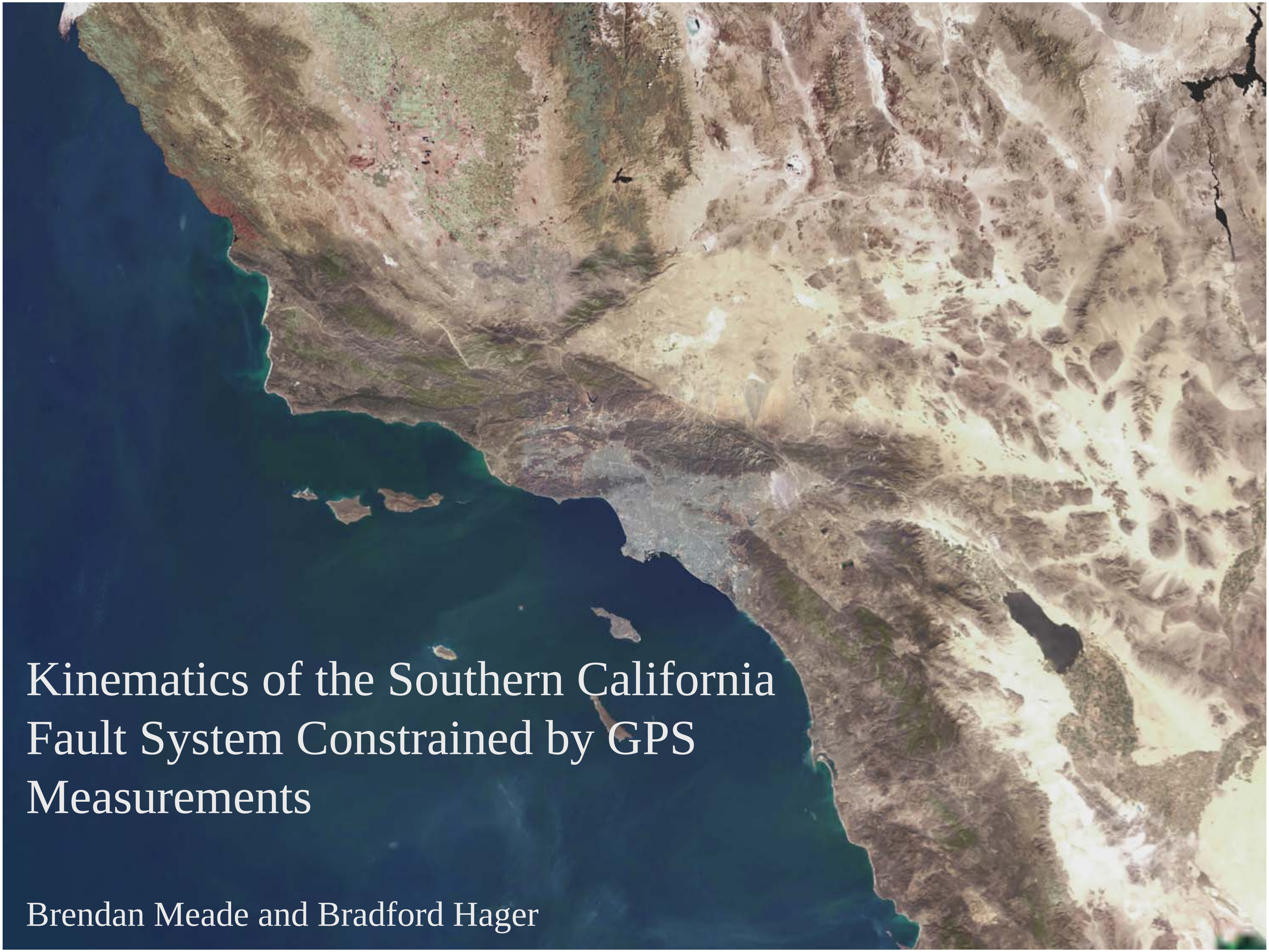
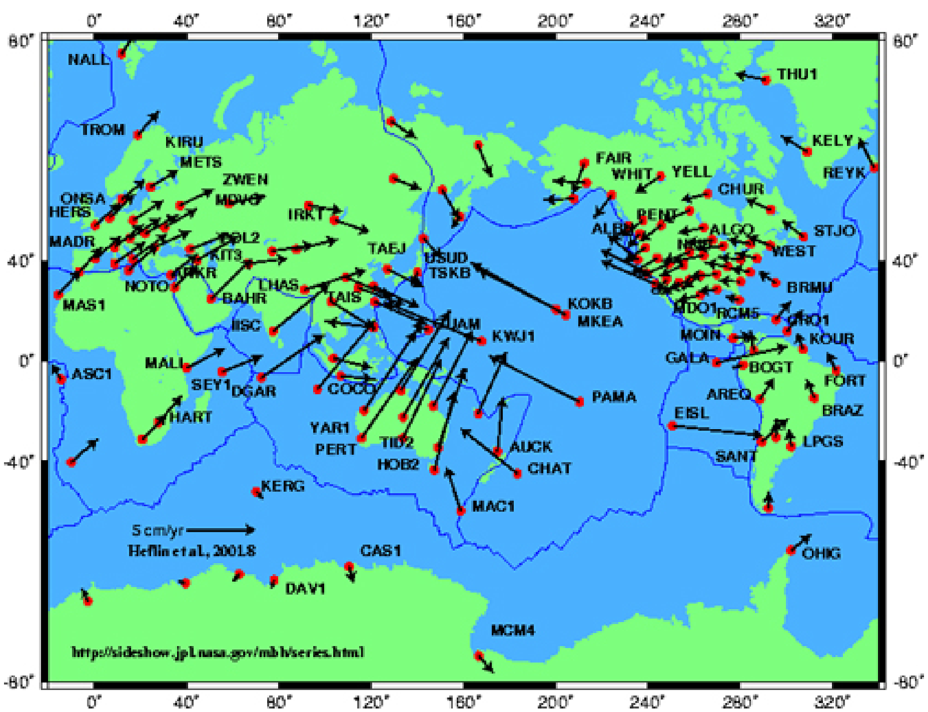


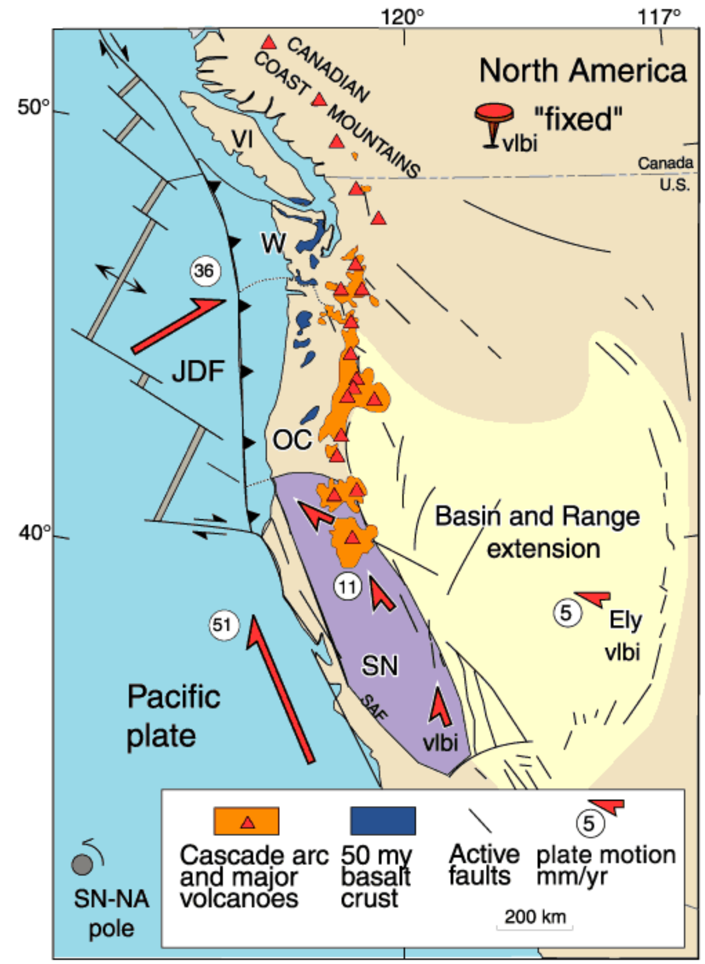
Kinematics of the Southern California Fault System Constrained by GPS Measurements

Brendan Meade and Bradford Hager

One basic question

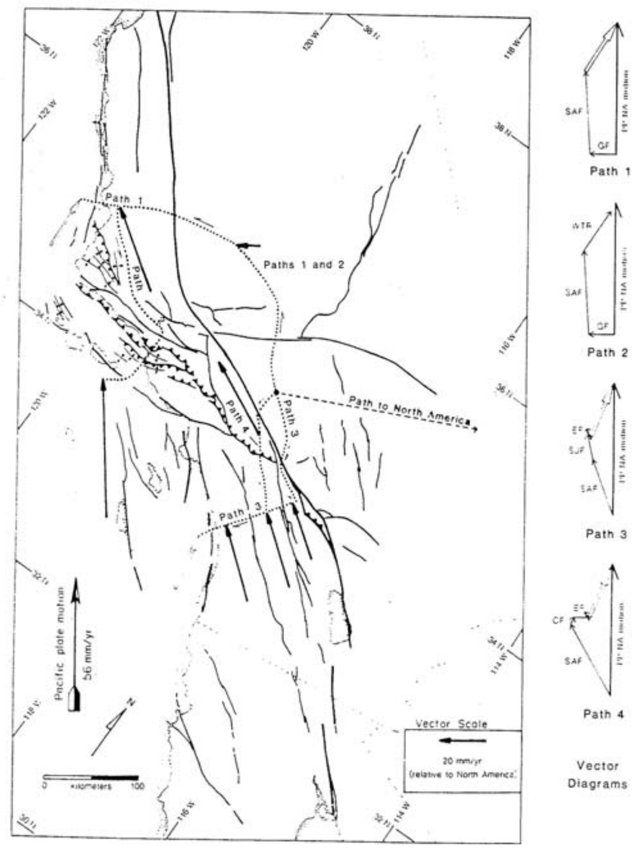
How is deformation distributed between the Pacific and North American plates?

