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Integrating Geodetic Measurements Into a Consistent Estimate of Regional Deformation

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IAG-IASPEI-WORKSHOP
ICTP, TRIESTE, ITALY
January 16-22, 2005

Outline

- Integrating geodetic measurements to deduce station displacements of a regional network
- Optimal estimation of regional strain rates from geodetic station velocities
- Optimal estimation of block motion and fault slip rates from geodetic station velocities

Integrating Geodetic Measurements to Deduce Station Displacements of a Regional Network

Challenges to Geodetic Measurement Integration

- Combination of heterogeneous data sets, e.g. GPS, EDM, and Triangulation
- GPS data collected with different modes, e.g. continuous vs campaign
- Mixing of receiver/antenna types during a survey
- Multiple types of receiver/antenna used between survey epochs
- No reliable satellite orbits to use pre- and during early IGS years
- Non-Gaussian data errors

GPS Data Analysis Procedures: a GAMIT-GLOBK-QOCA Approach

Daily GPS data processing using GAMIT softwares

- Data included: regional survey-mode measurements + data from regional fiducial (continuous) sites
- Parameters to estimate: station positions, tropospheric delay parameters, satellite orbits, ambiguity numbers, polar motion/ut1 (pmu) parameters, etc.
- Initial a prioris: IGS orbits, station positions of meter level accuracy (run iteration if initial positions are poor)
- Constraints: loose constraints for station positions and satellite orbits
- Result: daily solutions of loosely-constrained station, orbital, and pmu parameters with full their variance/covariance matrices (SINEX or h-files).

Daily solution combination using GLOBK softwares

Two ways to tie regional solutions with a global reference frame, with/out using tightly constrained IGS orbits. We find that IGS orbits are less reliable during its early years (mid 1990s). Therefore to achieve highest accuracy possible it is desirable to solve for the orbits oneself.

To accomplish this one can take advantage of existing global IGS daily solutions, e.g. SINEX files (h-files) reprocessed by SOPAC (Satellite Orbit Processing and Analysis Center, Scripps Institution of Oceanography, UCSD), and use the GLOBK softwares to combine the regional and global daily solutions, and output the combined solutions for position and pmu parameters (with the orbital parameters suppressed), plus their full variance/covariance matrices.

To make subsequent estimation more efficient, one can consider to aggravate several weeks of daily solutions together, loosely constrained, again using the GLOBK softwares.

QOCA softwares

- **QOCA (Quasi-Observation Combination Analysis, http://gipsy.jpl.nasa.gov) was designed and developed by Danan Dong at the Jet Propulsion Lab, NASA.**
- **QOCA is a software package that combines various loosely constrained solutions for geodetic site coordinates and velocities (as quasi observations) to obtain crustal deformation information.**
- **QOCA is used as the post-processing software package. It can combine space-geodetic quasi-observations (GPS, VLBI, SLR, ... etc.) and terrestrial geodetic survey quasi-observations (EDM, triangulation, leveling, ... etc.).**

GPS data modeling using QOCA softwares

- To estimate station positions, velocities, and coseismic displacements (if necessary) from combined daily solution files.
- In order to accommodate temporally correlated errors (such as those associated with orbital, seasonal, and atmospheric disturbances), it is recommended to allow a random-walk type perturbation to station positions in a Karman filtering process (e.g. assigning 1, 1, and 10 mm^2/yr increment for the variances of the north, east, and up components of all the sites).

Combination of GPS with EDM, VLBI, and/or triangulation data

Such a combination can be done in 2 steps:

(a) processing the non-GPS data separately to obtain loosely constrained position solutions with full variance/covariance matrices, (loose a priori constraints are usually necessary to suppress rank deficiency);

(b) combining these solutions with GPS solutions using the QOCA softwares

Establishment of reference frame

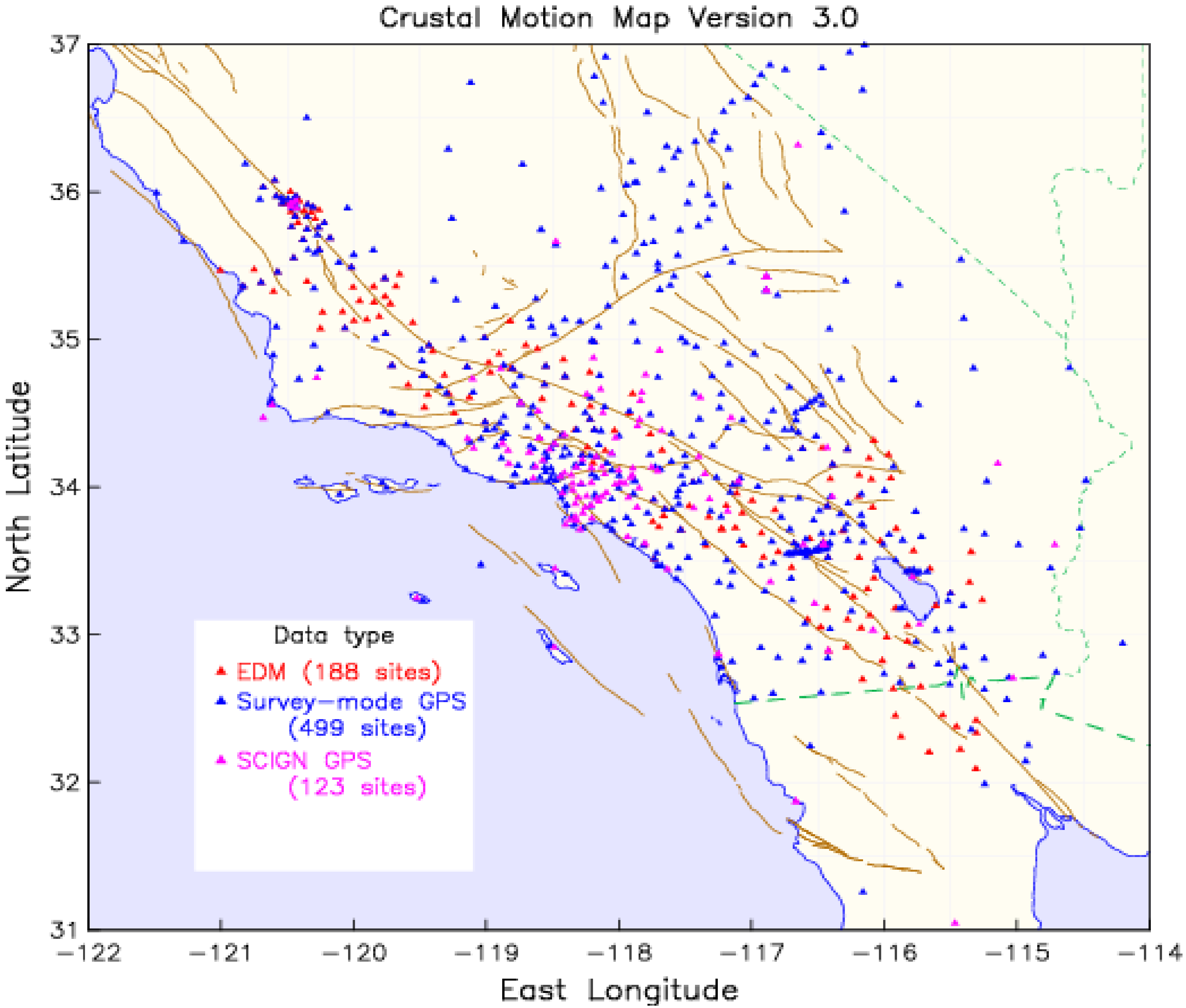
Final solution can be obtained by linking velocities of selected fiducial sites to their values under the ITRF2000 reference frame with finite uncertainties (e.g. 2, 2, 5 mm/yr for the east, north, and up components respectively).

Some useful features of QOCA softwares

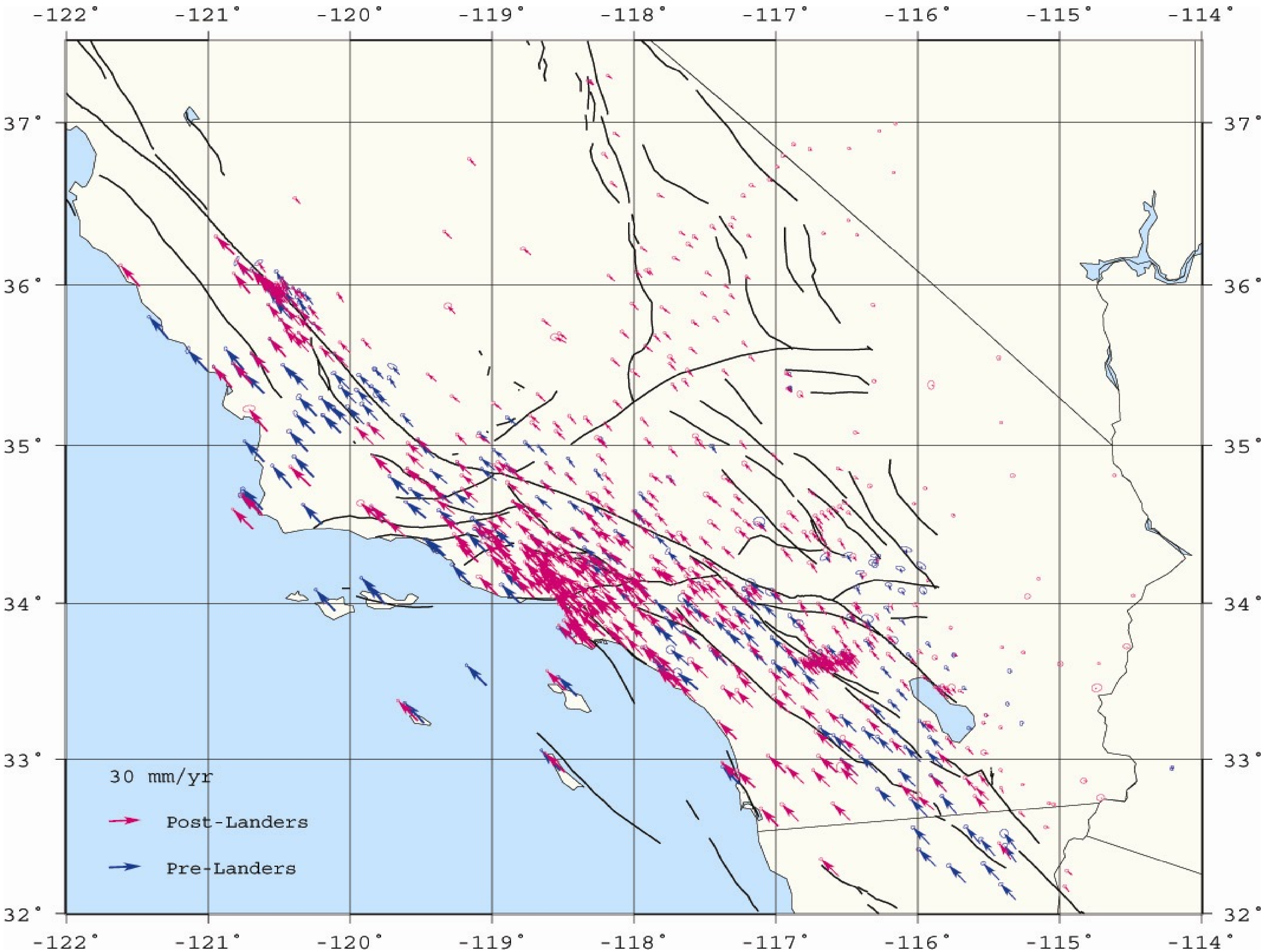
- Allowing postseismic velocity to differ from pre-seismic velocity
- Providing warnings to specific observational epochs/stations for unusually large postfit residuals
- Allowing reweighting of quasi-observation data files
- Providing estimation of reduced data postfit chi-square with proper counting of number of degree of freedom in parameter space in a Karman filter process
- Allowing visual inspection of postfit time series, important for spotting outliers
- Allowing estimation of antenna phase center change

Example I: Southern California Earthquake Center Crustal Motion Map version 3.0 (SCEC CMM3)

