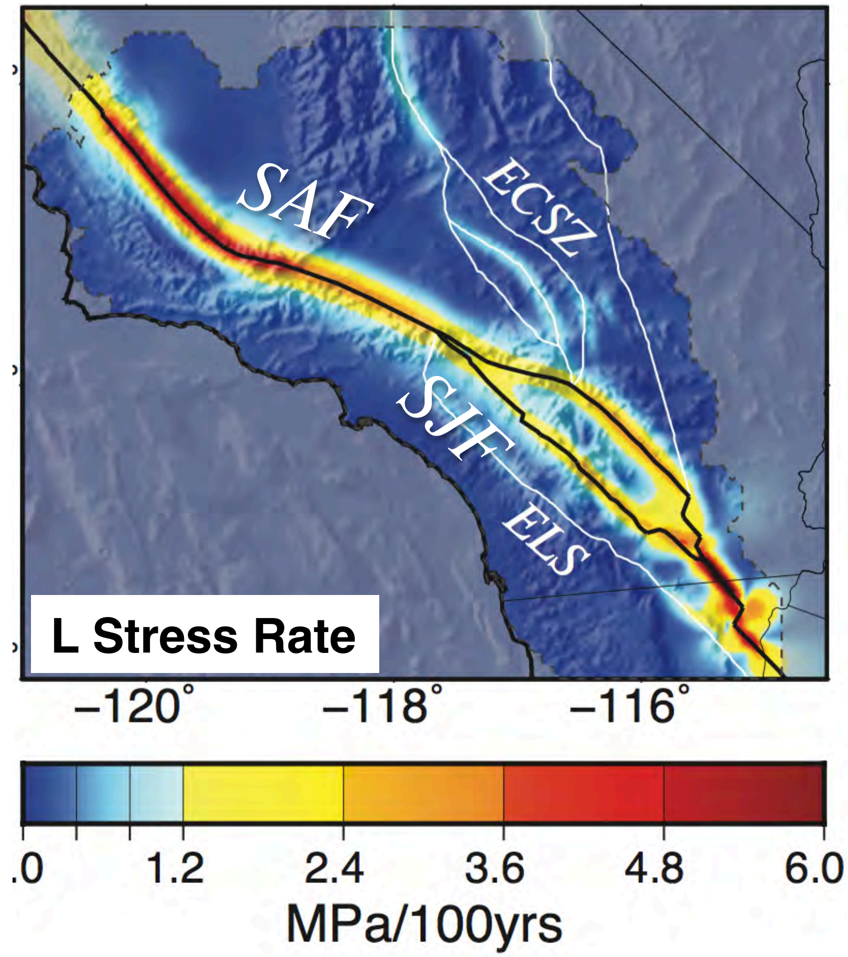
- **L**: Stress accumulation rate on locked faults from buried dislocation, constrained by geodesy, but **need to know time**
  - e.g. [Smith-Konter et al., 2011]





[Smith-Konter et al., 2011]

Independently calculated model components

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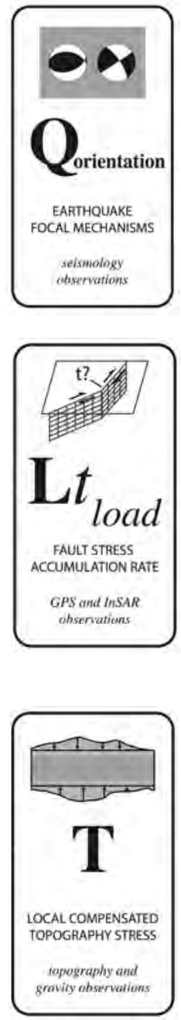
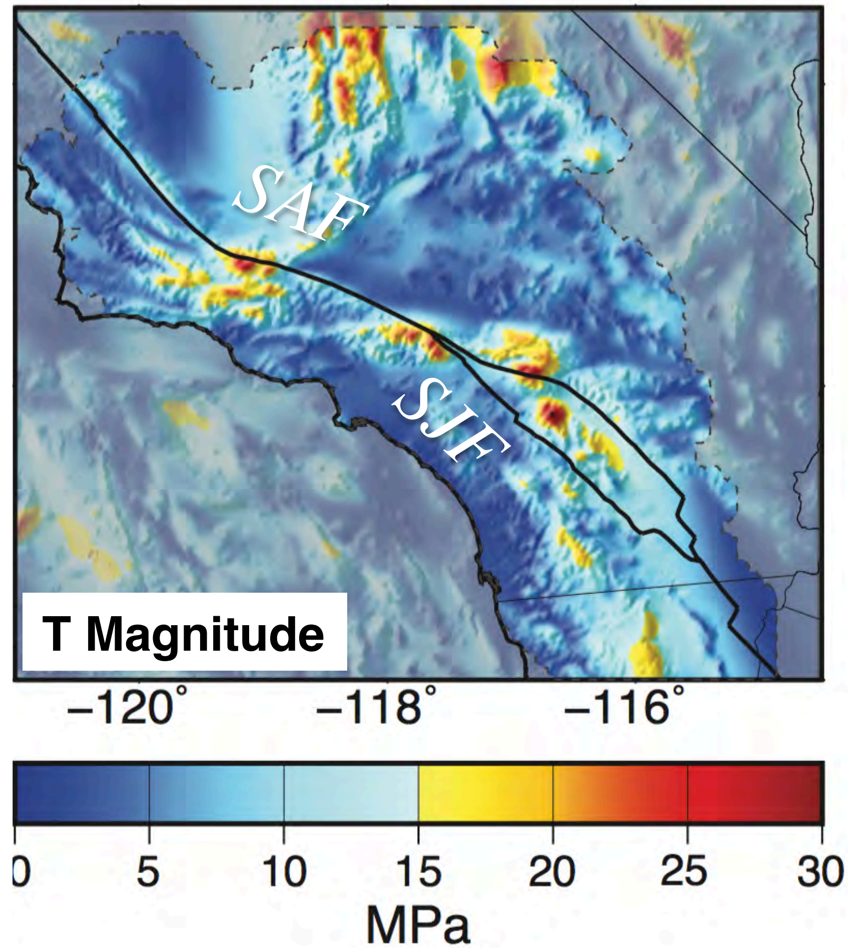
  - [Yang and Hauksson, 2013]
- **L**: Stress accumulation rate on locked faults from buried dislocation, constrained by geodesy, but **need to know time**
  - e.g. [Smith-Konter et al., 2011]
- **T**: crustal stress from Topography assuming critical stress state, constrained by gravity, but **minimum estimate of magnitude**
  - e.g. [Luttrell and Sandwell, 2012]