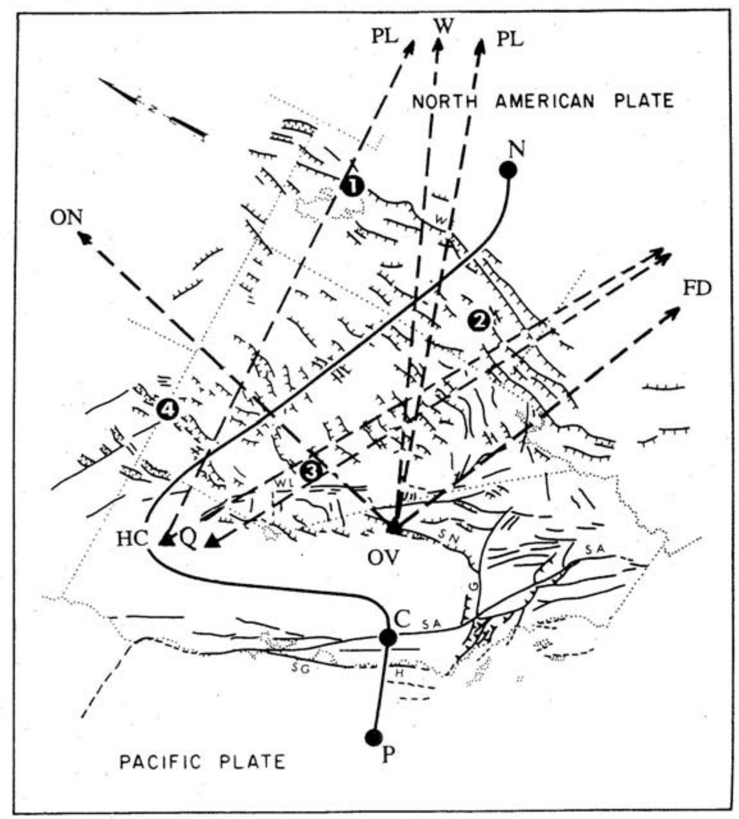




Summing slip from PA to NA

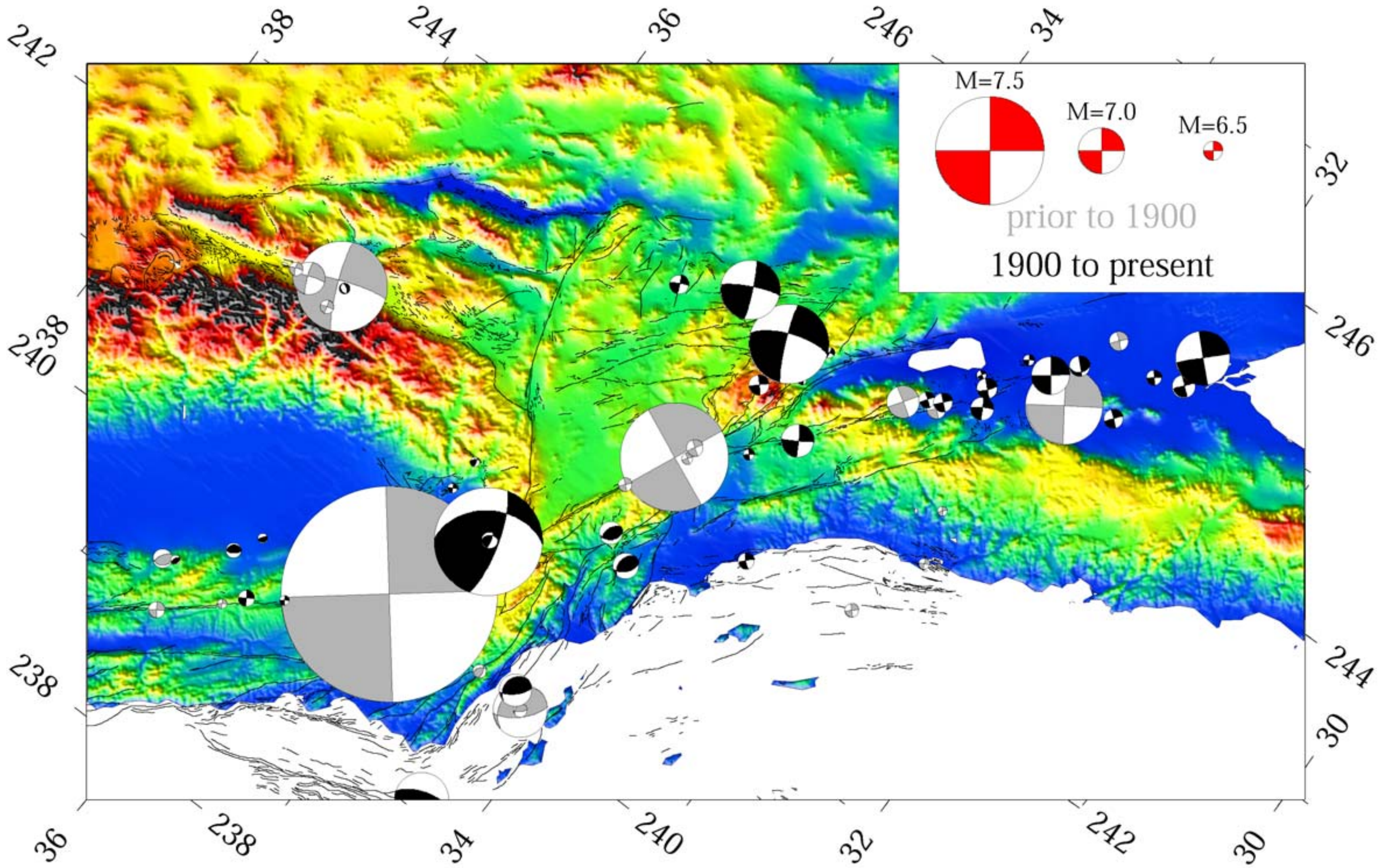
Are slip rate estimates kinematically consistent?





Bird and Rosenstock (1984)
Weldon and Humpries (1986)
Minster and Jordan (1987)

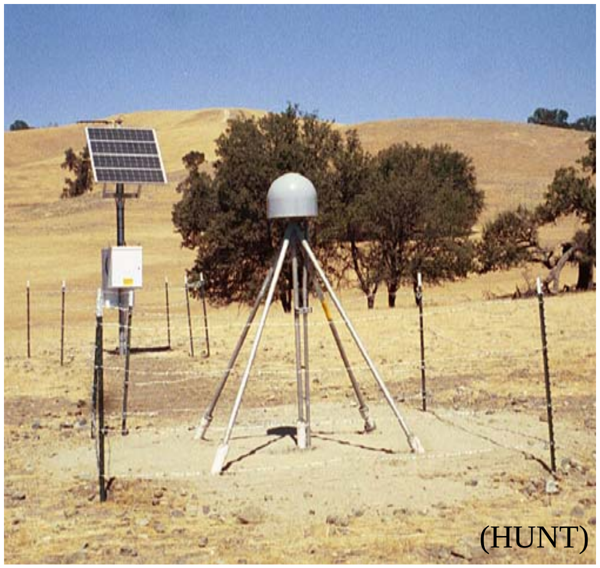
Coseismic deformation



During the last 200 years there have been 65 earthquakes with magnitude ≥ 6

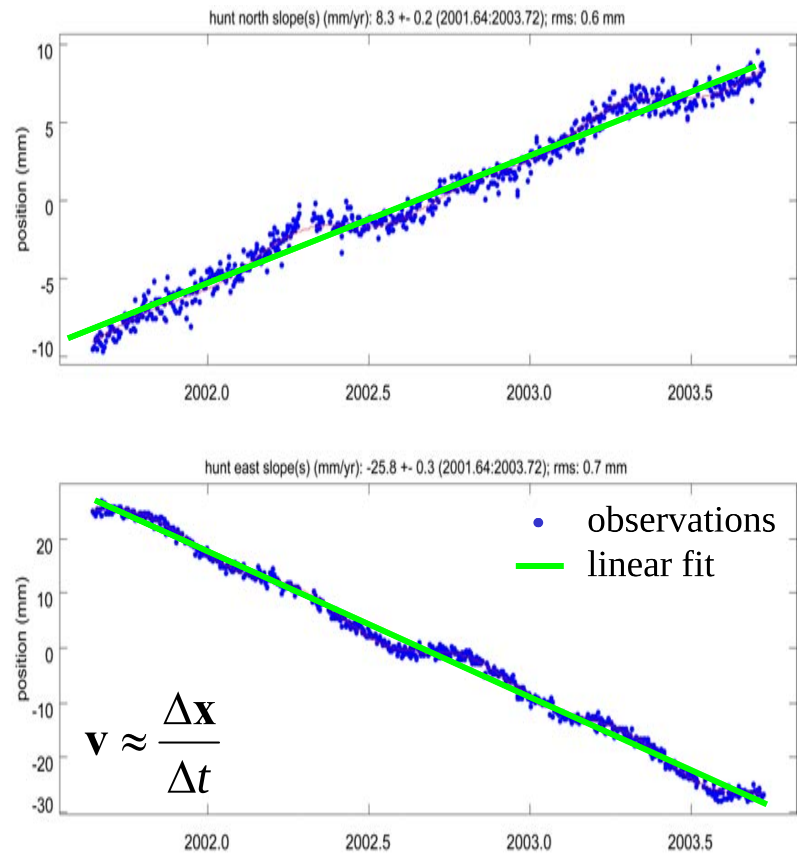
Sources : *Ellsworth* (1990), Harvard CMT catalog, compiled by *Kagan* (2004)

How fast is the crust moving in between earthquakes?