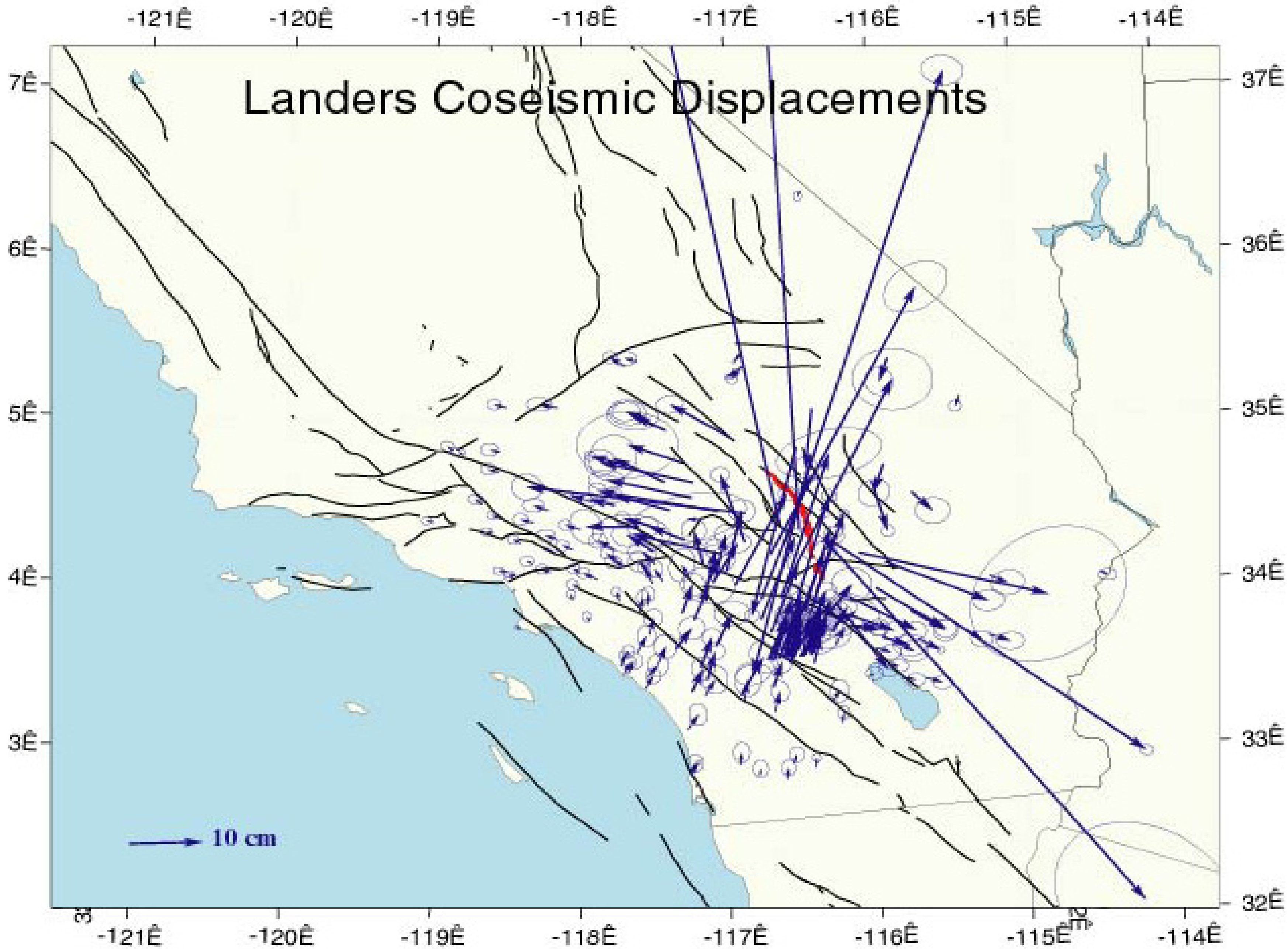
http://jacinto.ucsd.edu/cmm3



Crustal Motion Map Version 3.0
North Latitude
East Longitude
37
36
35
34
33
32
31
−122
−121
−120
−119
−118
−117
−116
−115
−114
Data type
EDM (188 sites)
Survey−mode GPS (499 sites)
SCIGN GPS (123 sites)



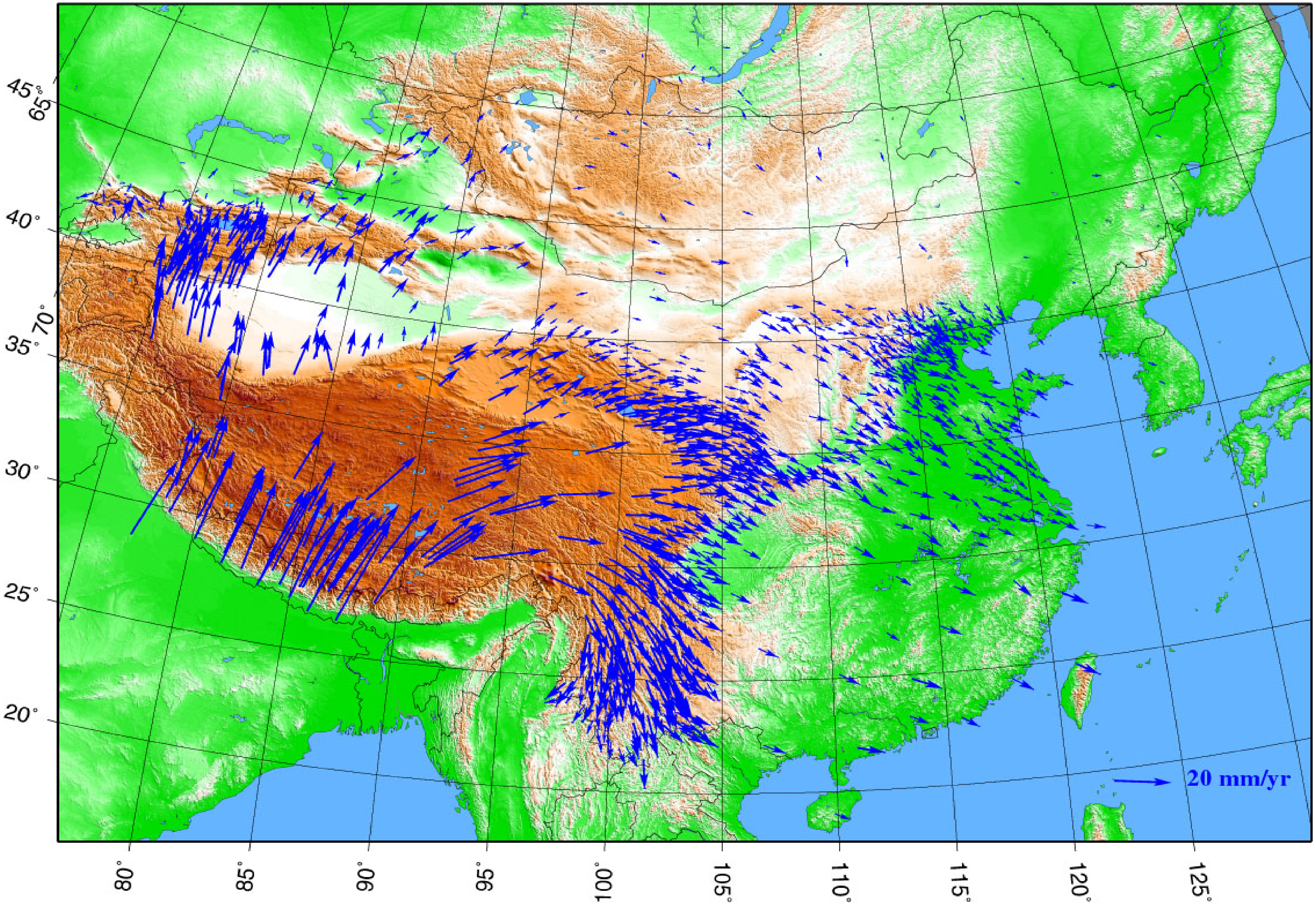
-122°
-121°
-120°
-119°
-118°
-117°
-116°
-115°
-114°
37°
36°
35°
34°
33°
32°
30 mm/yr
Post-Landers
Pre-Landers



Landers Coseismic Displacements
10 cm
-121Ê
-120Ê
-119Ê
-118Ê
-117Ê
-116Ê
-115Ê
-114Ê
37Ê
36Ê
35Ê
34Ê
33Ê
32Ê
7Ê
6Ê
5Ê
4Ê
3Ê

Example II: Crustal Motion Observation Network of China

GPS Velocity Field w.r.t. Eurasia Reference Frame



Optimal Estimation of Horizontal Strain Rates from Geodetic Station Velocities

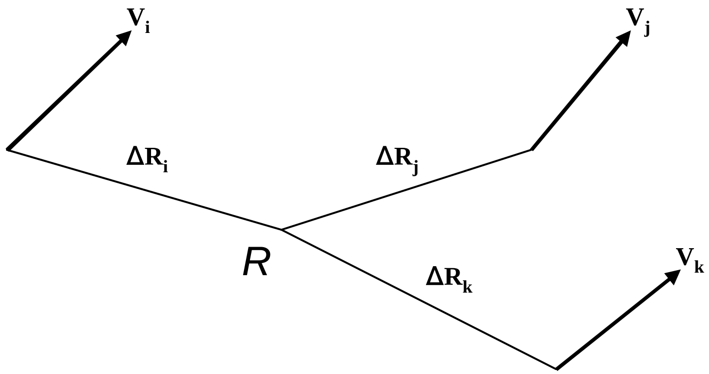
Model strain rates as continuous functions using a modified least-squares method.

Uniqueness of the method:

- Requires no assumptions of stationary of deformation field and uniform variance of the data that many other methods do;
- Implements the degree of smoothing based on *in situ* data strength.

At each location point $\underline{R}$, assuming a uniform strain rate field, the strain rates and the geodetic data can be linked by a linear relationship:

$$\underline{d} = A\,\underline{m} + \underline{\varepsilon}$$



$$\begin{bmatrix} Vx_1 \\ Vy_1 \\ Vx_2 \\ Vy_2 \\ \ldots \\ Vx_n \\ Vy_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & \Delta x_1 & \Delta y_1 & 0 & \Delta y_1 \\ 0 & 1 & 0 & \Delta x_1 & \Delta y_1 & -\Delta x_1 \\ 1 & 0 & \Delta x_2 & \Delta y_2 & 0 & \Delta y_2 \\ 0 & 1 & 0 & \Delta x_2 & \Delta y_2 & -\Delta x_2 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 1 & 0 & \Delta x_n & \Delta y_n & 0 & \Delta y_n \\ 0 & 1 & 0 & \Delta x_n & \Delta y_n & -\Delta x_n \end{bmatrix} \begin{bmatrix} Ux \\ Uy \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{yy} \\ \omega \end{bmatrix} + \begin{bmatrix} \varepsilon_{x1} \\ \varepsilon_{y1} \\ \varepsilon_{x2} \\ \varepsilon_{y2} \\ \ldots \\ \varepsilon_{xn} \\ \varepsilon_{yn} \end{bmatrix}$$

Ux, Uy: on spot velocity components

τxx, τxy, τyy: strain rate components

ω: rotation rate

$$\underline{d} = A\,\underline{m} + \underline{\varepsilon}$$

reconstitute the inverse problem with a weighting matrix *B*:

$$B\,\underline{d} = B\,A\,\underline{m} + \underline{\varepsilon}$$

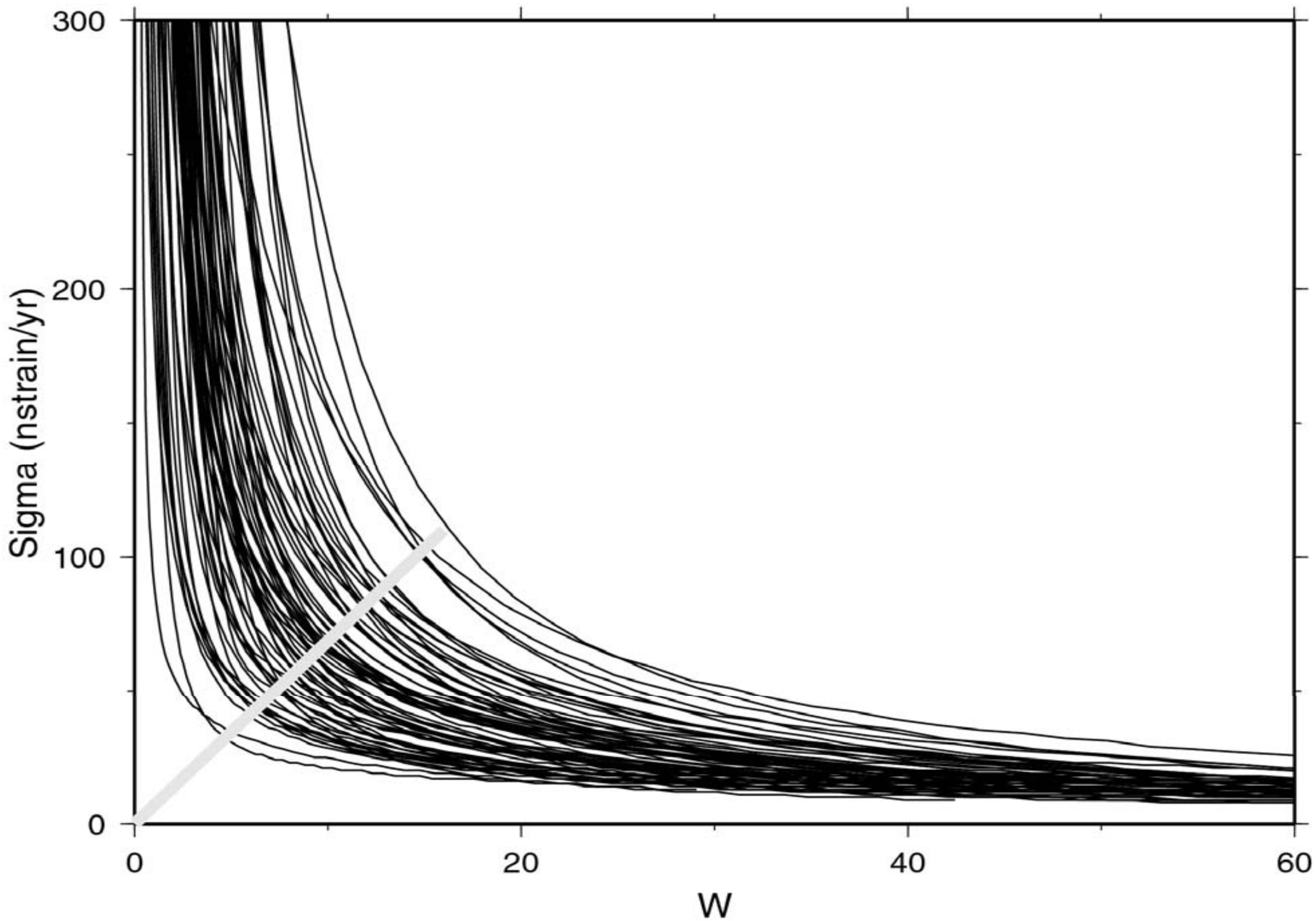
where *B* is a diagonal matrix whose *i*-th diagonal term is $exp(-\Delta R_i^2/D^2)$ and $\underline{\varepsilon} \sim N(0, E)$.

$$\underline{m} = (A^t\,B\,E^{-1}\,B\,A)^{-1}\,A^t\,B\,E^{-1}\,B\,\underline{d}$$

D is a smoothing distance.

