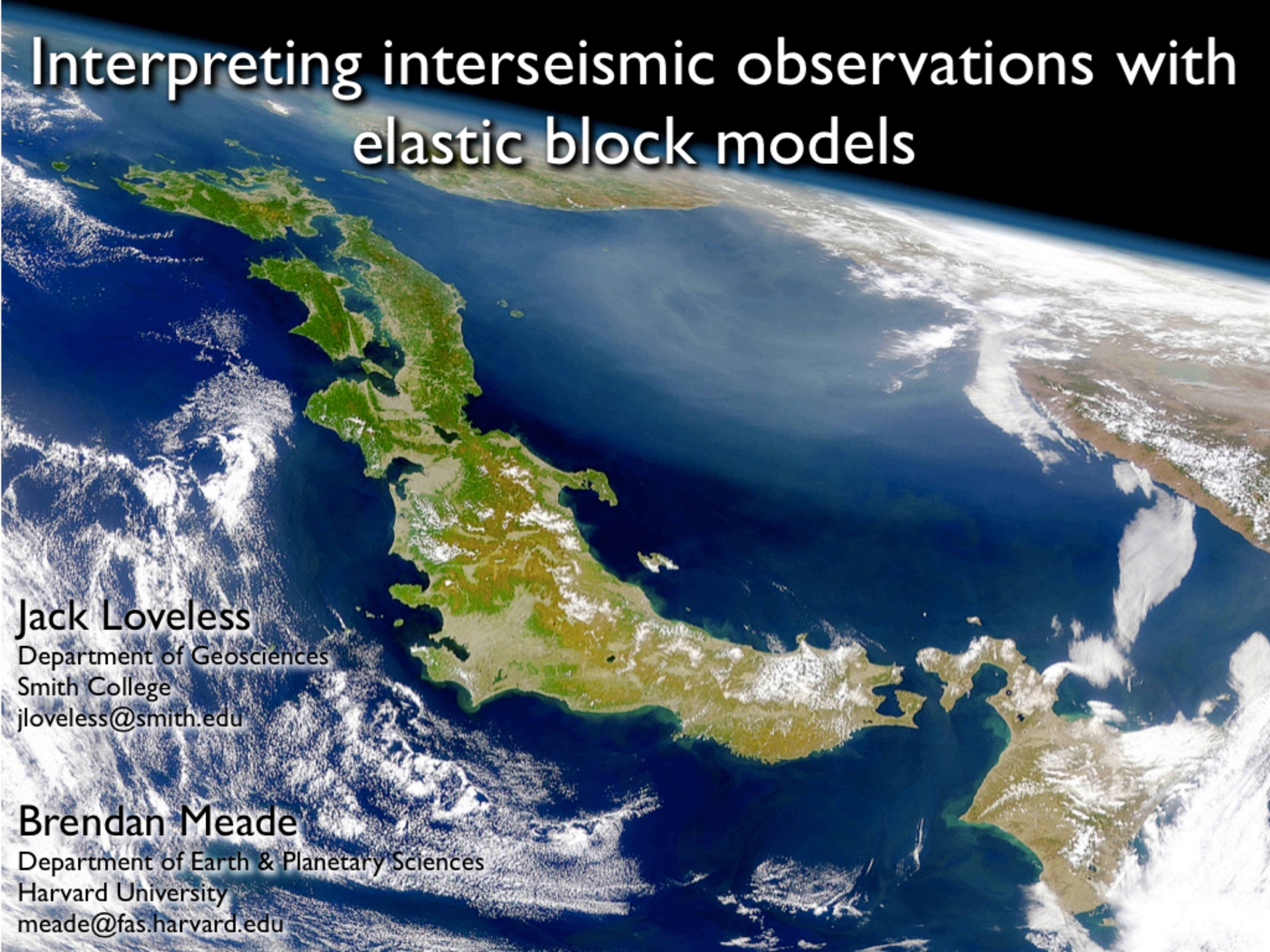

Interpreting interseismic observations with elastic block models

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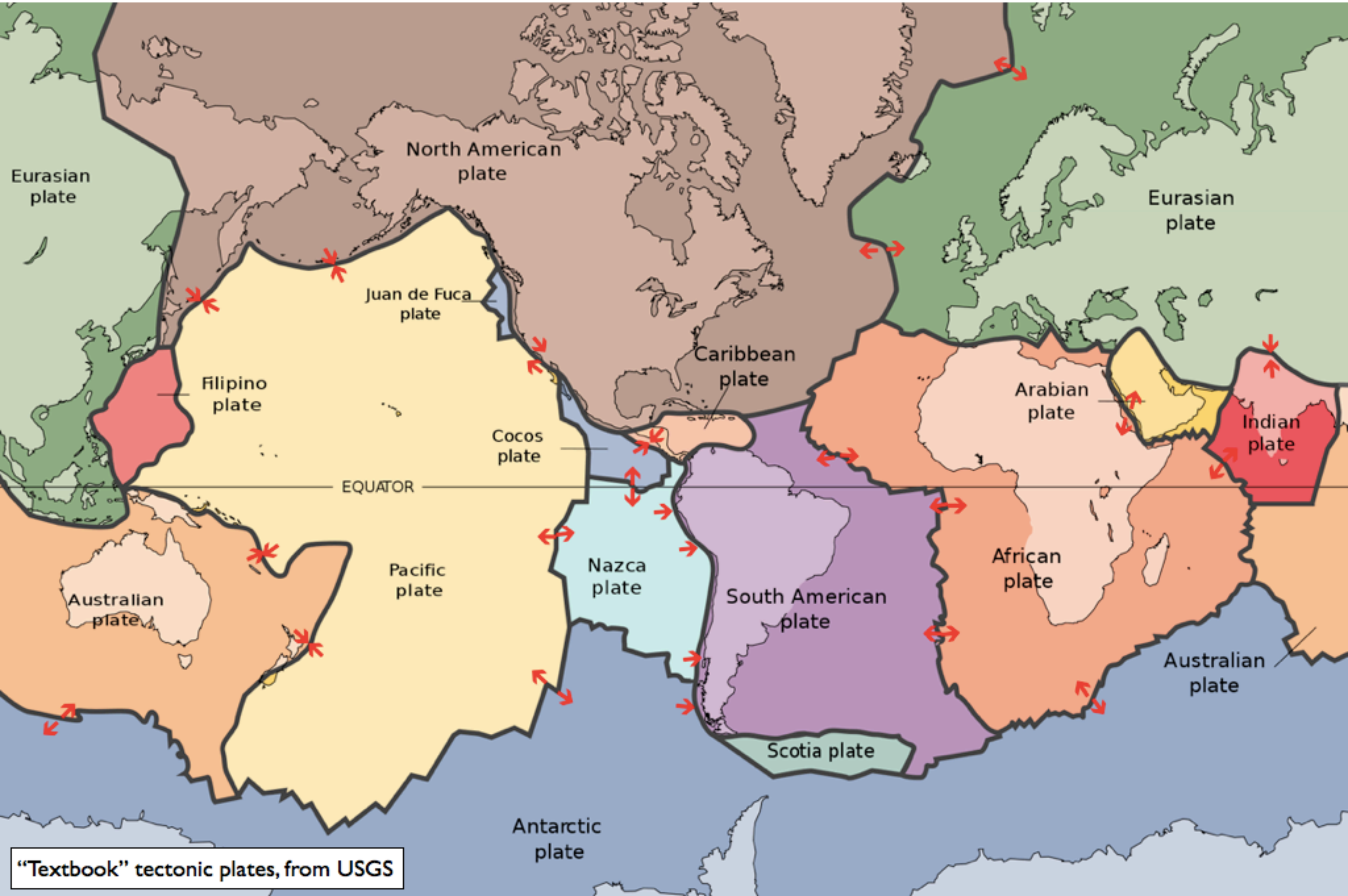
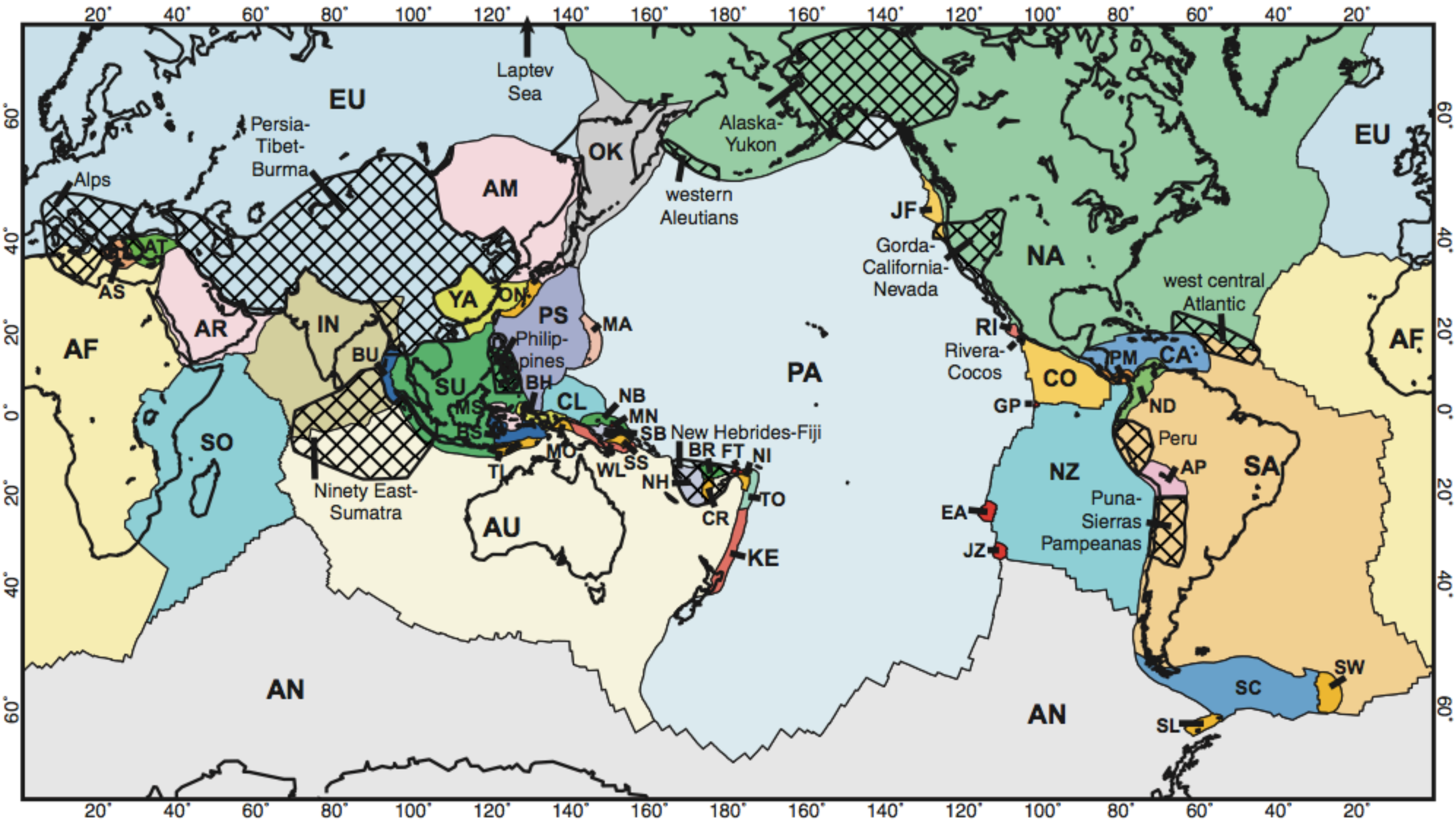
Evolving plate tectonic theory



"Textbook" tectonic plates, from USGS

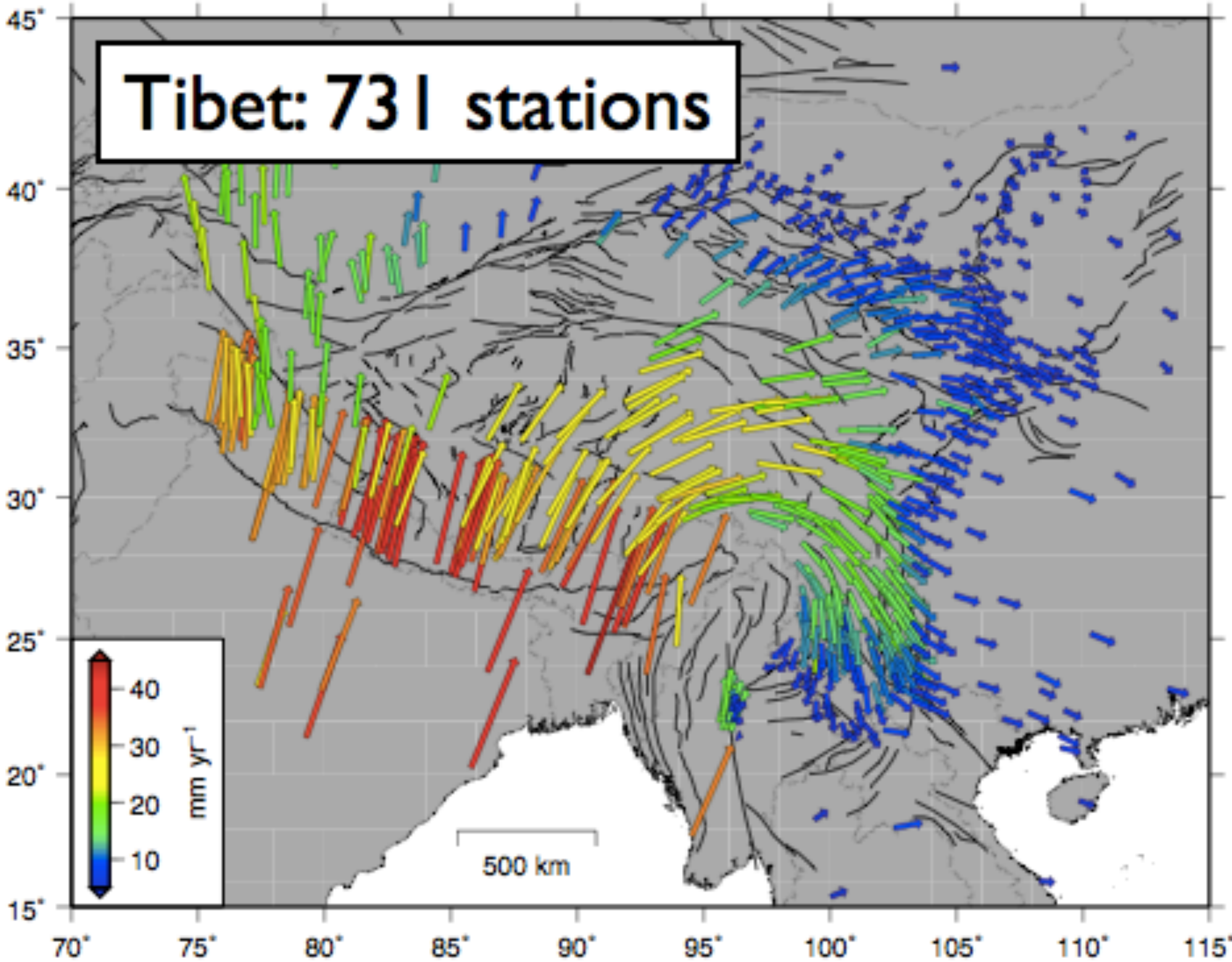
Evolving plate tectonic theory

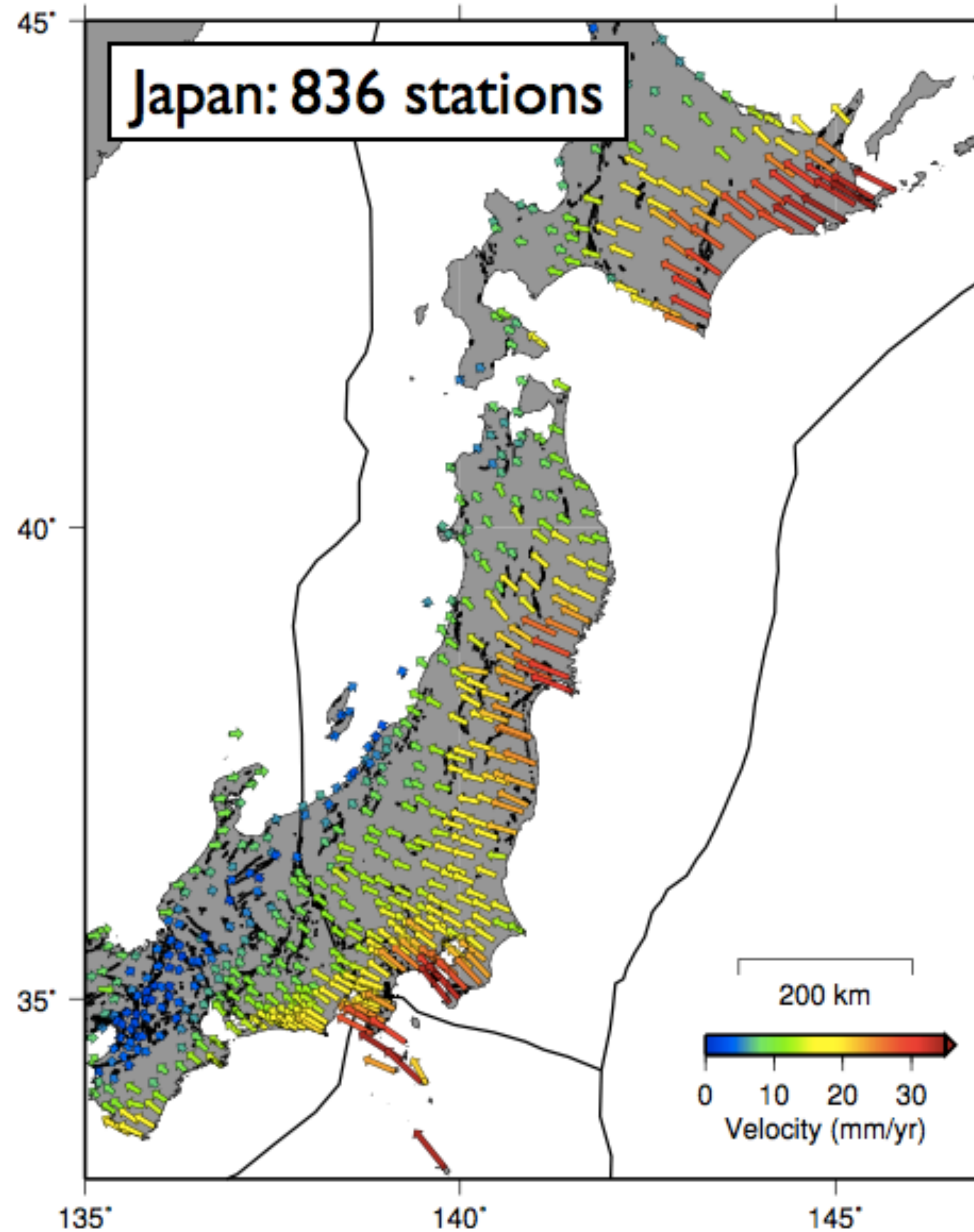


Tectonic plates revised, in part based on GPS observations

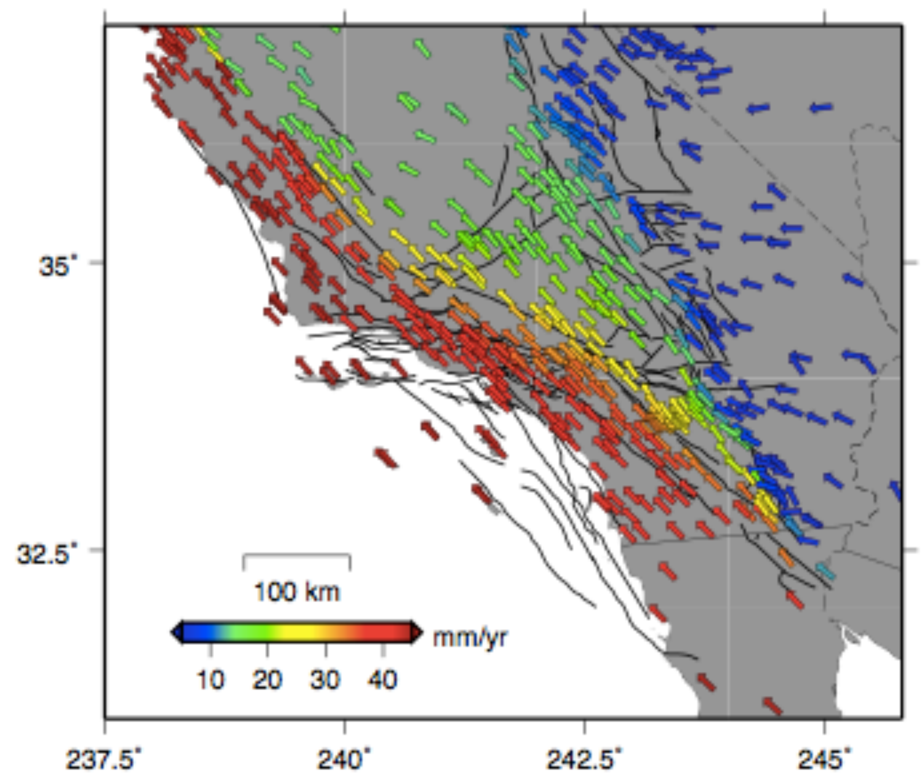
Bird, G^3, 2003

GPS observations of interseismic deformation





Southern California: 622 stations



Interpreting interseismic observations

Geodetically constrained block models provide kinematically consistent fault slip rate estimates, which can be used to:

- Examine how oblique convergence is partitioned between subduction zone(s) and crustal faults (Japan);
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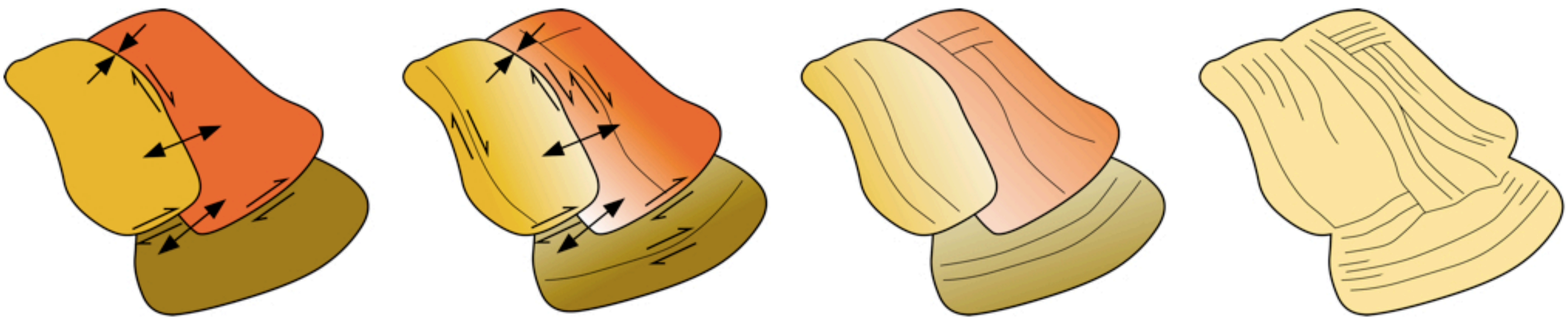
Interpreting interseismic observations

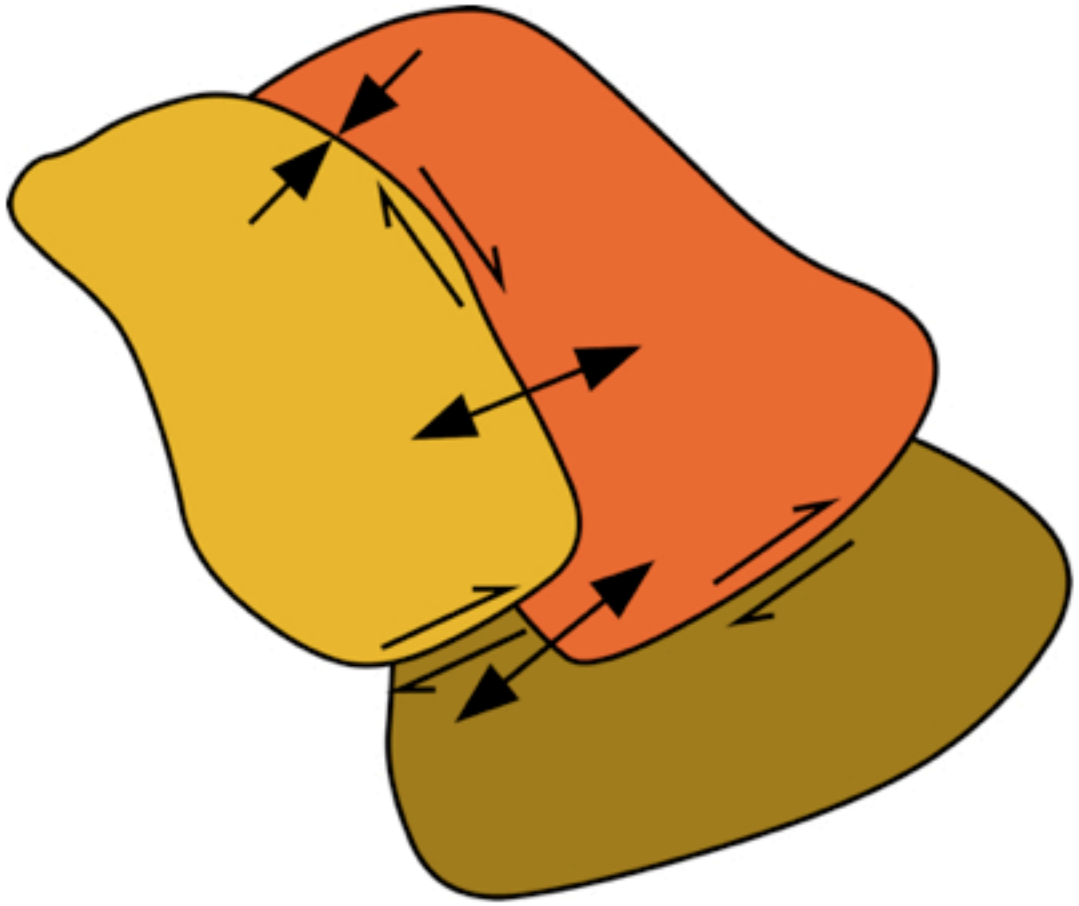


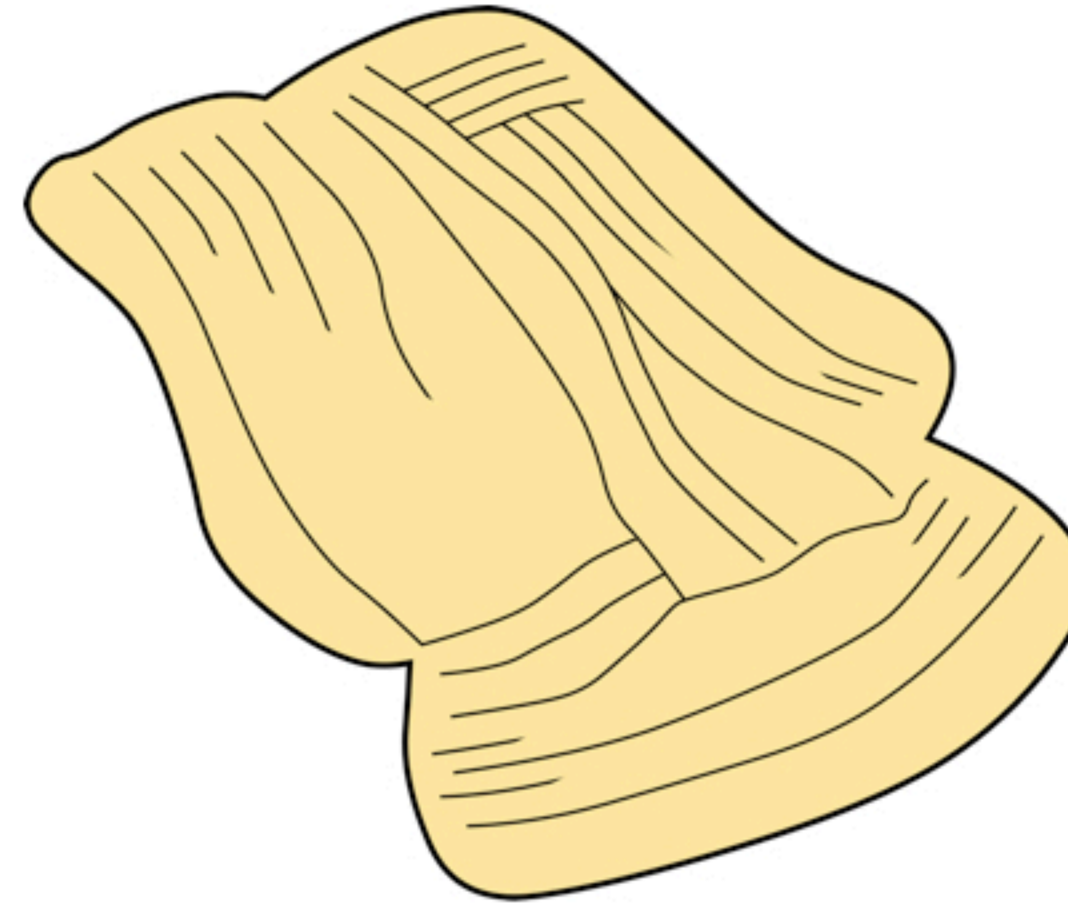
Microplate model → Continuum model

Greater number of faults
Fault slip rates more similar
Distinct blocks become smaller