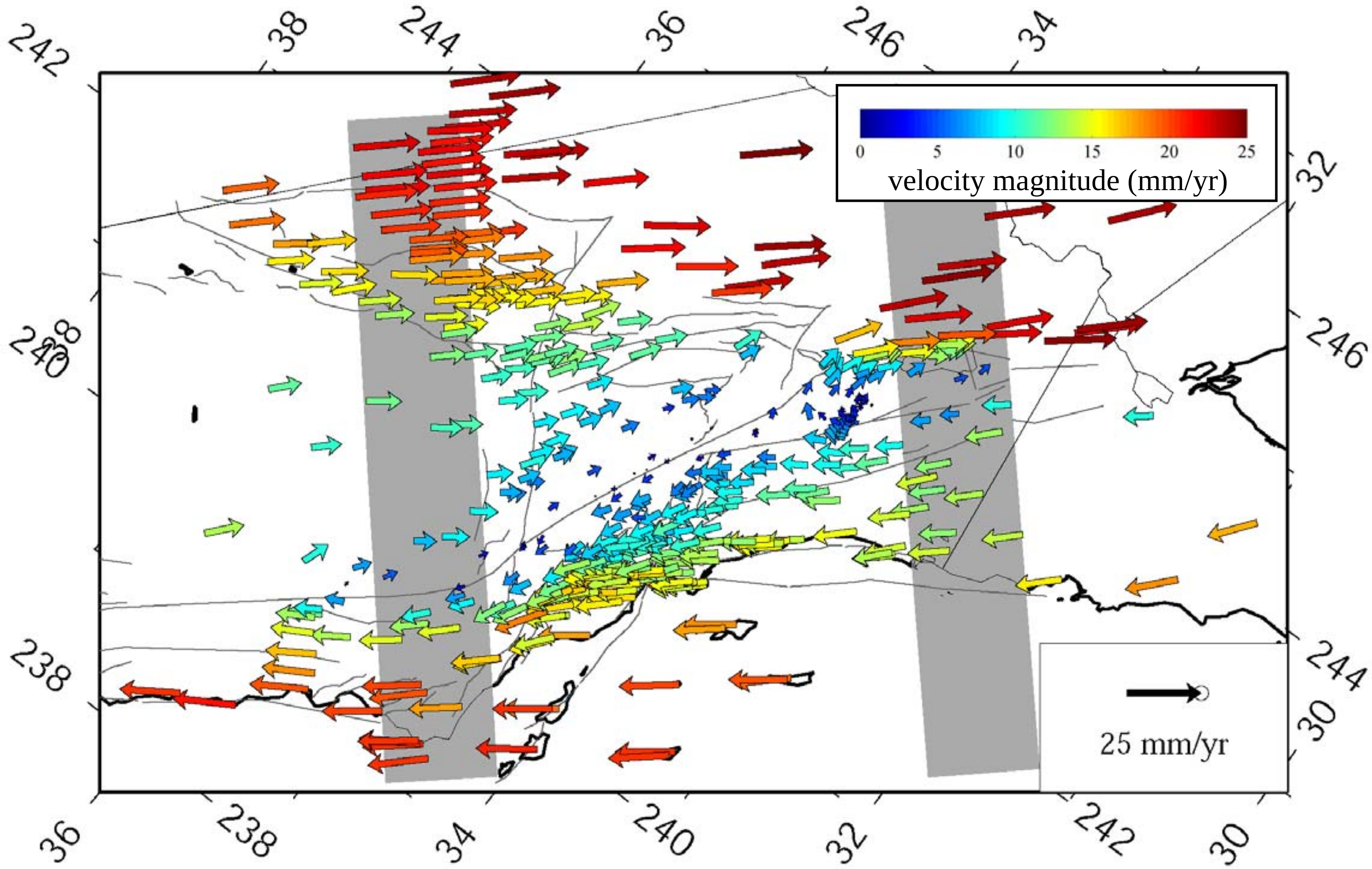
Time series span 2-15 years

The interseismic velocity is the slope of the line that best fits the position estimates



http://www.scign.org

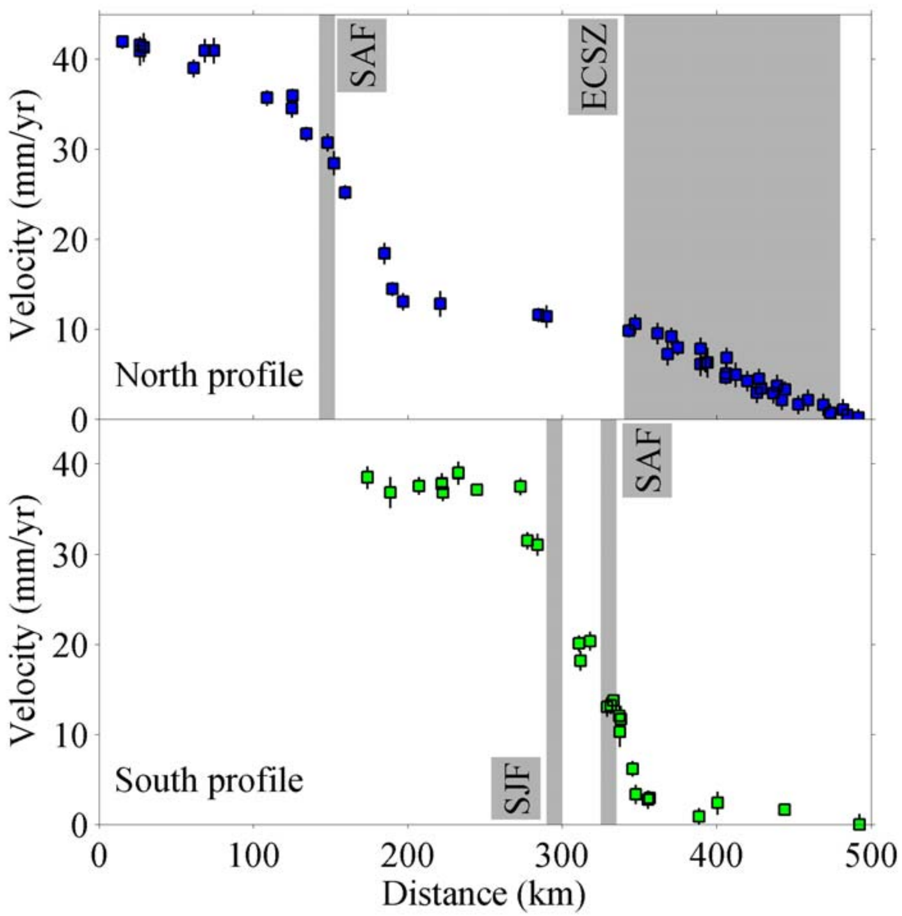
Interseismic GPS velocities



451 velocities (no EDM, ties?), 1.45 mm/yr mean uncertainty magnitude, ~50 mm/yr differential motion

Velocity fields : *Shen et al.* (2003), *McClusky et al.* (2001), *Steblov et al.* (2003), *Murray and Segall* (2001) Combined by minimization of common stations velocities

Fault parallel velocity profiles



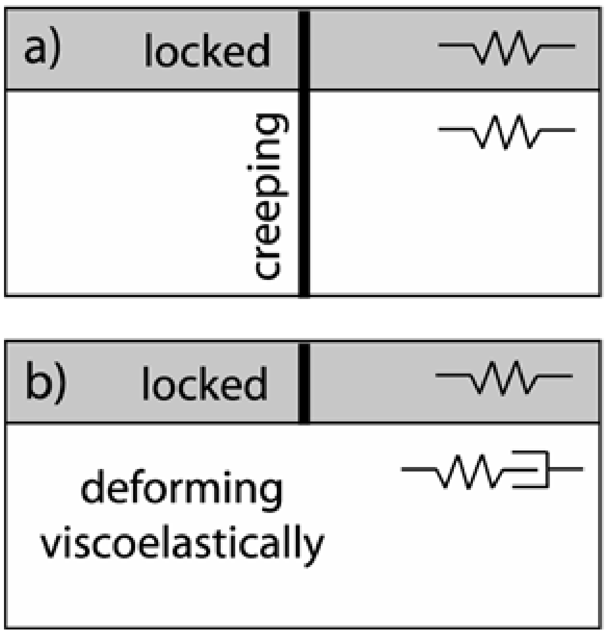
SAF : San Andreas Fault
SJF : San Jacinto Fault
ECSZ : Eastern California Shear Zone

Smooth velocity transitions, not jump, across faults

~40 mm/yr velocity transition between the Pacific and North American plates across both profiles

