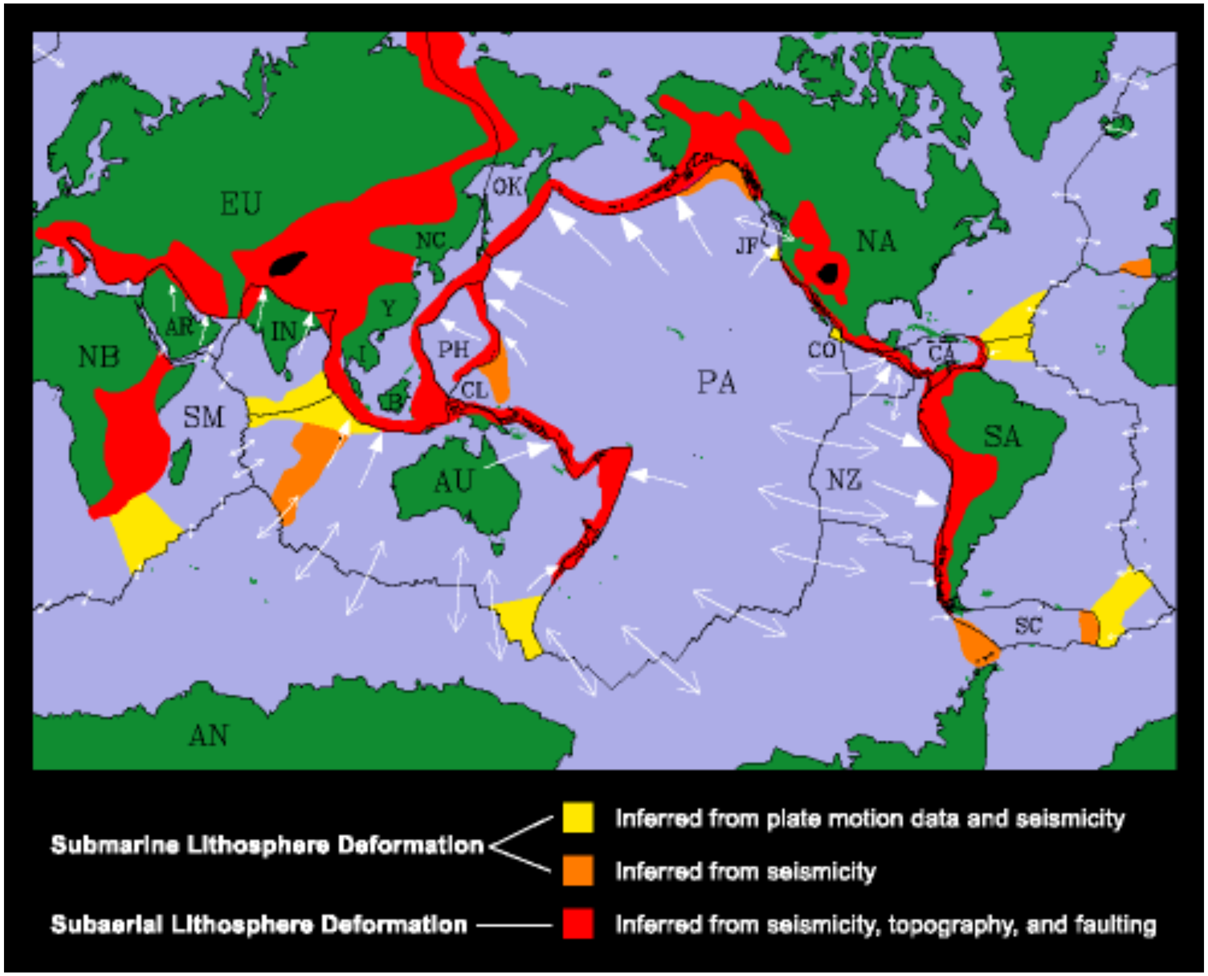
Lecture 9: Plate Boundary Zones



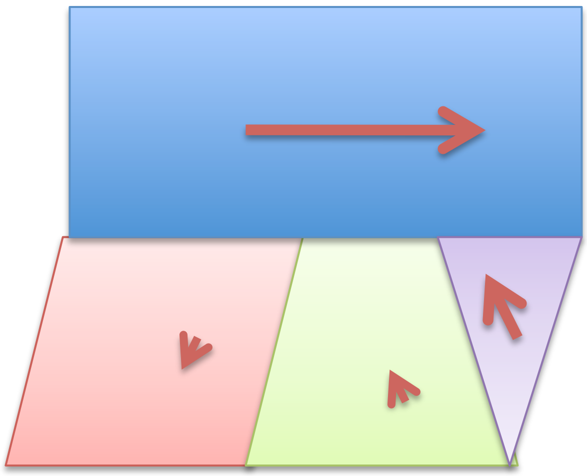
GEOS 655 Tectonic Geodesy

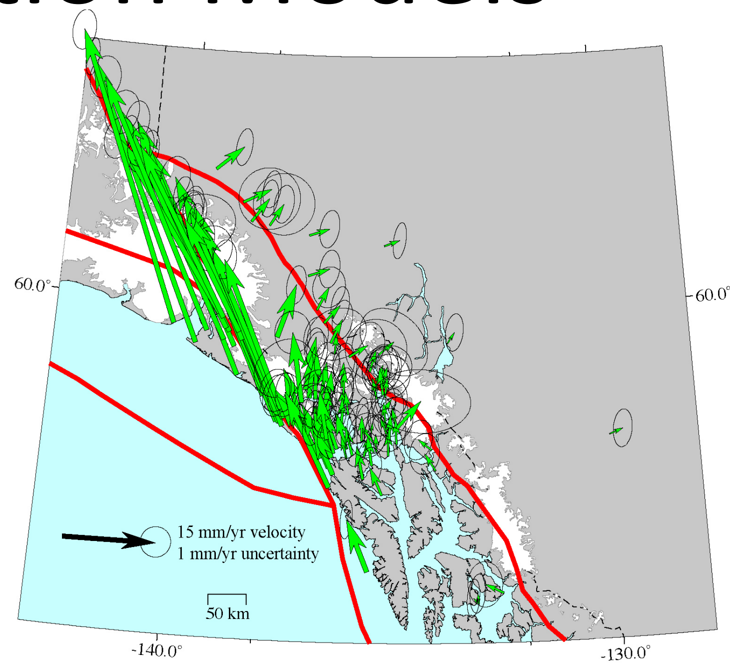
Jeff Freymueller, UAF

Most Plate Boundaries Complex

- Distributed deformation at plate boundaries is common. In continental crust, narrow boundaries are the exception, not the rule.
- Many broad plate boundary zones are made up of small blocks or microplates. In some regions, deformation is either quasi-uniform or the blocks are numerous and very small.
- Identification of microplate boundaries and motions is complicated by the elastic deformation associated with locked faults (a topic we will come back to in detail later in the course).

Block Motion Models

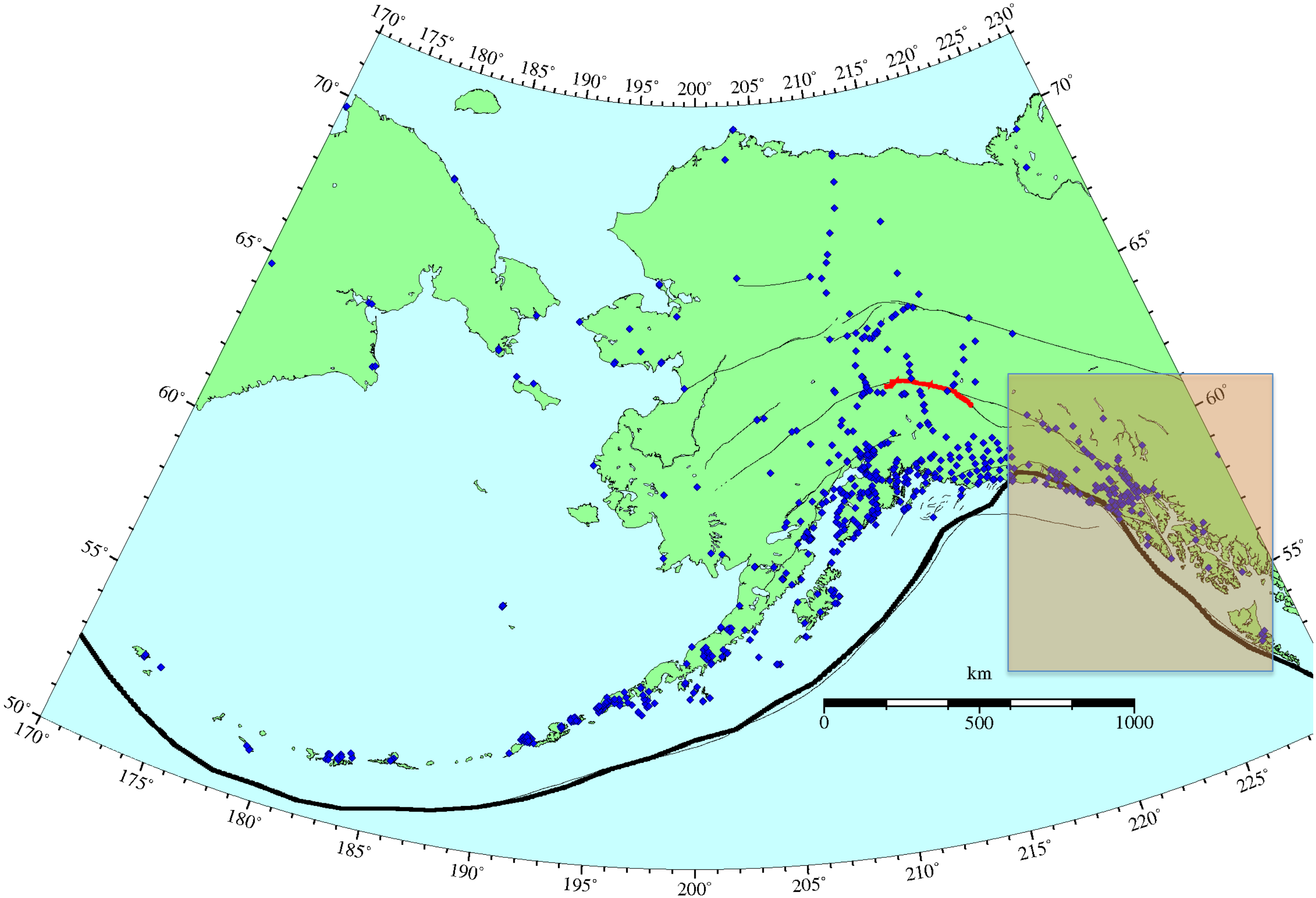




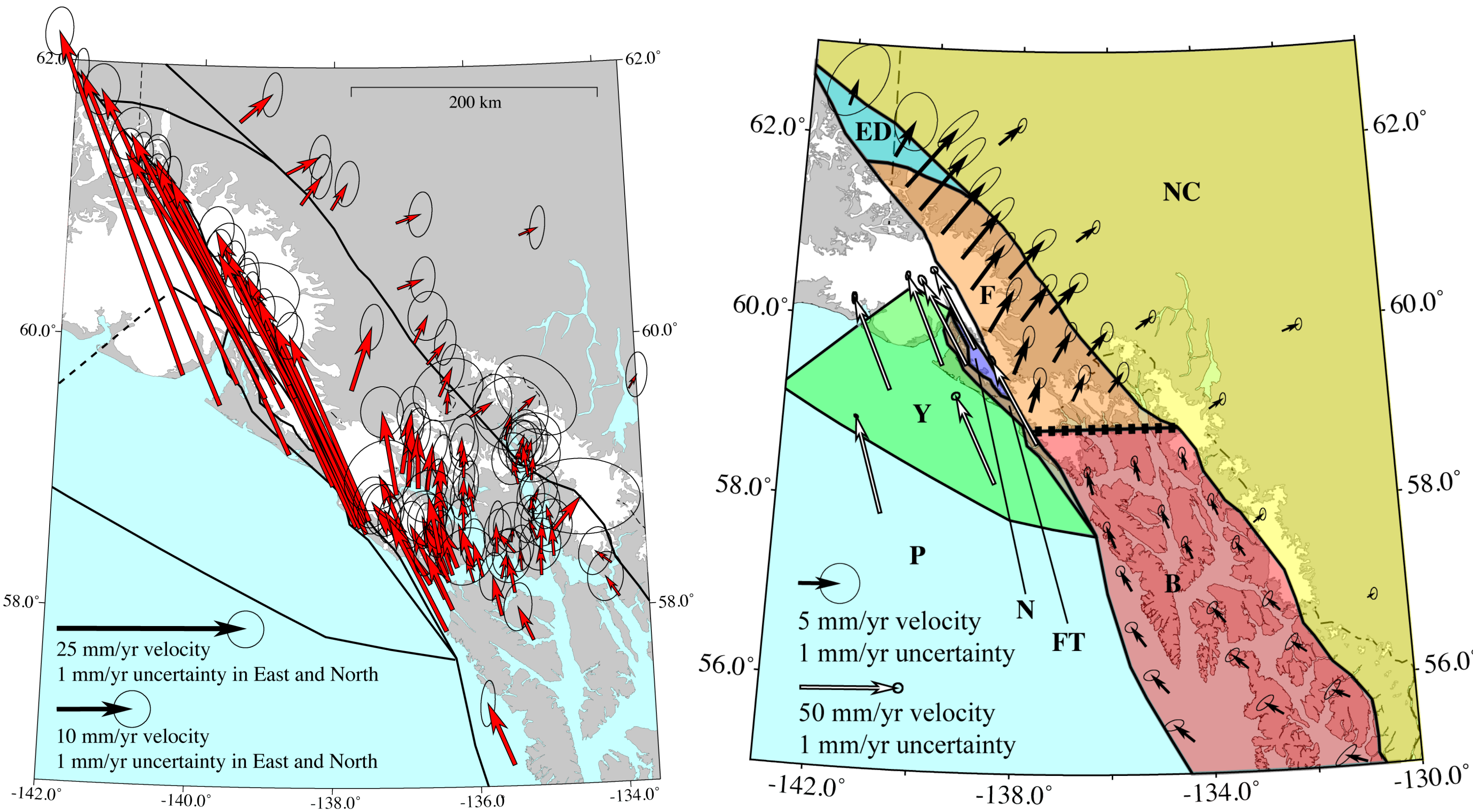
Key Elements

- Blocks usually assumed to be rigid
- Provide a means to separate elastic deformation from locked faults from long-term motions
- Enforces self-consistency in estimates of fault slip rates

Southeast Alaska Block Model

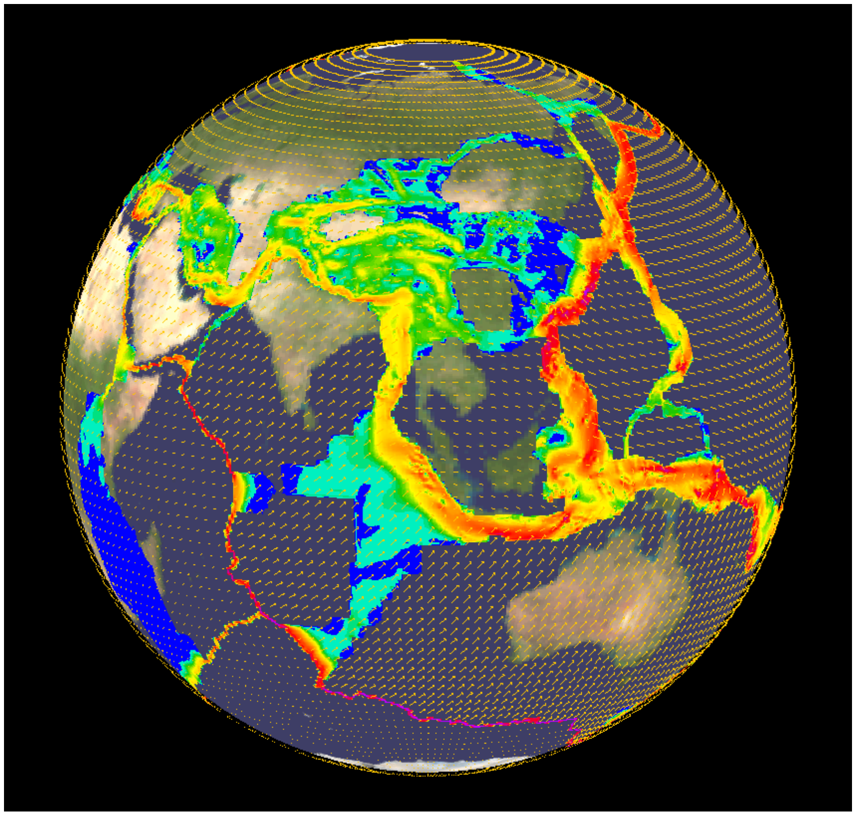


Block Model for SE Alaska



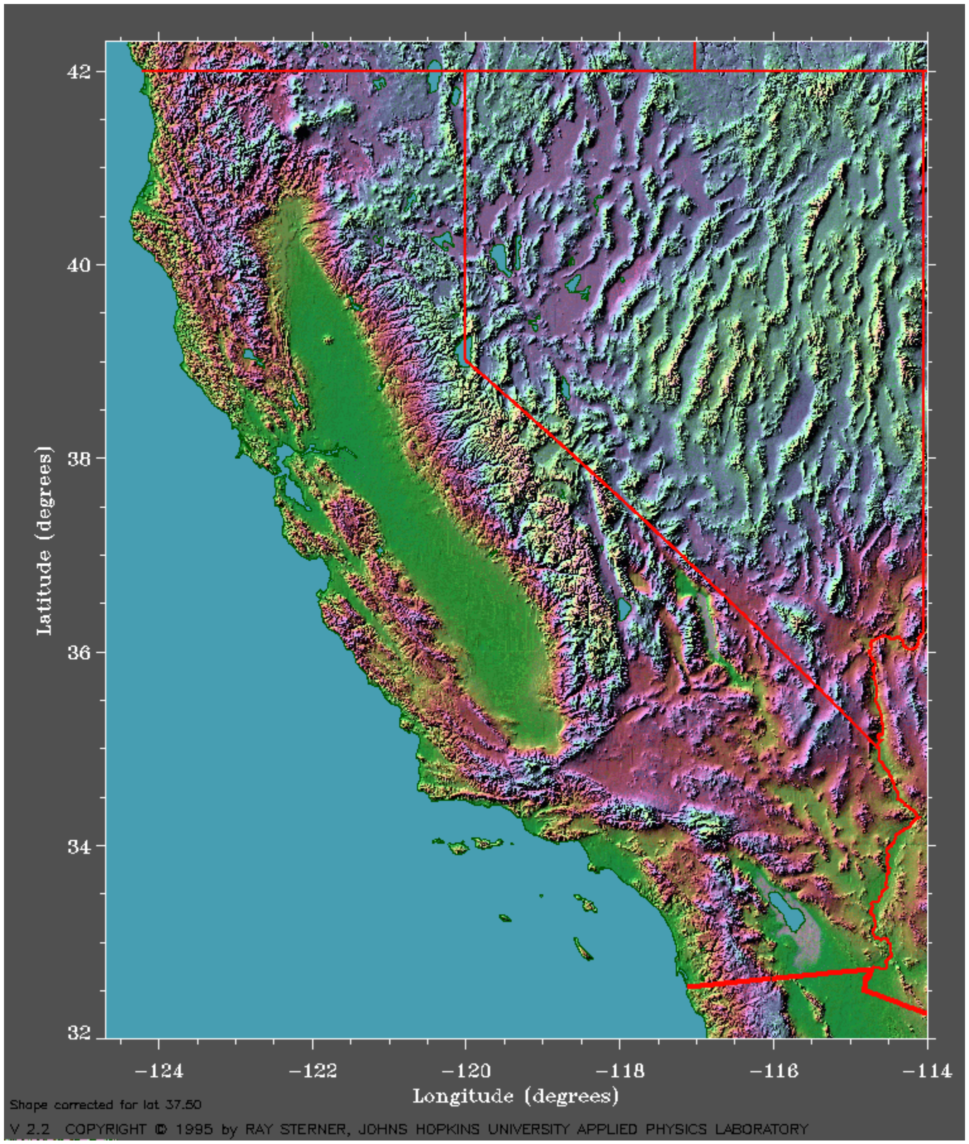
Elliott et al. (2010, JGR)

Global Strain Rate Map



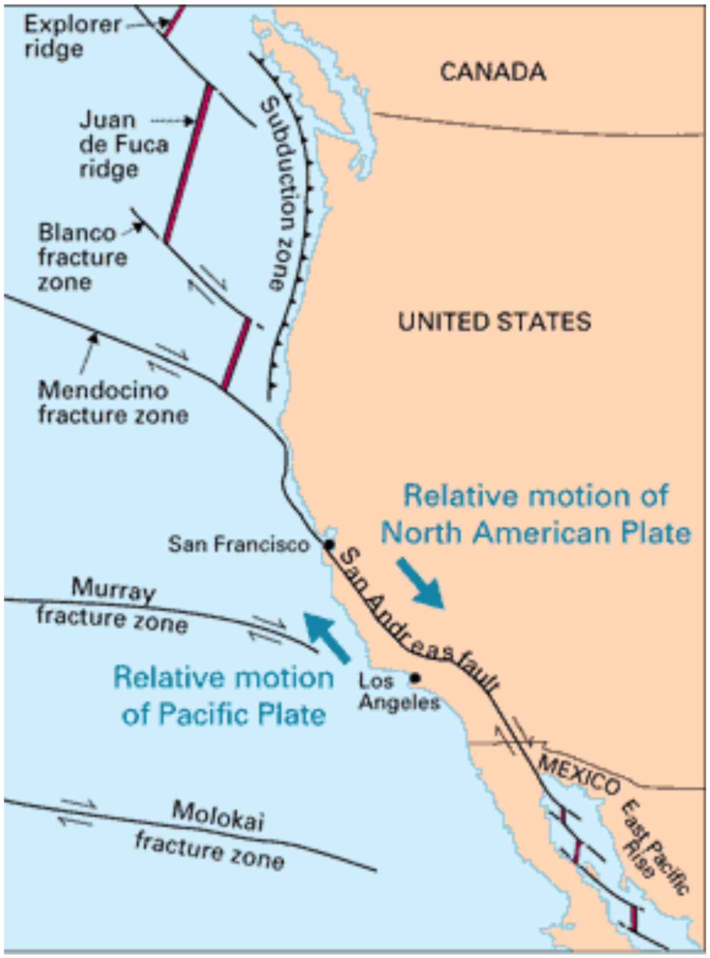
- An example of a product derived from GPS velocity field.
  - Rigid plate regions are shown with velocity grids to show motion.
  - Color coding shows magnitude of strain, a key measure of deformation.
  - We'll develop the mathematical basis for strain calculations starting next lecture.

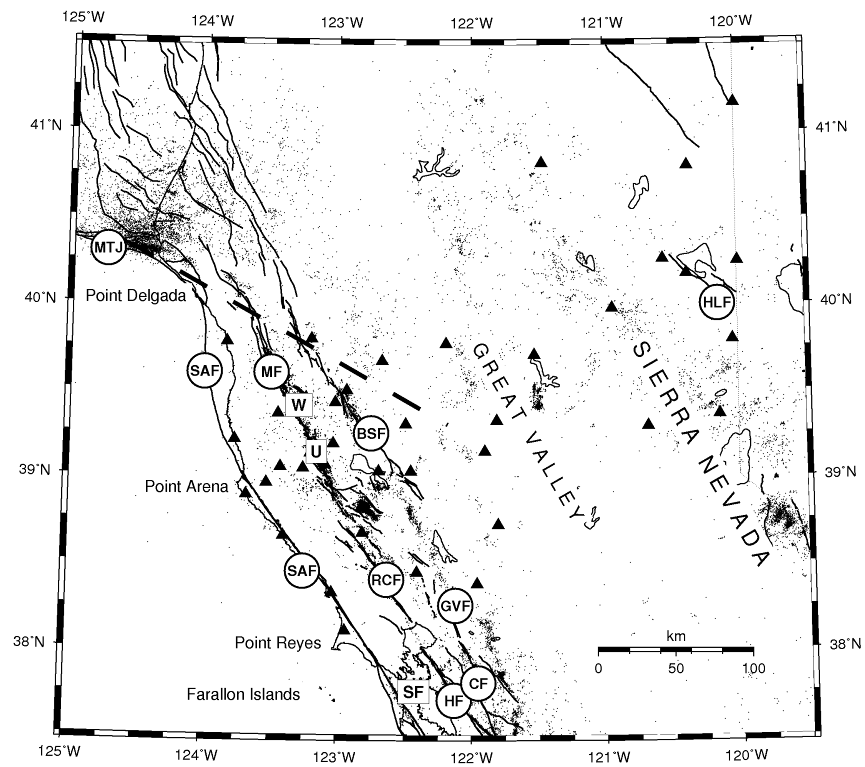
Slip Partitioned System



- Sierra Nevada-Great Valley (SNGV) block is stable
- Pure strike-slip west of SNGV
- Extension east of SNGV
- Also strike slip on eastern edge of SNGV

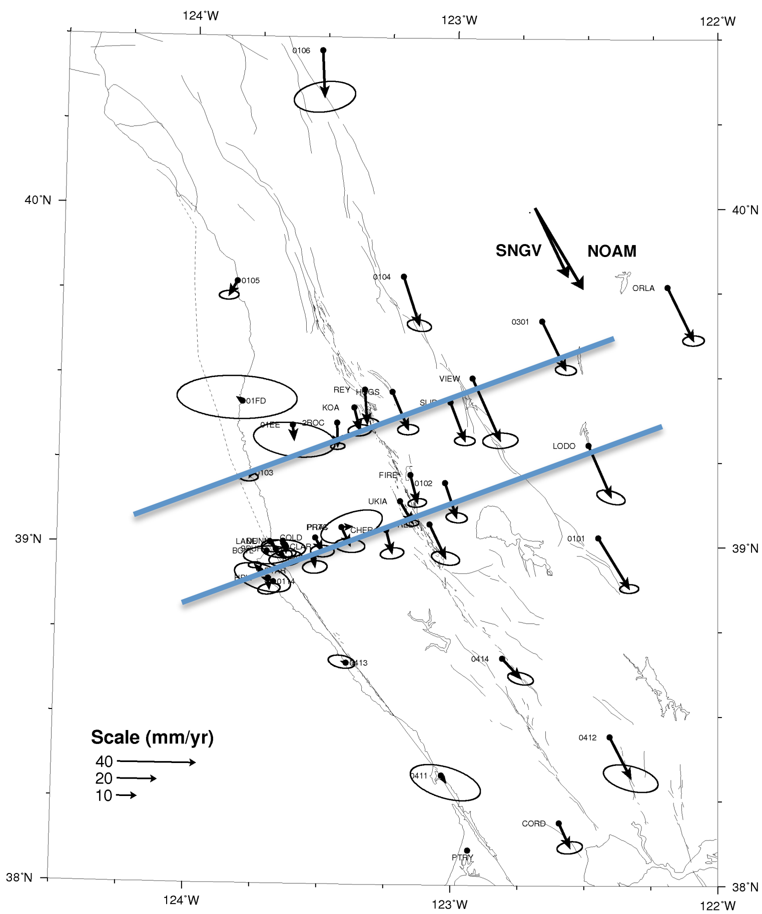
A “Simple” Plate Boundary Zone



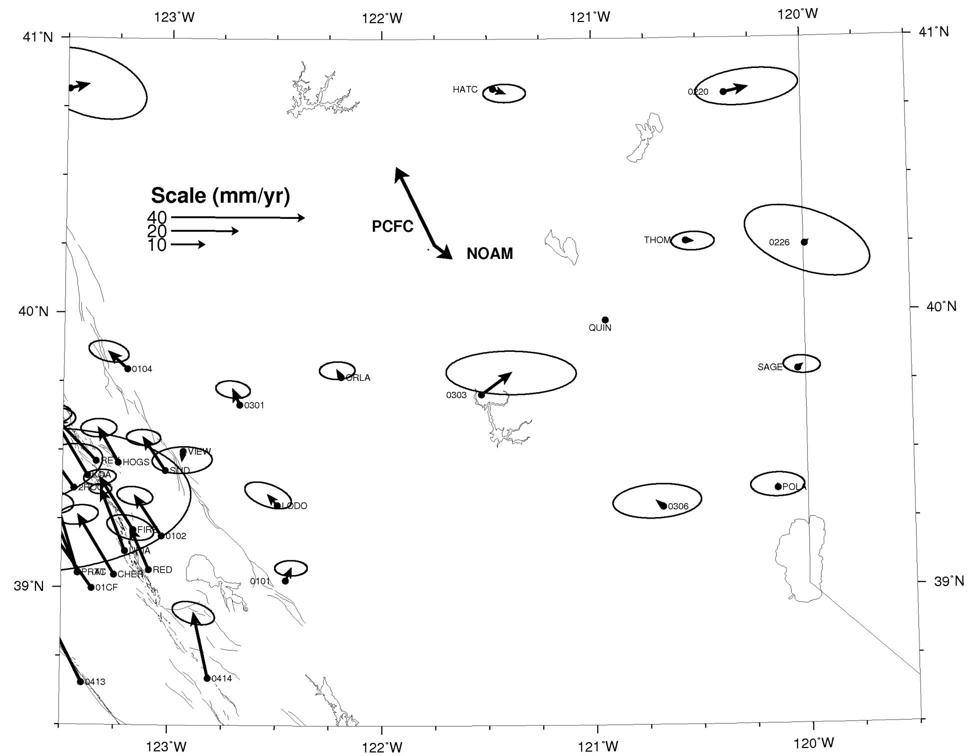


GMT Nov 5 15:17 Figure 1, Freymueller et al.

