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Plate motions and strain distribution in deforming regions (emphasis on regional deformation, mapping strain)

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From GPS Velocities to Plate Motions and Strain Distribution

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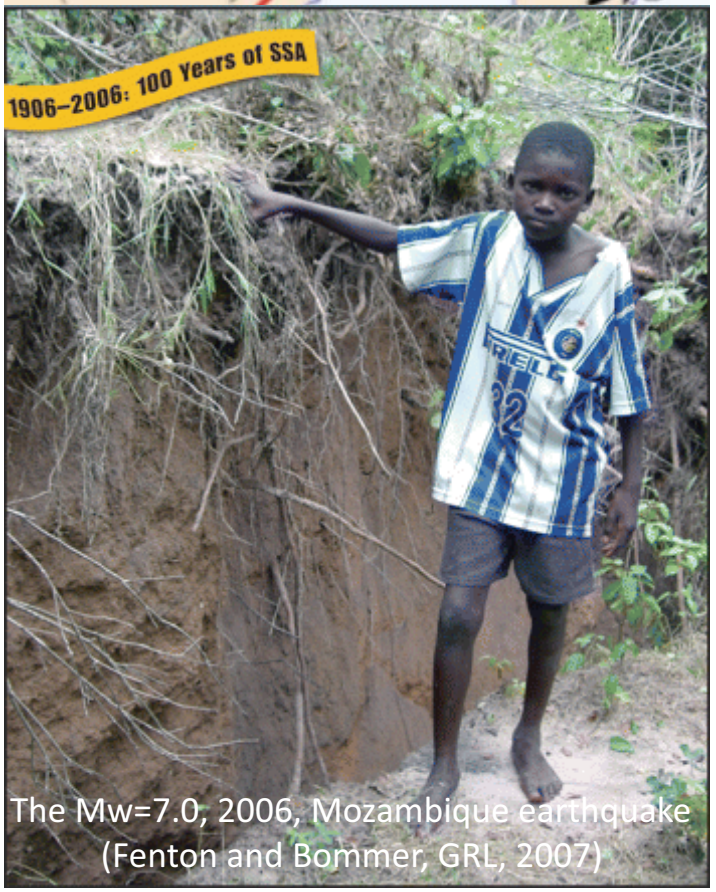
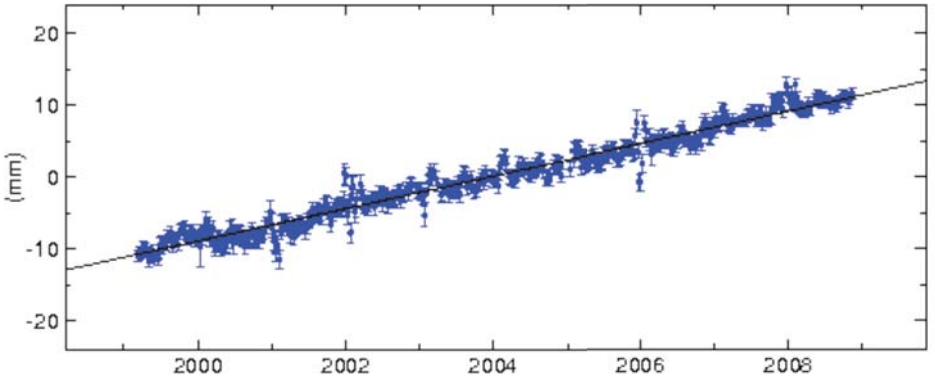
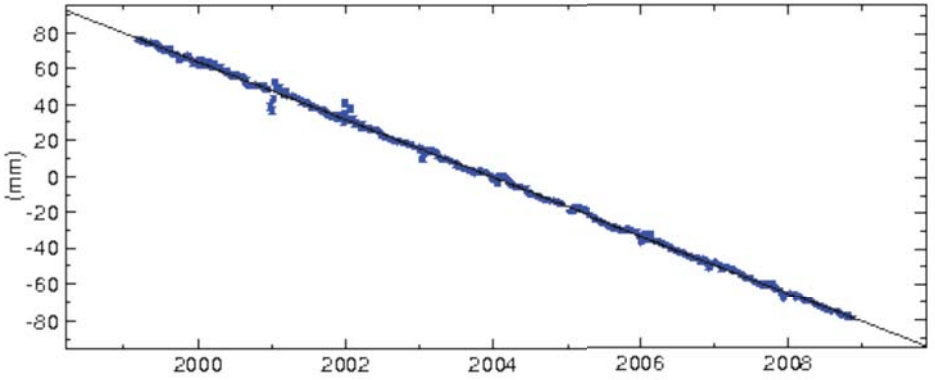


The Mw=7.0, 2006, Mozambique earthquake
(Fenton and Bommer, GRL, 2007)

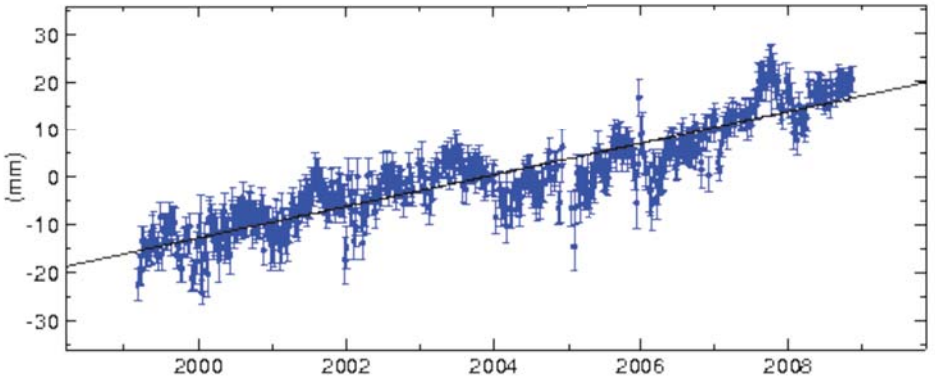
ALGO North Offset 5115776.281 m
rate(mm/yr)= 2.26 ± 0.01 nrms= 1.20 wrms= 1.1 mm # 471



ALGO East Offset 21818305.279 m
rate(mm/yr)= -16.10 ± 0.01 nrms= 1.30 wrms= 1.2 mm # 471



ALGO Up Offset 200.885 m
rate(mm/yr)= 3.31 ± 0.05 nrms= 1.29 wrms= 4.2 mm # 471



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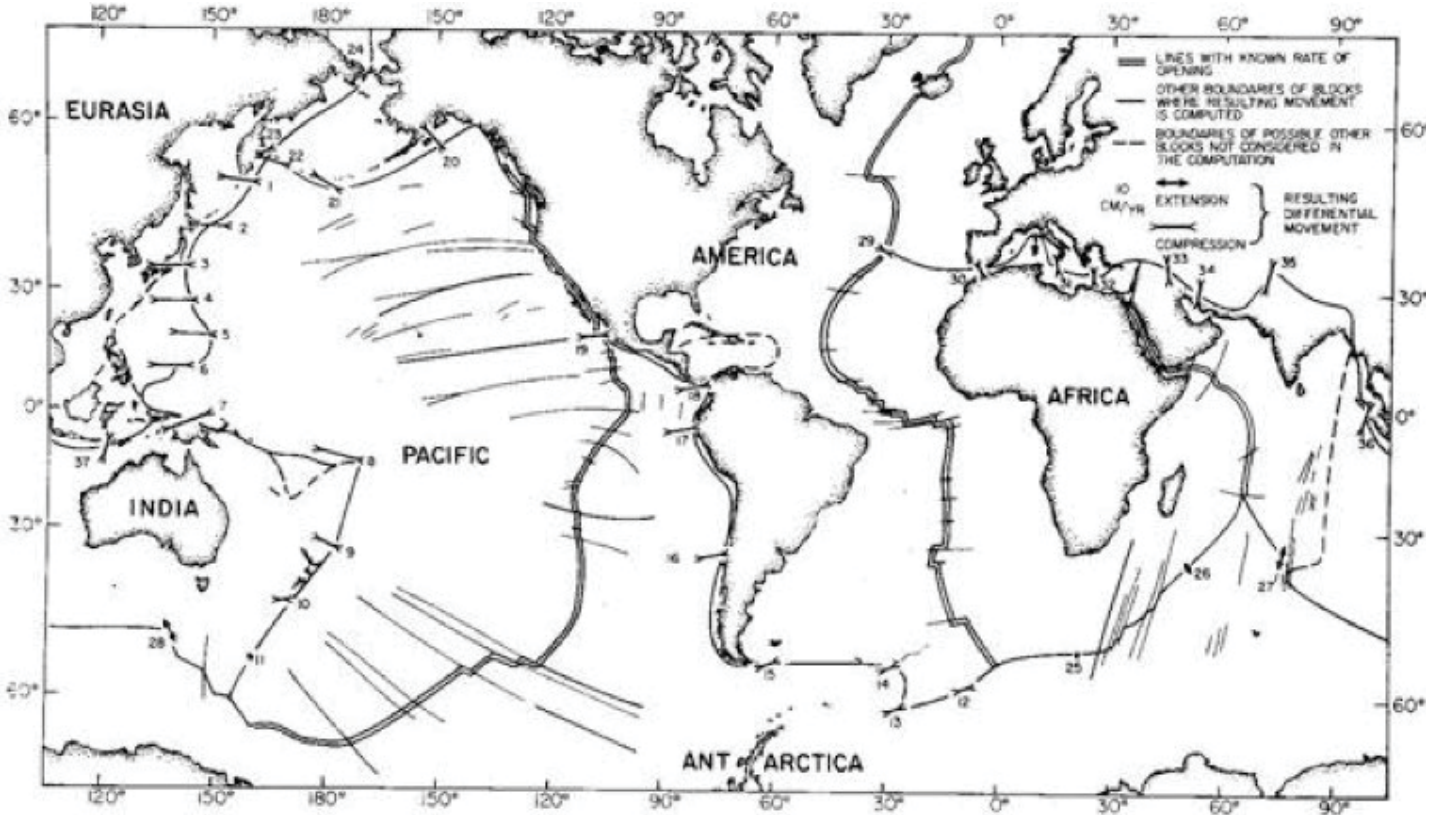
A few questions that GPS geodesy can help address:

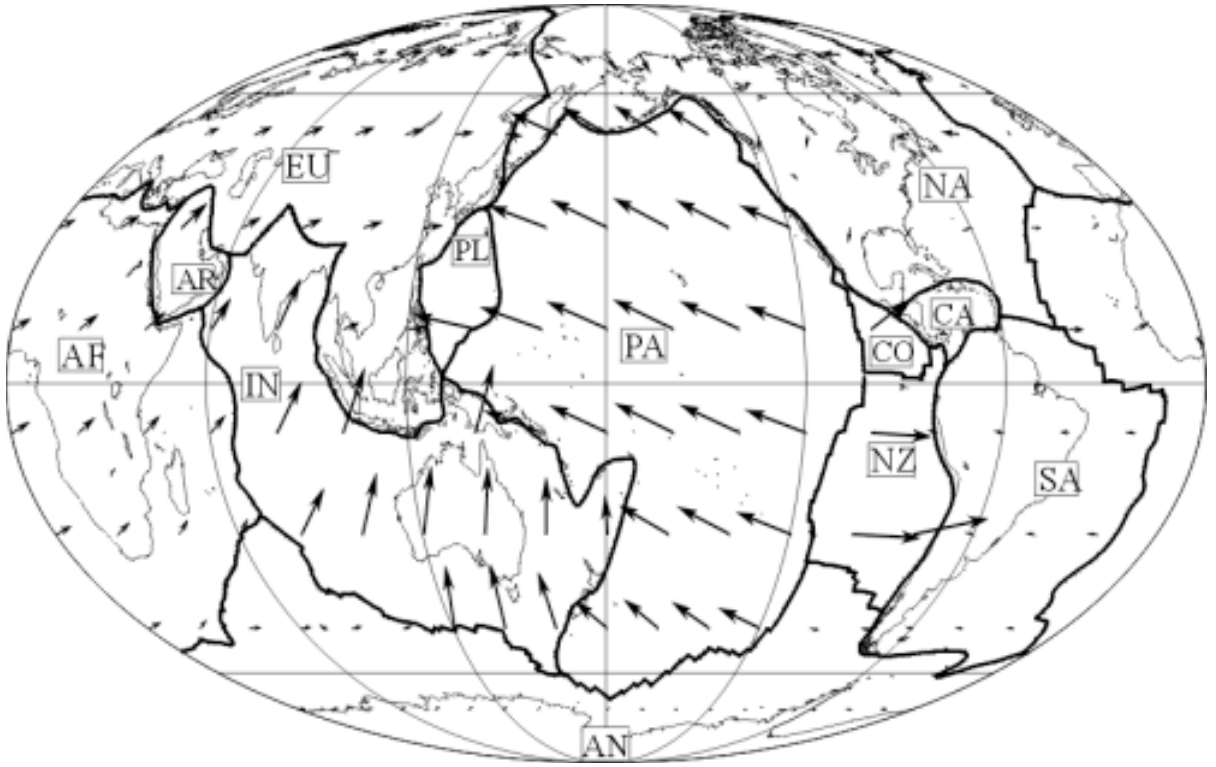
- How fast are plates moving?
- How fast are faults slipping?
- How is deformation distributed across an active region?
- Are continental interiors deforming?
- Are plate and fault motions constant with time?

A bit of history…



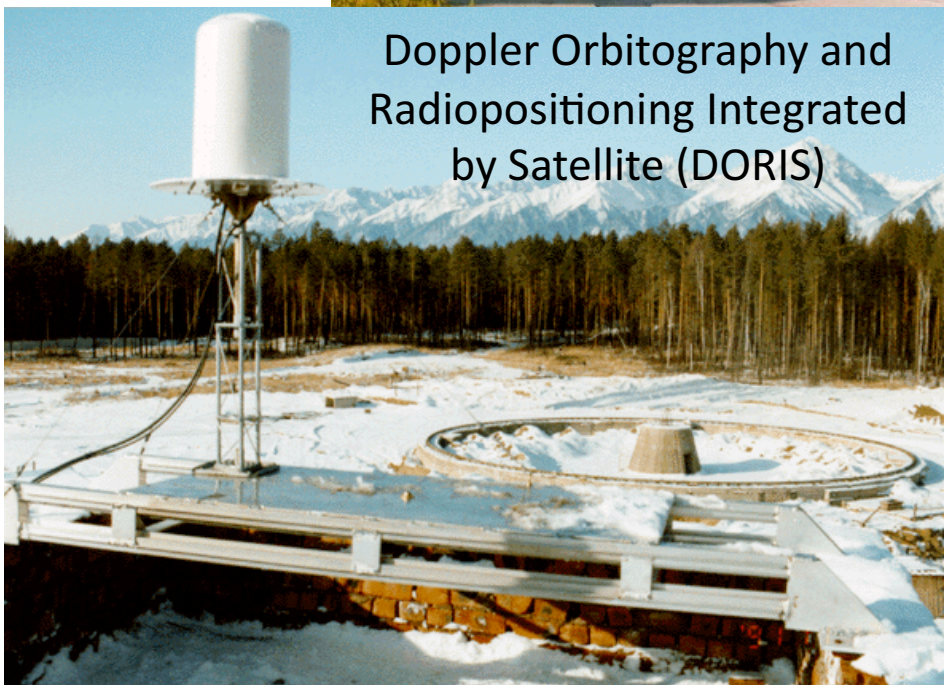
- 1967, **McKenzie and Parker:** hypothesis of rigid plates (rotation pole fit to the San Andreas fault predicts observed earthquake slip vectors in Alaska, Kouriles, and Japan.
- 1968, **Jason Morgan:** first angular rotation for the Atlantic based on transform faults and magnetic anomalies and a 5-plate model, but not fully quantified.
- 1968, **Xavier Le Pichon:** first global kinematic model and fully quantified, with 6 plates (based on anomaly 5, ~10 My).

NUVEL1A Geologic Plate Motion Model



- De Mets et al., 1990, 1994.
- **Geological** model: ocean floor magnetic anomalies, transform faults, earthquake slip vectors.
- Hypothesis:
  - **Limited** number of **rigid** plates
  - **Constant** velocity over the past **3 million years**