Thatcher, *JGR*, 1995; Thatcher, *Int. Geol. Rev.*, 2003; Thatcher, *JGR*, 2007

Interpreting interseismic observations





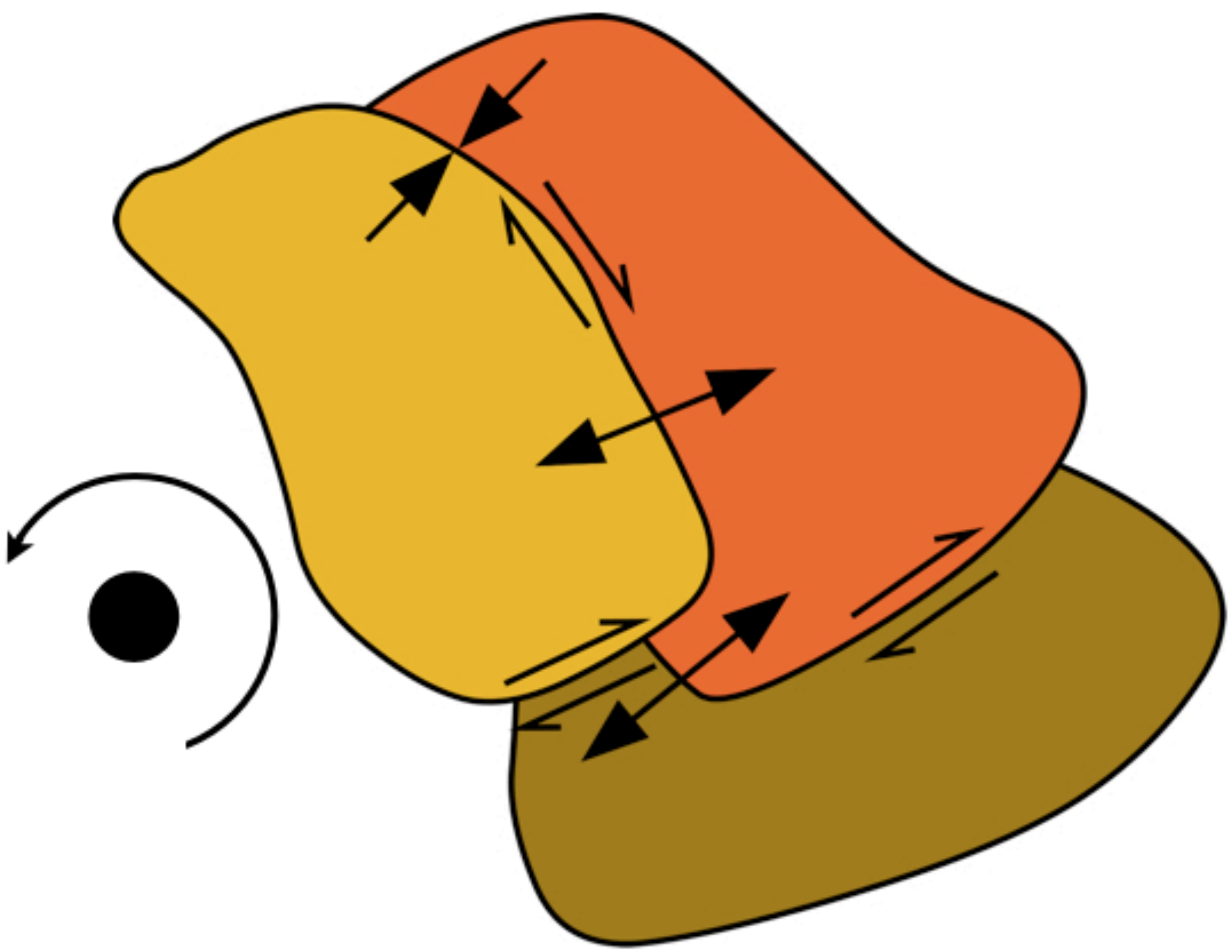
- Describes plate kinematics
- Motion described as rotation: plate tectonics
- Can estimate fault slip rates
- Blocks assumed rigid

- Describes distributed deformation
- Can estimate plate boundary forces & bulk rheology
- No explicit treatment of faults

Thatcher, *JGR*, 1995; Thatcher, *Int. Geol. Rev.*, 2003; Thatcher, *JGR*, 2007

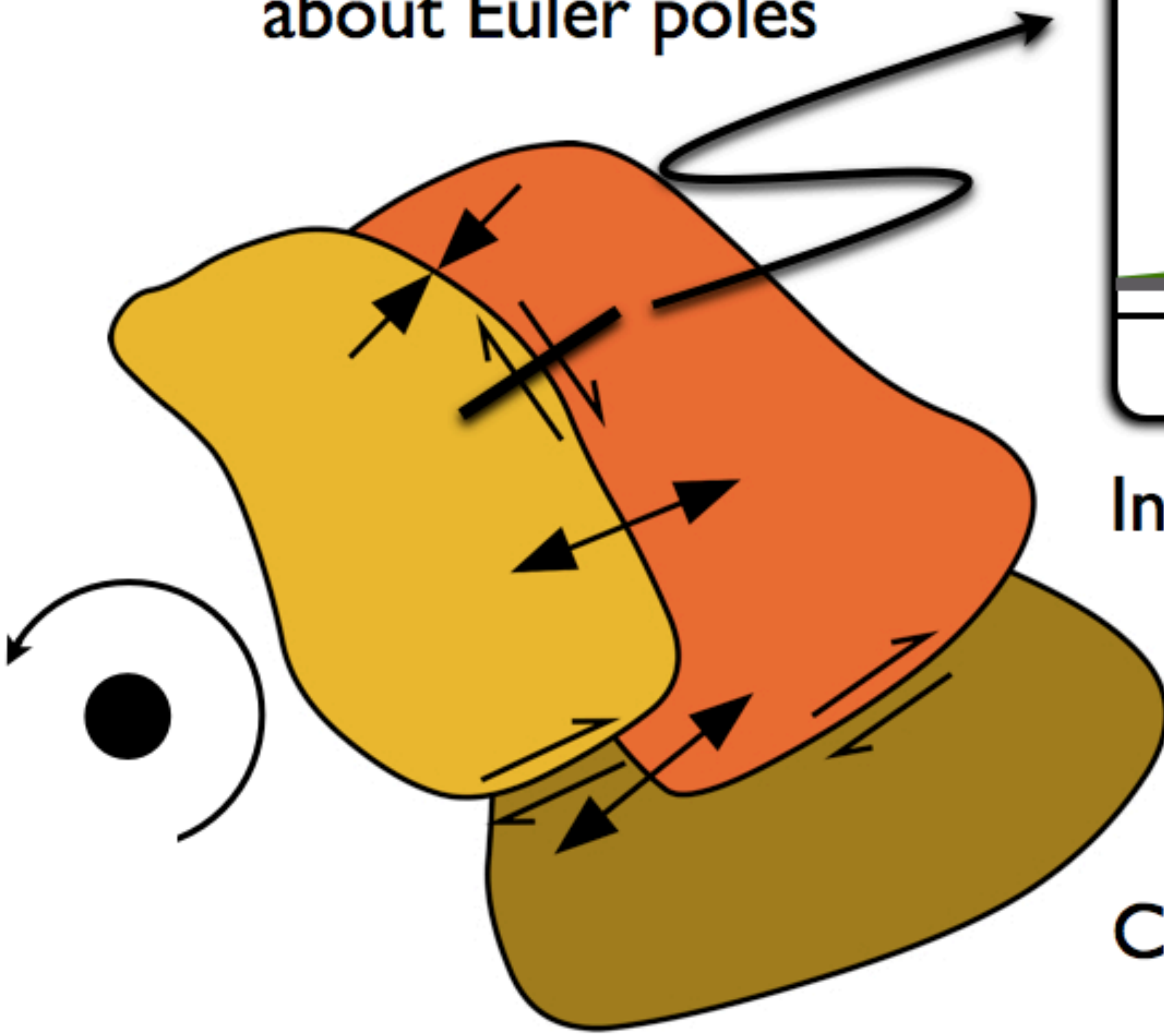
Interpreting interseismic observations

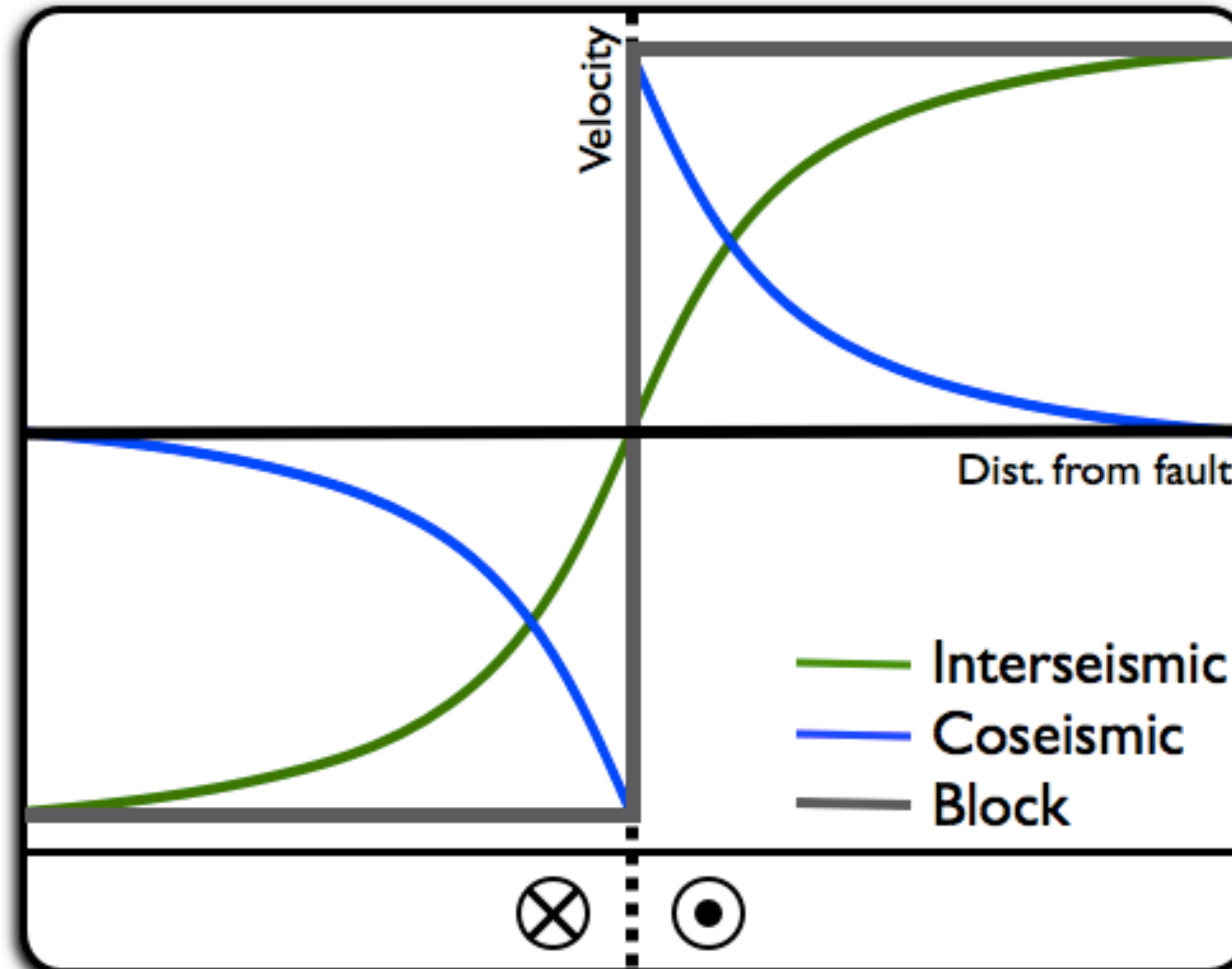
Block interactions described by rotation about Euler poles



Interpreting interseismic observations

Block interactions described by rotation about Euler poles





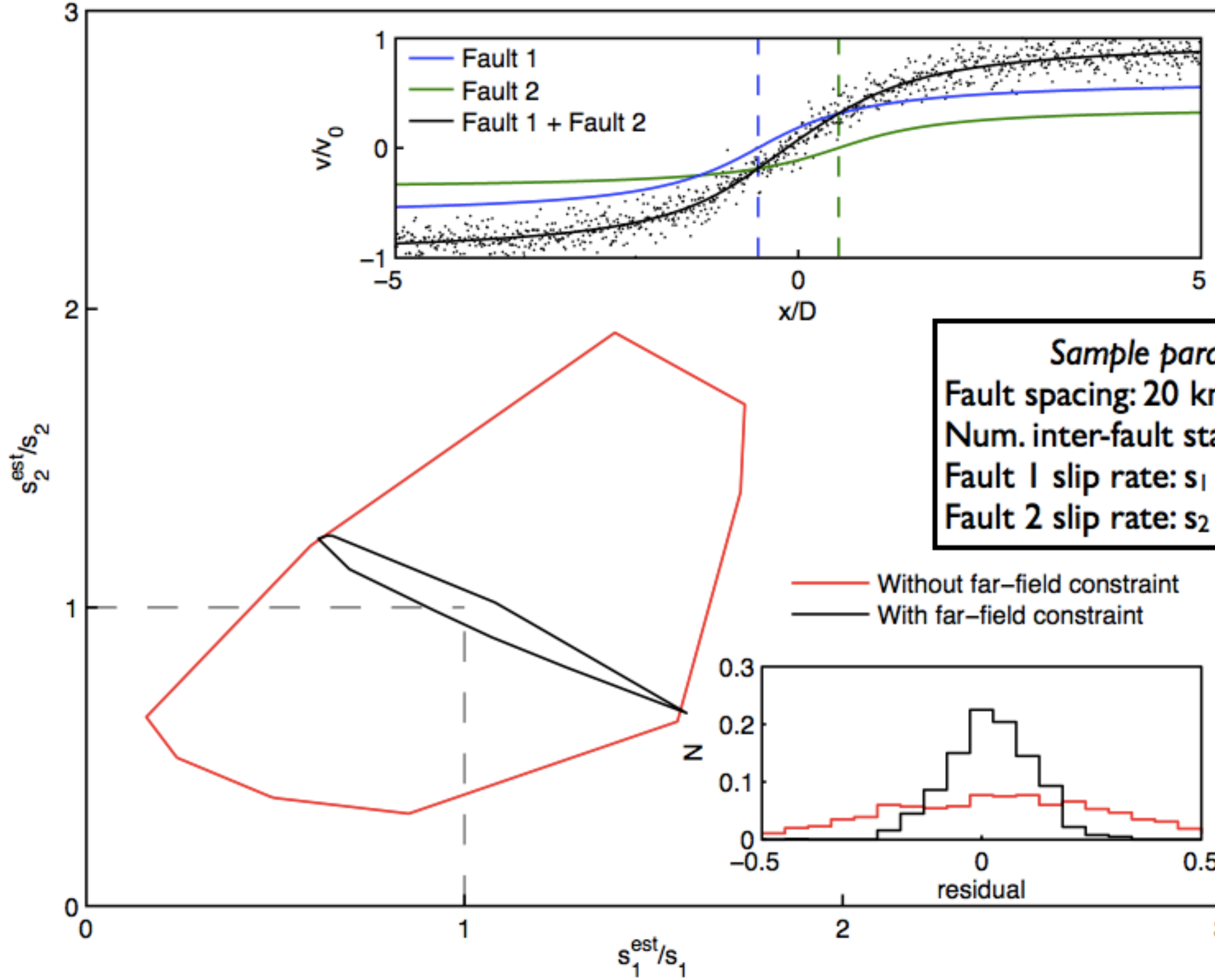
Interseismic = Block – Coseismic

Subtraction of coseismic: Coseismic Slip Deficit

Consideration of block motion + elastic effects → Block Model

Global constraints and slip rate estimates

Global slip rate constraints from plate tectonics and inherent in block models reduce covariance in slip rate estimated on closely spaced faults



Sample parameters:

Fault spacing: 20 km

Num. inter-fault stations: 20

Fault 1 slip rate: s_1 = 7.5 mm/yr

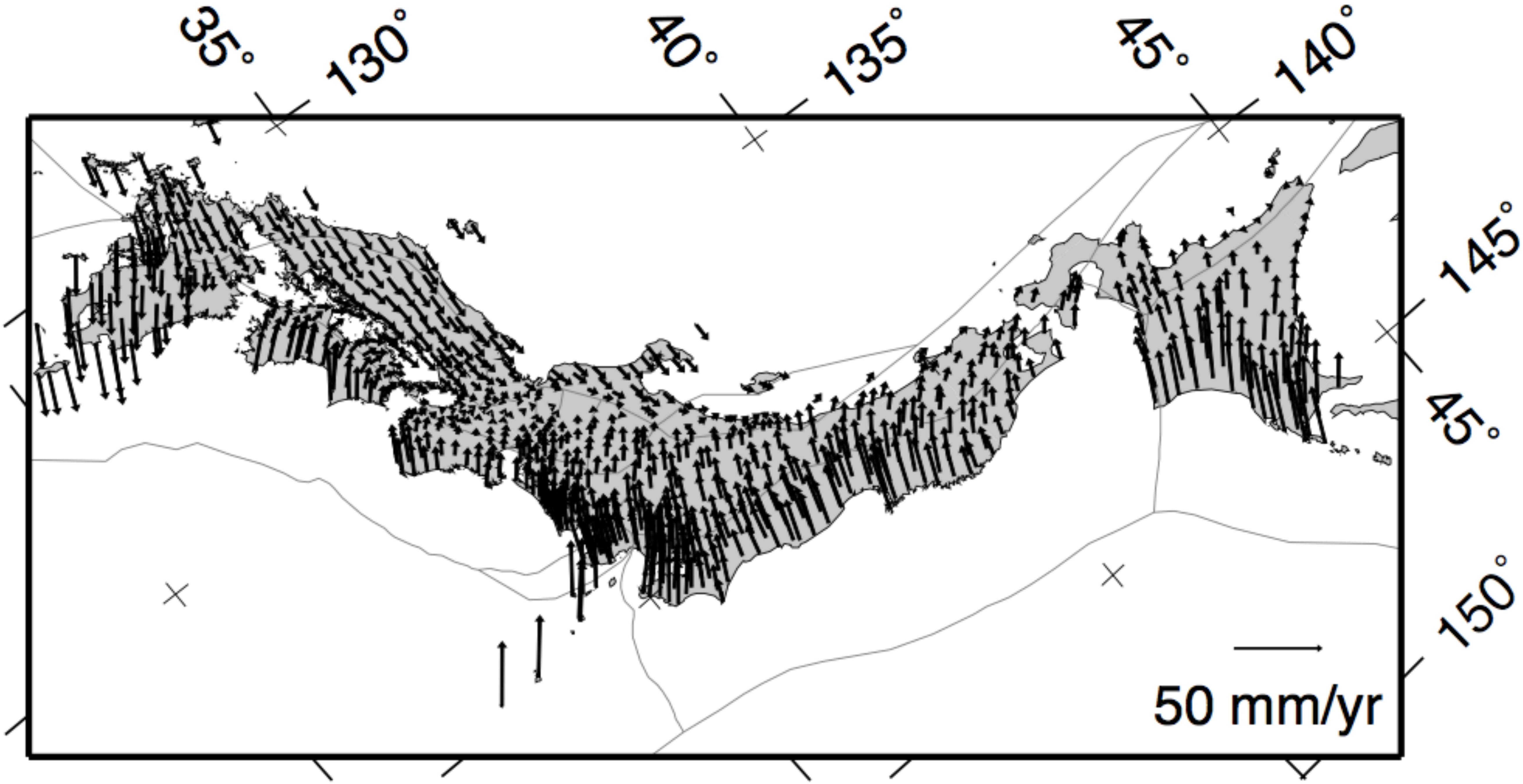
Fault 2 slip rate: s_2 = 12.5 mm/yr

Elastic block modeling I

- Decompose GPS velocity field with contributions from:
  - Block rotation,
  - Elastic strain accumulation on block-bounding faults,
  - Elastic strain accumulation on variably coupled faults

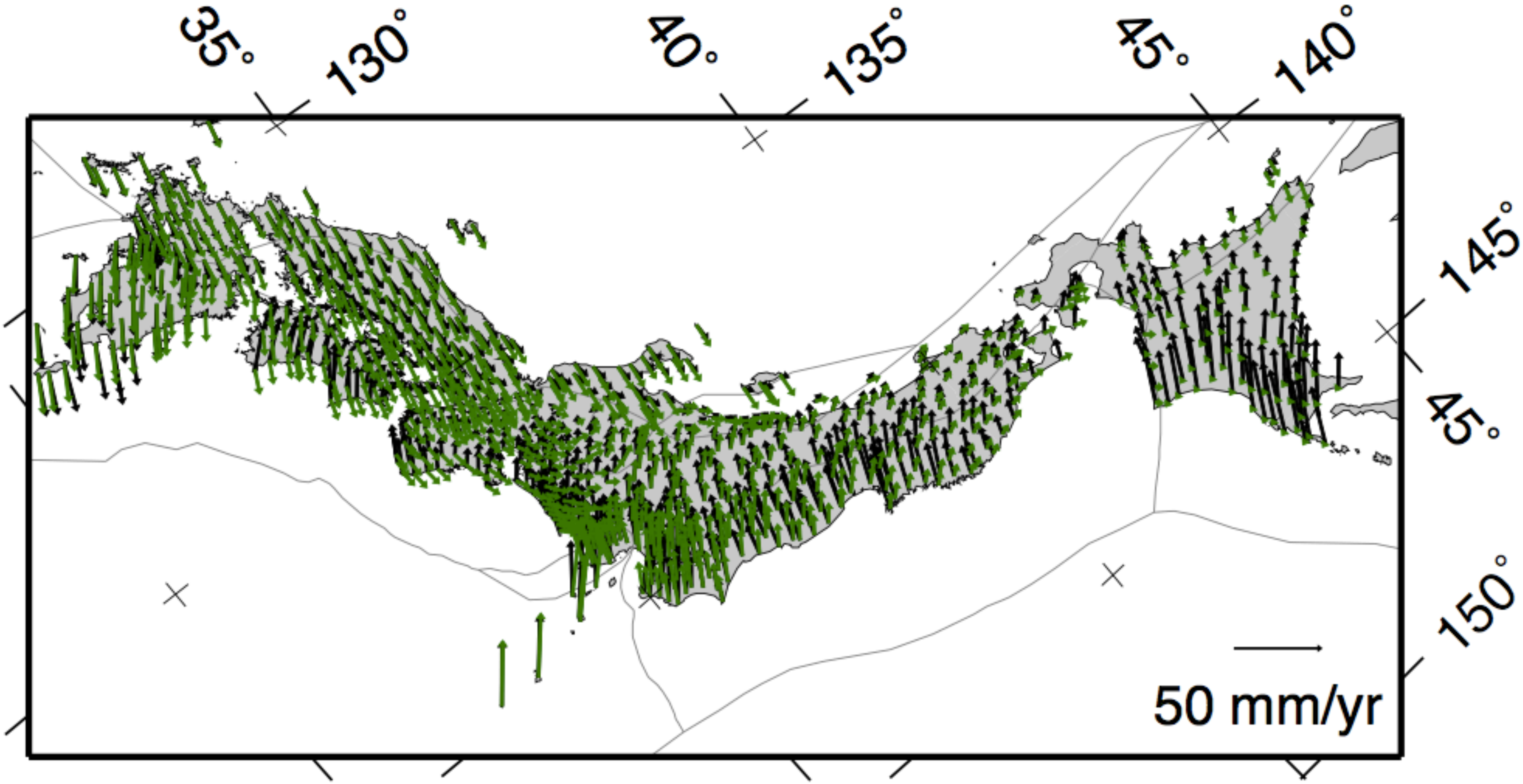
$$\underline{\mathbf{v}_{\mathrm{I}}} = \underline{\mathbf{v}_{\mathrm{B}}} - \underline{\mathbf{v}_{\mathrm{E}}} - \underline{\mathbf{v}_{\mathrm{T}}}$$

Elastic block modeling I



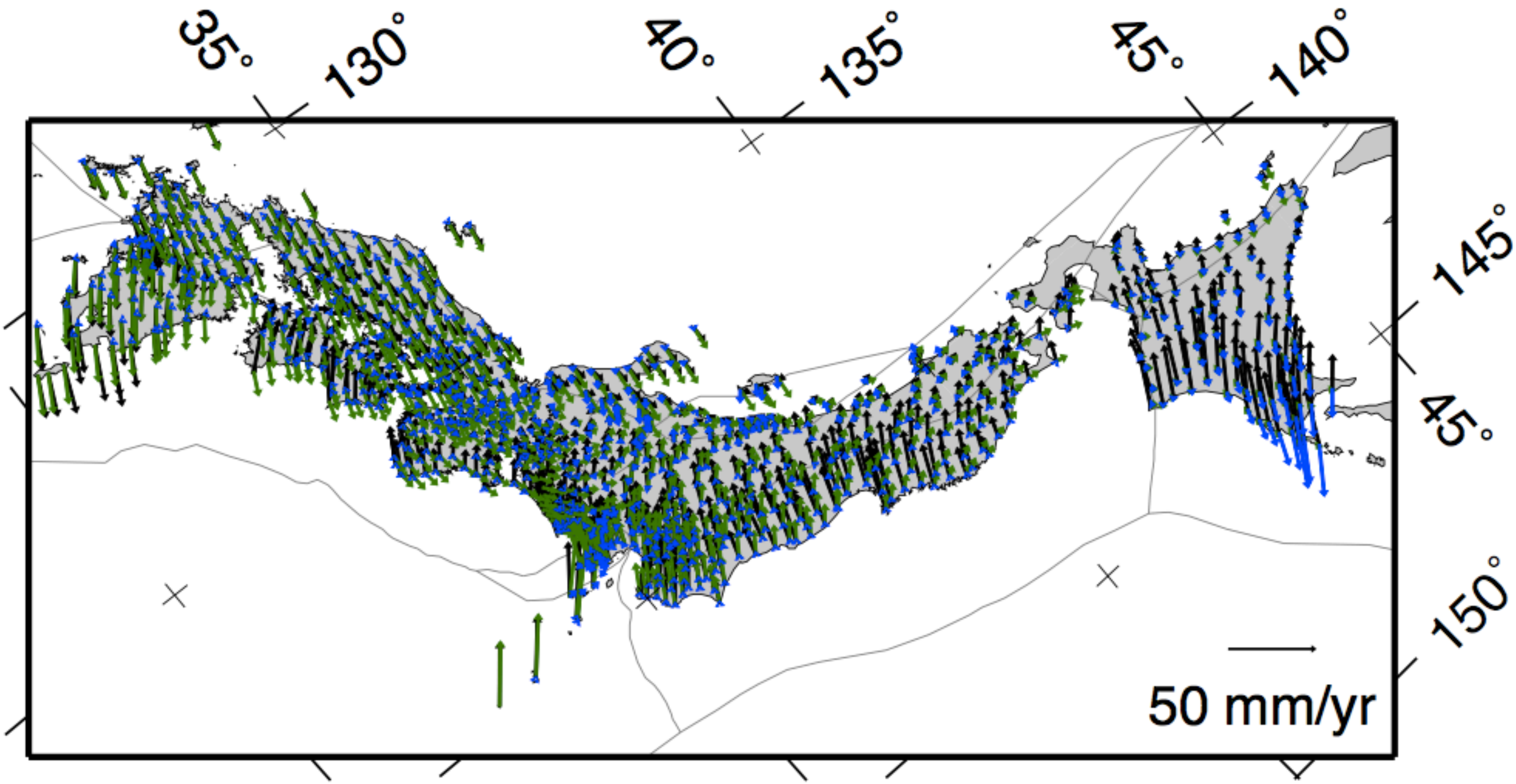
$\mathbf{v}_\mathrm{I}$

Elastic block modeling I



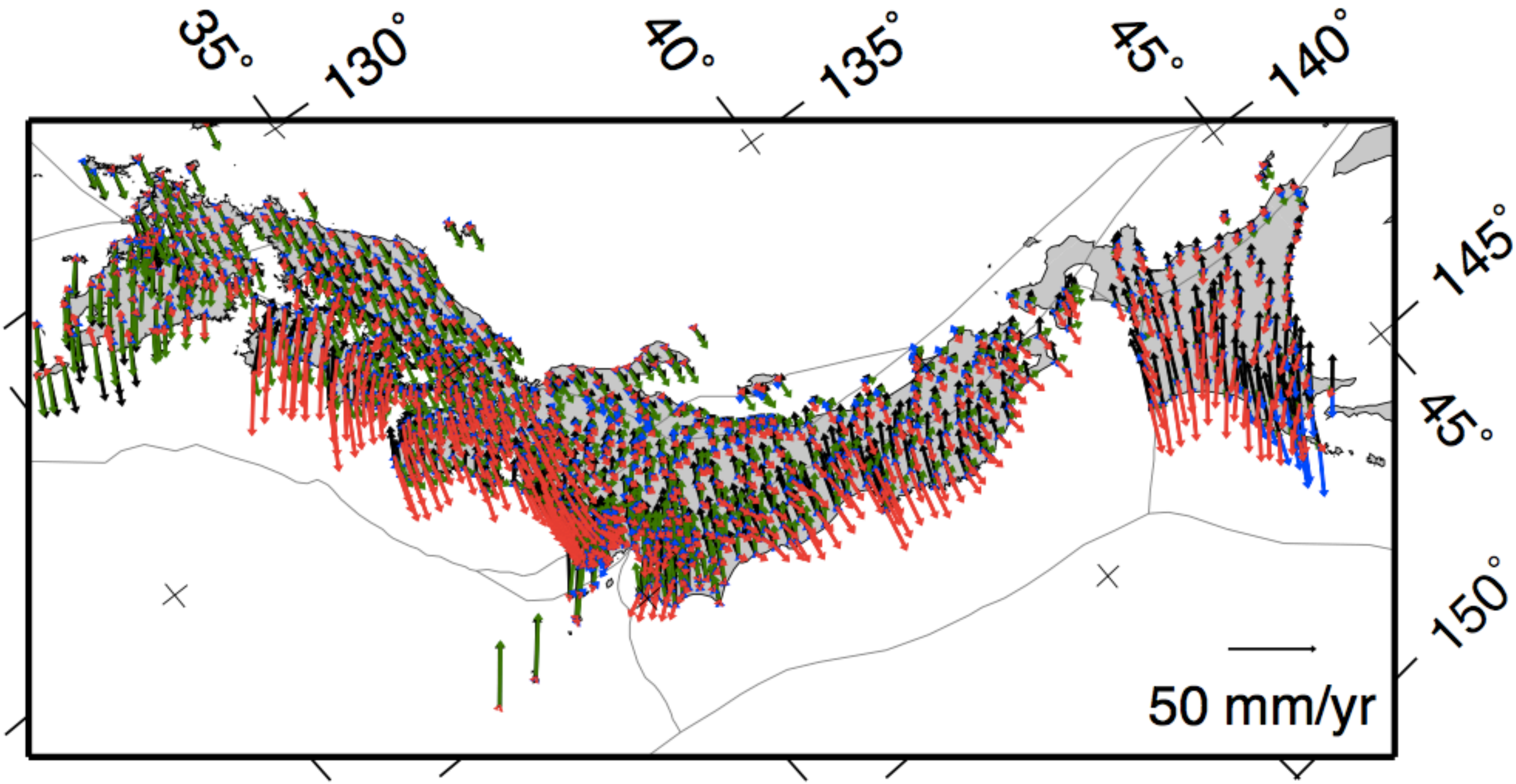
$$\mathbf{v}_{\mathrm{I}} = \underline{\mathbf{v}_{\mathrm{B}}}$$

