3D Viscoelastic Earthquake Cycle Models

Estimating fault slip rates, locking distribution, elastic/viscous properites of lithosphere/asthenosphere

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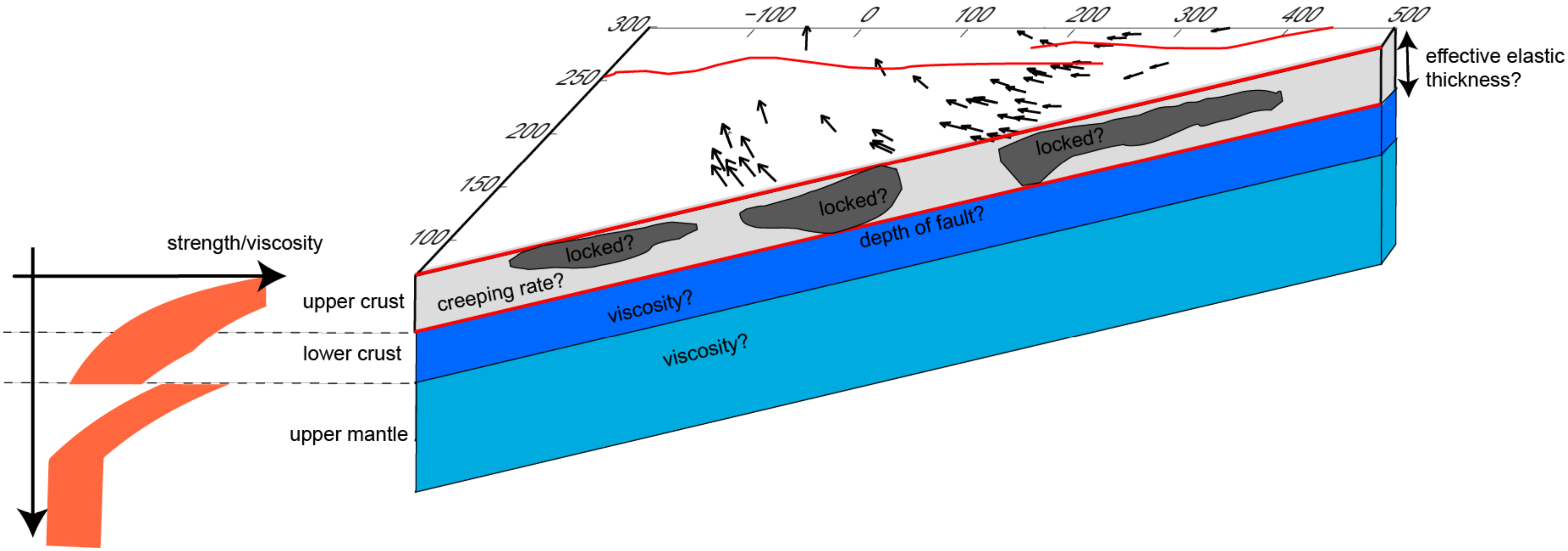
Indiana University

In collaboration with: Paul Segall, Stanford; Ray Chuang, Indiana; Junichi Fukuda, Indiana University (now at ERI)

Conceptual Model of Lithosphere



Approach: develop forward model and inverse method to obtain joint estimation of

(1) long-term fault slip rates
(2) Interseismic creep rates
(3) Location of locked patches
(4) Lithosphere viscosity
(5) Elastic thickness

Methodology/Philosophy

Forward Model

- Need fast models
- Semi-analytical methods
  propagator matrix method
- boundary element methods for stress boundary conditions

Inverse Method

- Bayesian, probabilistic
- large number of unknown model parameters – no optimization – want posterior probability distributions
- Monte Carlo sampling
- need to compute 100 K's of forward computations