The space geodesy revolution…



A first major result…

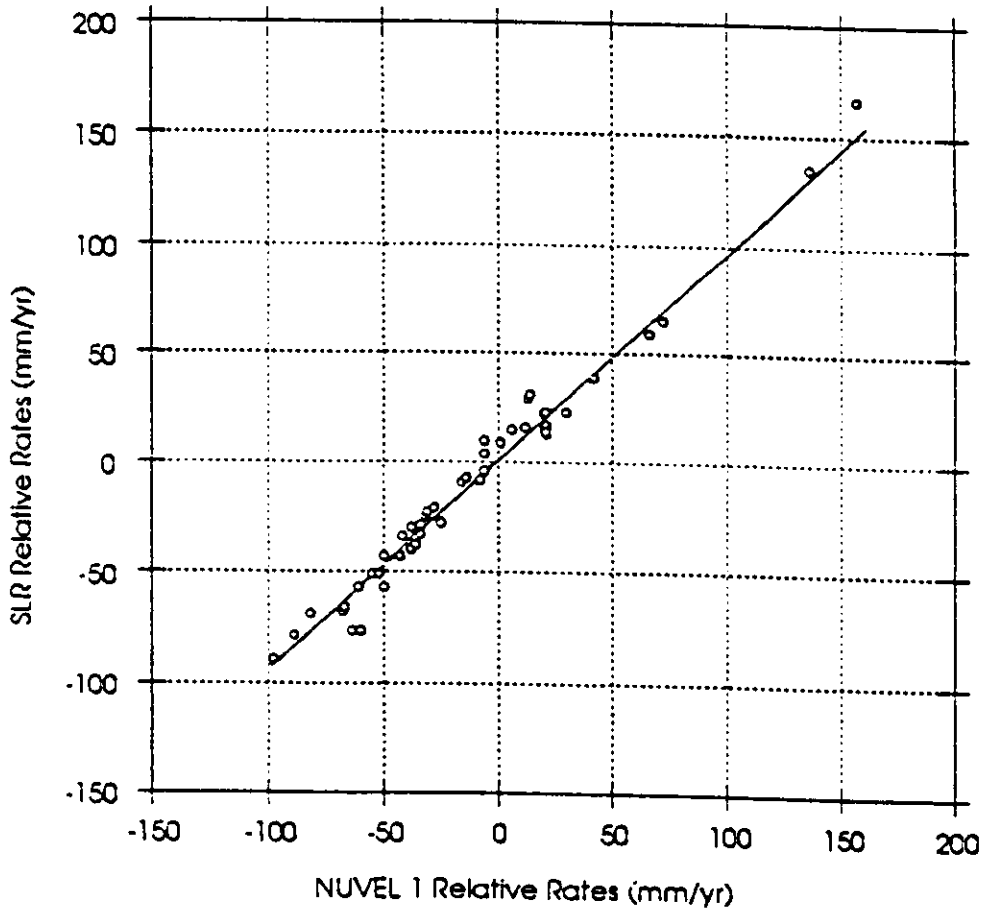


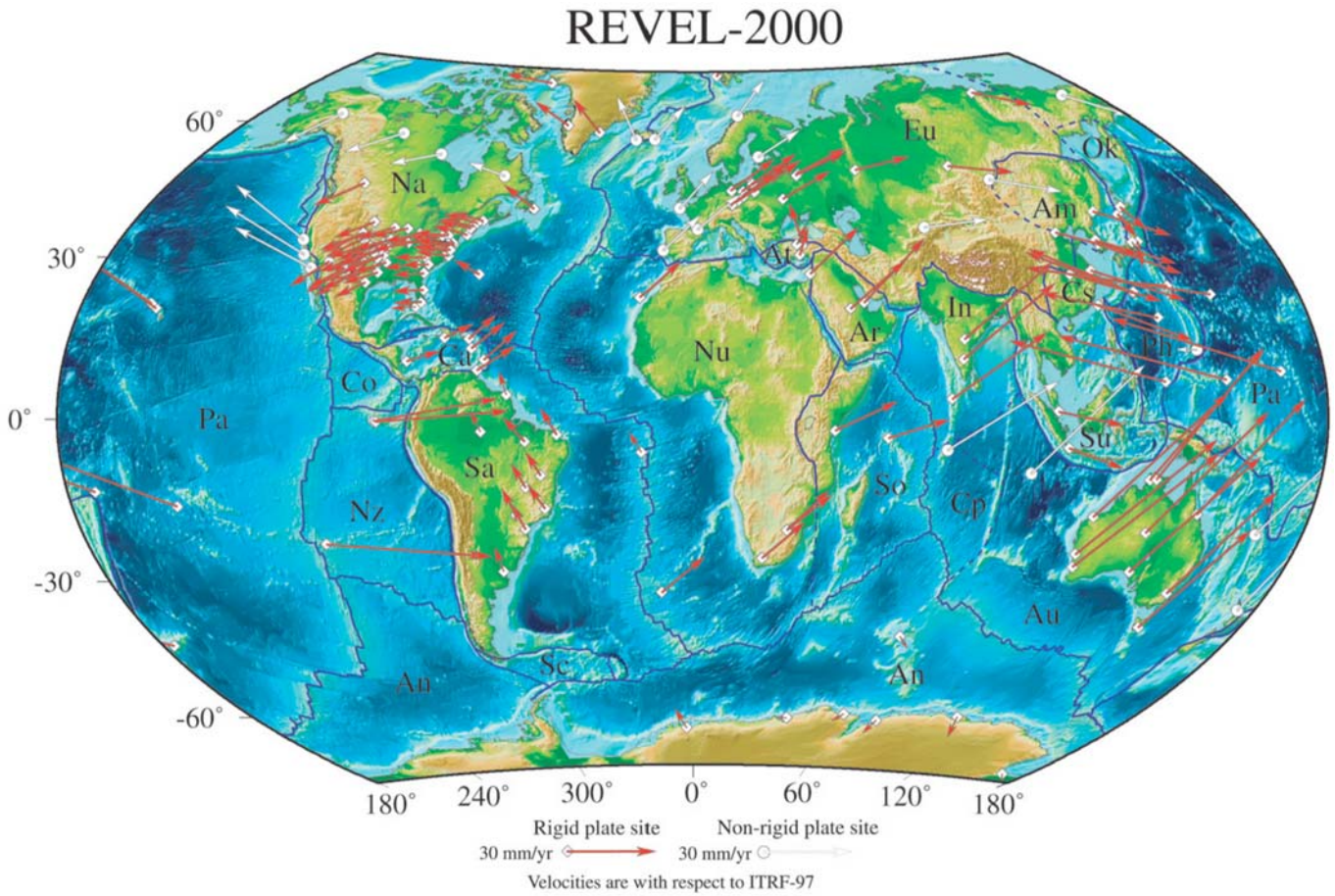
Fig. 11. Comparison of SLR determined geodesic rates with those implied by the NUVEL 1 geologic plate motion model for 54 lines connecting stations on five plates that are well within plate interiors and crossing at least one plate boundary. The slope of the line is 0.949 ± 0.019.

Plate Motions Are Steady

Richard G. Gordon

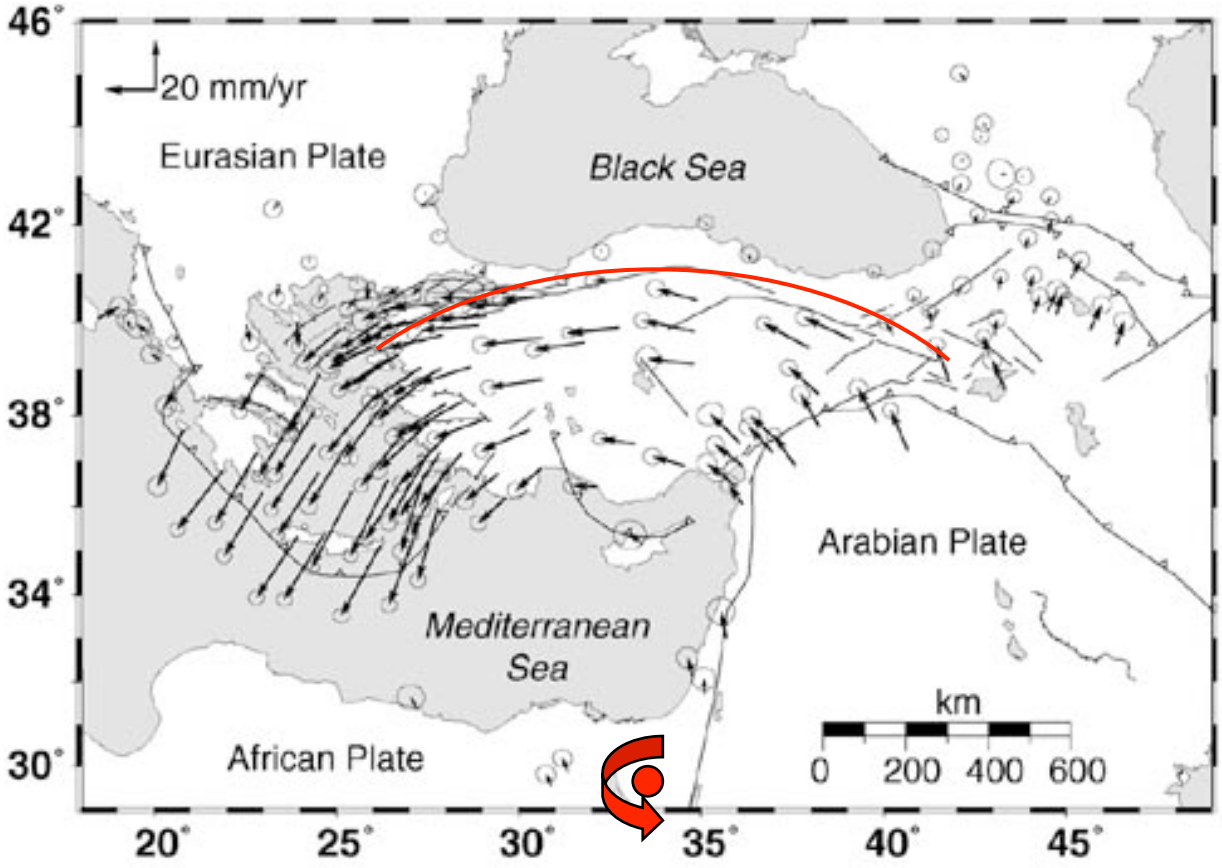
- Plate motions are steady (over the past 3 My)
- Validation of the geological model
- Validation of the geodetic measurements

Geodetic Plate Motion Models



- Global plate motions can be computed directly from geodetic velocities
- Many attempts since ~1995
- E.g. REVEL model (Sella et al., 2002) – Africa finally split in two…!

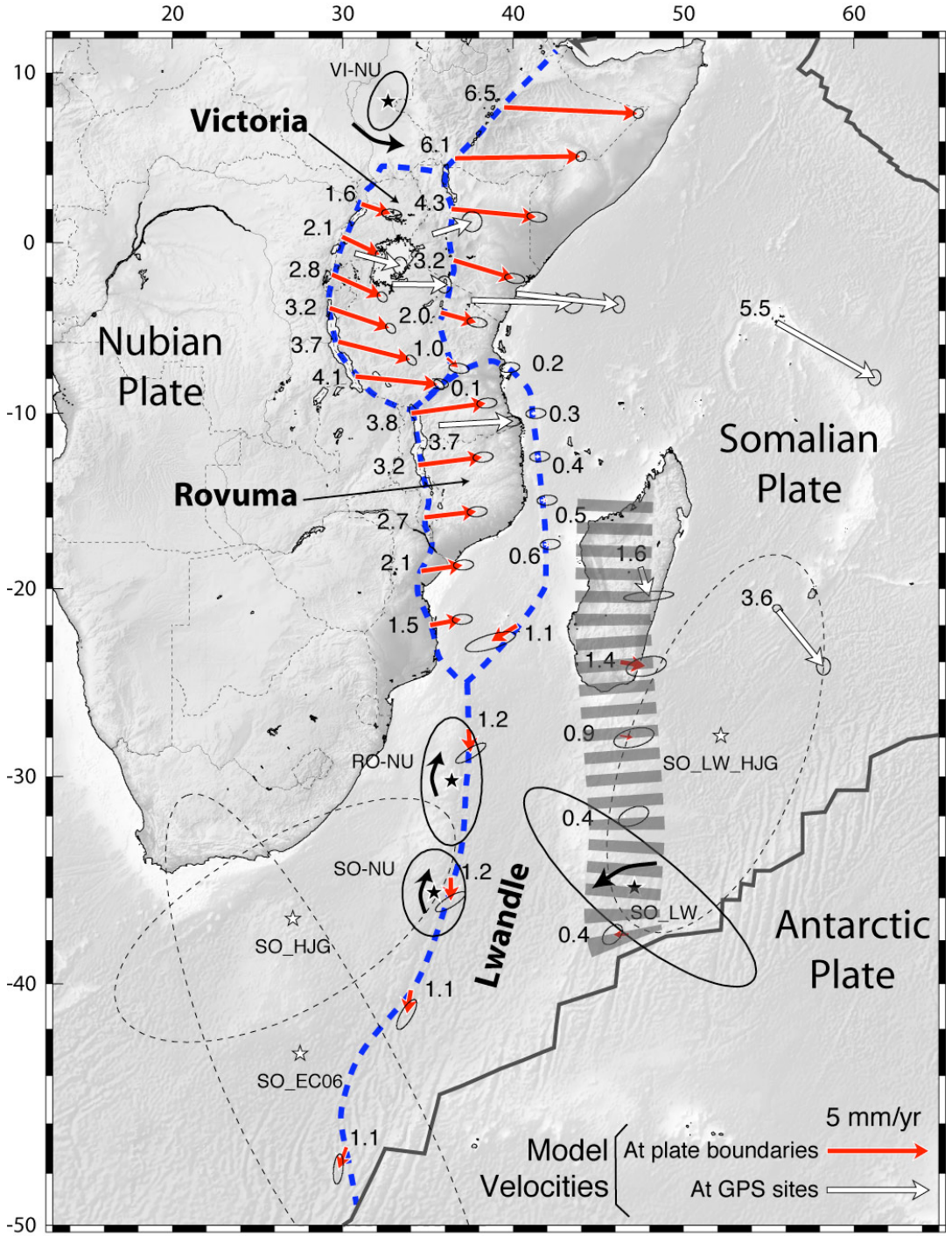
Smaller plates



- Anatolian plate (McClusky et al., JGR, 2000)
- North Anatolian Fault = small circle about rotation pole, right-lateral slip at ~25 mm/yr