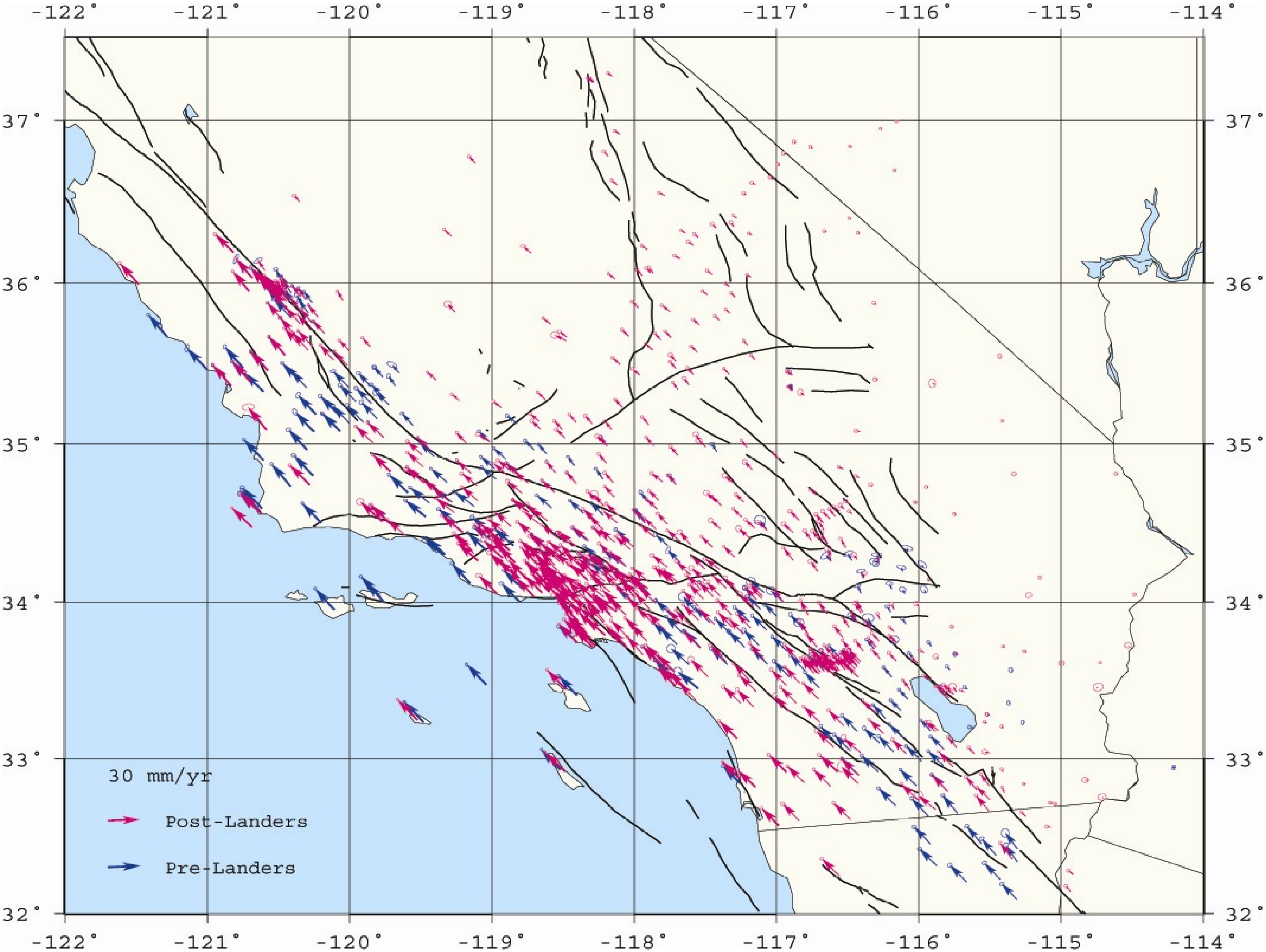
How to make a proper assignment of *D*?

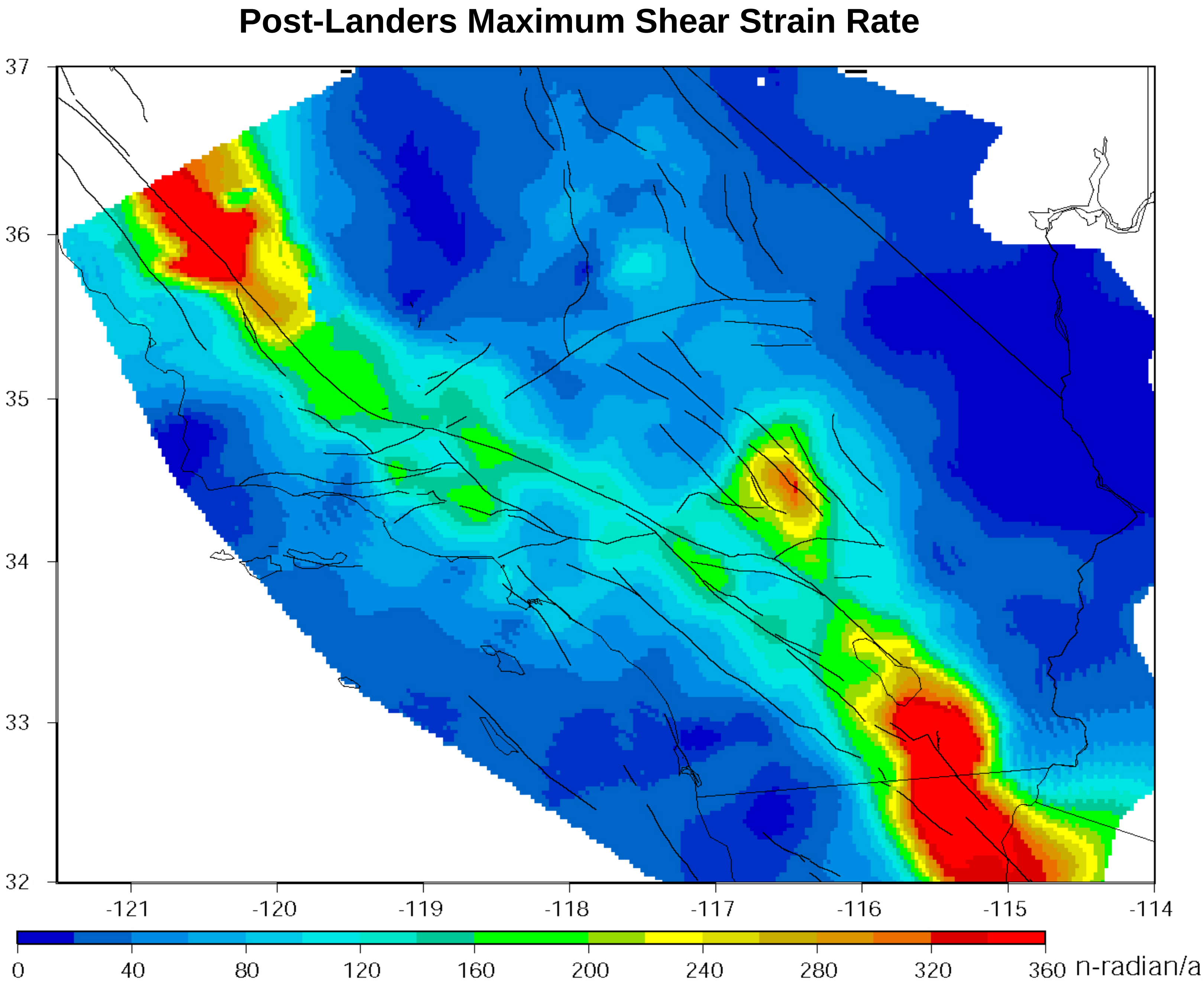
Trade-off between total weight W and strain rate uncertainty σ



$W = \Sigma_i \, exp(-\Delta R_i^2/D^2)$

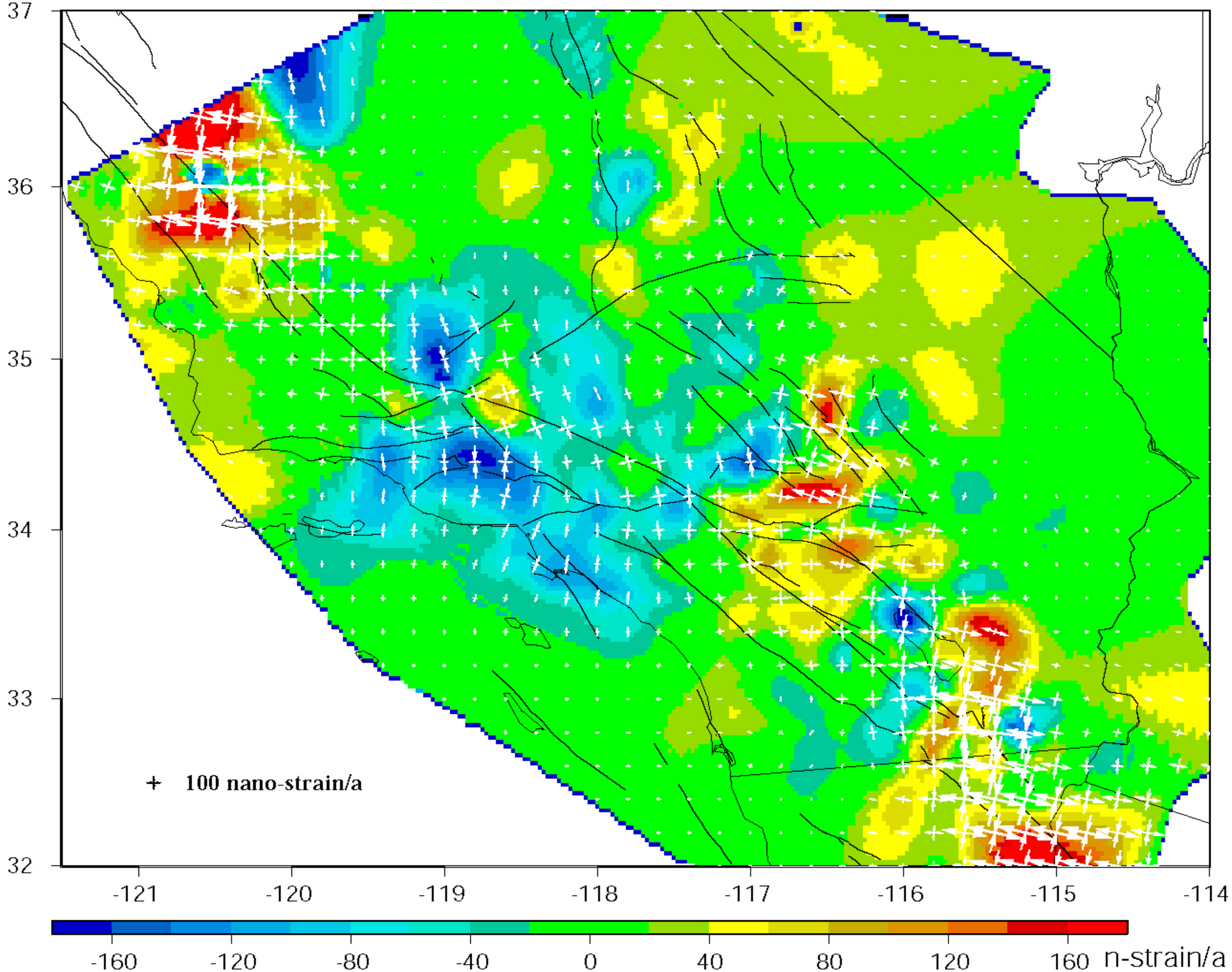
Example: Strain rate estimation from SCEC CMM3 (Post-Landers)



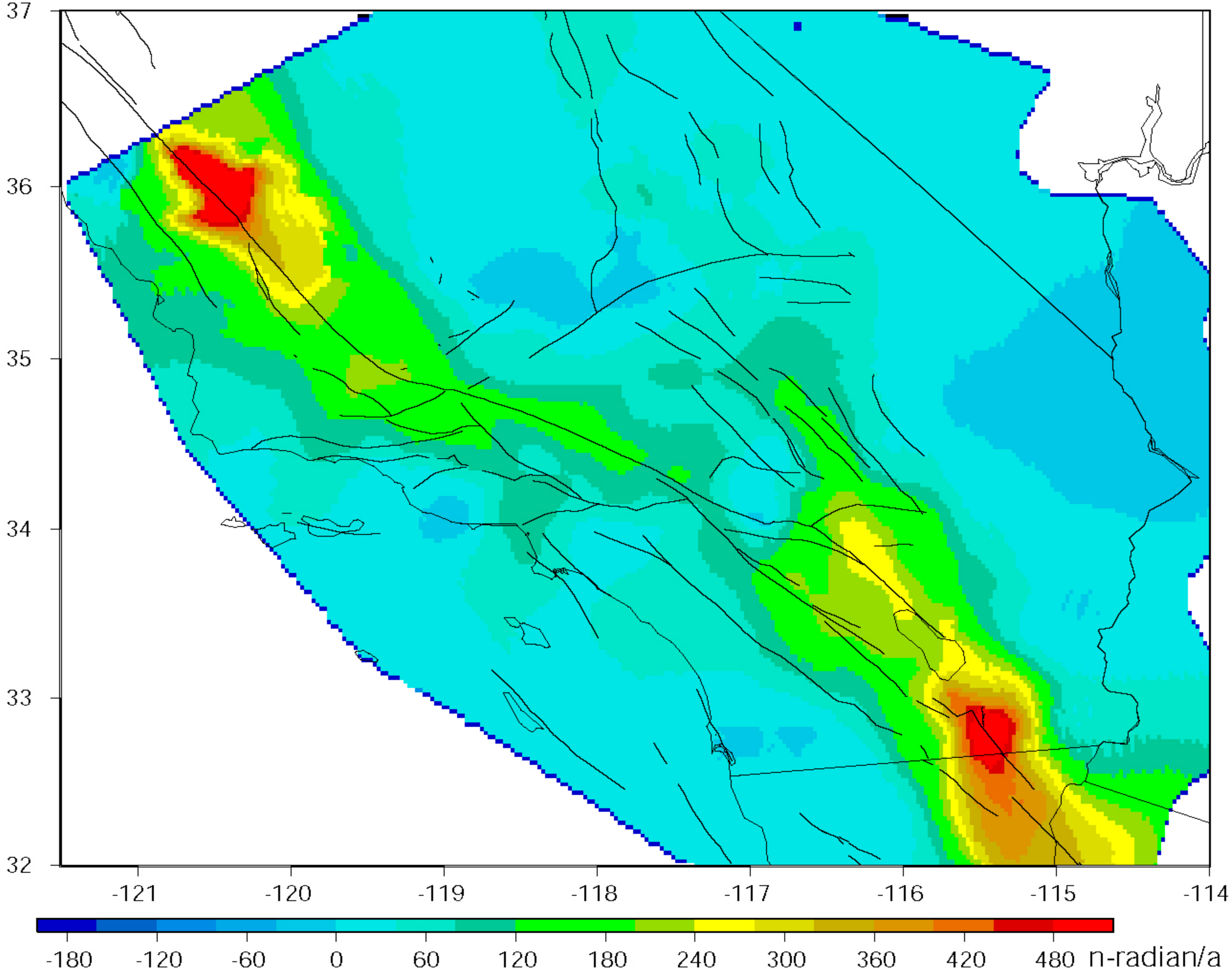


Post-Landers Maximum Shear Strain Rate
37
36
35
34
33
32
-121
-120
-119
-118
-117
-116
-115
-114
0
40
80
120
160
200
240
280
320
360
n-radian/a