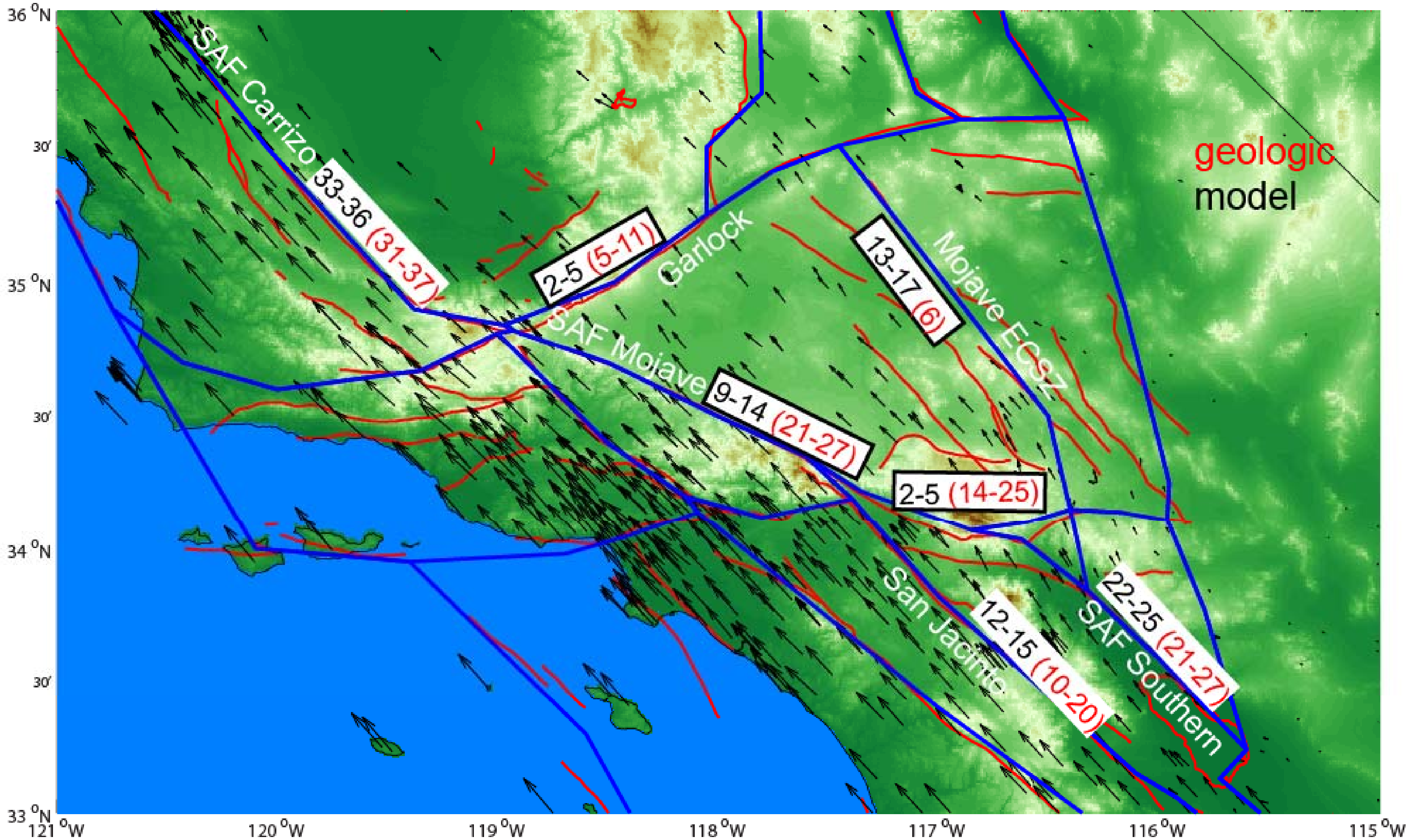
Talk Outline

- Geologic/Geodetic fault slip rate discrepancy in southern California
    - model dependence on slip rate estimate
    - Illustration with 2D models (infinitely long faults)
    - Inversions with 2D and 3D models -- reconcile discrepancy

