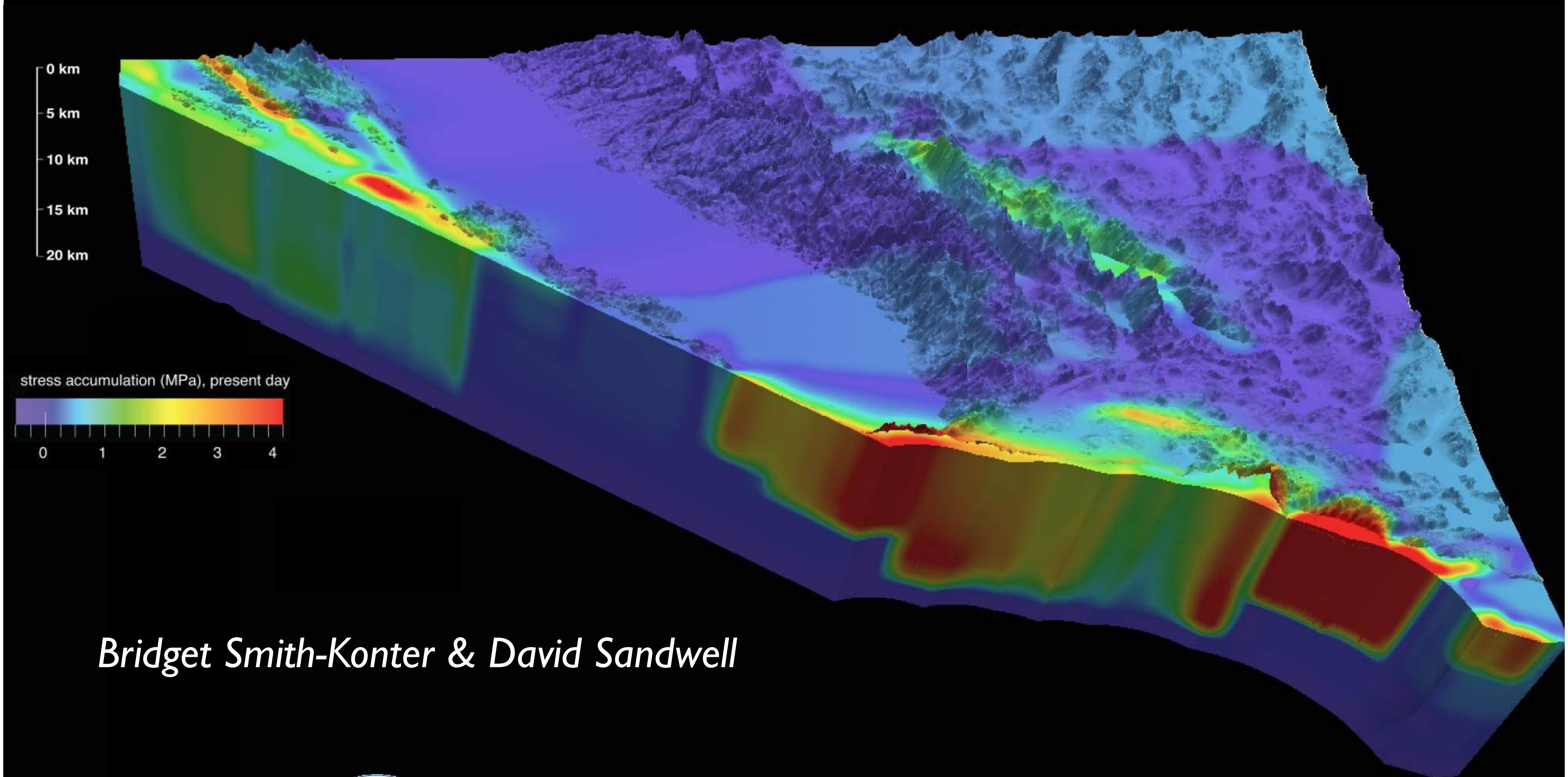
4-D earthquake cycle modeling of the San Andreas Fault System: *Stress rates, historical stress accumulation, and uncertainties*



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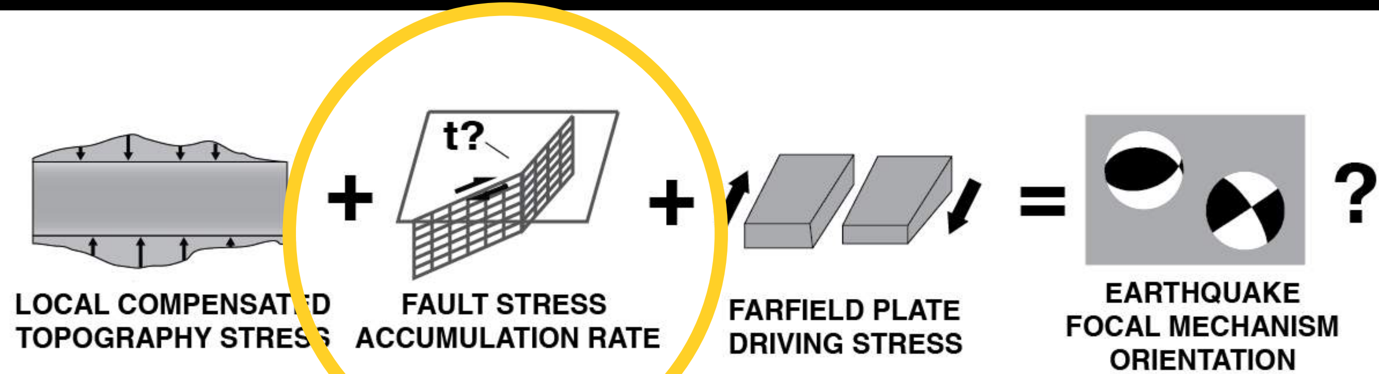
Reconciling Stress Models & Data

i.e., earthquake cycle stress rate, or fault loading stress rate

Does



Up next: *Earthquake cycle influence on the plate boundary stress budget, as constrained by seismology, geodesy, and topography – K. Luttrell*

Earthquake Cycle Stress

Which factors are most important for evaluating earthquake cycle stress?

1. Physical model: 3-D Maxwell viscoelastic
2. Long-term slip rates (geology)
3. Crustal velocity (geodesy) → fault locking depths
4. Slip history from major ruptures (paleoseismology)
5. Mantle viscosity, elastic plate thickness, coef. of friction, etc.

How sensitive is stress rate and stress accumulation to model parameters and assumptions?

A Preview

Most important factors for estimating earthquake cycle stress on faults today

Not very important

- lithospheric thickness/rheology
- coefficient of friction
- mantle viscosity

Very important

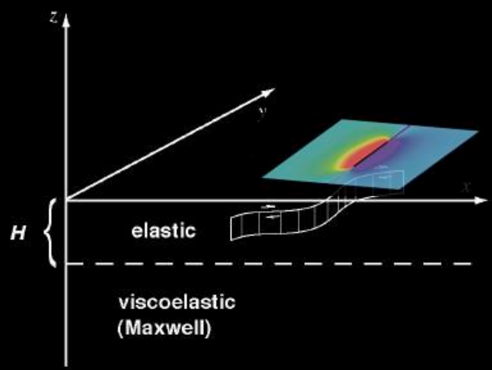
Stress accumulation rate

- locking depth
- long-term slip rate*

Stress (accumulation)

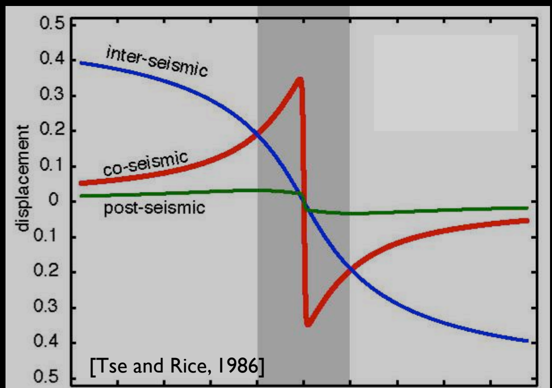
- rupture/slip history*

Modeling 4D Earthquake Cycle Deformation



3D semi-analytic Fourier model [*Smith and Sandwell*, 2004]

- analytic calculations for depth and time-dependence
- numeric calculations for 2-D Fourier transforms

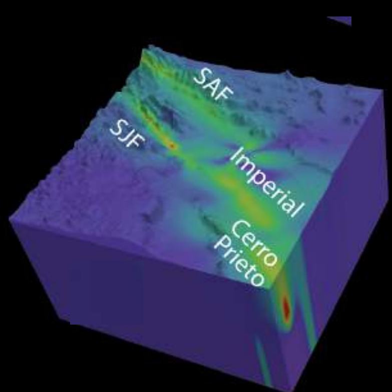


3D deformation(t) = interseismic + Σ earthquakes

(deep slip) (co. + postseismic)

Model efficiency

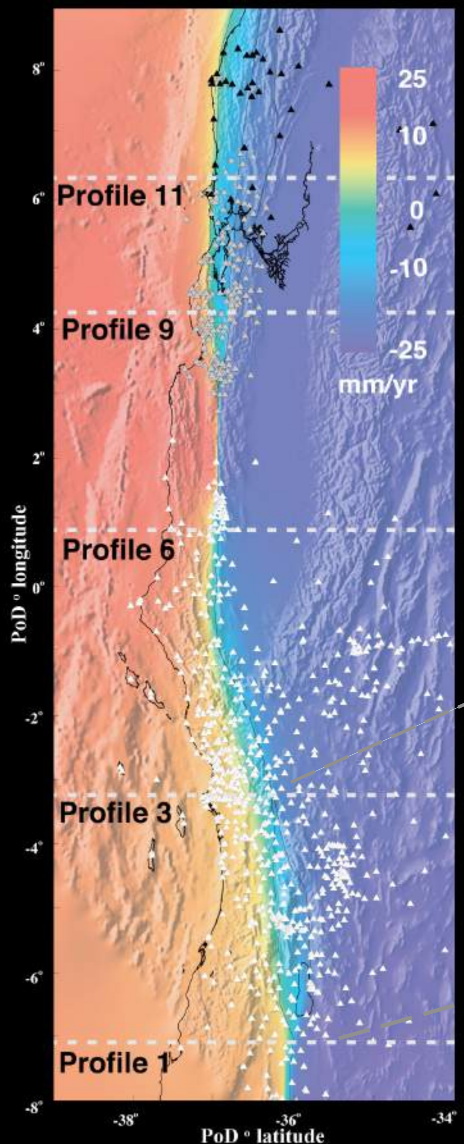
- 2048 x 2048 grid cells
- common locking depth, single event: ~ 3s of CPU time
- 50+ depths, 100+ events over 1000 years: ~20 min.