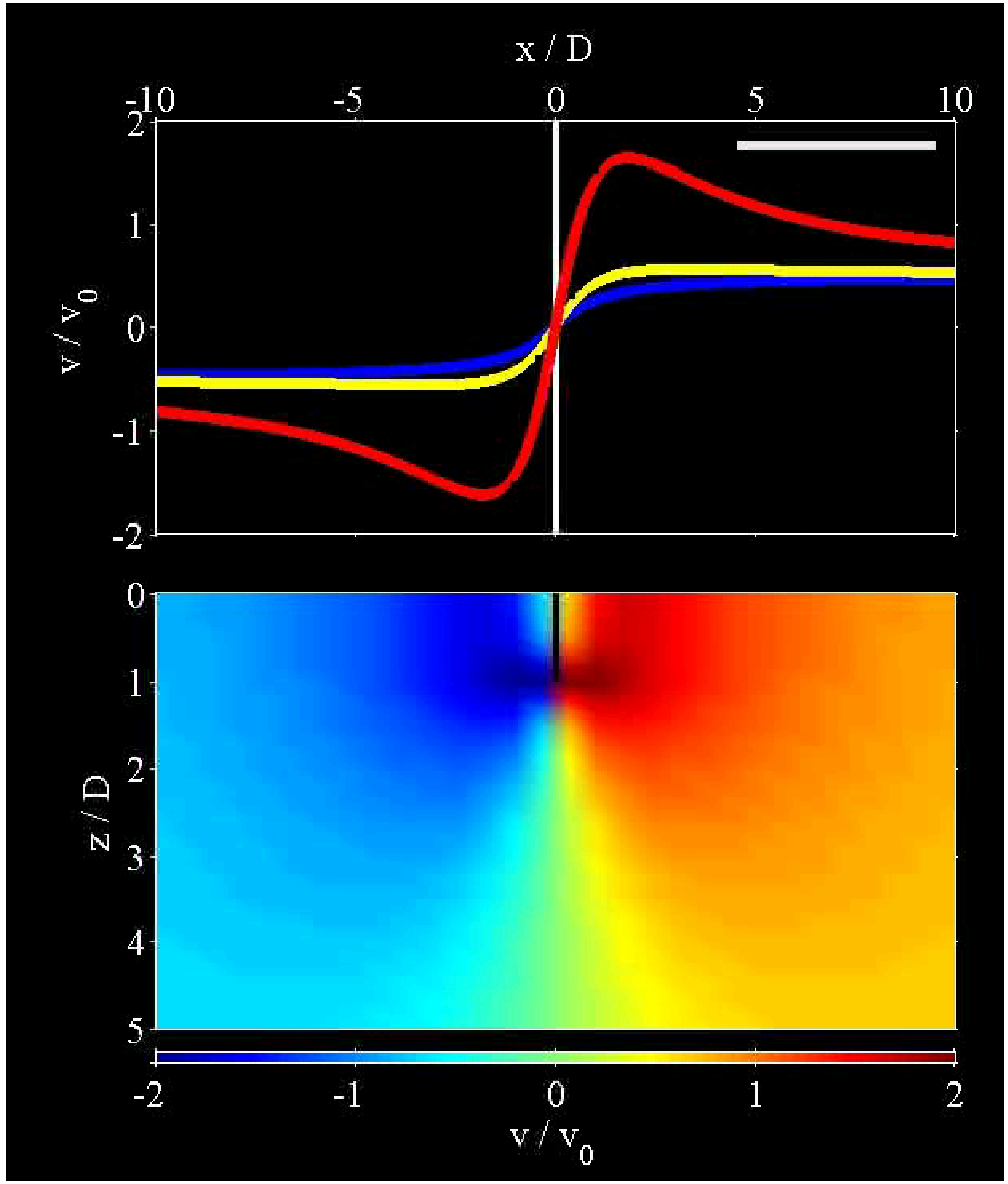
Velocity transition occurs over a narrower region in the south

Interseismic deformation in the high viscosity limit

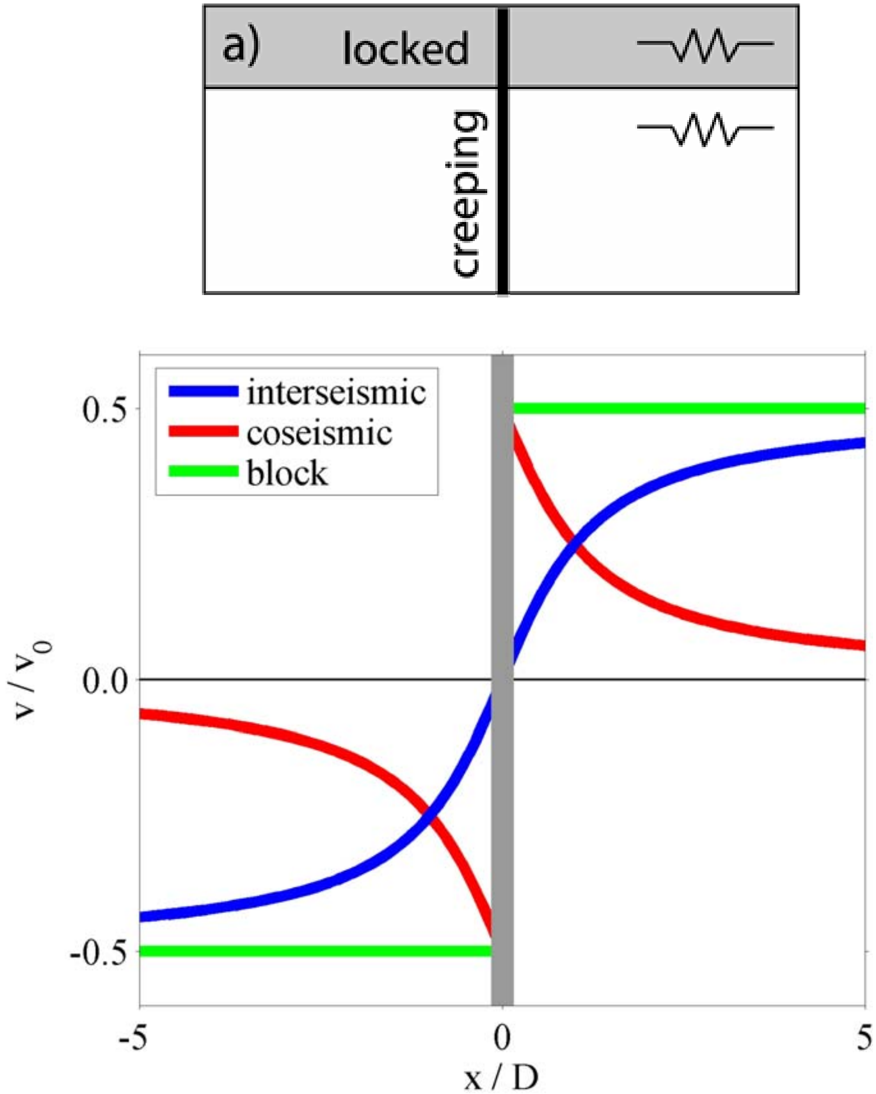


$$\tau_0 = \frac{\mu T}{2\eta} = \frac{T}{2\tau_M}$$

Savage and Prescott (1978), *Savage* (2000)



Steady state interseismic deformation



A smooth velocity transition is the signature of a locked fault

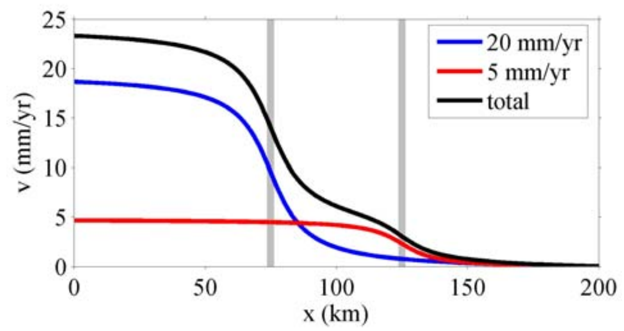
Elastic strain accumulates between earthquakes

Savage and Burford (1973): Solution for a 2-D infinitely long strike slip fault

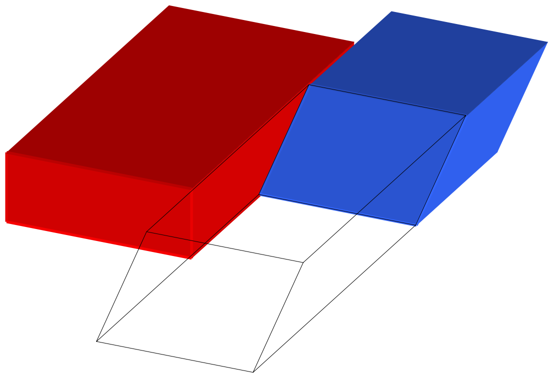
$$v_I = \dot{s}\pi^{-1}\tan^{-1}(x/D)$$

Block modeling: estimating kinematically consistent slip rates

Elastic strain accumulation couples blocks together

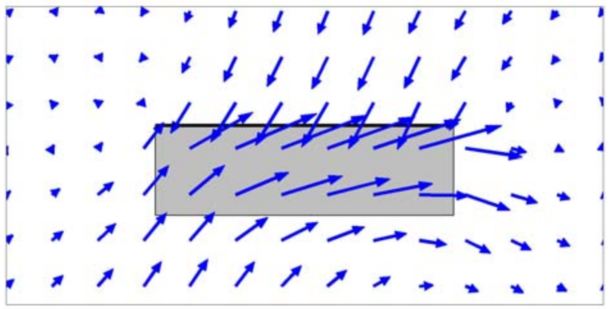


Slip rates are functions of block motions and blocks are coupled by elastic deformation. Slip rates are not independent and movement on one part of the fault system has implications elsewhere



Elastic deformation depends on slip rate, fault geometry and Poisson's ratio

$$\mathbf{v}_E = \dot{s}[\mathbf{g}_1 + (1-2\nu)\mathbf{g}_2]$$

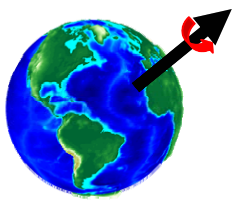


Block models I

Interseismic velocities are given by the differences between block and slip deficit velocities :

$$\mathbf{v}_I = \mathbf{v}_B - \mathbf{v}_E$$

Block motions on a sphere are described by rotation vectors :



$$\mathbf{v}_B(\boldsymbol{\omega}) = \boldsymbol{\omega} \times \mathbf{p} = \mathbf{R}_B \boldsymbol{\omega}$$

The elastic contribution to the velocity field is linearly related to the fault slip rates :

$$\mathbf{v}_E(\dot{\mathbf{s}}) = \mathbf{R}_E \dot{\mathbf{s}}$$

$\mathbf{R}_E$: partial derivatives of *Okada's* (1985) elastic dislocation equations

Block models II

Fault slip rates are the projections of the differential block velocity vectors on to the fault surface :

$$\dot{\mathbf{s}} = \mathbf{R}_{\dot{s}}\boldsymbol{\omega}$$

Both the block velocity and the elastic velocity can be written in terms of the rotation vectors :

$$\mathbf{v}_I = (\mathbf{R}_B - \mathbf{R}_E\mathbf{R}_{\dot{s}})\boldsymbol{\omega}$$