- San Francisco Bay Area interseismic deformation
    - inversion for:

    Fault slip rate
    Locking distribution
    Asthenosphere viscosity
    Earthquake repeat times

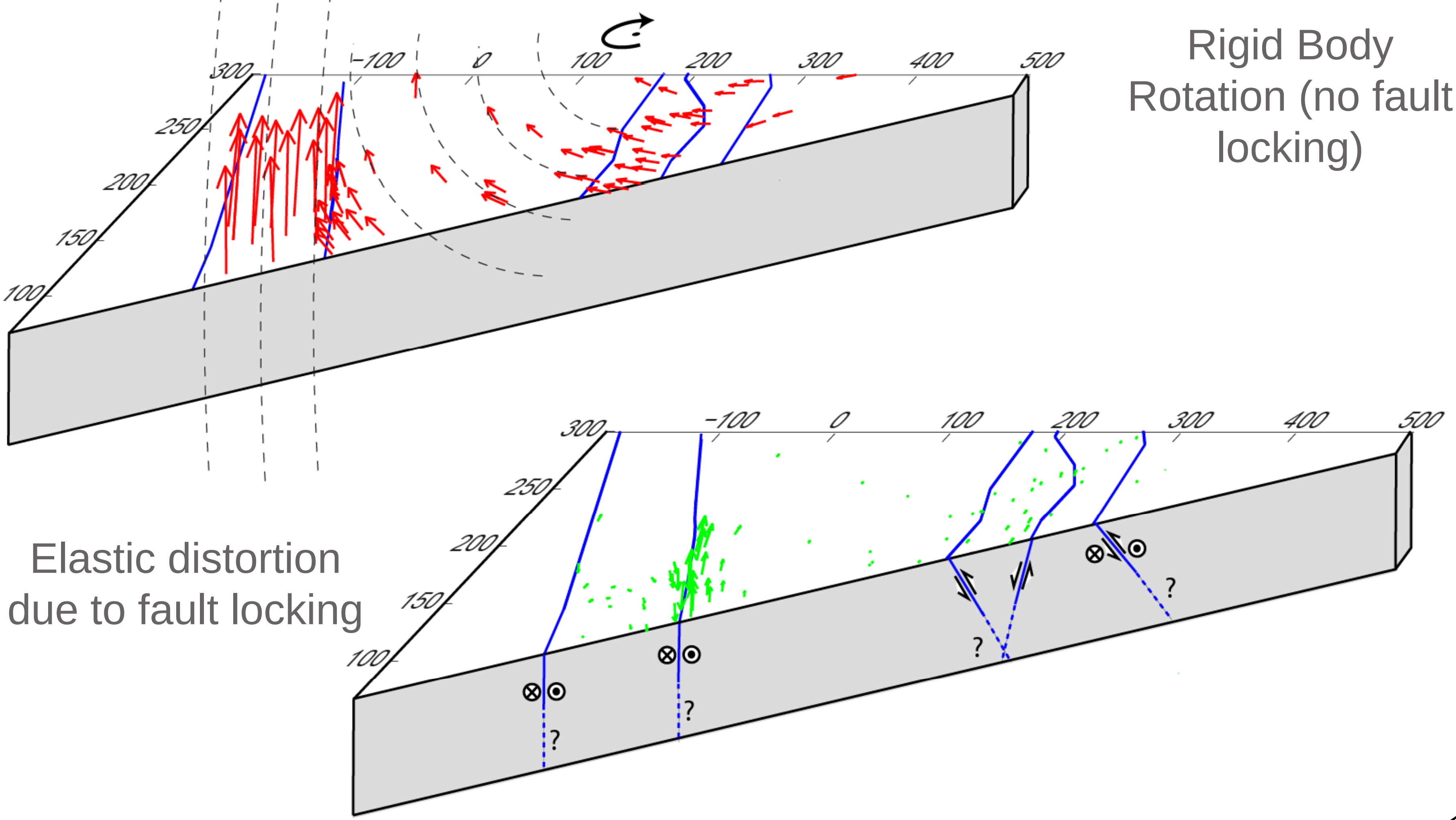
Slip Rate Discrepancies in Southern California