Elastic block modeling I



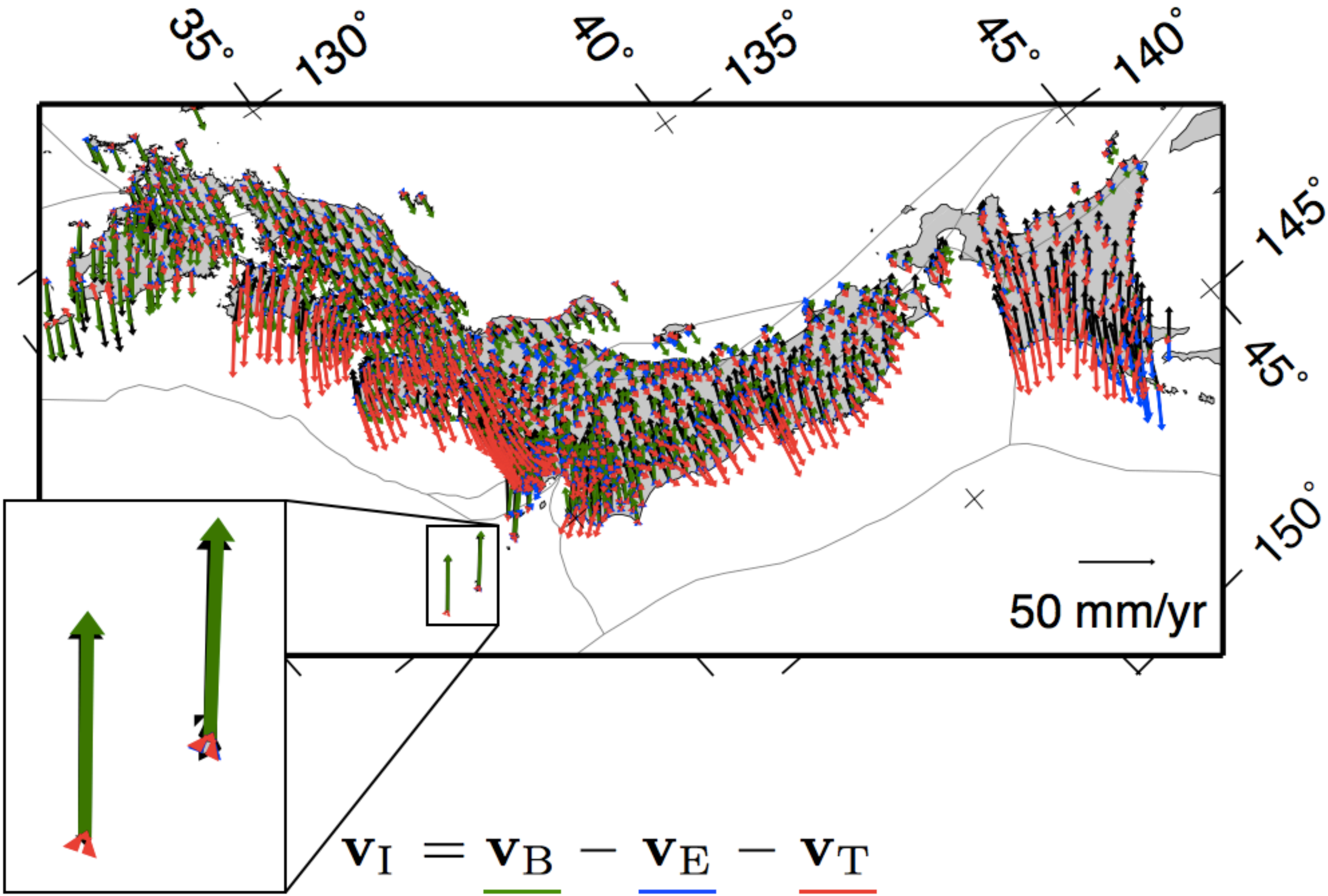
$$\mathbf{v}_{\mathrm{I}} = \underline{\mathbf{v}_{\mathrm{B}}} - \underline{\mathbf{v}_{\mathrm{E}}}$$

Elastic block modeling I



$$\mathbf{v}_{\mathrm{I}} = \mathbf{v}_{\mathrm{B}} - \mathbf{v}_{\mathrm{E}} - \mathbf{v}_{\mathrm{T}}$$

Elastic block modeling I



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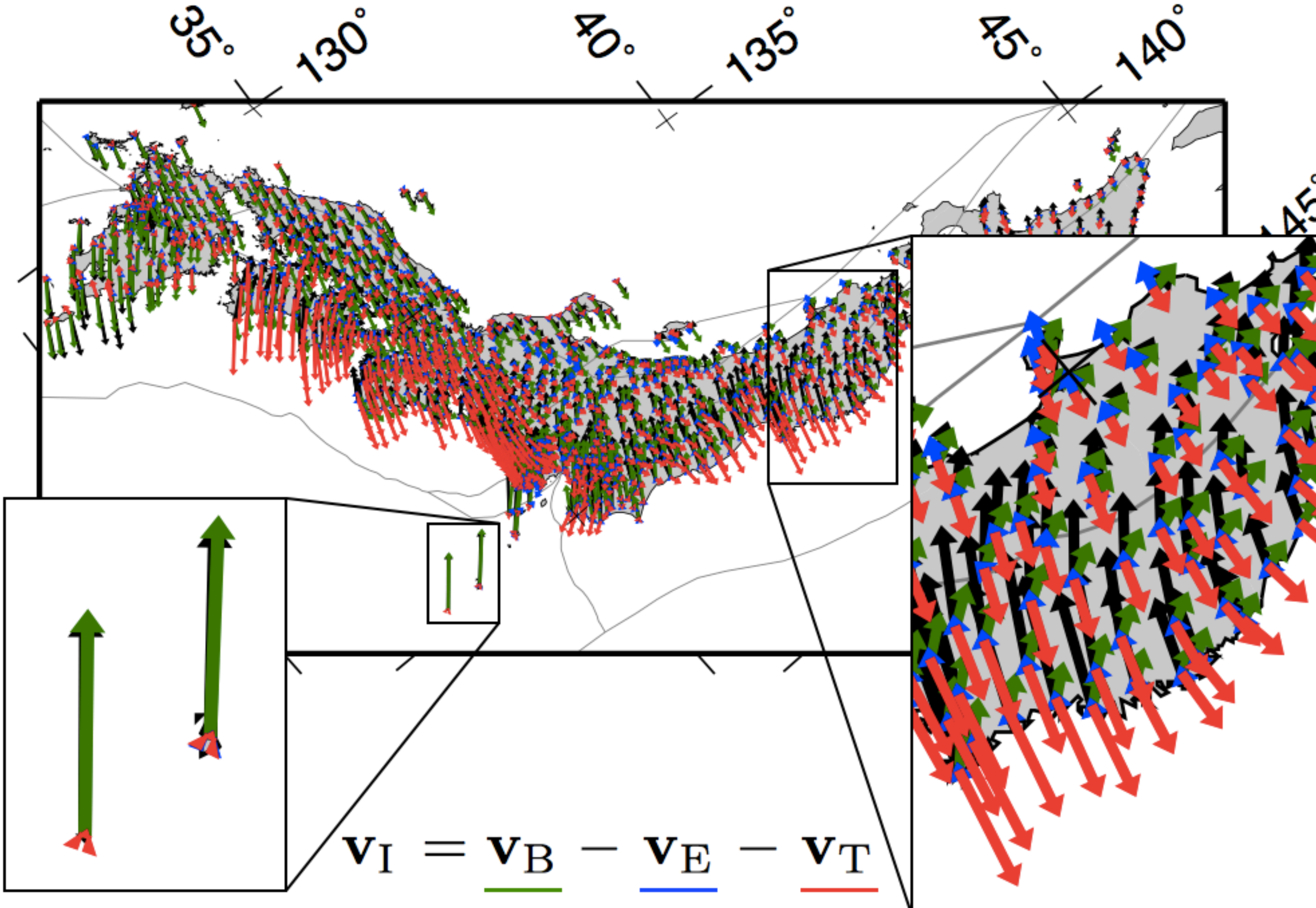
Elastic block modeling I



$$\mathbf{v}_{\mathrm{I}} = \mathbf{v}_{\mathrm{B}} - \mathbf{v}_{\mathrm{E}} - \mathbf{v}_{\mathrm{T}}$$

Elastic block modeling II

$$\mathbf{v}_{\mathrm{I}} = \mathbf{v}_{\mathrm{B}} - \mathbf{v}_{\mathrm{E}} - \mathbf{v}_{\mathrm{T}}$$

Block velocities, $\mathbf{v}_{\mathrm{B}}$, due to rotation about Euler pole, Ω:

$$\mathbf{v}_{\mathrm{B}}(\Omega) = \Omega \times \mathbf{p} = \mathbf{R}_{\mathrm{B}}\Omega$$

Velocities, $\mathbf{v}_{\mathrm{E}}$, due to elastic strain accumulation, related to slip deficit rates on block-bounding faults, $\dot{\mathrm{s}}$:

$$\mathbf{v}_{\mathrm{E}}(\dot{\mathbf{s}}) = \mathbf{R}_{\mathrm{E}}\dot{\mathbf{s}}$$

Velocities, $\mathbf{v}_{\mathrm{T}}$, due to elastic strain accumulation, related to slip deficit rates on triangular dislocation elements, $\dot{\mathrm{t}}$:

$$\mathbf{v}_{\mathrm{T}}(\dot{\mathbf{t}}) = \mathbf{R}_{\mathrm{T}}\dot{\mathbf{t}}$$

Elastic block modeling III

Use weighted least-squares to solve linear problem for Ω^{est} and $\dot{\mathbf{t}}^{\text{est}}$:

$$\begin{bmatrix} \mathbf{v}_\mathrm{I} \\ \dot{\mathbf{s}}_\mathrm{obs} \\ 0 \end{bmatrix} = \begin{bmatrix} \mathbf{R}_\mathrm{B} - \mathbf{R}_\mathrm{E} & -\mathbf{R}_\mathrm{T} \\ \mathbf{R}_\mathrm{F} & 0 \\ 0 & \mathbf{M}_\mathrm{T} \end{bmatrix} \begin{bmatrix} \Omega \\ \dot{\mathbf{t}} \end{bmatrix}$$

Data:	Linear operators:
$\mathbf{v}_\mathrm{I}$: GPS velocities	$\mathbf{R}_\mathrm{B}$: Rotation cross-product
$\dot{\mathbf{s}}_\mathrm{obs}$: *a priori* slip rates	$\mathbf{R}_\mathrm{E}$: from Okada (1985)
	$\mathbf{R}_\mathrm{F}$: fault slip projection
	$\mathbf{R}_\mathrm{T}$: from Meade (2007)
	$\mathbf{M}_\mathrm{T}$: Laplacian smoothing

Constructing the block geometry

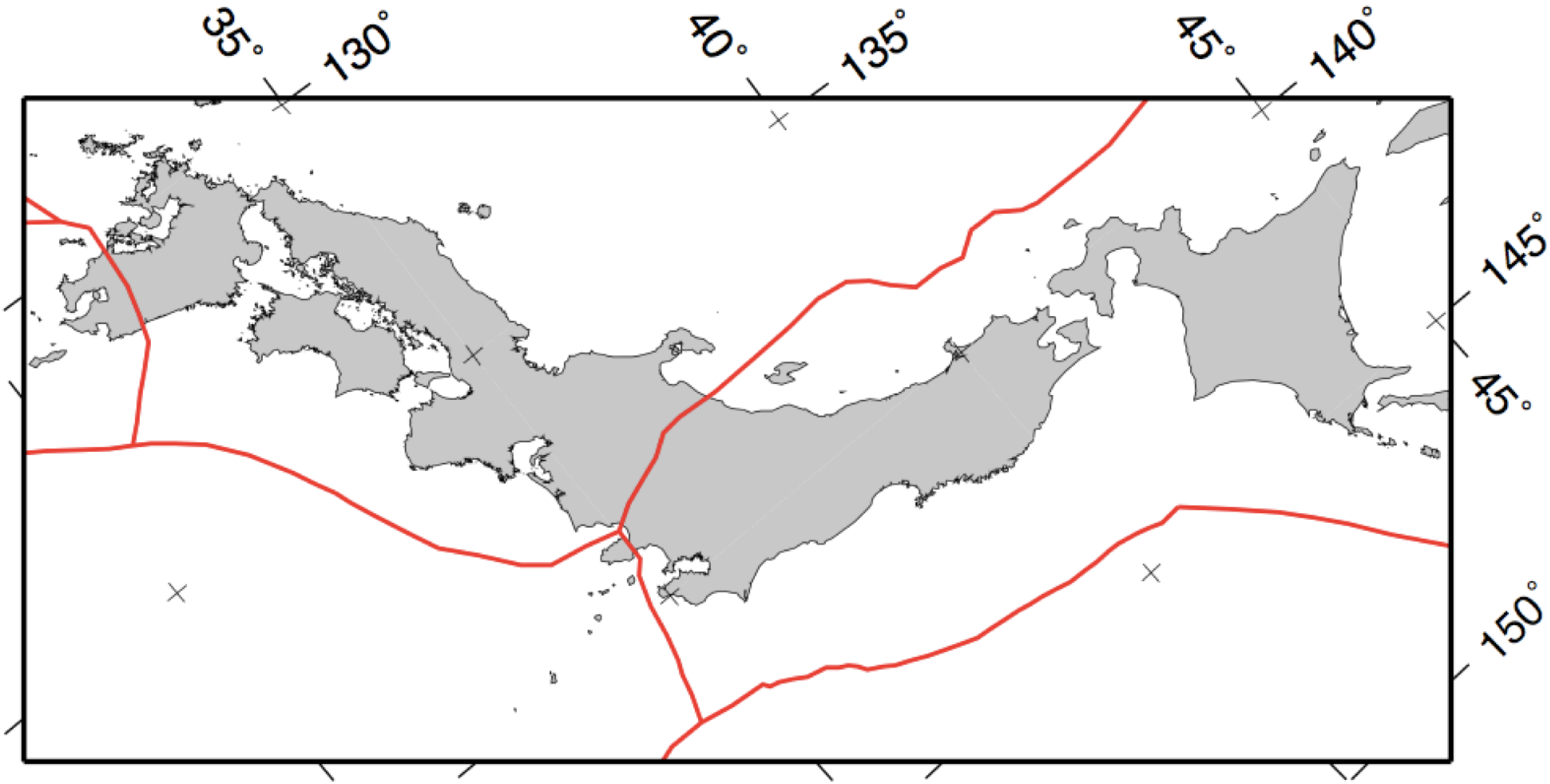


Plate boundaries

e.g., Bird, G^3, 2003

Constructing the block geometry

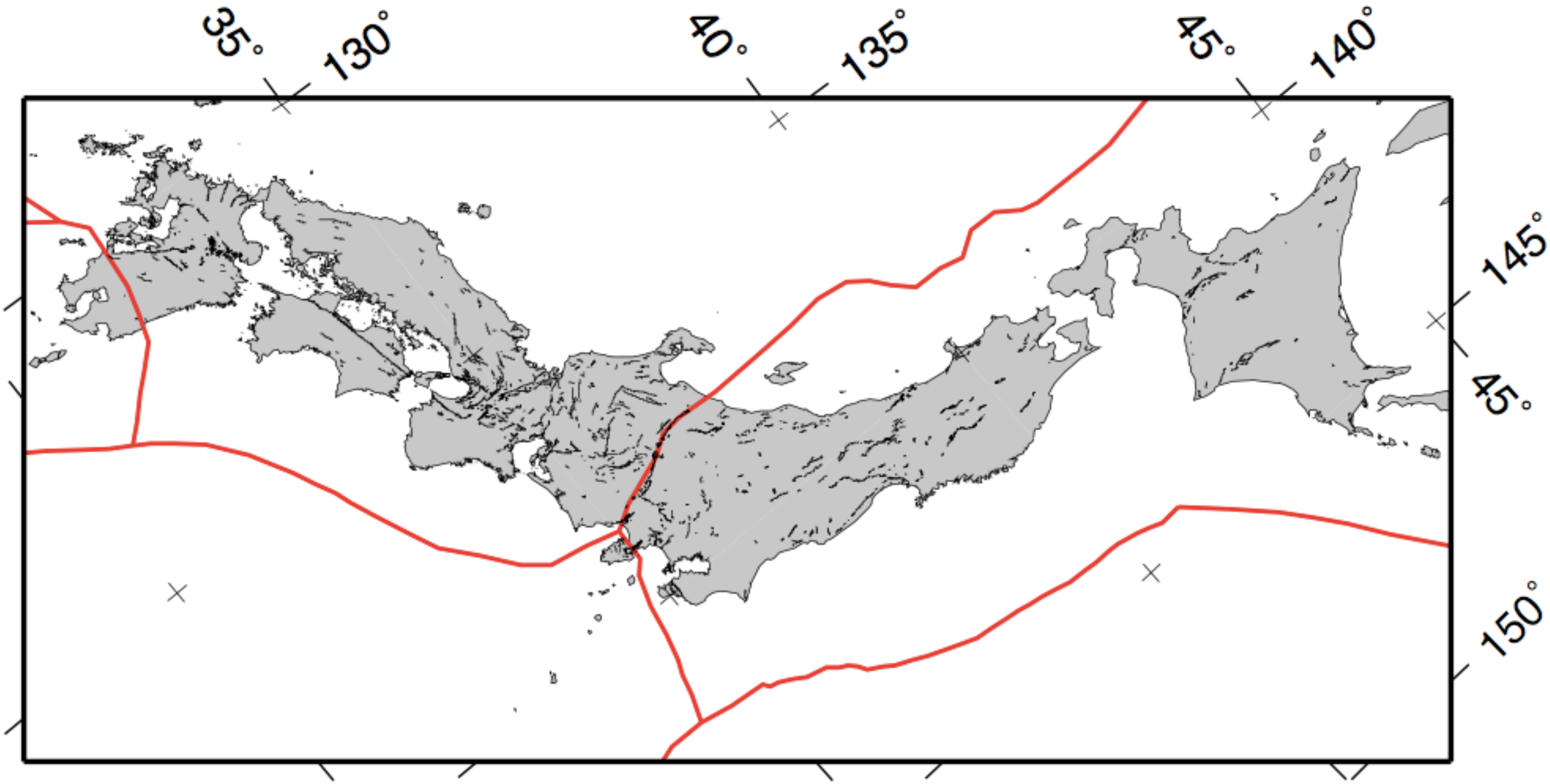


Plate boundaries → Active fault traces

e.g., Bird, G^3, 2003

Digital Active Fault Map of Japan,
AIST online active fault database

Constructing the block geometry

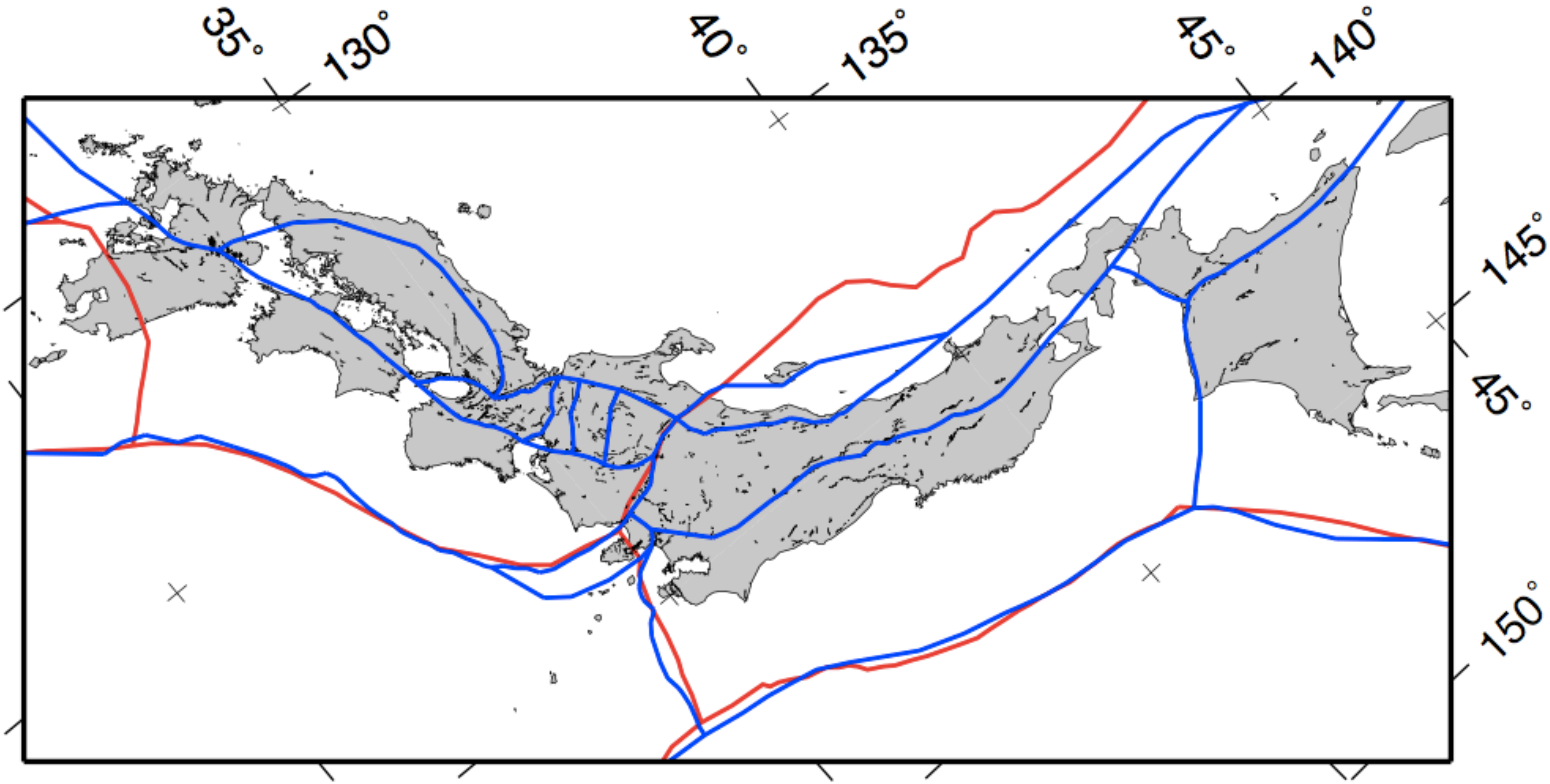


Plate boundaries ⟶ Active fault traces ⟶ Block geometry

e.g., Bird, G^3, 2003

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Constructing the block geometry