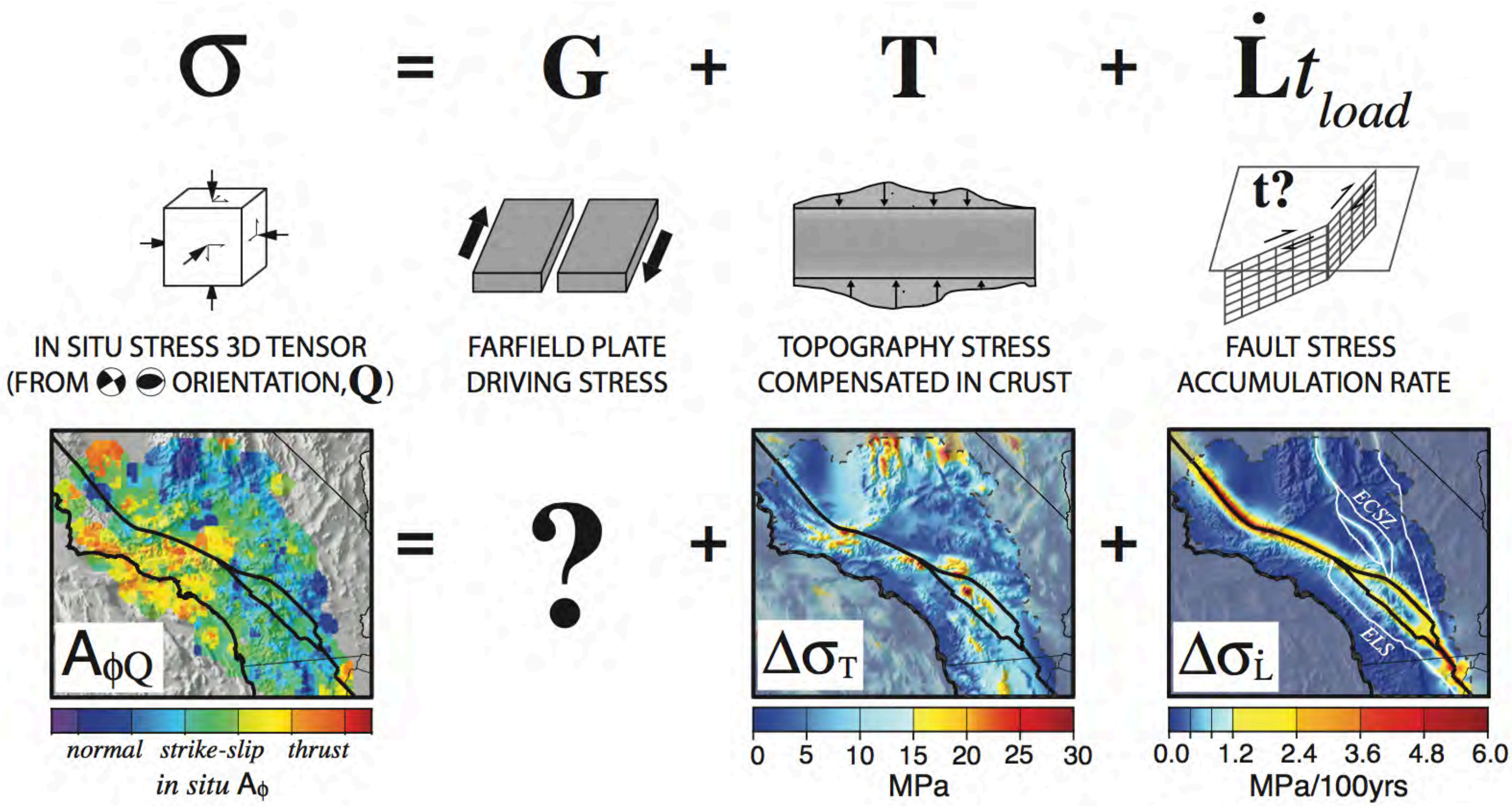




[Luttrell and Smith-Konter, 2016, in review]

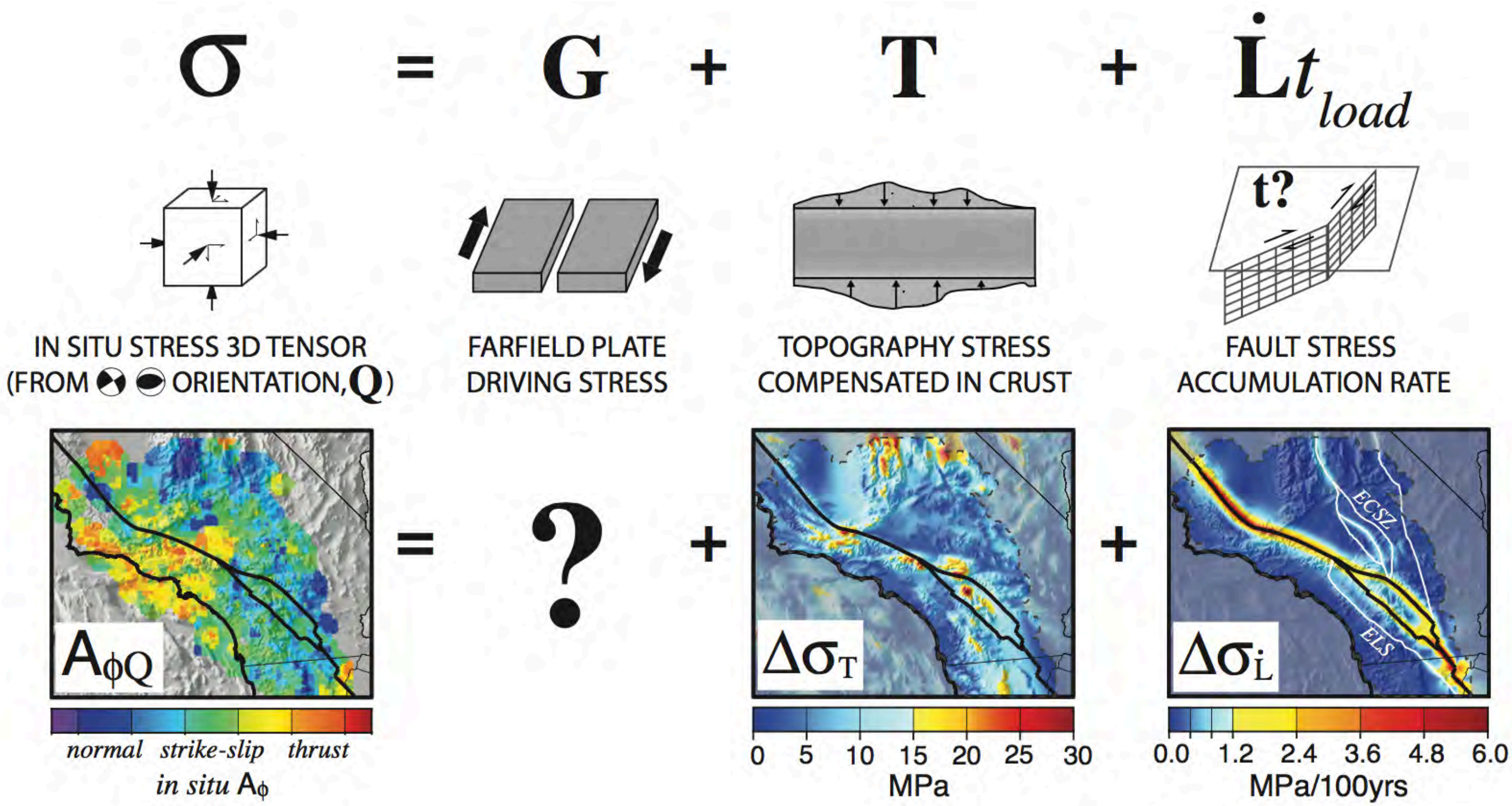
What about the driving stress (G) ?

- 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 ~uniformly distributed about mean SHmax.



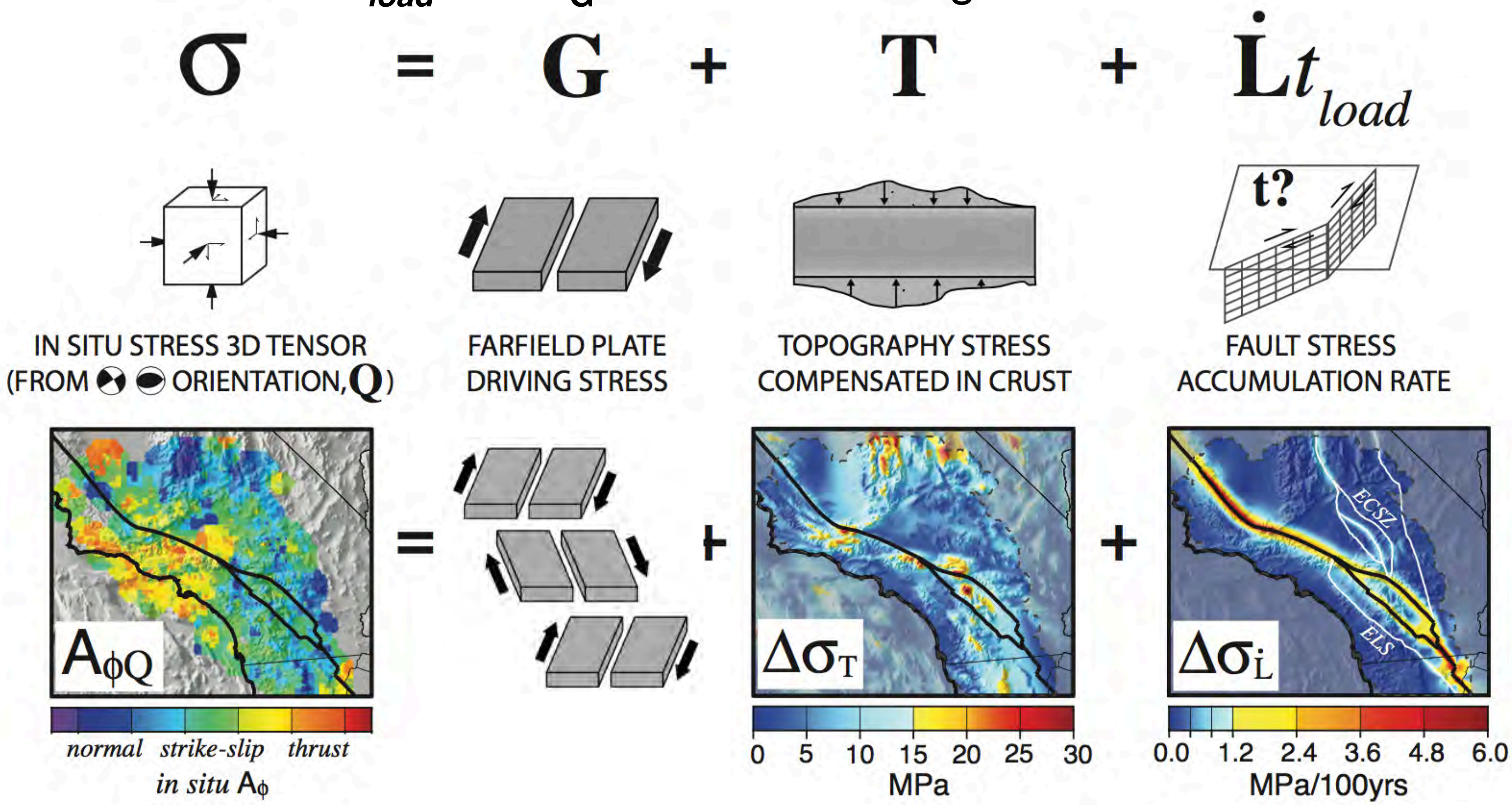
What about the driving stress (G) ?