Becker et al. (2004), Meade et al. (2005)

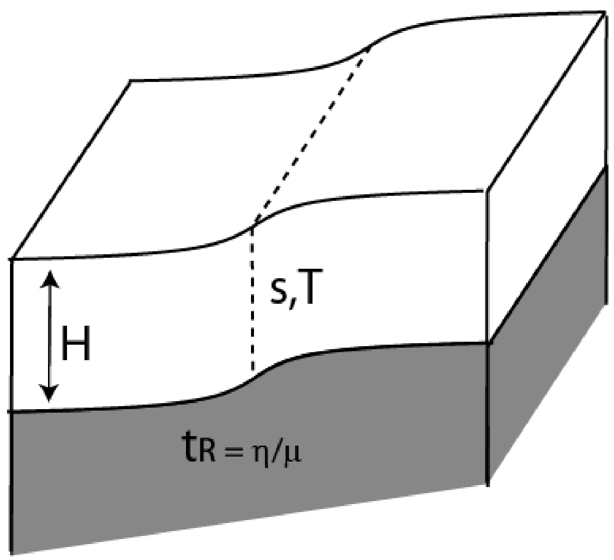
Standard Elastic Block Model

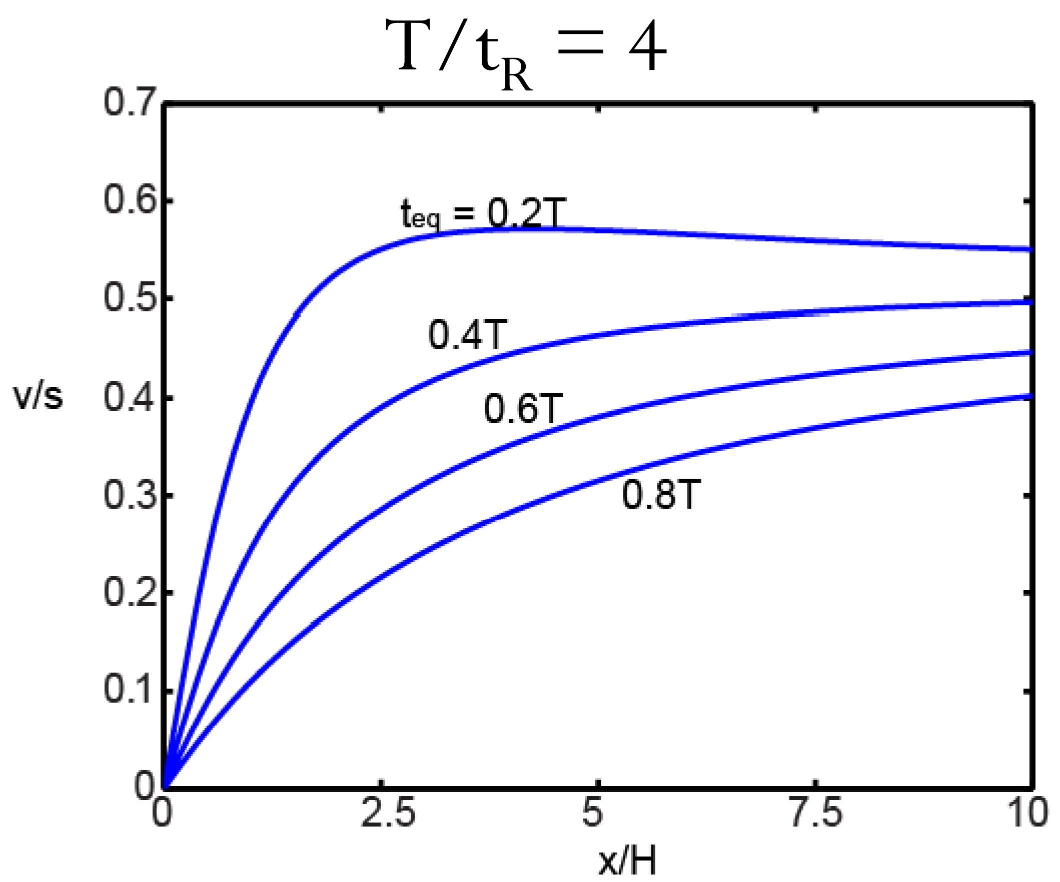
e.g., Jim Savage, Rob McCaffrey, Brendan Meade