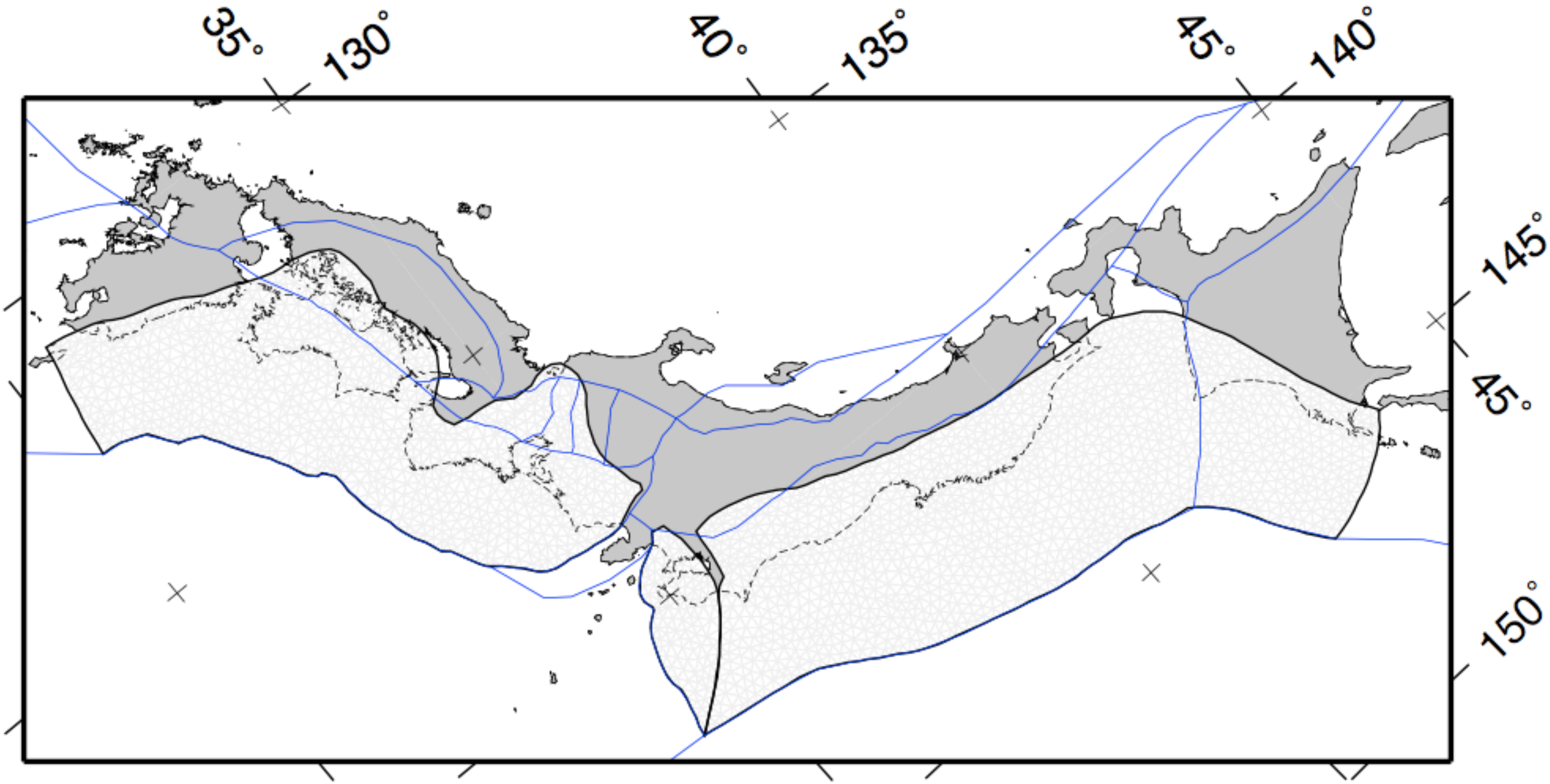
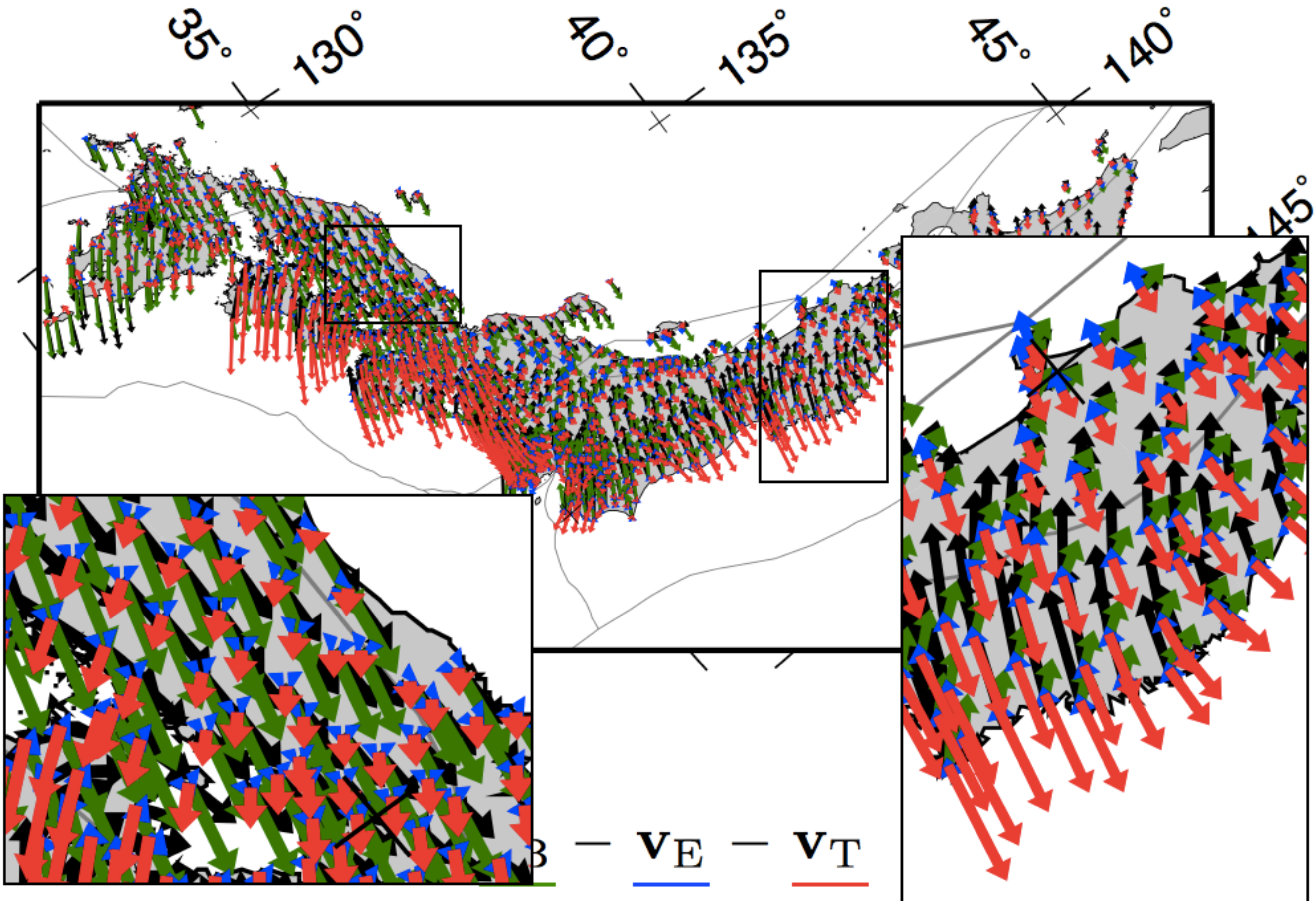


Plate boundaries → Active fault traces → Block geometry

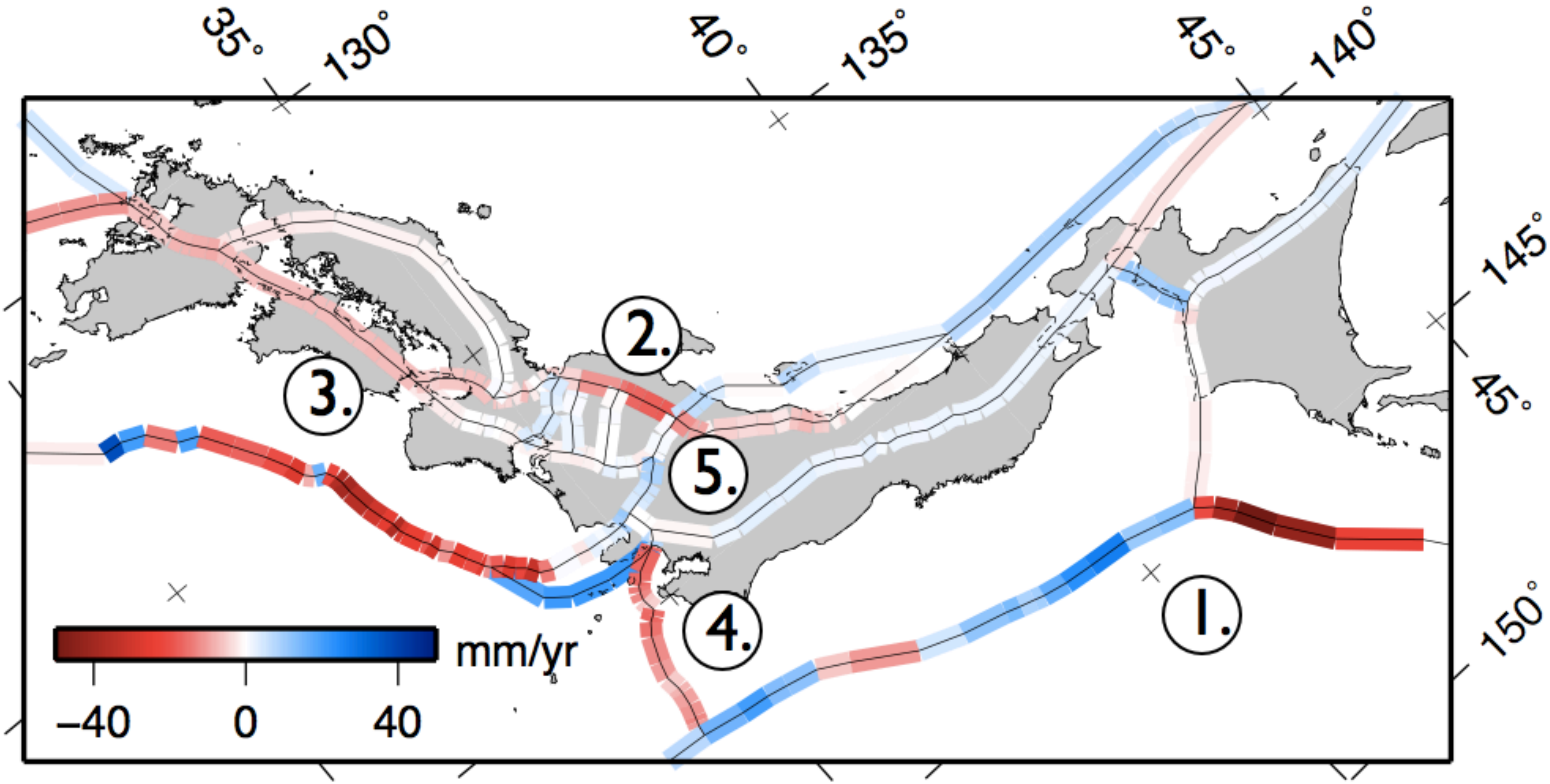
e.g., Bird, G^3, 2003

Digital Active Fault Map of Japan,
AIST online active fault database

Interaction of subduction zone and crustal faults



Geodetically constrained strike-slip rates: Japan



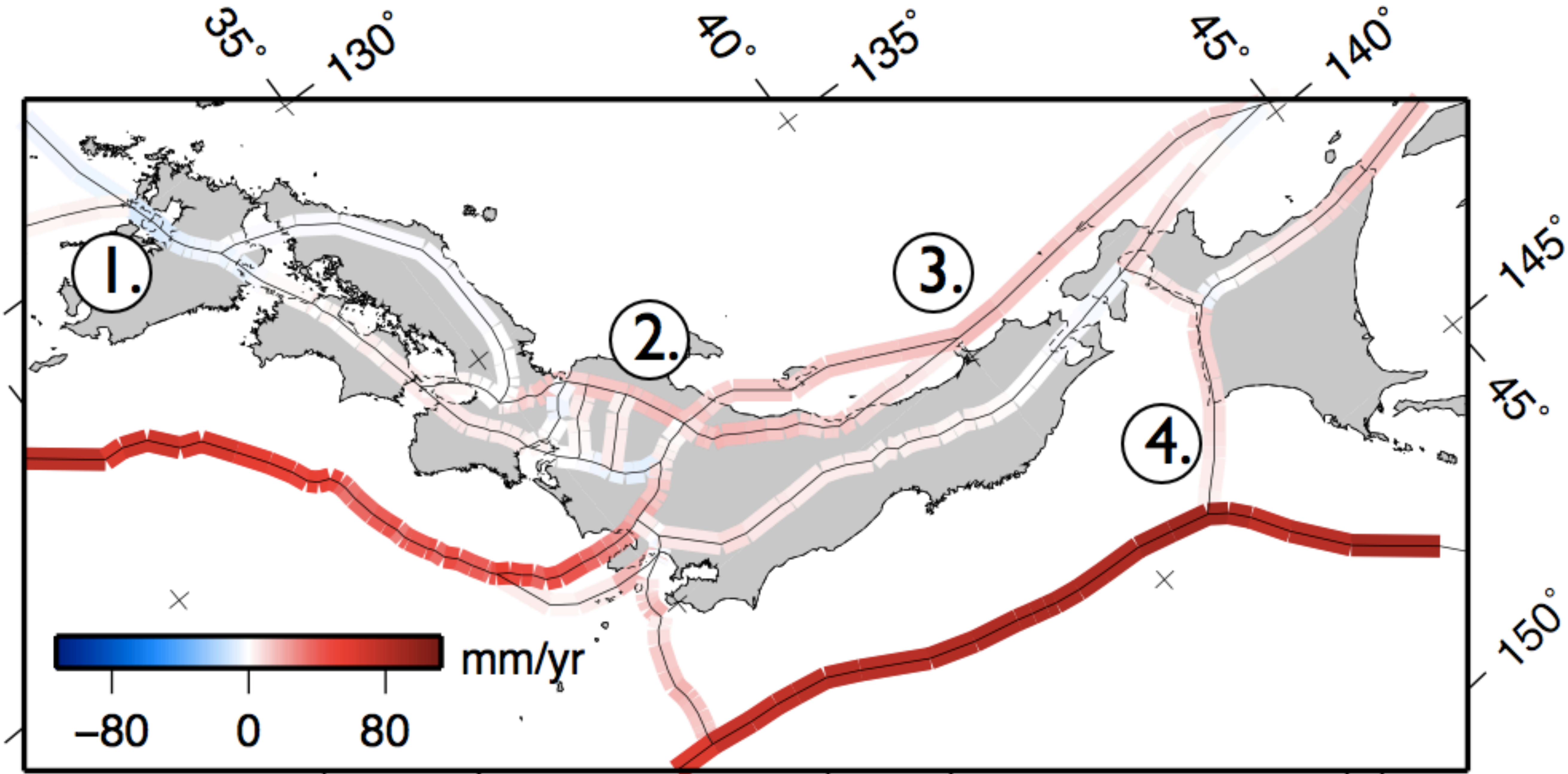
Right-lateral

Left-lateral

1. Sign depends on strike of trench
2. ~15 mm/yr R-L on NKTZ
3. ~7 mm/yr R-L on MTL, ~22 mm/yr at Nankai
4. ~17 mm/yr R-L at Sagami Trough
5. Up to 10 mm/yr L-L on ISTL

Loveless & Meade, *JGR*, 2010

Geodetically constrained dip-slip rates: Japan



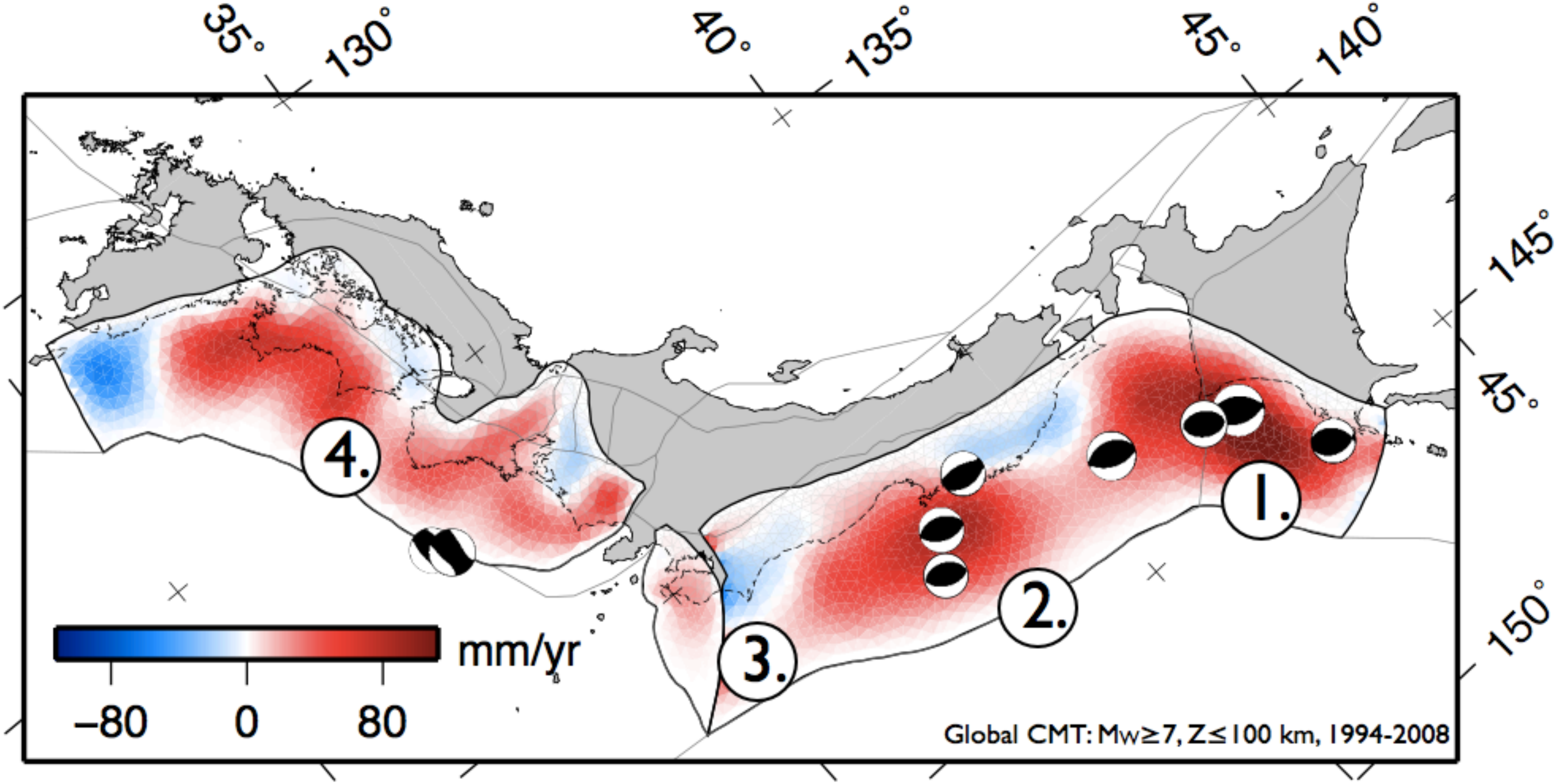
Opening Normal

Closing Reverse

1. 5-8 mm/yr extension across Beppu Graben
2. ~15 mm/yr shortening on NKTZ
3. 8-14 mm/yr shortening at Sea of Japan
4. 6-9 mm/yr shortening at Hidaka Collision Zone

Loveless & Meade, *JGR*, 2010

Geodetically constrained dip-slip rates: Japan



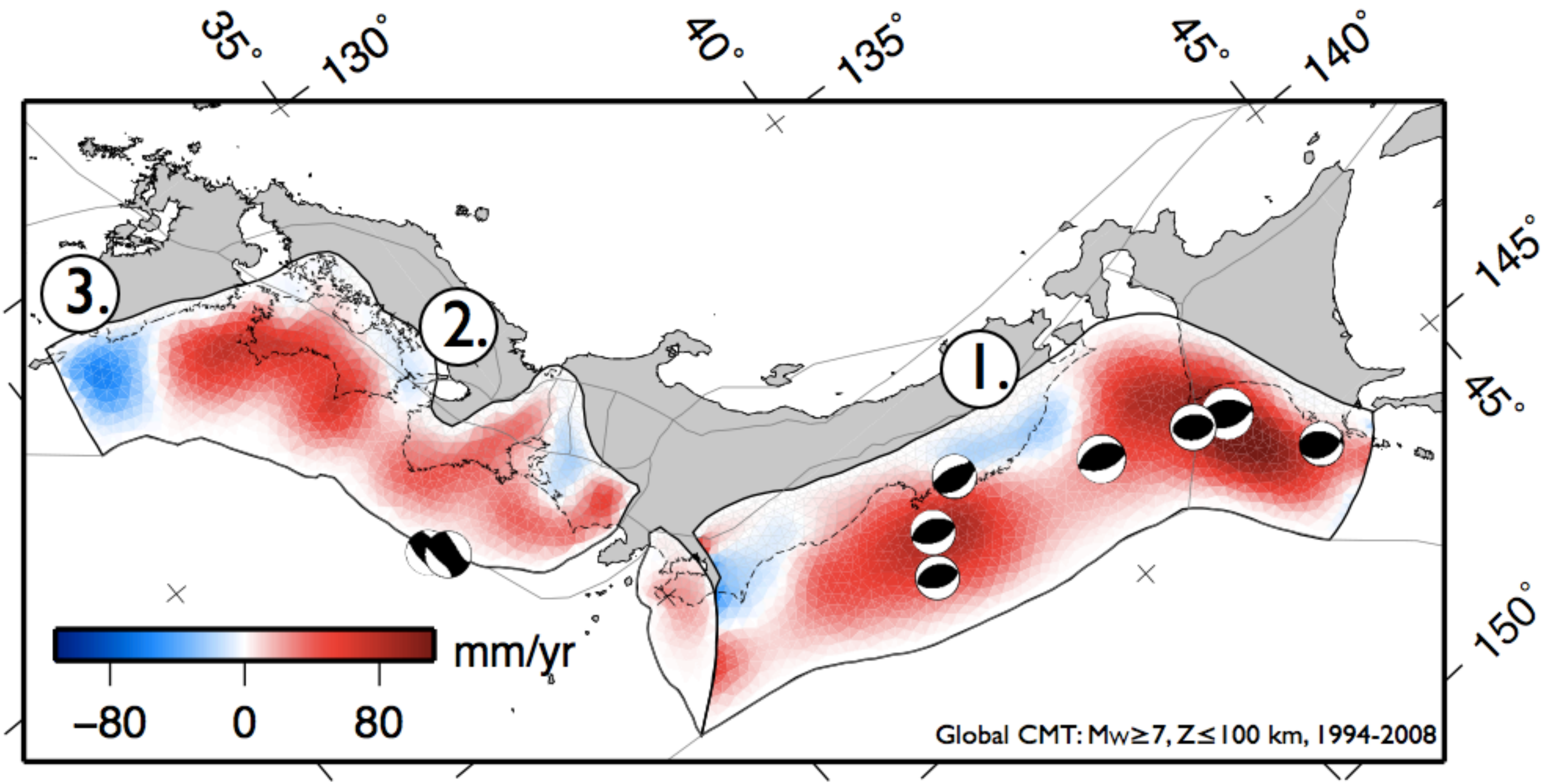
Thrust-sense Slip deficit

Concentrations of slip deficit:

1. 2003 Tokachi-oki rupture area
2. 2003–2005 Mw > 7 offshore Sendai
3. Beneath Boso Peninsula
4. 1944 & 1946 rupture areas

Loveless & Meade, *JGR*, 2010

Geodetically constrained dip-slip rates: Japan



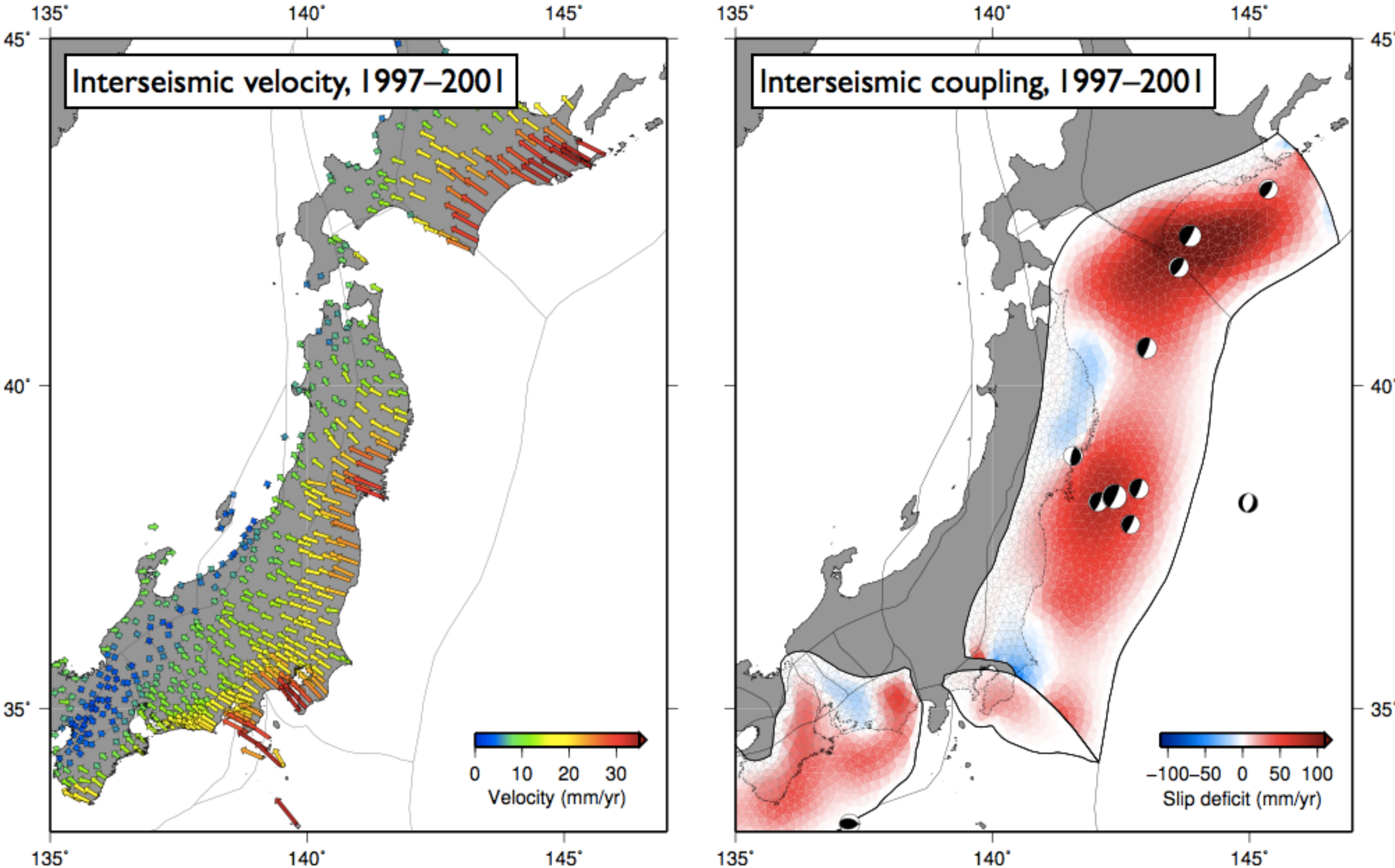
Thrust-sense Slip deficit

Thrust-sense slip:

1. Afterslip following 1994 Sanriku-oki event
2. Downdip extent of Nankai interface
3. Postseismic following 1996 Hyuga-nada events