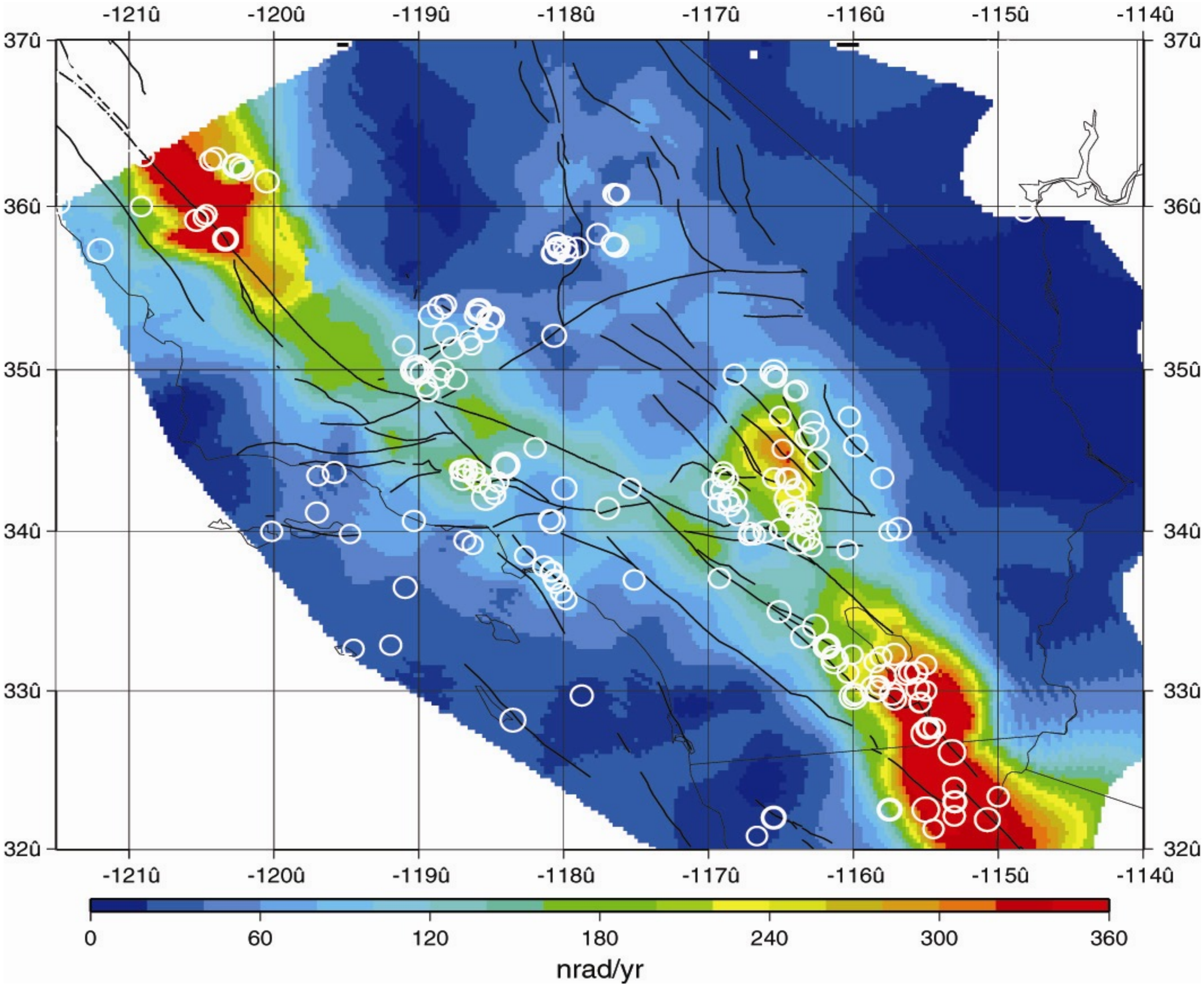
Post-Landers Principal Strain Rate and Dilatation Rate

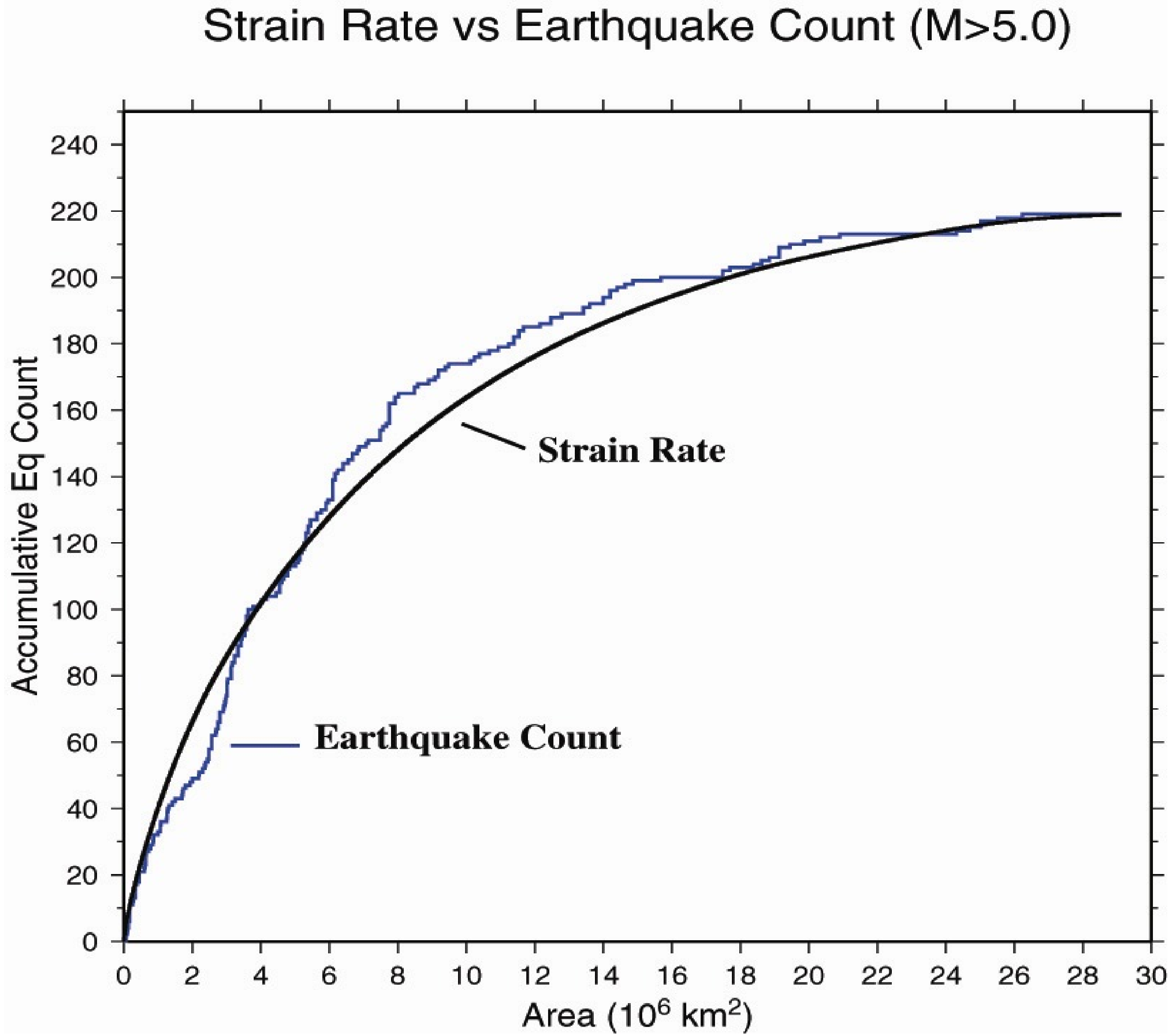


Post-Landers Rotation Rate



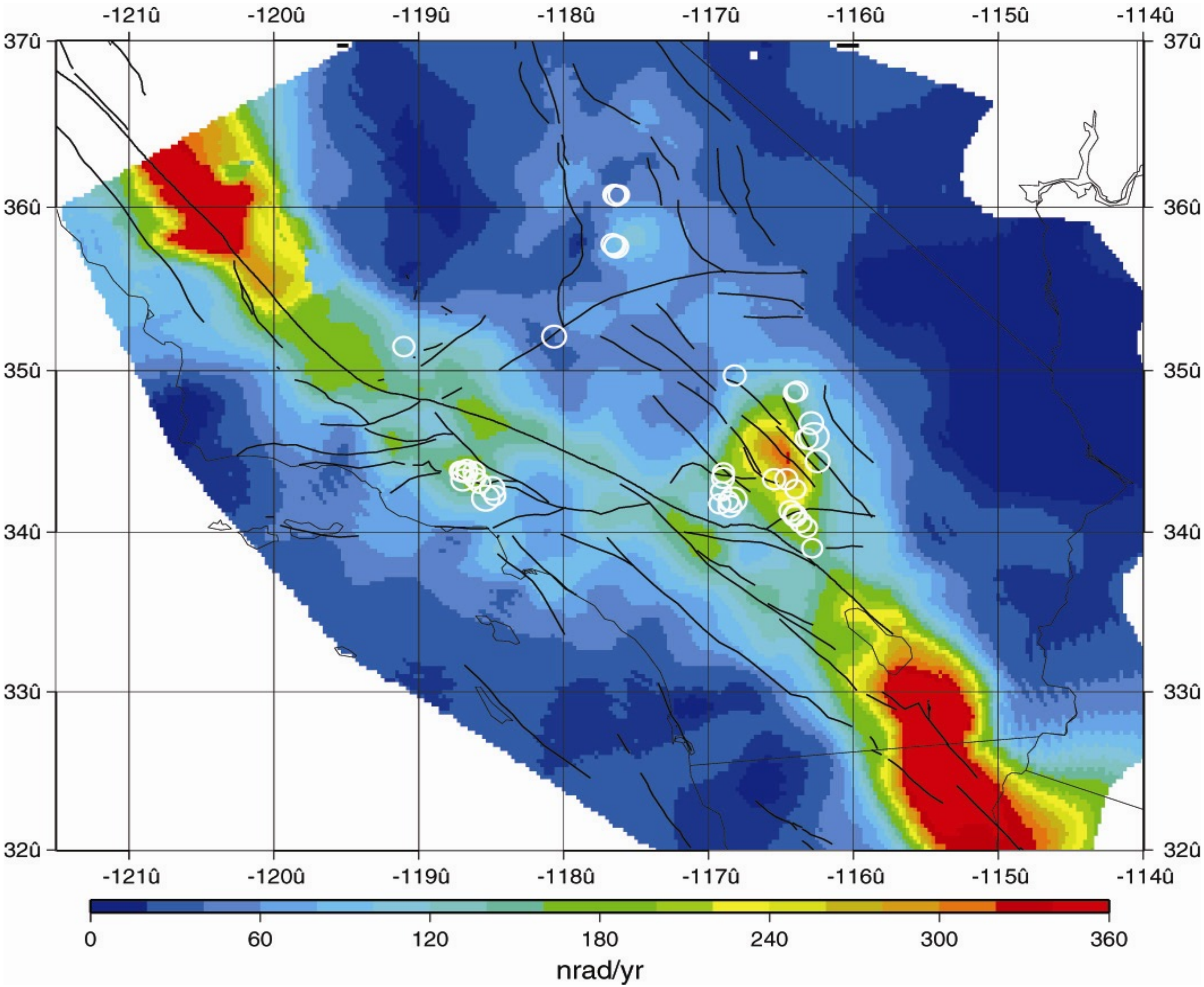
Post-Landers Maximum Strain Rate and Earthquakes of M>5.0 1950-2000