- **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) ?

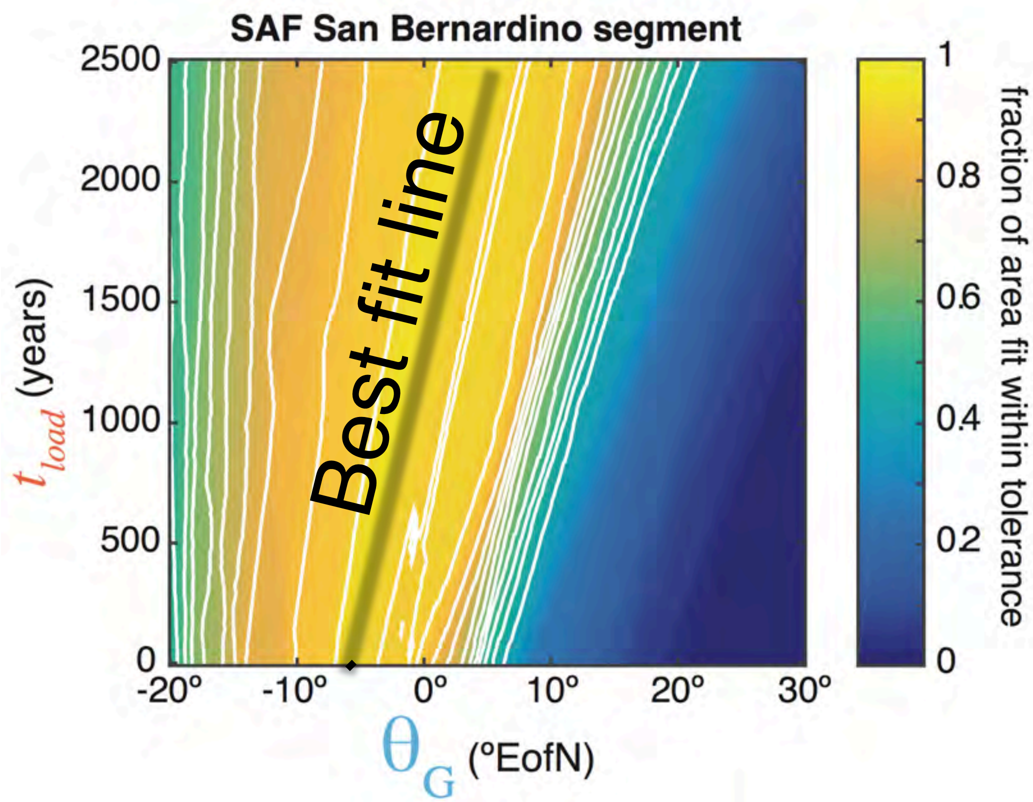
- Let driving stress **(G)** be 2D horizontal strike-slip
  - Let magnitude $\Delta\sigma_G$ = 62 MPa (sufficient to support near fault topography, [*Luttrell and Smith-Konter, in revision*])
  - Let orientation $\boldsymbol{\theta_G}$ vary between 12 individual SAF/SJF fault segments
  - Let loading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

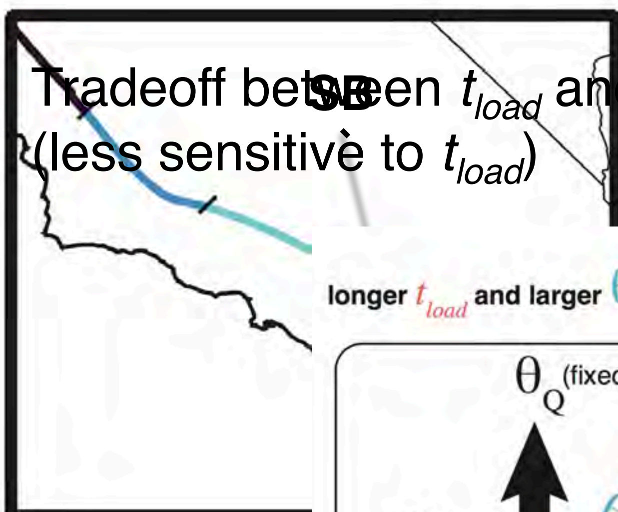


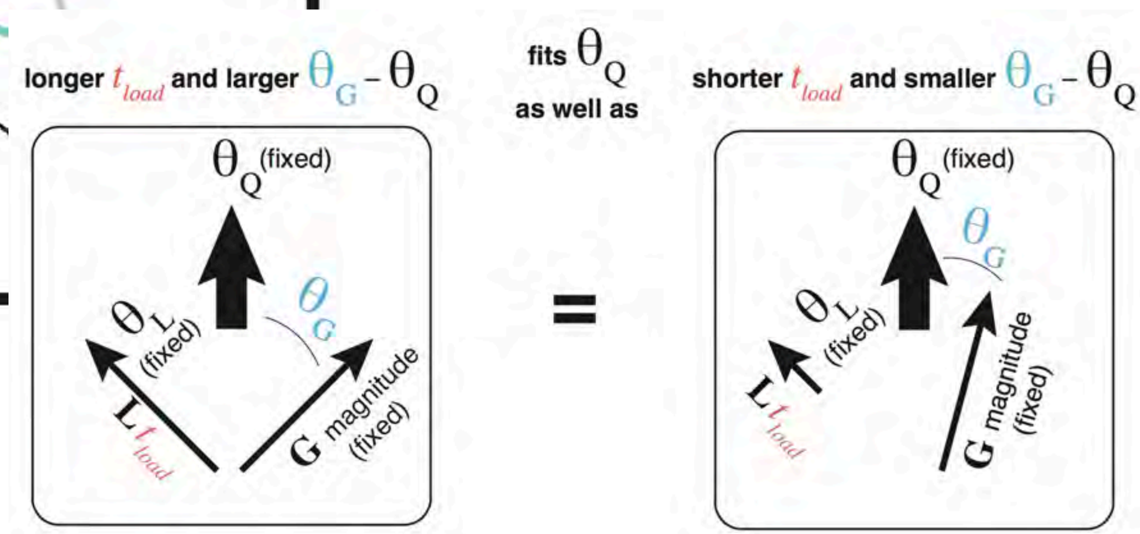
Results for one segment

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

- Tradeoff between t_{load} and θ_G (less sensitive to t_{load})