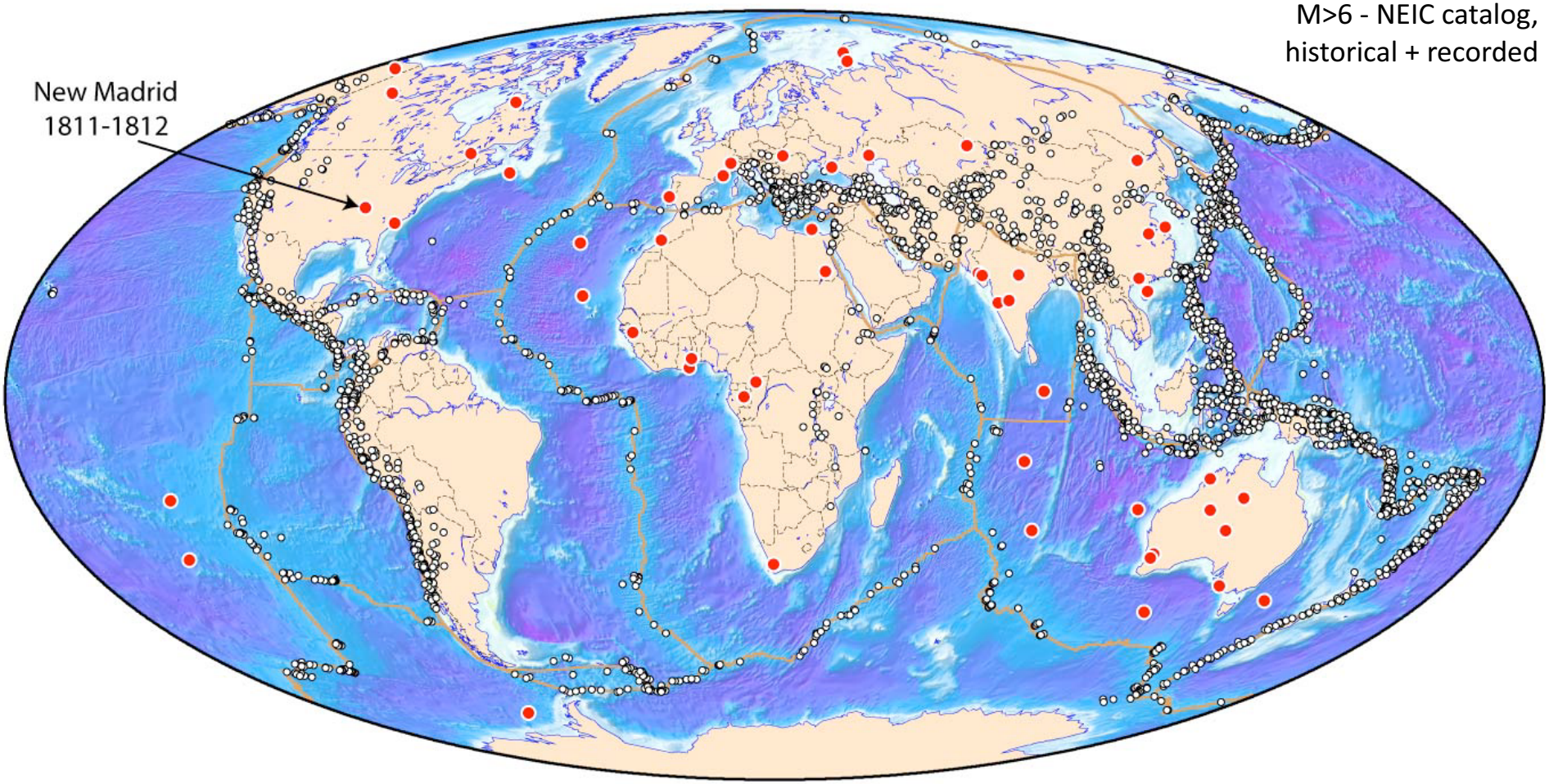
East Africa

- Much less GPS data… (white arrows)
- Use of earthquake slip vectors along rift segments
- 3 plates embedded within rift
- Predicted extension rate and directions along rift faults



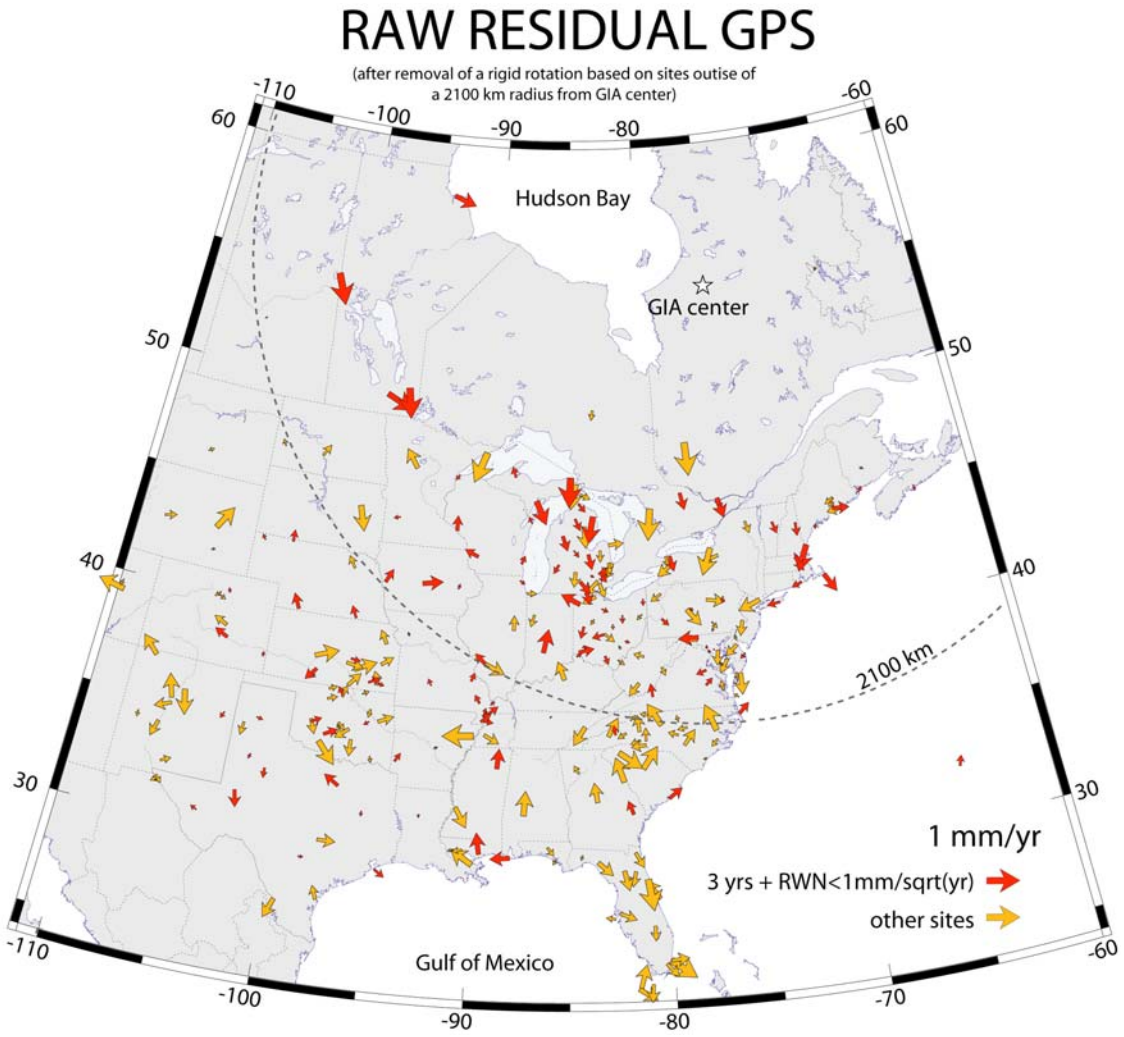
Stamps et al., GRL, 2008

How rigid are plates?