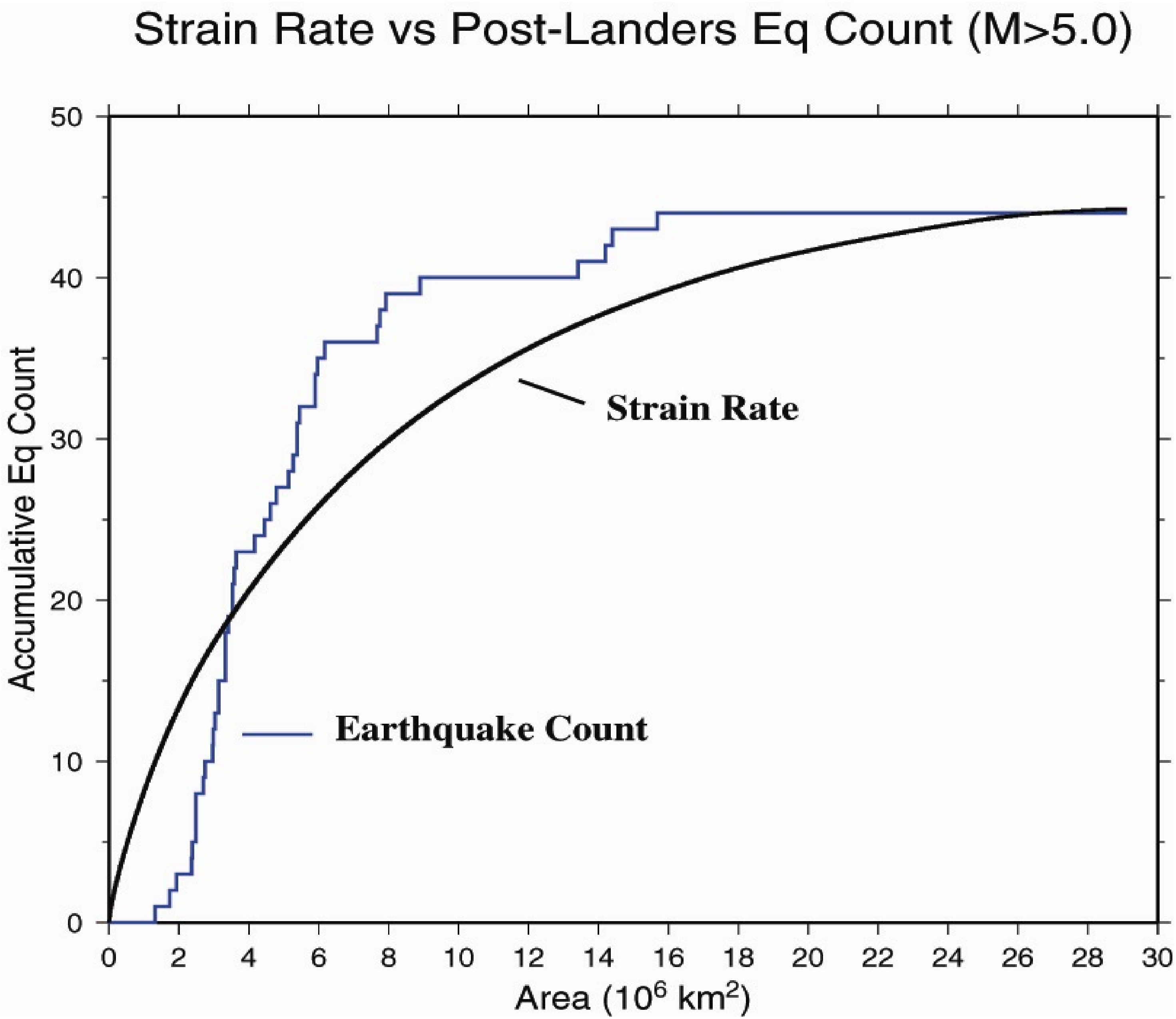




Strain Rate vs Earthquake Count (M>5.0)
Accumulative Eq Count
Area (10^6 km^2)
Strain Rate
Earthquake Count
0
20
40
60
80
100
120
140
160
180
200
220
240
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

Post-Landers Maximum Shear Strain Rate and Earthquakes of M>5.0 1992.5-2004.0



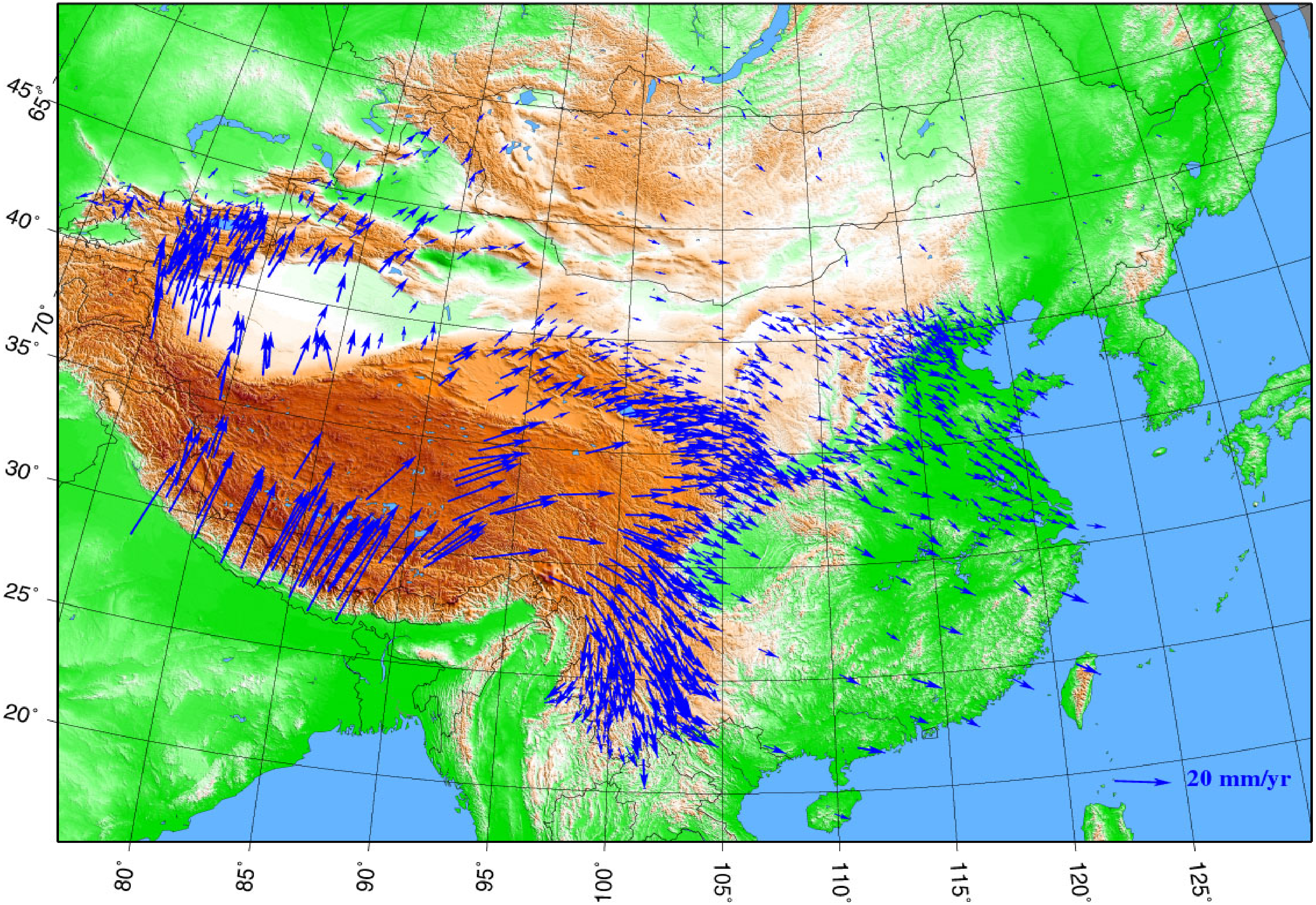

Strain Rate vs Post-Landers Eq Count (M>5.0)
Accumulative Eq Count
Area (10^6 km^2)
Strain Rate
Earthquake Count
0
10
20
30
40
50
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

Optimal Estimation of Block Motion and Fault Slip Rates From Geodetic Station Velocities

--taking advantage of known information about regional tectonic setting, to optimally estimate deformation parameters such as block motion and fault slip rates

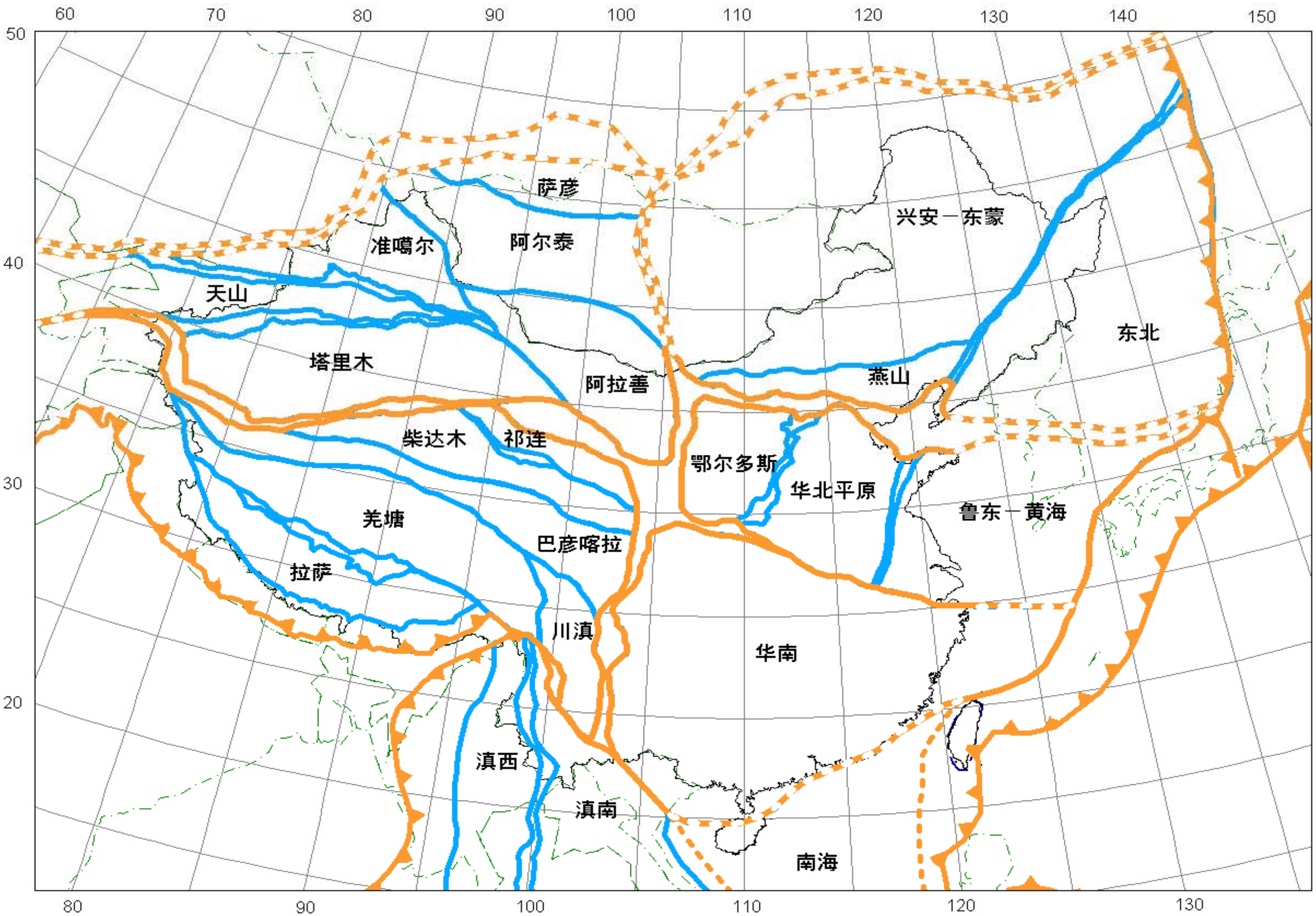
Approach I:
Deformable block motion

Example:
Continental east Asia



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

Starting Active Tectonic Block Model (Zhang *et al.*, Science in China, 2003)