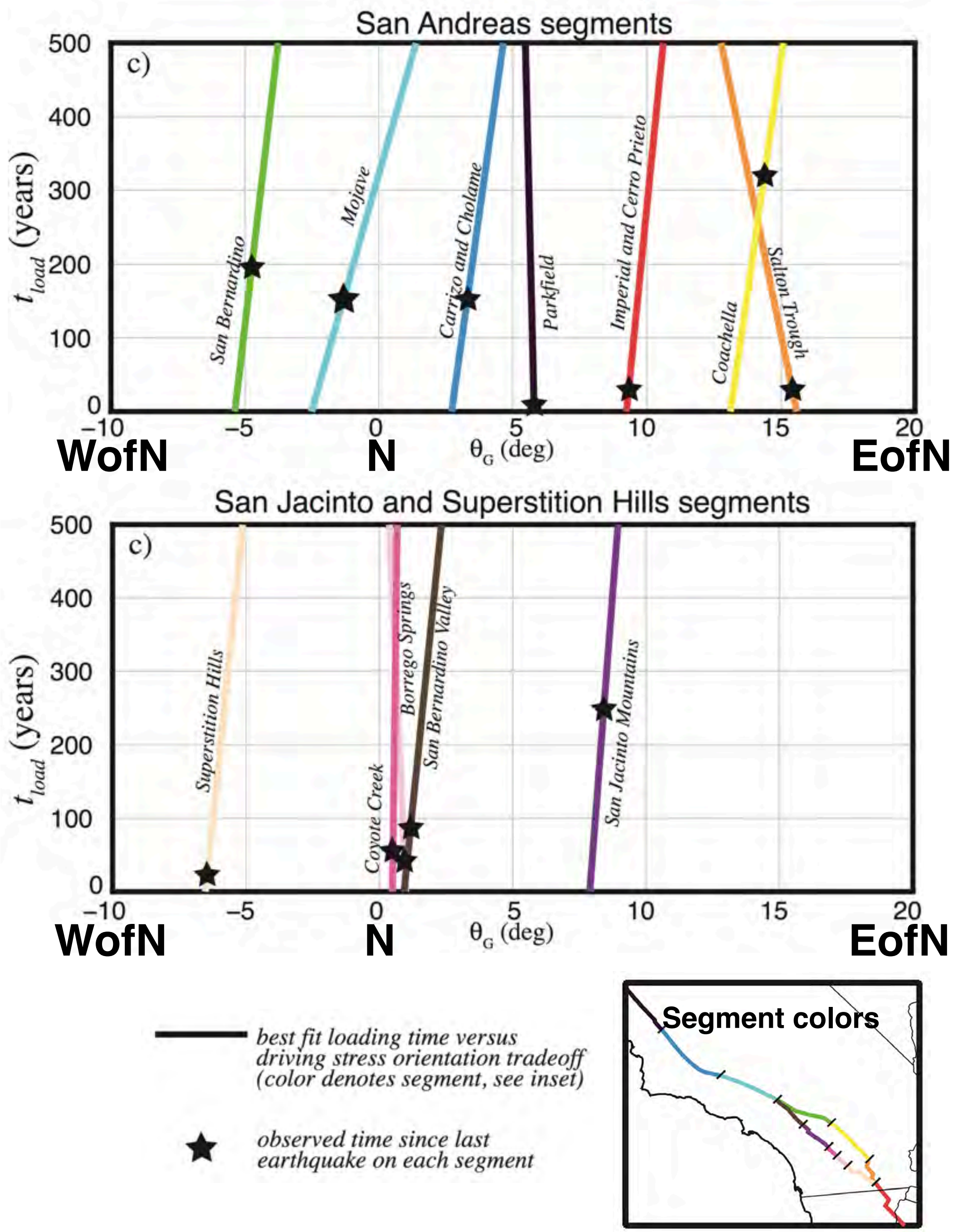






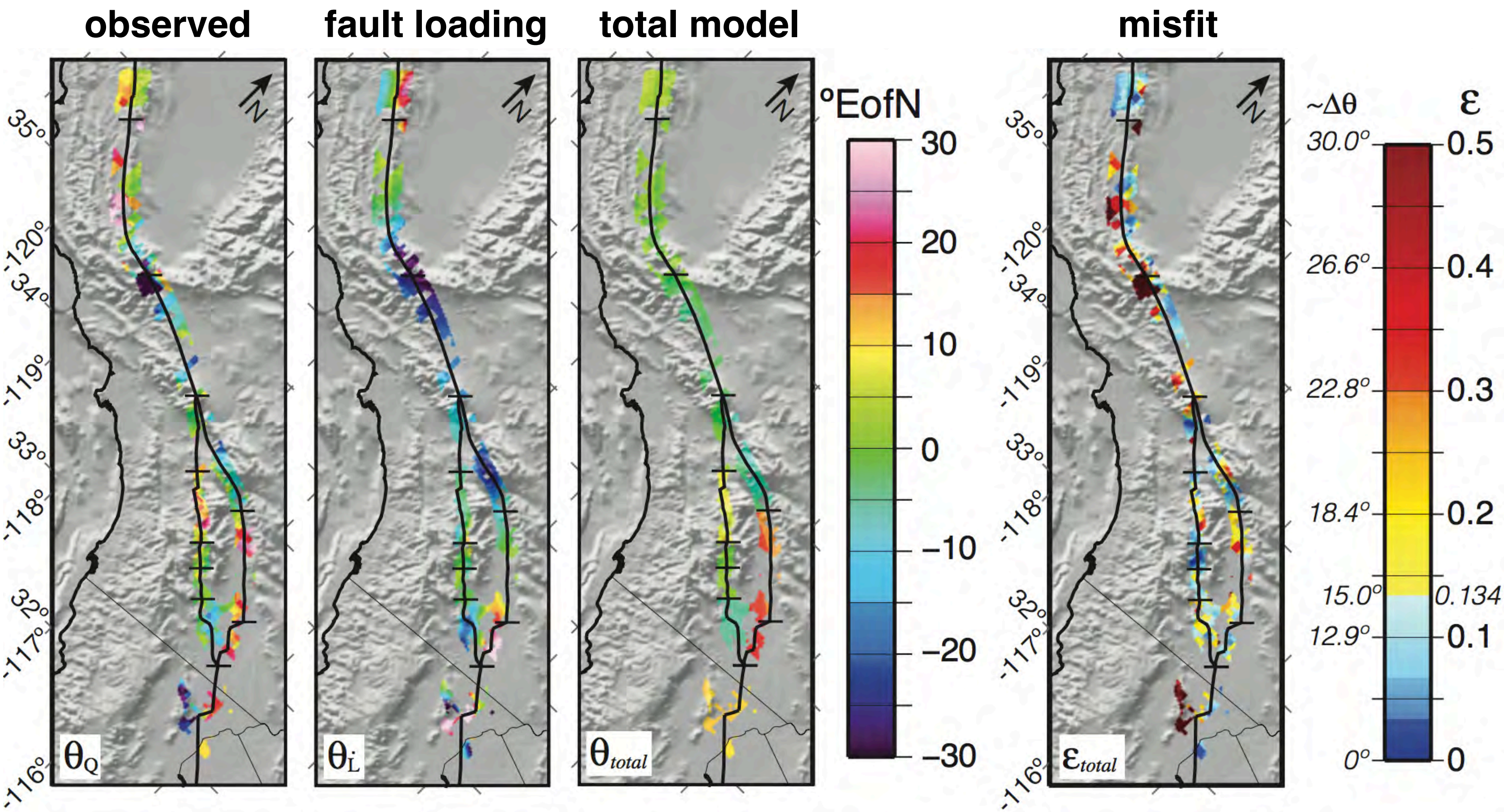
Results for all the segments

- 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 ±30º, ~60% fits to better than ±15º
- **Along-fault driving stress rotations are required** **(can't be homogeneous)**



<u>What does this mean?</u>

- 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.