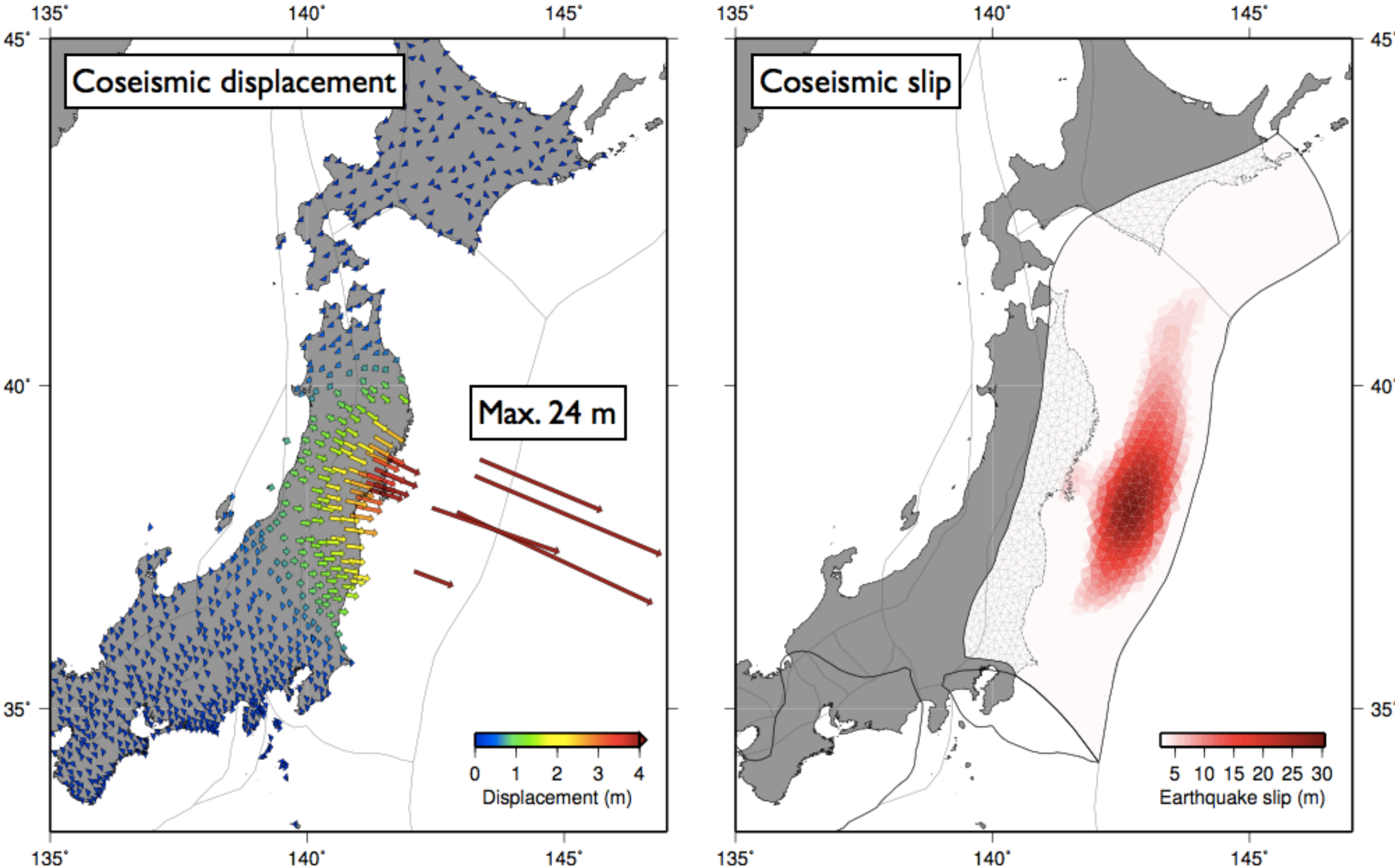
Loveless & Meade, *JGR*, 2010

Interseismic velocities and locking on the Japan Trench

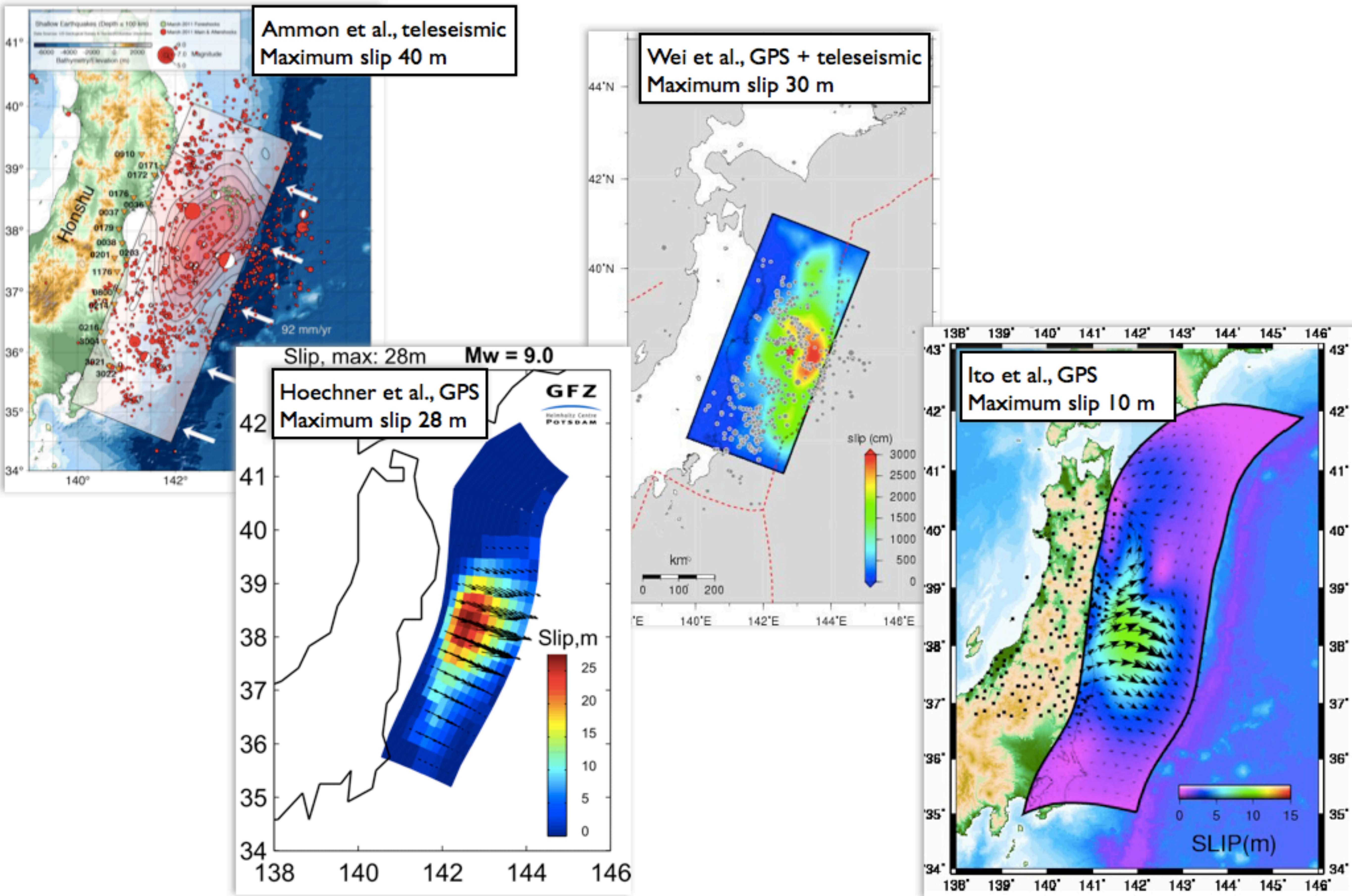


Loveless & Meade, *JGR*, 2010

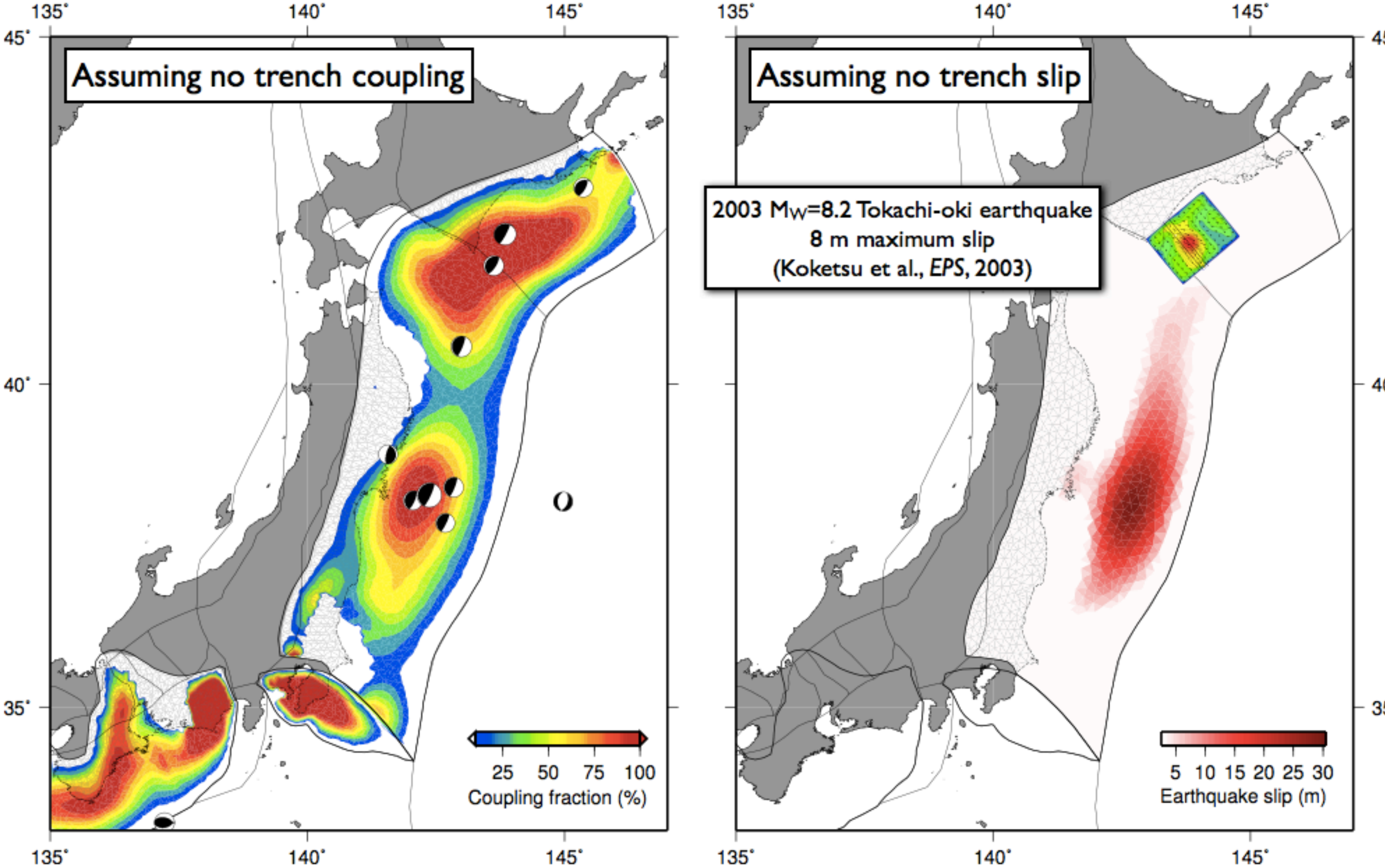
March 2011 Tohoku-oki earthquake displacement and slip



Coseismic slip of the Tohoku-oki earthquake



Correlation of interseismic coupling and coseismic slip



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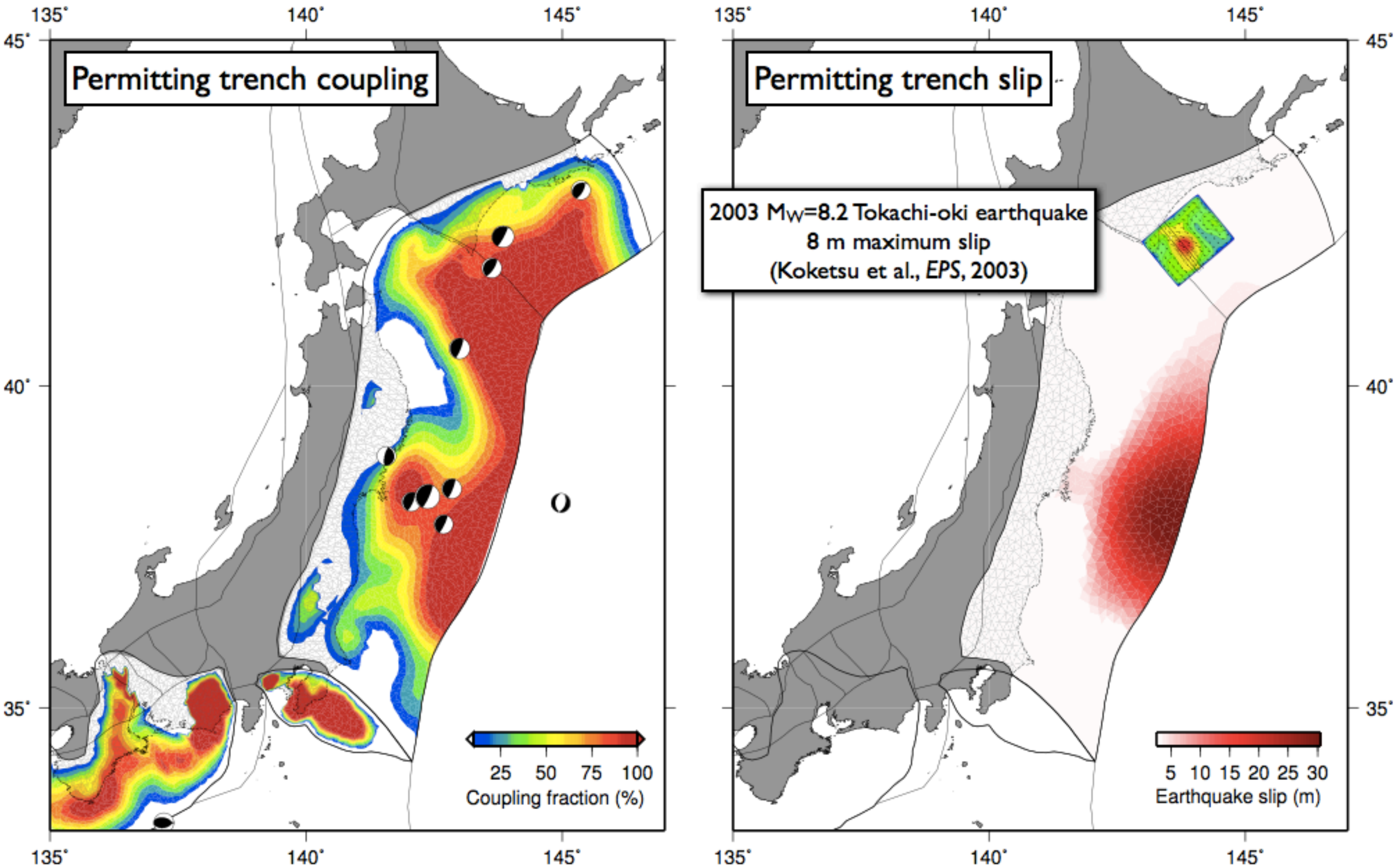

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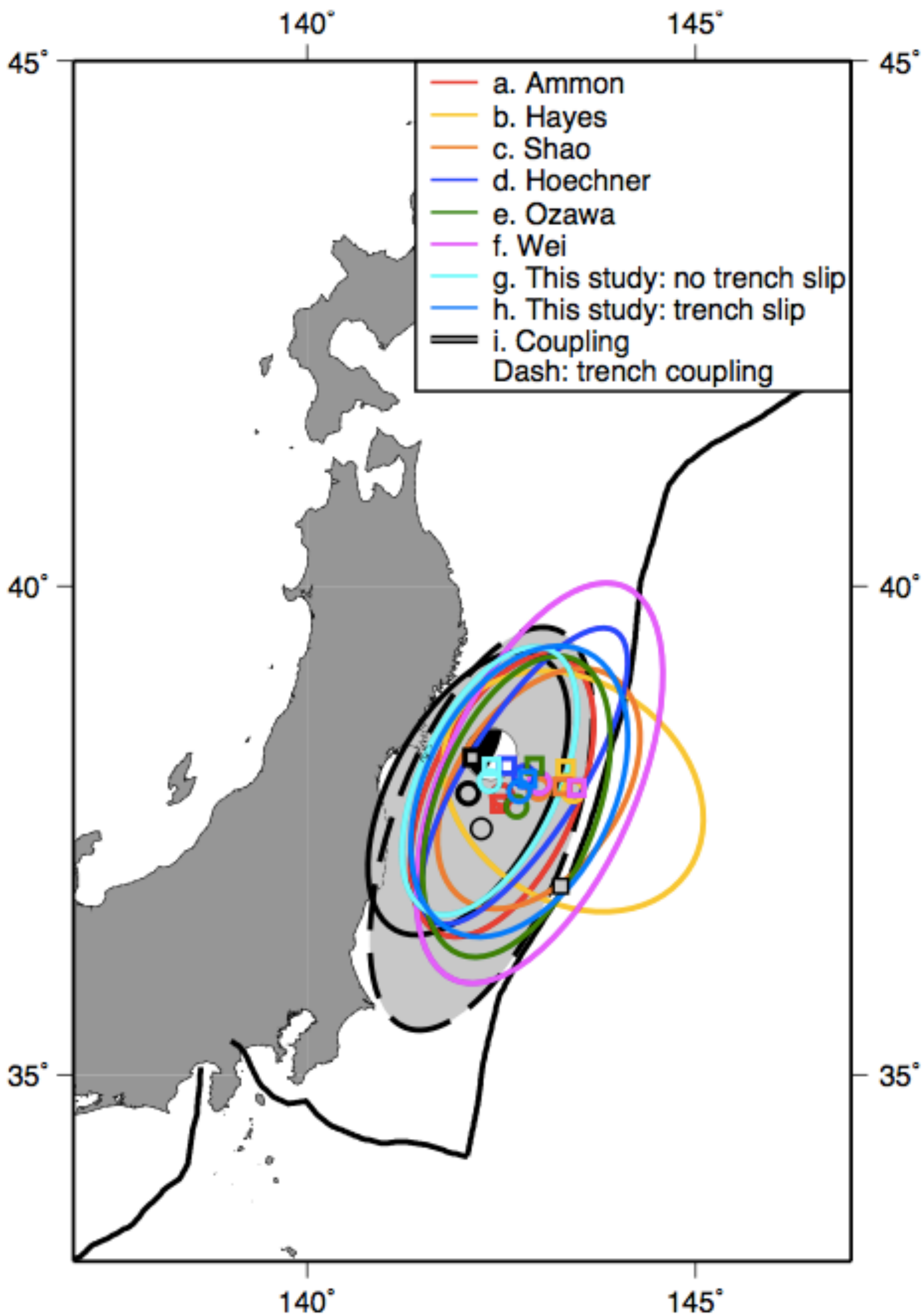


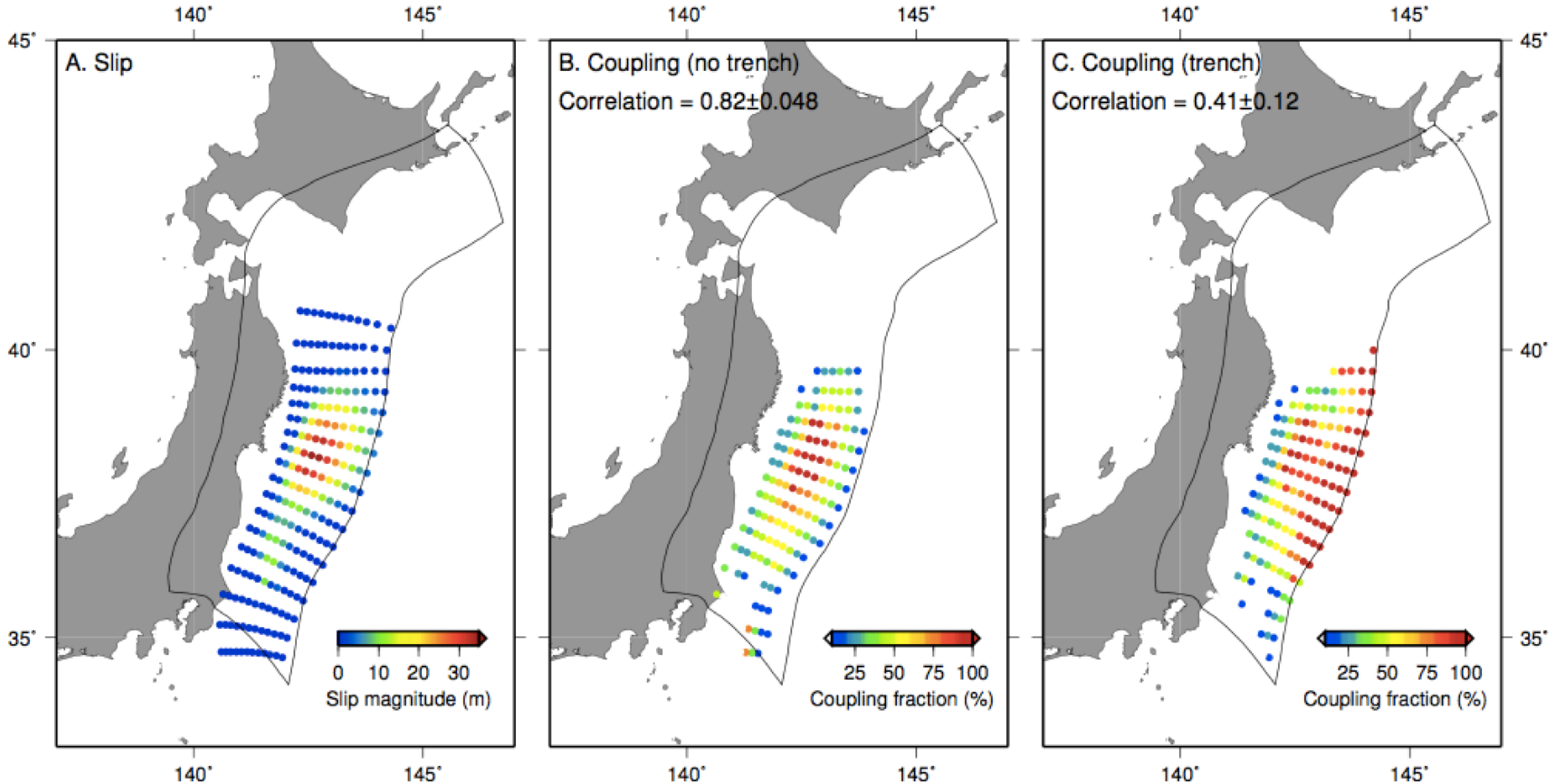
Coseismic ellipses: Best-fit to 4 m slip contour
Interseismic ellipses: Best-fit to 30% coupling

Circle: Ellipse center
Square: Location of maximum slip/coupling

Maximum coseismic slip magnitude range: 18–60 m
Maximum coseismic slip depth range: 12–24 km

Loveless & Meade, *GRL*, 2011

Correlation of interseismic coupling and coseismic slip



Slip model from Hoechner et al., 2011

Coupling distribution mapped onto Hoechner et al. fault model (trench uncoupled)

Coupling distribution mapped onto Hoechner et al. fault model (trench coupled)

Loveless & Meade, *GRL*, 2011

Correlation of interseismic coupling and coseismic slip

		Interseismic coupling	
		Trench uncoupled	Trench coupled
Seismic	Ammon	0.54±0.06	0.54±0.06
Seismic	UCSB	0.25±0.13	0.46±0.11
Seismic	Hayes	0.43±0.10	0.51±0.09
Joint seismic/geodetic	Wei	0.32±0.10	0.56±0.08
Joint seismic/geodetic	Koketsu	0.64±0.13	0.50±0.17
Joint seismic/geodetic	Chu	0.09±0.12	0.52±0.09
Geodetic	Simons (mean)	0.56±0.07	0.32±0.09
Geodetic	Simons (median)	0.55±0.07	0.31±0.09
Geodetic	Ozawa	0.80±0.04	0.37±0.10
Geodetic	Hoechner	0.82±0.05	0.41±0.12
Geodetic	This study (no trench)	0.83±0.02	0.42±0.04
Geodetic	This study (trench slip)	0.40±0.04	0.83±0.02
	Random (Gaussian slip)	0.00±0.03	0.00±0.03
	Random (Sparse slip)	0.01±0.05	0.01±0.05

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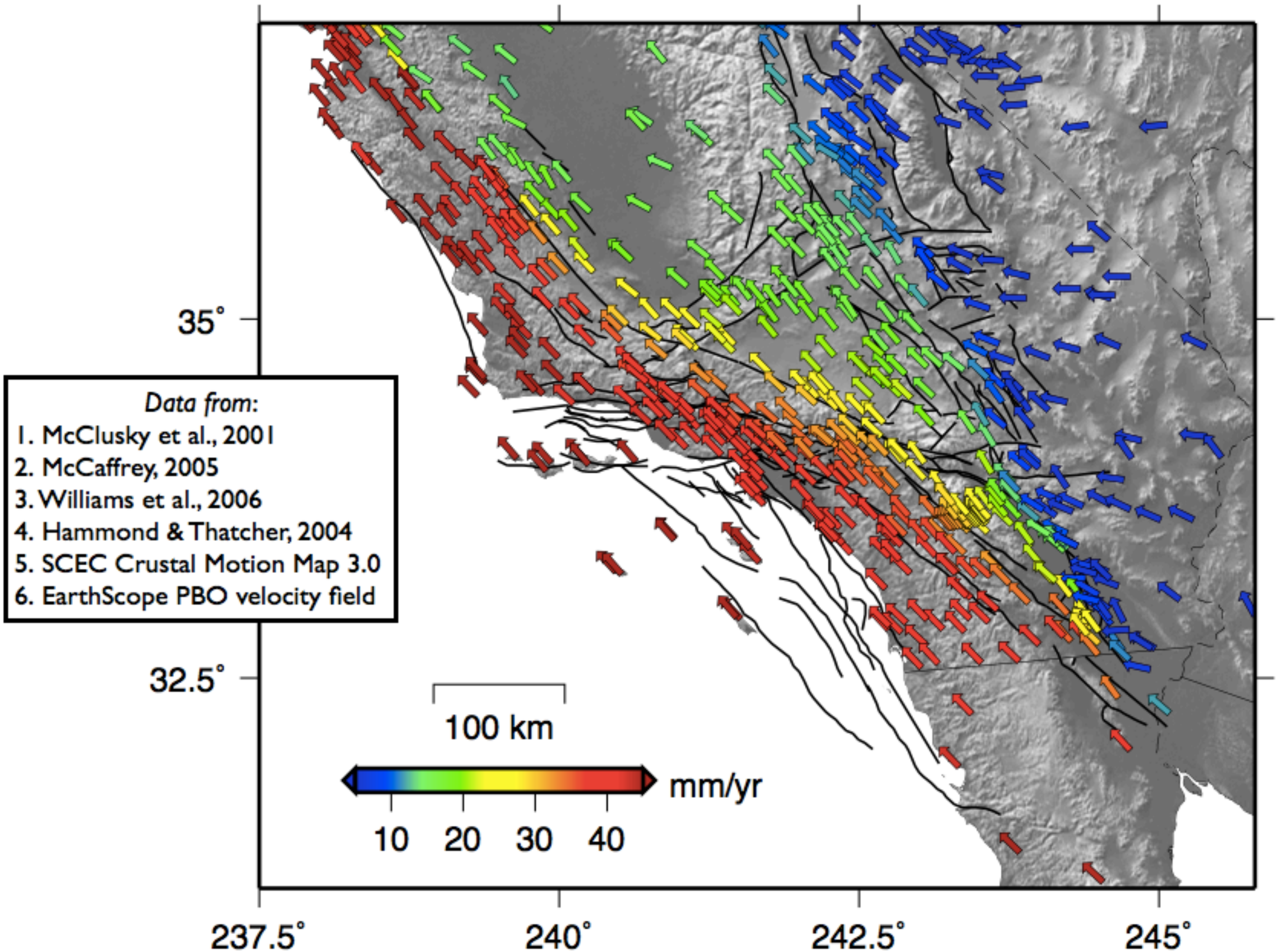
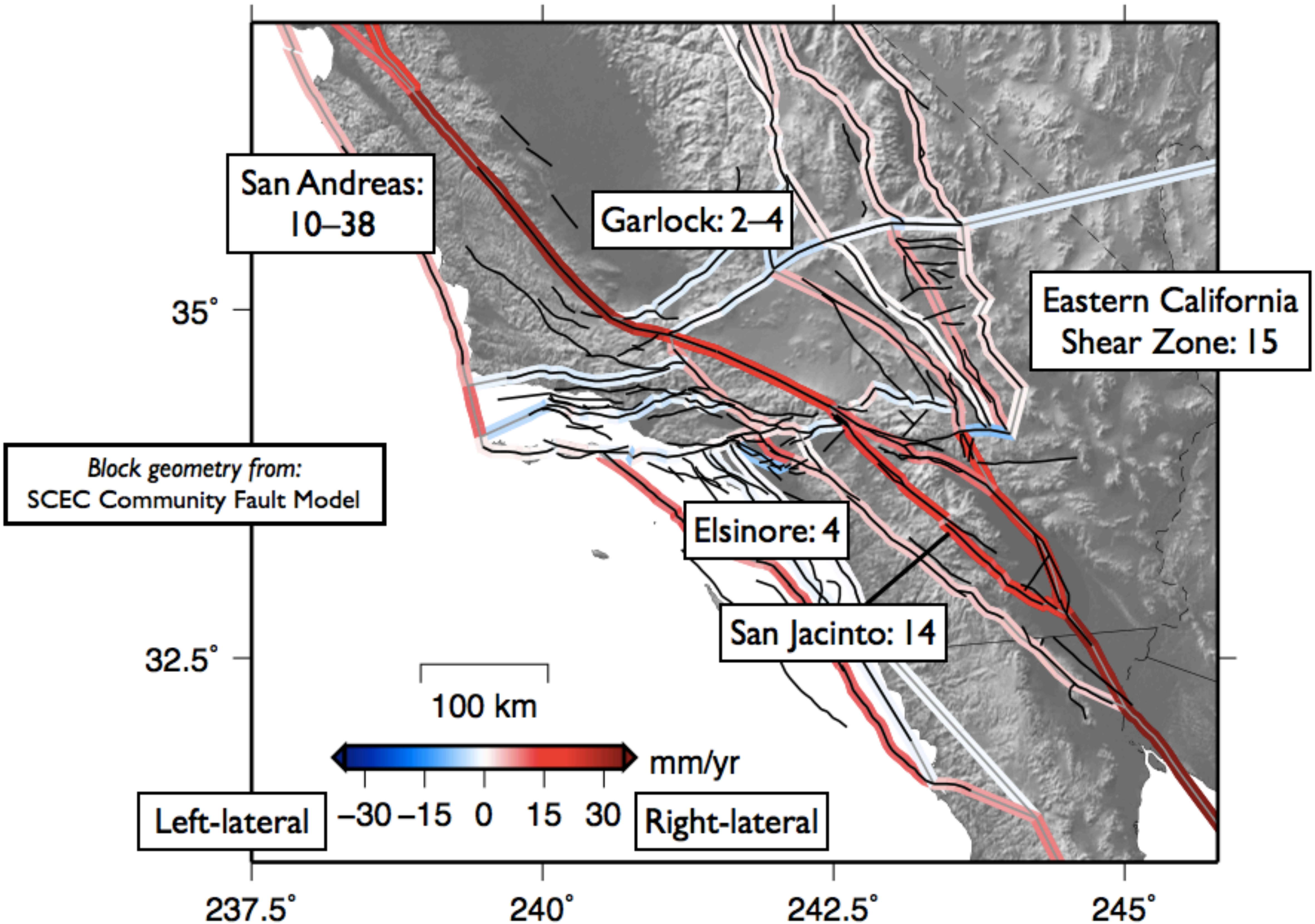
Southern California interseismic velocity field