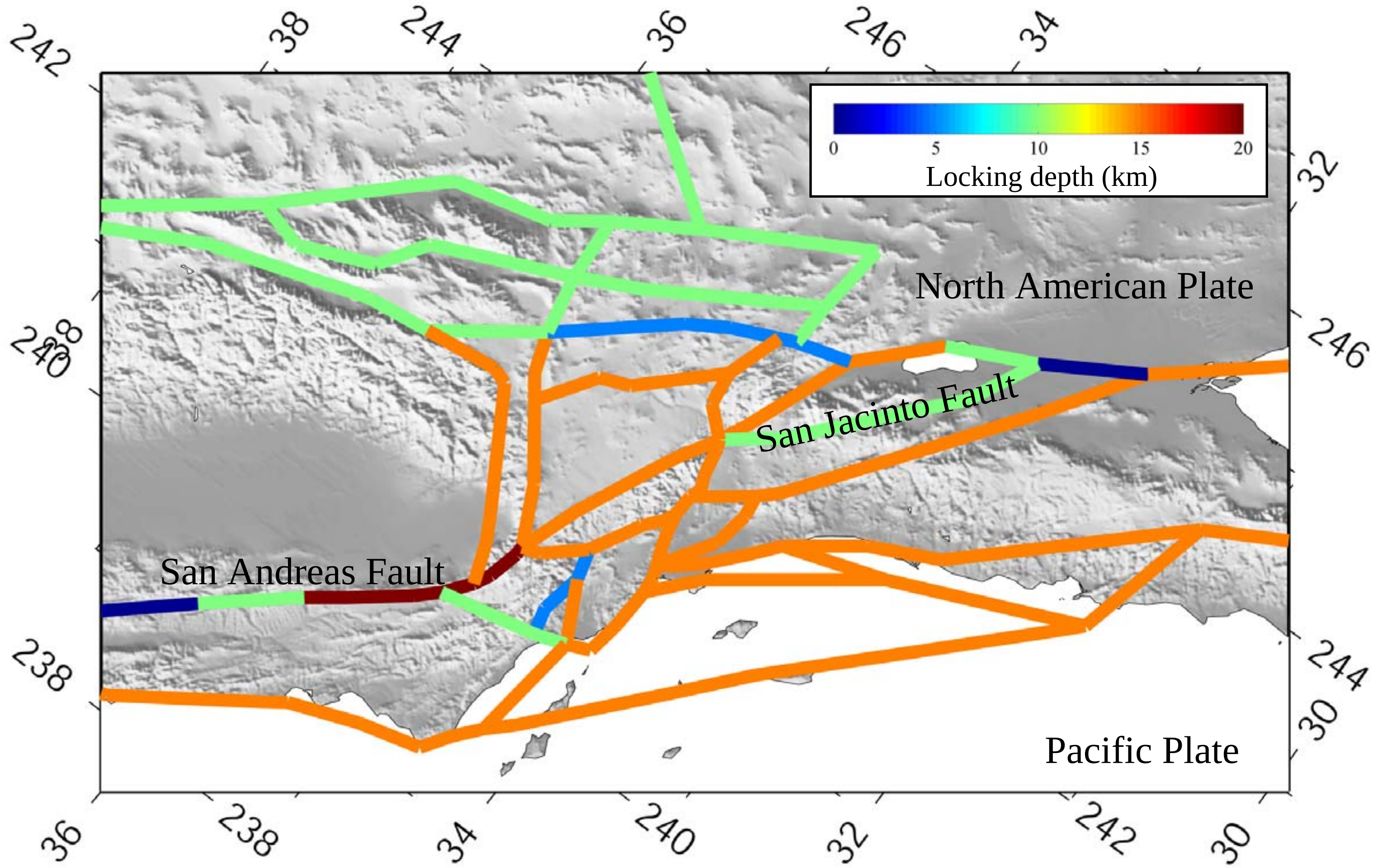
We can use GPS data to solve for the best fitting set of rotation vectors :

$$\boldsymbol{\omega}_{est} = (\mathbf{R}^{\mathrm{T}}\mathbf{W}\mathbf{R})^{-1}\mathbf{R}^{\mathrm{T}}\mathbf{W}\mathbf{v}_{GPS}$$

…and the estimated slip rates :

$$\dot{\mathbf{s}}_{est} = \mathbf{R}_{\dot{s}}\boldsymbol{\omega}_{est}$$

Block model geometry

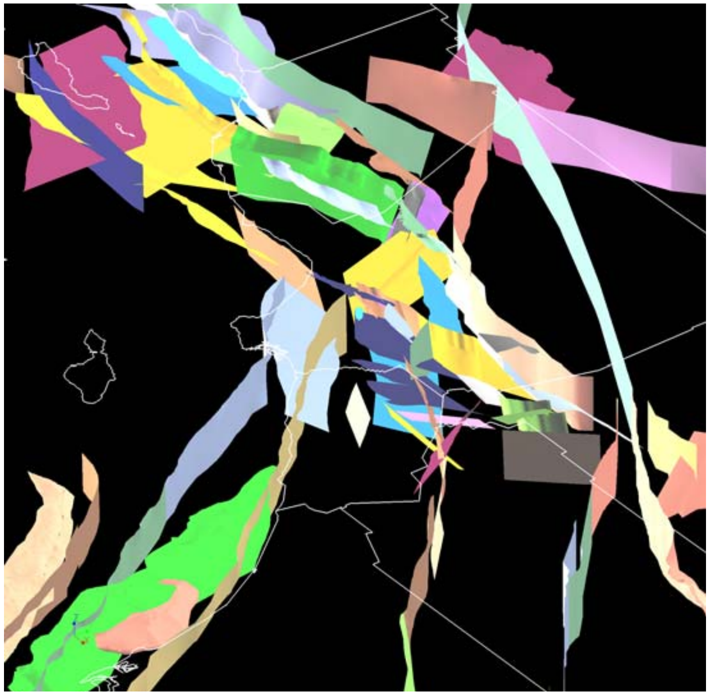


24 blocks with ~ 50 major tectonic structures and ~50,000 km^2 of fault surface area