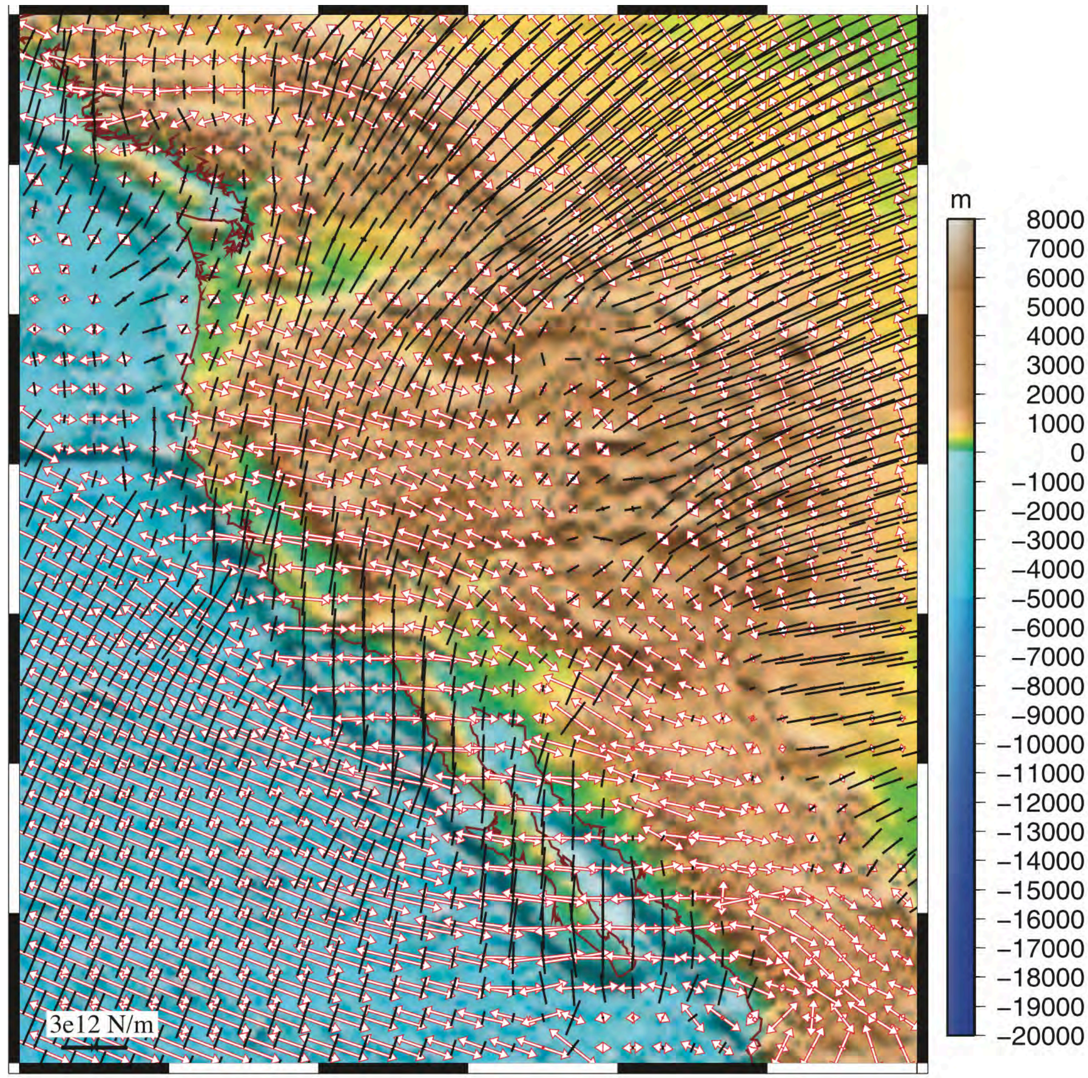
- **<u>Observations:</u>** driving stress **(G)** is **~bimodal**,
- **Loading of major faults is not sufficient** to explain the gross heterogeneities of the *in situ* stress field, despite matching the surface geodetic observations very well.

- 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?

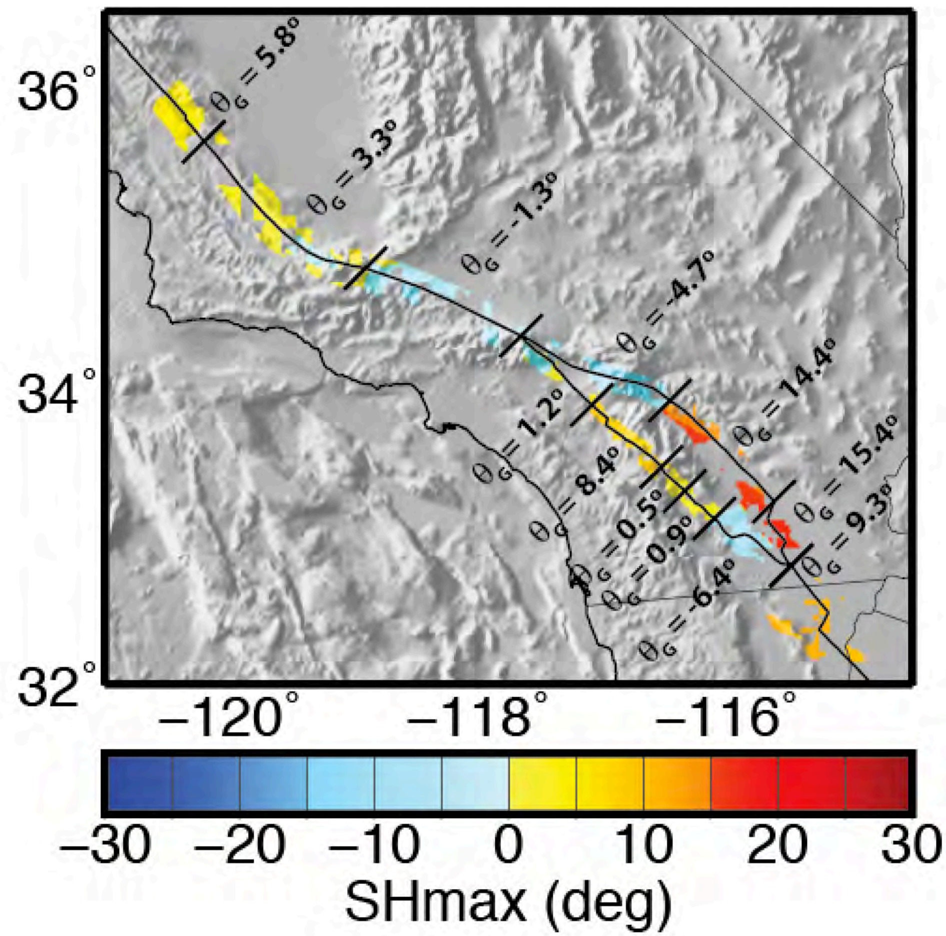
- Geodynamic forward models of stress in lithosphere globally
- Global model, but SoCal has a few pixels…
- Along SAF, stress rotates CCW then CW from south to north

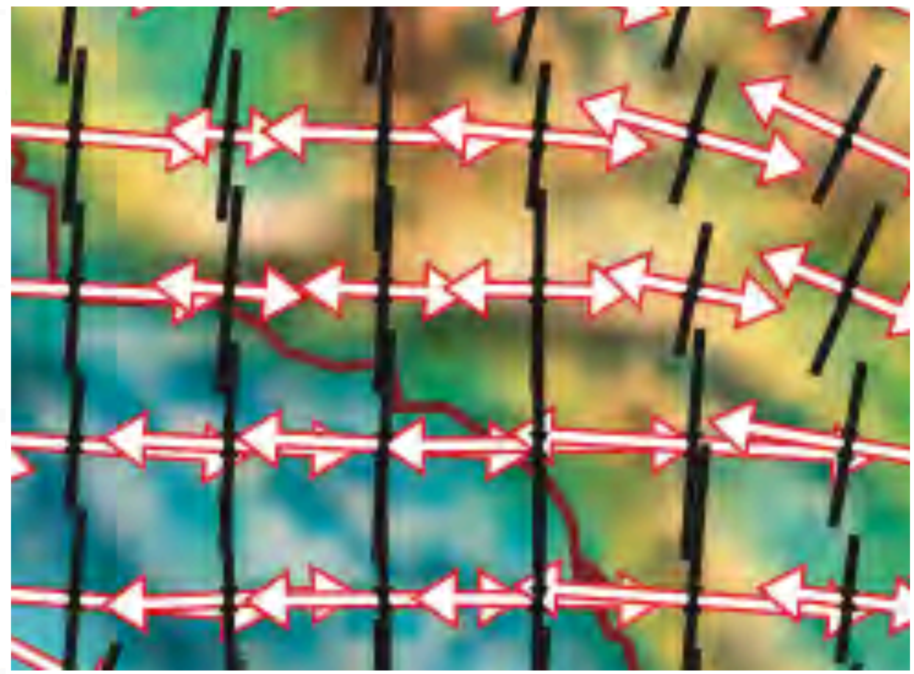
Predicted deviatoric stress



[Ghosh and Holt, 2012]

<u>Side by side</u>





[Ghosh and Holt, 2012]

Conclusions so far…

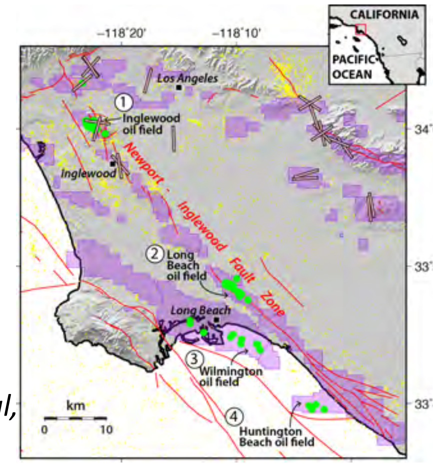
- Lower-bound estimate on differential stress magnitude
- Simple forward model **fits pretty well**
  - Corroborates individual model components
- Plate driving stress has rotations **(not homogeneous)**
  - Sudden ~14º CCW rotation along sSAF, between Coachella and San Bernardino segments
  - Gradual ~14º 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?
  - ?????