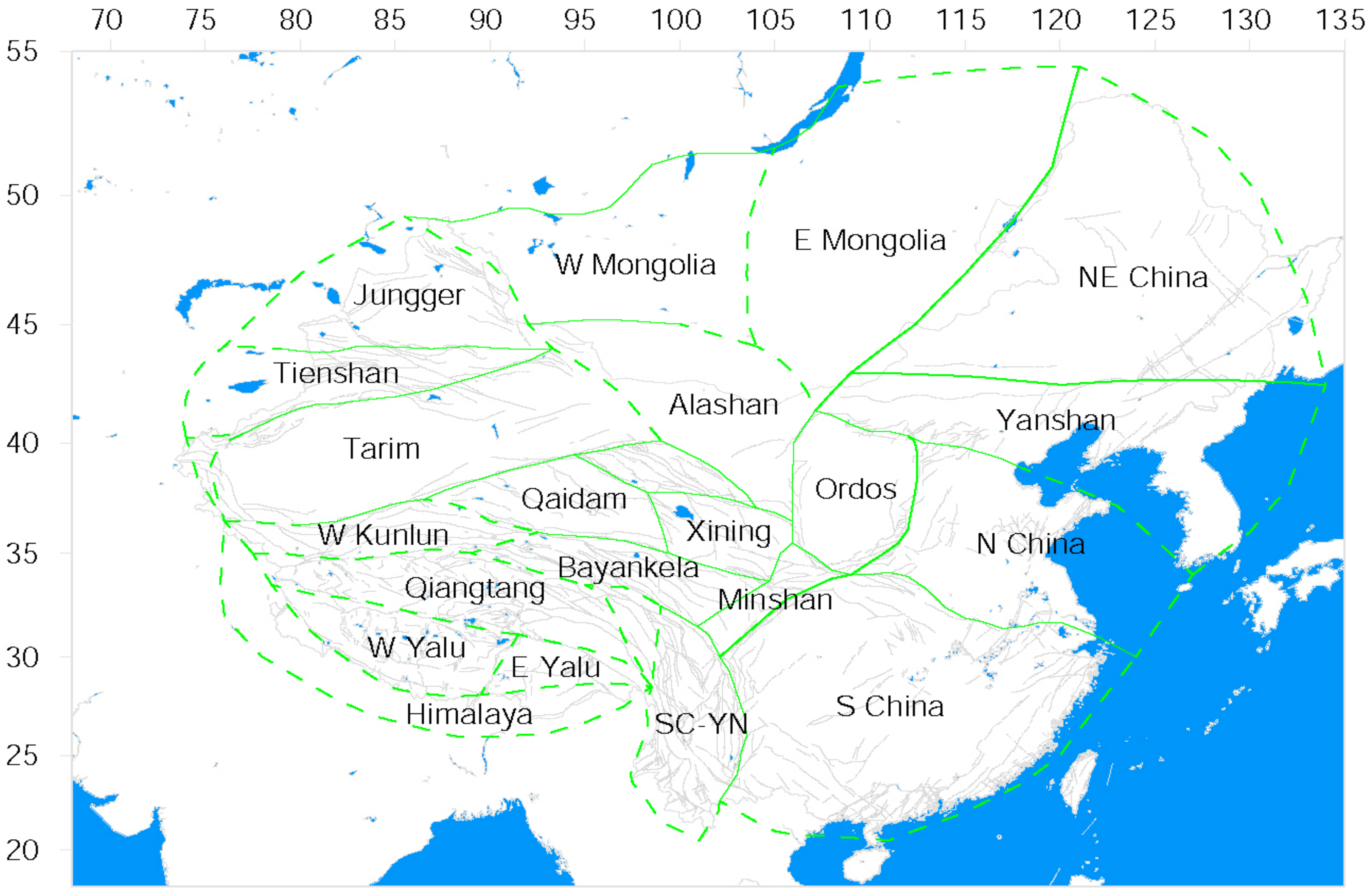


Model assumptions

- Deformation is manifested by: (a) relative block motion, and (b) uniform internal deformation within blocks.
- Elastic strain accumulation at block boundaries is ignored (for convenience if most of the sites are away from fault zones).

--Model parameters are justified and solved for through an iterative procedure

Starting Block Motion Model



Tectonic Block Model Realization

- **Starting model is composed of 22 blocks and developed based on: (a) geologically derived Active Tectonic Block Model (Zhang et al., 2003), and (b) deformation patterns identified from GPS velocity field.**
- **Model is refined through an iterative process:**

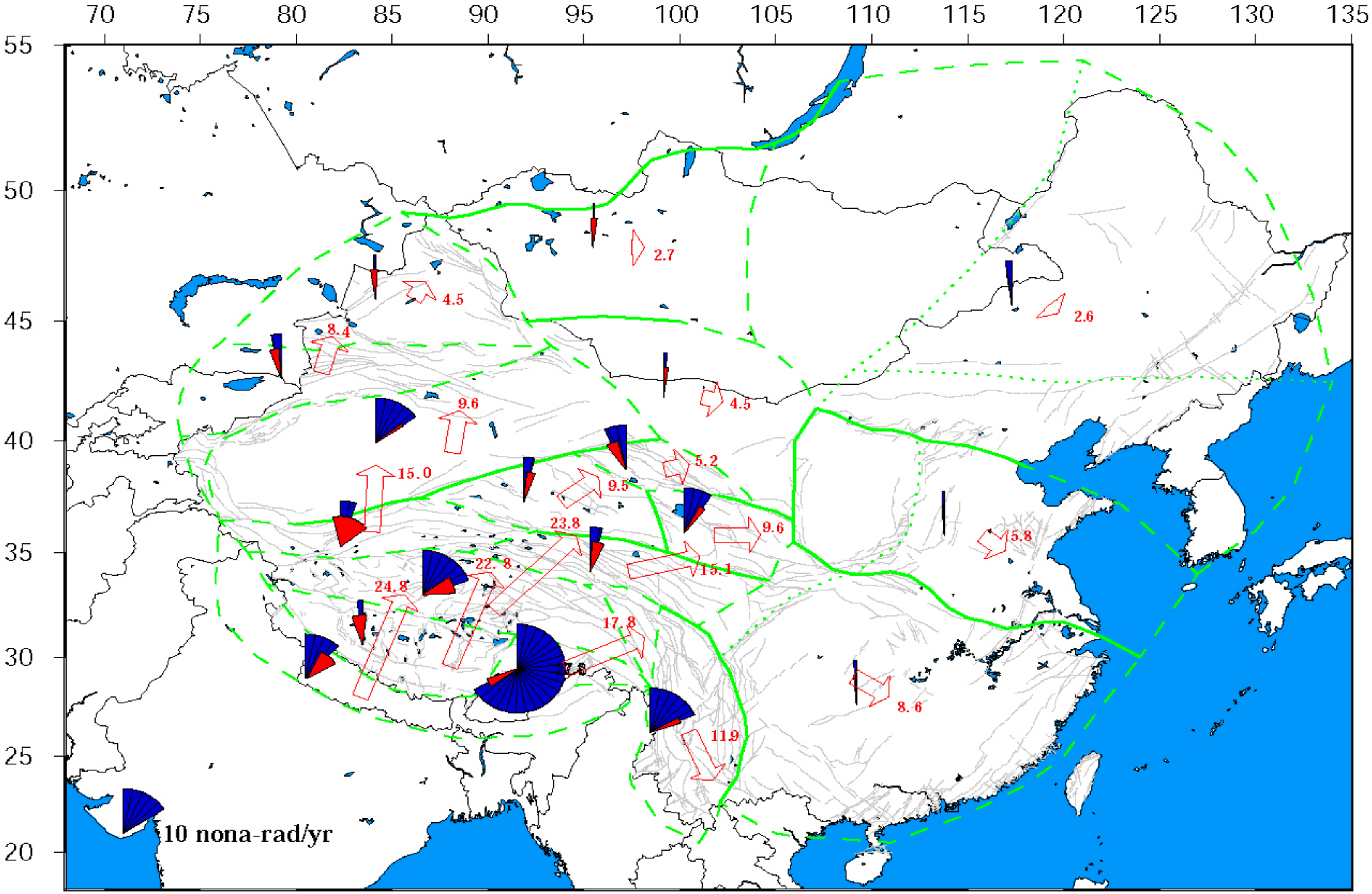
(1) Assuming rigid blocks, estimate angular velocity of each block using least squares and obtain postfit chi-squares $X_{rig\_i}^2$;

(2) Assuming deforming blocks, estimate angular velocity and uniform strain rate for each block using least squares and obtain postfit chi-squares $X_{def\_i}^2$;

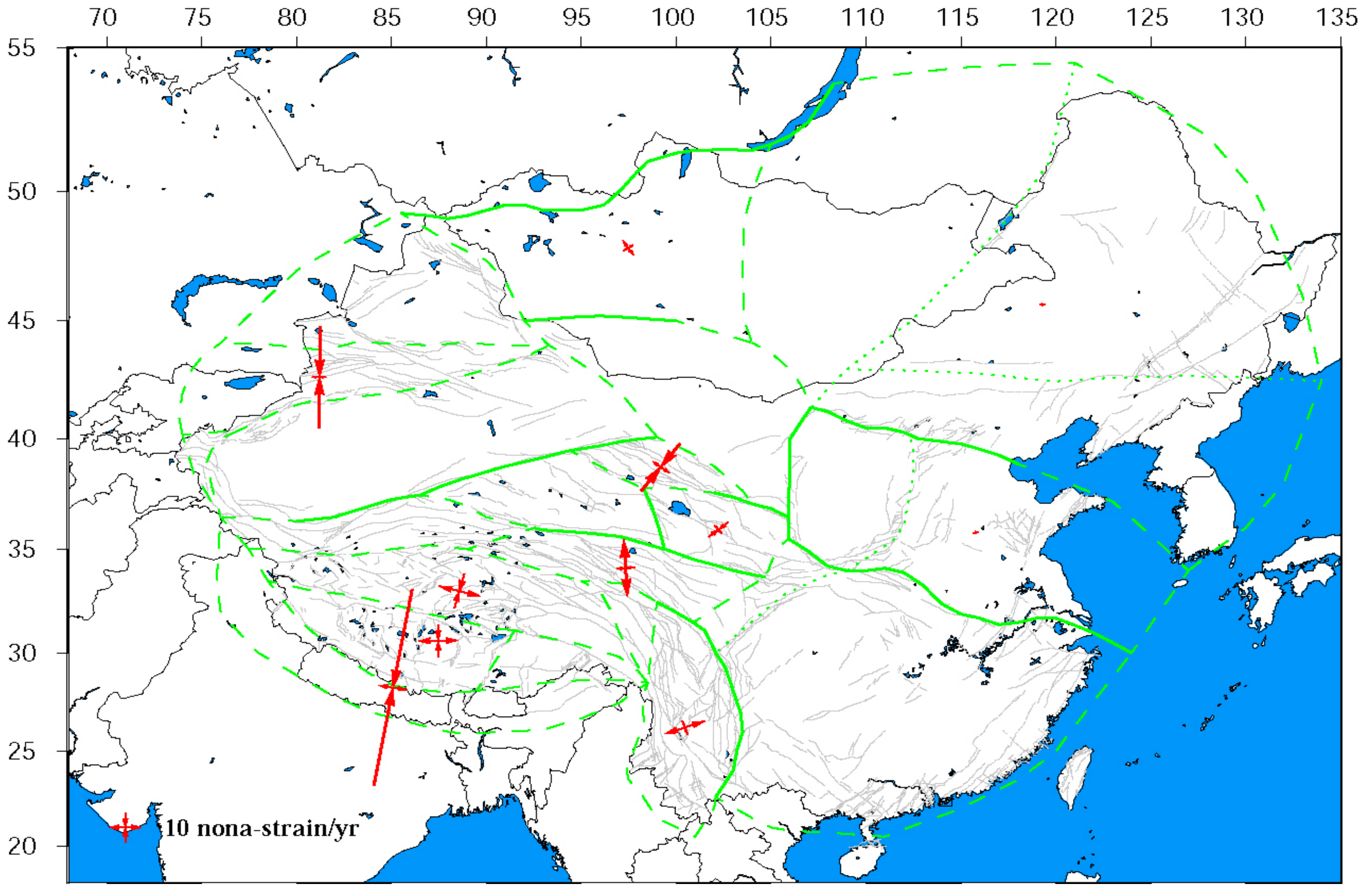
(3) Use F-test on $X_{rig\_i}^2$ and $X_{def\_i}^2$ to justify the necessity of 3 additional strain parameters, and choose between rigid or deforming block model;

(4) For each pair of neighboring blocks *a* and *b* of same kind, estimate their joint angular velocity (and strain rates as well for deforming blocks) and obtain postfit X_{ab}^2 , use F-test to determine if the two neighboring blocks should be merged.

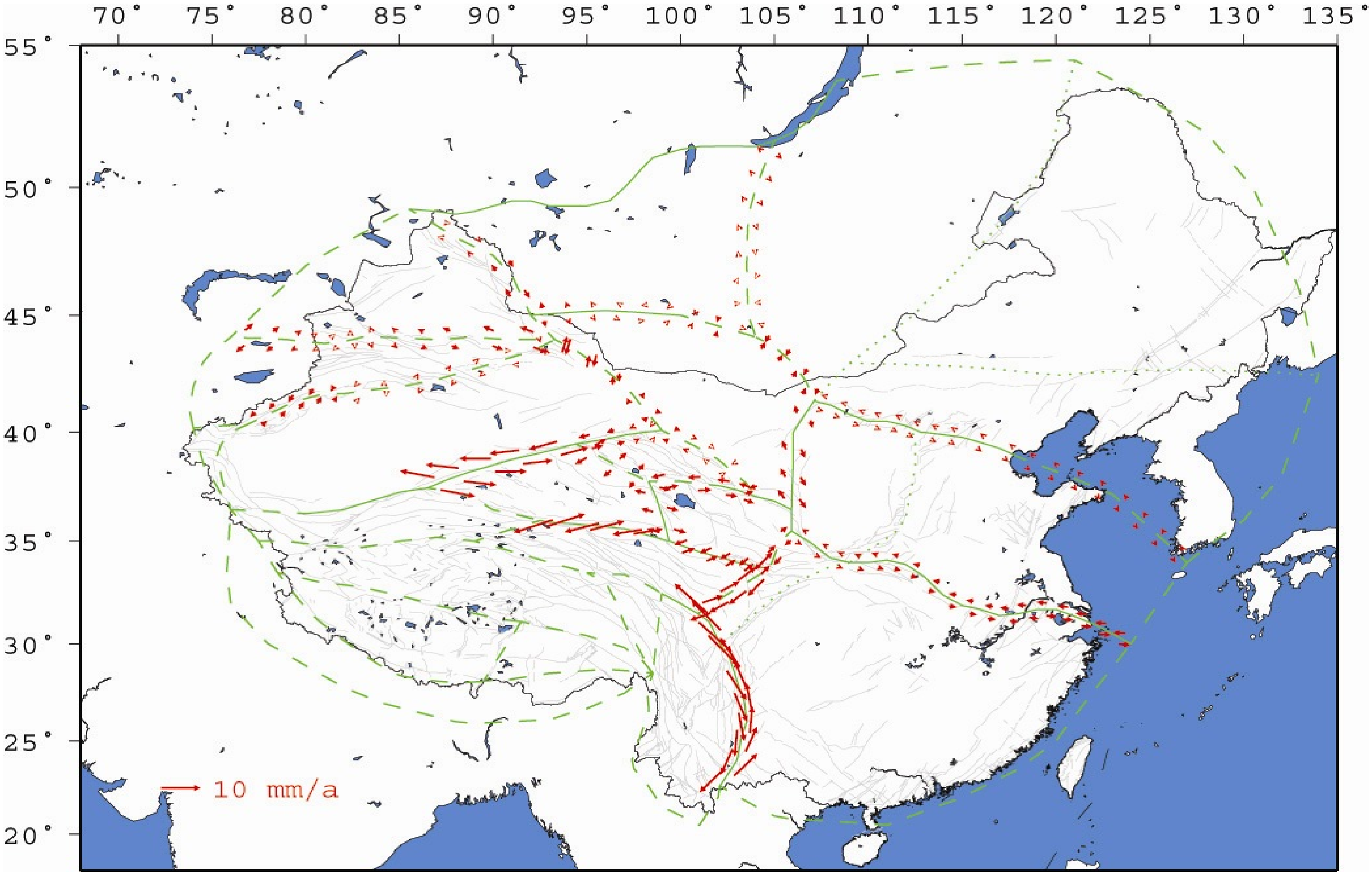
Block motion velocities and rotation rates