Locking depth and dip define the third-dimension of the fault system

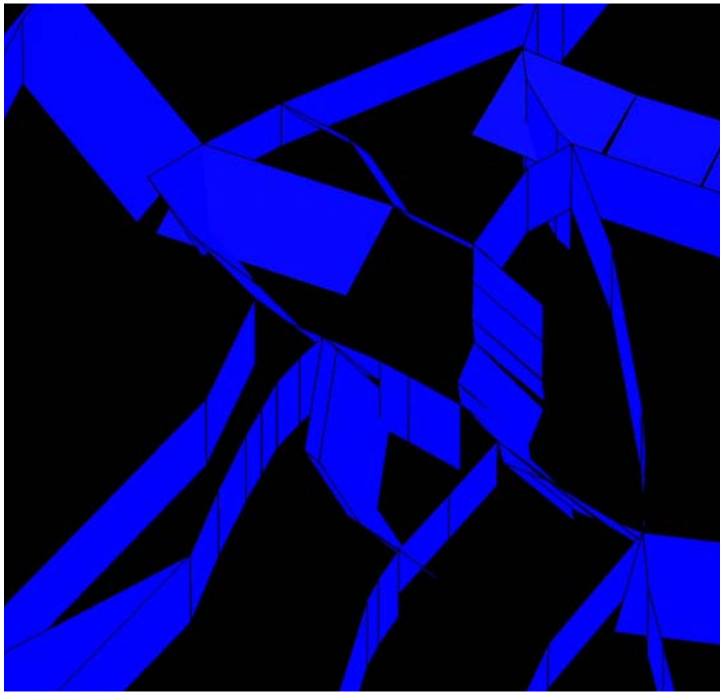
Los Angeles basin geometry

Community Fault Model:
A synthesis of geologic
and seismic data

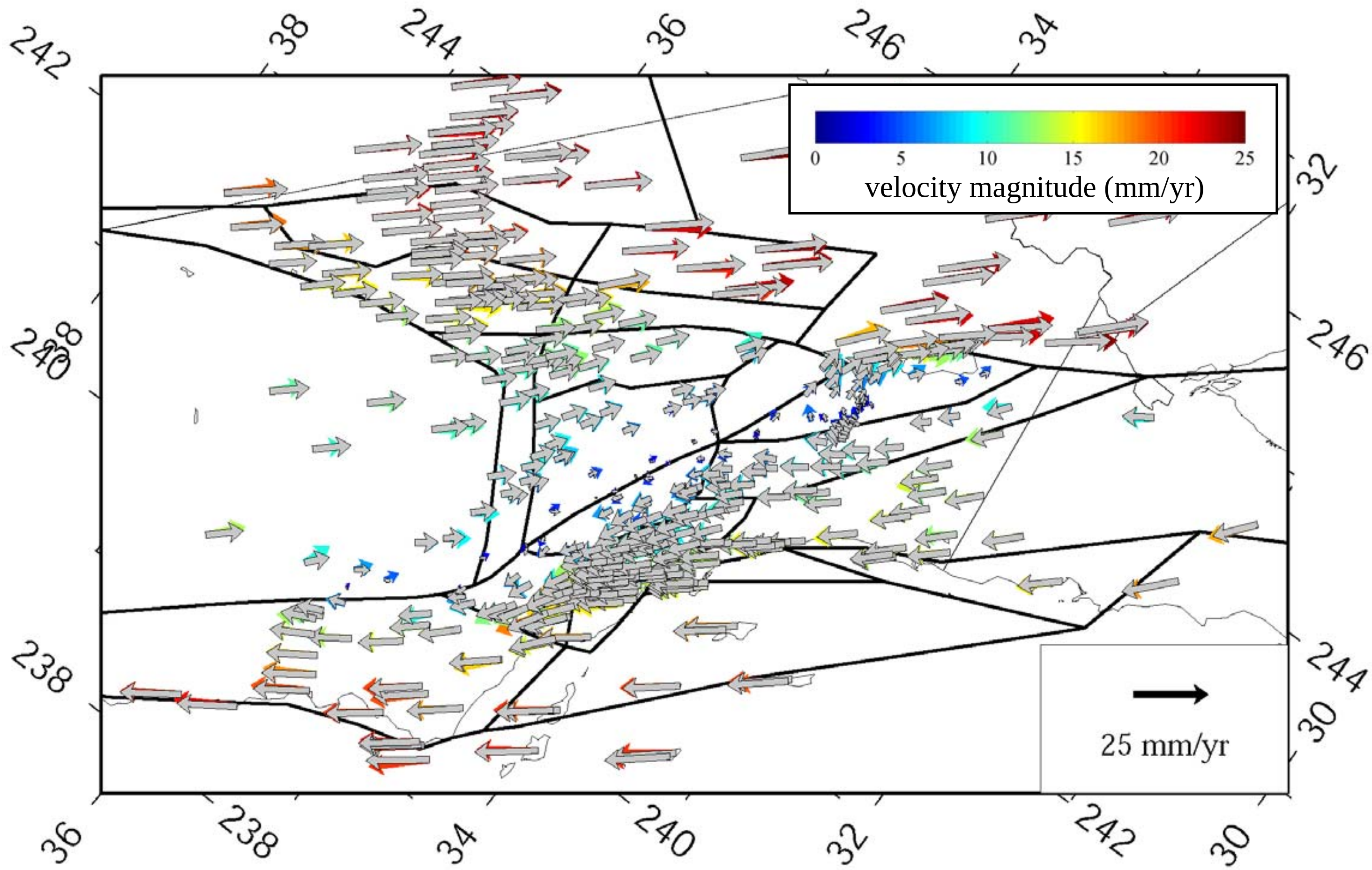


Andreas Plesch and John Shaw
http://structure.harvard.edu/cfm/

Block Model:
A simplification of the CFM +
boundaries implied by geodesy

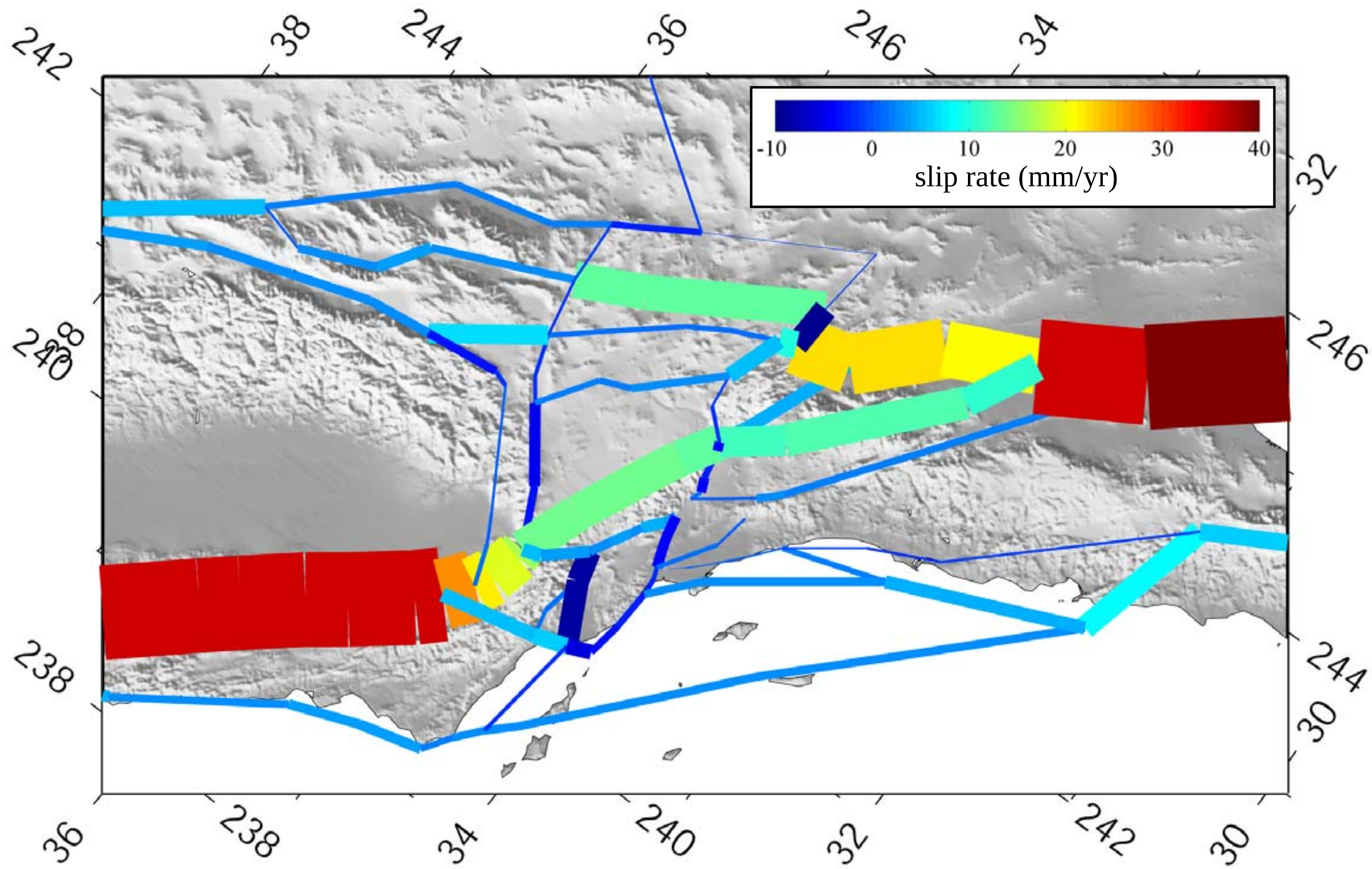


Model velocities



Residual velocity = Observed velocity - Model velocity
Mean velocity magnitude = 1.27 mm/yr
Mean uncertainty magnitude = 1.45 mm/yr

Estimated strike-slip rates



Slip rate uncertainties range from 0.5 to 3.0 mm/yr

San Andreas fault strike-slip rate varies by from 5 to 40 mm/yr

San Bernardino segment of the San Andreas Fault

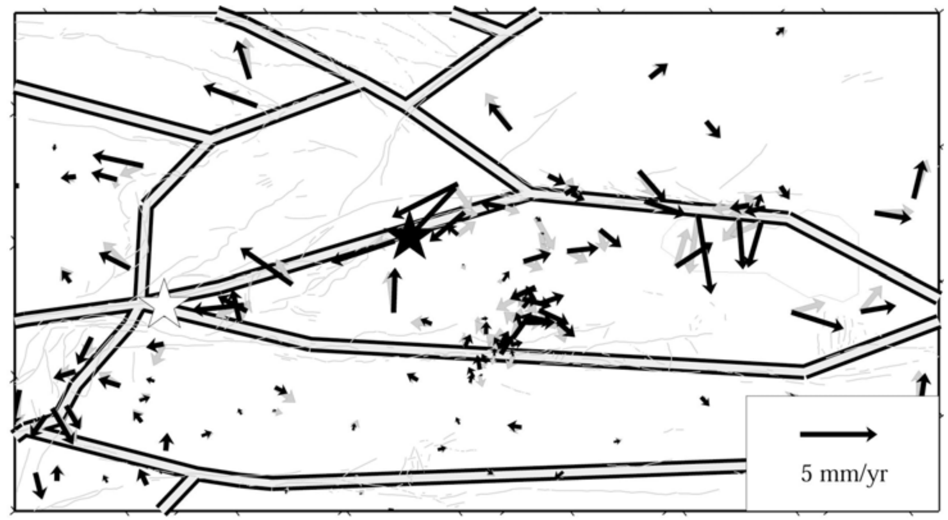
Block model estimate 5.1 +/- 1.5 mm/yr

14,000 year estimate 25+/-4 mm/yr at Cajon Pass (Weldon and Sieh, 1985)

How can we reconcile these estimates?

We can test how this slip rate might work out…Combined inverse with geodetic data and *a priori* SBSAF slip rate

And more geology…

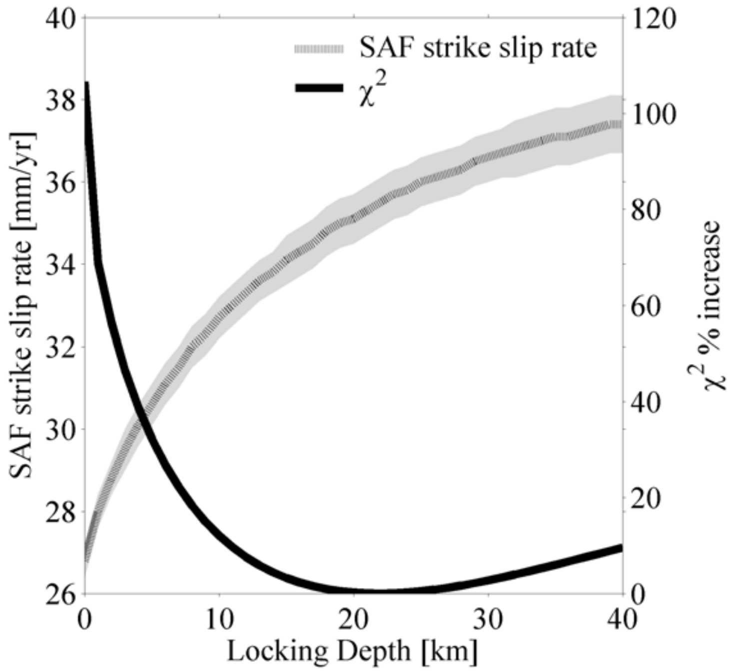


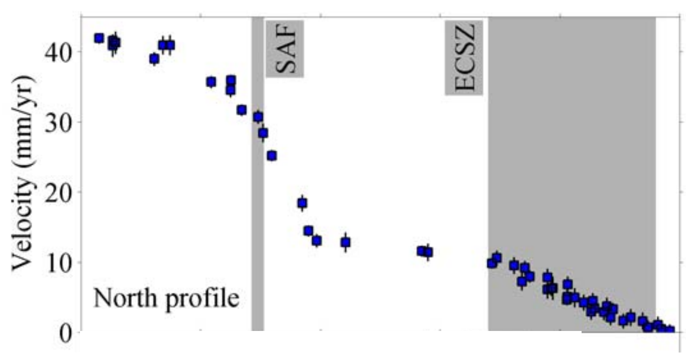
Latest Pleistocene Slip Rate of the San Bernardino Segment of the San Andreas fault in Highland: Possible Confirmation of the Low Rate Suggested by Geodetic Data.