Northern California Velocity Field



GMT Apr 6 14:18 **Figure 3, Freymueller et al.**



GMT Apr 6 14:36 **Figure 4, Freymueller et al.**

Southern Profile

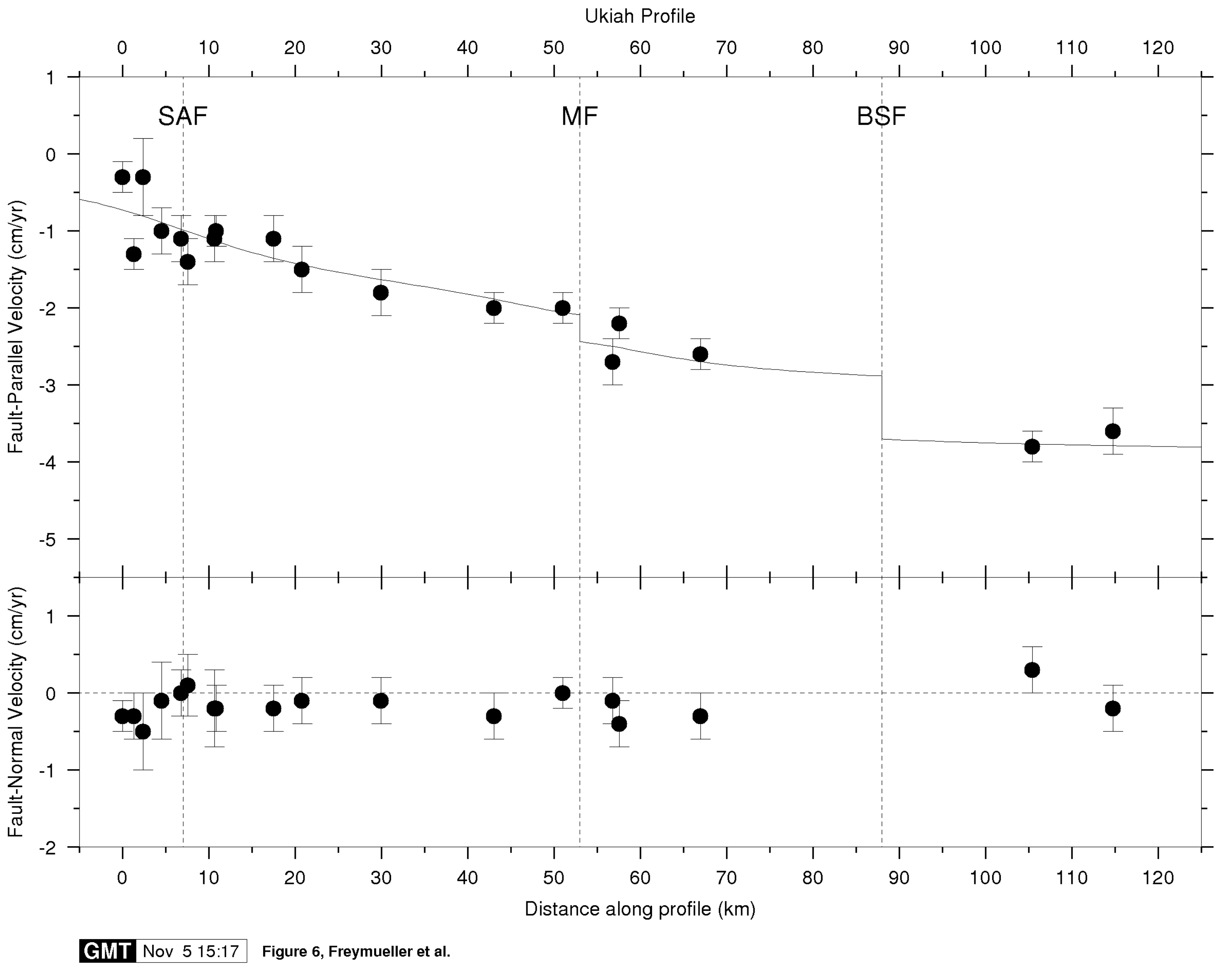
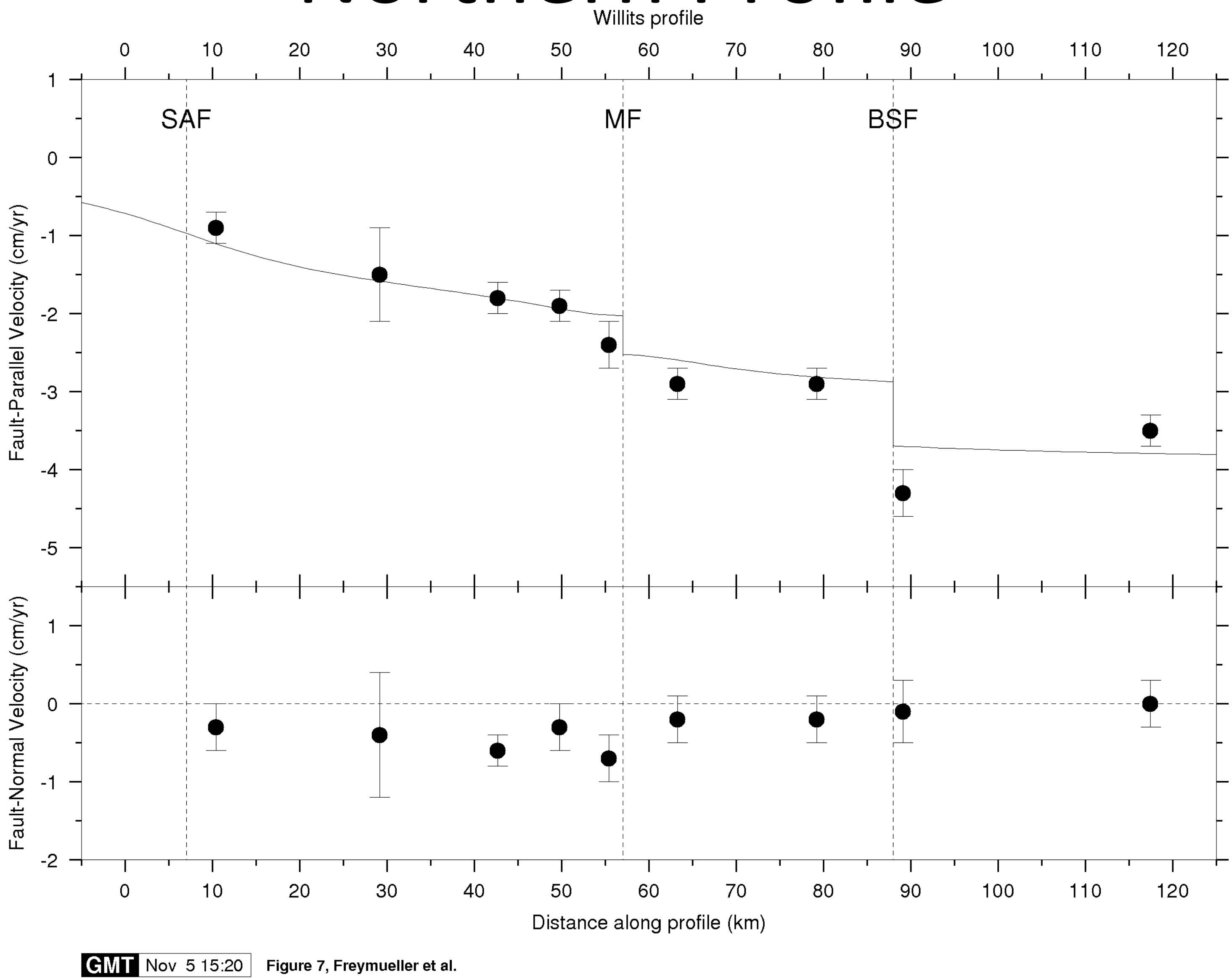
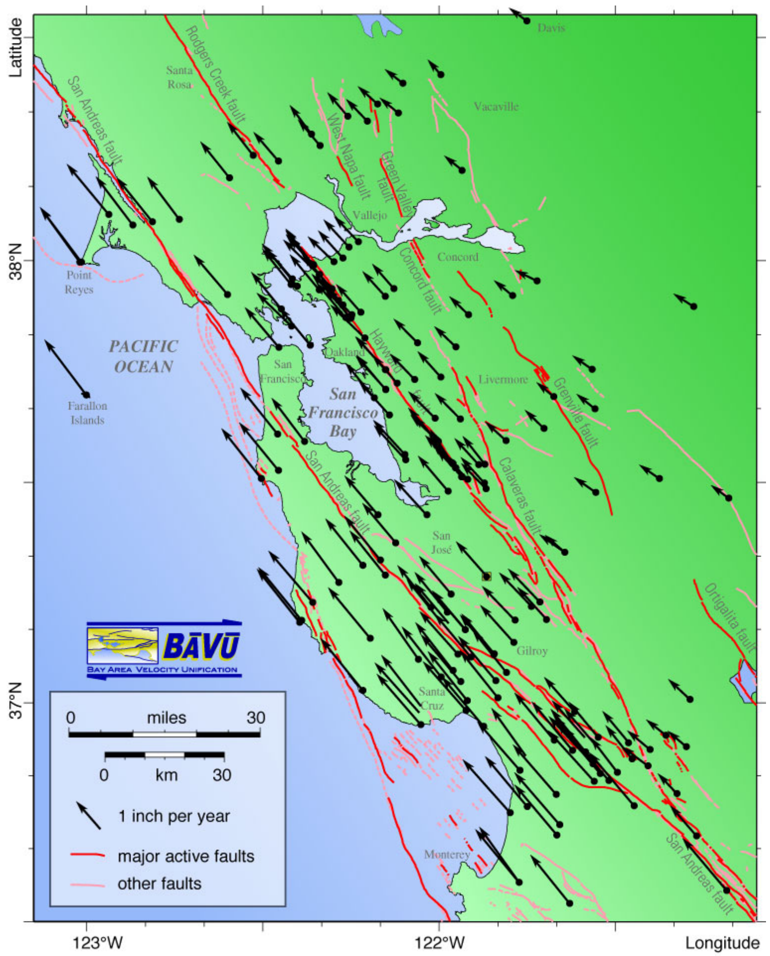


Figure 6, Freymueller et al.

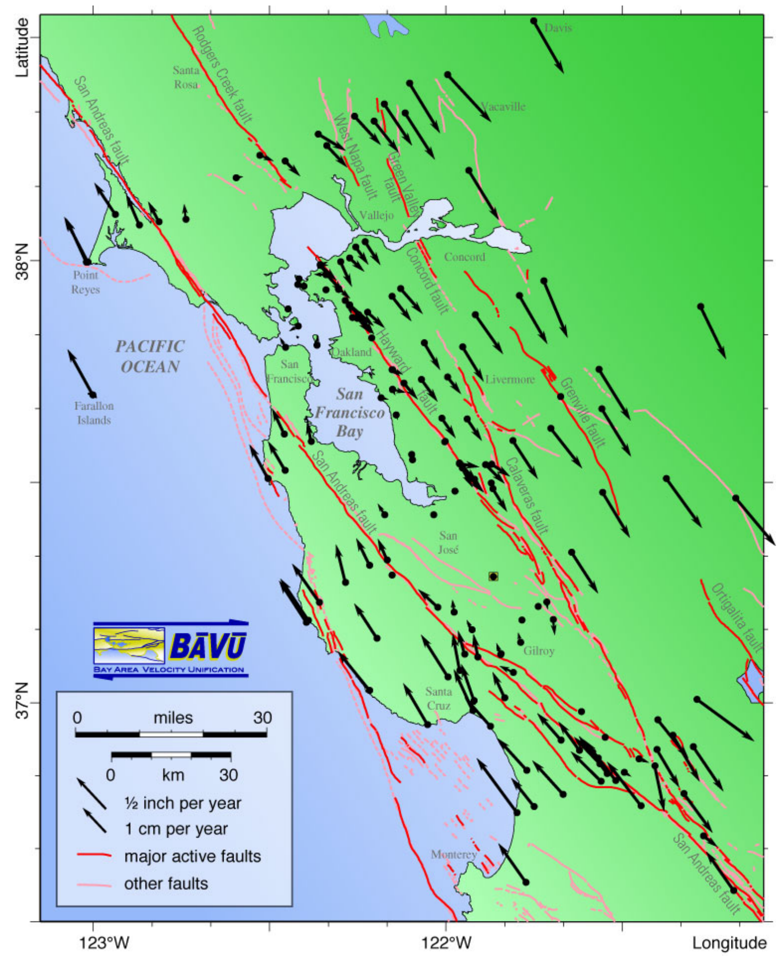
Northern Profile



SF Bay Area

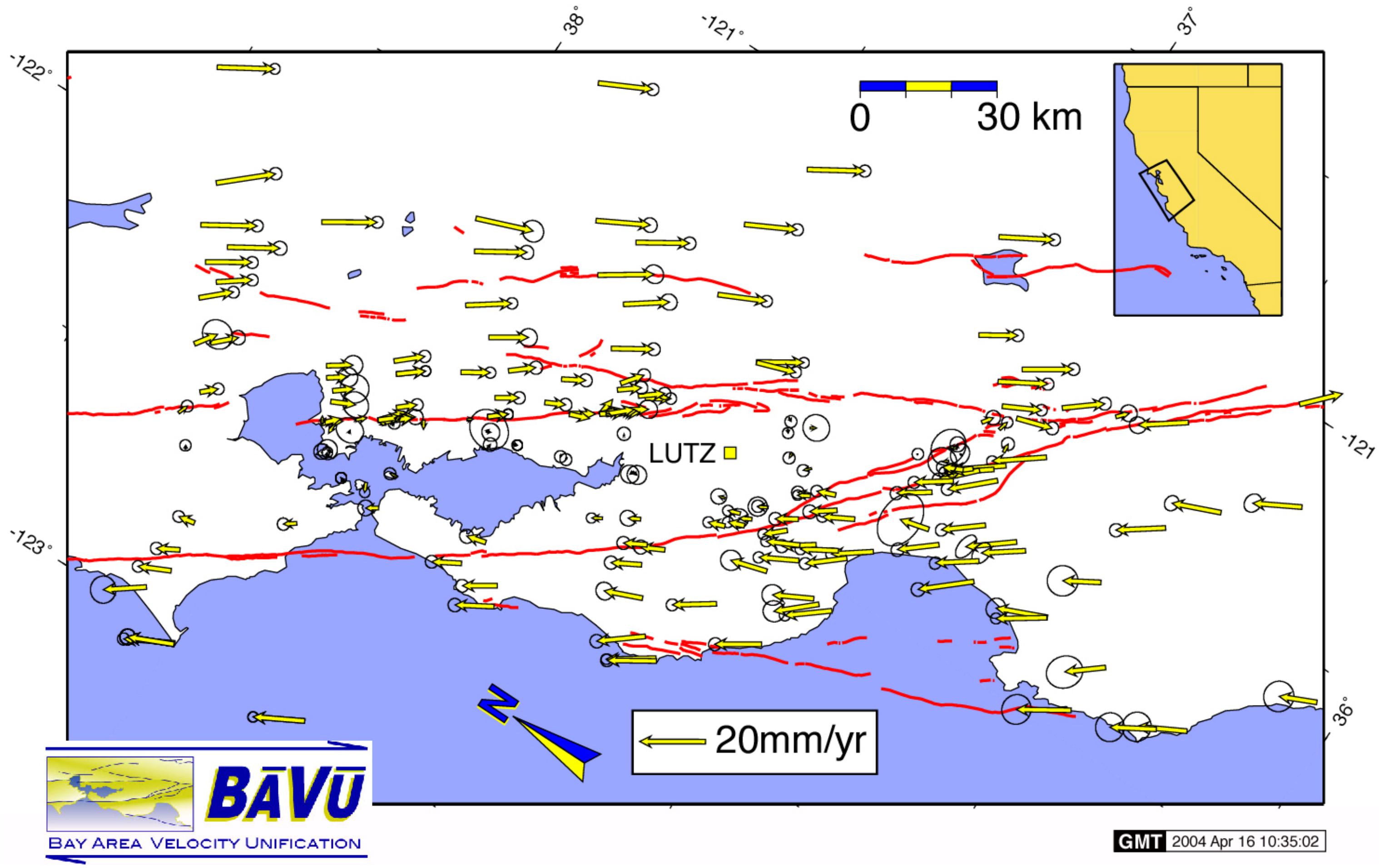


Latitude
Davis
Santa Rosa
Rodgers Creek fault
San Andreas fault
West Napa fault
Green Valley fault
Vacaville
Vallejo
Concord
Concord fault
Point Reyes
PACIFIC OCEAN
Farallon Islands
San Francisco
Oakland
Hayward fault
San Francisco Bay
Livermore
Greenville fault
Calaveras fault
San José
Ortigalita fault
Gilroy
Santa Cruz
Monterey
BĀVŪ
BAY AREA VELOCITY UNIFICATION
0 miles 30
0 km 30
1 inch per year
major active faults
other faults
38°N
37°N
123°W
122°W
Longitude



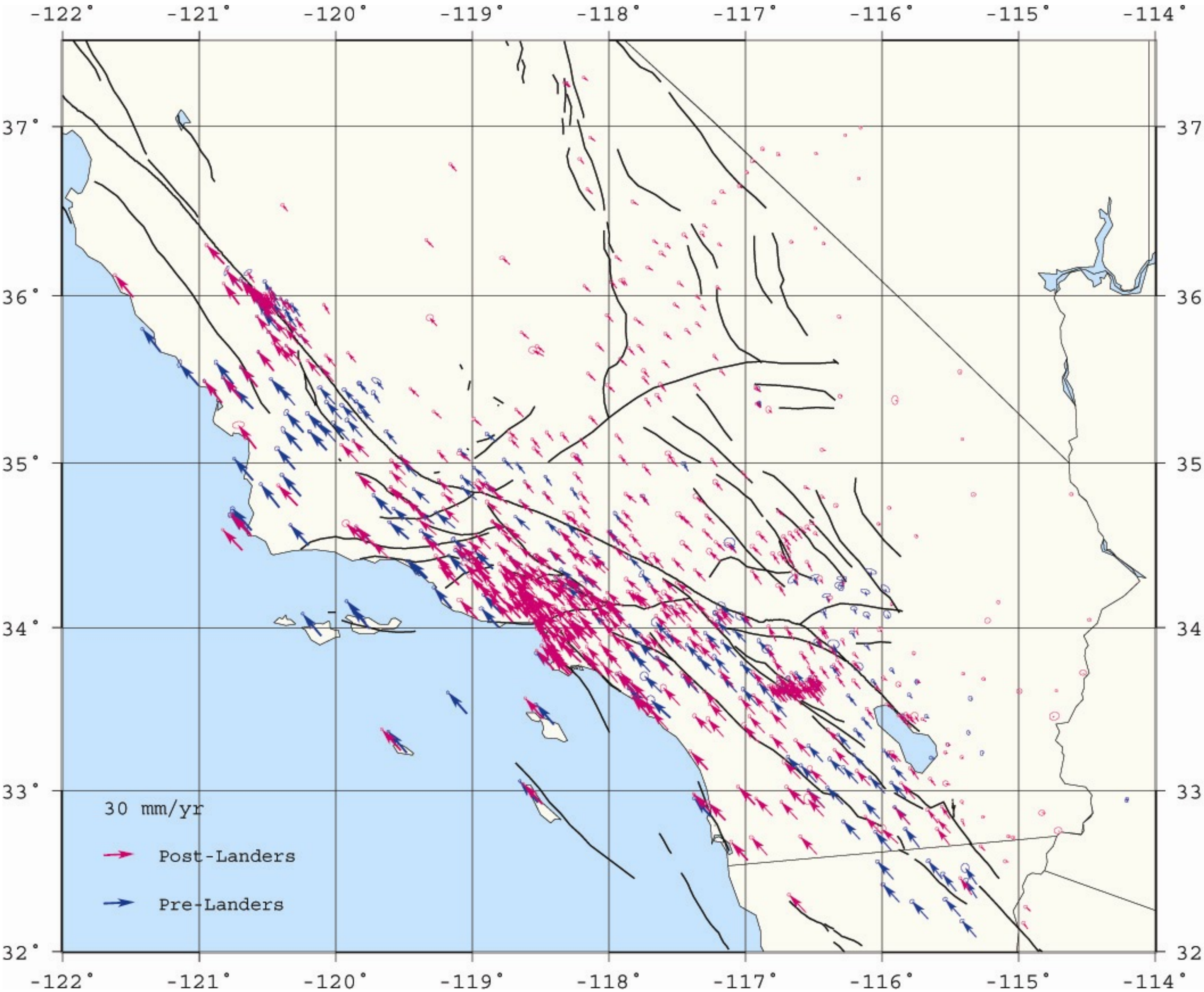
Latitude
Davis
Santa Rosa
Rodgers Creek fault
San Andreas fault
West Napa fault
Green Valley fault
Vacaville
Vallejo
Concord
Concord fault
Point Reyes
PACIFIC OCEAN
Farallon Islands
San Francisco
Oakland
Hayward fault
San Francisco Bay
Livermore
Greenville fault
Calaveras fault
San José
Ortigalita fault
Gilroy
Santa Cruz
Monterey
BĀVŪ
BAY AREA VELOCITY UNIFICATION
0 miles 30
0 km 30
½ inch per year
1 cm per year
major active faults
other faults
38°N
37°N
123°W
122°W
Longitude

Block Model



d'Alessio et al. (2005, JGR), doi: 10.1029/2004JB003496

Example: Strain rate estimation from SCEC CMM3 (Post-Landers)