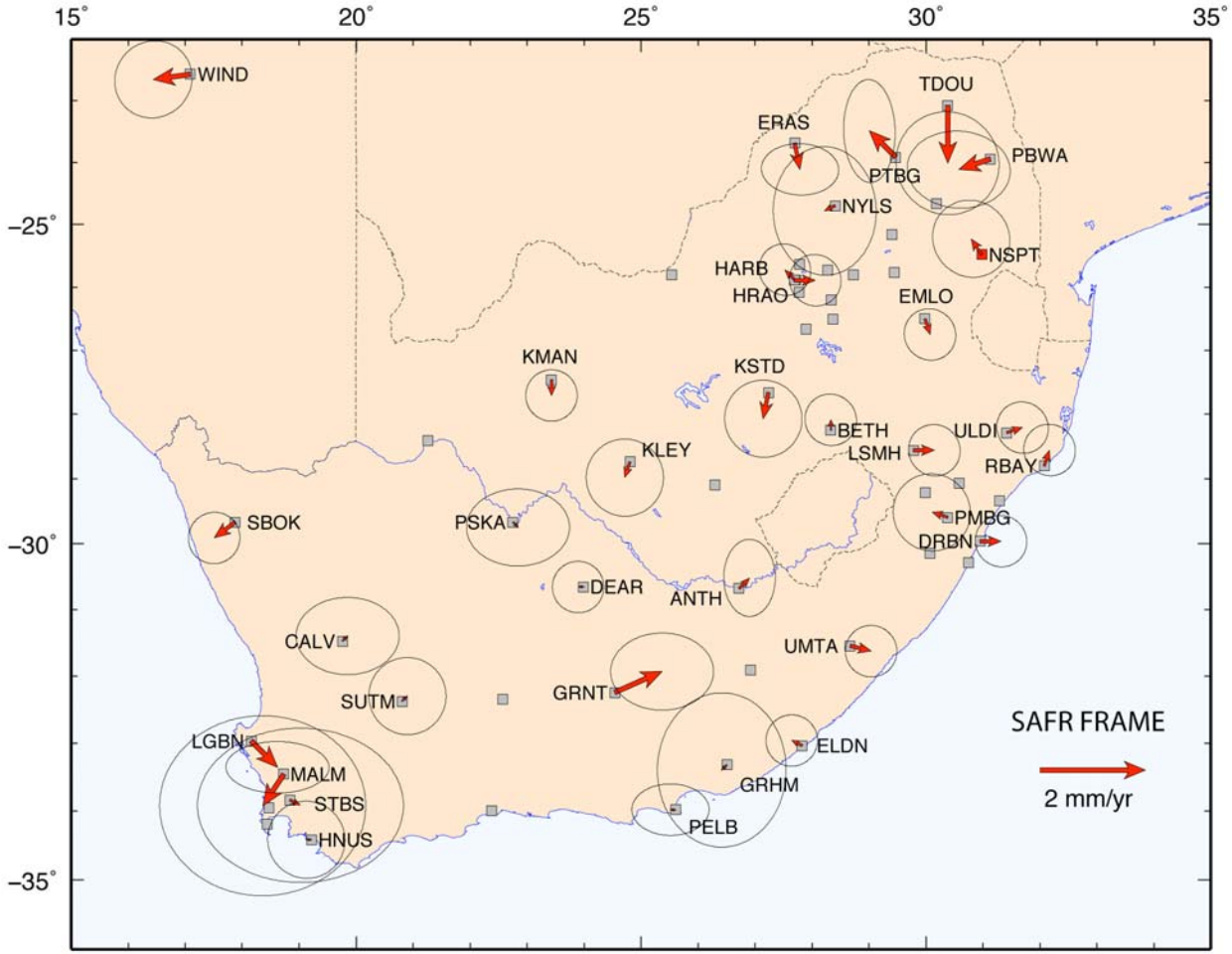


North America

- ~400 continuous GPS sites (best sites in red)
- Residual velocities with respect to rigid plate model:
  - Small (most not significant at a 95% confidence level)
  - Random
- Upper bound of internal deformation = 0.5 mm/yr

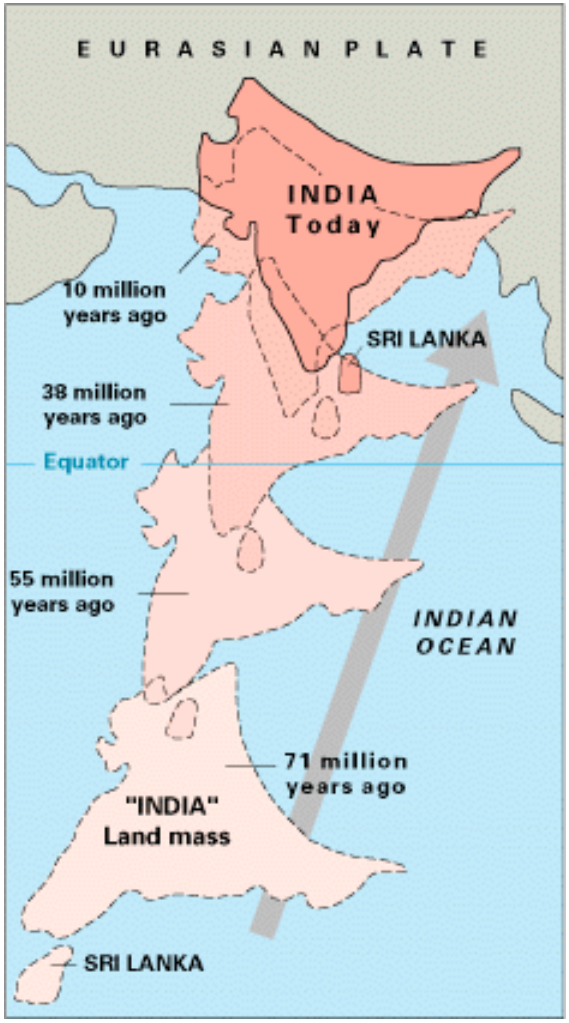


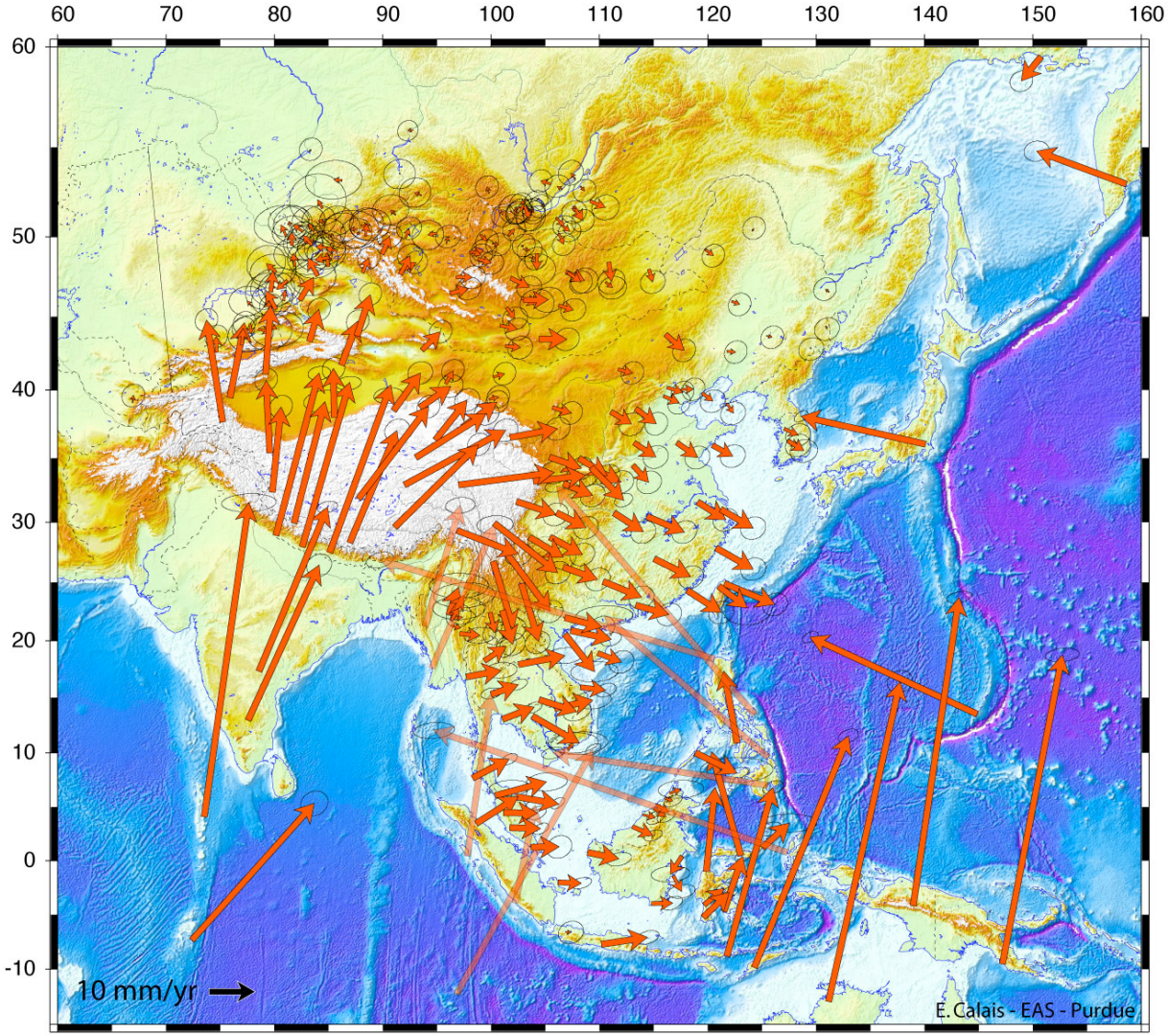
South Africa



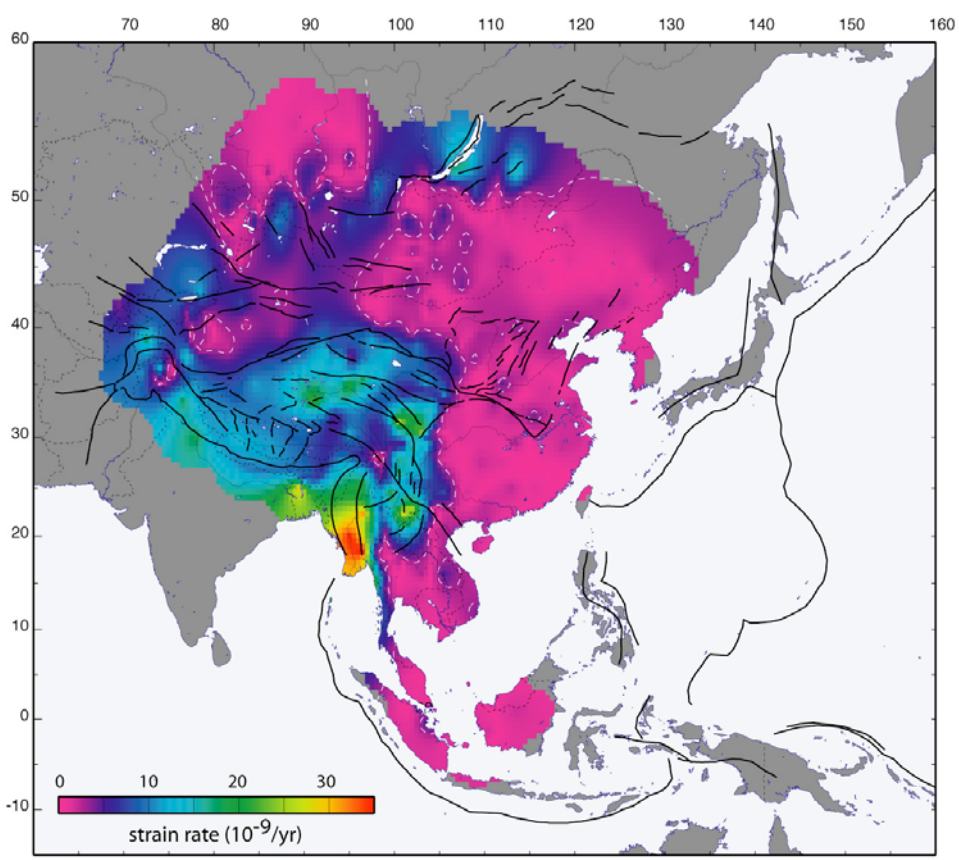
- 50 continuous GPS, 34 used here
- Upper bound for internal deformation = 0.4 mm/yr…