Outline

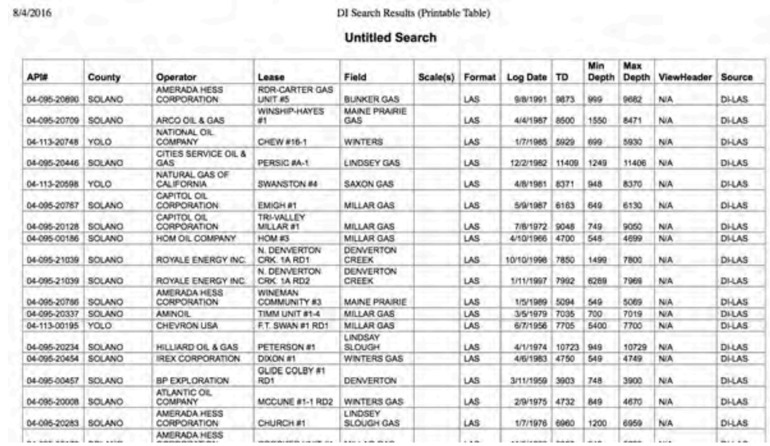
1. Contributions and questions
2. Estimates of stress magnitude
3. Which processes dominate crustal stress heterogeneity?
4. What's next?

What's Next? More Observations

- Finding more borehole observations



Persaud et. al, 2015 AGU



8/4/2016 DI Search Results (Printable Table)

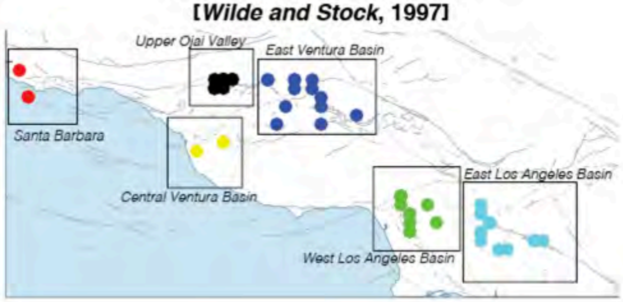
Untitled Search

API#	County	Operator	Lease	Field	Scale(s)	Format	Log Date	TD	Min Depth	Max Depth	ViewHeader	Source
04-095-20890	SOLANO	AMERADA HESS CORPORATION	RDR-CARTER GAS UNIT #5	BUNKER GAS		LAS	9/8/1991	9873	999	9682	N/A	DI-LAS
04-095-20709	SOLANO	ARCO OIL & GAS	WINSHIP-HAYES #1	MAINE PRAIRIE GAS		LAS	4/4/1987	8500	1550	8471	N/A	DI-LAS
04-113-20748	YOLO	NATIONAL OIL COMPANY	CHEW #16-1	WINTERS		LAS	1/7/1985	5929	699	5930	N/A	DI-LAS
04-095-20446	SOLANO	CITIES SERVICE OIL & GAS	PERSIC #A-1	LINDSEY GAS		LAS	12/2/1982	11409	1249	11406	N/A	DI-LAS
04-113-20598	YOLO	NATURAL GAS OF CALIFORNIA	SWANSTON #4	SAXON GAS		LAS	4/8/1981	8371	948	8370	N/A	DI-LAS
04-095-20767	SOLANO	CAPITOL OIL CORPORATION	EMIGH #1	MILLAR GAS		LAS	5/9/1987	6163	649	6130	N/A	DI-LAS
04-095-20128	SOLANO	CAPITOL OIL CORPORATION	TRI-VALLEY MILLAR #1	MILLAR GAS		LAS	7/8/1972	9048	749	9050	N/A	DI-LAS
04-095-00186	SOLANO	HOM OIL COMPANY	HOM #3	MILLAR GAS		LAS	4/10/1966	4700	548	4699	N/A	DI-LAS
04-095-21039	SOLANO	ROYALE ENERGY INC.	N. DENVERTON CRK. 1A RD1	DENVERTON CREEK		LAS	10/10/1998	7850	1499	7800	N/A	DI-LAS
04-095-21039	SOLANO	ROYALE ENERGY INC.	N. DENVERTON CRK. 1A RD2	DENVERTON CREEK		LAS	1/11/1997	7992	6289	7969	N/A	DI-LAS
04-095-20786	SOLANO	AMERADA HESS CORPORATION	WINEMAN COMMUNITY #3	MAINE PRAIRIE		LAS	1/5/1989	5094	549	5069	N/A	DI-LAS
04-095-20337	SOLANO	AMINOIL	TIMM UNIT #1-4	MILLAR GAS		LAS	3/5/1979	7035	700	7019	N/A	DI-LAS
04-113-00195	YOLO	CHEVRON USA	F.T. SWAN #1 RD1	MILLAR GAS		LAS	6/7/1956	7705	5400	7700	N/A	DI-LAS
04-095-20234	SOLANO	HILLIARD OIL & GAS	PETERSON #1	LINDSAY SLOUGH		LAS	4/1/1974	10723	949	10729	N/A	DI-LAS
04-095-20454	SOLANO	IREX CORPORATION	DIXON #1	WINTERS GAS		LAS	4/6/1983	4750	549	4749	N/A	DI-LAS
04-095-00457	SOLANO	BP EXPLORATION	GLIDE COLBY #1 RD1	DENVERTON		LAS	3/11/1959	3903	748	3900	N/A	DI-LAS
04-095-20008	SOLANO	ATLANTIC OIL COMPANY	MCCUNE #1-1 RD2	WINTERS GAS		LAS	2/9/1975	4732	849	4670	N/A	DI-LAS
04-095-20283	SOLANO	AMERADA HESS CORPORATION	CHURCH #1	LINDSEY SLOUGH GAS		LAS	1/7/1976	6960	1200	6959	N/A	DI-LAS
[illegible]	[illegible]	AMERADA HESS [illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Phoenix Harris, LSU undergrad

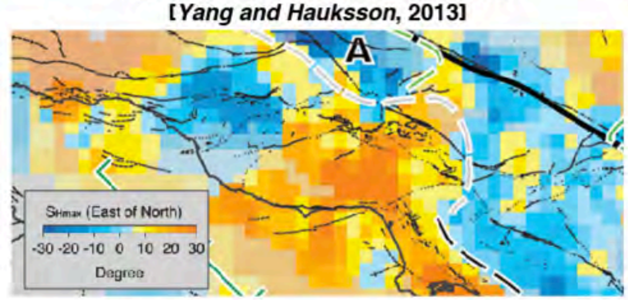
- Incorporating the borehole observations we already have

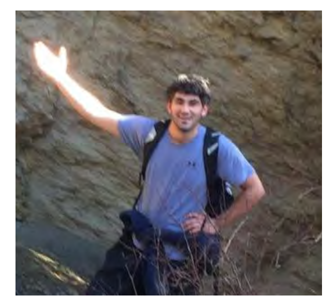
Borehole observations
[*Wilde and Stock*, 1997]



vs.