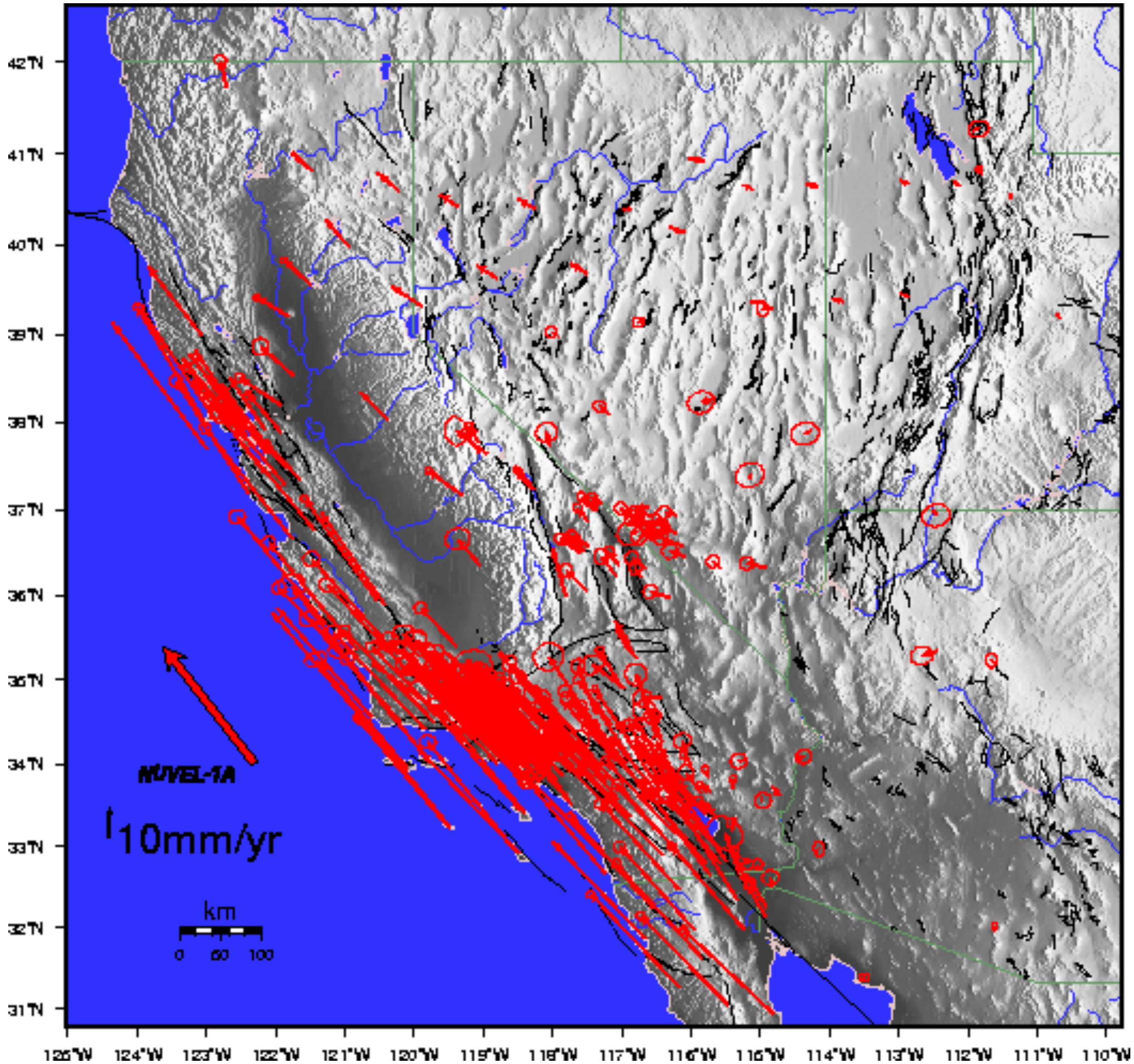
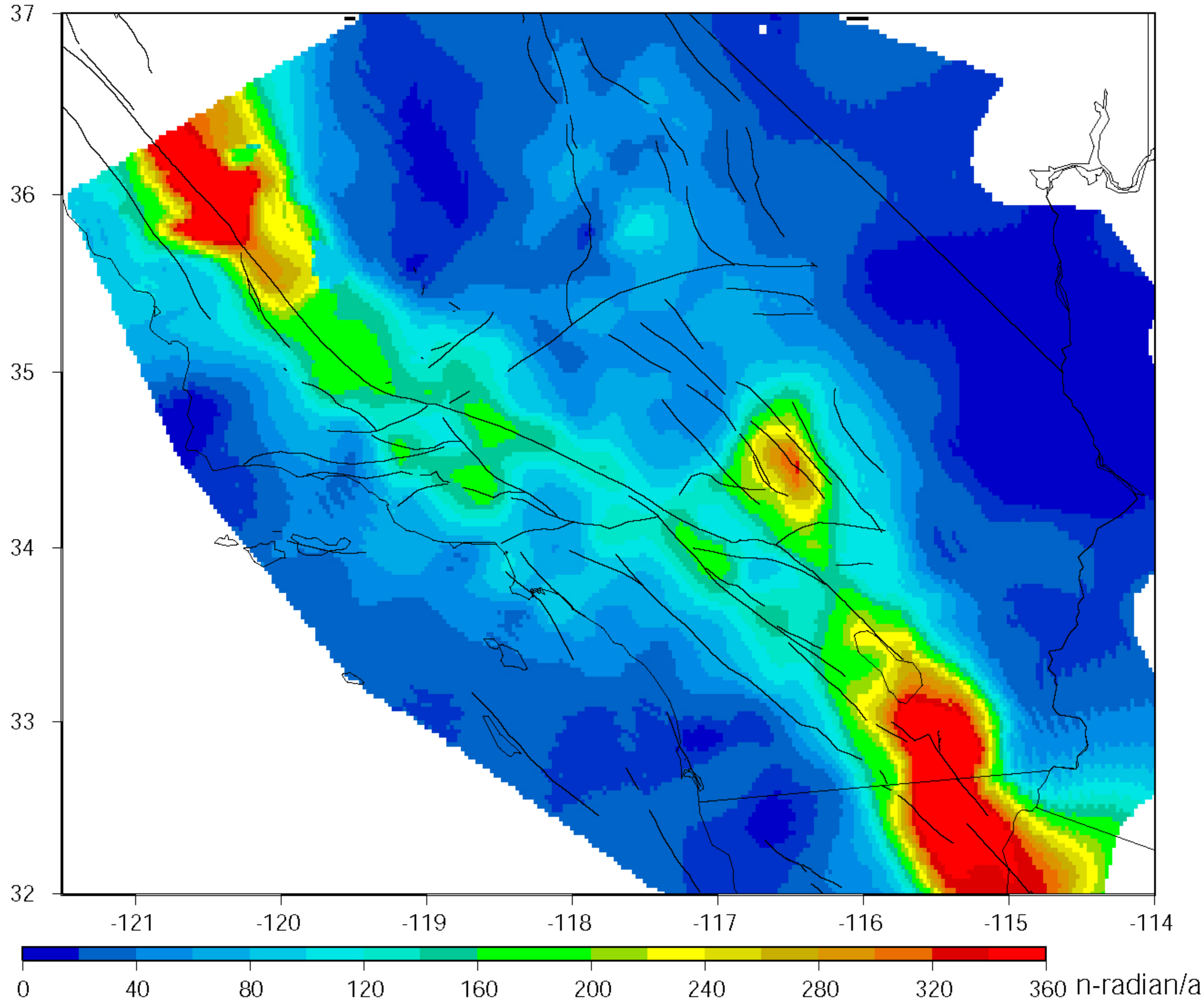
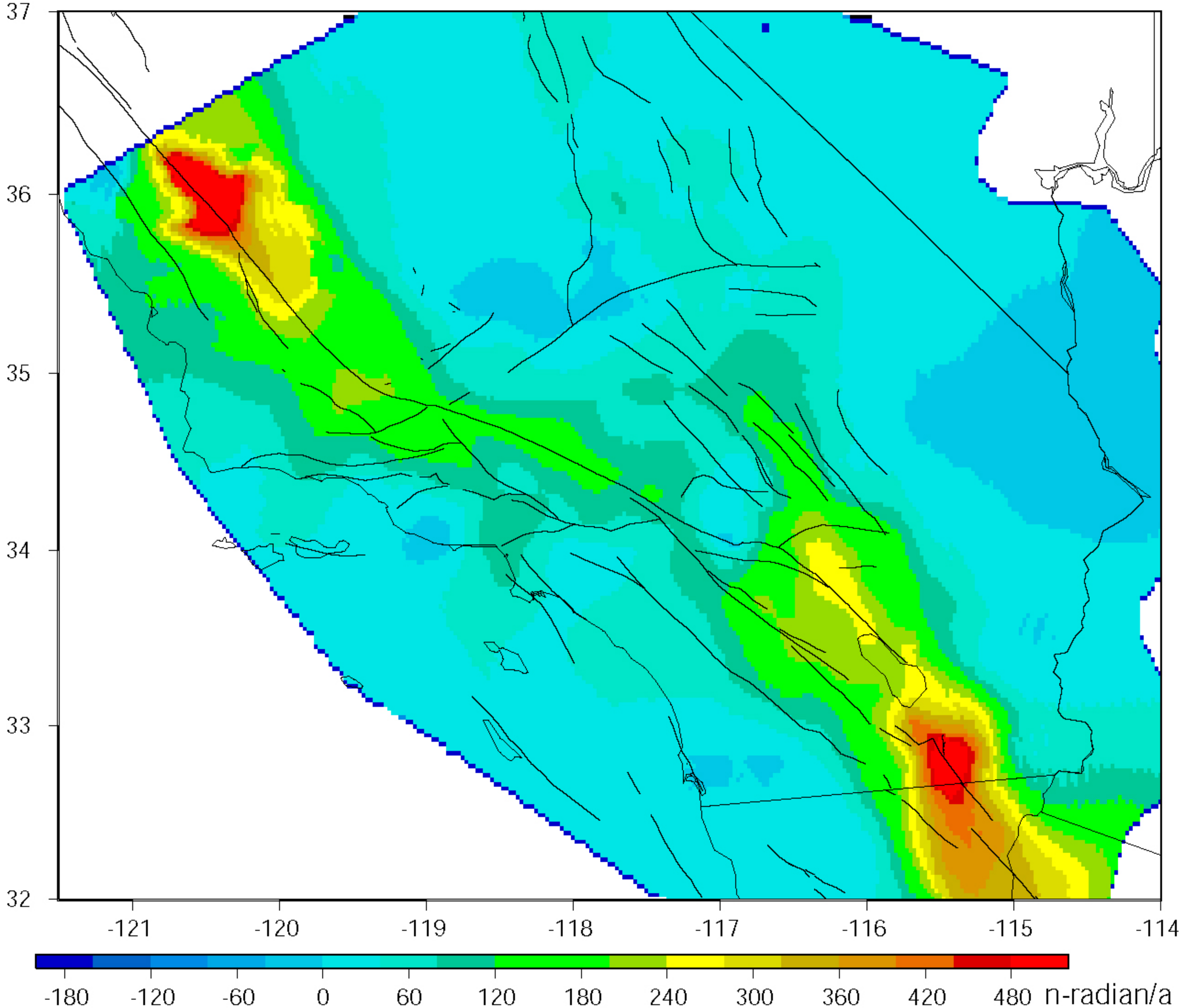


Figure from R. Bennett (website)

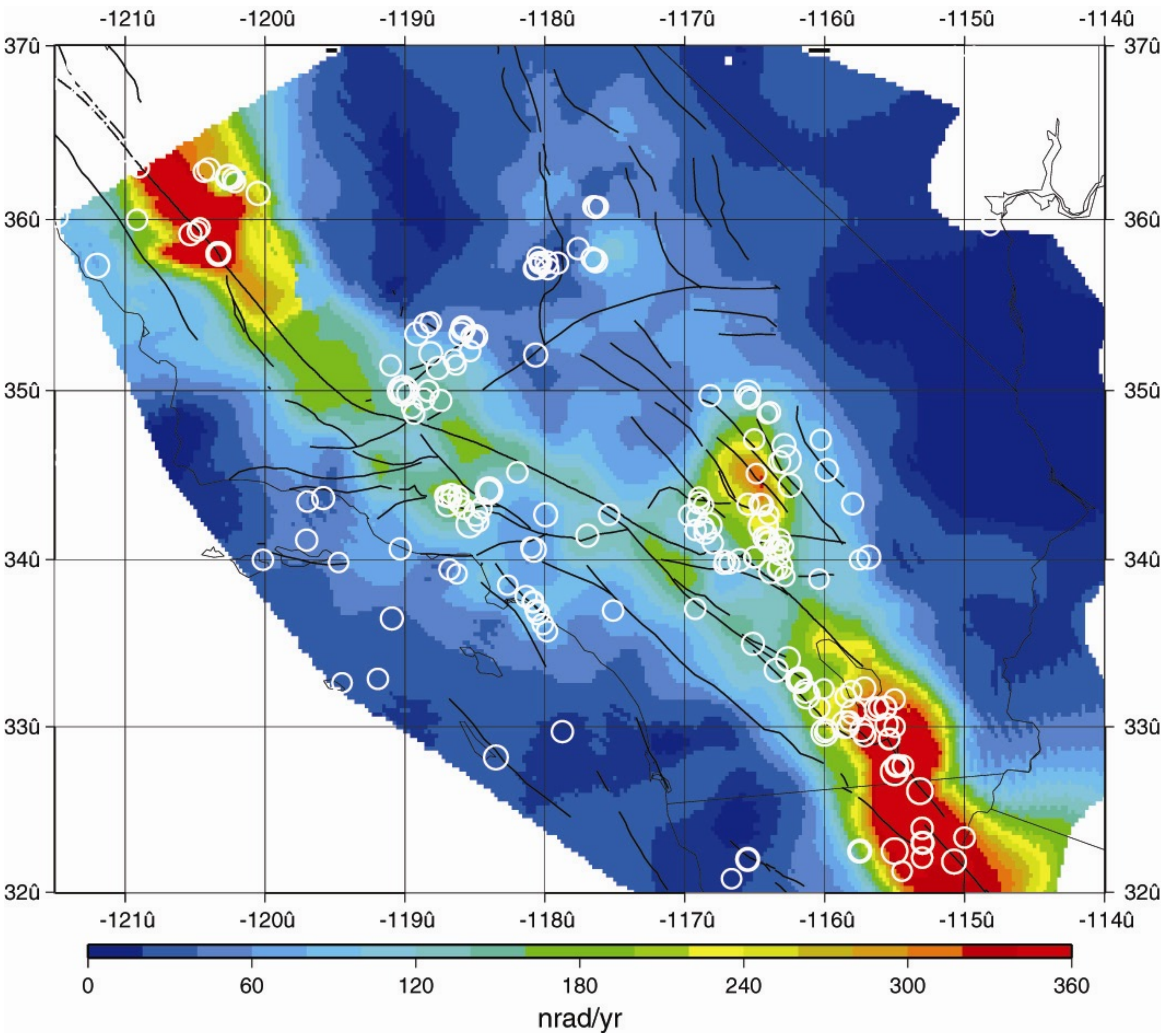
Post-Landers Maximum Shear Strain Rate

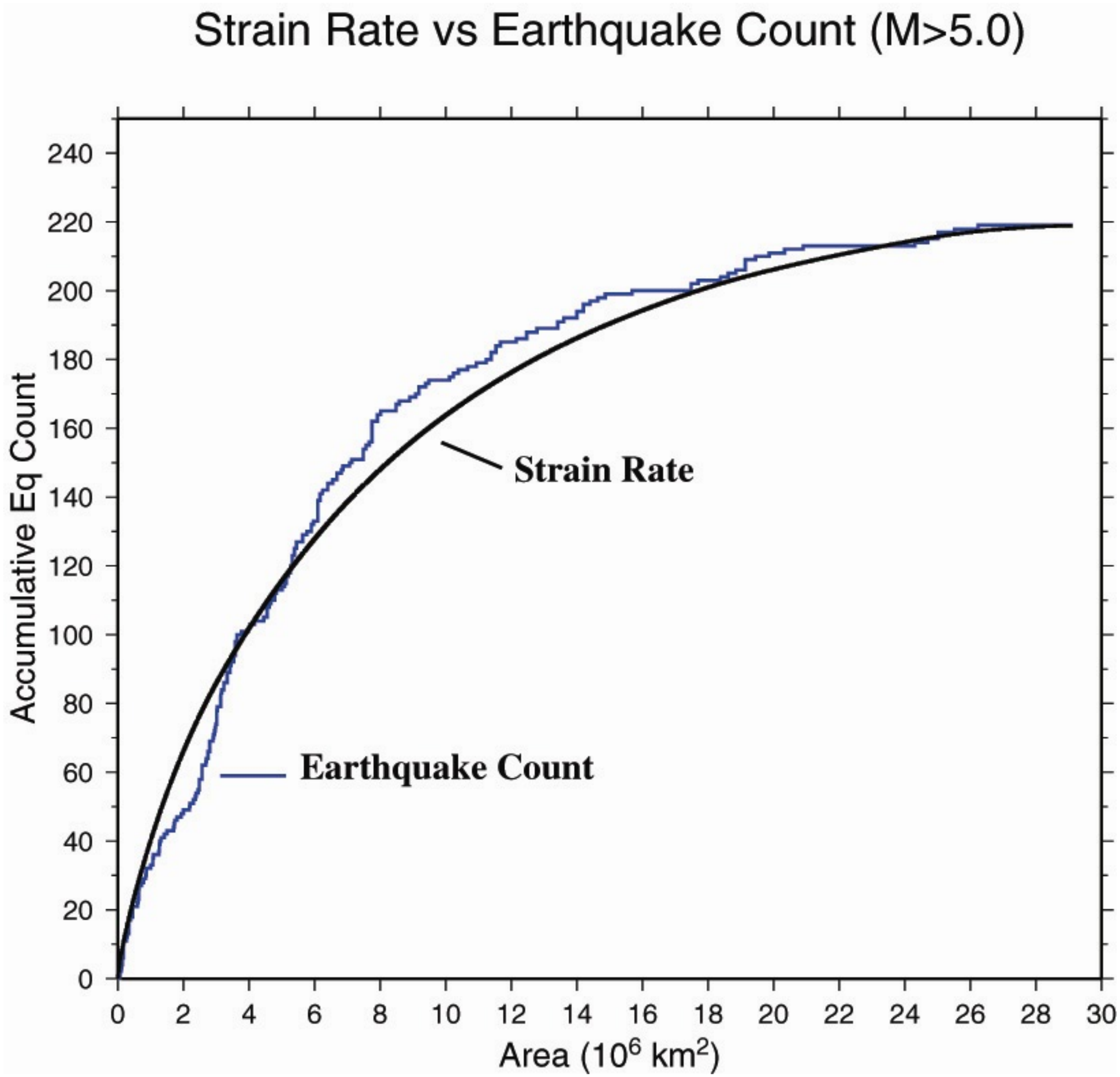


Post-Landers Rotation Rate



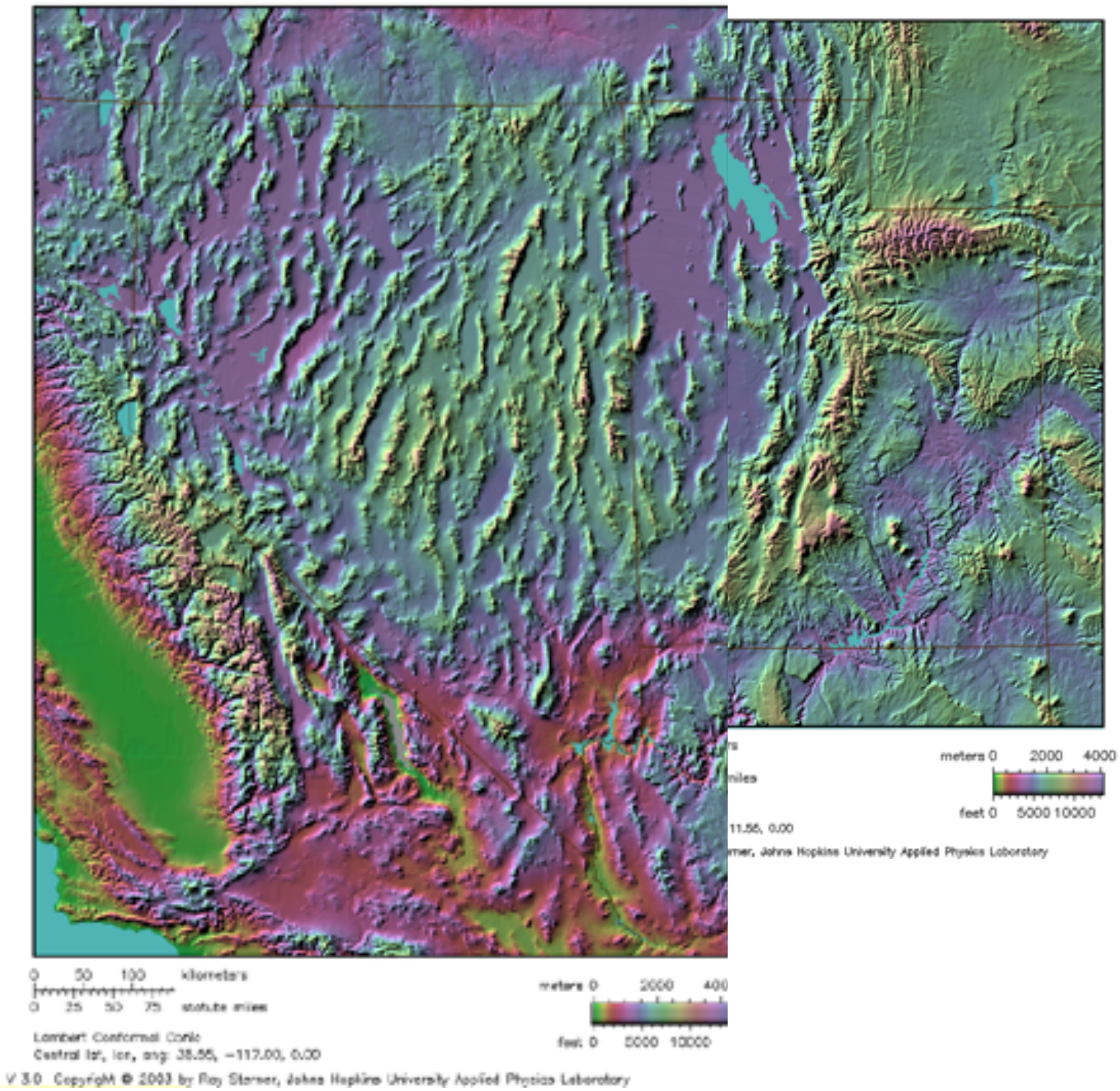
Post-Landers Maximum Strain Rate and Earthquakes of M>5.0 1950-2000



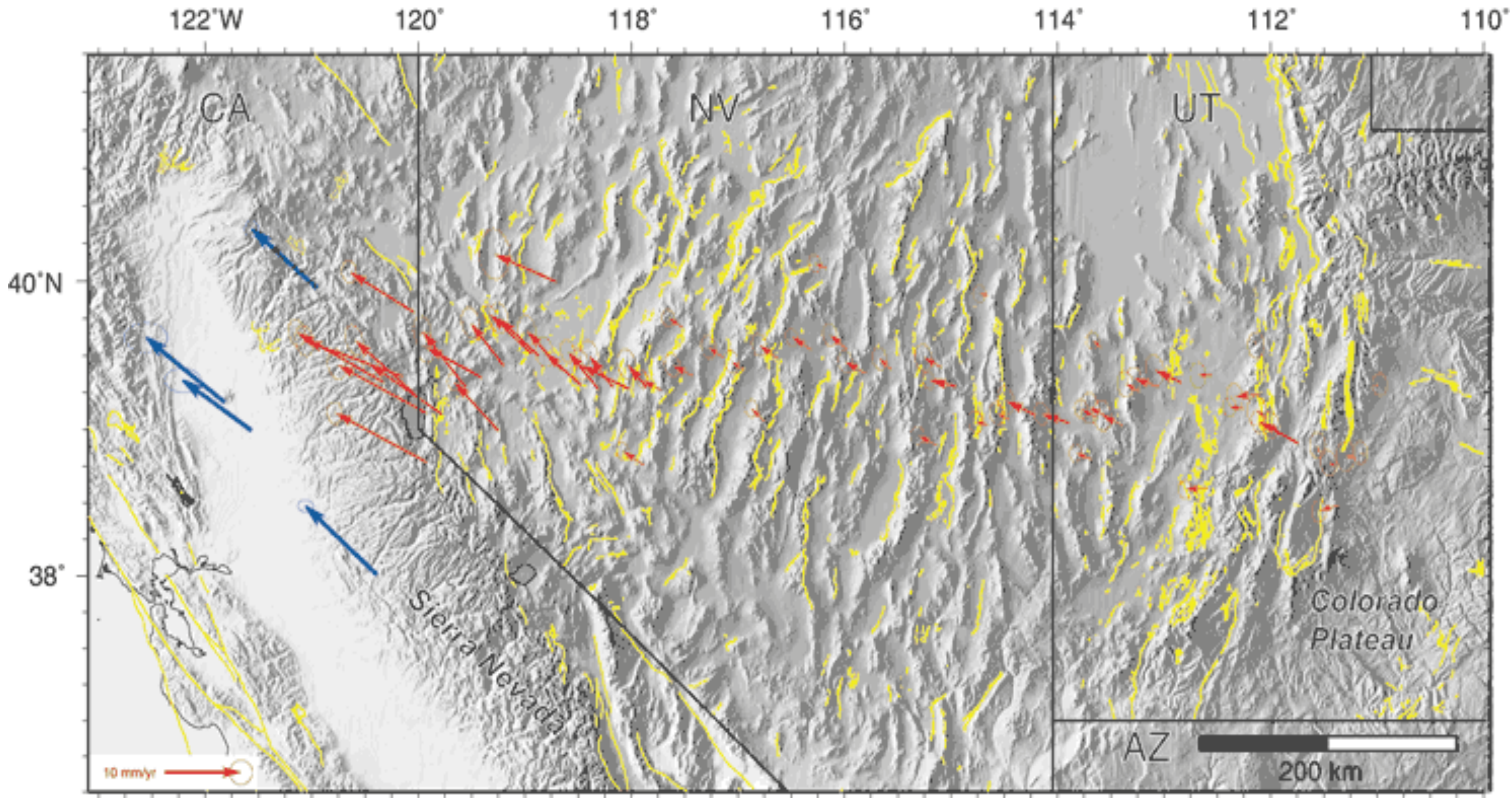


Strain Rate vs Earthquake Count (M>5.0)
Accumulative Eq Count
240
220
200
180
160
140
120
100
80
60
40
20
0
Strain Rate
Earthquake Count
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Area (10^6 km^2)

Basin and Range



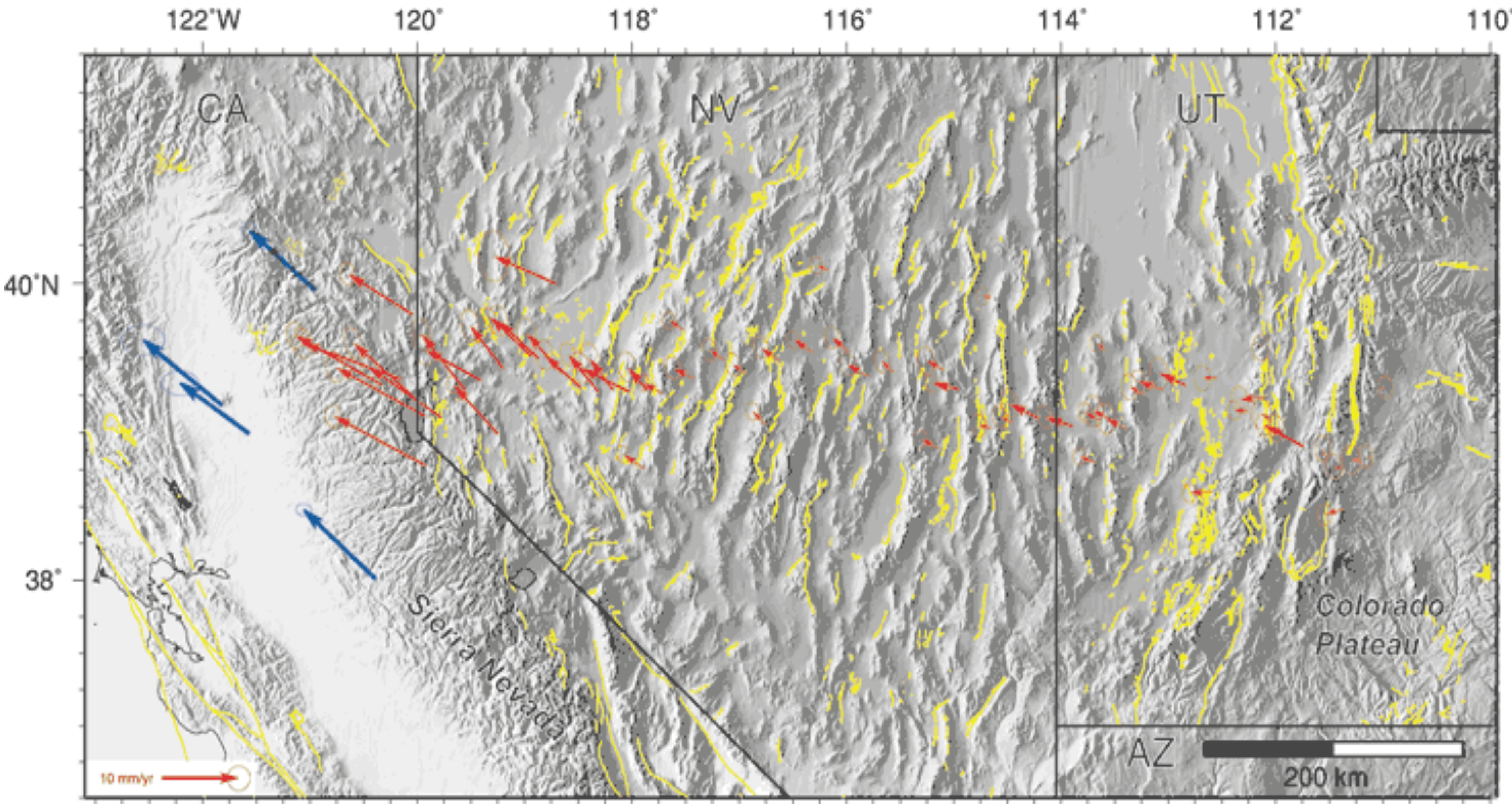
Basin and Range Velocities



Main Features: Basin and Range

- Pure extension in eastern half of B&R
  - Slow distributed extension
  - Zones of concentrated extension
- Mix of extension and strike-slip motion in western part of B&R
  - Central Nevada Seismic Belt
  - Eastern California Shear Zone/Walker Lane
- Total motion across Basin and Range reaches 10 mm/yr