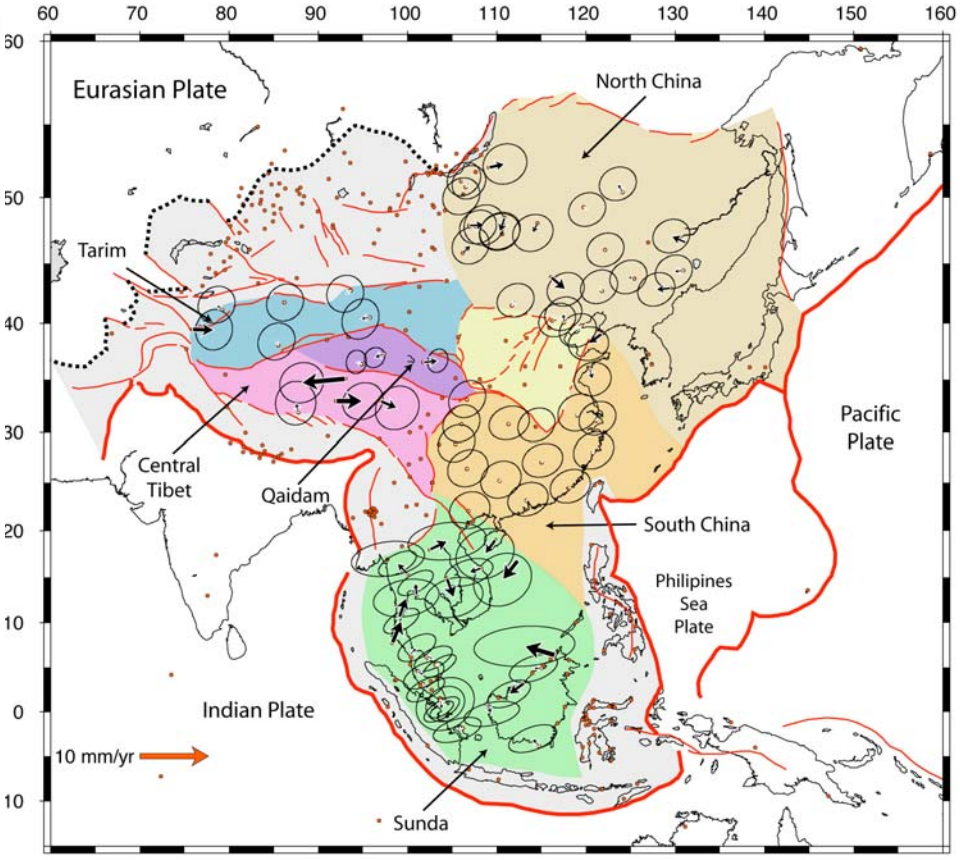
Asia


EURASIAN PLATE
INDIA
Today
10 million
years ago
SRI LANKA
38 million
years ago
Equator
55 million
years ago
INDIAN
OCEAN
71 million
years ago
"INDIA"
Land mass
SRI LANKA


60
70
80
90
100
110
120
130
140
150
160
60
50
40
30
20
10
0
-10
10 mm/yr
E. Calais - EAS - Purdue

Asia

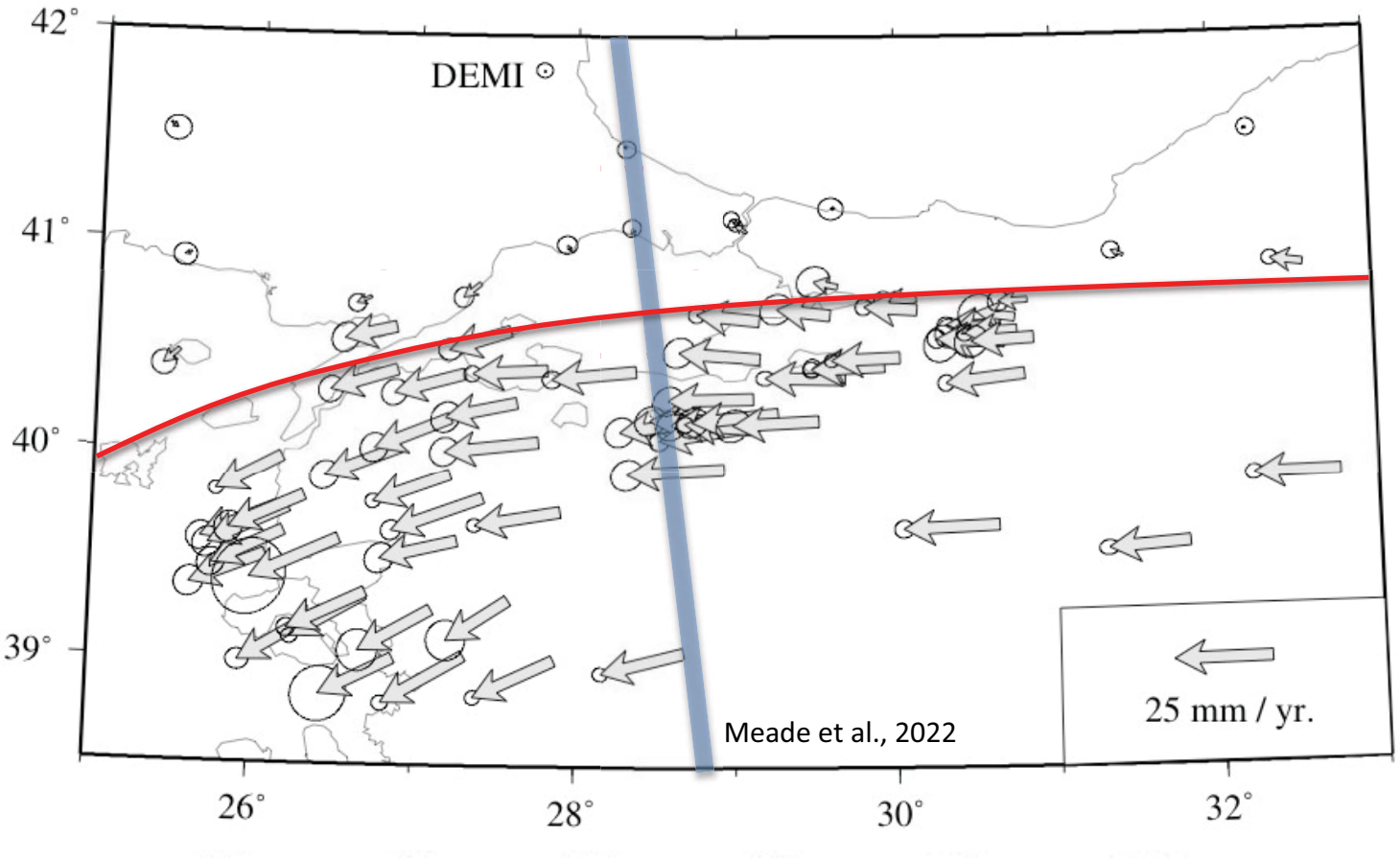




- Strain rates: large part of Asia deforms at less than $3x10^{-9}$ yr^{-1} (magenta) => plate-like
- Some areas (Tibet, Tien Shan,etc.) appear to deform internally

- Block motions: works well (small residuals for a large part of Asia
- Needs more (and smaller) blocks to work in Tibet and other deforming areas…

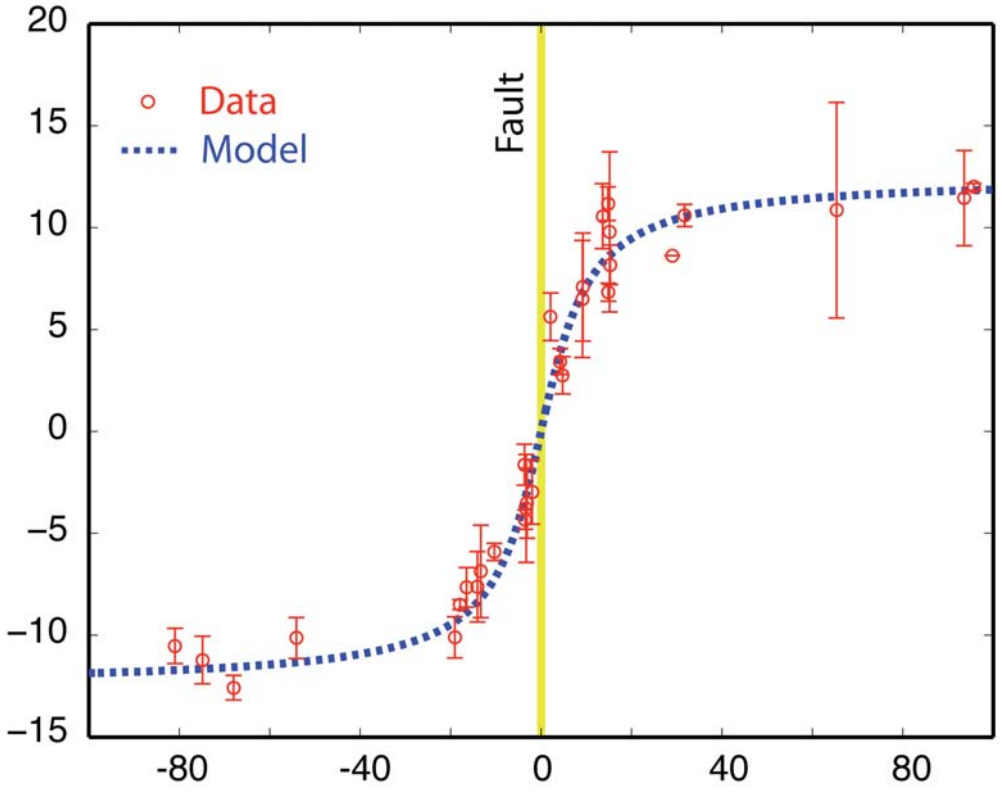
The Marmara Sea area

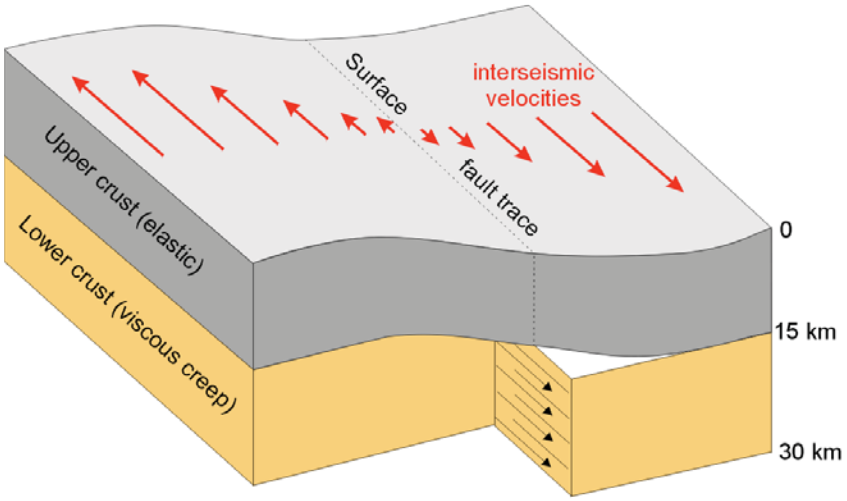


GPS observations:

- Right-lateral shear
- Velocity gradient perpendicular to the fault

The Marmara Sea area

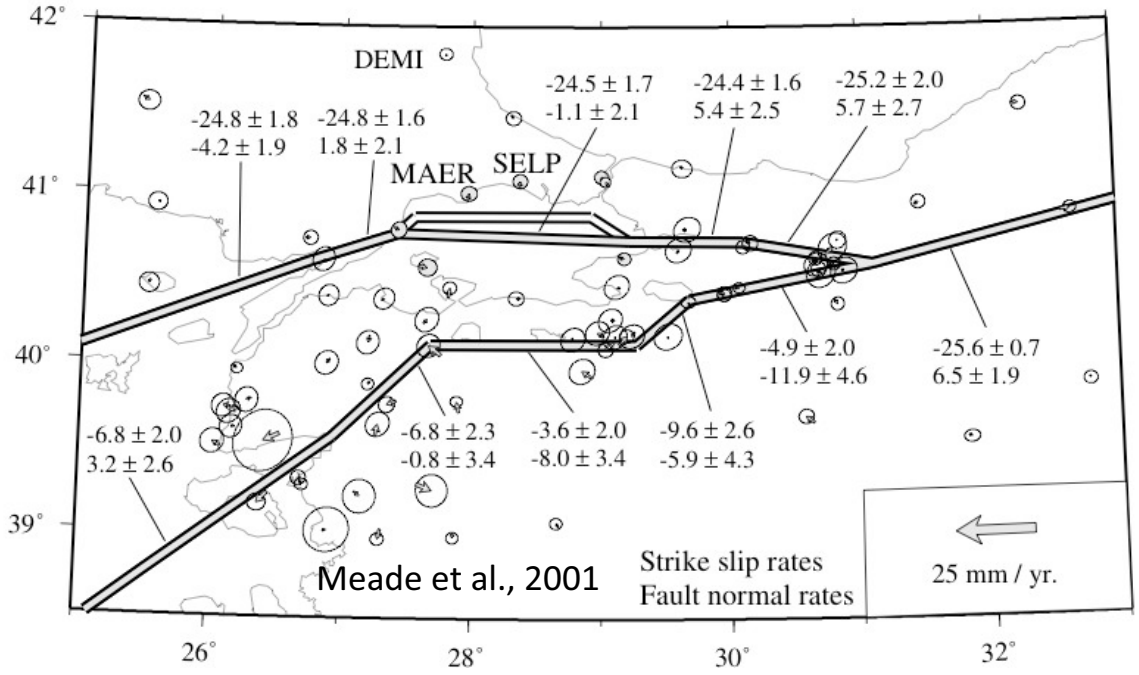




In between large earthquakes:
Fault is locked in the crust =>
accumulation of strain

$$Velocity = \frac{\text{slip rate}}{\pi} \times \text{atan}\left(\frac{\text{distance}}{\text{locking depth}}\right)$$

The Marmara Sea area



Solid lines = preferred fault model. Dashed line in the Marmara Sea = alternate stepped geometry. Slip rate estimates and one-sigma uncertainties associated with our preferred shown as pairs. Upper values = strike-slip rates, with negative values indicate right-lateral motion; lower values = the fault-normal motion, negative values indicate opening.

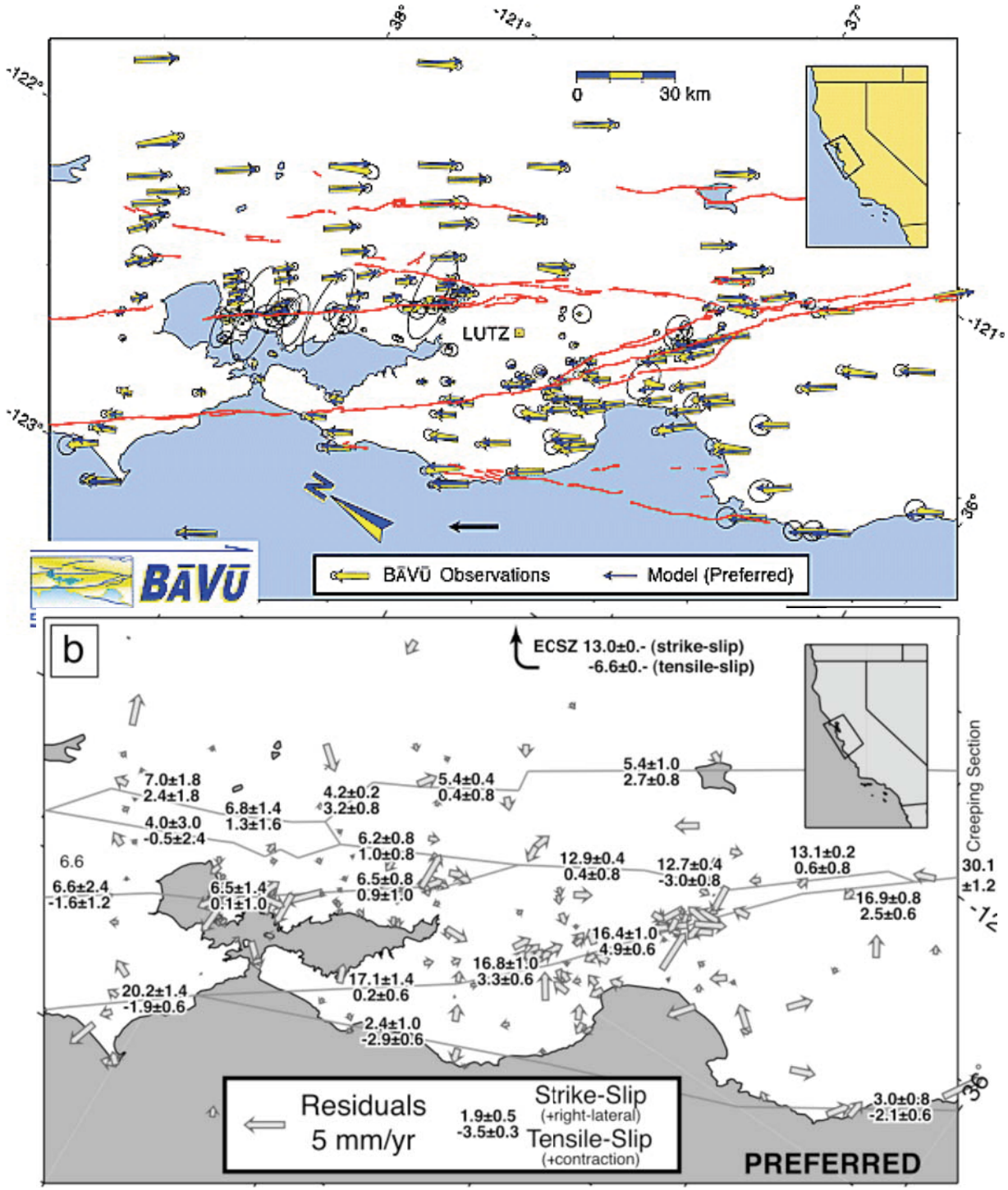
velocity residuals

Solid black = straight fault geometry. Grey = stepped-fault geometry. White bell-curve = distribution of fault slip rates from Monte Carlo tests. Dashed line: slip rate as a function of locking depth

- Solve for block rotations and fault locking depth => fault slip rates
- = “block model”, describes the kinematics of the fault system
- Applicable to seismic hazard