Viscoelastic Coupling Model

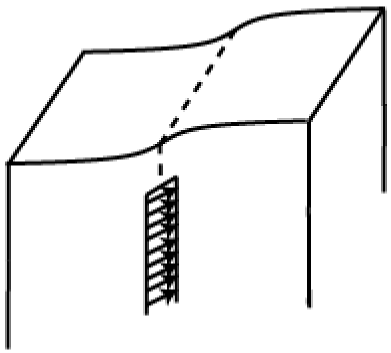
Savage and Prescott (1978)

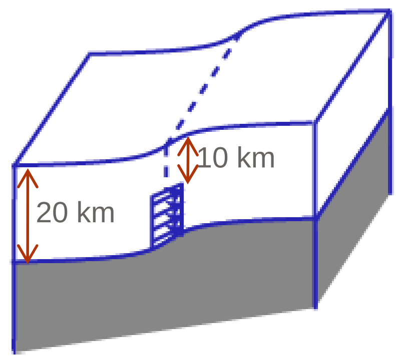




2D Models of Interseismic Deformation

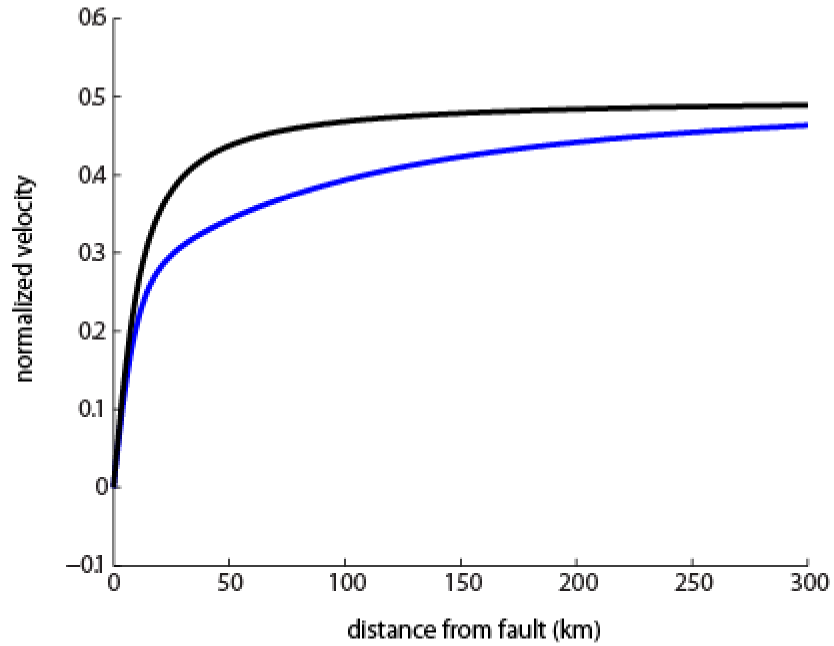
Screw dislocation
Savage and Burford (1978)