Focal Mechansim observations
[*Yang and Hauksson*, 2013]

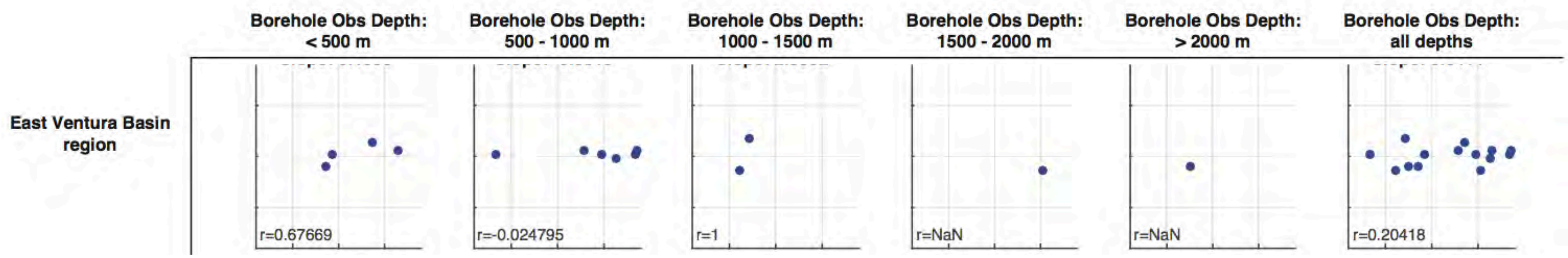




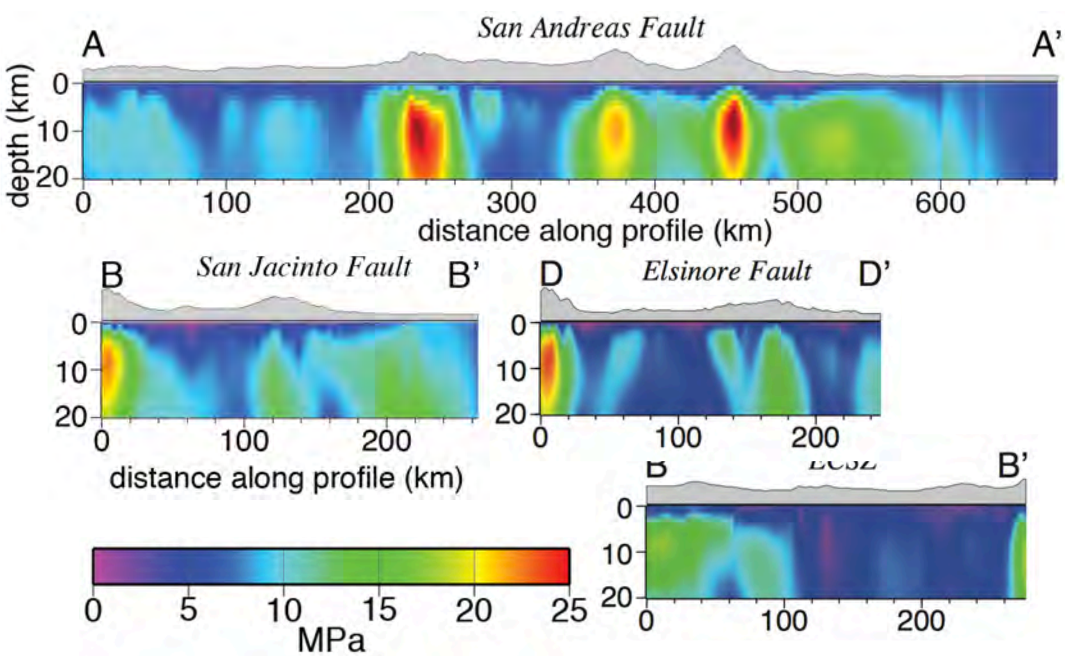
Joel Spansel, LSU undergrad

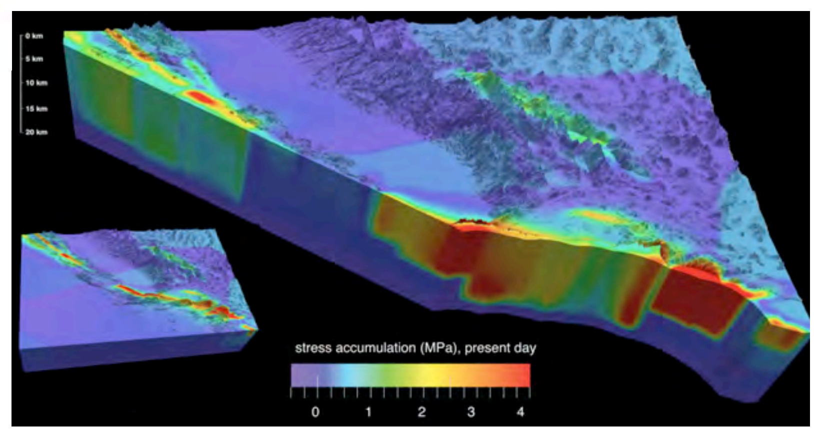
What's Next? Incorporating Depth

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



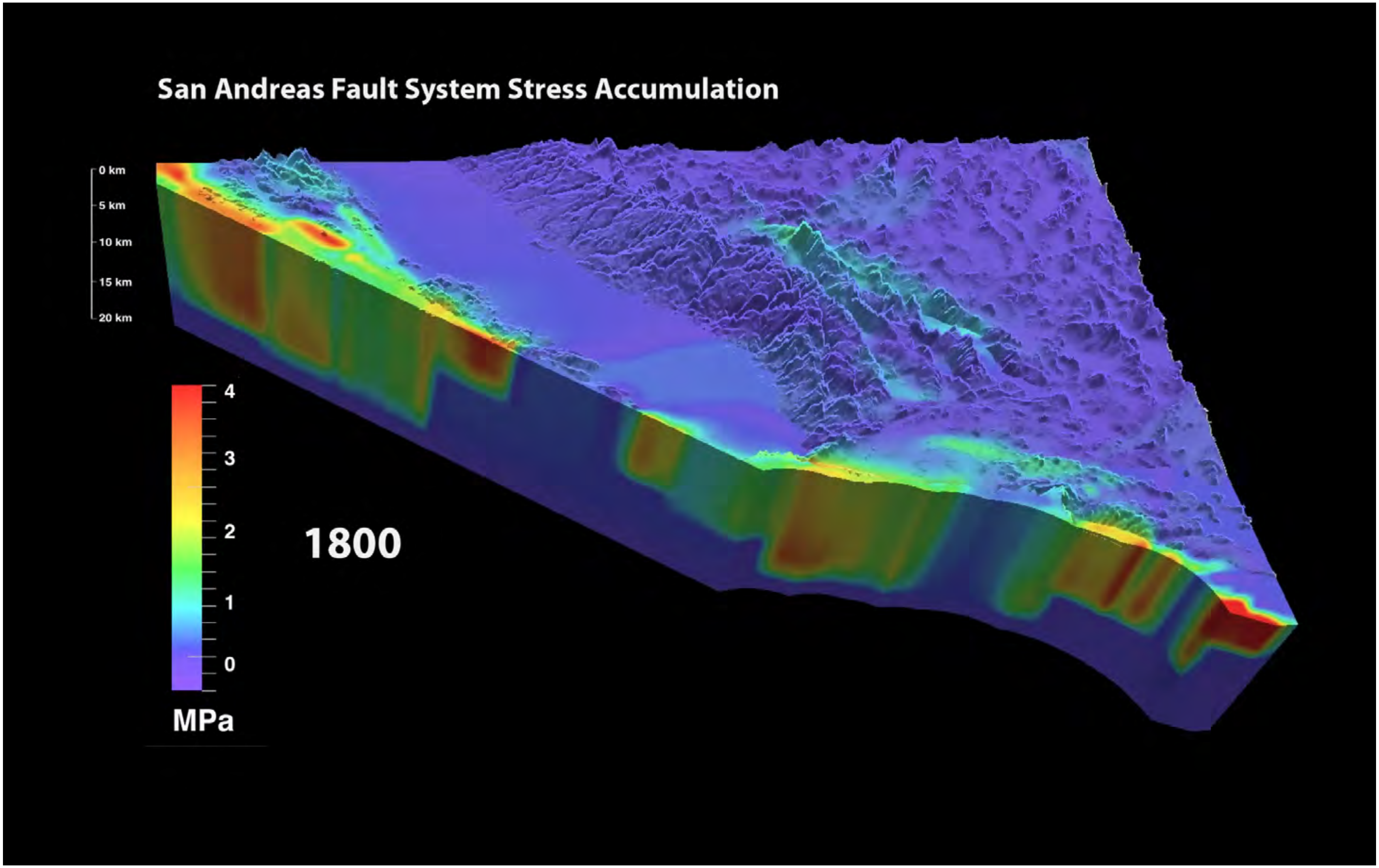
- Depth dependent component models
  - e.g., topography and fault loading