San Francisco

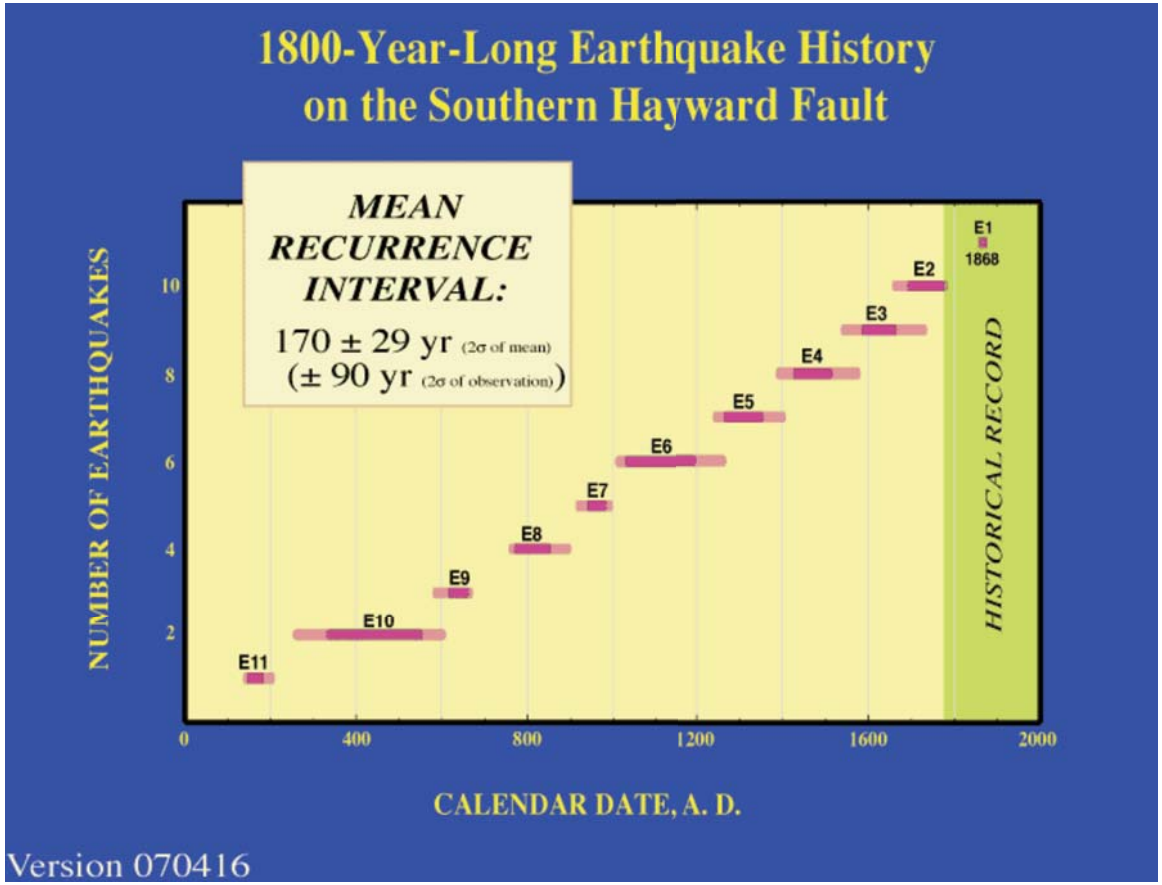
- Dense GPS data set
- Active faults well mapped
- Block model used to derive slip rates
- Hayward fault: 6.5+-0.8 mm/yr



D'Alessio et al., 2005

Paleoseismology…

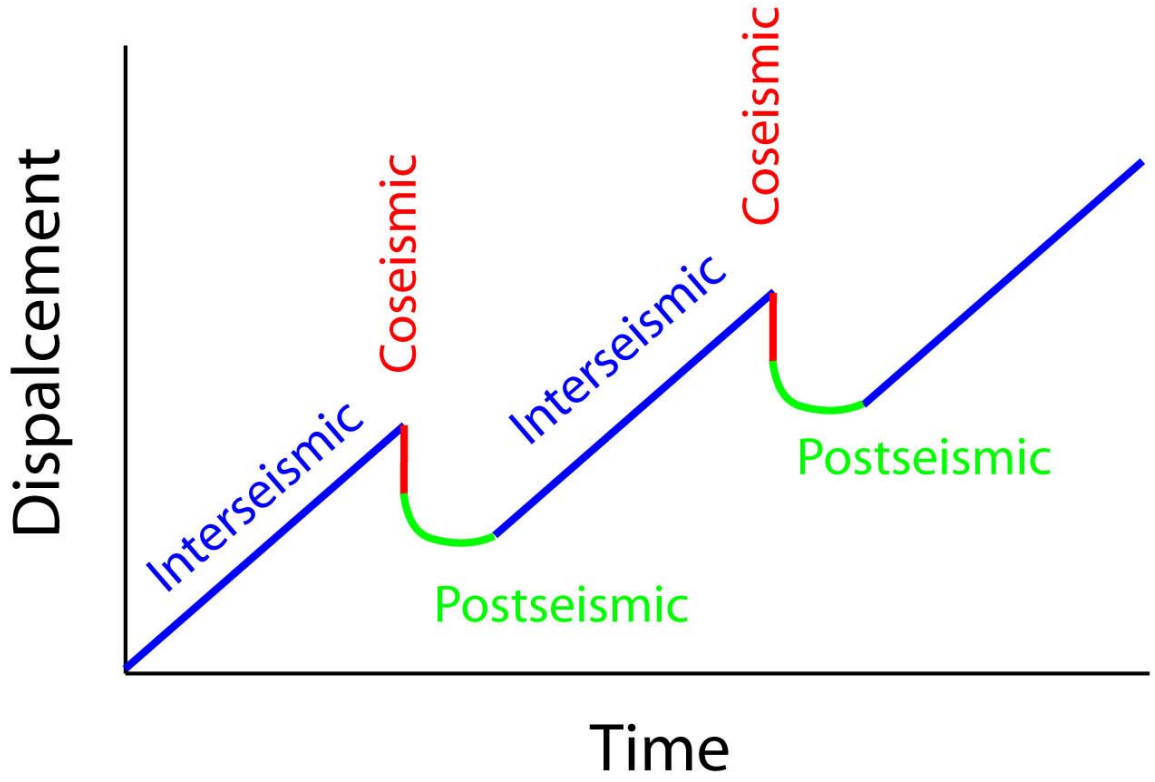
http://earthquake.usgs.gov/research/geology/paleoseis/index.php



- 1868 M_w 6.8, about 1 m of slip => 1 m/170 years = 5.9 +- 1.0 mm/yr
- GPS slip rate = 6.5 +- 0.8 mm/yr, 1 m slip events => 1 m /6.5 mm/yr = 154 +- 15 years

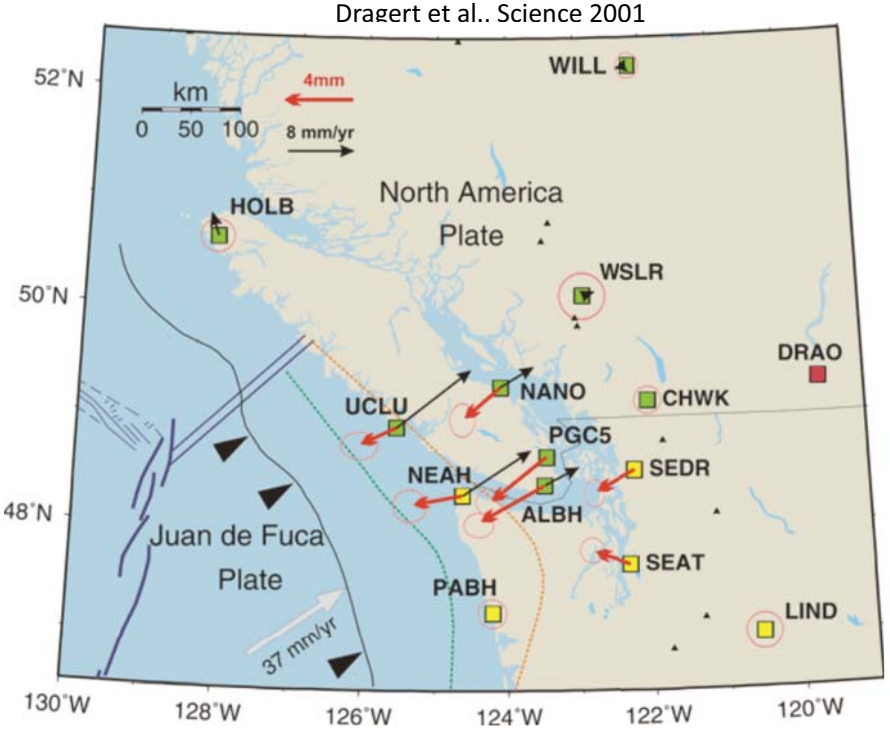
The deformation cycle

- Theoretical geodetic time series
- **Interseismic**: displacement at a given site is linear as a function of time ⇒ constant velocity
- **Coseismic**: jump in the time series, related to the magnitude, location, and depth of the seismic rupture
- **Postseismic**: strain readjustments (afterslip, viscoelastic relaxation, poroelasticity), decay related to the mechanism and the lithospheric rheology

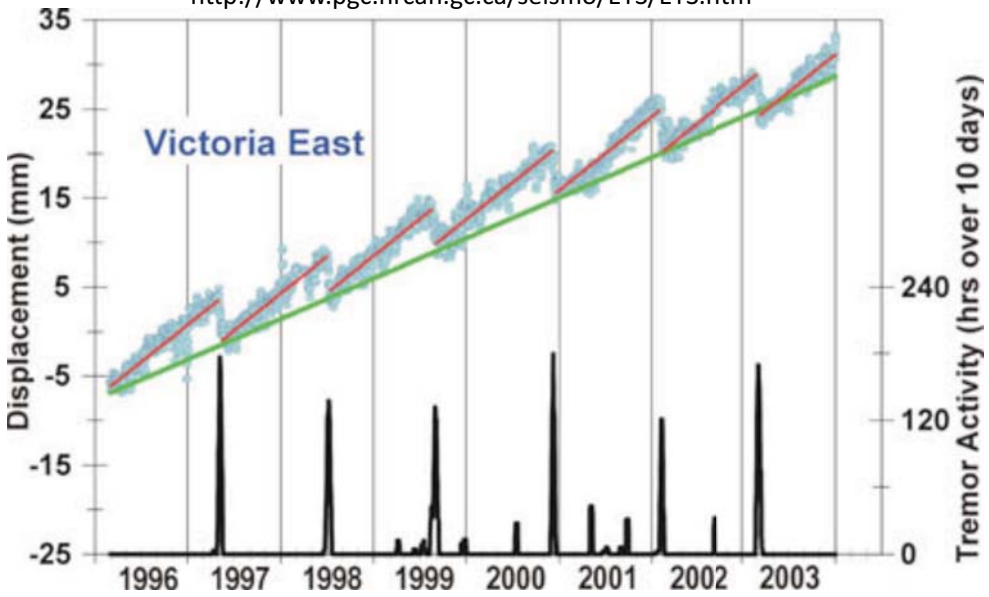


Episodic Tremors and Slip

Dragert et al.. Science 2001



http://www.pgc.nrcan.gc.ca/seismo/ETS/ETS.htm



- Juan de Fuca subduction
- Black arrows: typical interseismic strain accumulation
- Red arrows:
  - Episodes of aseismic slip every 13 to 16 months
  - Typically 10 day long, 5 mm surface displacement
  - Associated with seismic tremors

Episodic Tremors and Slip

- Modeling shows:
  - ~ 2 cm slip on the subduction
  - Slip area ~50 km x 300 km
  - Depth of ~25 km to 45 km
  - Equivalent to a M6.7 earthquake (similar to 2001 Nisqually earthquake near Seattle)
- Cause?
- Consequences? (e.g. for future earthquakes)