McGill, Sally F., Weldon, Ray J. II, Kendrick, Katherine J., and Lewis Owen

Recent block modeling of geodetic data from southern California (e.g., Meade and Hager, 2005) has suggested a slip rate of 5.1 +/- 1.5 mm/yr for the San Bernardino strand of the San Andreas fault, which is nearly five times lower than the average rate over the past 14,400 years in Cajon Pass, near the northwestern end of the segment (Weldon and Sieh, 1985), and is 3-5 times lower than the rate since the latest Pleistocene in Yucaipa, farther southeast within the segment (Harden and Matti, 1989). Preliminary results of our mapping and dating of an offset channel wall of Plunge Creek, in Highland (between Cajon Pass and Yucaipa), may be consistent with the low rate suggested by geodetic data.

San Andreas fault locking depth and back to rheology





The time since the last rupture of the SAF is greater than half the mean recurrence interval

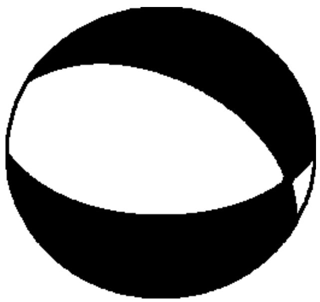
Sharp velocity gradients and average locking depths are consistent with a high viscosity lower crust/upper mantle

$$\eta > 10^{19}\ \mathrm{Pa \cdot s}$$

How to reconcile with short term-postseismic relaxation?
Alternate earthquake cycle models?

Balancing the moment budget

Has coseismic activity been consistent with interseismic behavior?



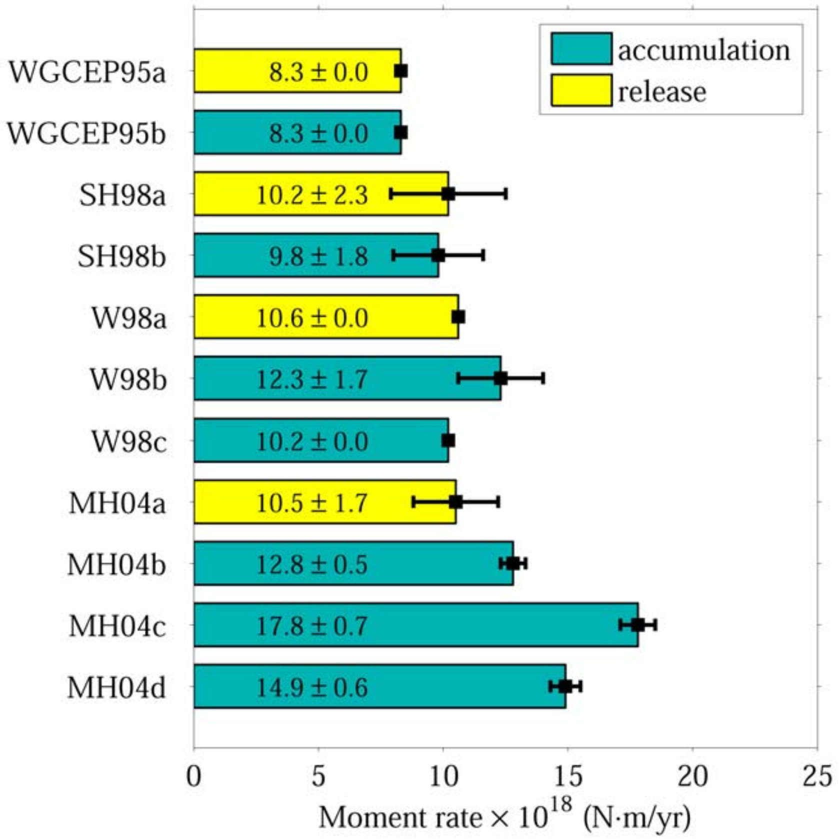
Coeseismic moment release rate

$$T^{-1} \sum^{\text{earthquakes}} \mathrm{M}_0$$

Interseismic moment accumulation rate due to elastic strain accumulation

$$\mu \sum^{\text{faults}} A\dot{s}$$

Regional moment budget



Sources : WGCEP95: Working Group on California Earthquake Probabilities (BSSA, 1995), SH98: Stein and Hanks (BSSA, 1998), W98: Ward (GJI, 1998), MH04: Meade and Hager (submitted, 2004) [b: geology, c: preferred block model, d: shallow block model]

Moment release rate:

$$\sim 10 \times 10^{18}\ \mathrm{N \cdot m/yr}$$

Moment accumulation rate:

$$8 - 18 \times 10^{18}\ \mathrm{N \cdot m/yr}$$

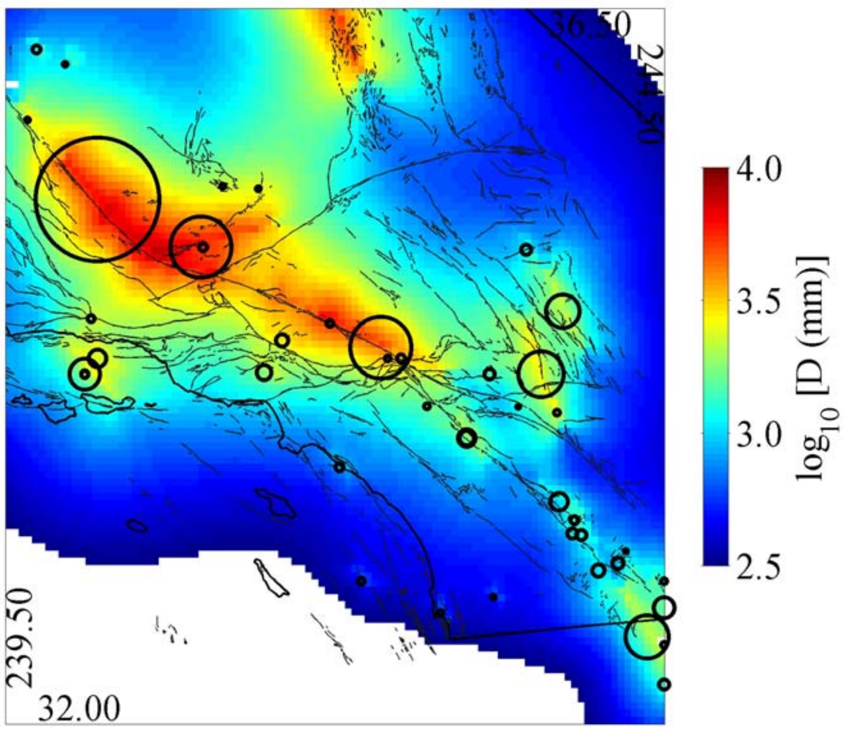
Block model moment accumulation rates are higher for three reasons :

1) Greater fault system area

2) More than one component of fault slip

3) Geodetic data are projected onto the fault system

Displacements from 200 years of earthquakes



Compare elastic displacement fields to localize moment deficits

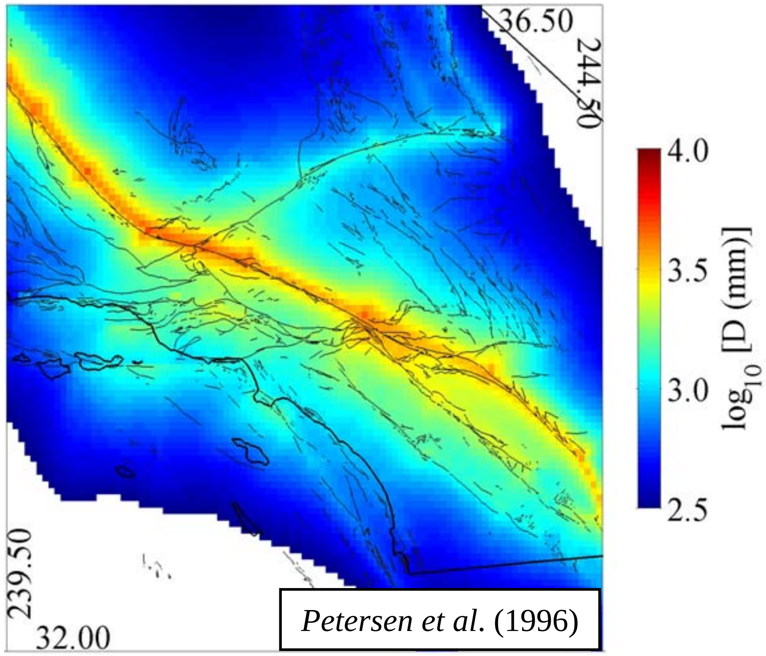
Convert *Kagan* (2004) moment tensor compilation to rupture width, length, and slip

Sieh (1978) field mapping for Ft. Tejon slip distribution

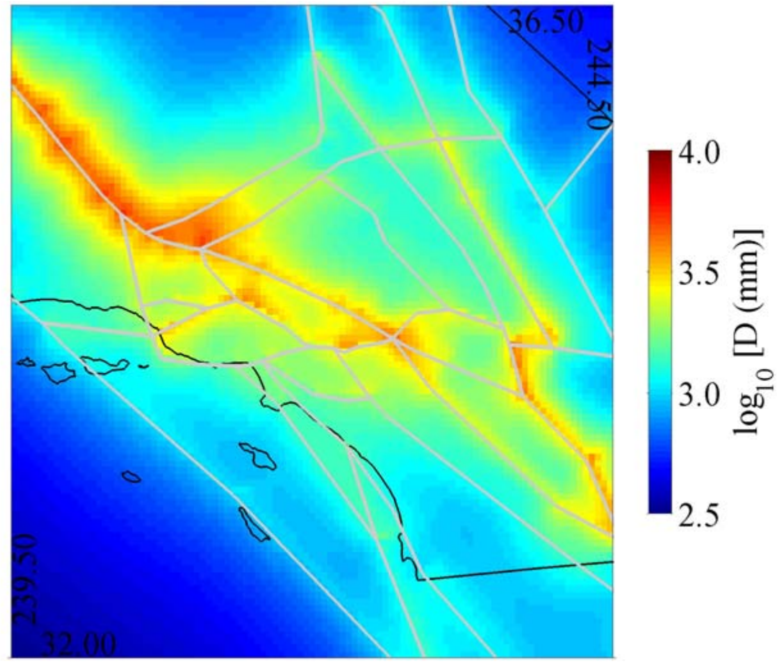
Displacements localized along the central San Andreas fault