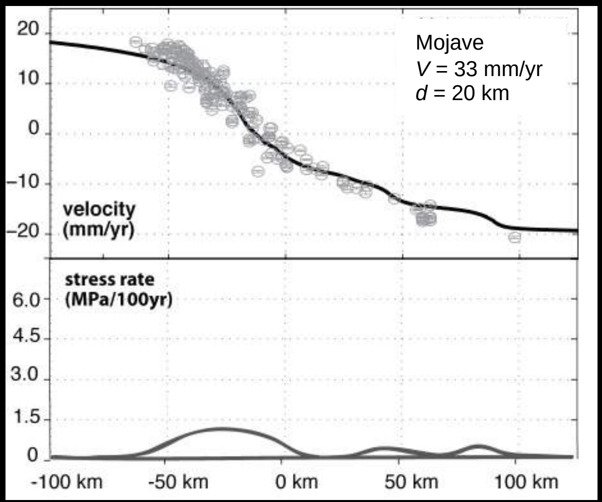
4D visualization

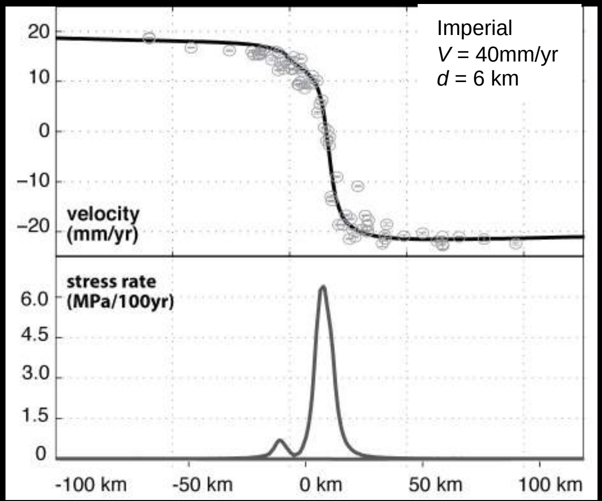
- ParaView visualization package
- 3D meshed volumes

Resolving Fault Depths With PBO Velocities



- Locking depth inversion from PBO velocity field
- Modeled stress rates inversely proportional to locking depth



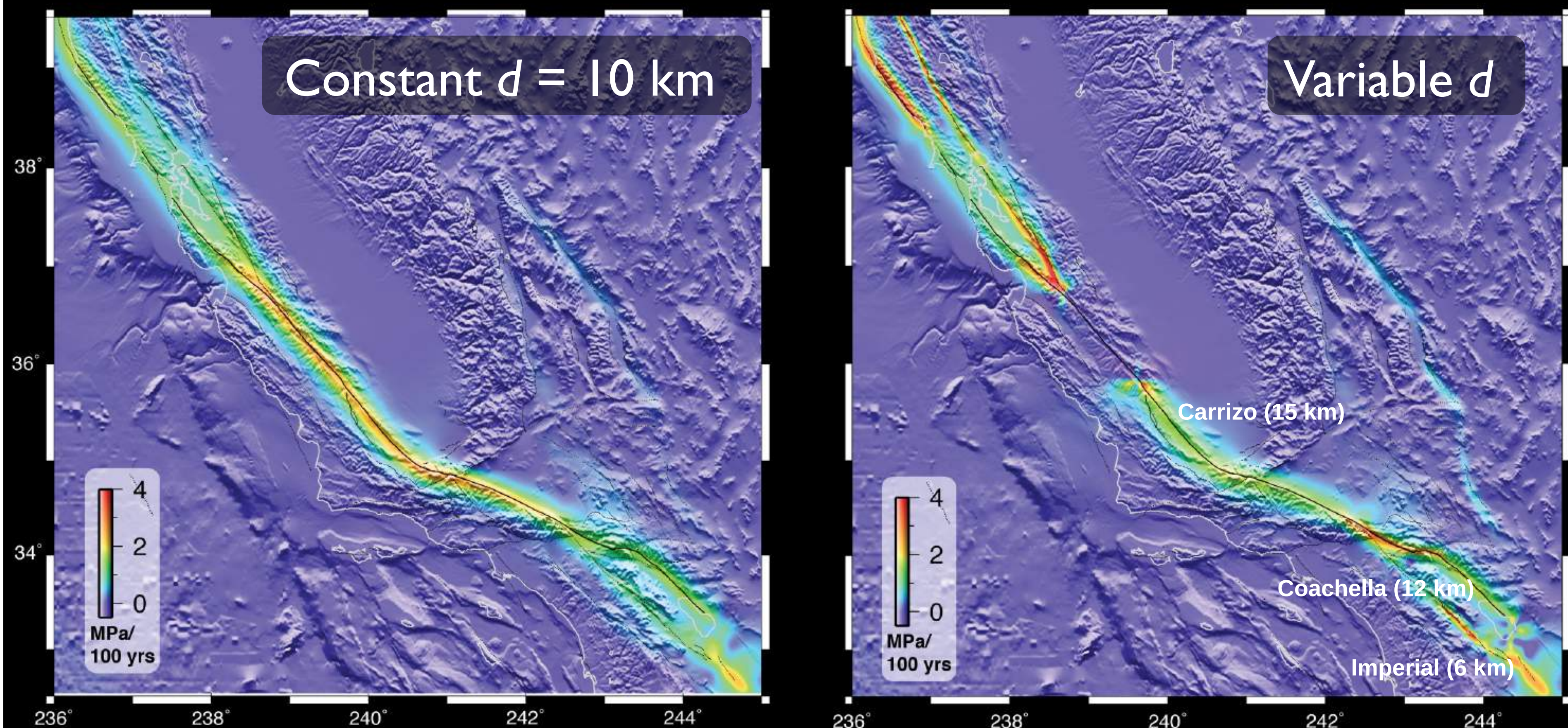


[*Smith-Konter and Sandwell, 2009*]
[Tong, *Smith-Konter, and Sandwell, 2014*]

Interseismic Stress Rates

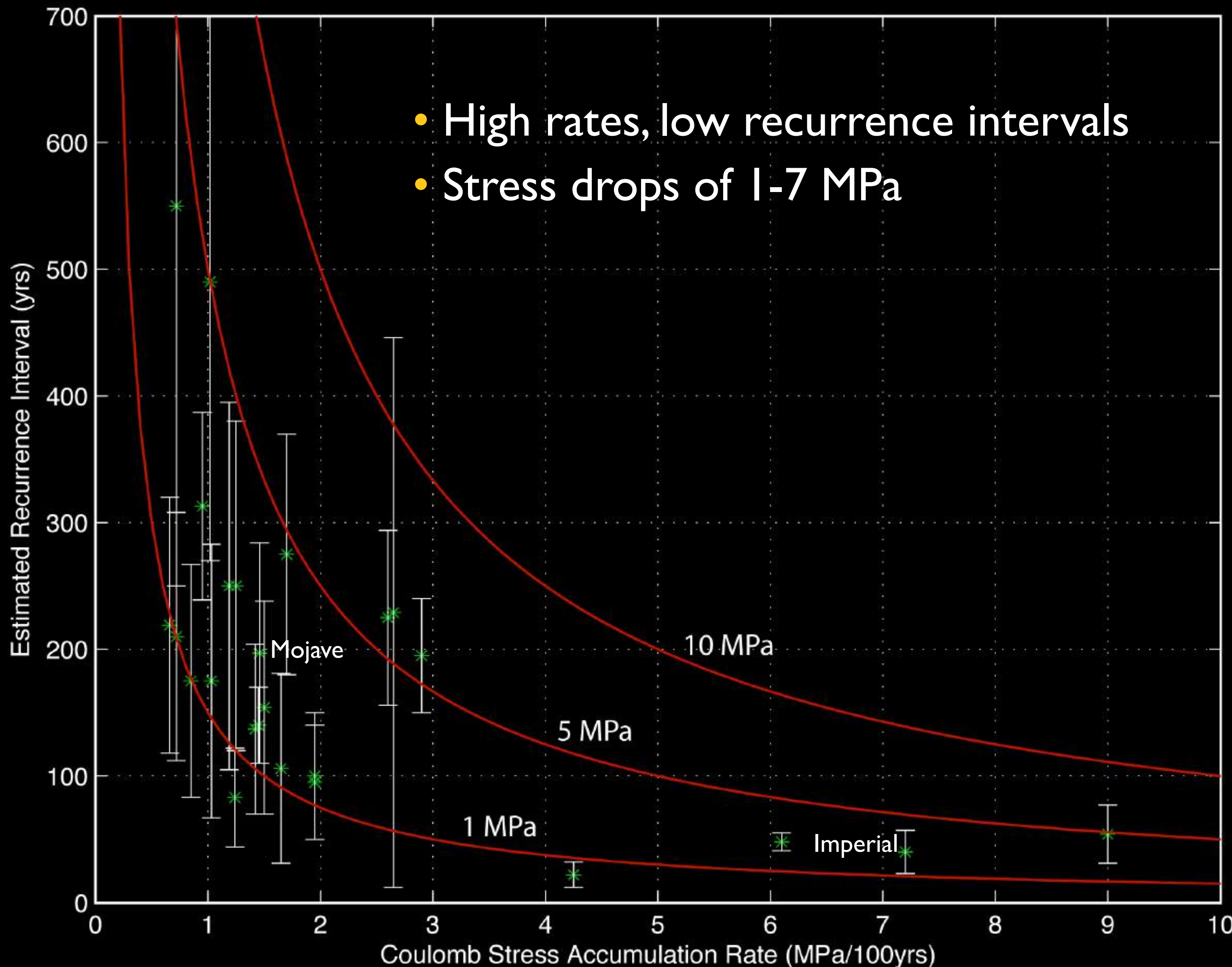
- Static <u>Coulomb stress</u> rates due to interseismic strain accumulation at depth
- Variations due to slip rate, *locking depth (d)*, local fault geometry
- Observation depth is important

$$\tau_c = \tau - \mu_f \sigma$$



[*Smith-Konter and Sandwell*, 2009]