Basin and Range Velocities



Discrete High-Strain Shear Zones

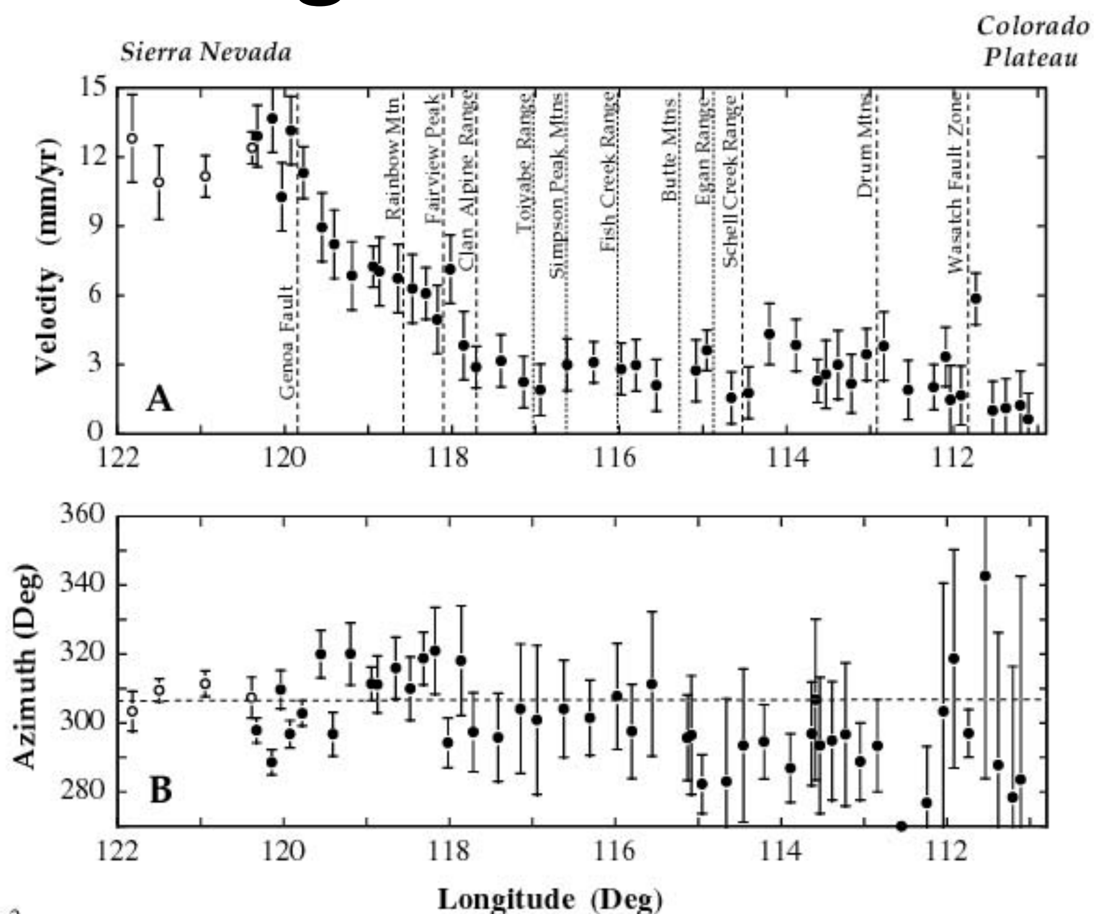
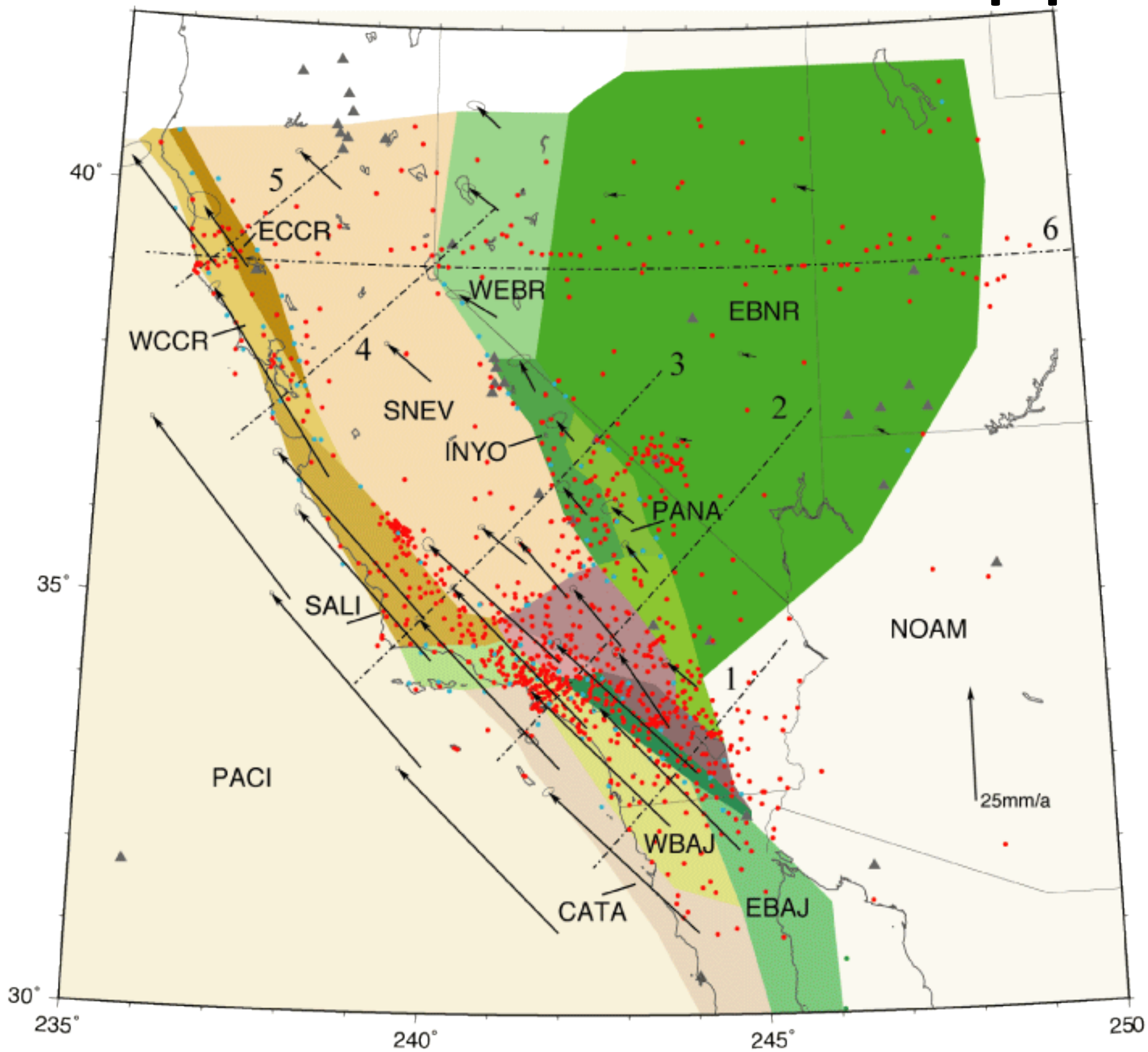


Fig. 2

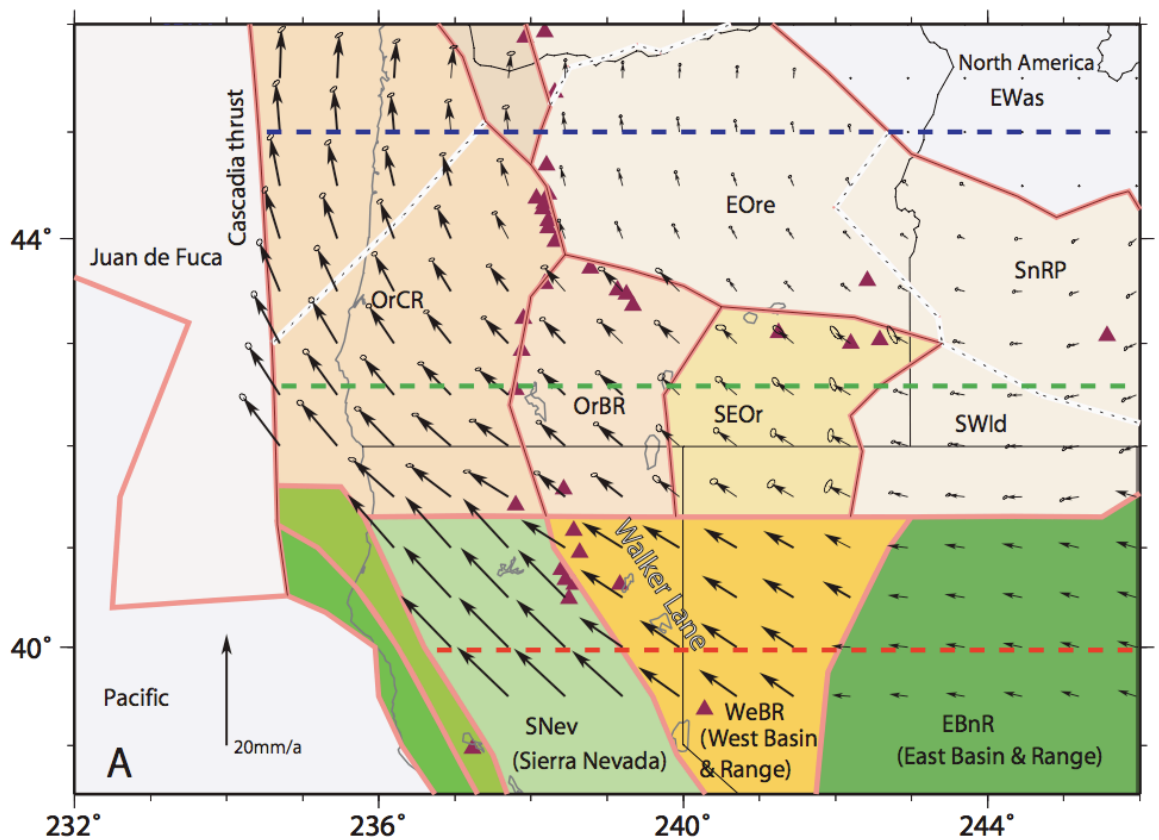
- Broad deforming zone consists of a few discrete high-strain shear zones separated by regions of low strain (*Thatcher et al.*, 1999).

Leads to a Block Model Approach

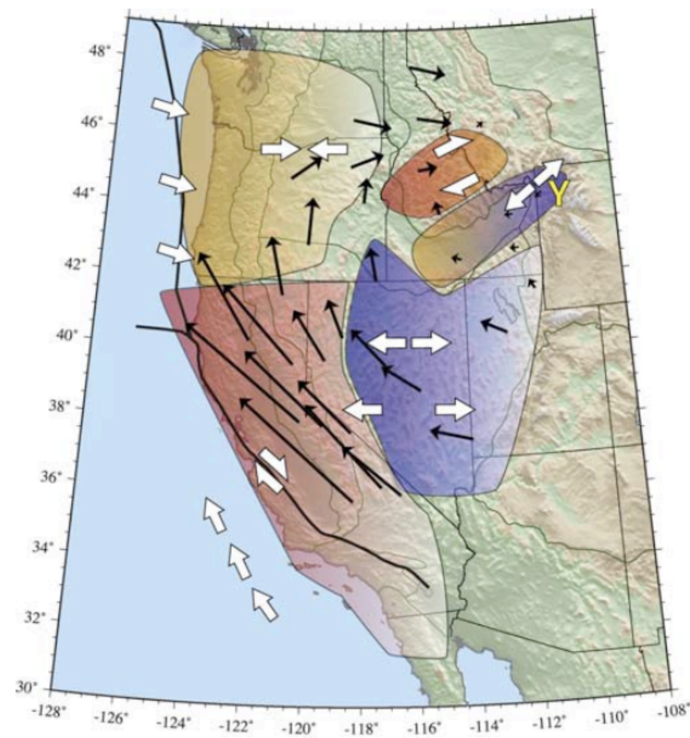


Rob McCaffrey, 2003, Fall AGU

Block Models for the Lower 48

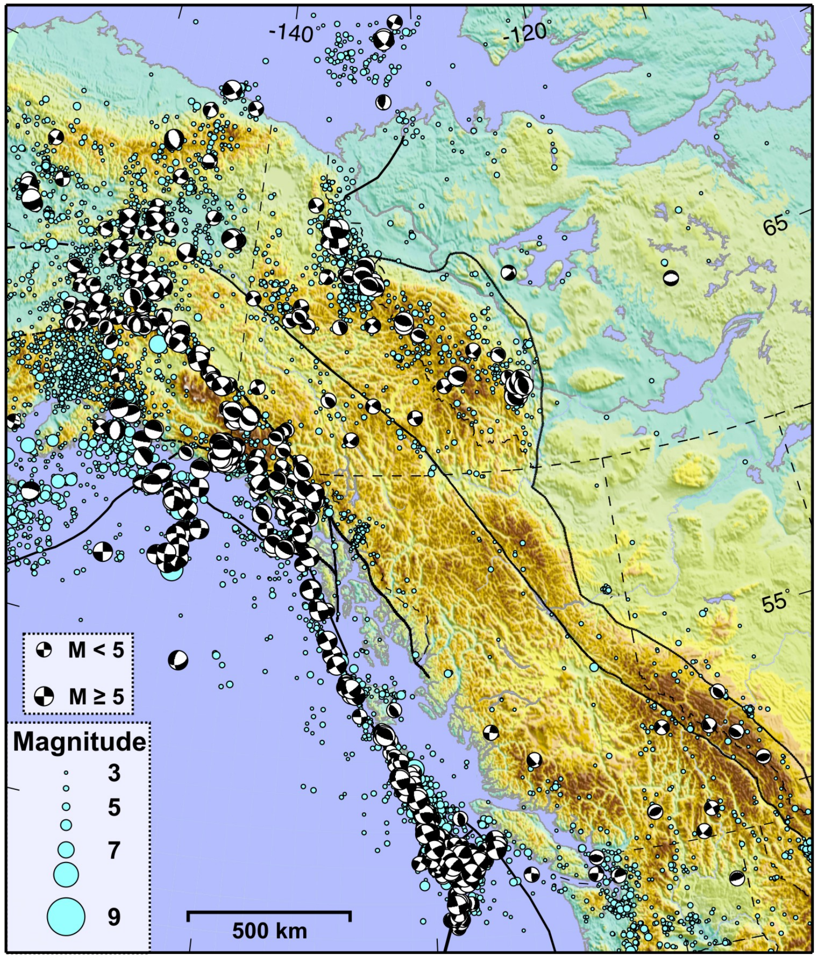


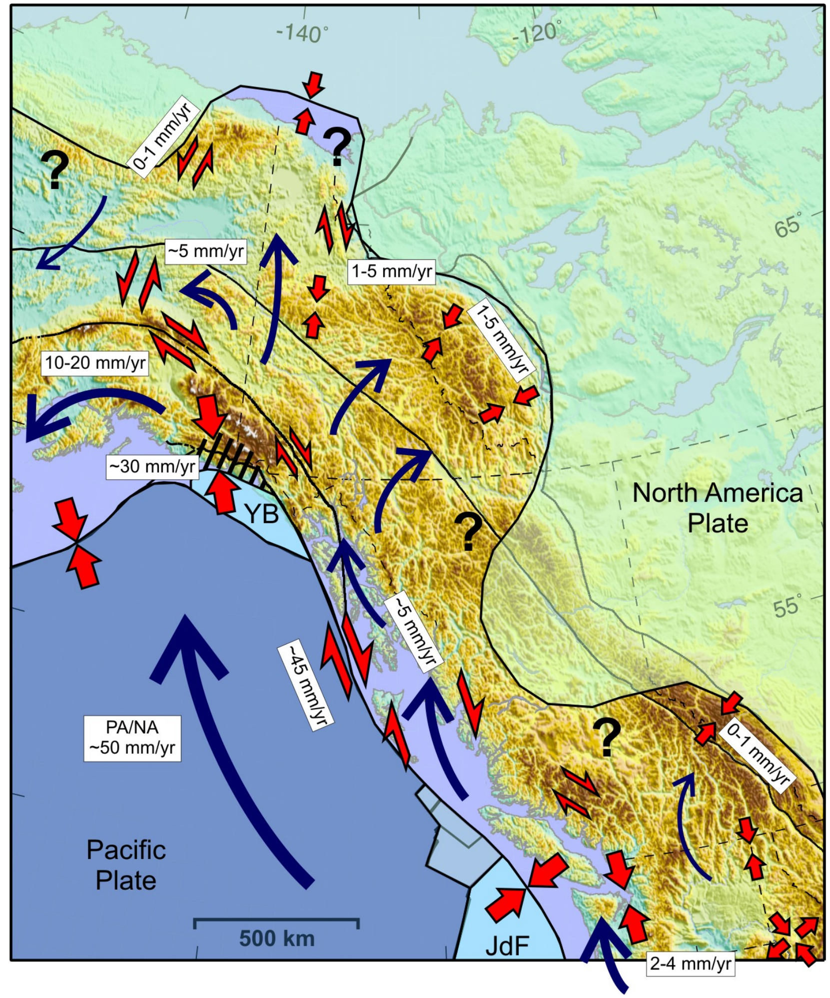
McCaffrey et al. (2007)



Puskas and Smith (2009)

Northern Cordillera





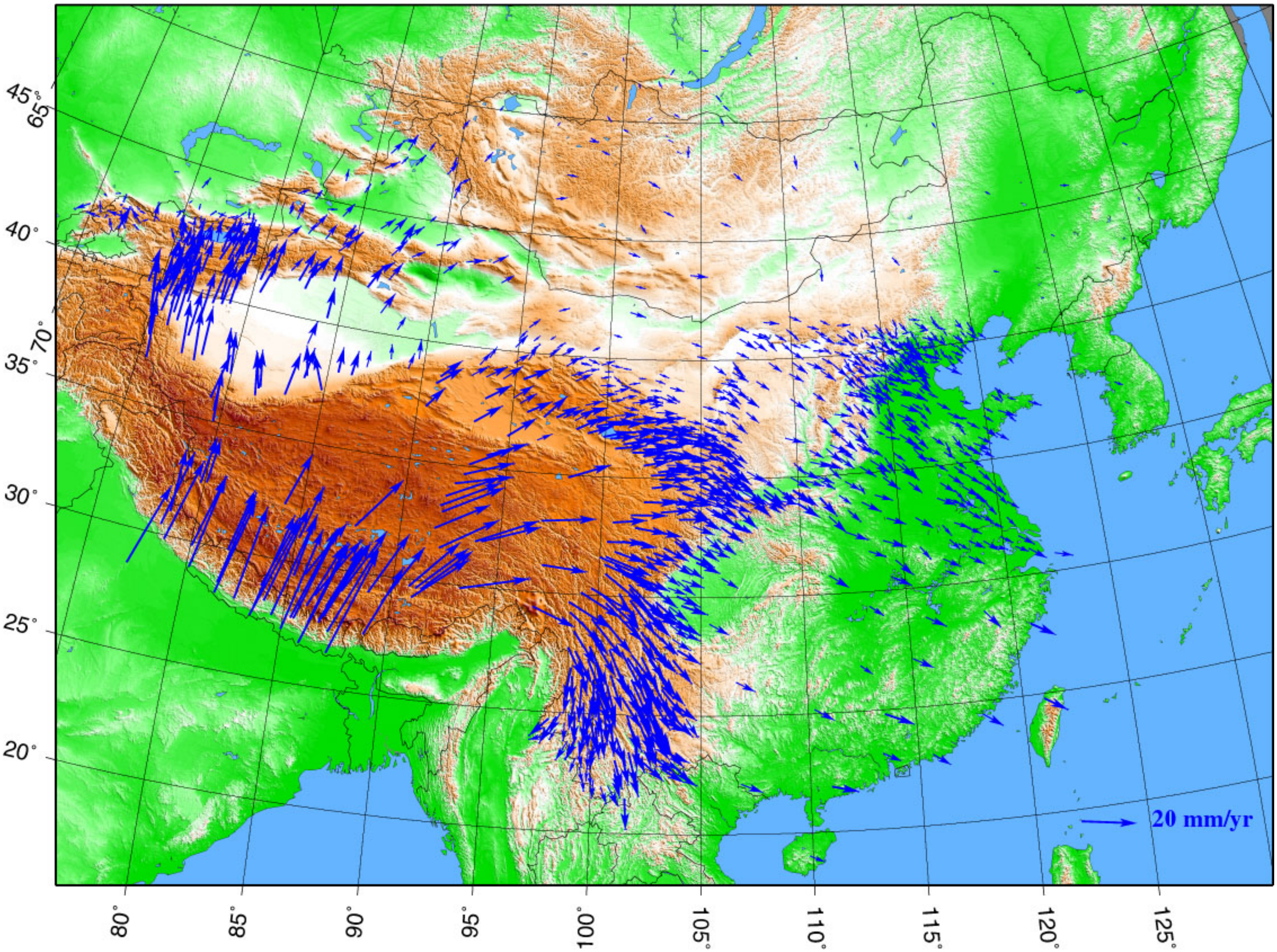
Mazzotti et al., 2008

Blocks Around the North Pacific

Blocks Around the North Pacific

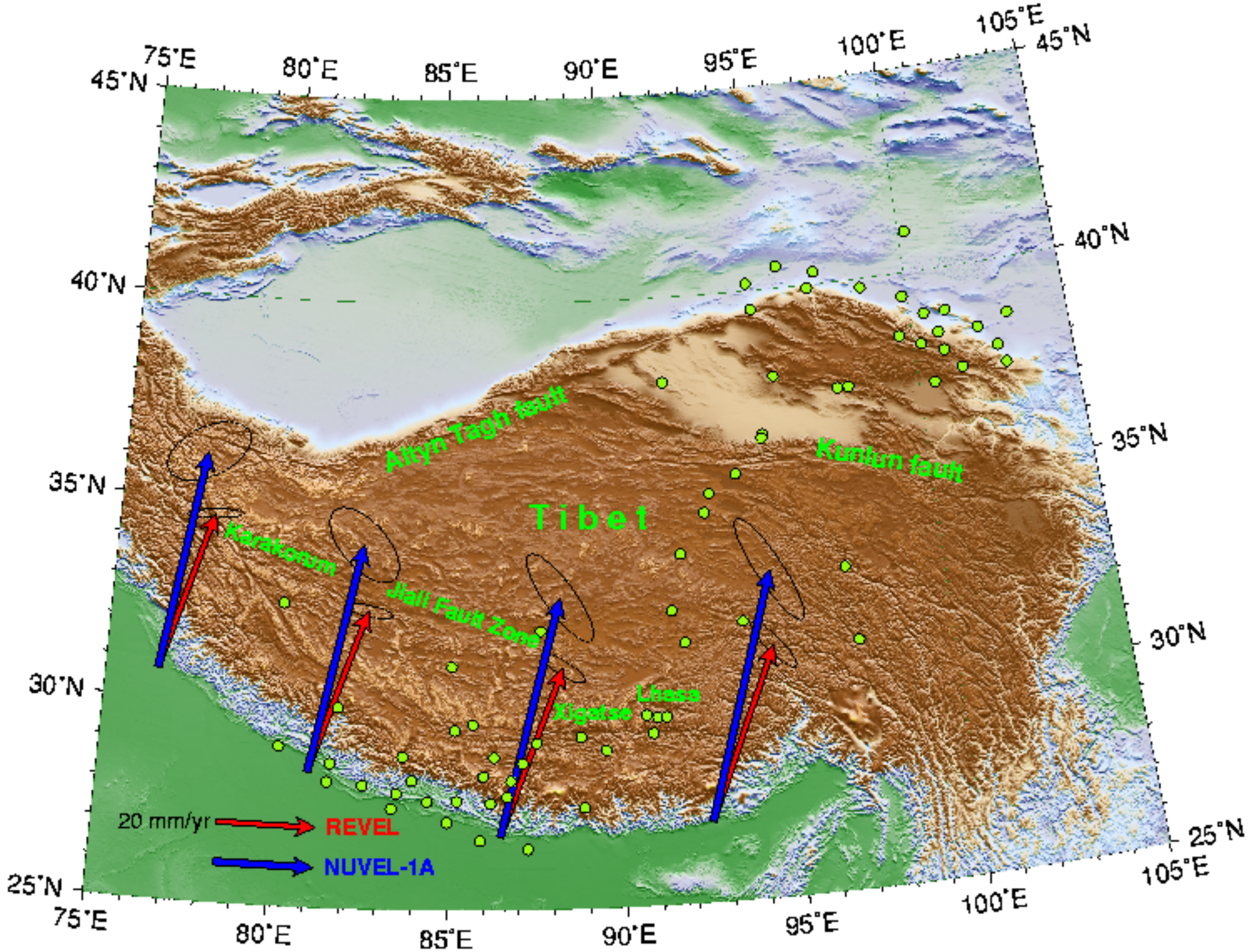
A Decade of GPS in China and Tibet

- First GPS survey in Tibet and Nepal in 1991
- Chinese agencies began surveys in 1992
- Built collaborative relationships with Chinese agencies
- Current China – Alaska – Colorado collaboration began in 1995 with goals of:
  - Measure convergence across Himalaya
  - Measure extension across southern Tibet
  - Investigate large-scale tectonic models for India-Eurasia collision