Accumulated interseismic displacements

Geologic catalog



GPS + block model

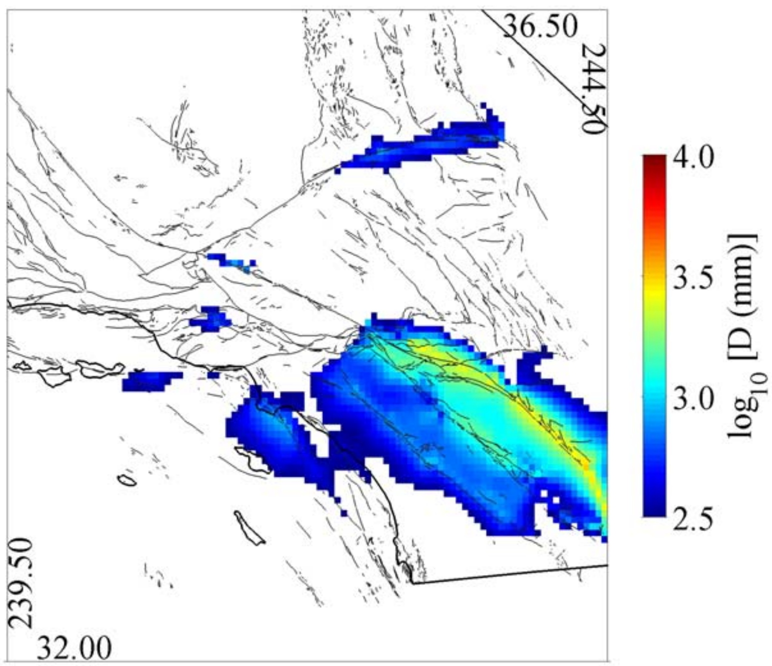


Geologic catalog has less deformation in the ECSZ, offshore and in the basins

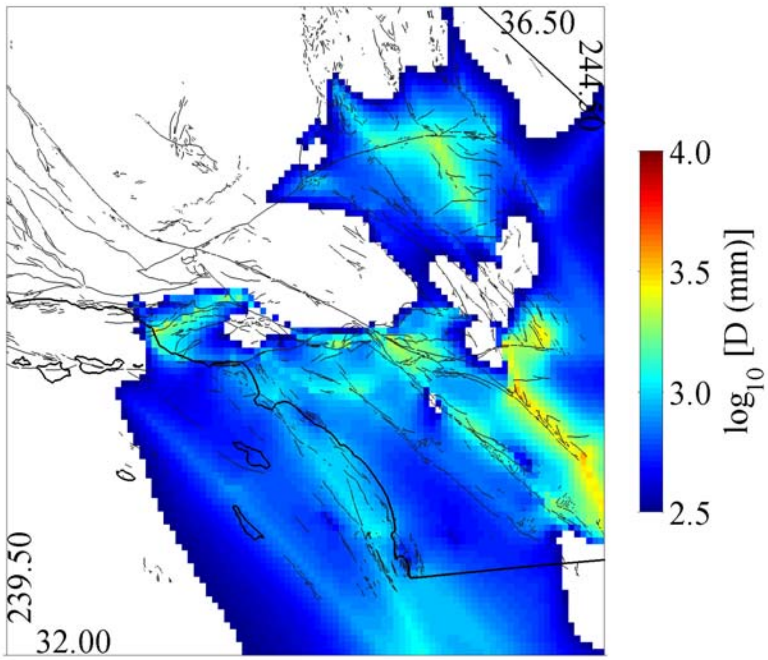
Block model shows less accumulated displacement along the SAF

Differential displacement fields

Geologic catalog



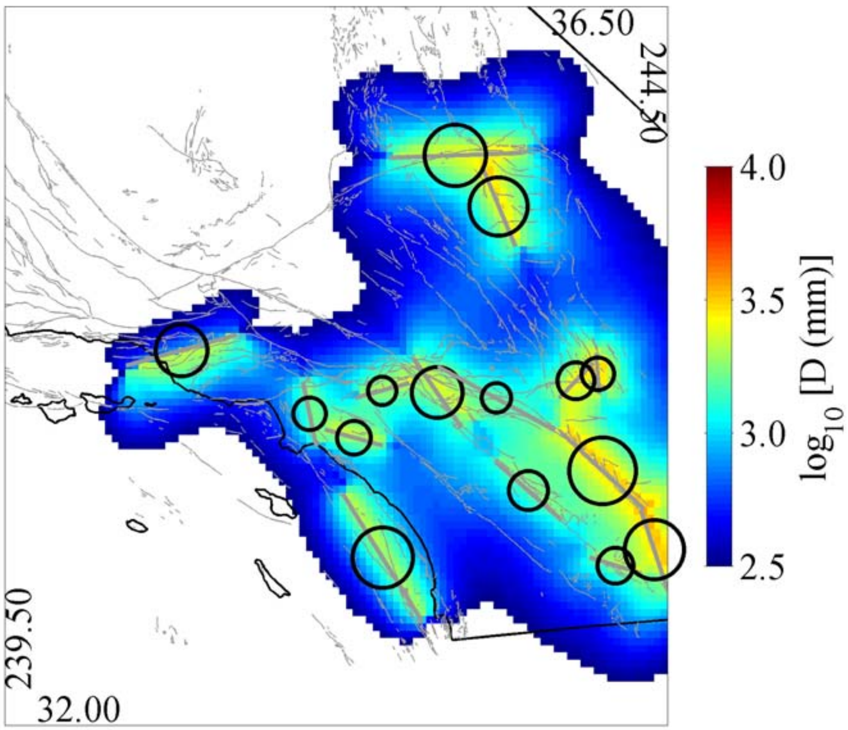
GPS + block model



Geologic deficits are localized along the southern SAF

Block model deficits are localized along the SAF, ECSZ, offshore and basin faults

What would it take to balance the moment budget?



Estimate potential earthquake sources that could balance the moment budget

14 $M_W > 7$ model sources with a composite magnitude of $M_W \approx 8$

What about other mechanisms?

What have we learned?

SAF slip rate varies by at least a factor of five

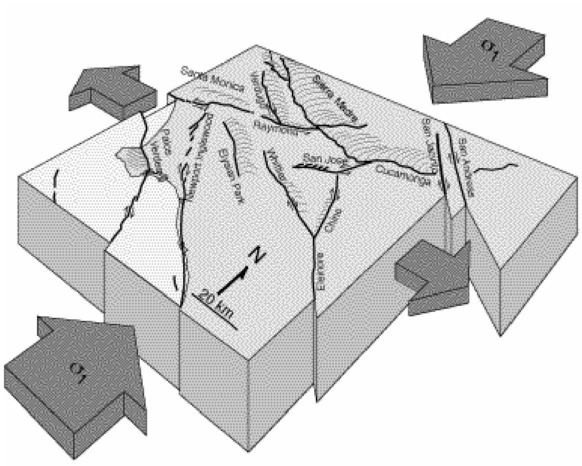
LA faults accommodate both thickening & escape tectonics

Lack of evidence for long-term postseismic deformation implies a high viscosity lower crust/upper mantle using classic earthquake cycle models

Moment release deficits are localized in three areas:

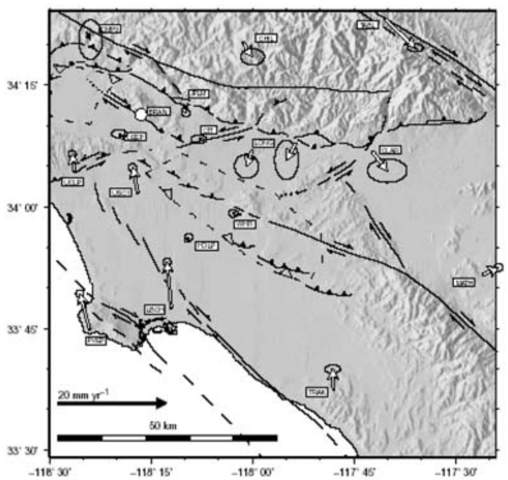
1) Southern San Andreas fault
2) Eastern California Shear Zone
3) Los Angeles and Ventura Basins

Escape tectonics vs. thrust faulting

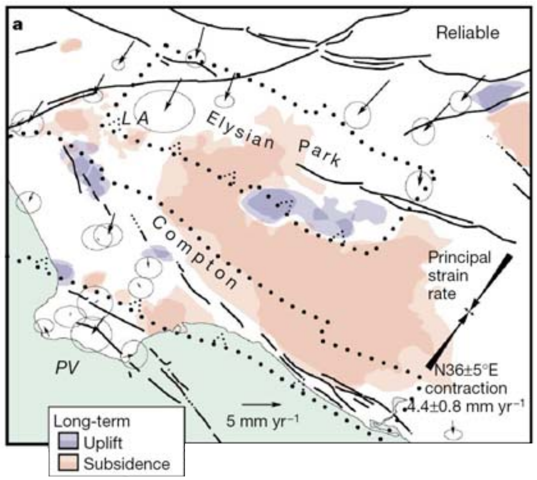


Is deformation around the Los Angeles basin accommodated by strike-slip or thrust faulting?

Geodetic studies have reached different conclusions



Walls et al. (1998)



Argus et al. (1999) , *Bawden et al.* (2001)

Escape tectonics and thrust faulting

Geodetic evidence for shortening and conjugate strike-slip faulting