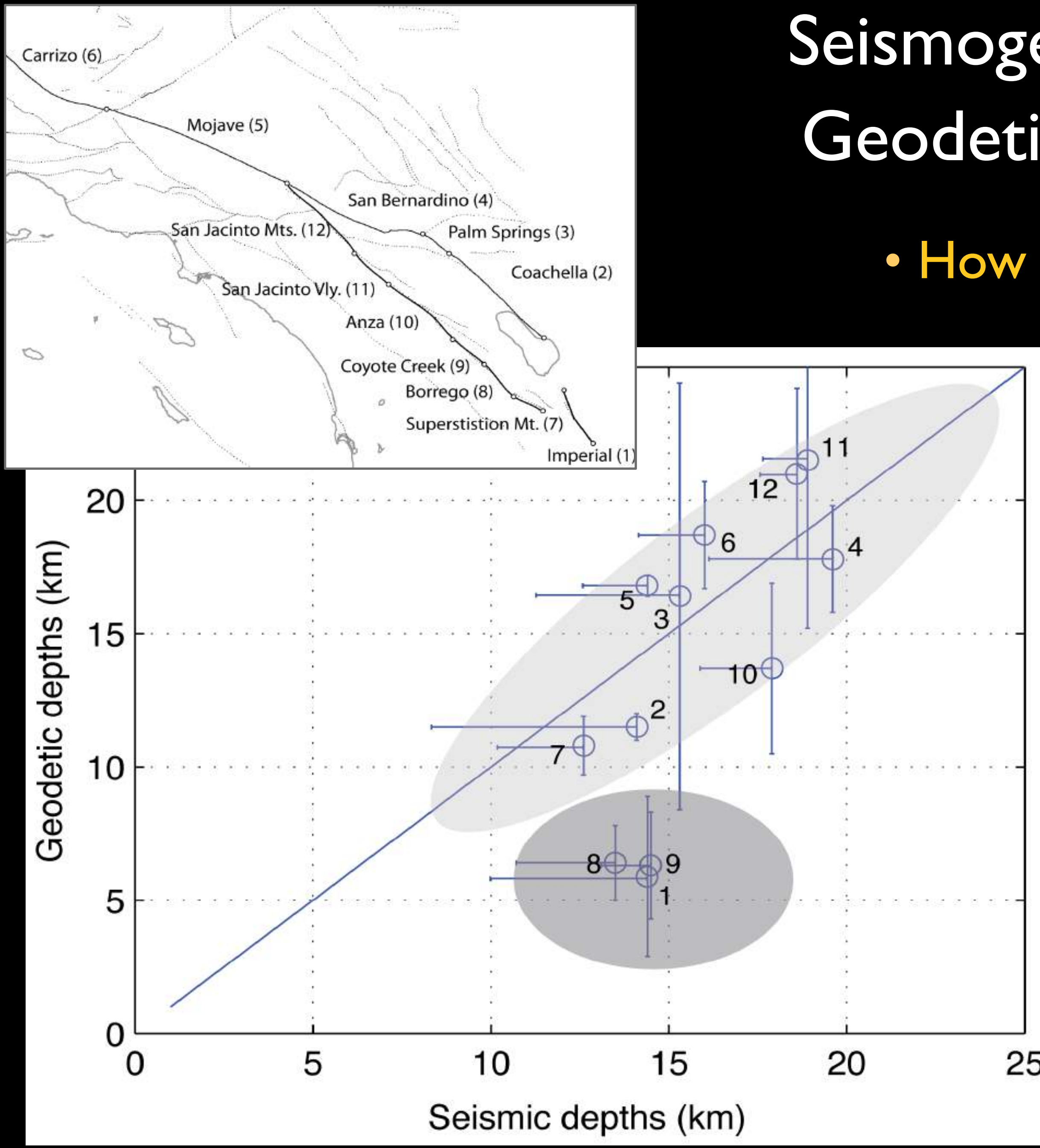
Stress Accumulation Rates vs. Recurrence Intervals



[*Smith-Konter and Sandwell,* 2009]

Seismogenic Thickness vs. Geodetic Locking Depth

- How well do we know *d* ?



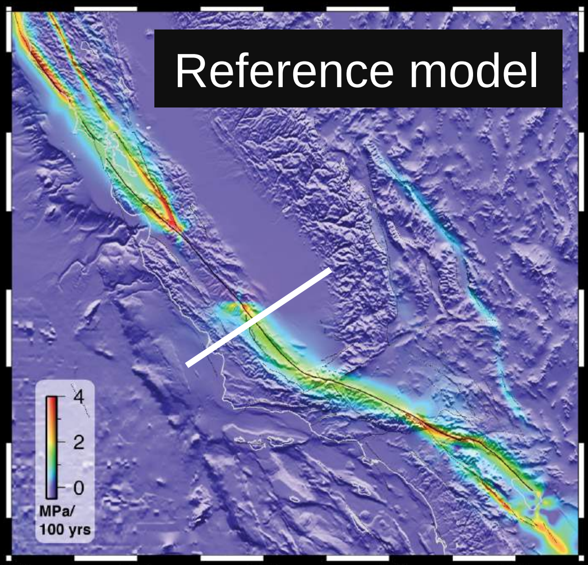
[*Smith-Konter, Sandwell, Shearer*, JGR 2011]

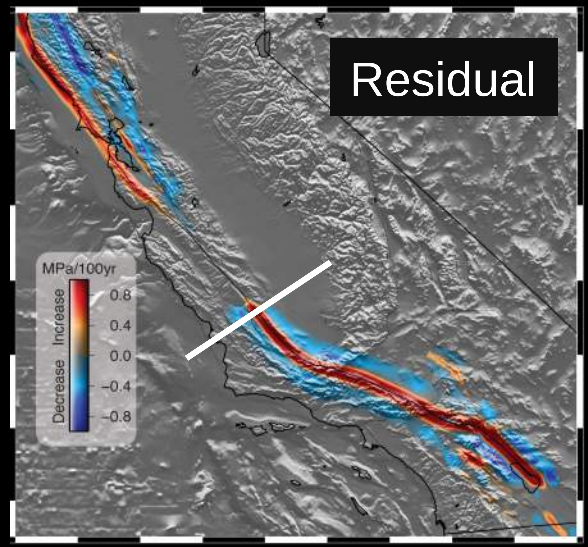
Seismic depths
- 95% cutoff depth
- 12-20 km

Geodetic depths
- thickness of locked zone
- 6-22 km

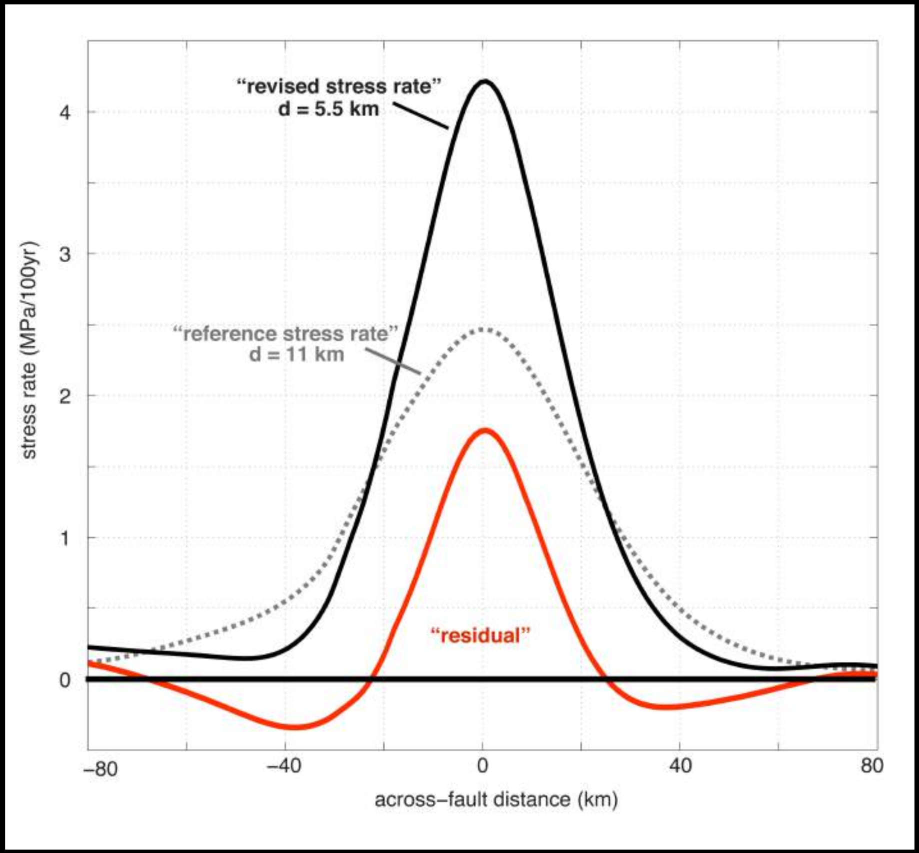
Outliers
- Coyote Creek, Borrego, Imperial