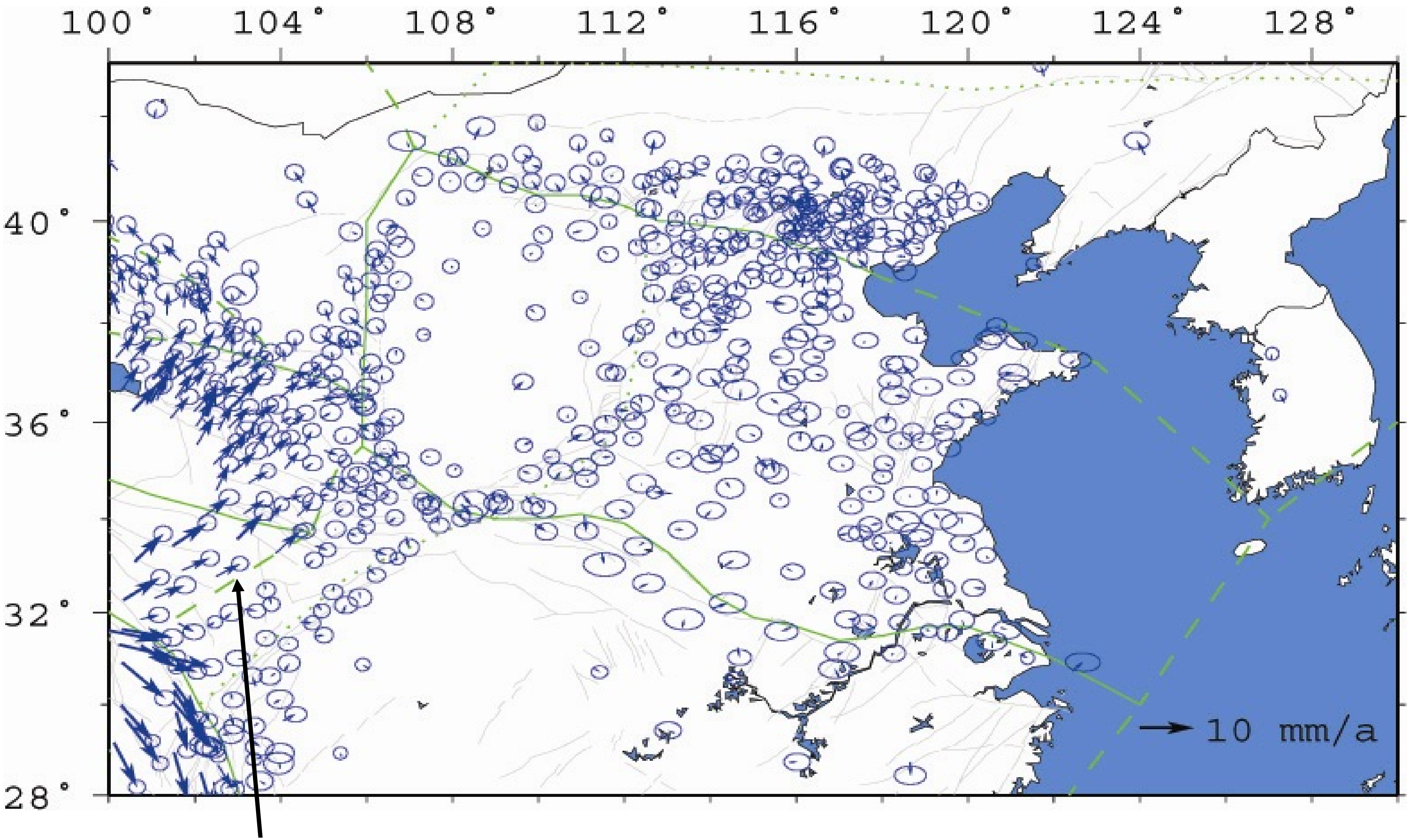


Block internal principal strain rates

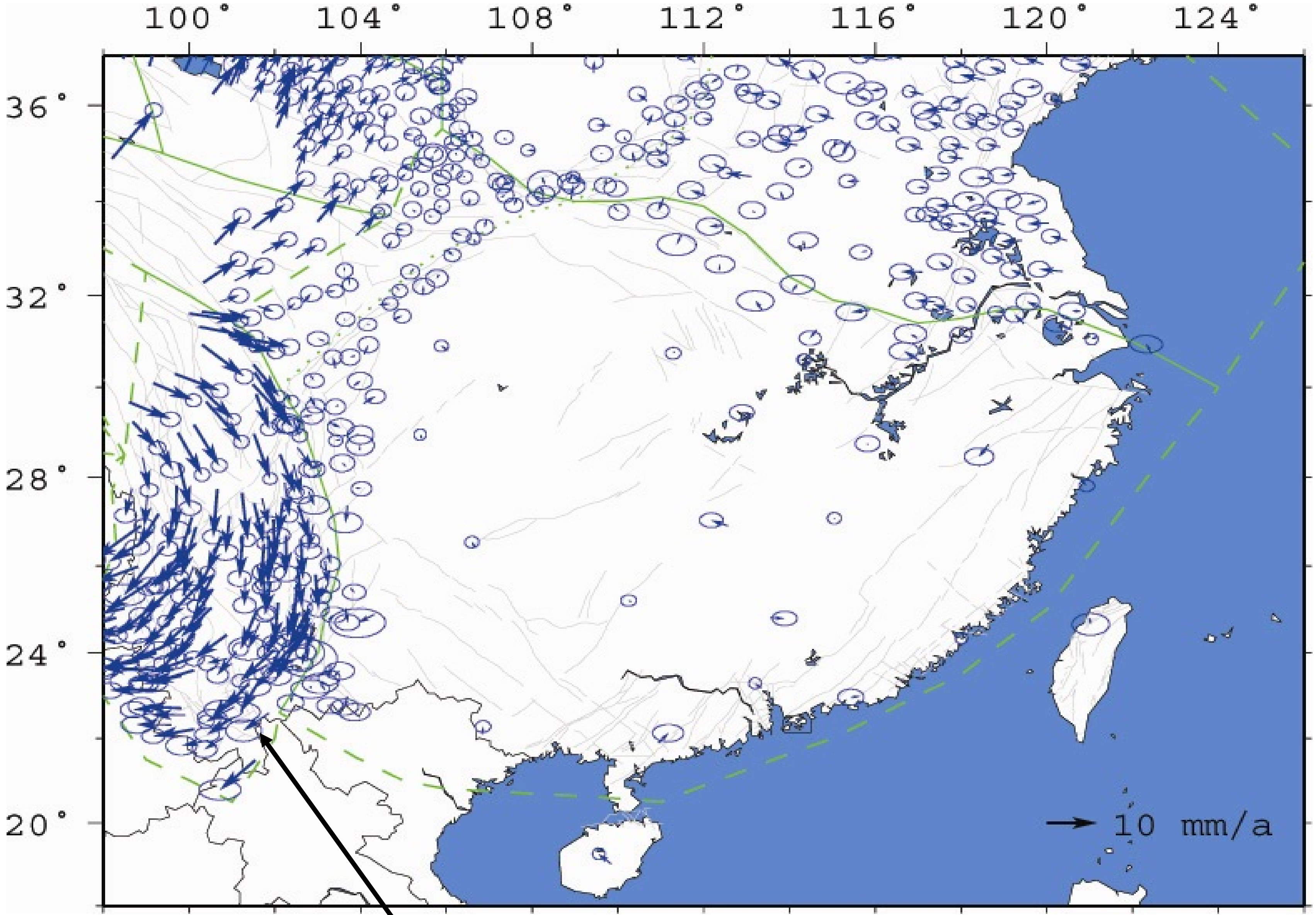


Relative Motion (Fault Slip) Rates at Block Boundaries



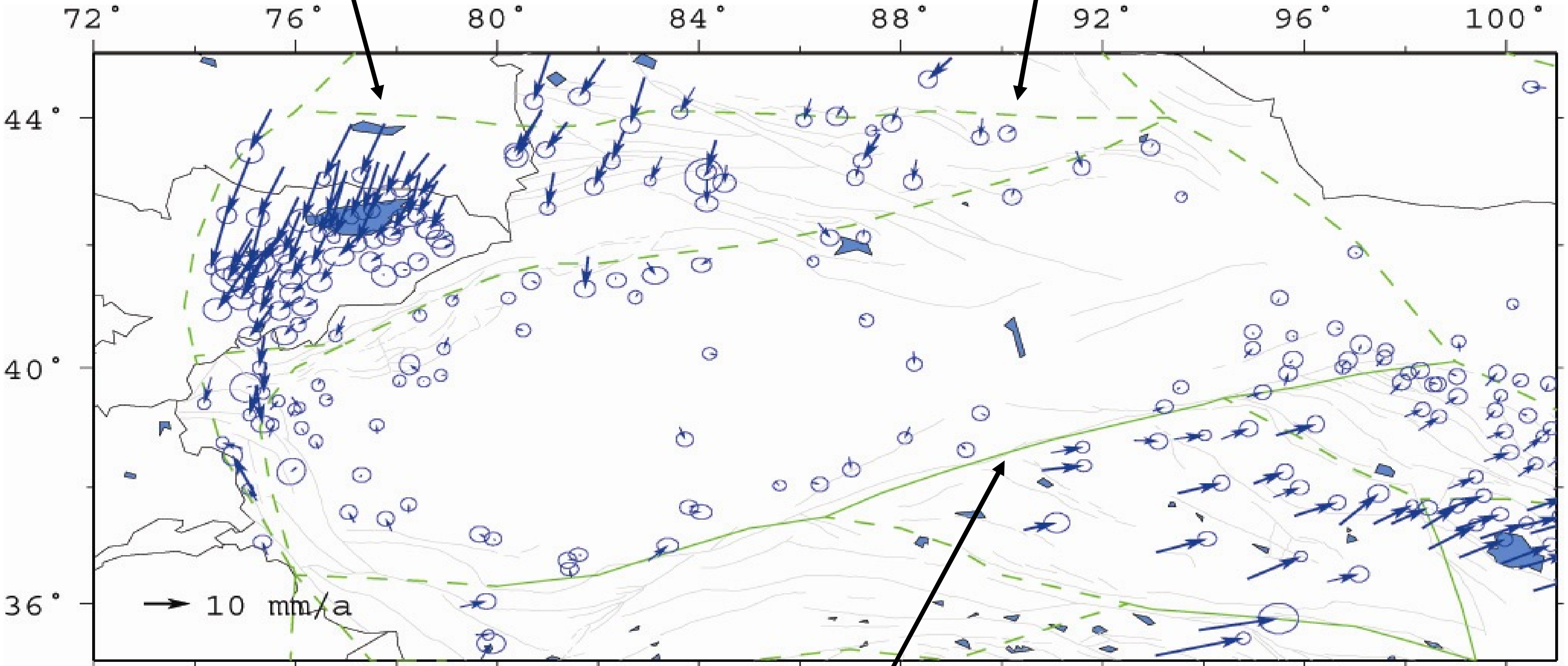


4-5 mm/yr right slip along a previously unknown fault zone



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

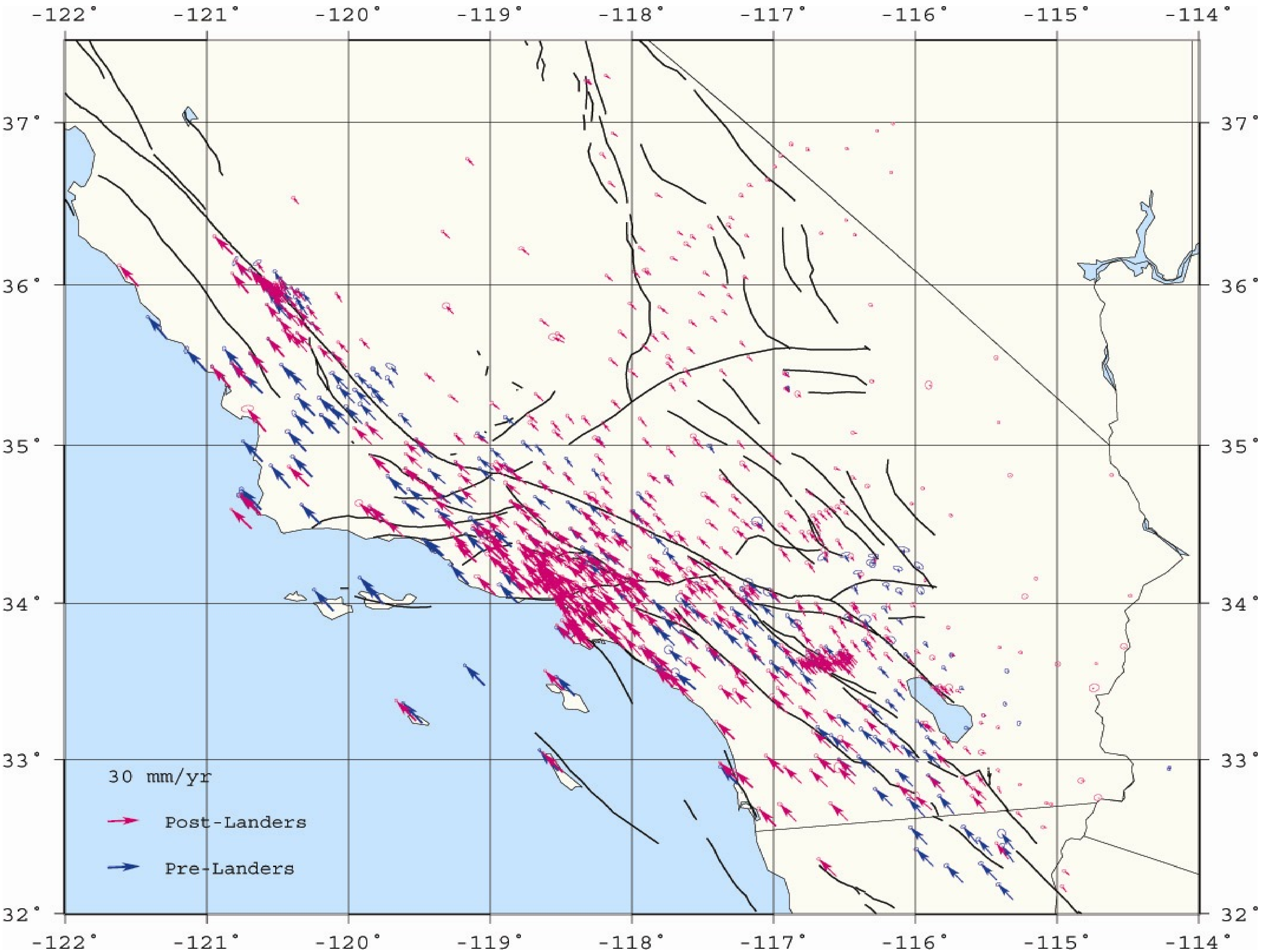
Progressive westward increase of north-south convergence across Tien Shan range



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

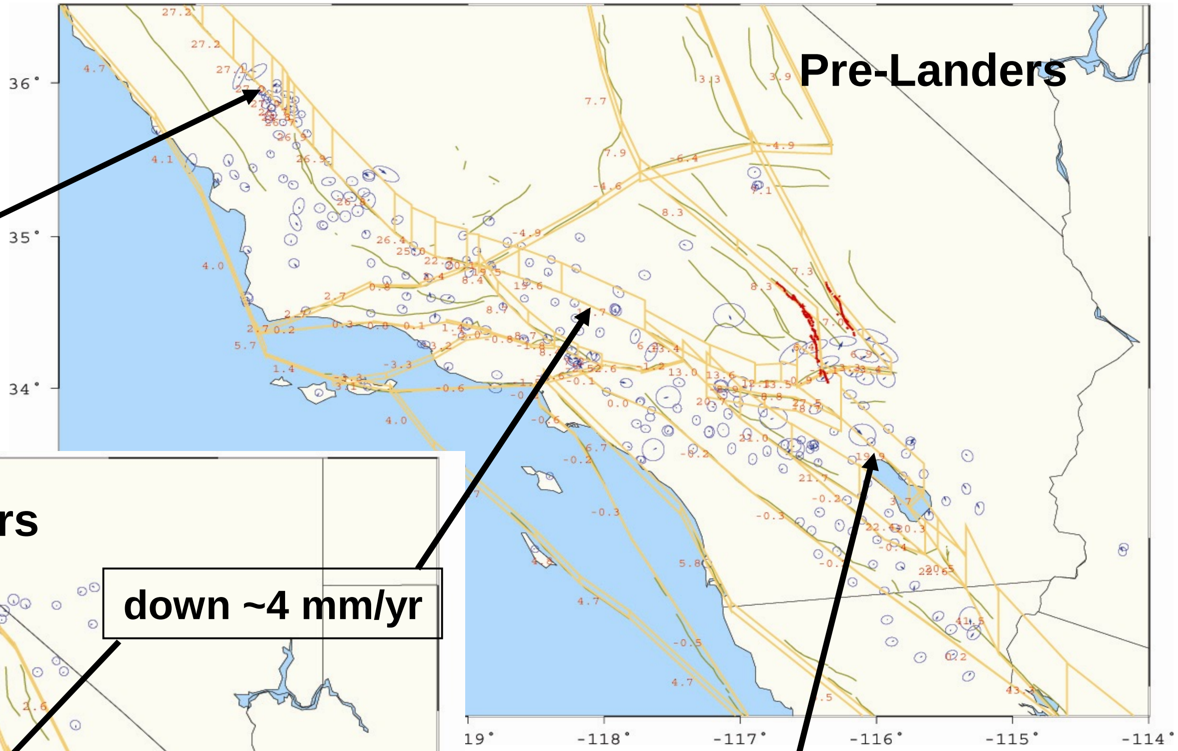
Approach II:
Linked fault segment approach
Example: Southern California

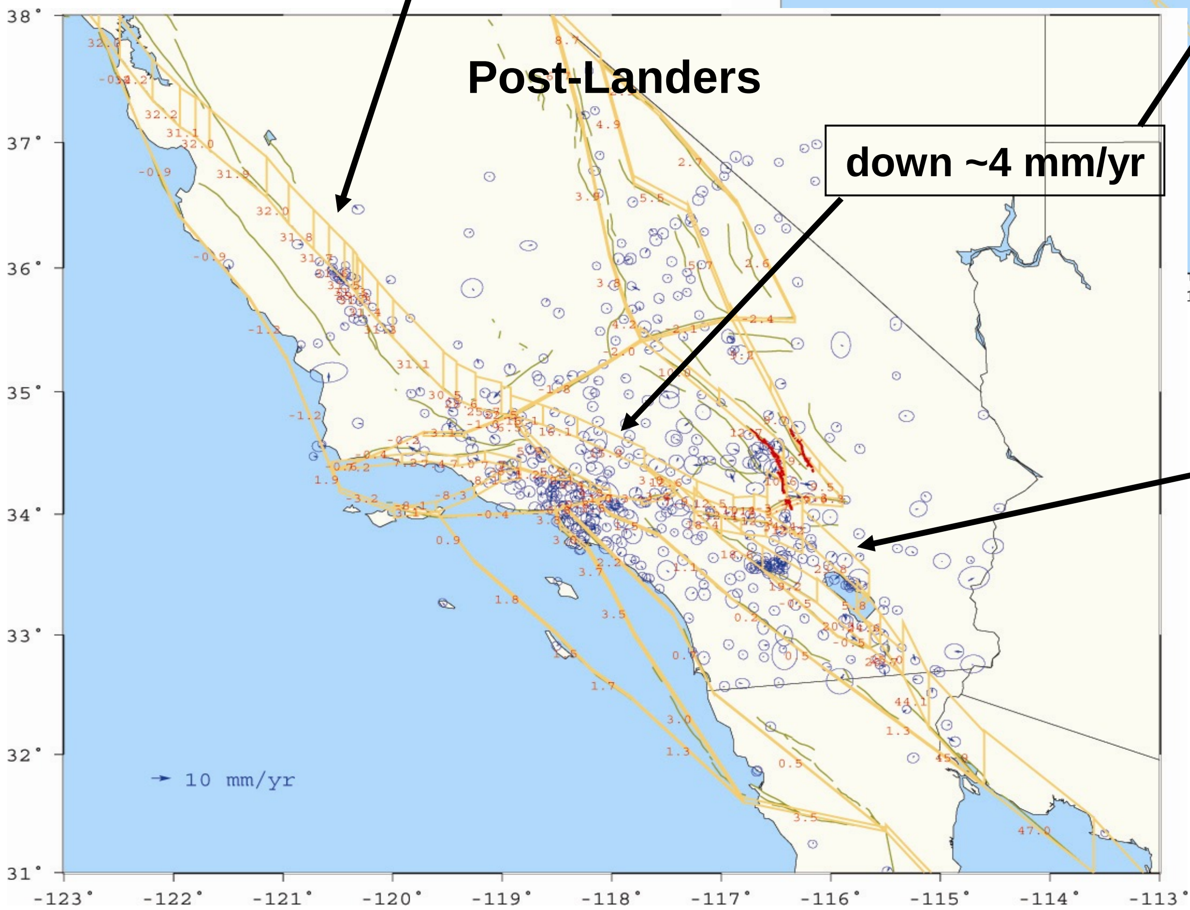
Surface deformation is interpreted by dislocation along fault segments beneath locking depth, and fault slip continuity is enforced by imposing finite constraints on slips along adjacent fault segments. If strict constraints are imposed, the model simulates a block-fault