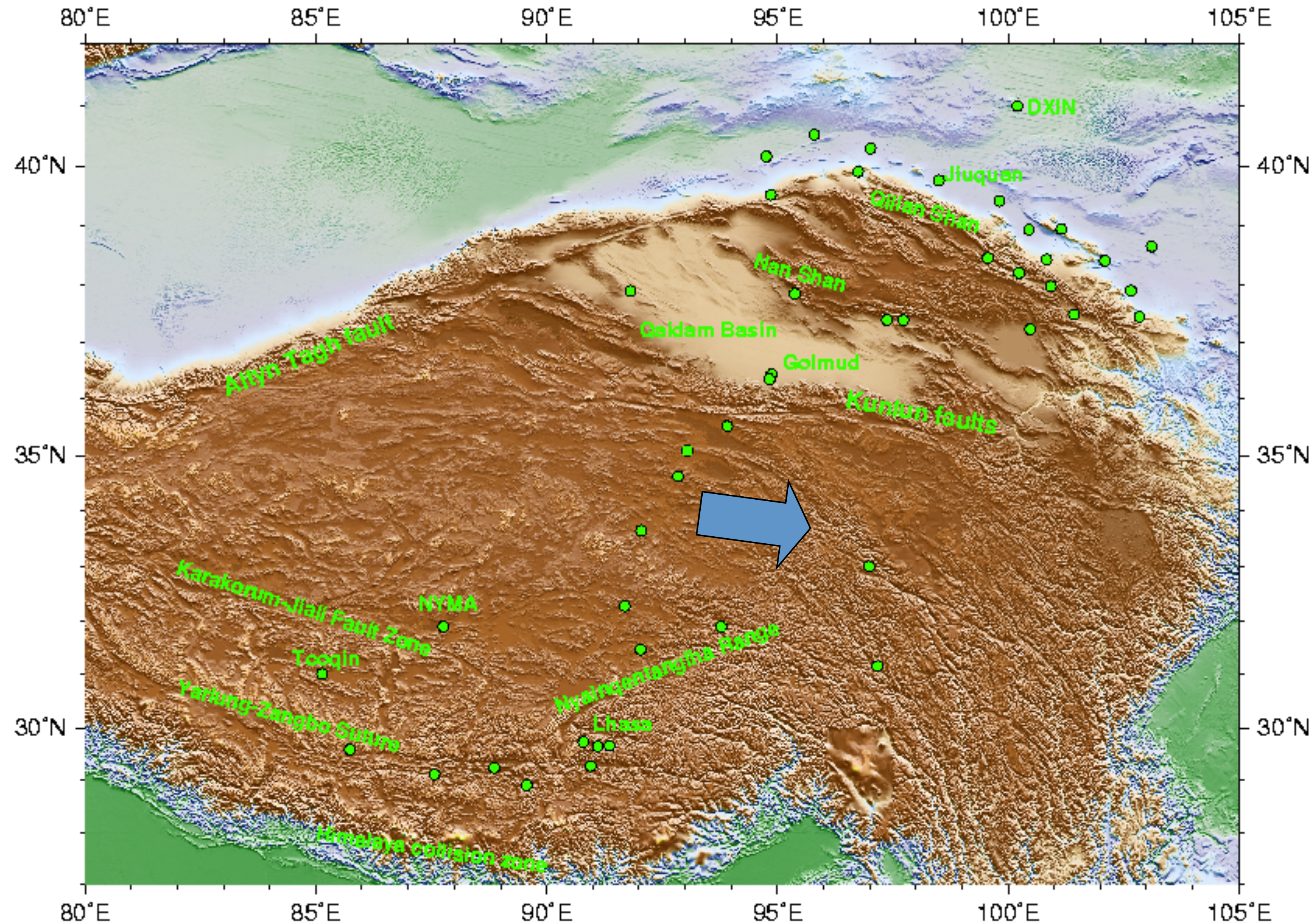


20 mm/yr
45°
40°
35°
30°
25°
20°
65°
70°
80°
85°
90°
95°
100°
105°
110°
115°
120°
125°

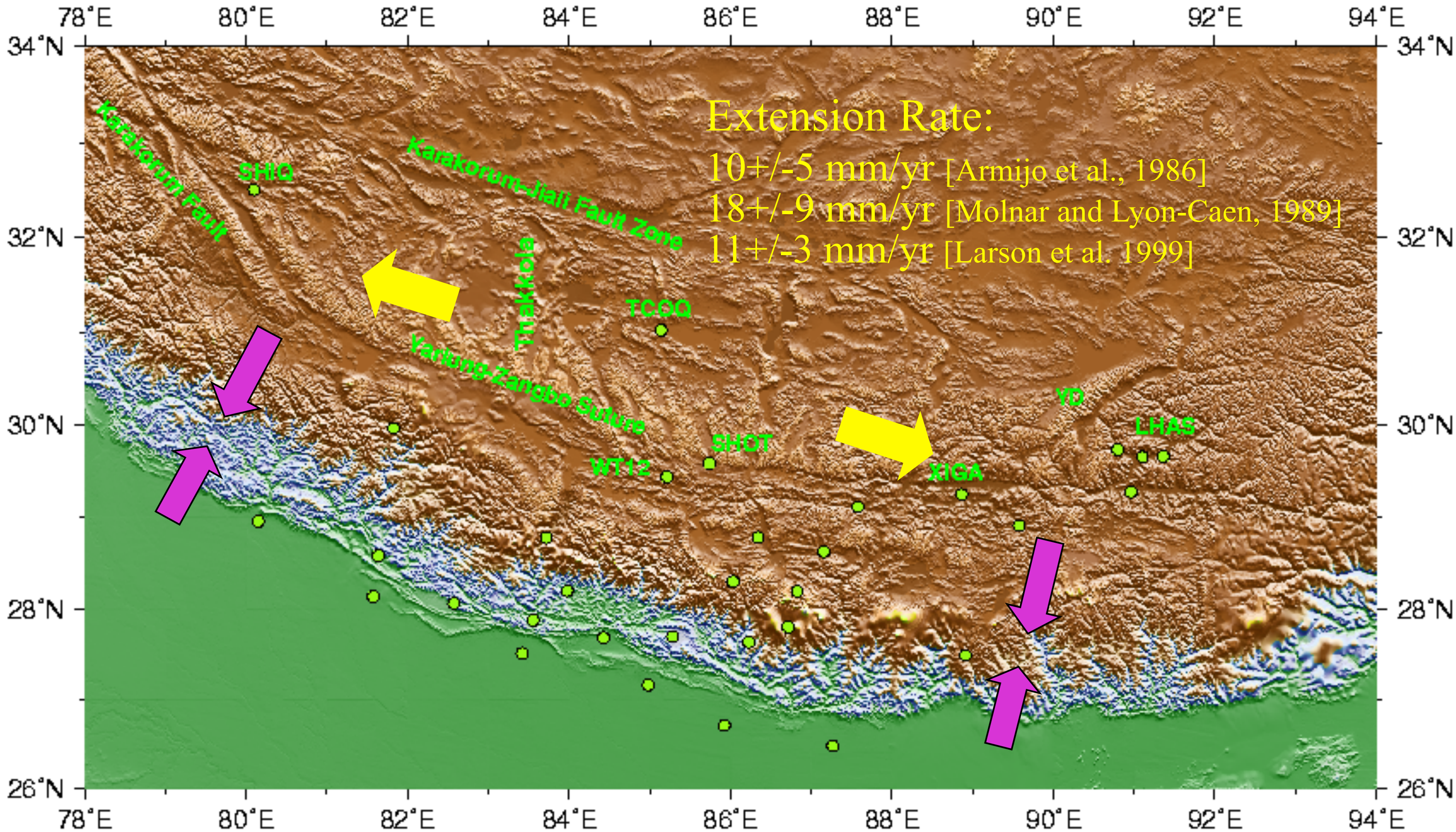
Relative Plate Motions



Tectonic Setting



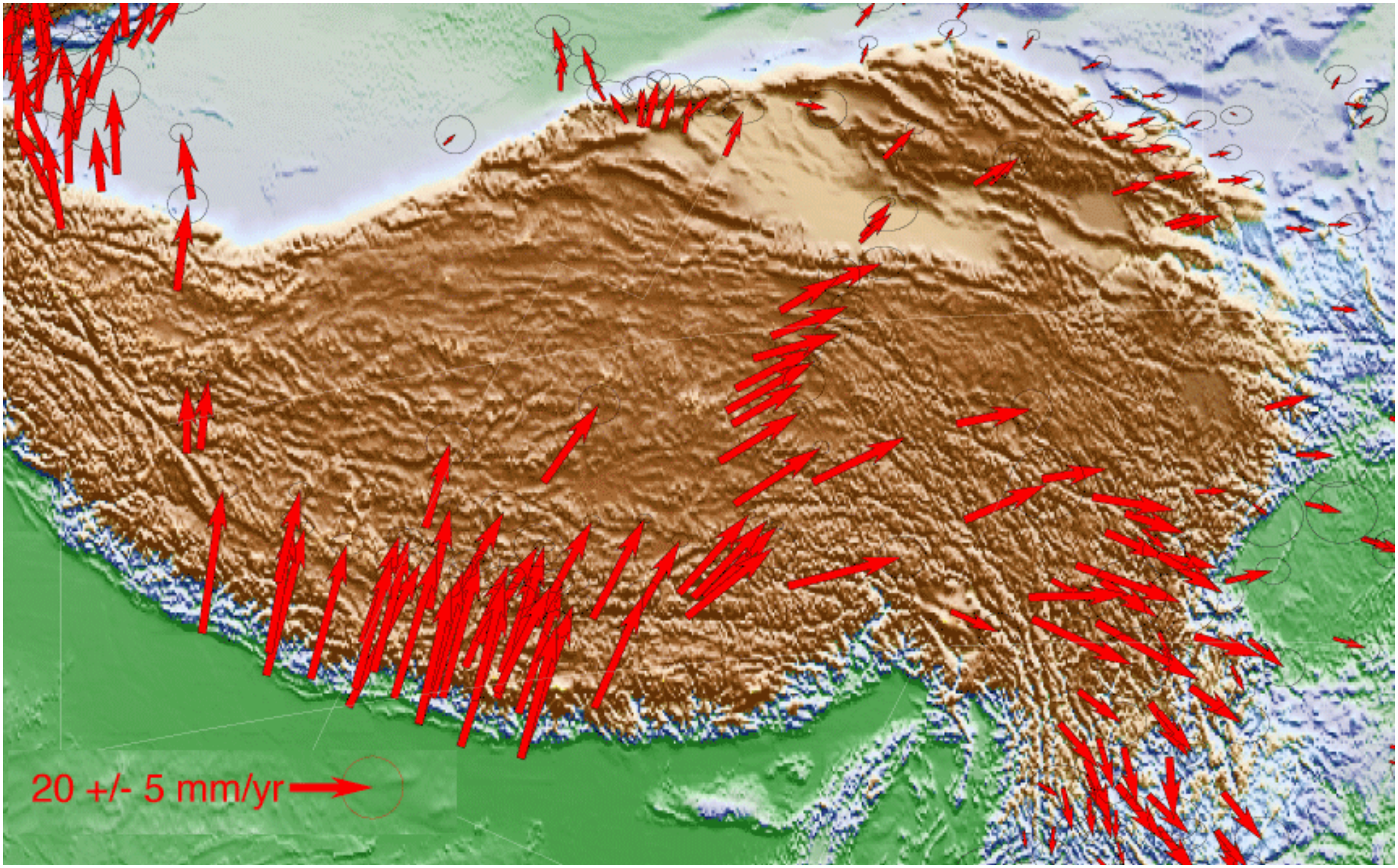
Tectonic Setting



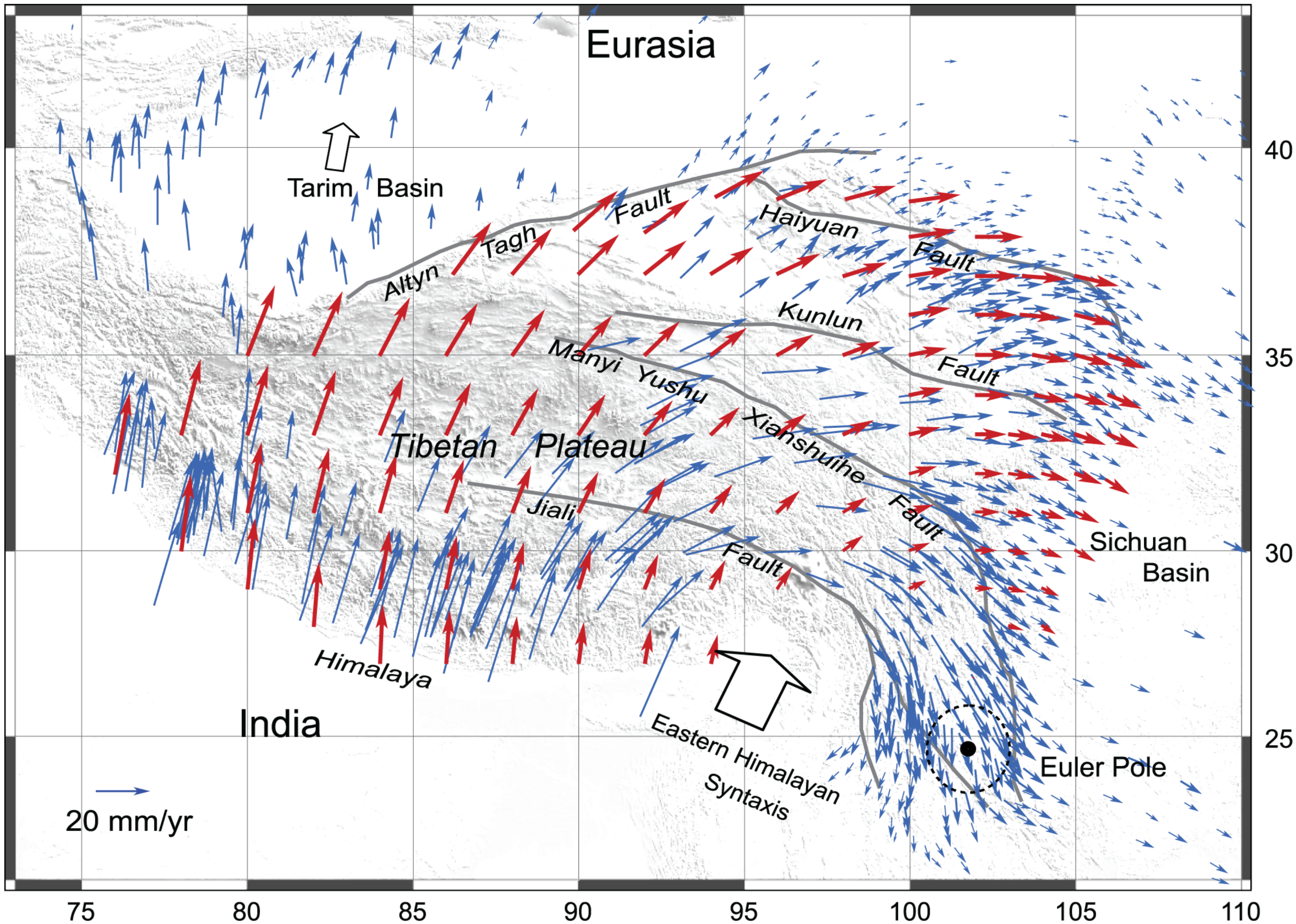
Convergence Rate:

10-25 mm/yr [Molnar and Deng, 1984; Molnar, 1987]
18+/-7 mm/yr [Molnar and Lyon-Caen, 1989]
~18 mm/yr [Larson et al., 1999; Bilham et al, 1997]

Tibet Velocities

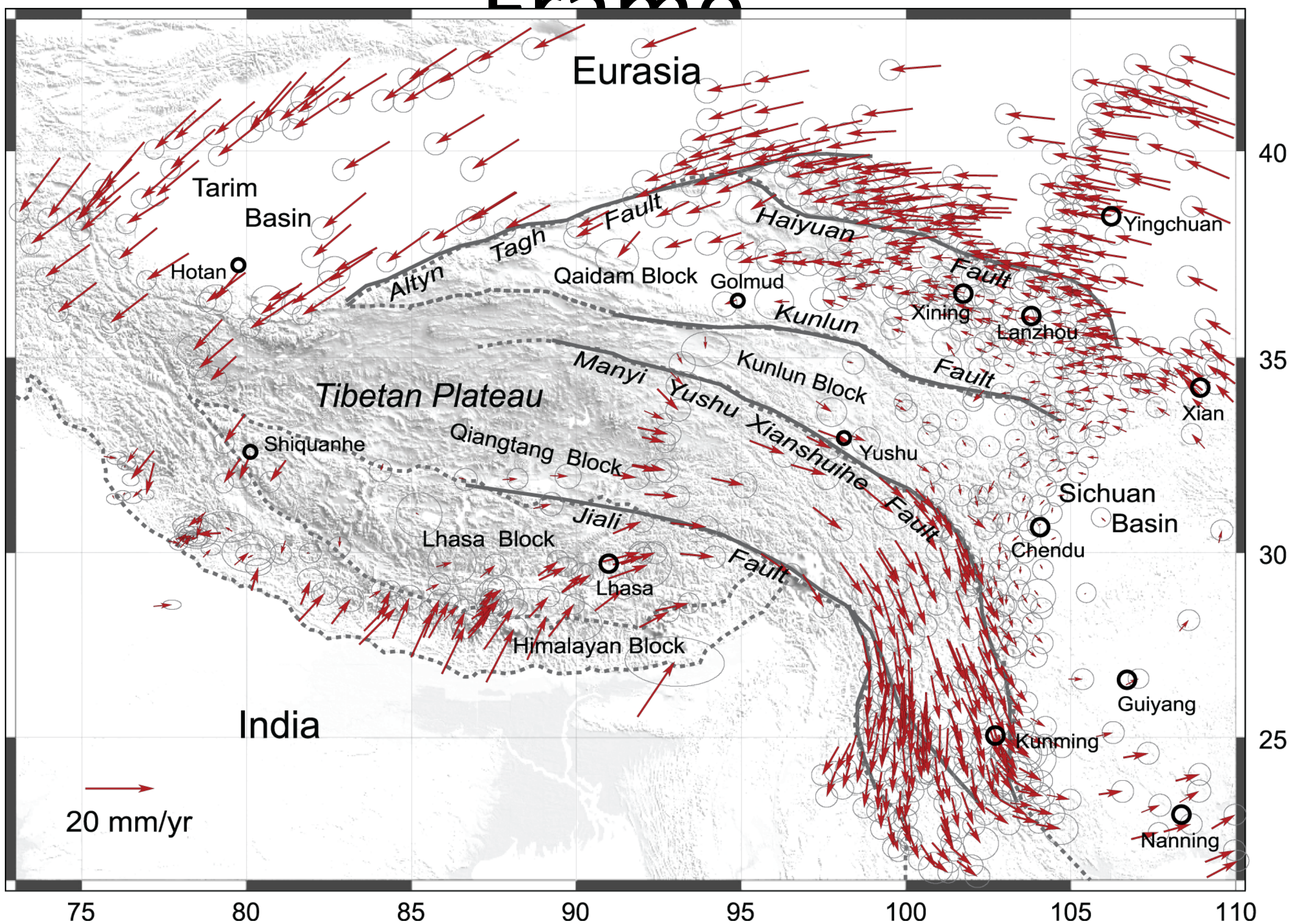


Latest Published Velocity Field



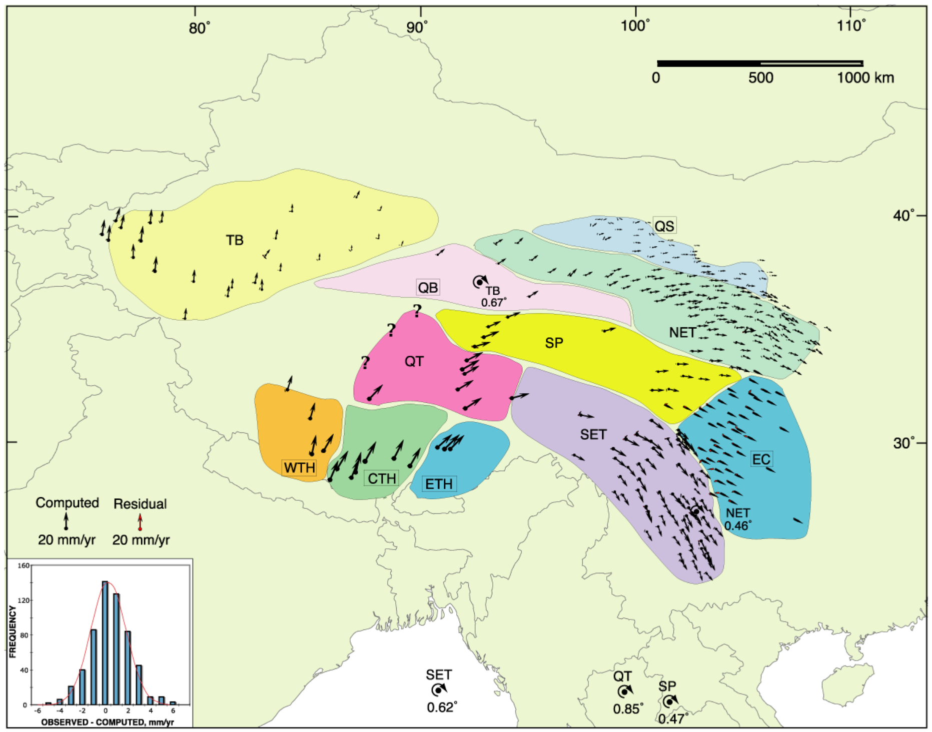
Gan et al. (2007 JGR)

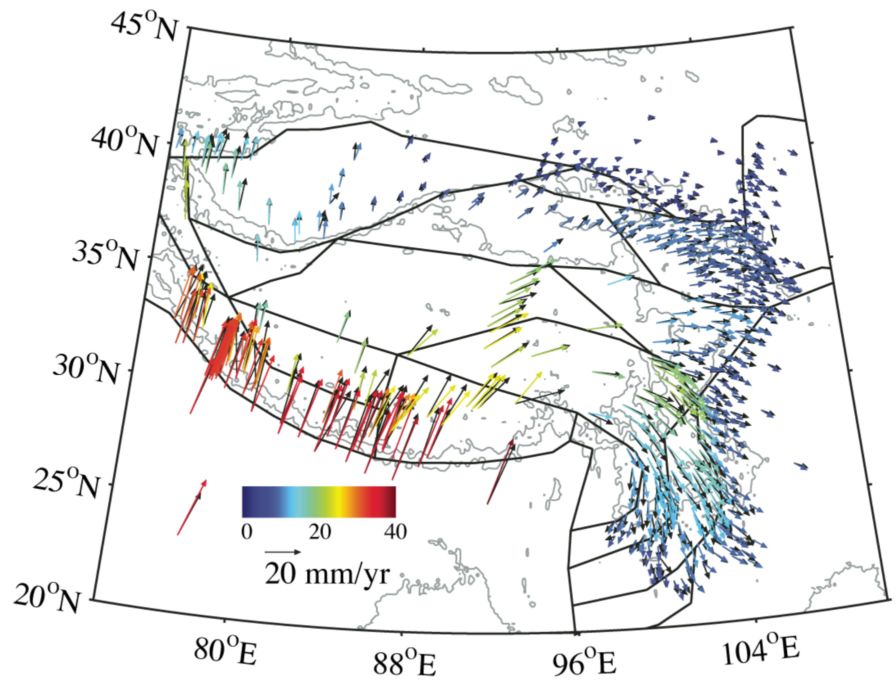
“Tibetan Plateau Reference Frame”



Gan et al. (2007) explained these motions in terms of a series of blocks separated by mostly strike-slip faults ➔ plateau is deforming, but not changing area.