Stress Rate Sensitivity Test

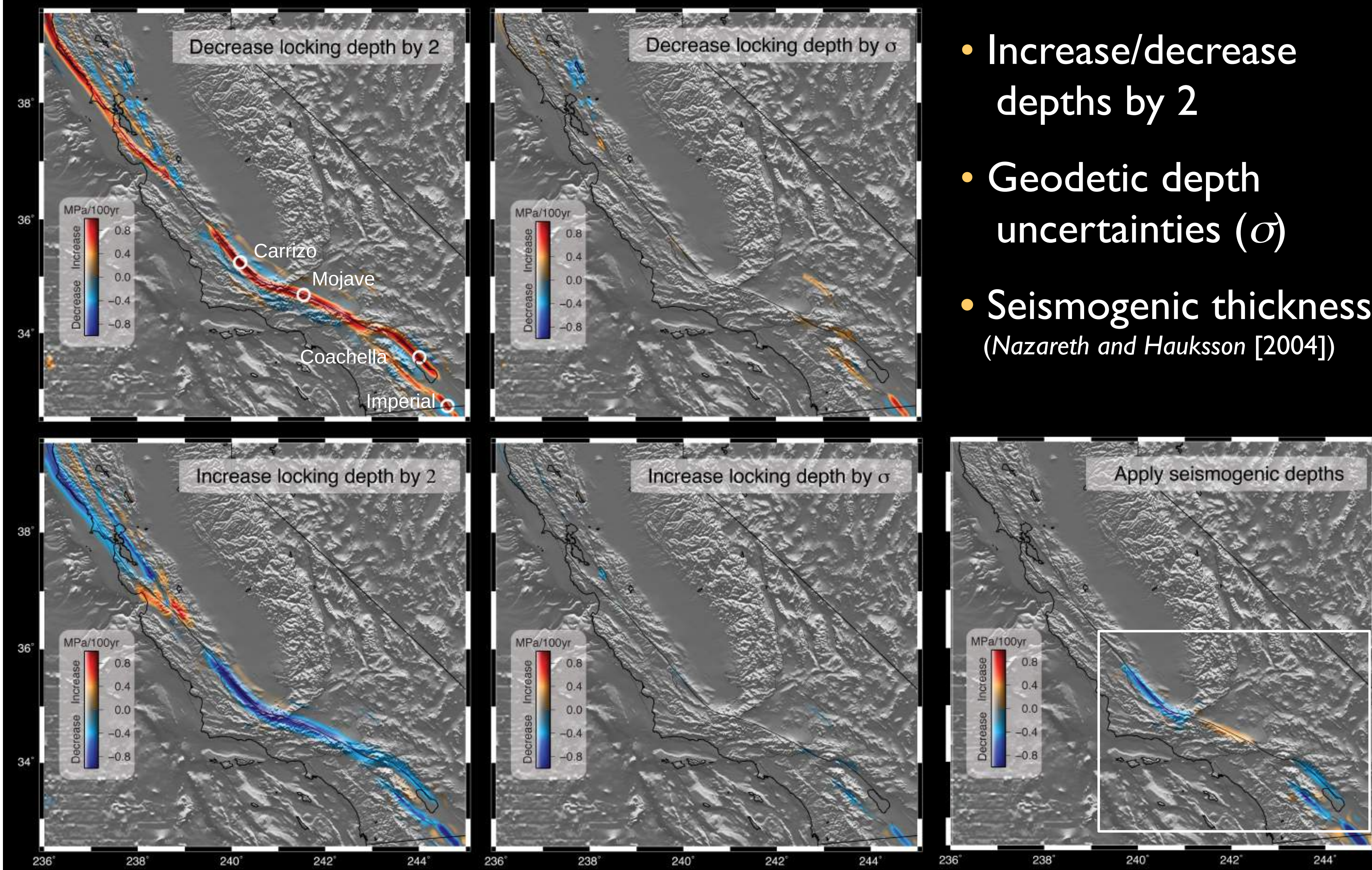




- How does stress rate vary as a function of locking depth d ?



Stress Rate Uncertainties: Locking Depth



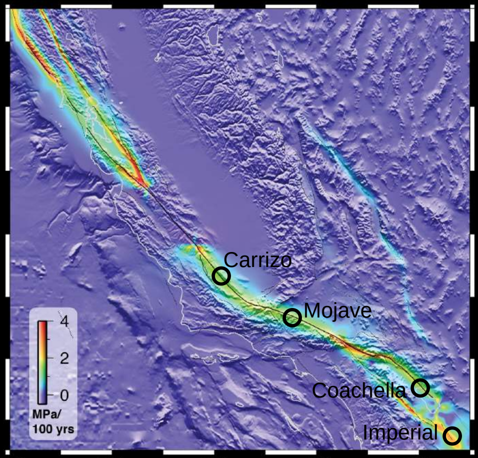
- Increase/decrease depths by 2
- Geodetic depth uncertainties (σ)
- Seismogenic thickness
  (*Nazareth and Hauksson* [2004])

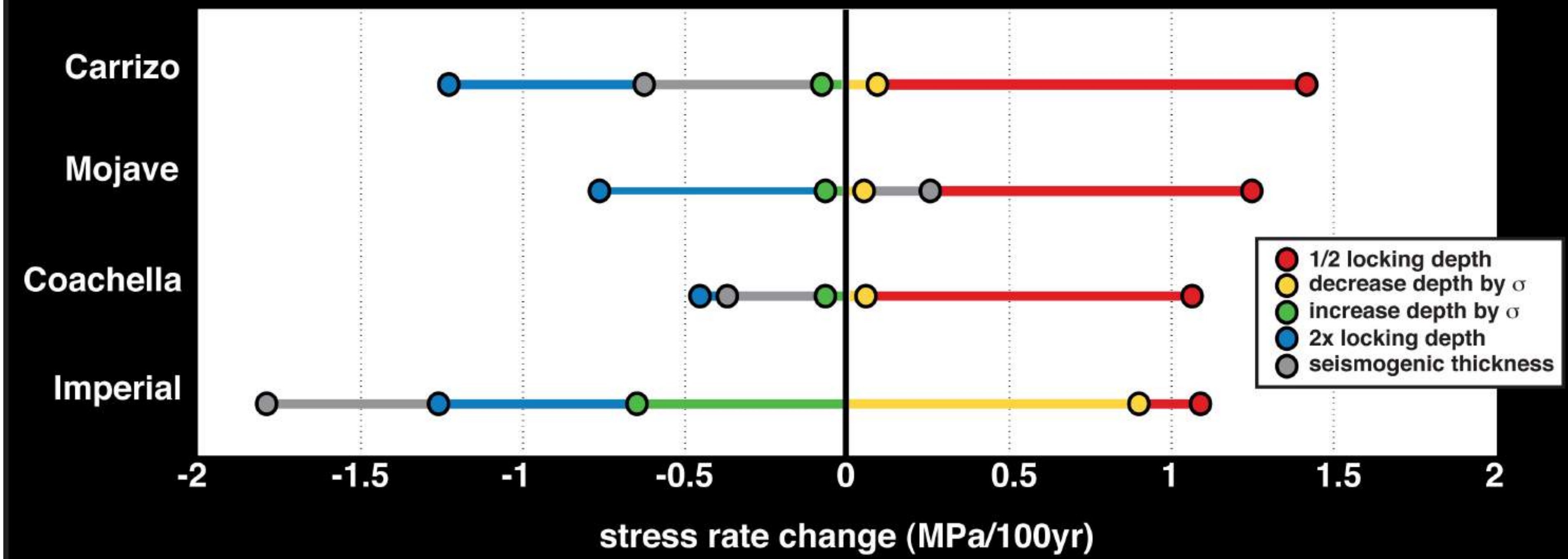
Stress Rate Uncertainties

- Maximum uncertainties in stress rate from locking depth uncertainties:

  -0.7 to 0.9 MPa/100 yrs (geodetic σ)
  -1.8 to 0.4 MPa/100yrs (seismogenic thickness)

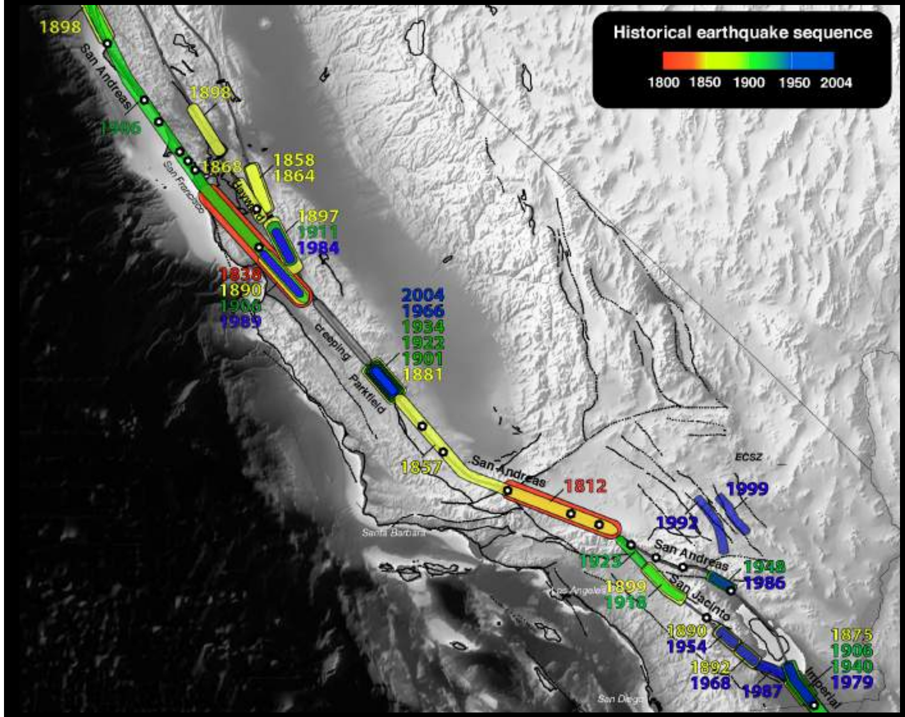
- Individual segment uncertainties highly variable