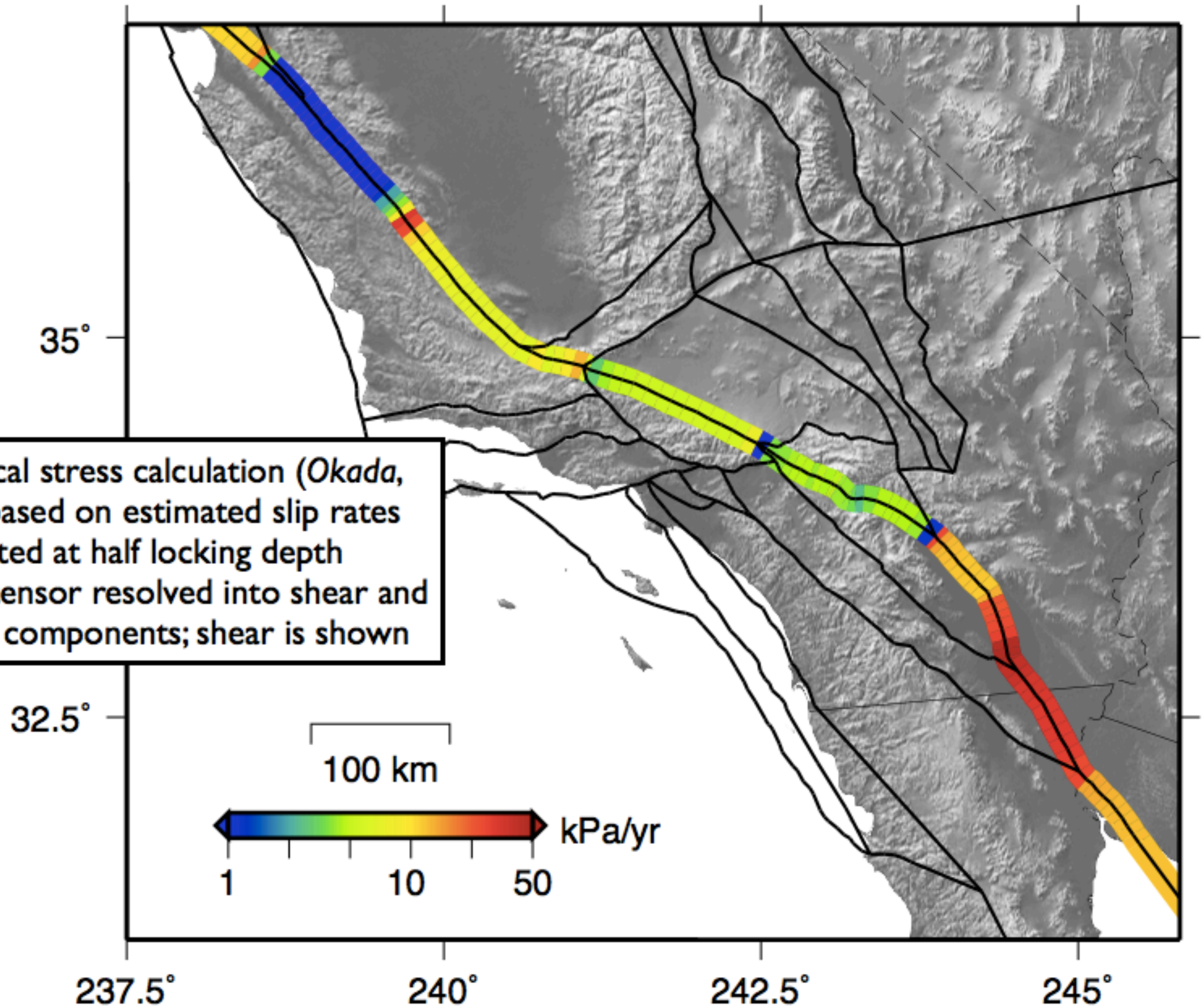
622 stations; 6-parameter (rotation + translation) velocity field combination

Geodetically constrained strike-slip rates: Southern CA



Loveless & Meade, *Geology*, 2011

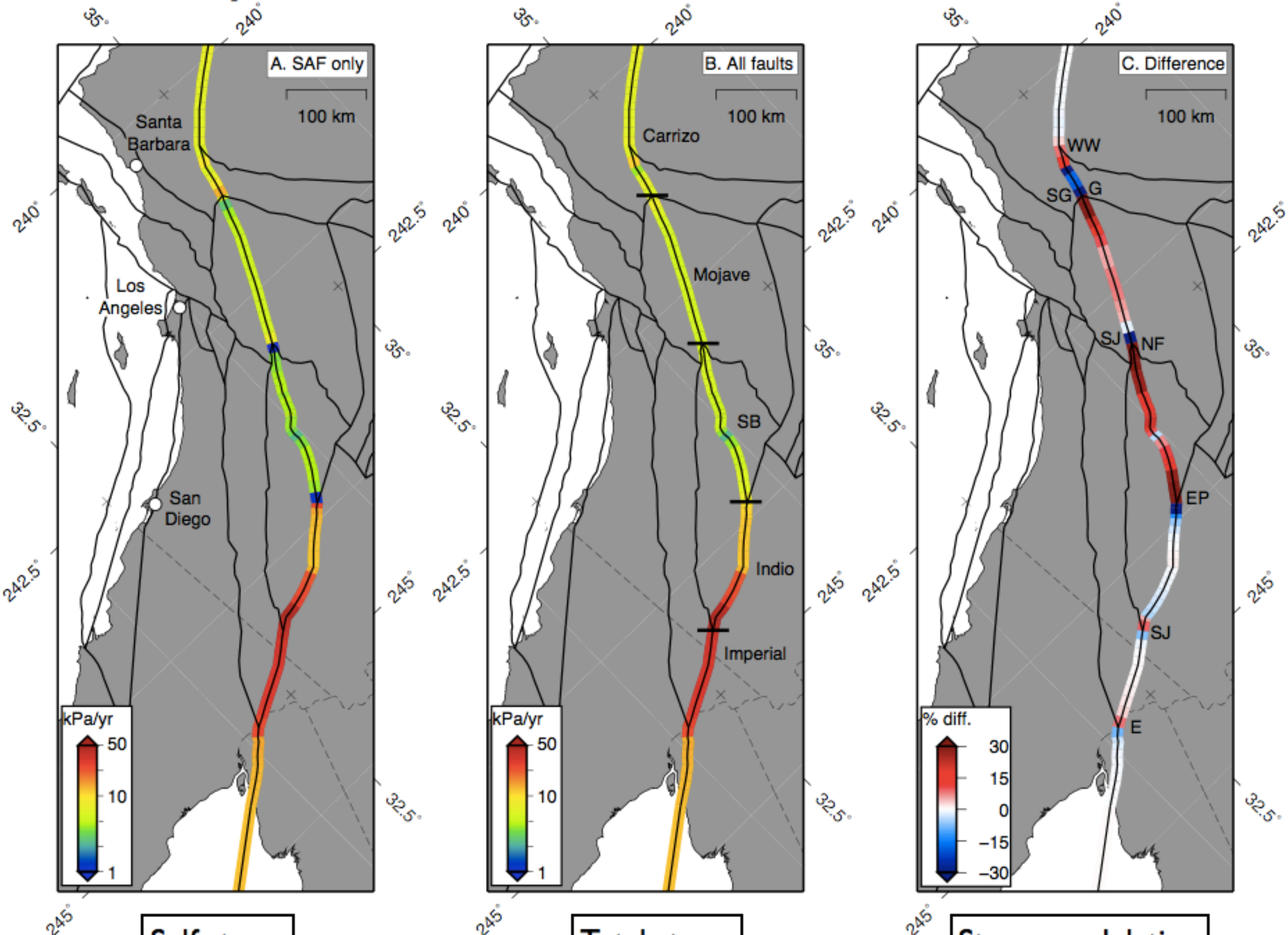
San Andreas interseismic stressing rate



- Analytical stress calculation (*Okada*, 1992) based on estimated slip rates
- Calculated at half locking depth
- Stress tensor resolved into shear and normal components; shear is shown

Loveless & Meade, *Geology*, 2011

Stress amplification from interseismic fault interactions

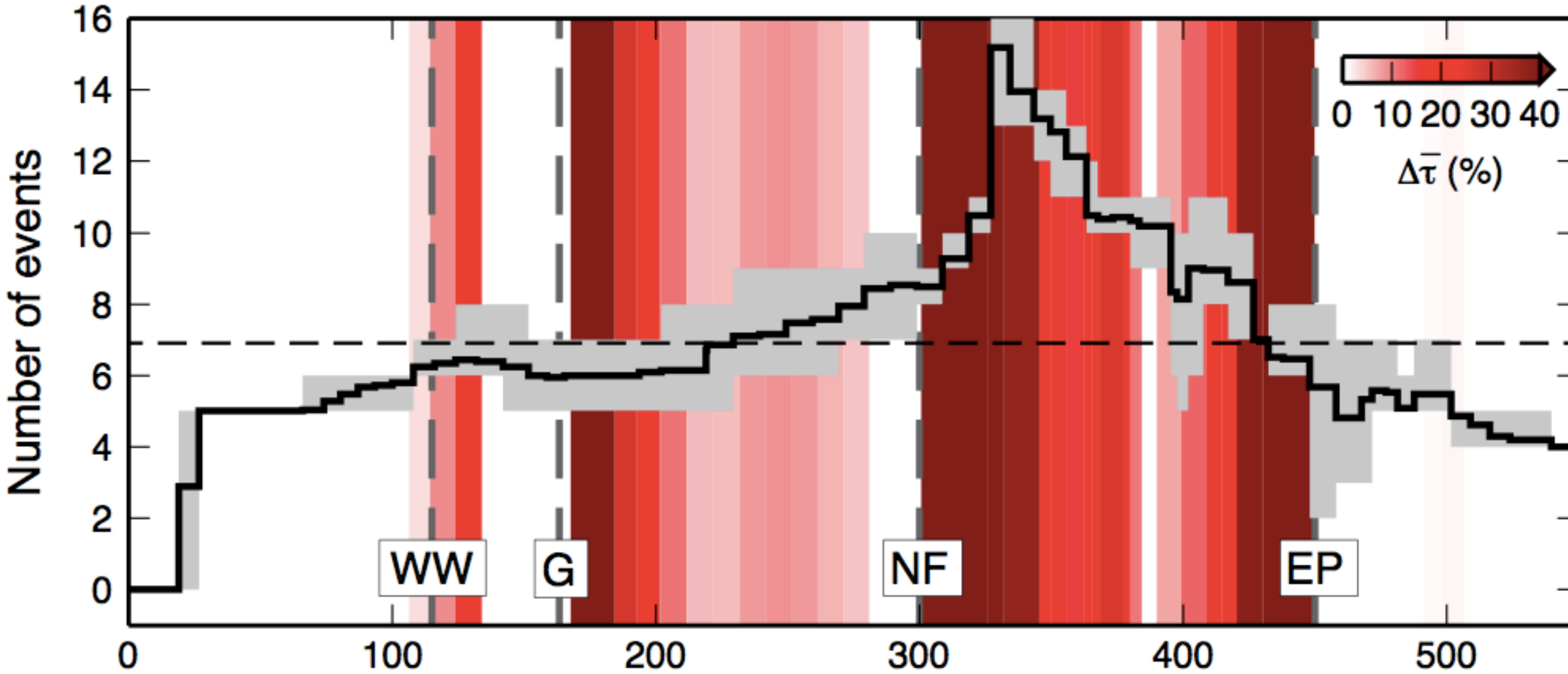


Self stress

Total stress

Stress modulation

Stress amplification and paleoseismicity



Paleoseismic events from
Biasi and Weldon, *BSSA*, 2009

Interseismic stress amplification along the Mojave and San Bernardino segment of the SAF induced by slip on all other faults, when integrated over 150 years, exceeds co- and post-seismic stress changes from the Landers-Hector Mine earthquake sequence

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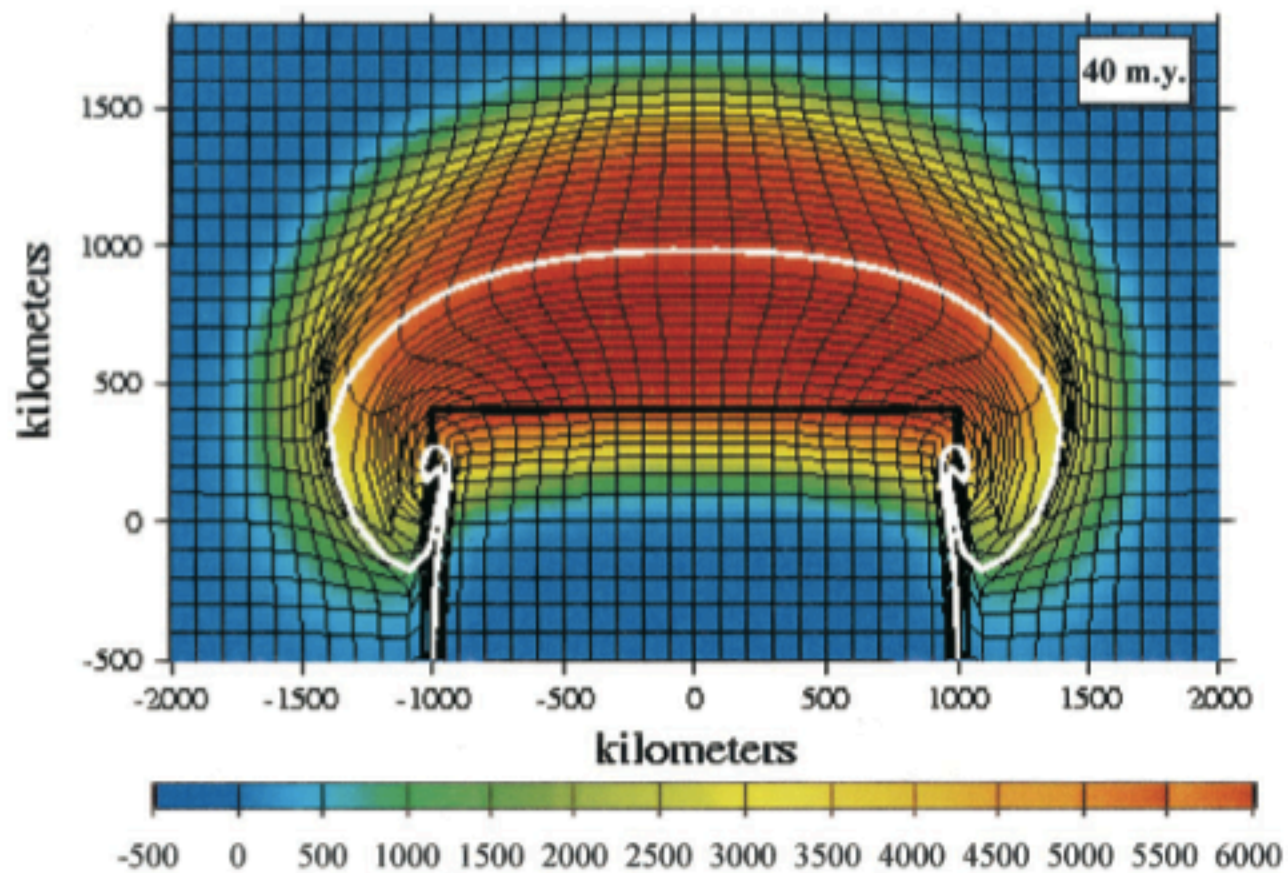
Modeling continental deformation in Tibet

Rigid block model (modeling clay analog)

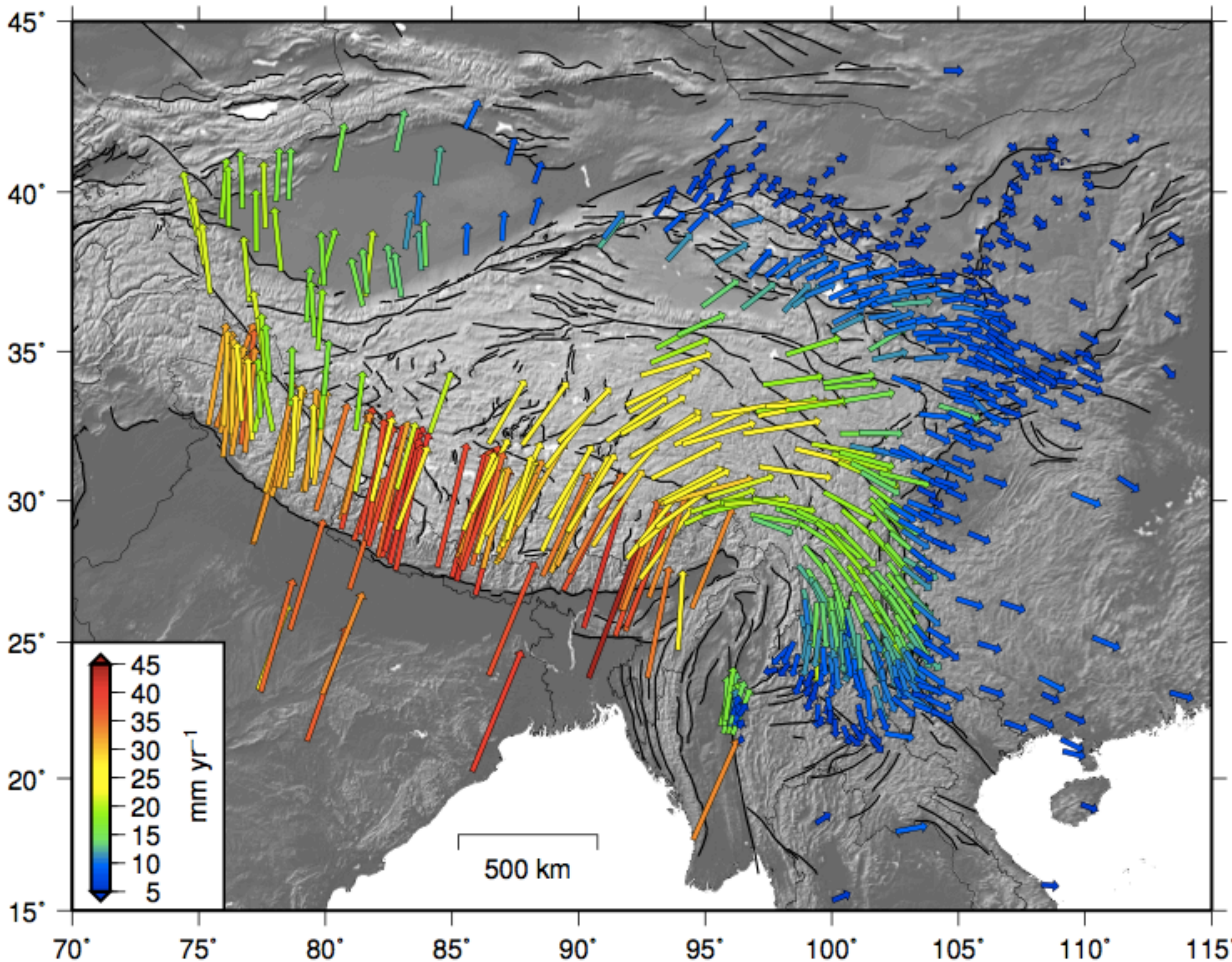
Tapponnier et al., *Geology* 1982

Continuum model (fluid sheet analog)



Shen et al., *JGR*, 2001

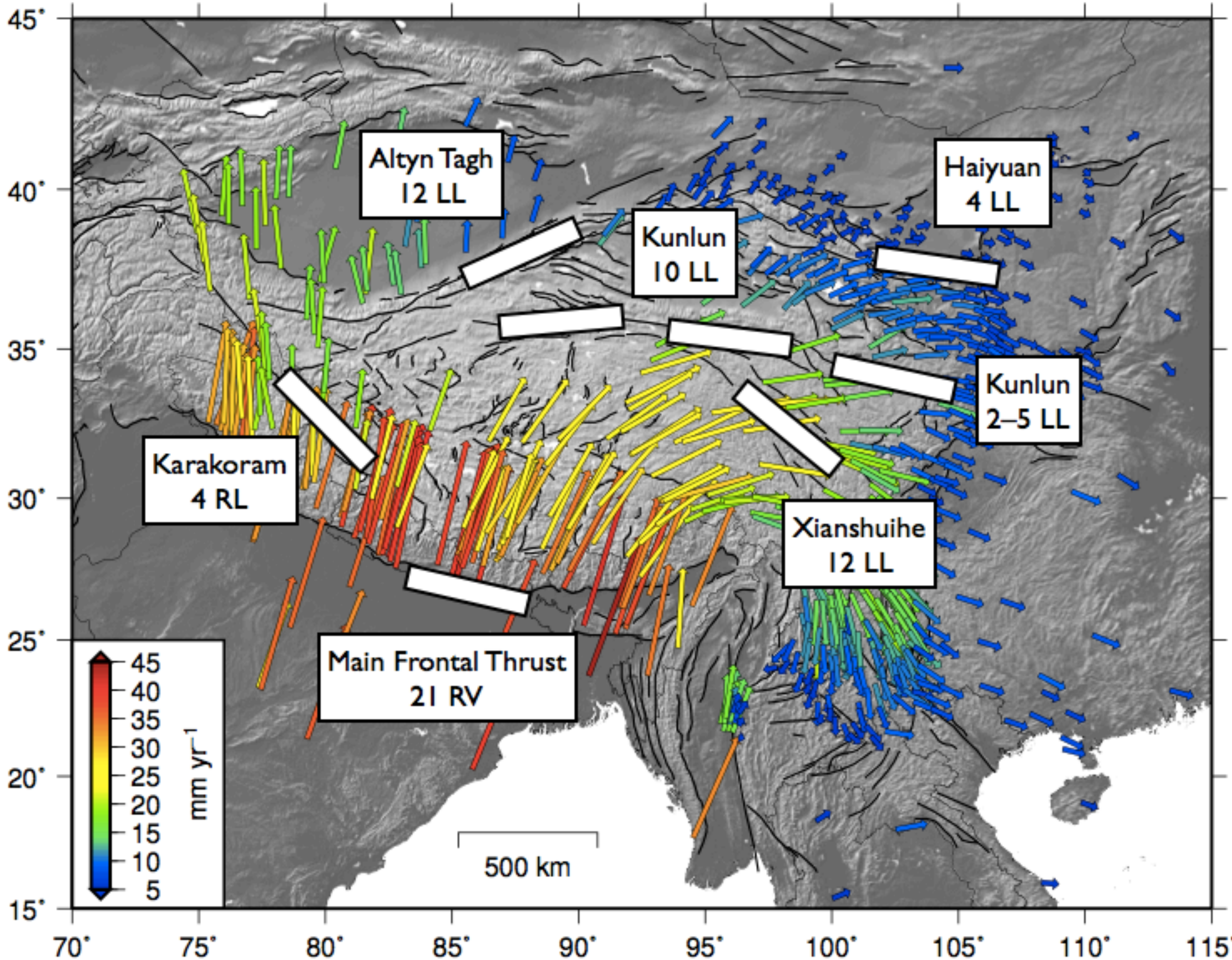
Geodetically & geologically constrained slip rates: Tibet



731 stations recording interseismic deformation

Data from Apel et al., 2006; Banerjee et al., 2008; Calais et al., 2006; Gan et al., 2007; Vigny et al., 2003

Geodetically & geologically constrained slip rates: Tibet



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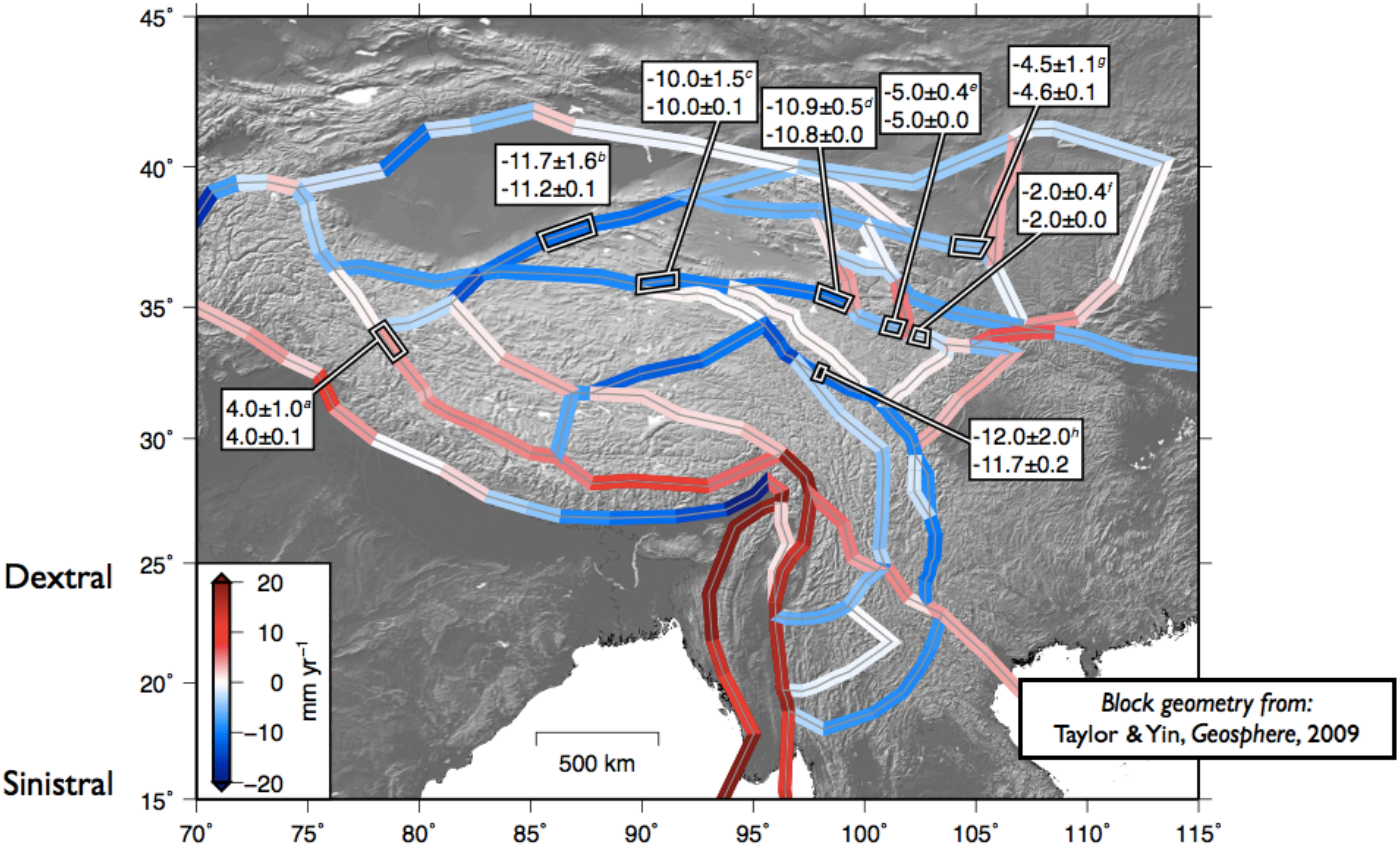
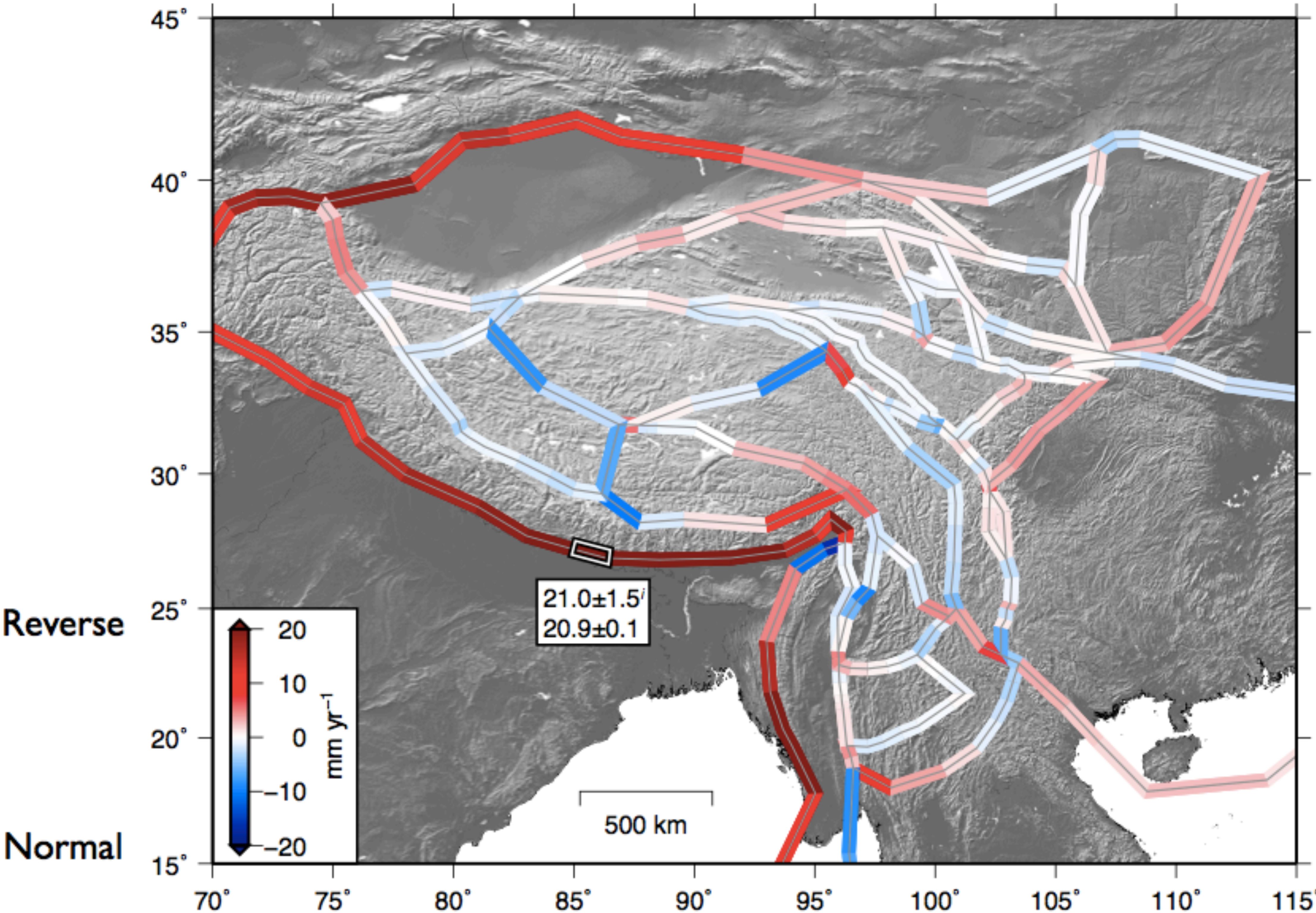