Thatcher vs. Meade

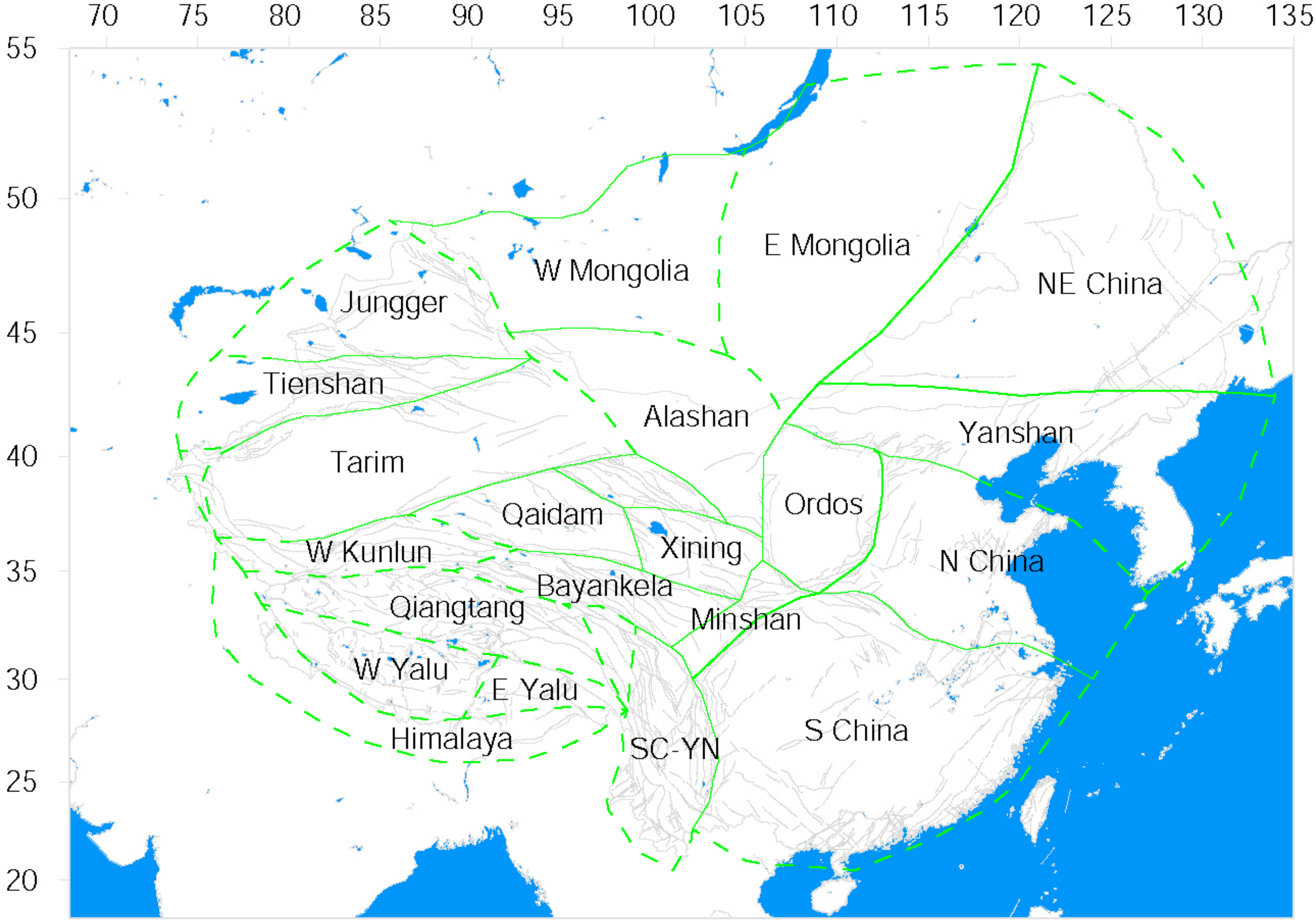




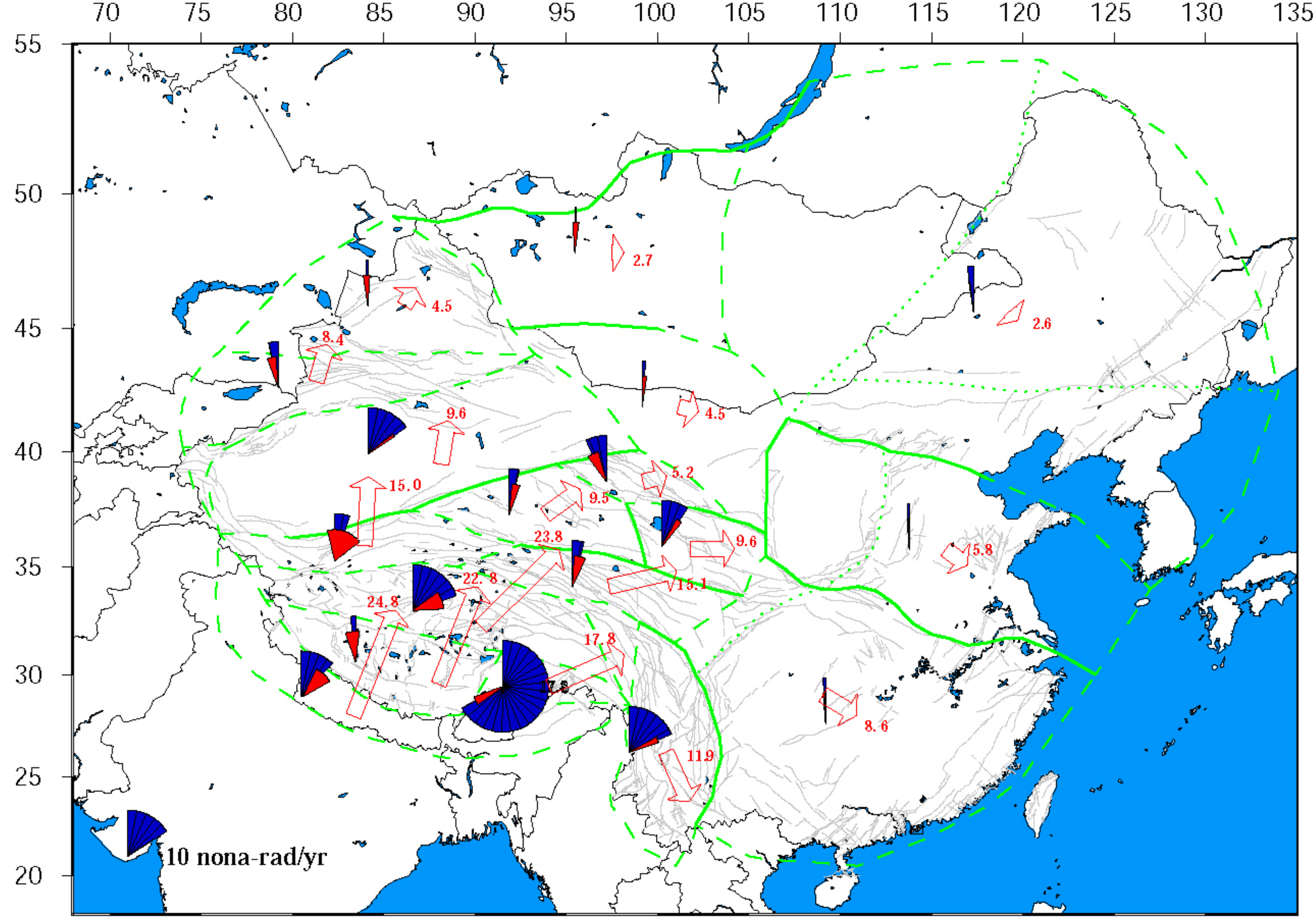
Thatcher, 2007

Meade, 2007

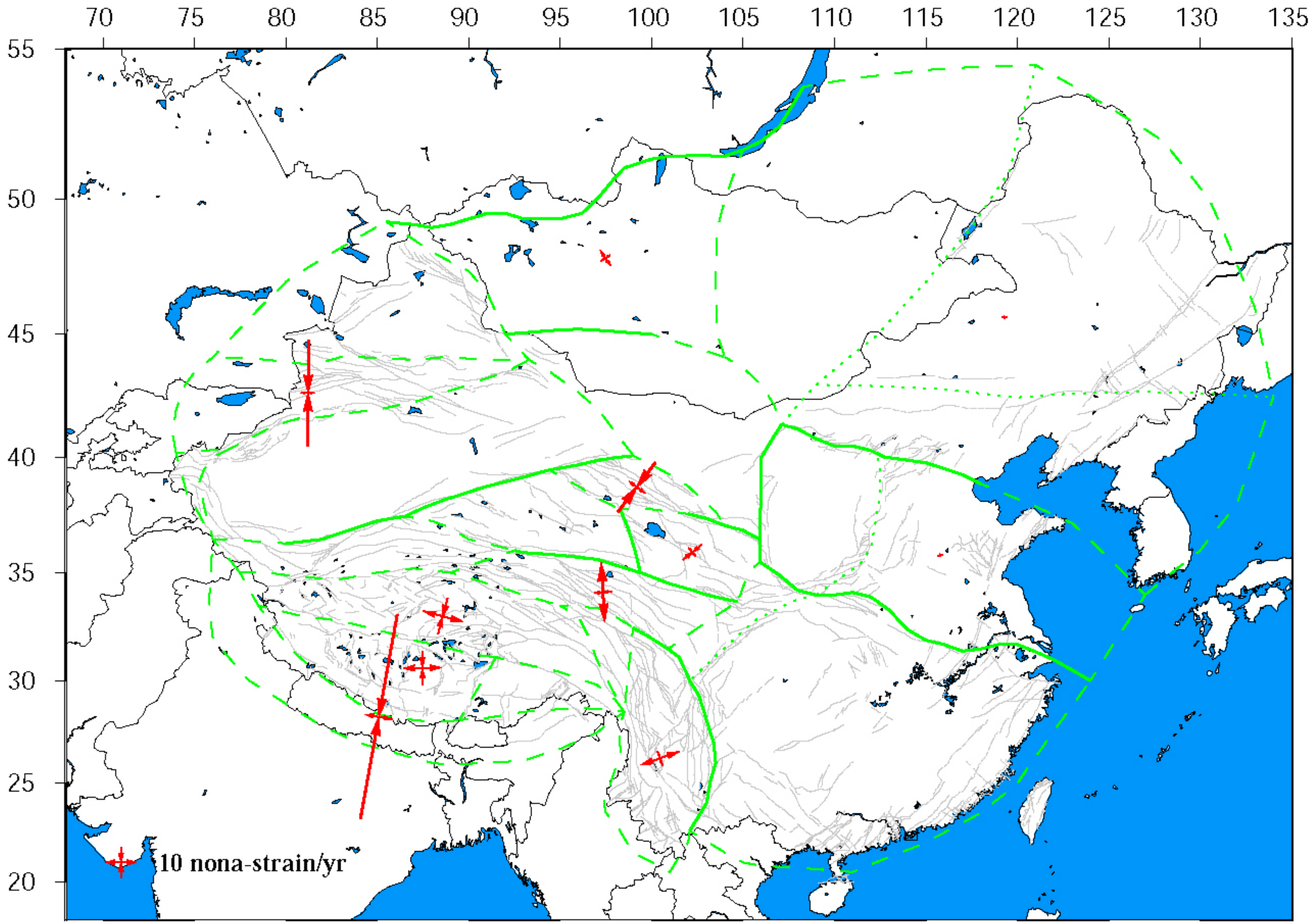
Starting Block Motion Model



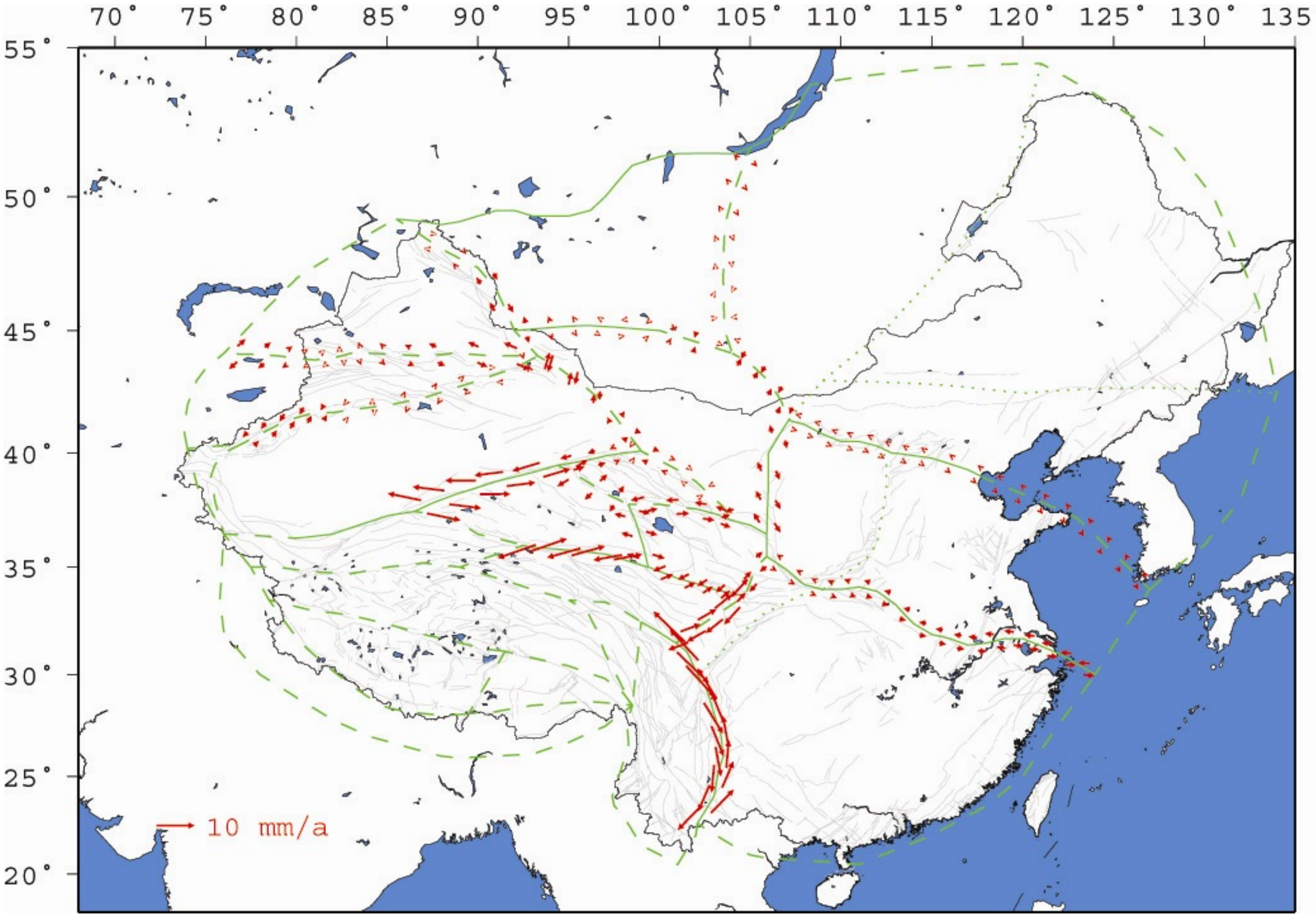
Block motion velocities and rotation rates

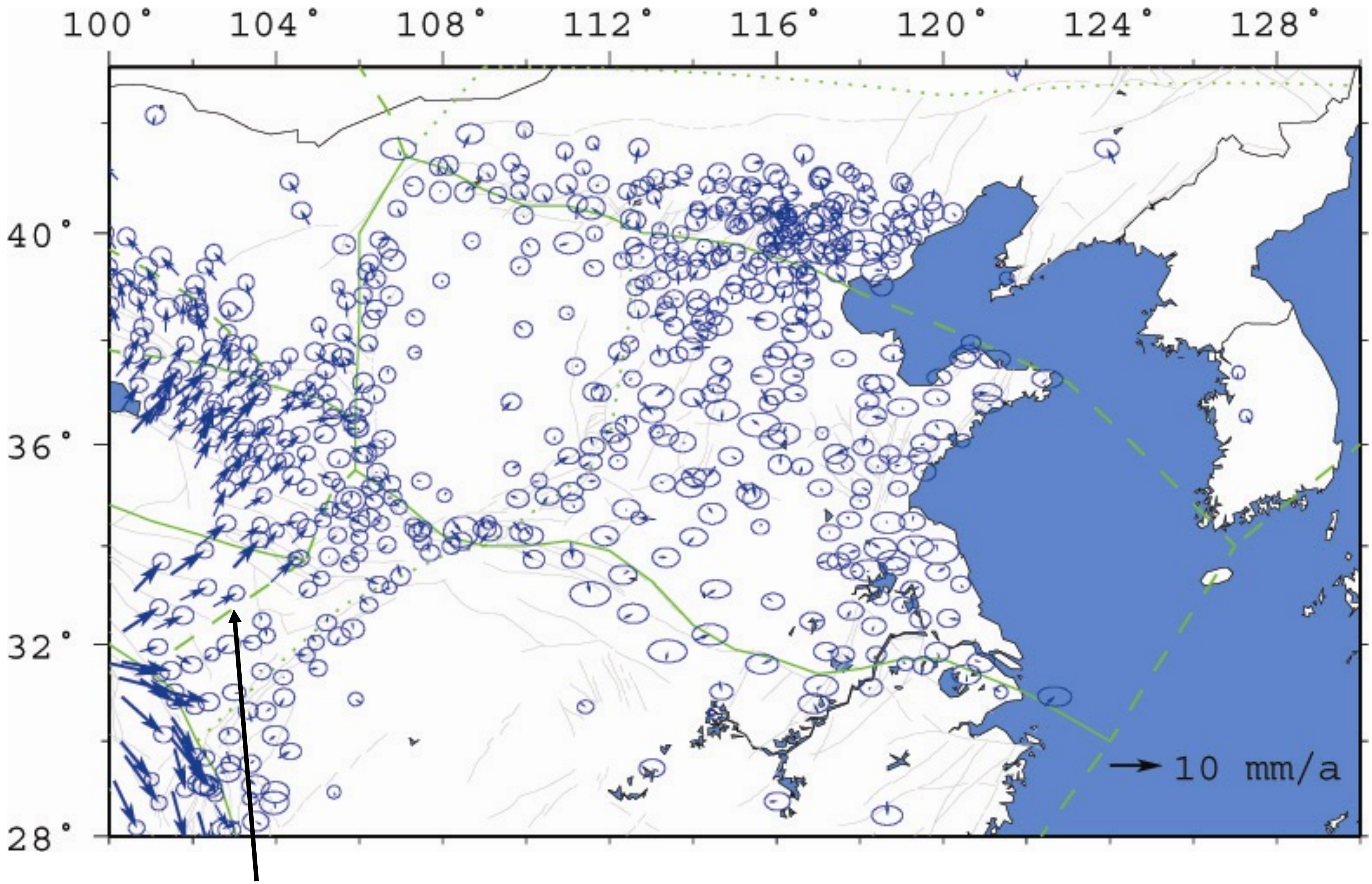


Block internal principal strain rates

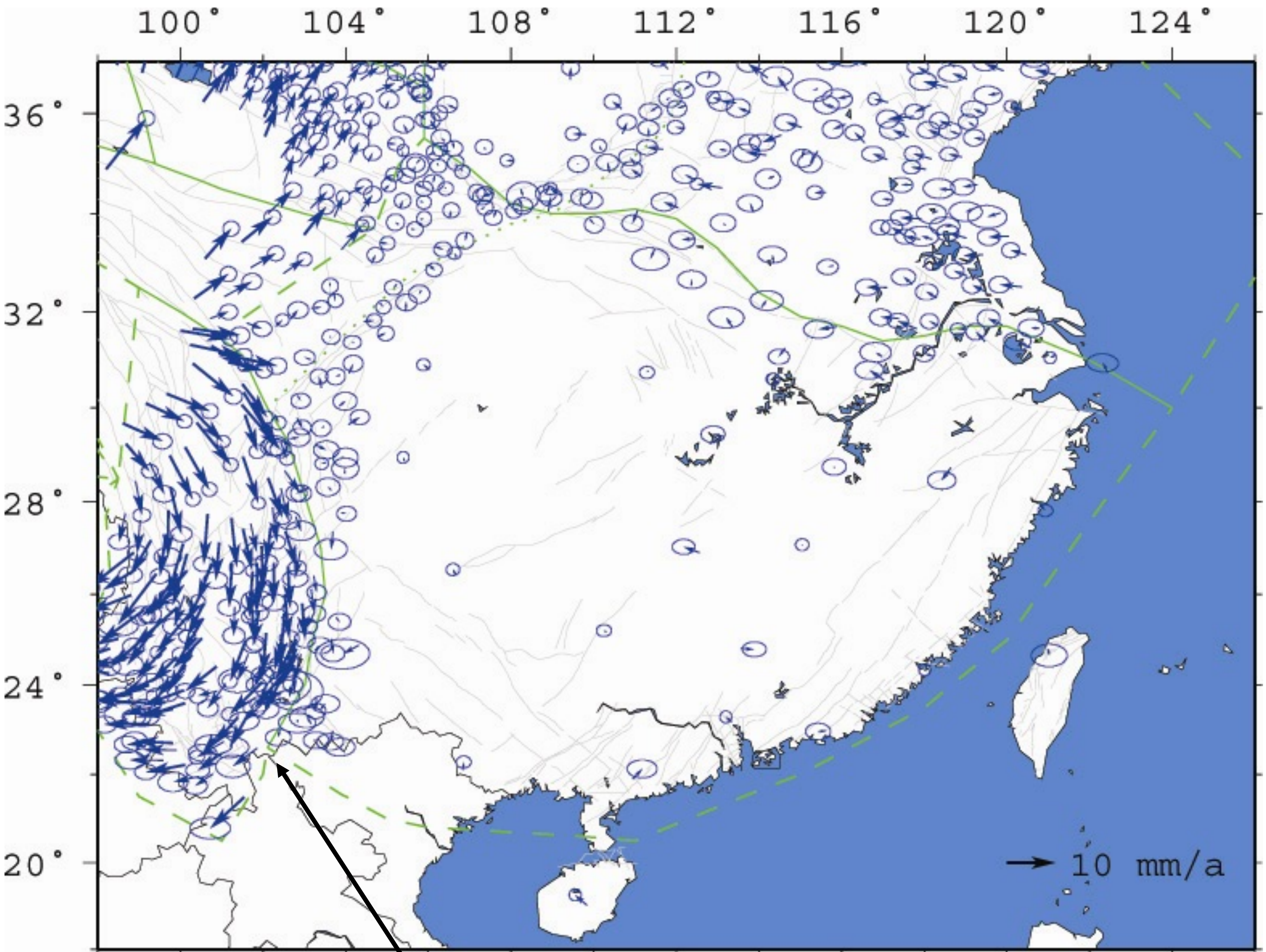


Relative Motion (Fault Slip) Rates at Block Boundaries



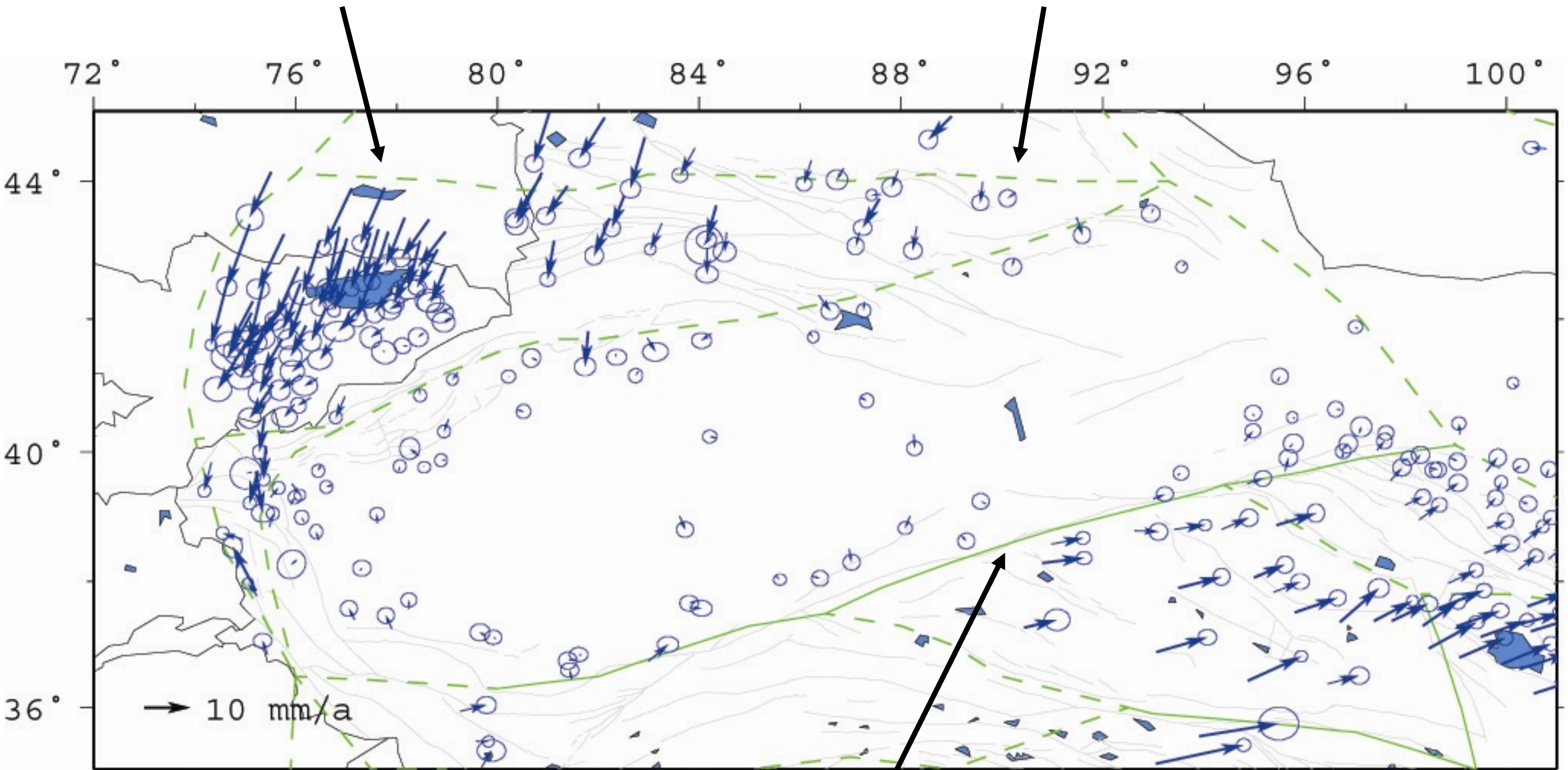


4-5 mm/yr right slip along a previously unknown fault zone



8-10 mm/yr left slip along Xianshuihe-Xiaojiang fault system, extending southwestward across Red River fault

Progressive westward increase of north-south convergence across Tien Shan range



Slow (~6 mm/yr) left slip along central Altyn Tagh fault

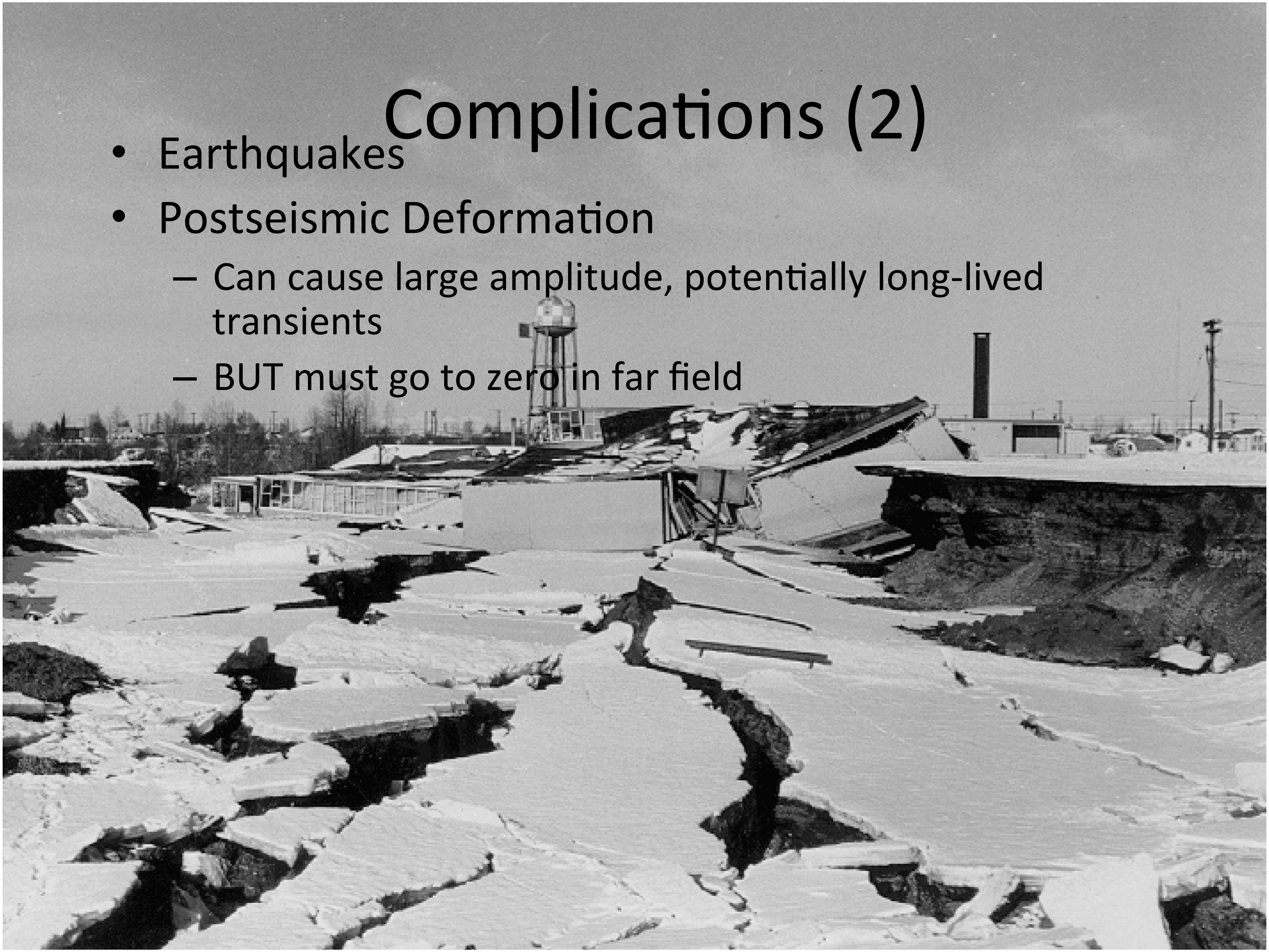
Complications (1)

All of the work shown here assumes short-term velocity equals long-term velocity. It may not! Velocities can be biased by several effects:

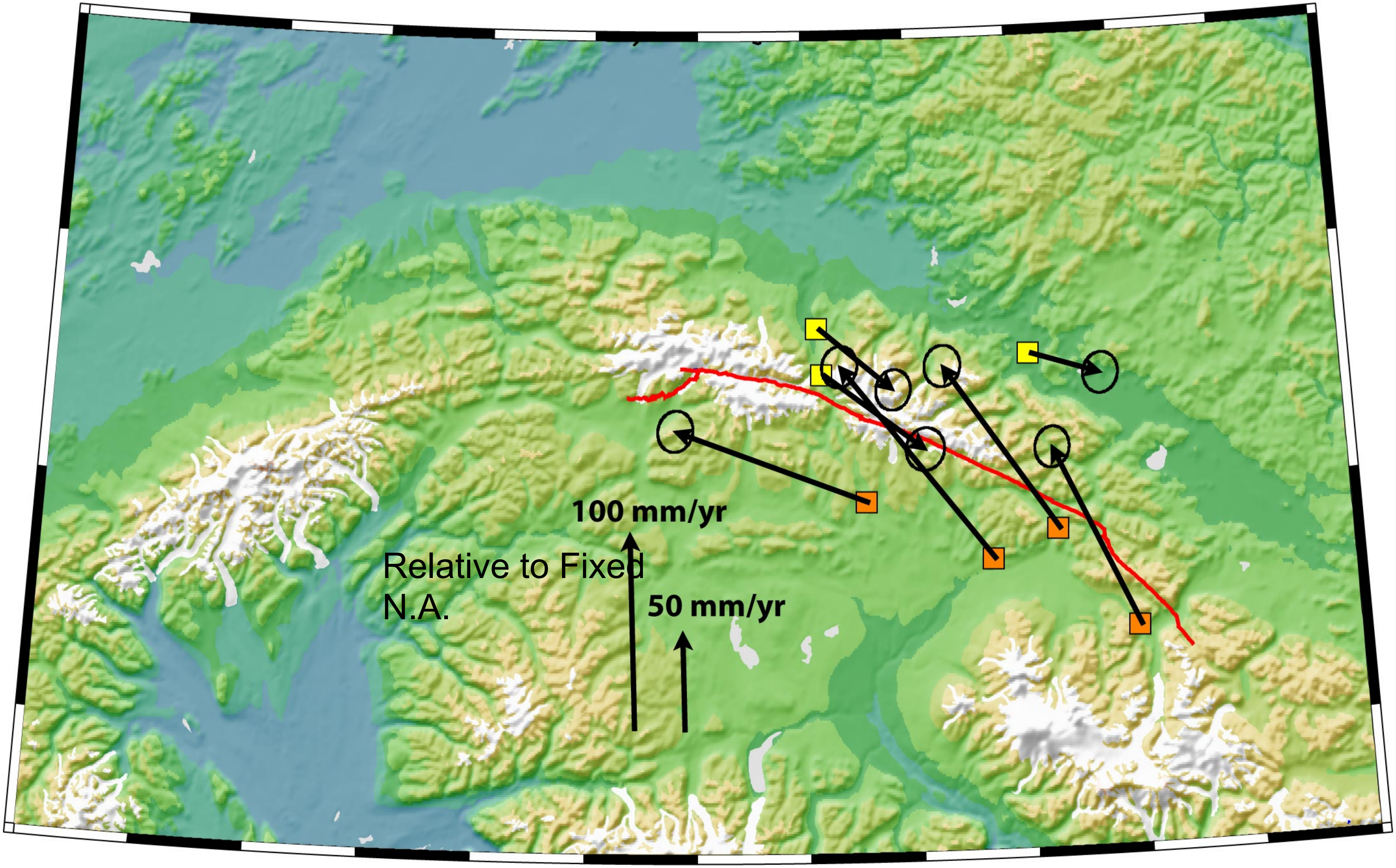
- Loading (seasonal and other)
  – Heki (2003) showed that the strong seasonal signals in Japanese network explainable by physical loading models
- Hydrologic effects (famous subset of SCIGN)

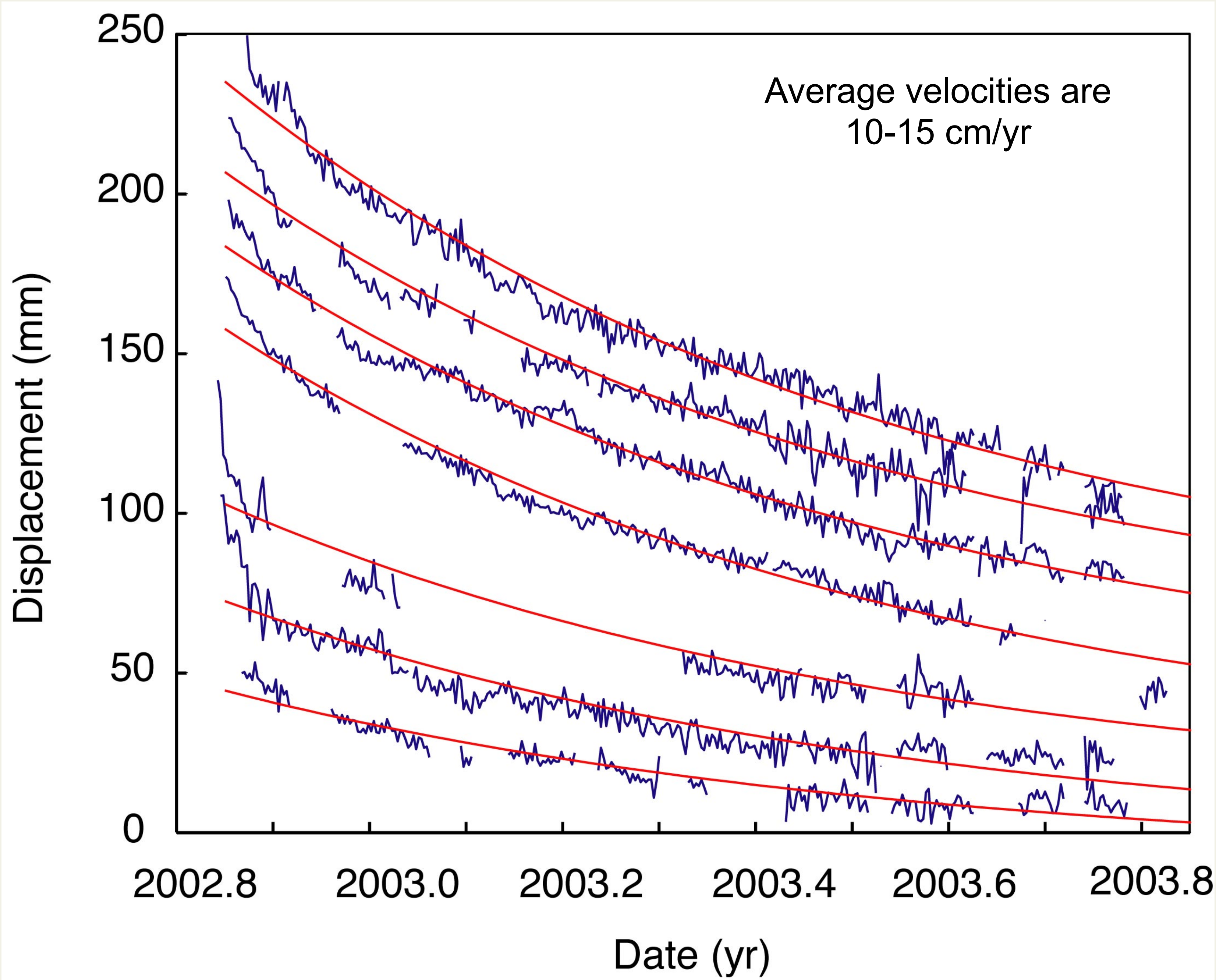
Complications (2)

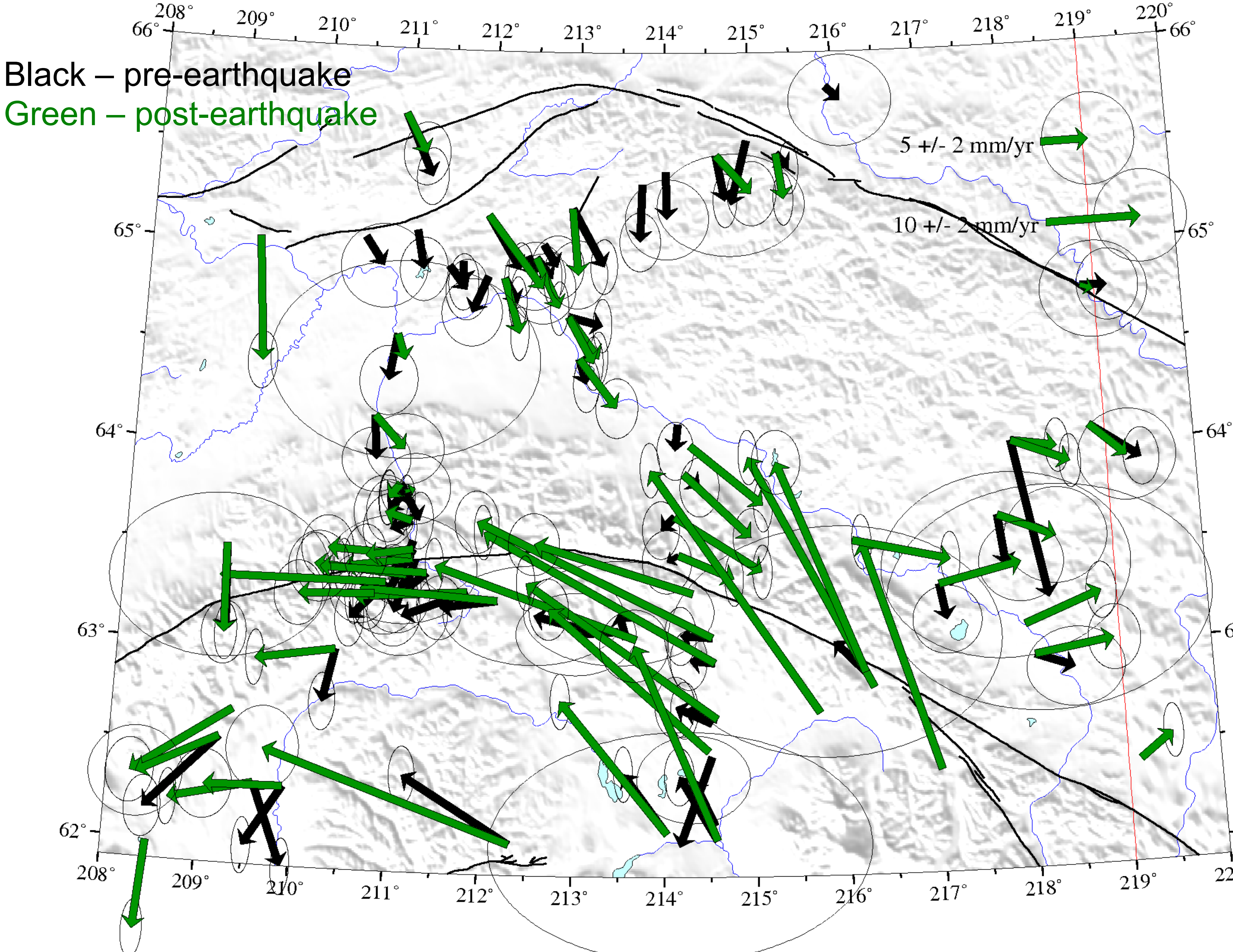
- Earthquakes
- Postseismic Deformation
  - Can cause large amplitude, potentially long-lived transients
  - BUT must go to zero in far field



One year of postseismic deformation: Average velocities are 20-25 times faster than before the earthquake

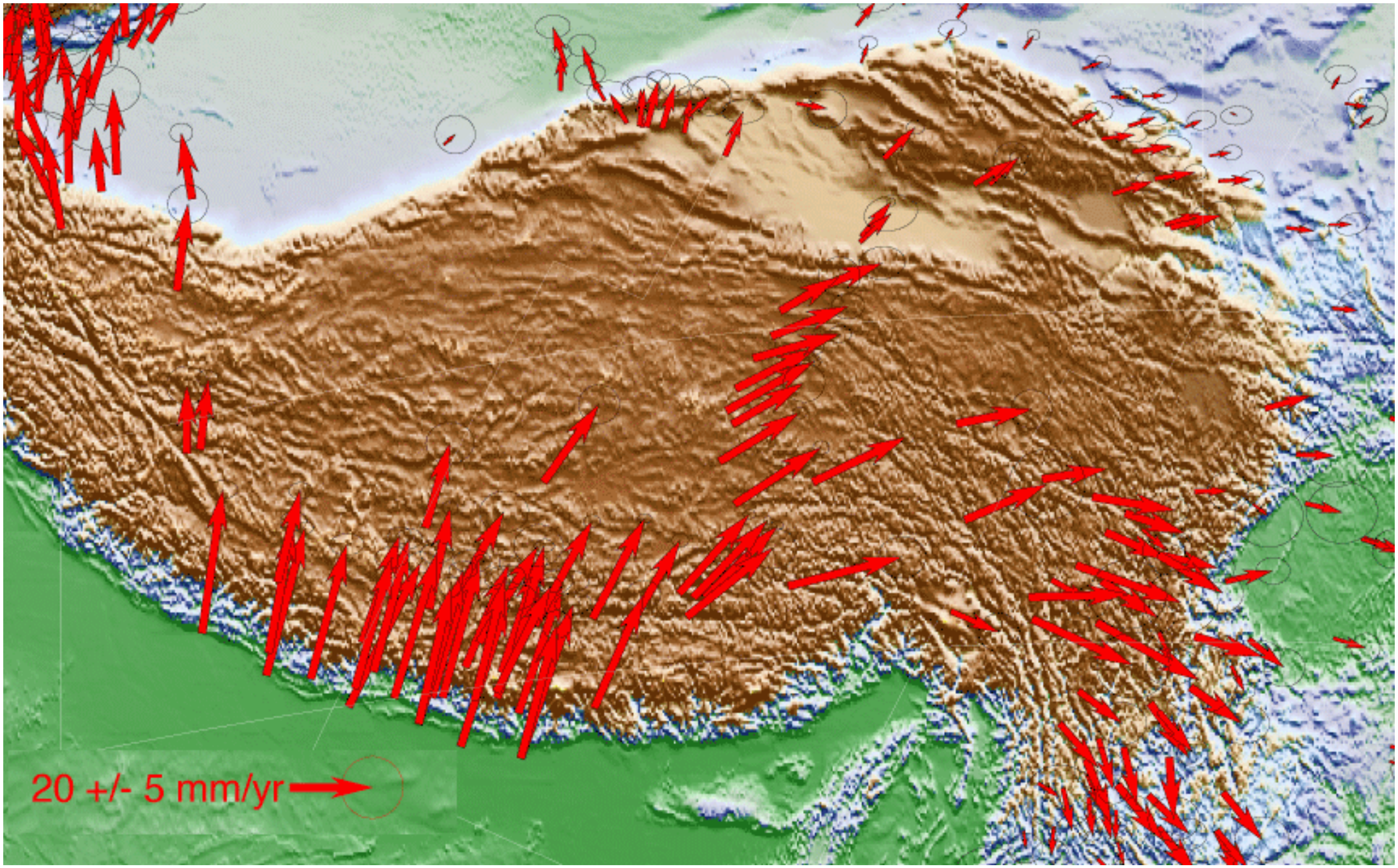



Average velocities are
10-15 cm/yr
250
200
150
100
50
0
Displacement (mm)
2002.8
2003.0
2003.2
2003.4
2003.6
2003.8
Date (yr)

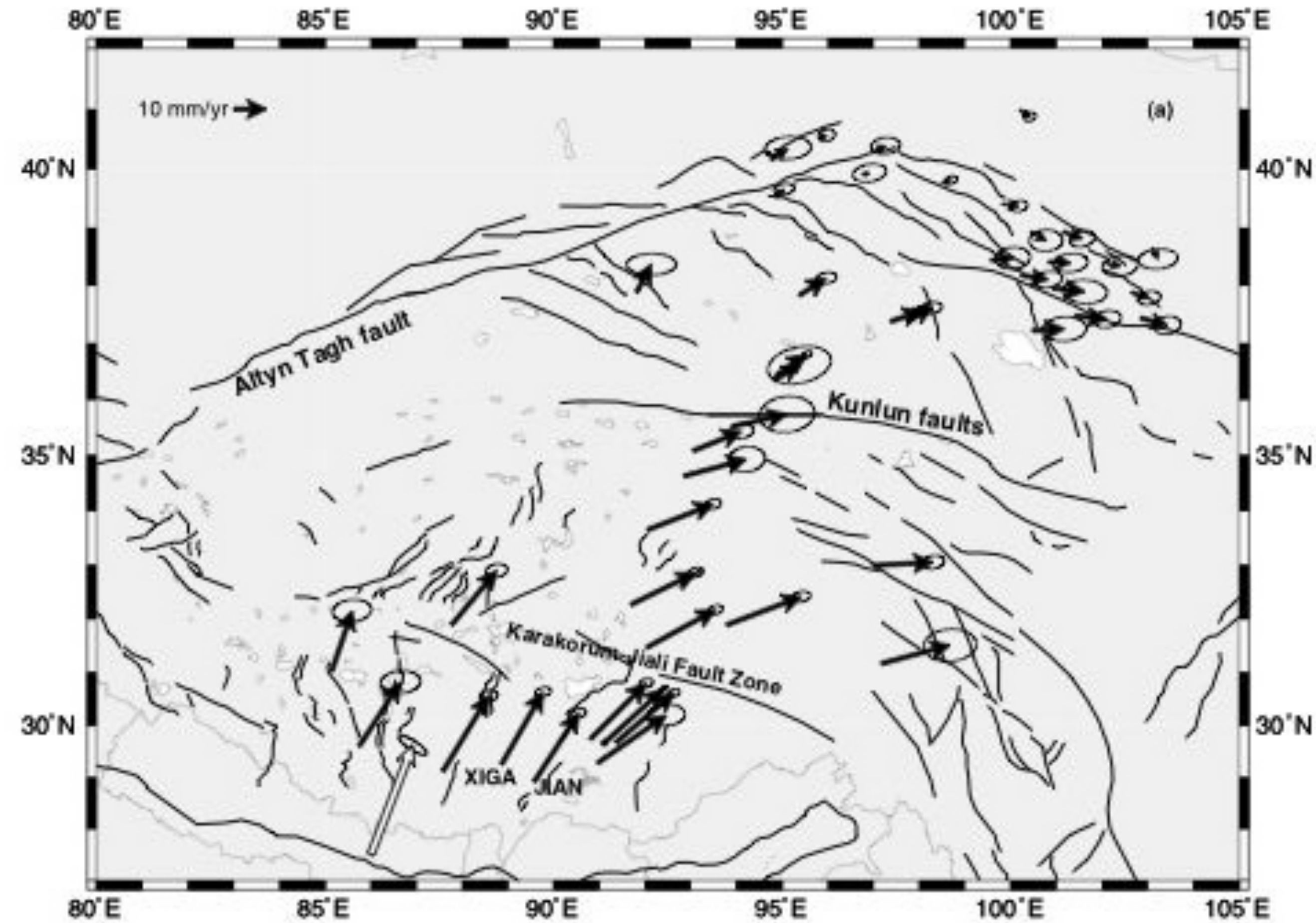


Black – pre-earthquake
Green – post-earthquake
5 +/- 2 mm/yr
10 +/- 2 mm/yr
208°
209°
210°
211°
212°
213°
214°
215°
216°
217°
218°
219°
220°
66°
65°
64°
63°
62°

Tibet Velocities



Velocities Relative to Eurasia



Chen et al. (2004), JGR

Displacement and Strain

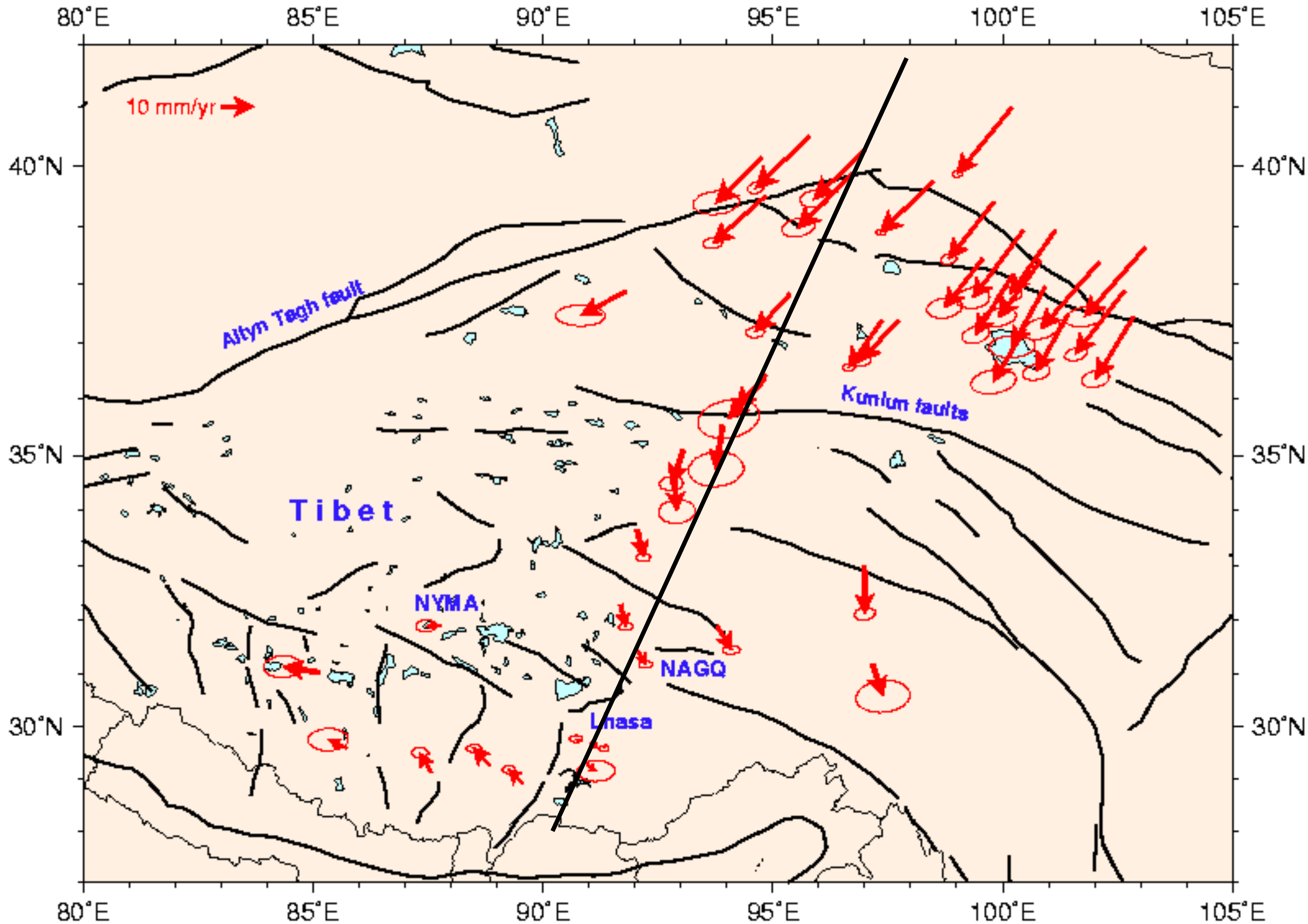
- Displacements (or rates) are a combination of rigid body translation, rotation and internal deformation

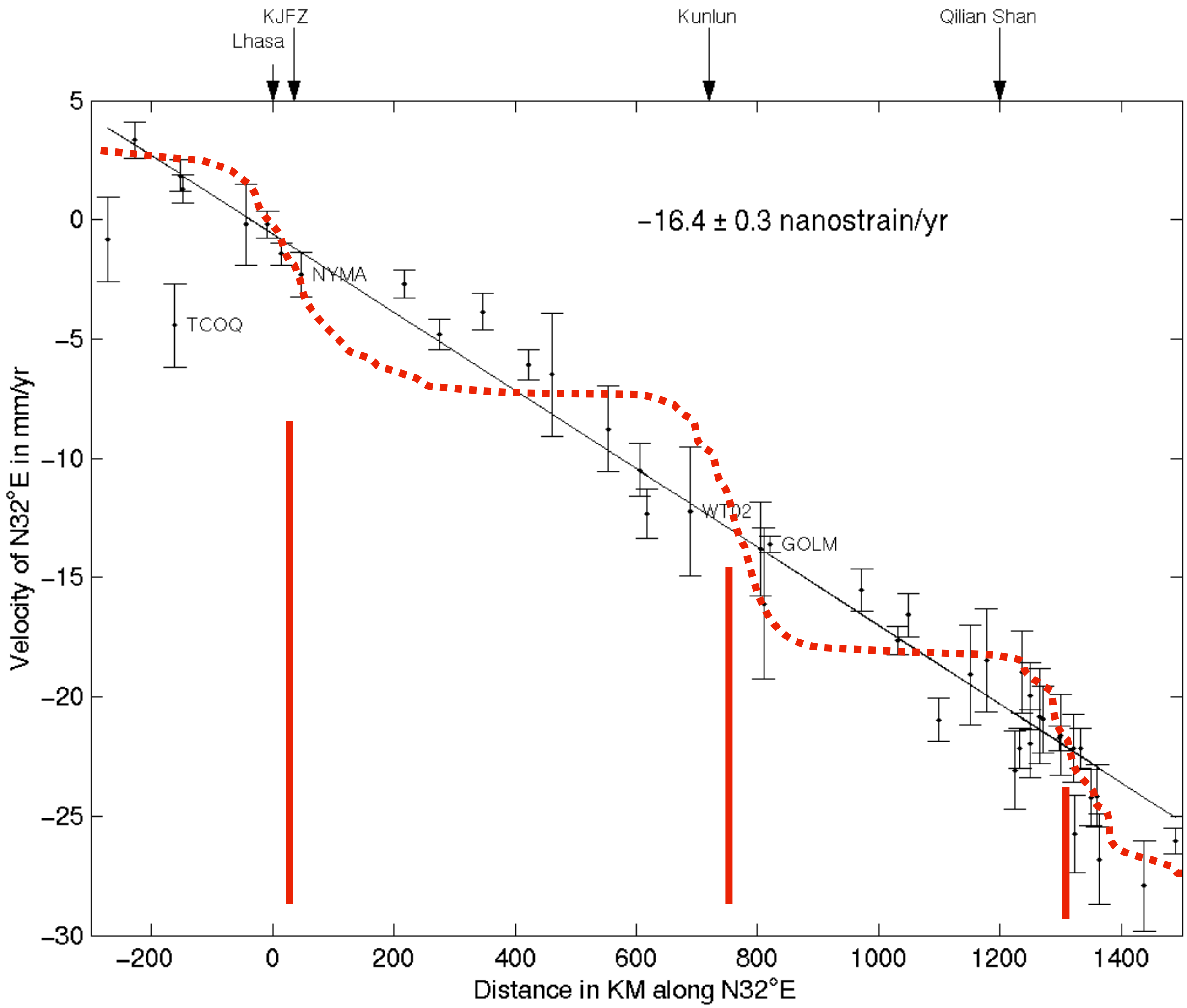
$$\begin{bmatrix} v_{east} \\ v_{north} \end{bmatrix} = \begin{bmatrix} v_{e,body} \\ v_{n,body} \end{bmatrix} + \begin{bmatrix} \dot{\varepsilon}_{11} & \frac{1}{2}\left(\dot{\varepsilon}_{12} + \dot{\omega}\right) \\ \frac{1}{2}\left(\dot{\varepsilon}_{12} - \dot{\omega}\right) & \dot{\varepsilon}_{22} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

$\boldsymbol{\varepsilon}$ = strain tensor components
$\boldsymbol{\omega}$ = rotation