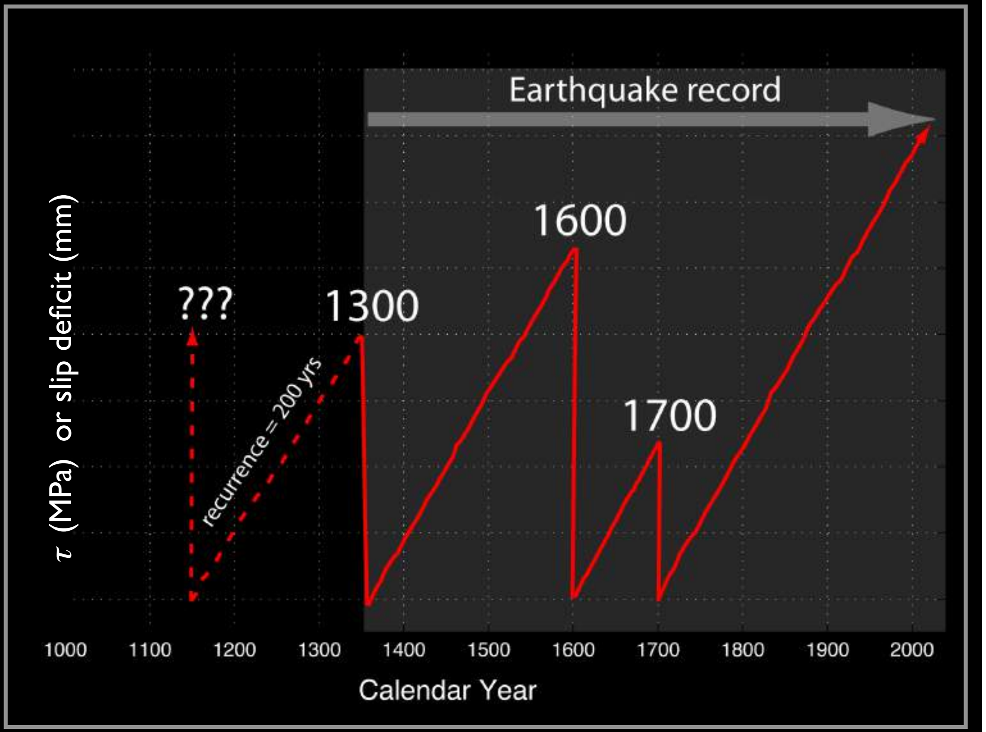




Time-Dependent Stress Evolution

- Prescribed rupture year & fault segmentation assigned from historical + prehistorical database
- Events preceding prehistorical data are prescribed by recurrence intervals
- Every event relieves accumulated slip deficit (unjustified assumption)





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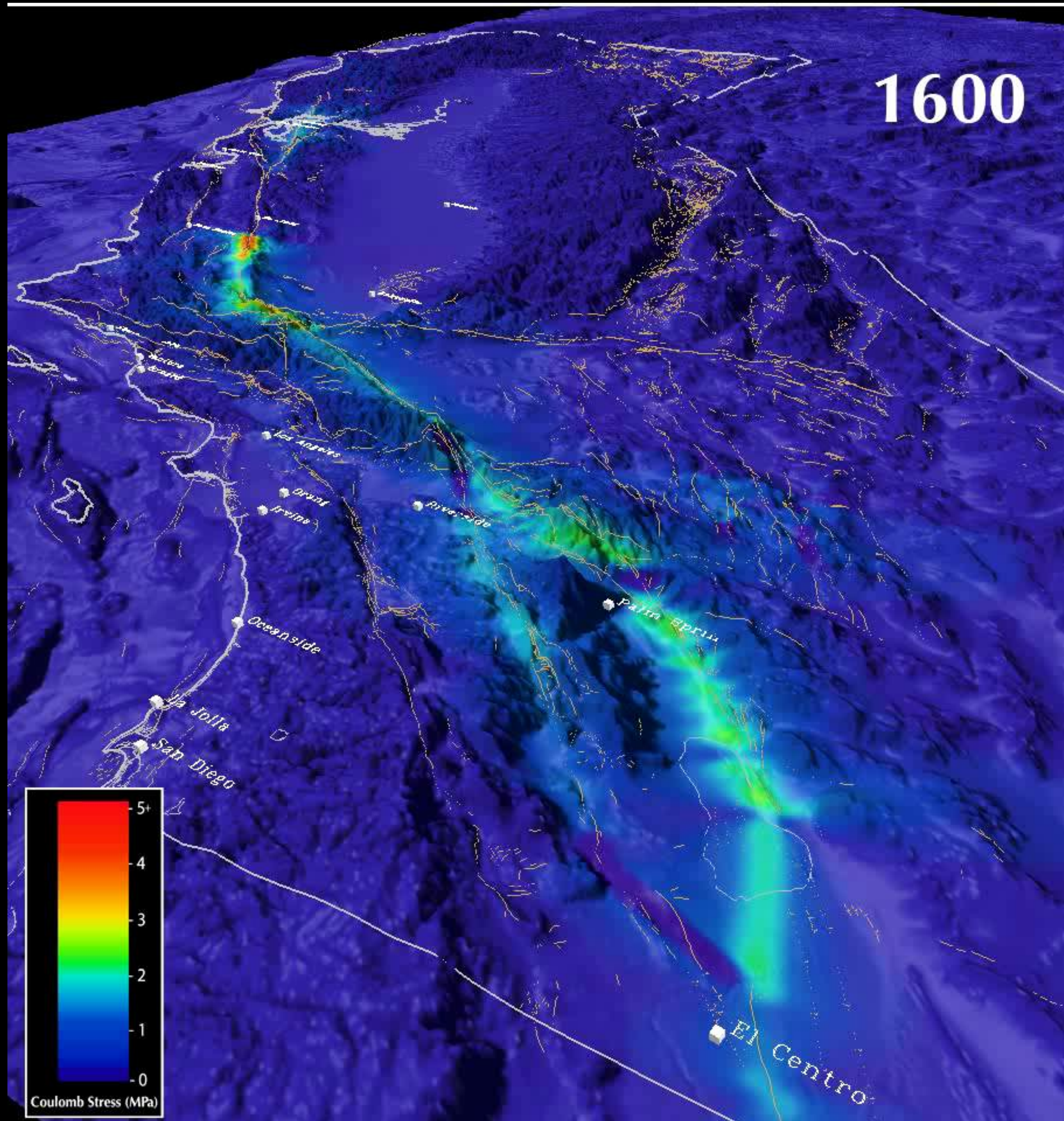
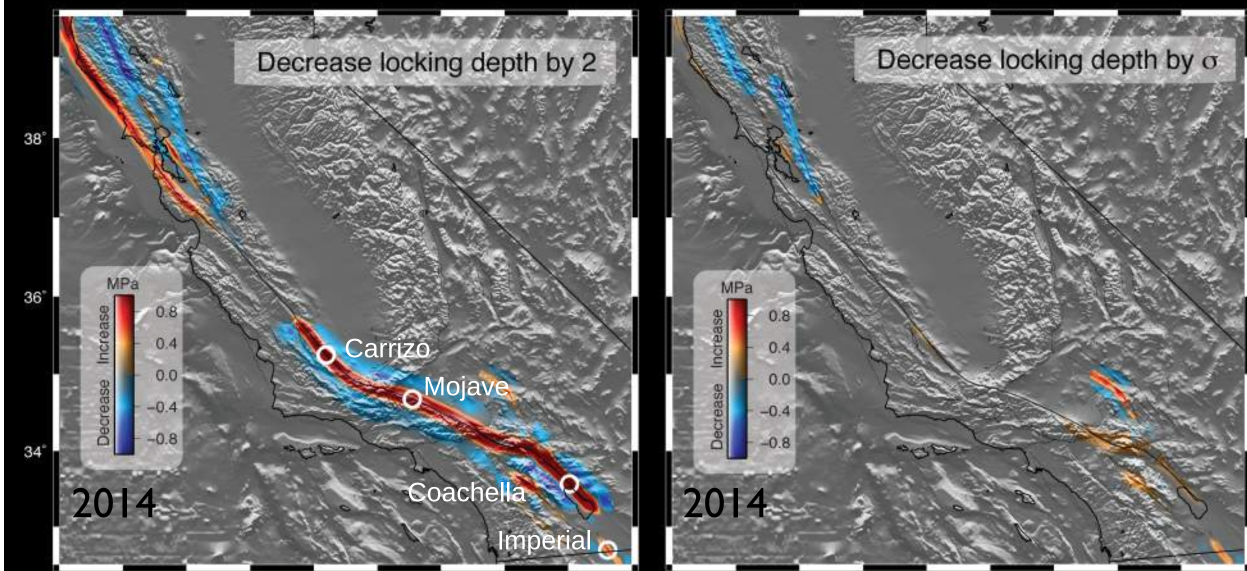
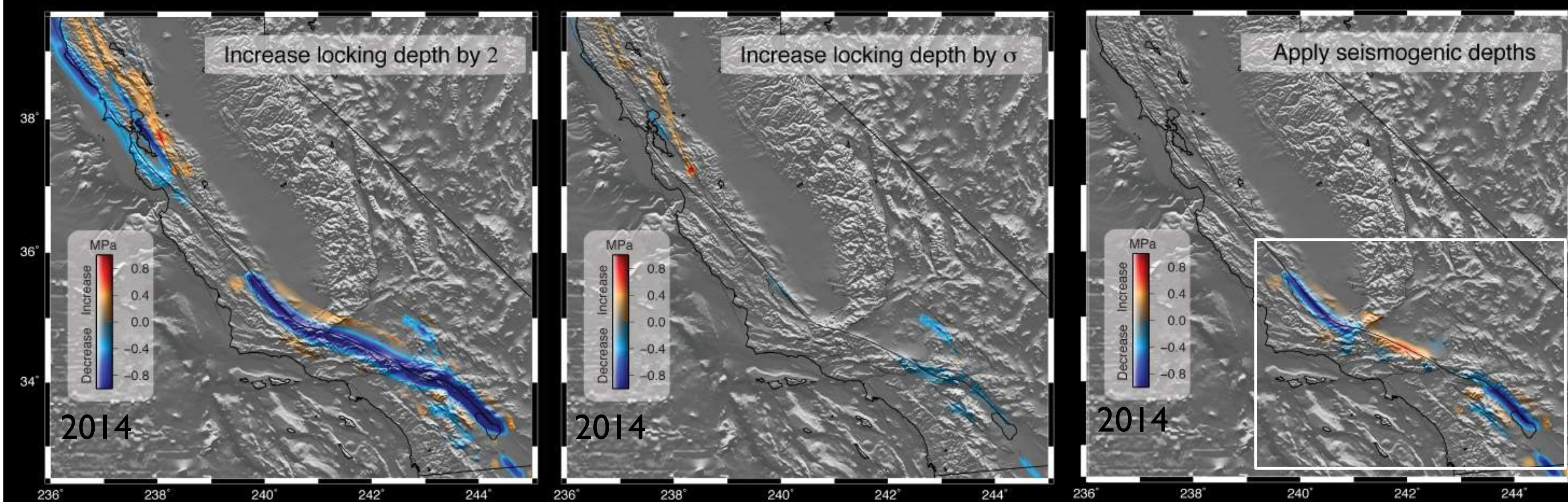