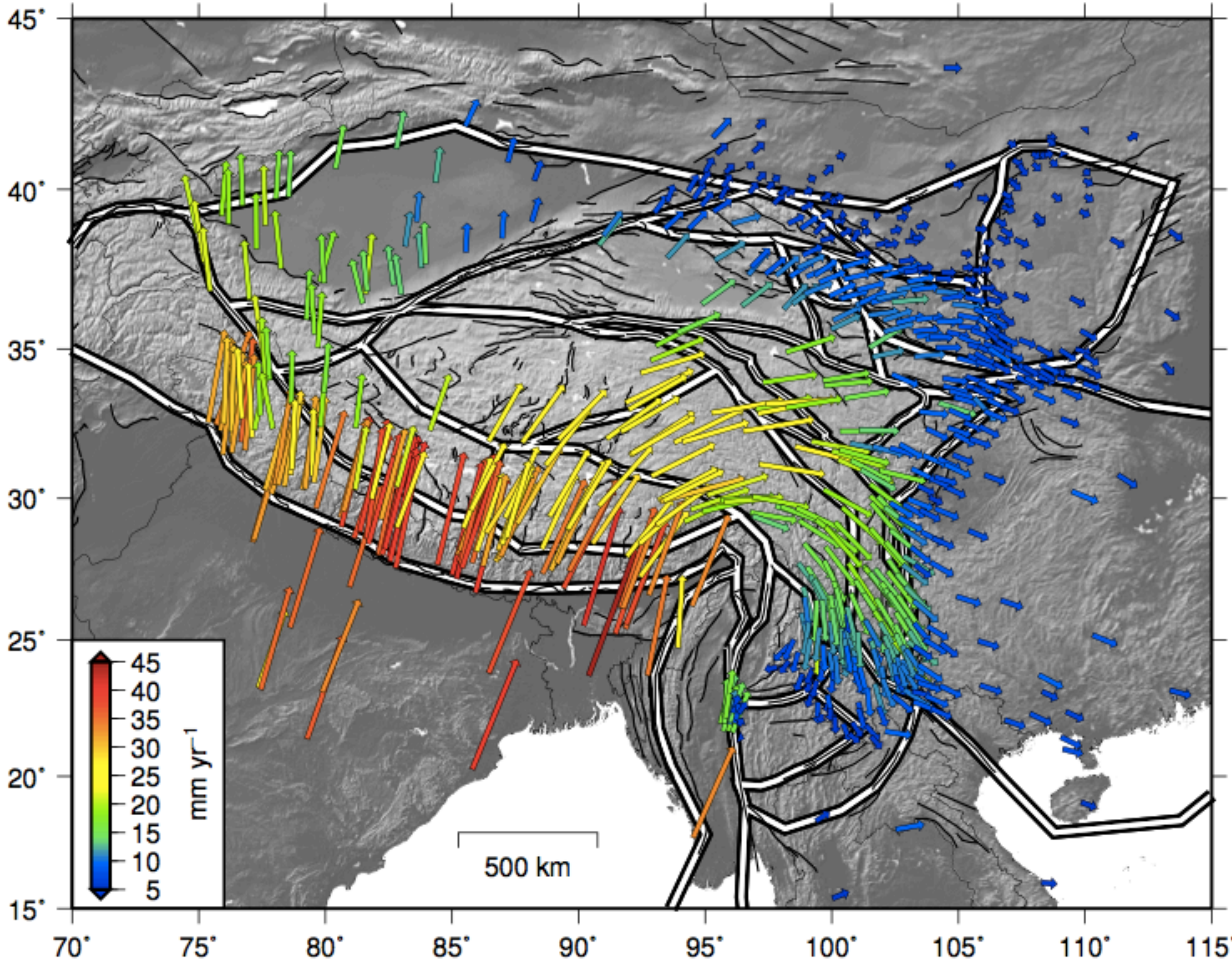
[a]Brown et al. (2002); [b]Cowgill (2007); [c]Haibing et al. (2005); [d]Van der Woerd et al. (2002); [e,f]Kirby et al. (2007); [g]Li et al. (2009); [h]Wen et al. (2003); [i]Lavé and Avouac (2000).

Geodetically & geologically constrained slip rates: Tibet



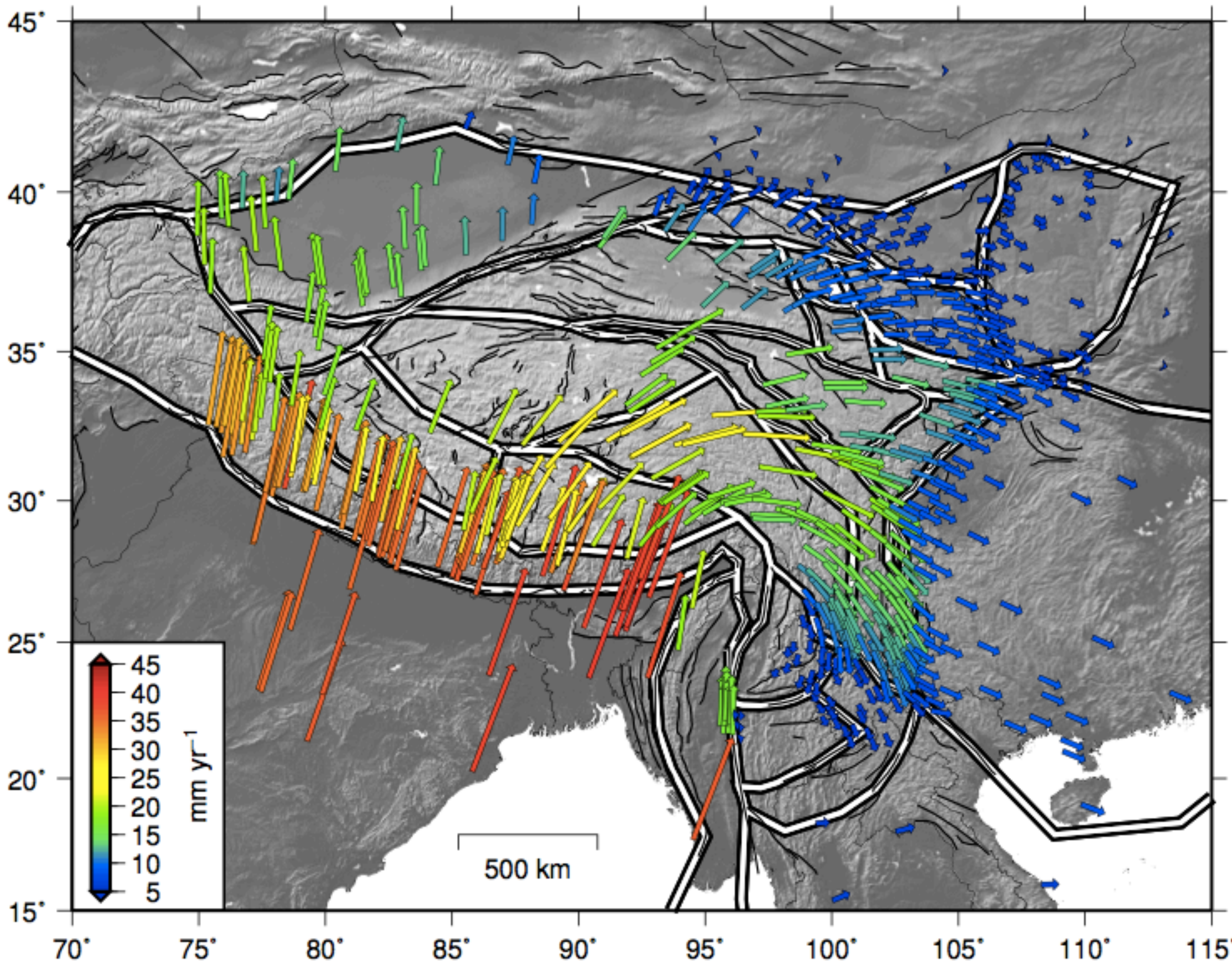
[a]Brown et al. (2002); [b]Cowgill (2007); [c]Haibing et al. (2005); [d]Van der Woerd et al. (2002); [e,f]Kirby et al. (2007); [g]Li et al. (2009); [h]Wen et al. (2003); [i]Lavé and Avouac (2000).

Evaluating deformation partitioning: Residual velocities



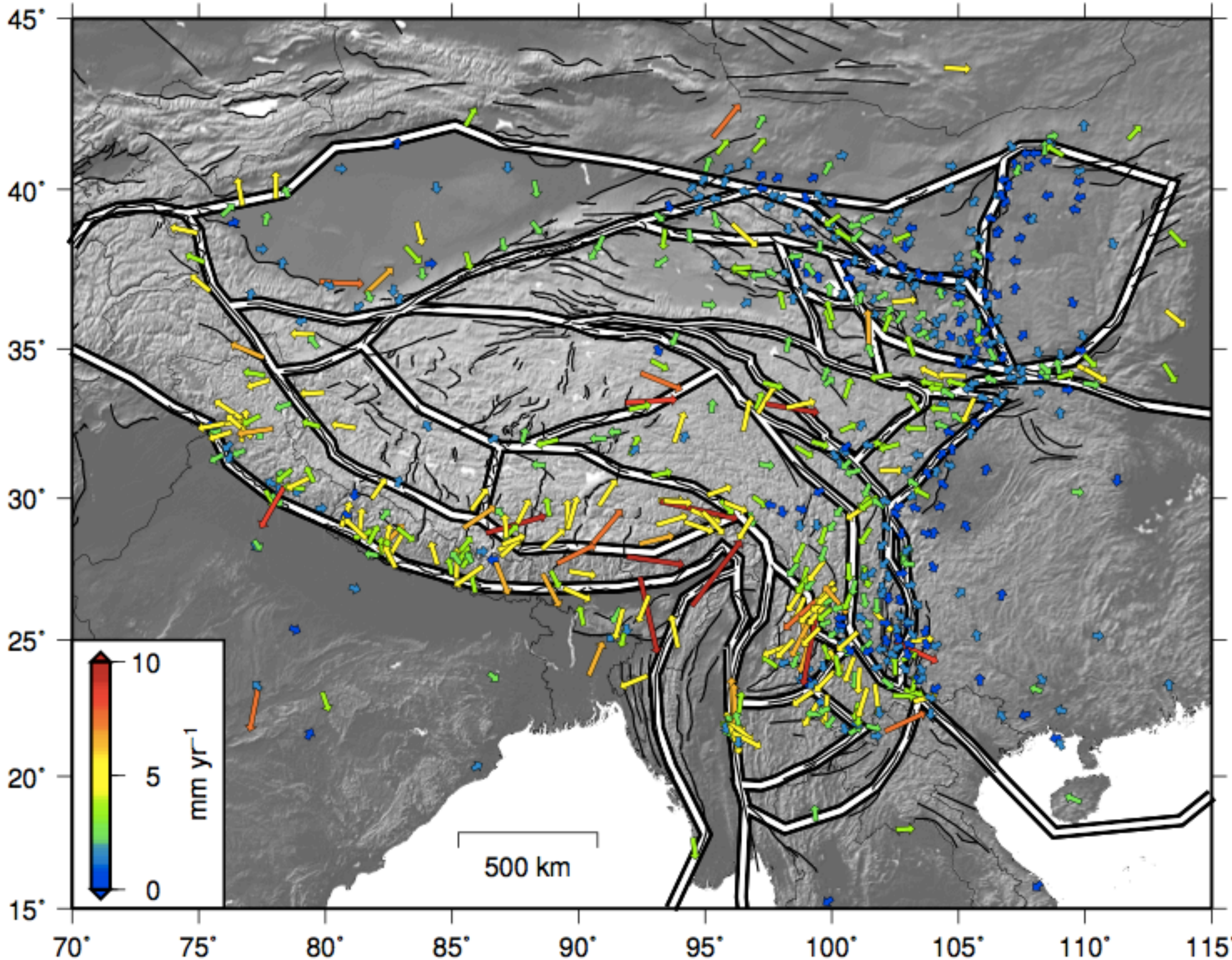
Observed

Evaluating deformation partitioning: Residual velocities



Observed – Modeled

Evaluating deformation partitioning: Residual velocities



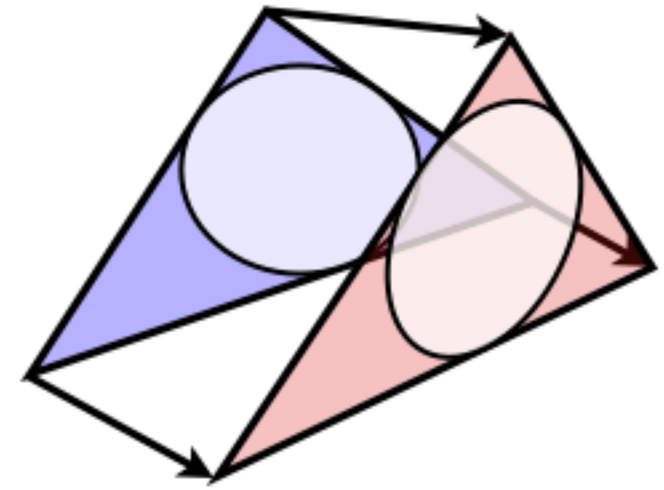
Observed – Modeled = Residual

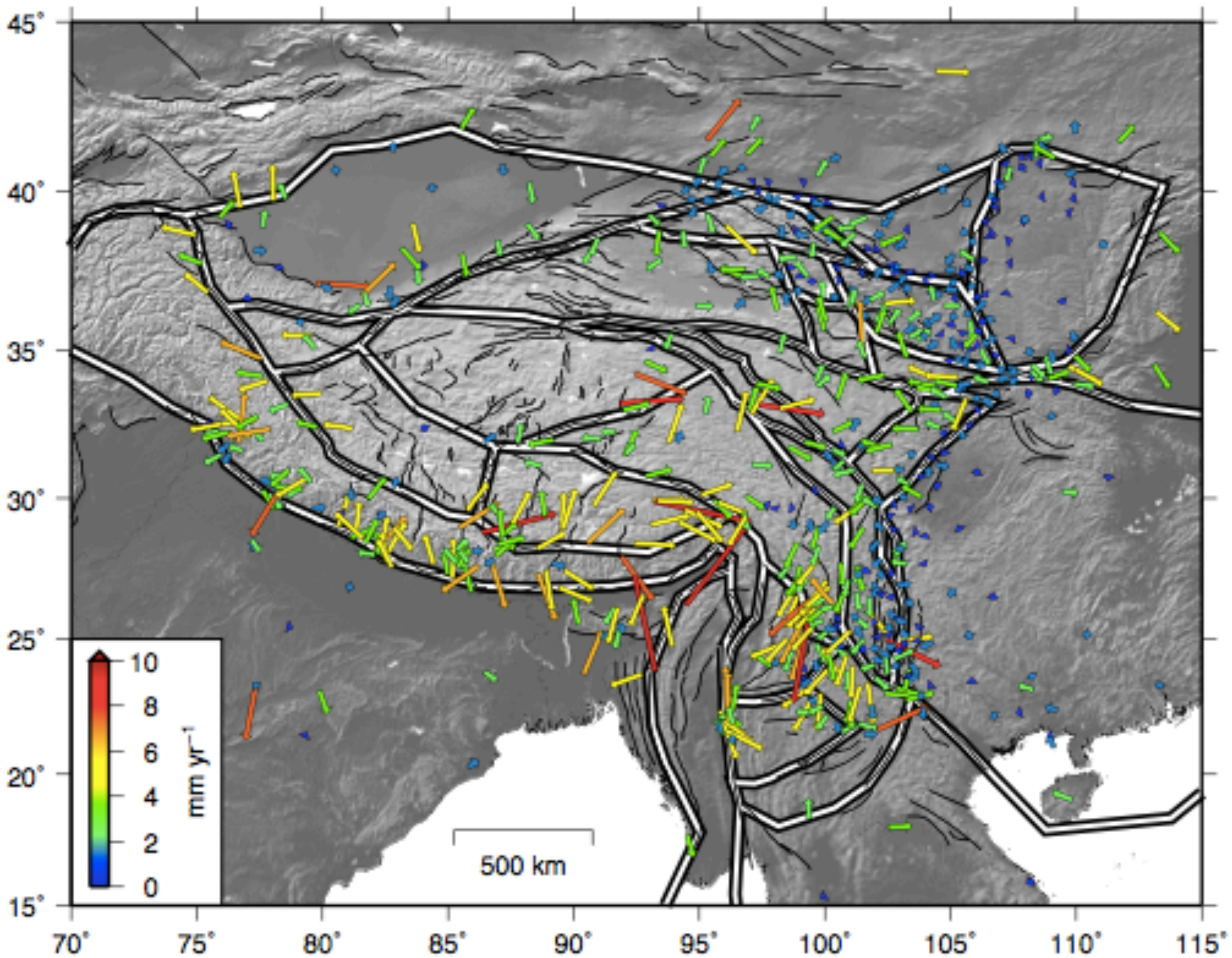
Mean residual magnitude: 2.62 mm/yr

Mean observational uncertainty: 2.05 mm/yr

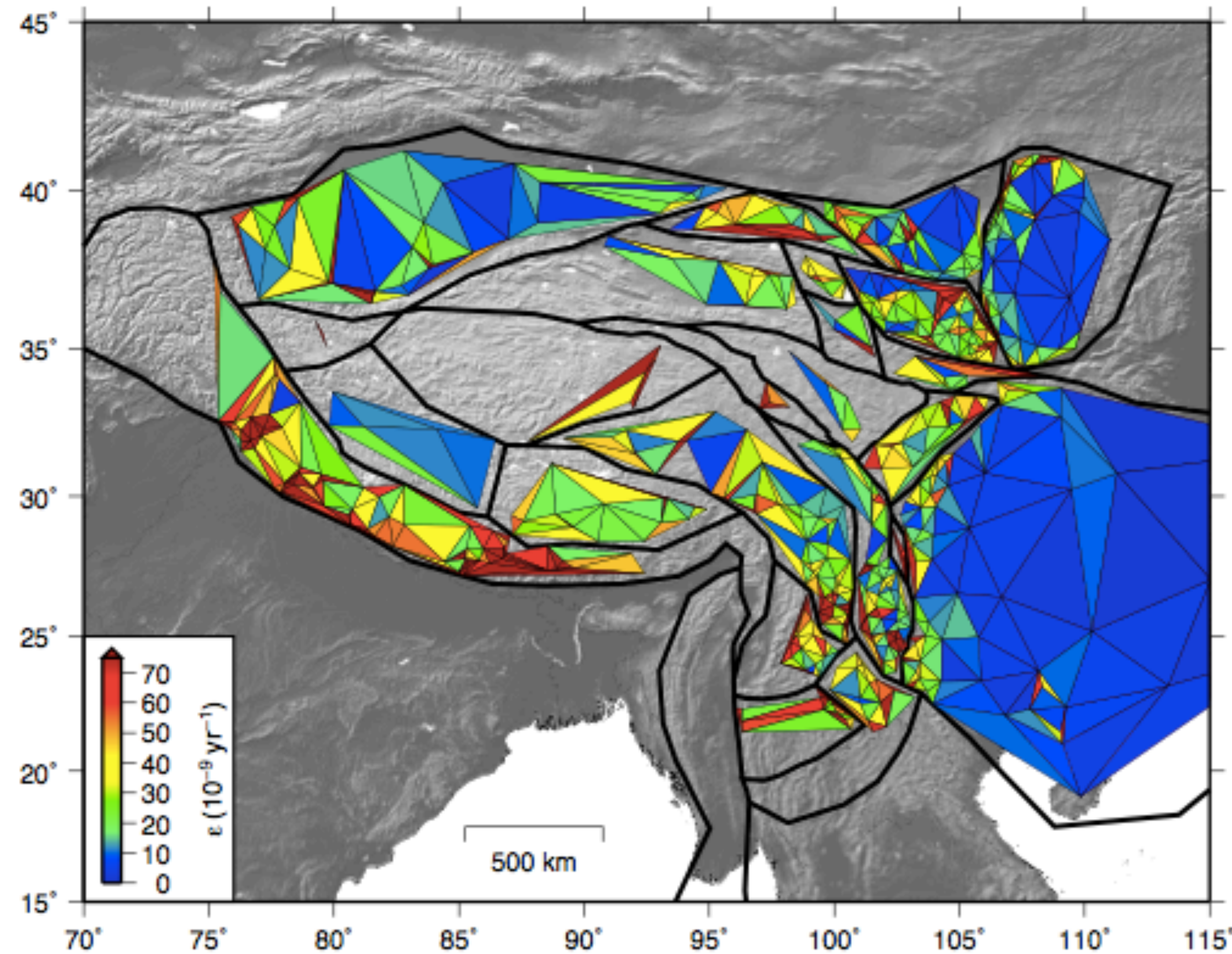
Strain rate from residual velocities

Use residual velocity field to calculate strain inside crustal blocks – deformation not represented in the block model



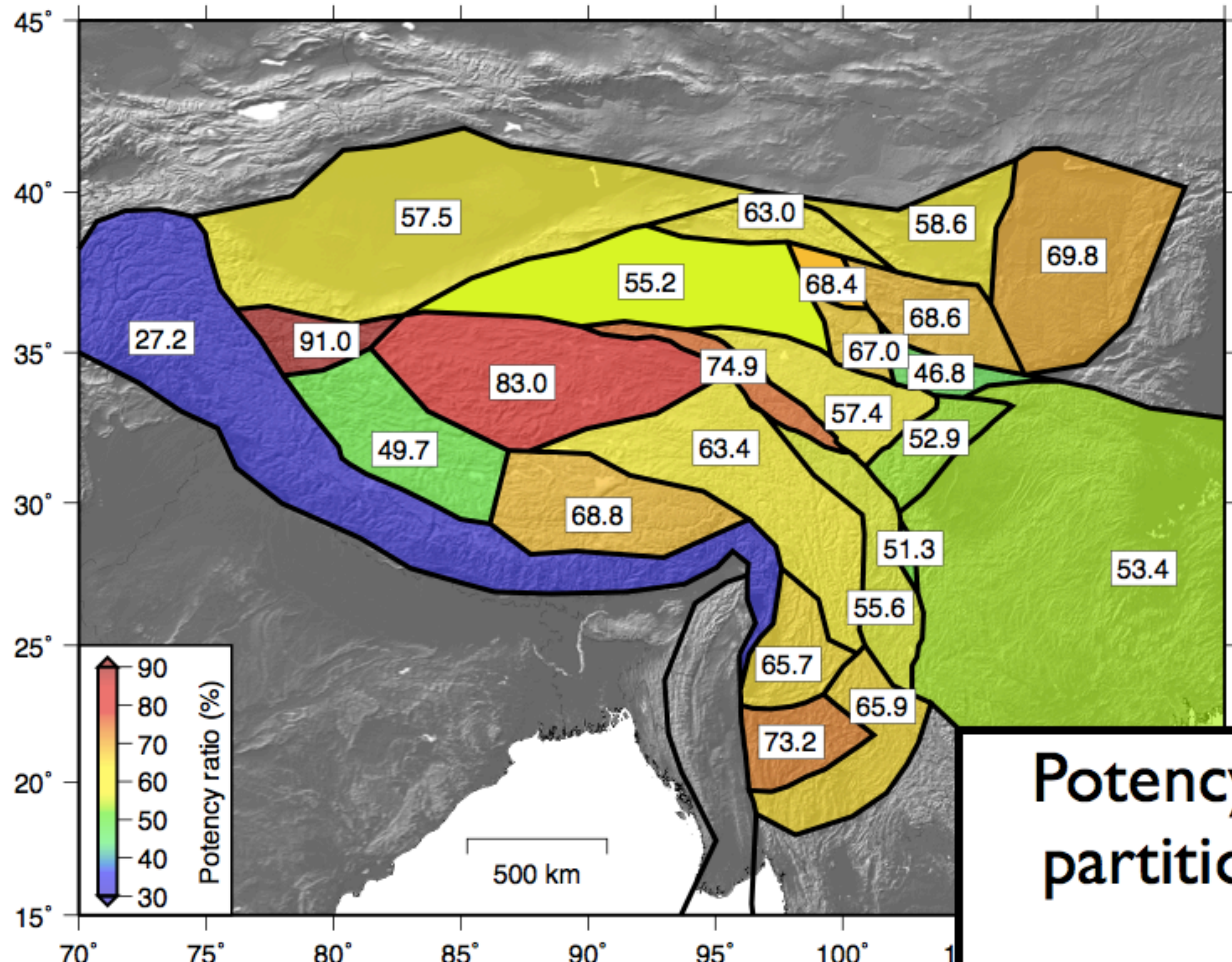


Residual velocity field



Residual strain rates

Evaluating deformation partitioning

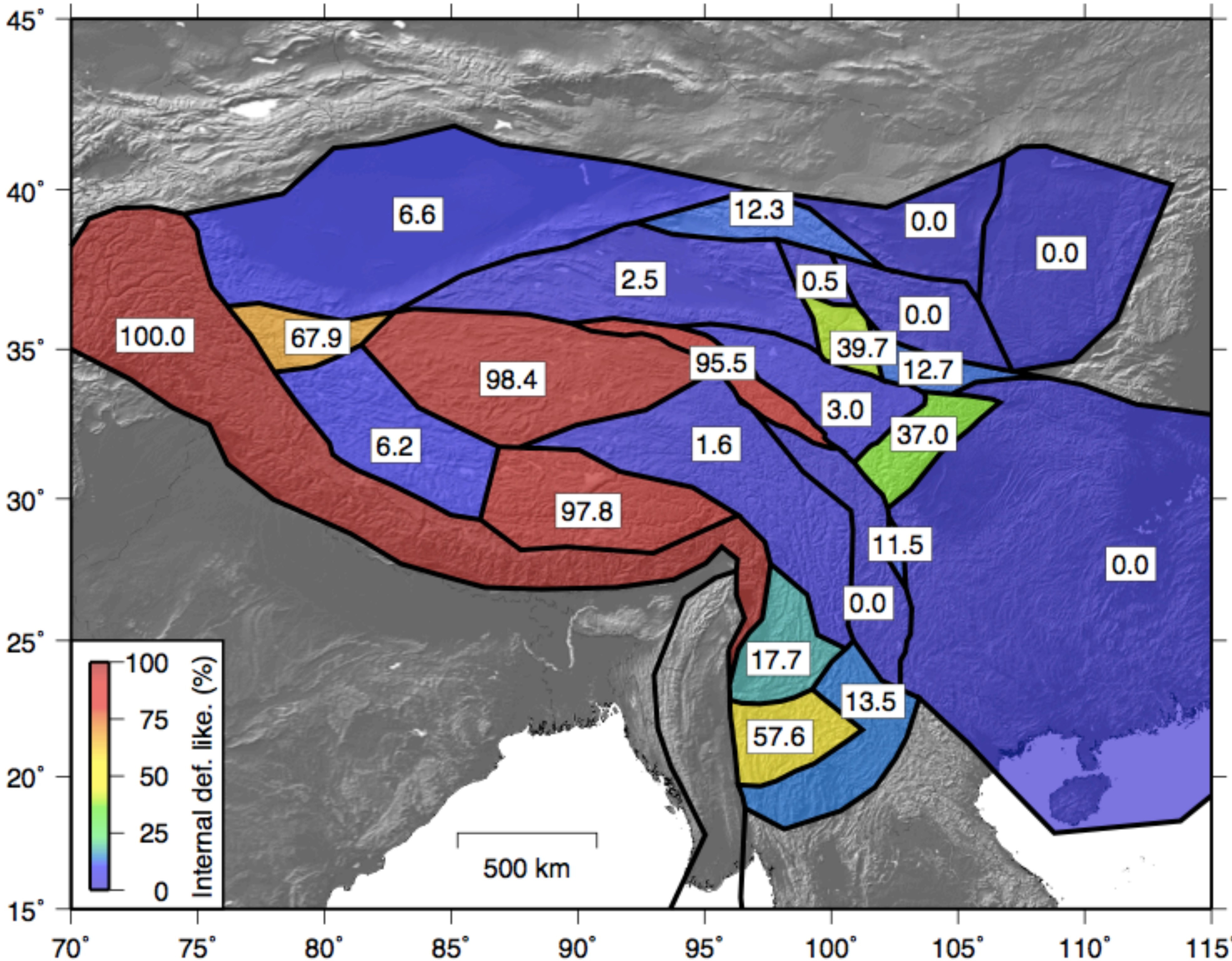


Proportion of total potency accommodated by diffuse processes within the blocks

Potency rate partitioning:

$$\phi = \frac{P_{\mathrm{B}}}{P_{\mathrm{B}} + P_{\mathrm{F}}}$$

Internal deformation likelihood

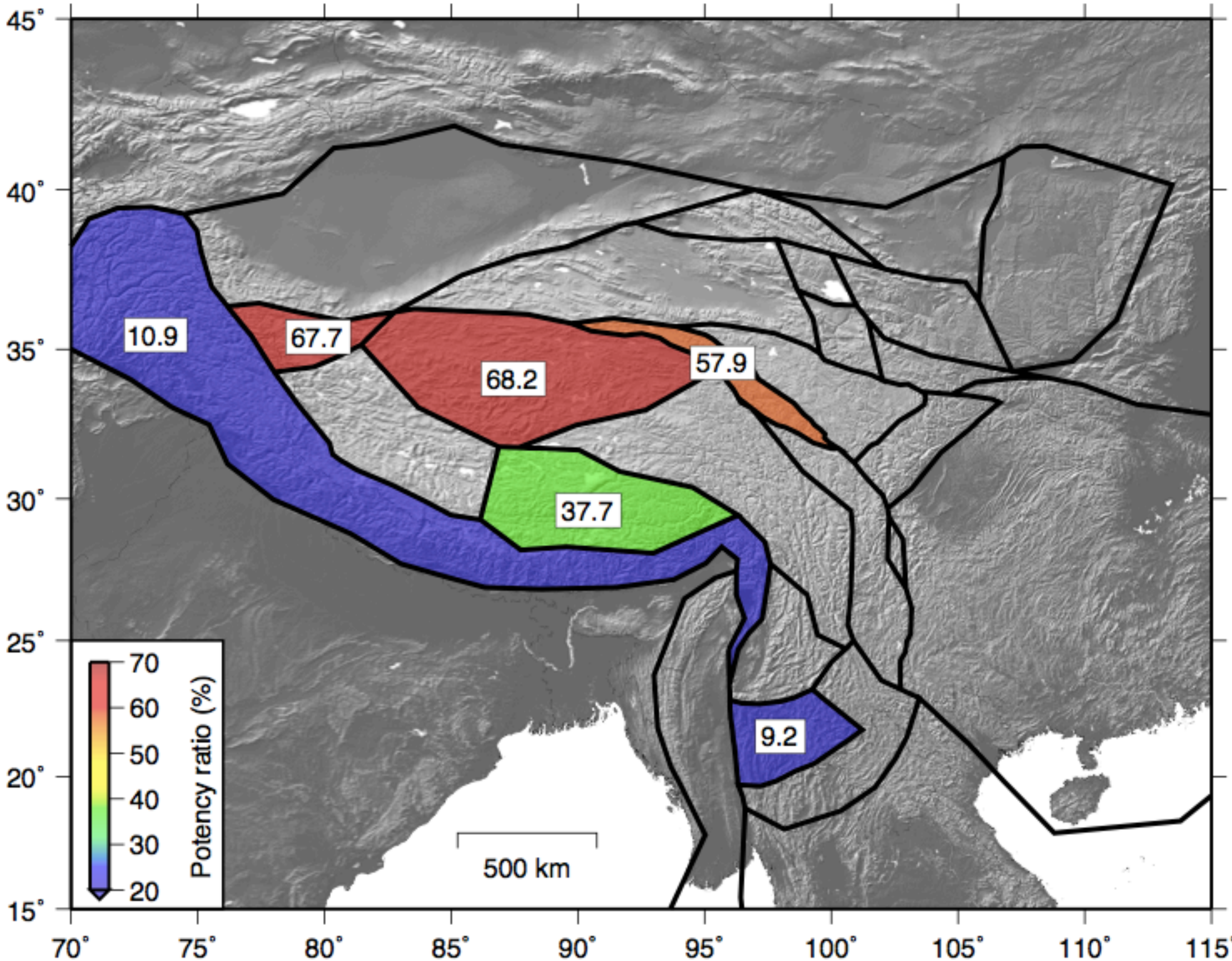


Likelihood that some part of the intra-block potency represents deformation, not just data noise

0% = entirely noise

100% = partly diffuse deformation

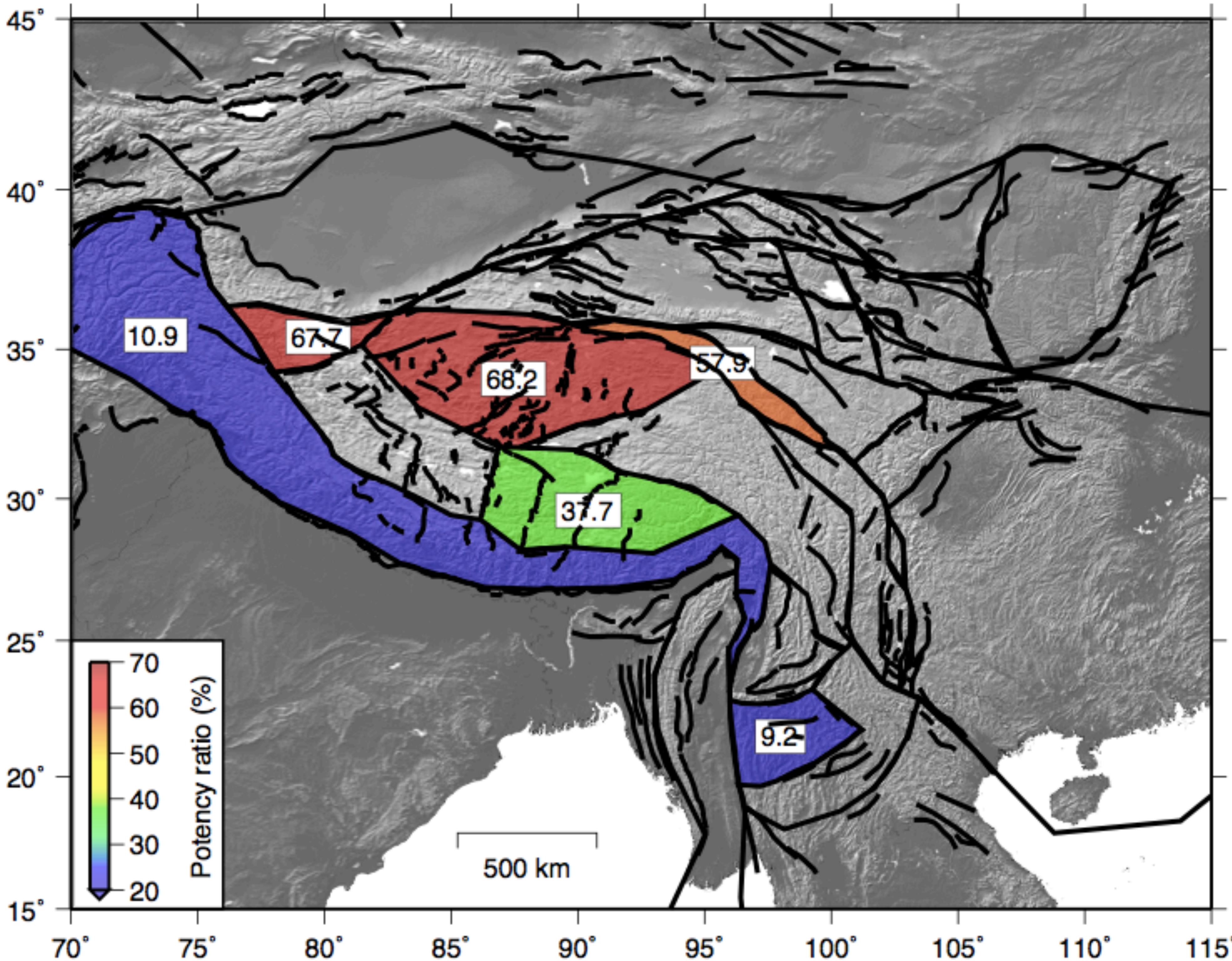
Adjusted potency rate partitioning



Proportion of total potency rate accommodated by likely intrablock deformation
(Reference potency rate – median noise potency rate)

Loveless & Meade, *EPSL*, 2011

Adjusted potency rate partitioning



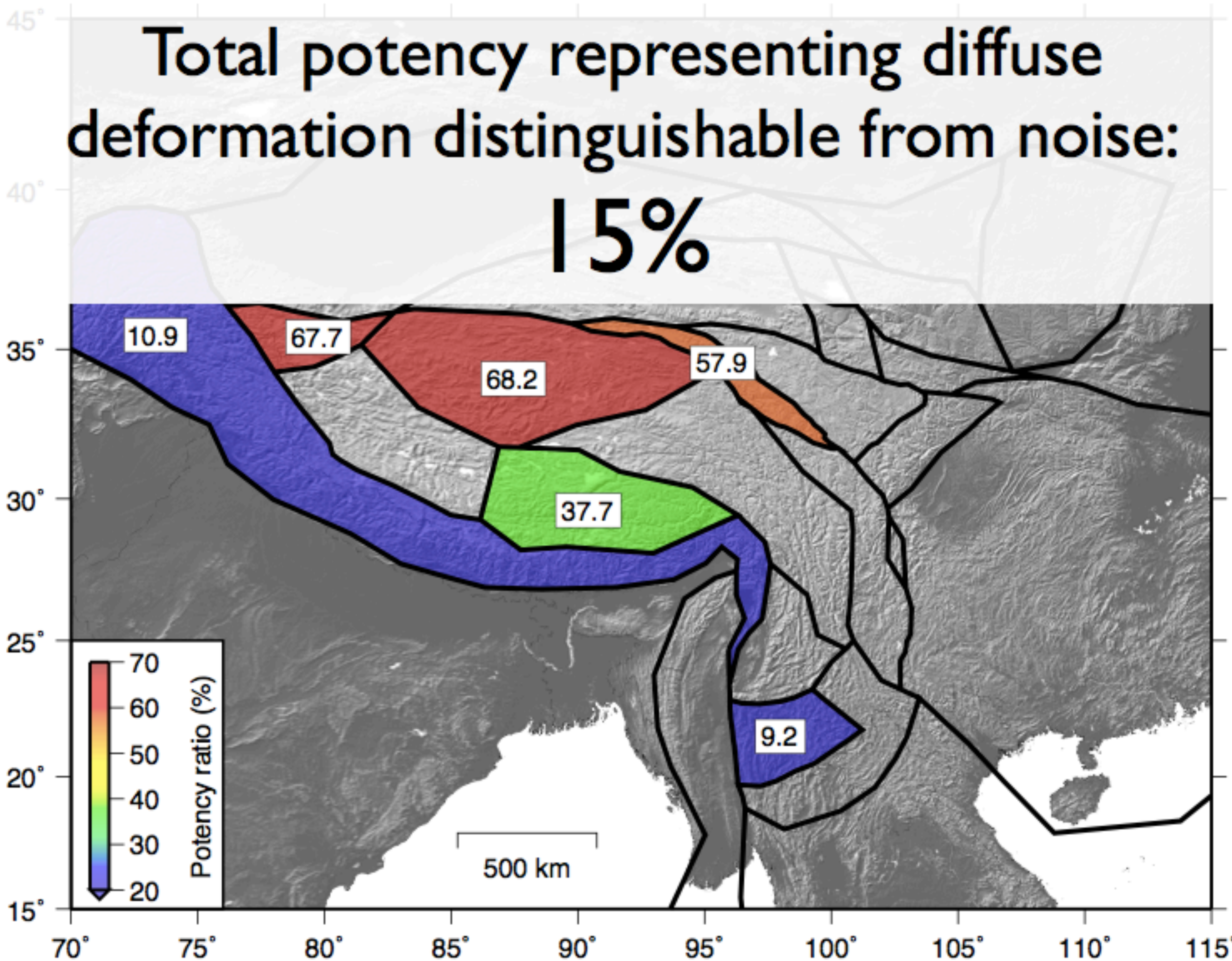
Proportion of total potency rate accommodated by likely intrablock deformation
(Reference potency rate – median noise potency rate)

Loveless & Meade, *EPSL*, 2011

Adjusted potency rate partitioning

Total potency representing diffuse deformation distinguishable from noise:

15%



Proportion of total potency rate accommodated by likely intrablock deformation
(Reference potency rate – median noise potency rate)

Loveless & Meade, *EPSL*, 2011

Interpreting interseismic observations

Geodetically constrained block models provide kinematically consistent fault slip rate estimates, which can be used to:

- Examine how oblique convergence is partitioned between subduction zone(s) and crustal faults;
- Evaluate consistency in patterns of interseismic strain accumulation and coseismic release;
- Calculate interseismic stress accumulation rates on geometrically complex, interacting fault networks;
- Assess the partitioning of deformation between slip on major mapped structures and more diffuse processes.

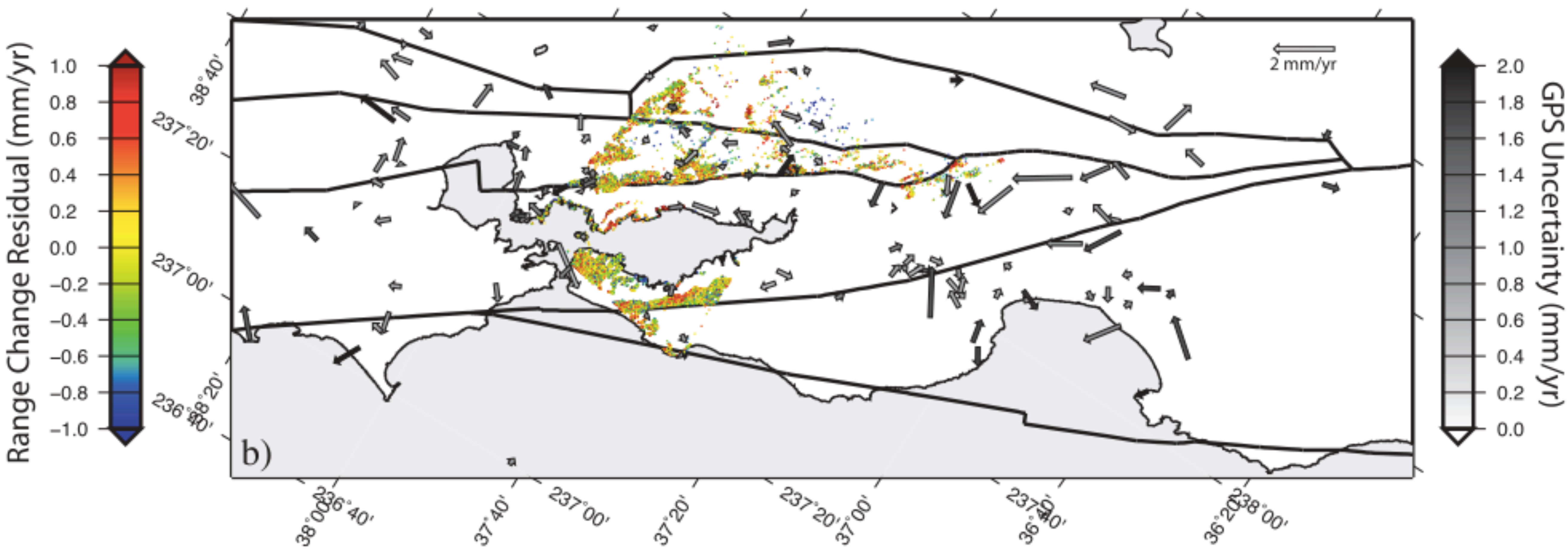
Block modeling software available at:

http://summit.fas.harvard.edu → Software

- MATLAB-based
- GUI for creating and editing block geometry files
- Requires Mapping Toolbox
- Parallel Computing Toolbox supported for calculation of elastic Green's functions
- Coming soon: Support for joint inversion of GPS and InSAR velocity fields (Evans et al., *JGR*, 2012)

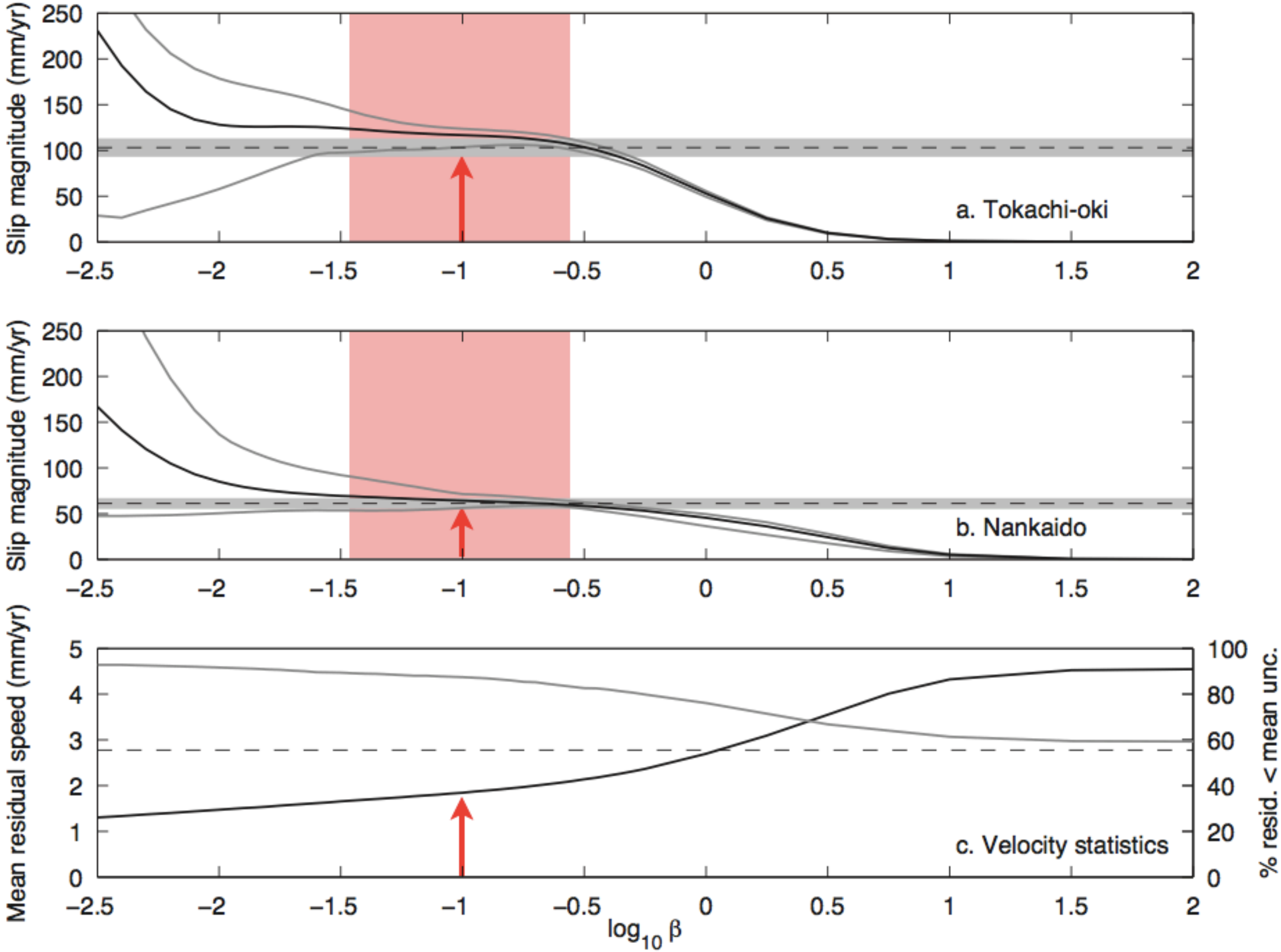
Contact me (jloveless@smith.edu) for GMT output scripts, M_Map-compatible version (no Mapping Toolbox required)

Joint inversion of GPS and InSAR data



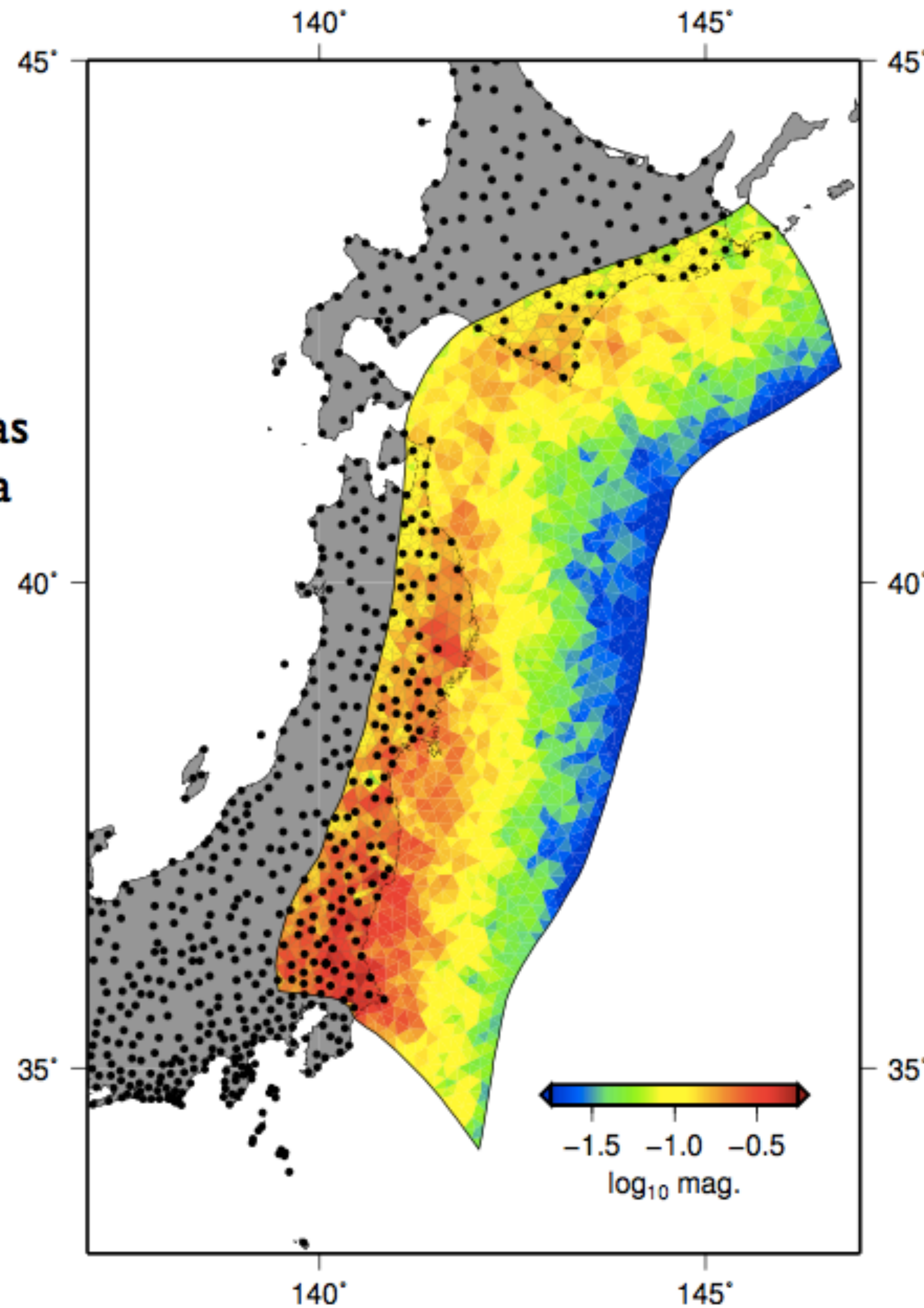
Evans, Loveless, & Meade, *JGR*, 2012

Choosing a smoothing weight



What can land-based GPS data indicate about slip pattern?

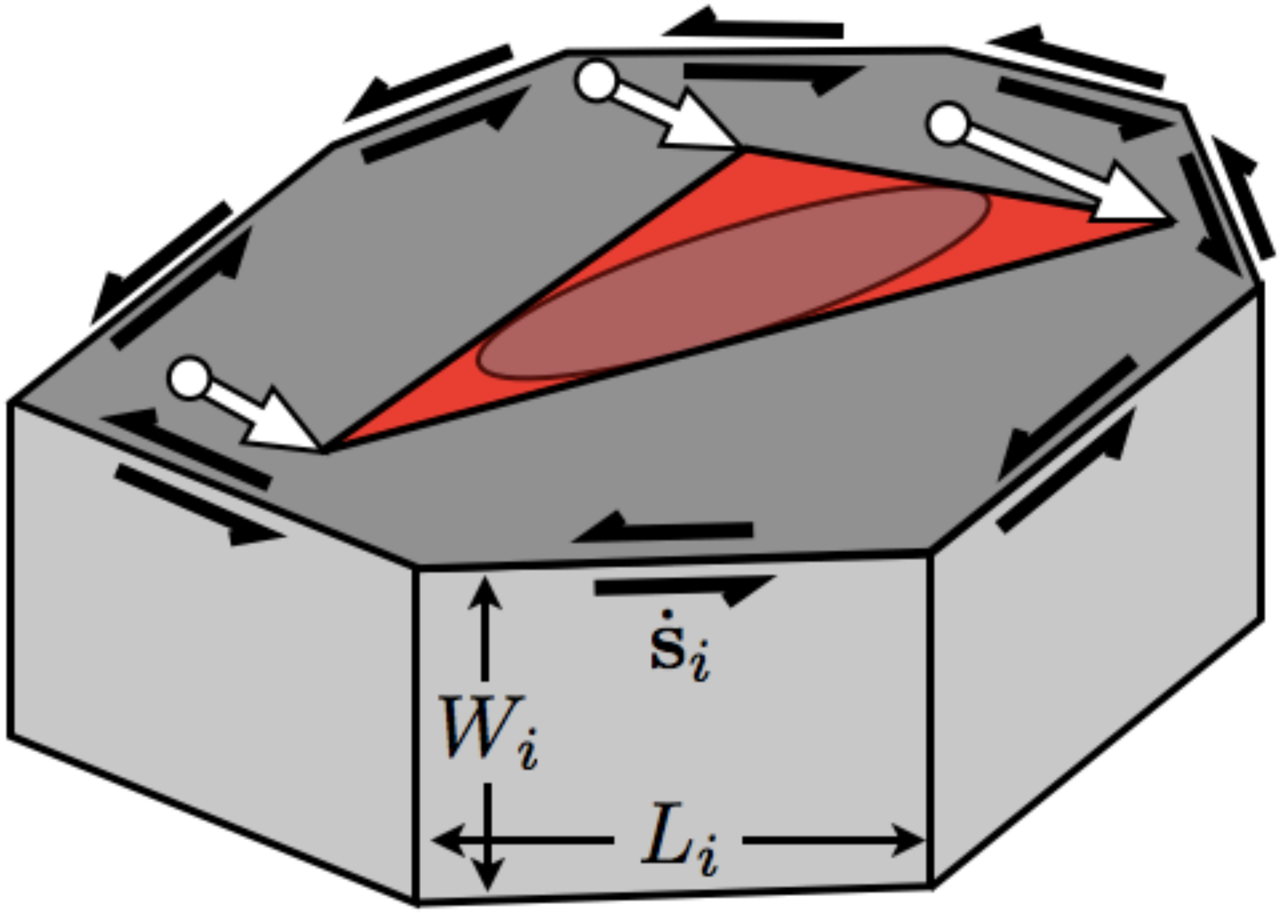
Warm colors indicate areas well resolved by GPS data



Cool colors indicate areas poorly resolved by GPS data

Sum of the partial derivatives relating slip to GPS displacement

Localized and diffuse potency rates



Intra-block (diffuse):

$P_\mathrm{B} \propto |\dot{\epsilon}|\, V_\mathrm{B}$

V_B = Block volume

$|\dot{\epsilon}|$ = Strain rate

On-fault (localized):

$P_\mathrm{F} = \dot{\mathbf{s}} L W$

$\dot{\mathbf{s}}$ = Fault slip rate

L, W = Fault length, width

Potency rate partitioning:

$$\phi = \frac{P_\mathrm{B}}{P_\mathrm{B} + P_\mathrm{F}}$$