model; and if no constraint is imposed, slips along fault segments are independent. Thus by optimally adjusting the degree of constraints, one can limit the number of free model parameters, and still accommodate part of the deformation field which is not exactly “block-like”.



-122°
-121°
-120°
-119°
-118°
-117°
-116°
-115°
-114°
37°
36°
35°
34°
33°
32°
30 mm/yr
Post-Landers
Pre-Landers

Fault Strike Slip Rate Estimates

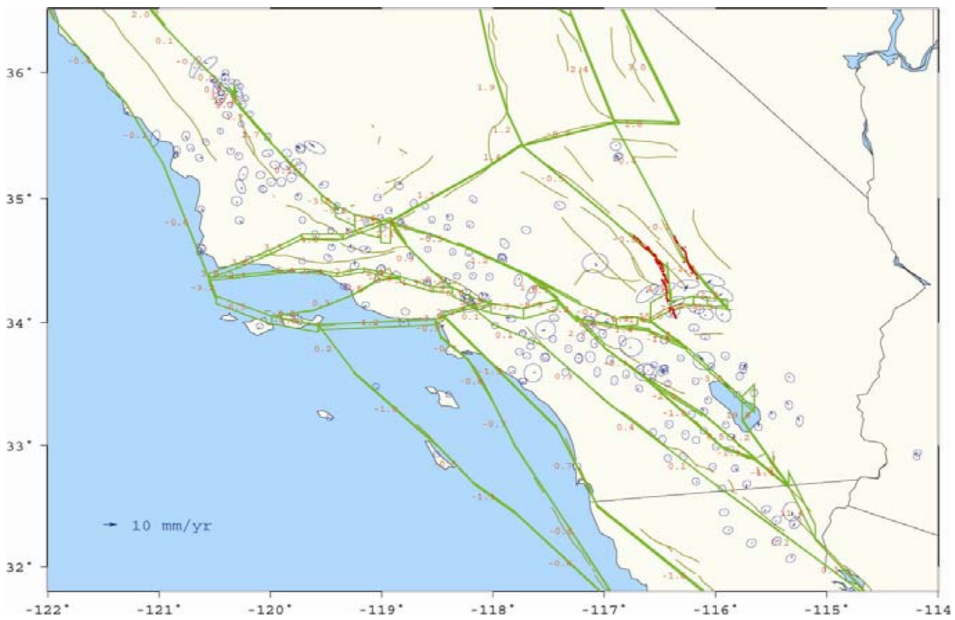




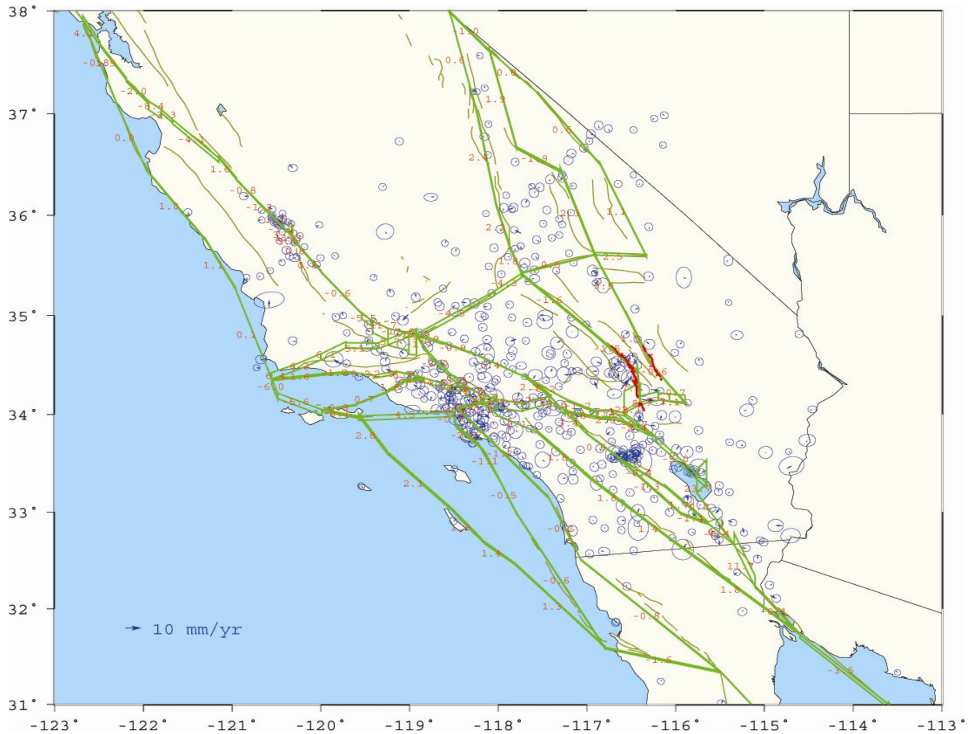
Post-Landers fault slip rate changes qualitatively agree with predicted Coulomb stress changes along fault, must reflect changes in seismic potential!

Fault Normal Slip Rate Estimates

Pre-Landers



Post-Landers



--Fault slip rates and block internal strain rates can be used to infer seismic moment accumulation rate, and estimate long term regional seismic hazard potentials.

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