Stress Accumulation Uncertainties

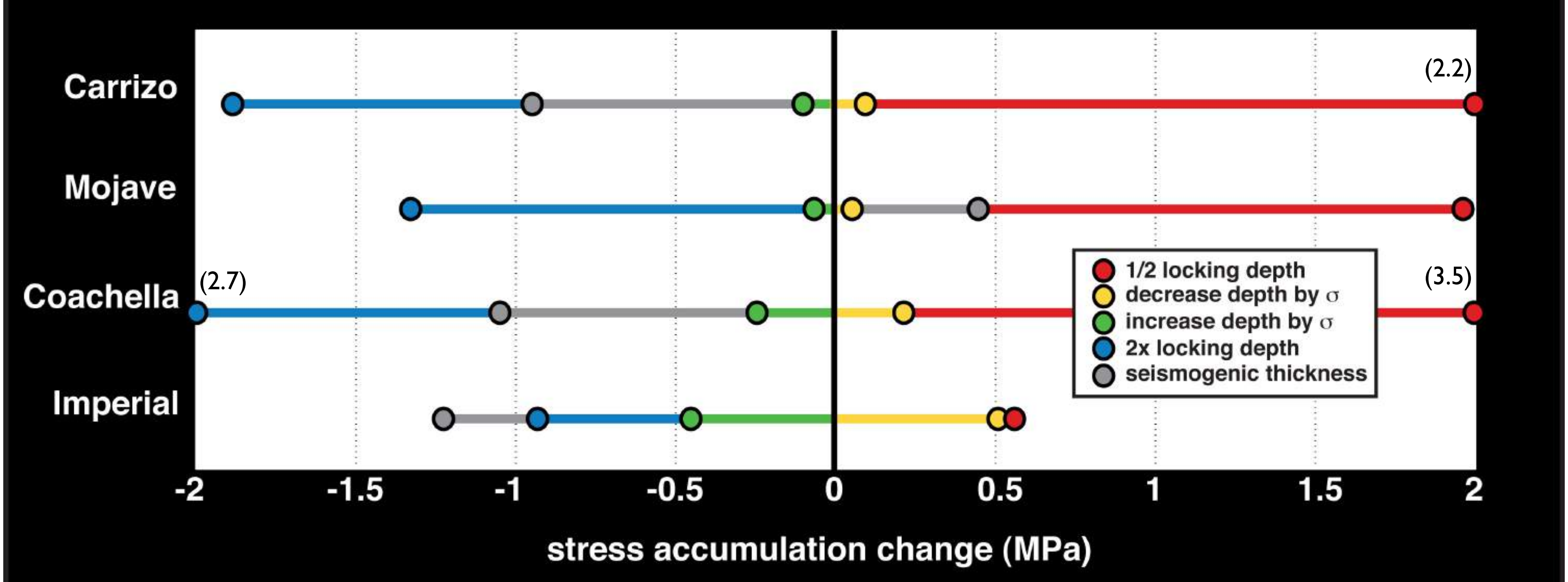


- Increase/decrease depths by 2
- Geodetic depth uncertainties (σ)
- Seismogenic thickness
  (*Nazareth and Hauksson* [2004])

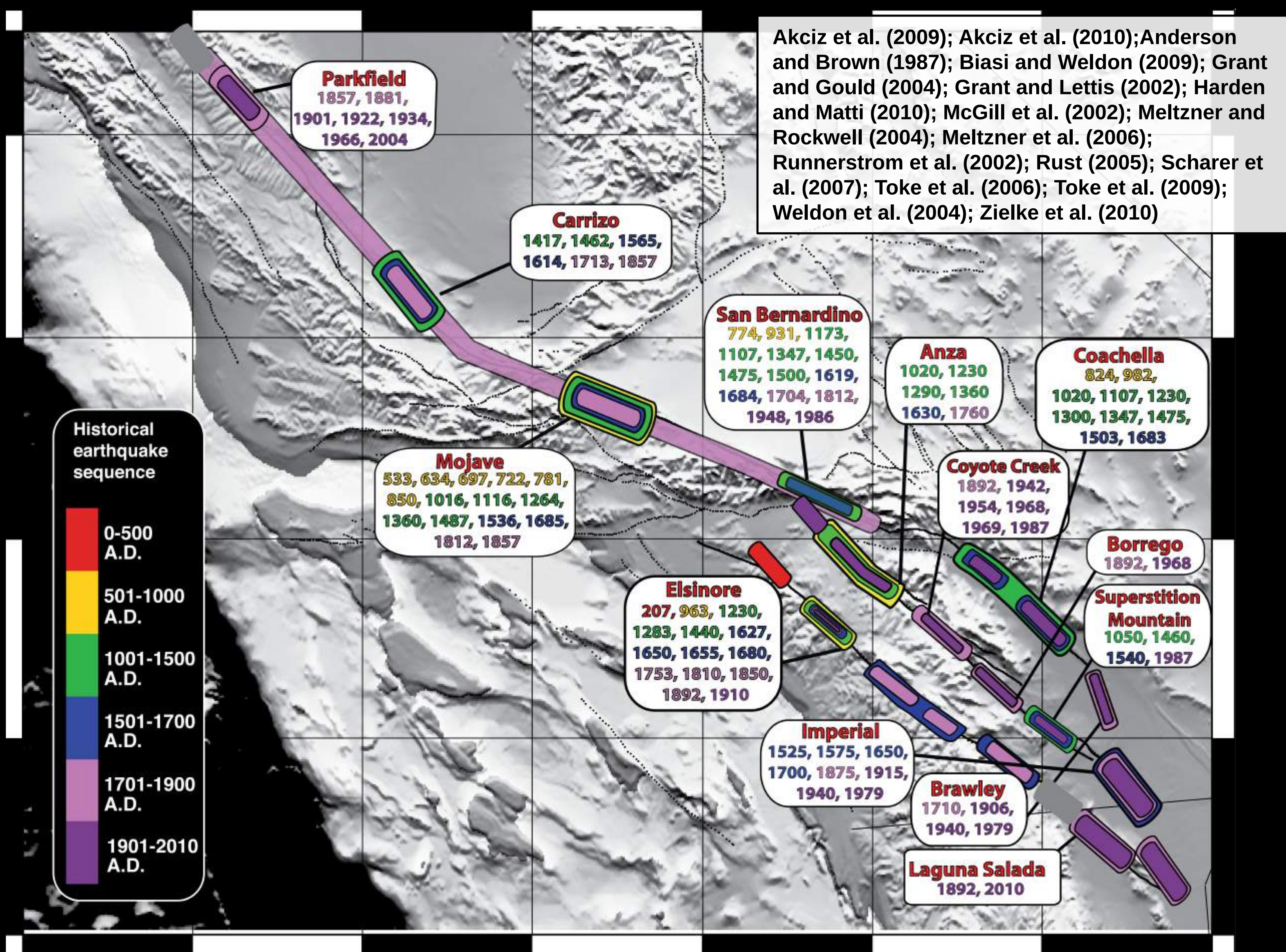


Stress Accumulation Uncertainties

- Maximum uncertainties in stress accumulation from locking depth uncertainties: -0.6 to 0.9 MPa (geodetic σ)
  -1.3 to 0.6 MPa (seismogenic thickness)
- Present day stress accumulation largely depends on time since last event