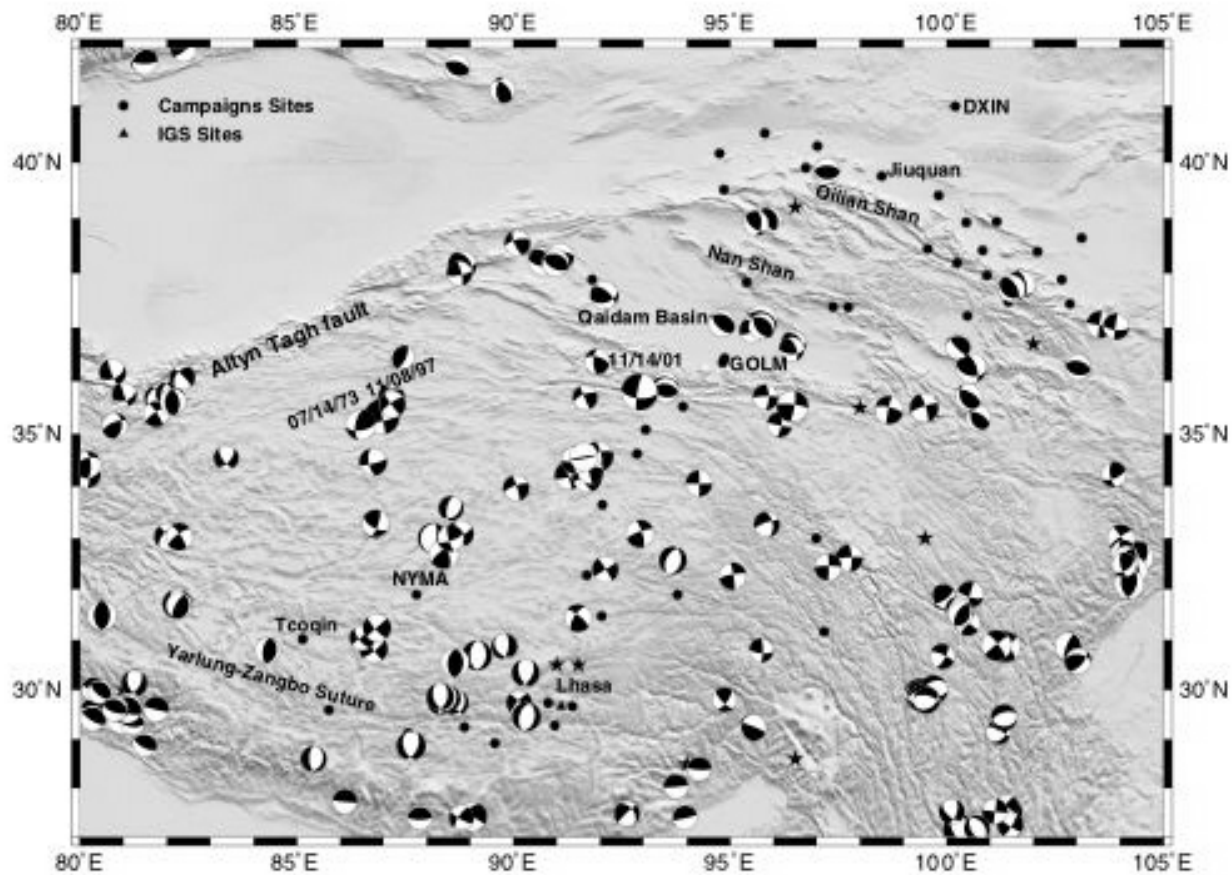
(x, y) = position
v = velocity

Velocity Field Relative to Lhasa

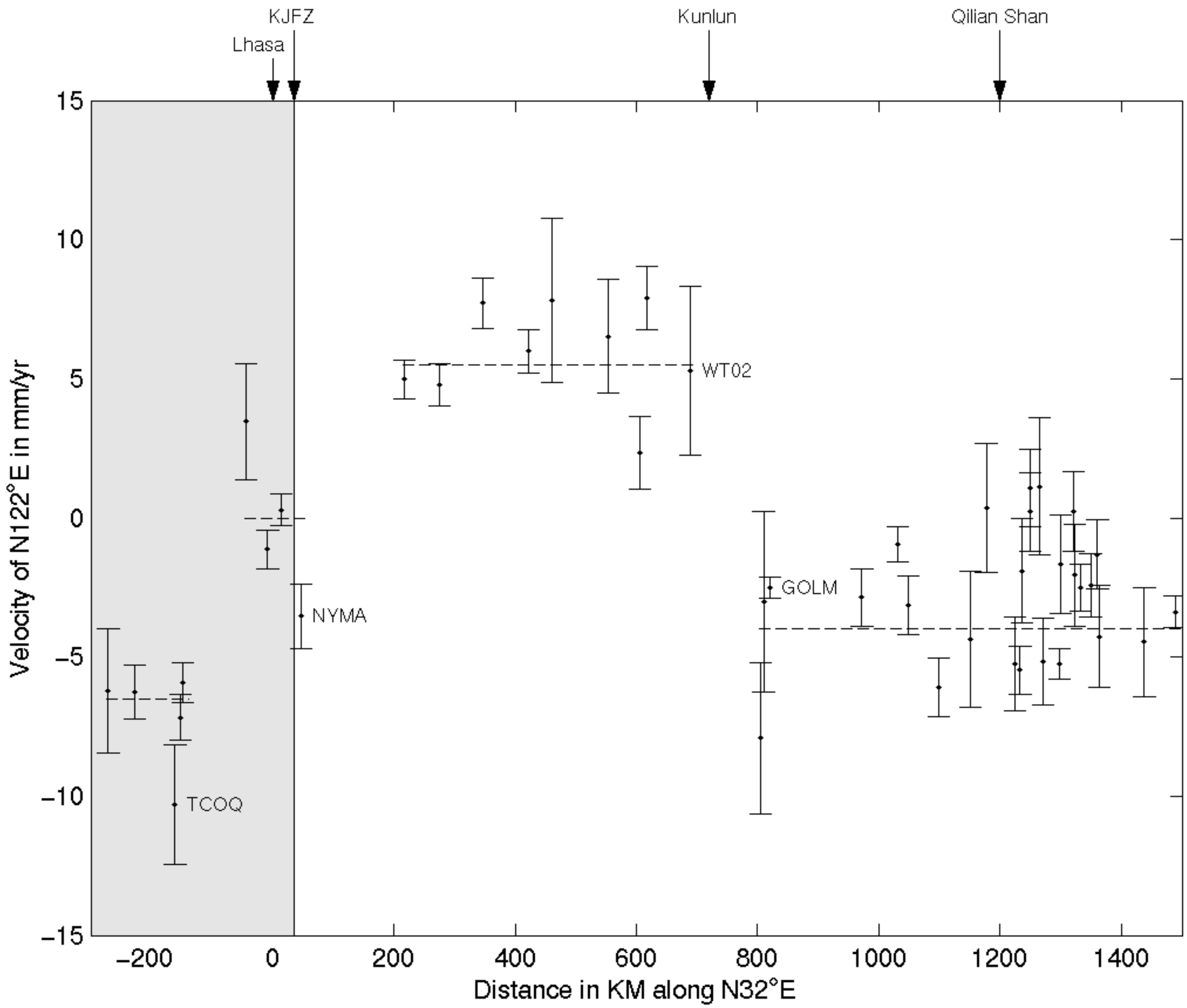



KJFZ
Lhasa
Kunlun
Qilian Shan
−16.4 ± 0.3 nanostrain/yr
NYMA
TCOQ
WT02
GOLM
Velocity of N32°E in mm/yr
Distance in KM along N32°E
5
0
−5
−10
−15
−20
−25
−30
−200
0
200
400
600
800
1000
1200
1400

No Thrust Faults Within Plateau



Coupled ~E-W extension and ~N-S contraction via N-S normal and distributed conjugate strike-slip faulting



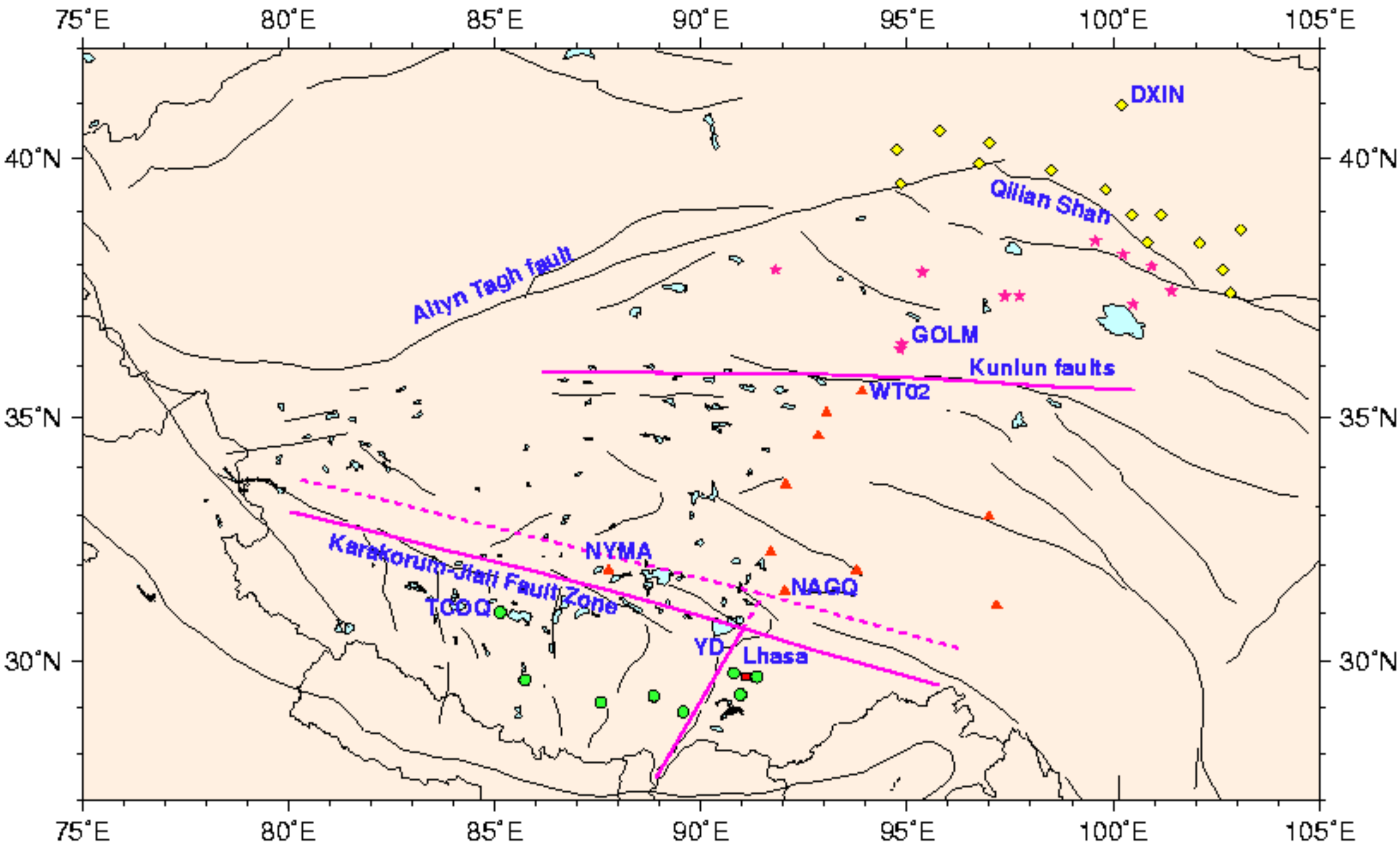
KJFZ
Lhasa
Kunlun
Qilian Shan
15
10
5
0
−5
−10
−15
Velocity of N122°E in mm/yr
−200
0
200
400
600
800
1000
1200
1400
Distance in KM along N32°E
WT02
GOLM
NYMA
TCOQ

Blocks or Continuum?

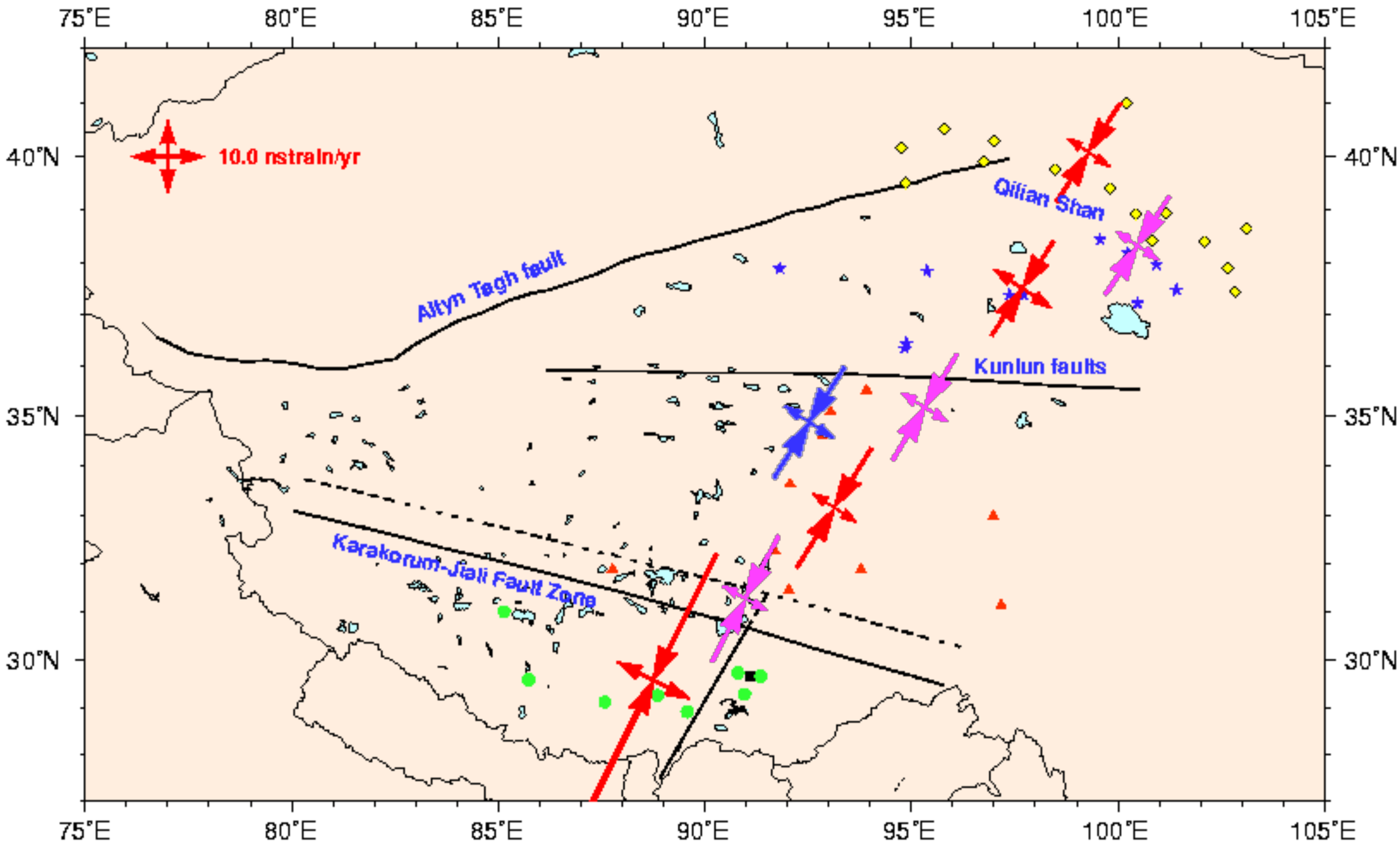
- N32°E component resembles continuum deformation
  - Possibly continuum deformation
  - or distributed slip on many small faults
- N122° component resembles quasi-rigid block motion
- Both at the same time? How can this be?

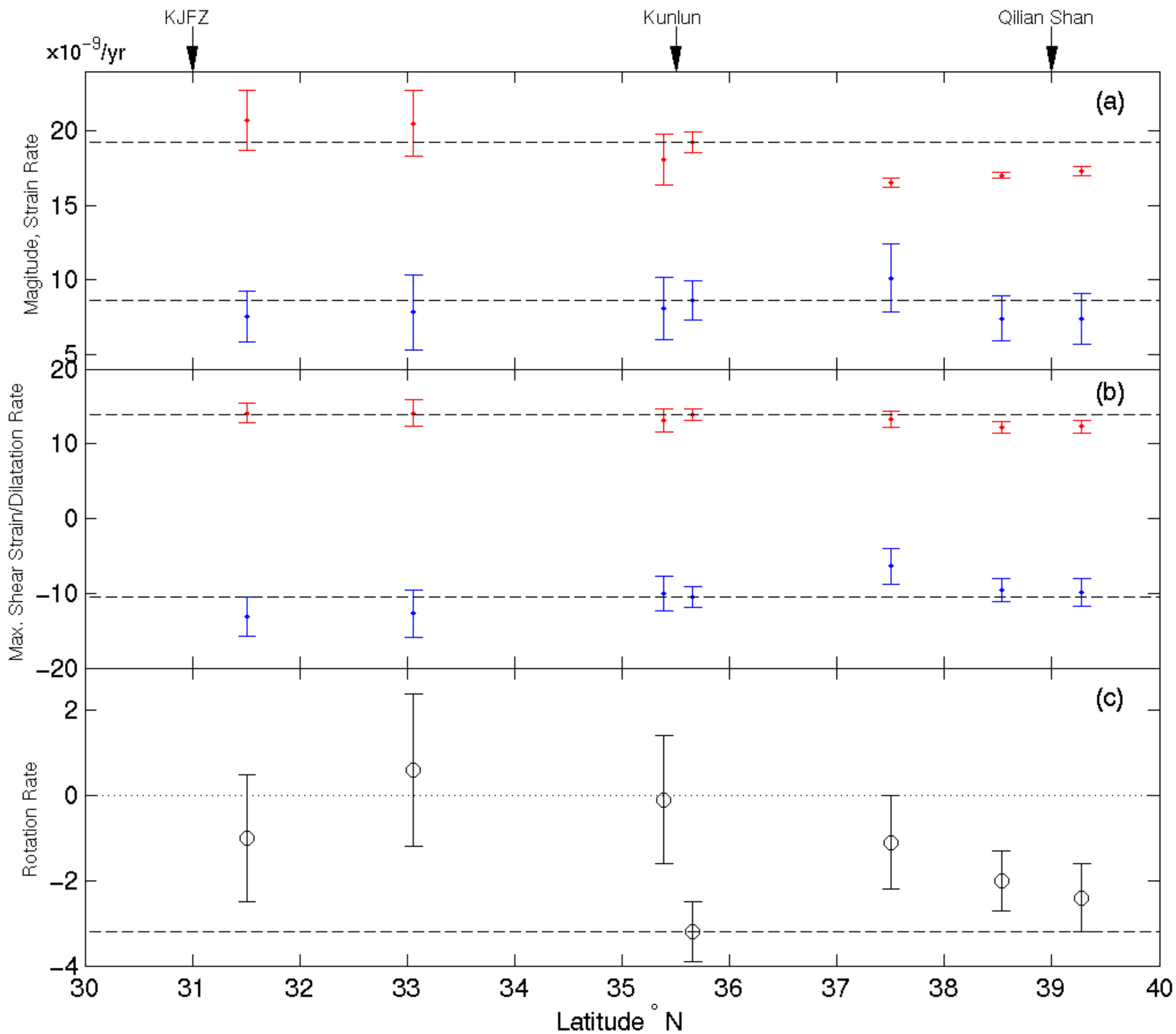
What if blocks are not rigid, but instead deform internally?

Block Boundaries



Uniform Strain Rate

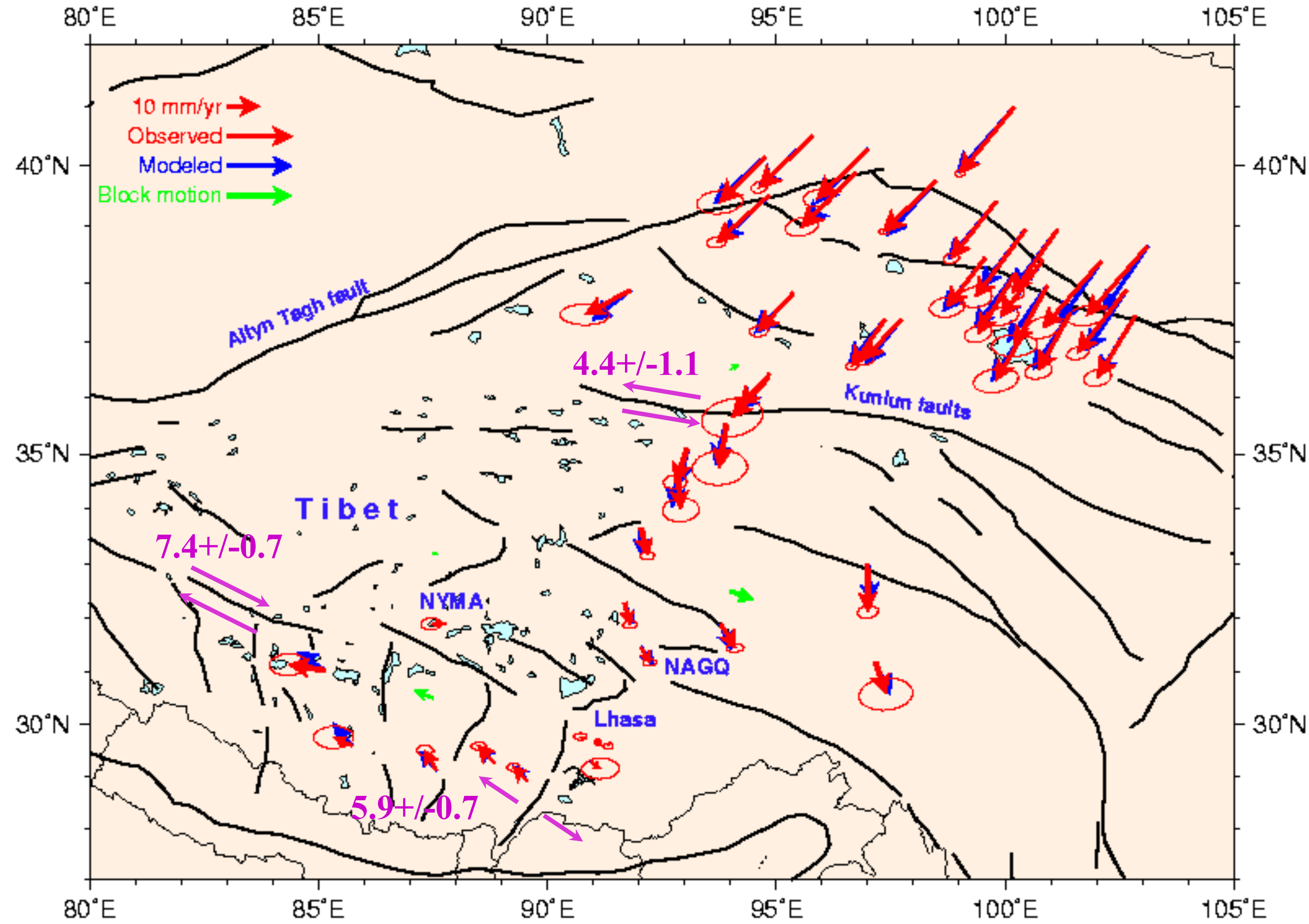




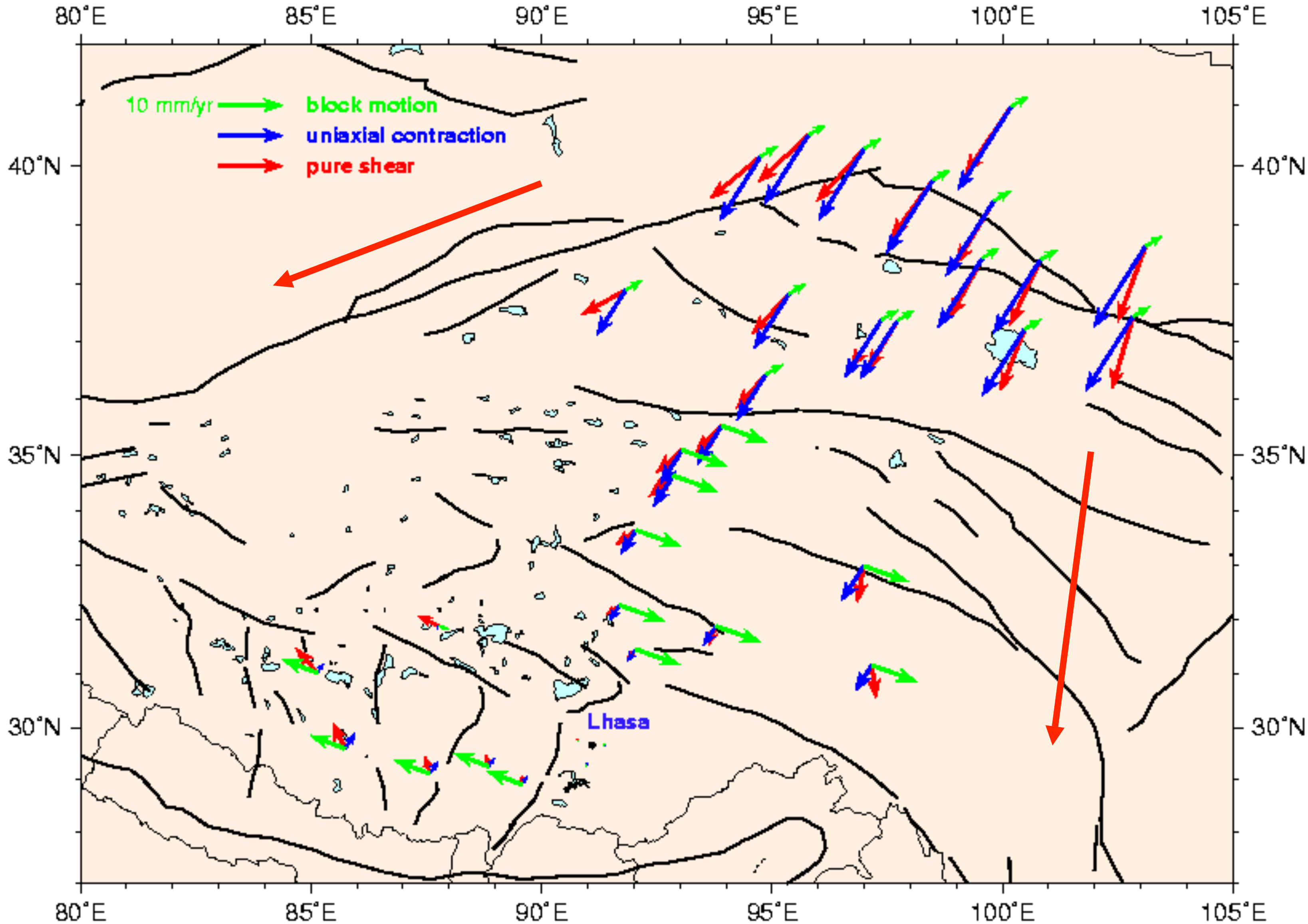
$$\begin{pmatrix} \dot{\varepsilon}_1 & 0 \\ 0 & \dot{\varepsilon}_2 \end{pmatrix} = \dot{\varepsilon}_2 \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} + \dot{\varepsilon}_2 \begin{pmatrix} -1 & 0 \\ 0 & 0 \end{pmatrix}$$

Deforming Block Model

- Based on GPS data from 44 sites
- Four blocks moving relative to each other on major faults, plus uniform strain
  - Block motions are predominantly strike-slip
- Models with spatial variations in strain do not fit significantly better than uniform strain
- Models with all slip concentrated on a few faults fit worse than the deforming block model.



80°E
85°E
90°E
95°E
100°E
105°E
40°N
35°N
30°N
10 mm/yr
Observed
Modeled
Block motion
Altyn Tagh fault
Kunlun faults
Tibet
4.4+/-1.1
7.4+/-0.7
5.9+/-0.7
NYMA
NAGQ
Lhasa



80°E
85°E
90°E
95°E
100°E
105°E
40°N
35°N
30°N
10 mm/yr
block motion
uniaxial contraction
pure shear
Lhasa

Chen et al. Deforming Block Model