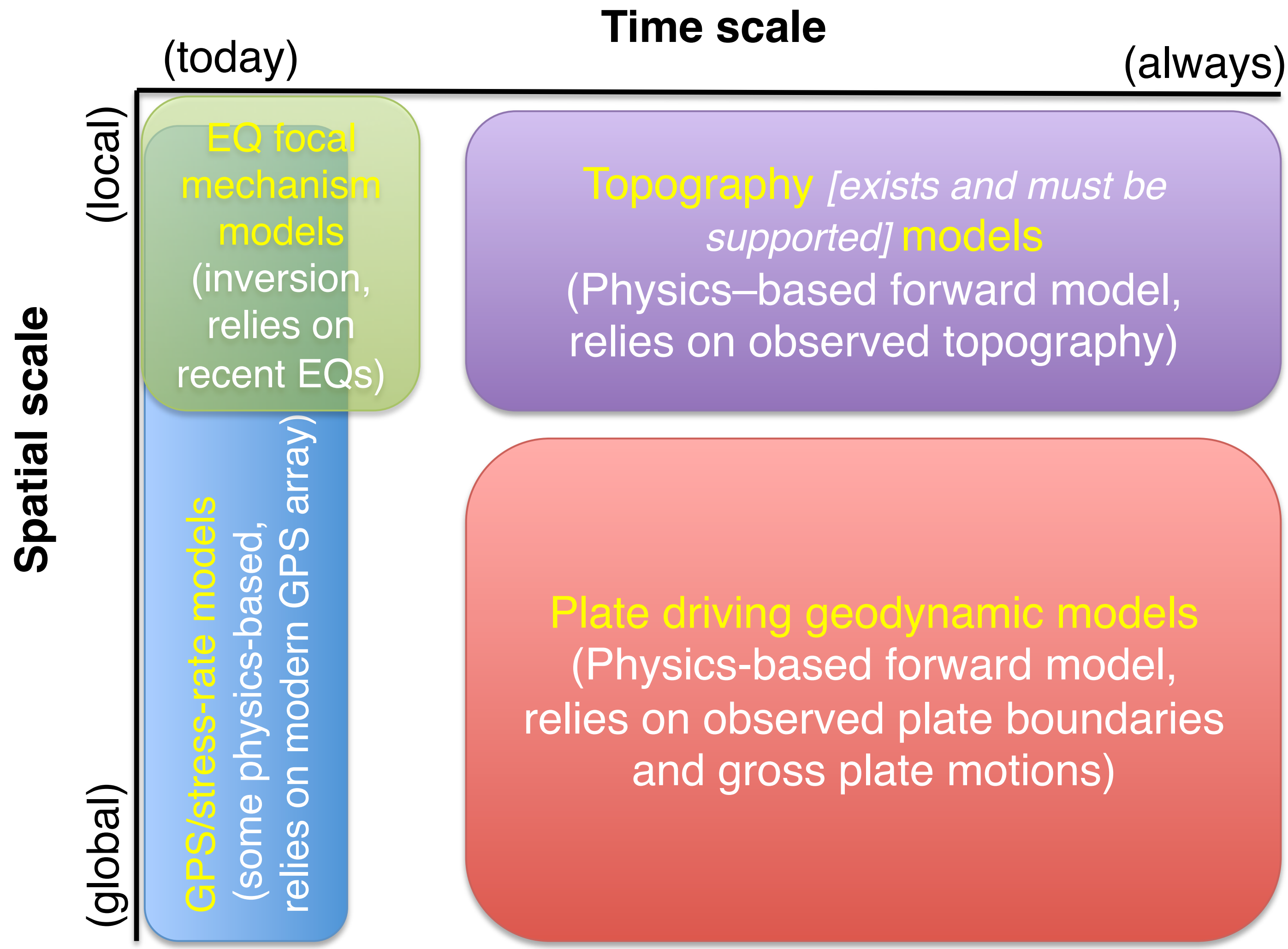


What’s Next? Incorporating Time

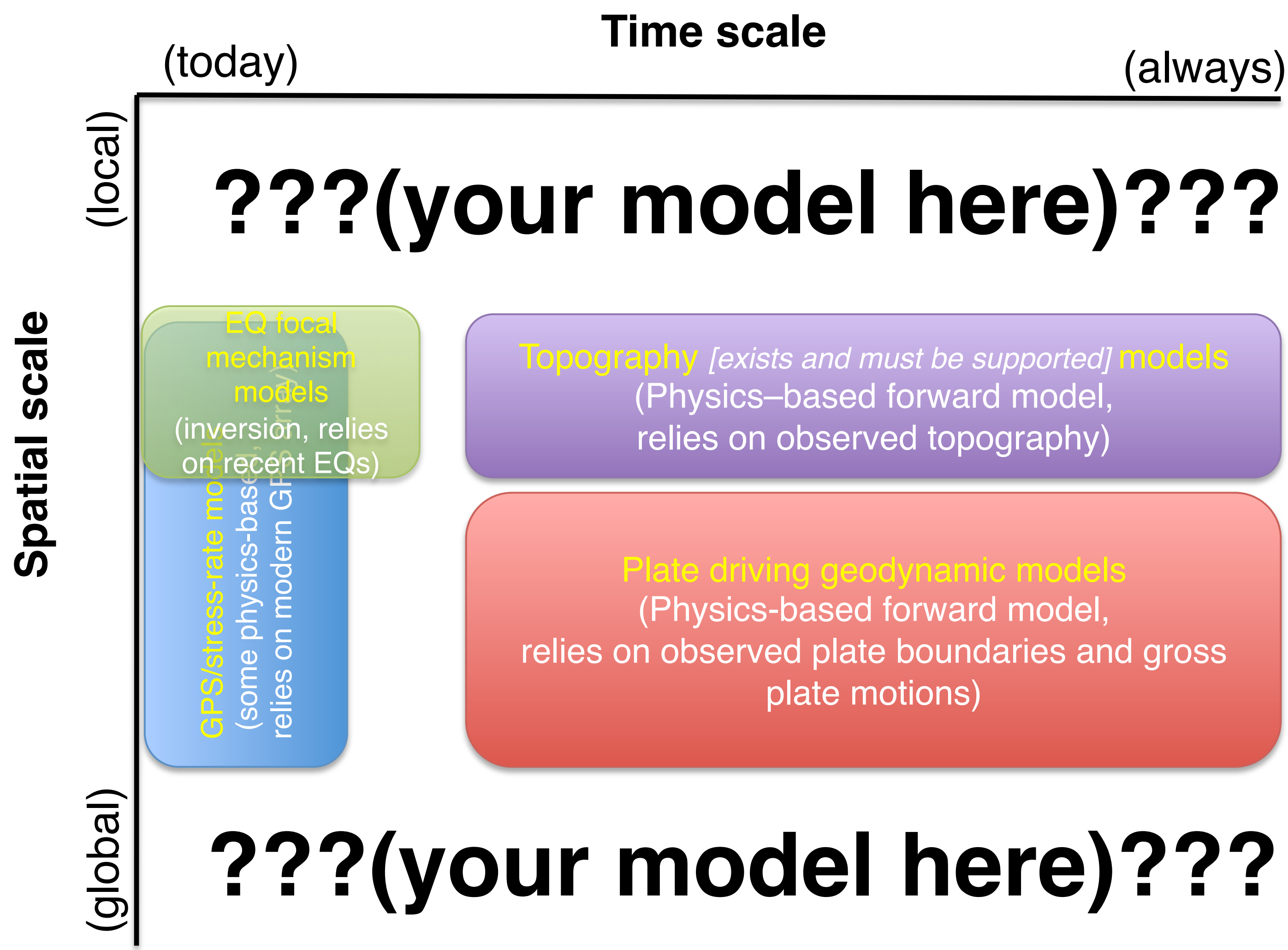
Smith-Konter et. al, Poster #010



What's Next? Bridging Processes



What's Next? Bridging Processes




Thanks!