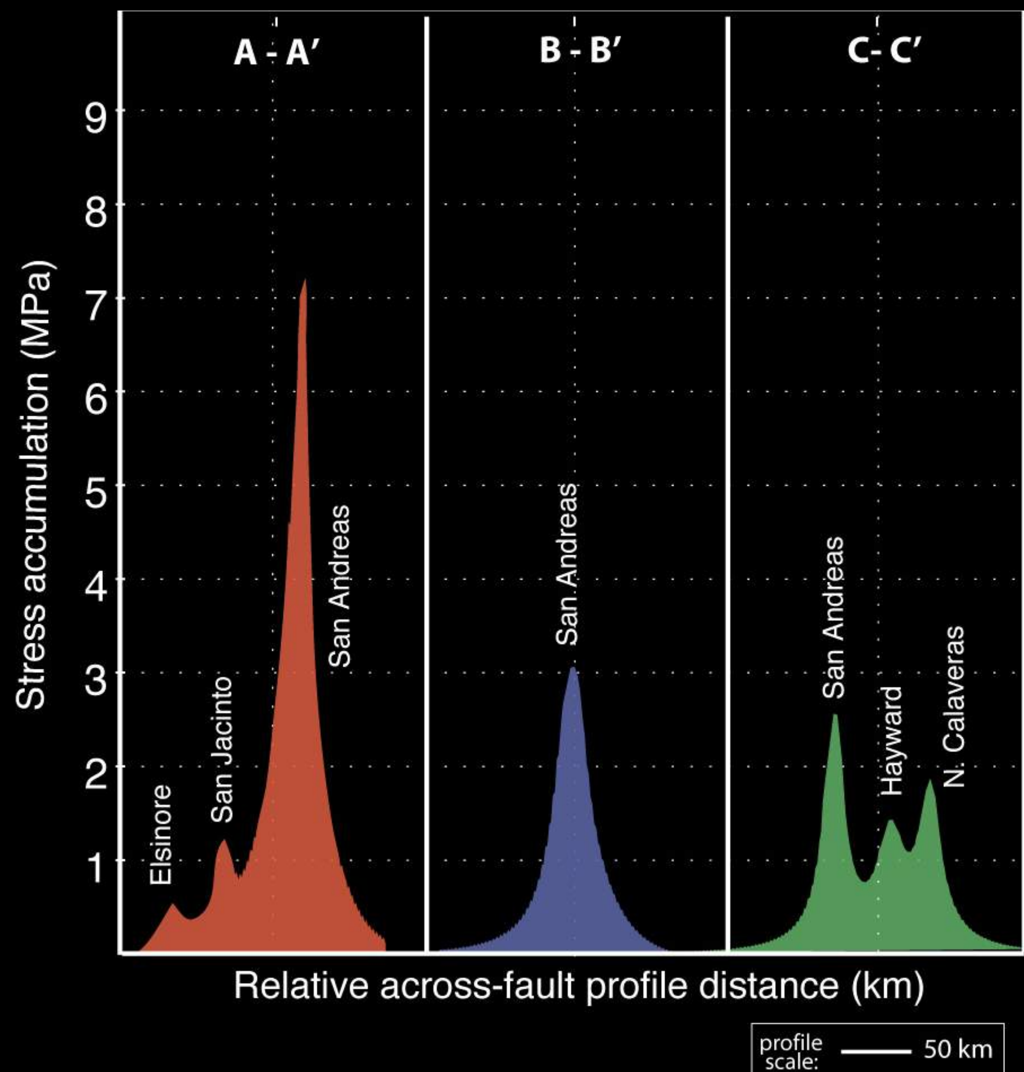


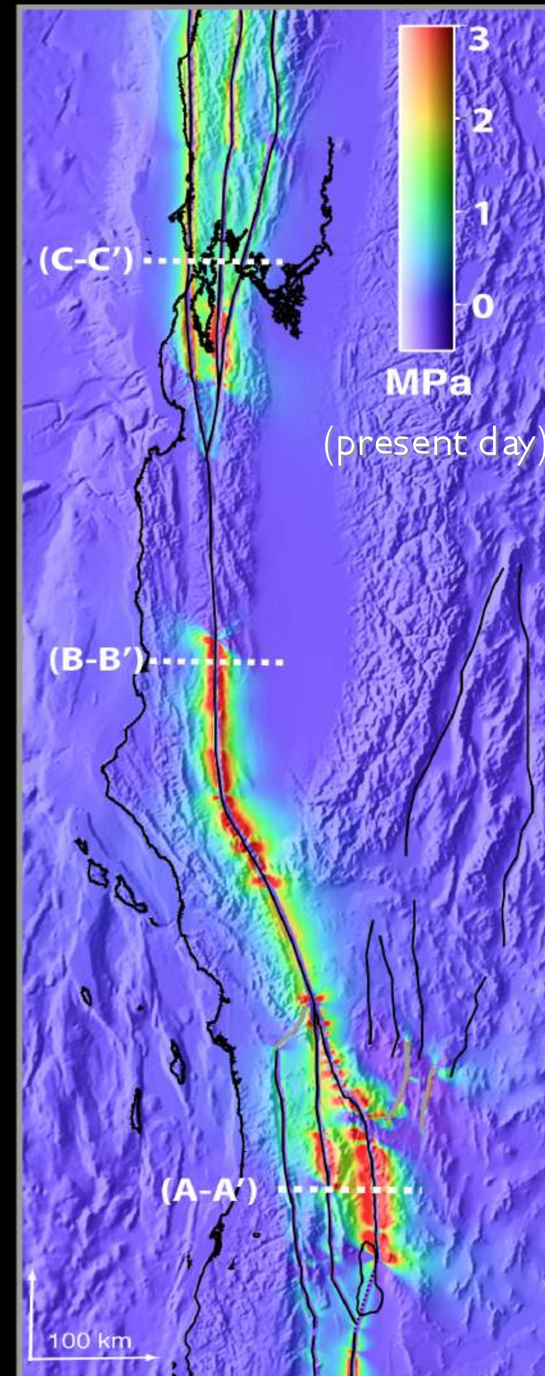
Paleoseismic Data – How to use it, when to trust it?



Present-Day Stress Accumulation

Is stress accumulation consistent over multiple cycles?

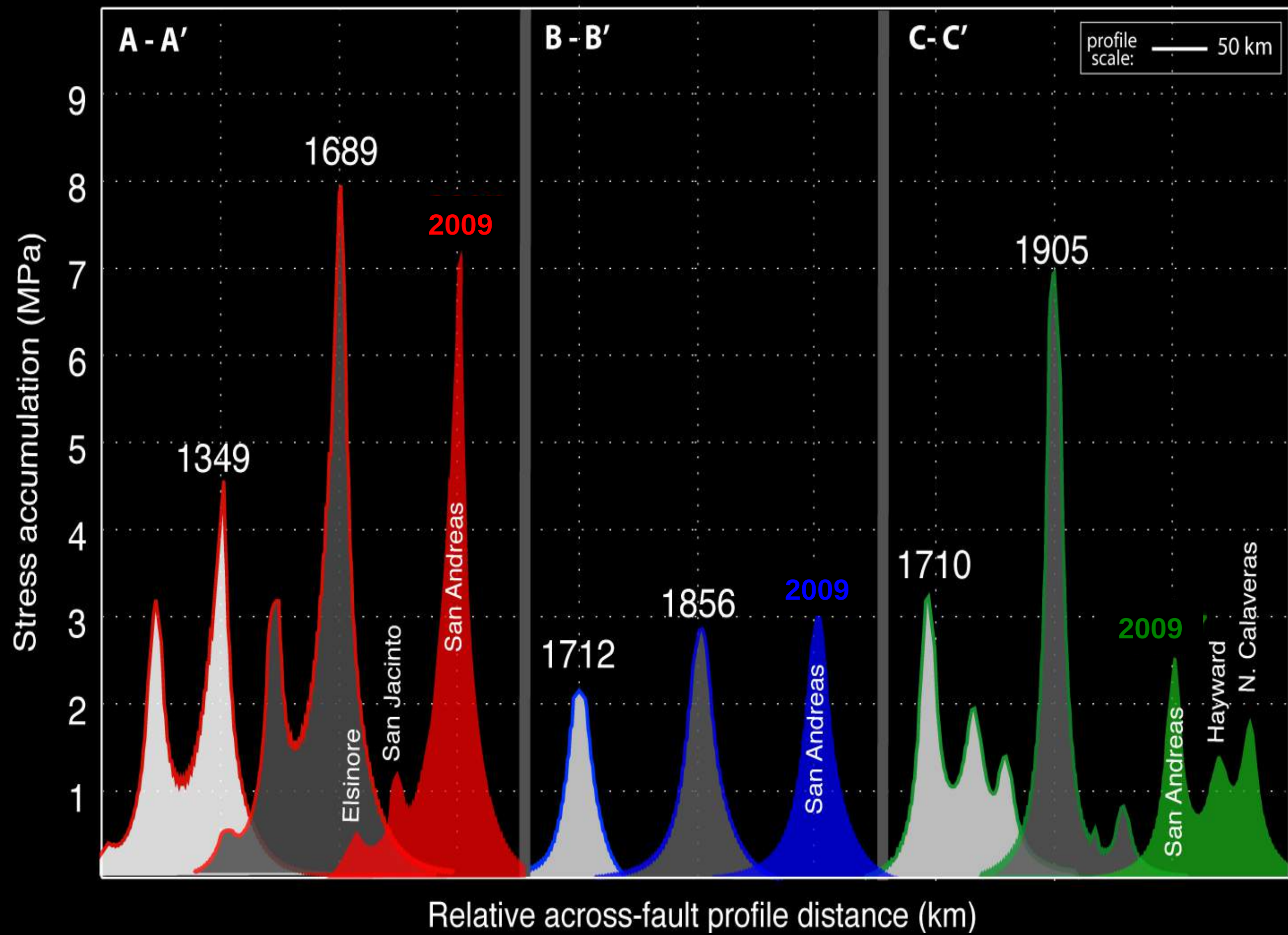


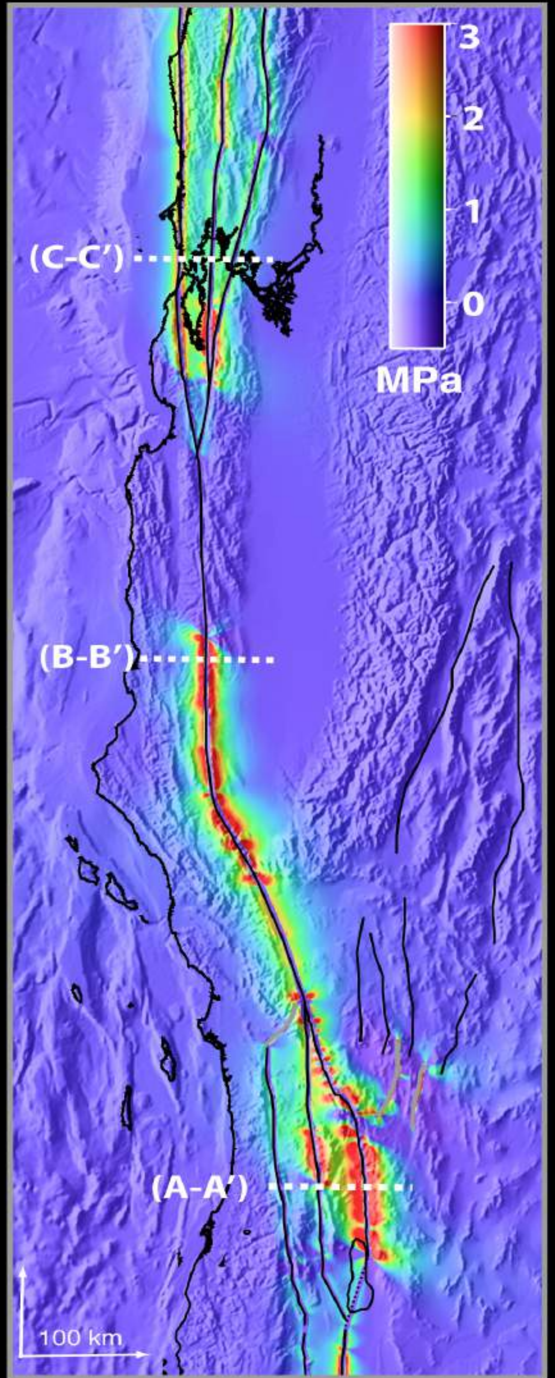


[*Smith-Konter & Sandwell*, GRL 2009]

Hindcast Stress Estimates

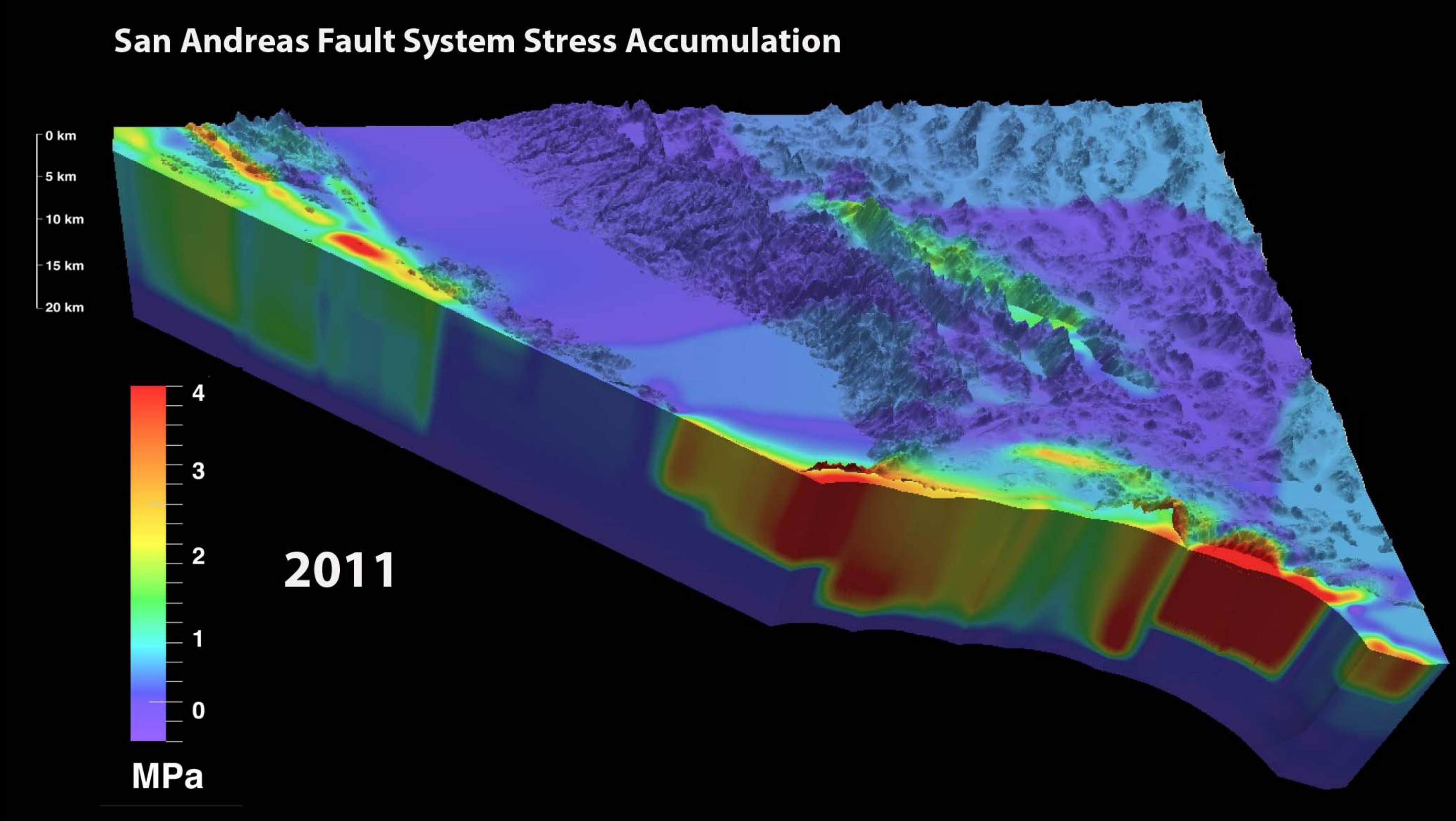
Is stress accumulation consistent over multiple cycles?



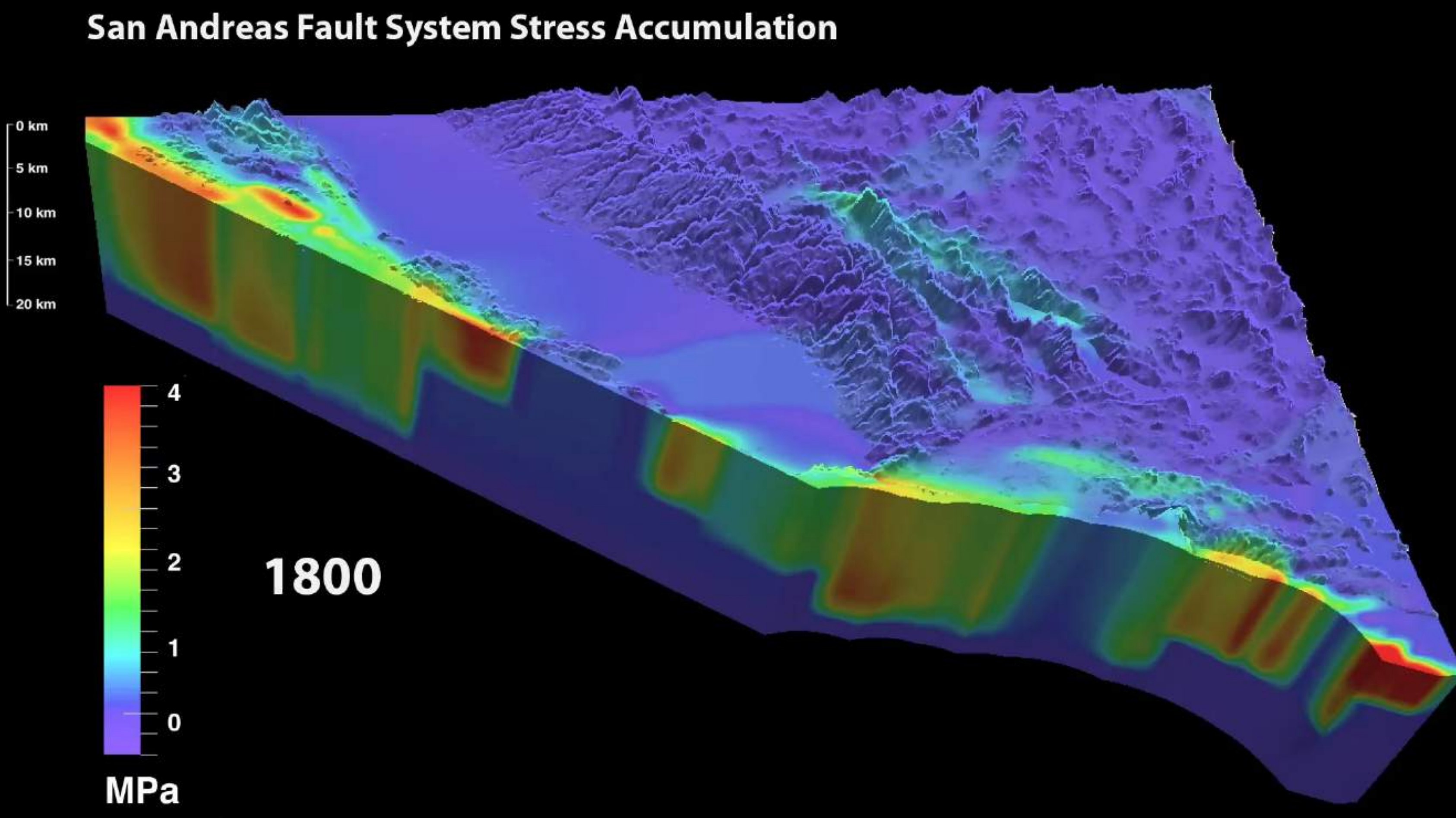


[*Smith-Konter & Sandwell*, GRL 2009]

How Does Stress Vary With Depth and Time?



How Does Stress Vary With Depth and Time?



Conclusions/Summary

- Uncertainty in locking depth/seismogenic thickness:
  - Stress rate uncertainties -2 to 1 MPa/100 yrs
  - Stress accumulation uncertainties -1 to 1 MPa

- Uncertainty in slip rate:
  - Stress rate uncertainties -0.5 to 1 MPa/100 yrs

- Uncertainty in paleoseismic slip:
  - Stress accumulation uncertainties -1 to 3 MPa

- *Worst case, stress rates could be off by +/- 10-20 kPa/yr (not too bad)*
- *Stress accumulation could be off by 3 MPa (bad)*

- *How do these uncertainty estimates map into present day stress field (focal mechanisms)?*