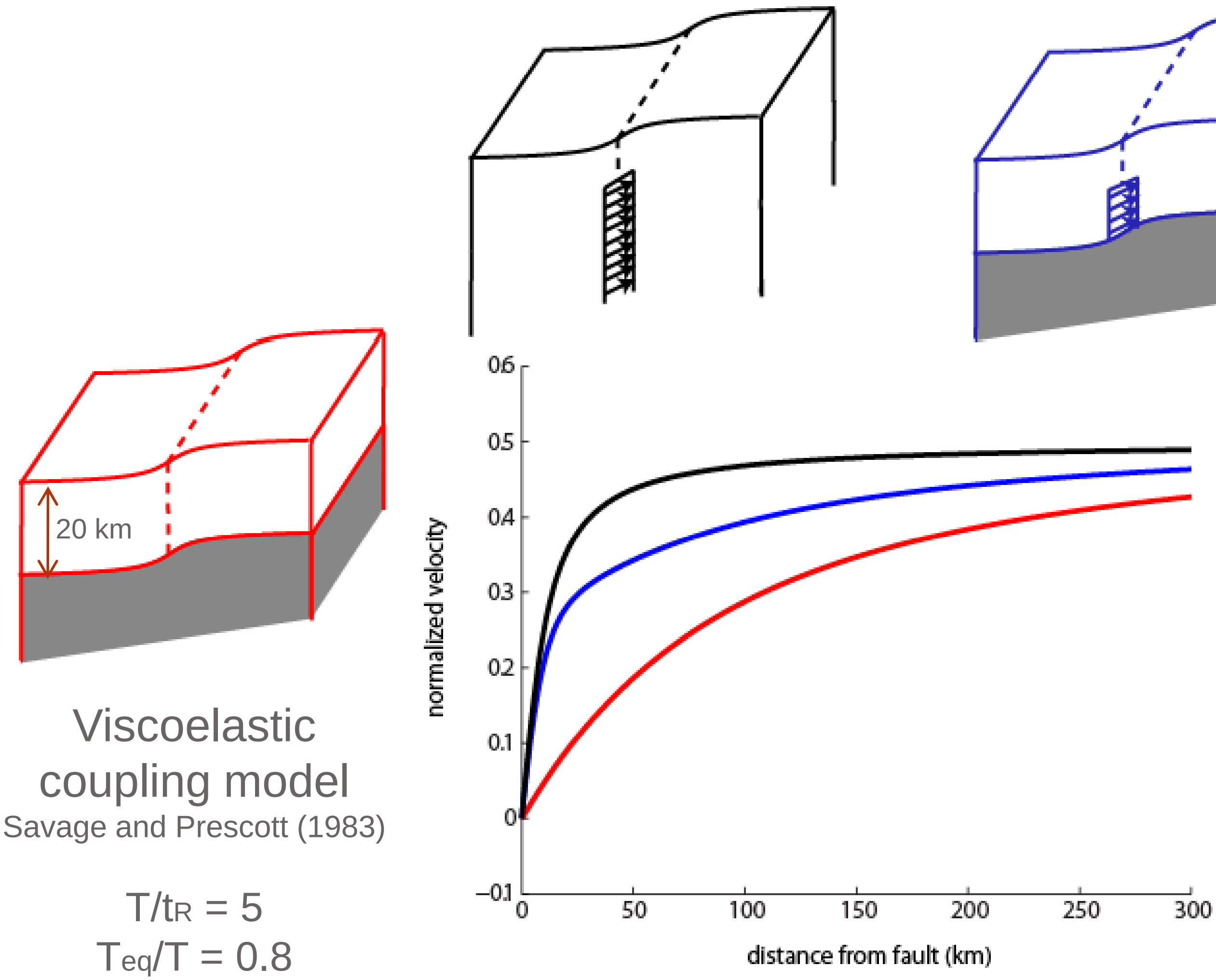


Viscoelastic coupling model
Savage and Prescott (1983)

$T/t_R = 5$
$T_{eq}/T = 0.8$



2D Models of Interseismic Deformation



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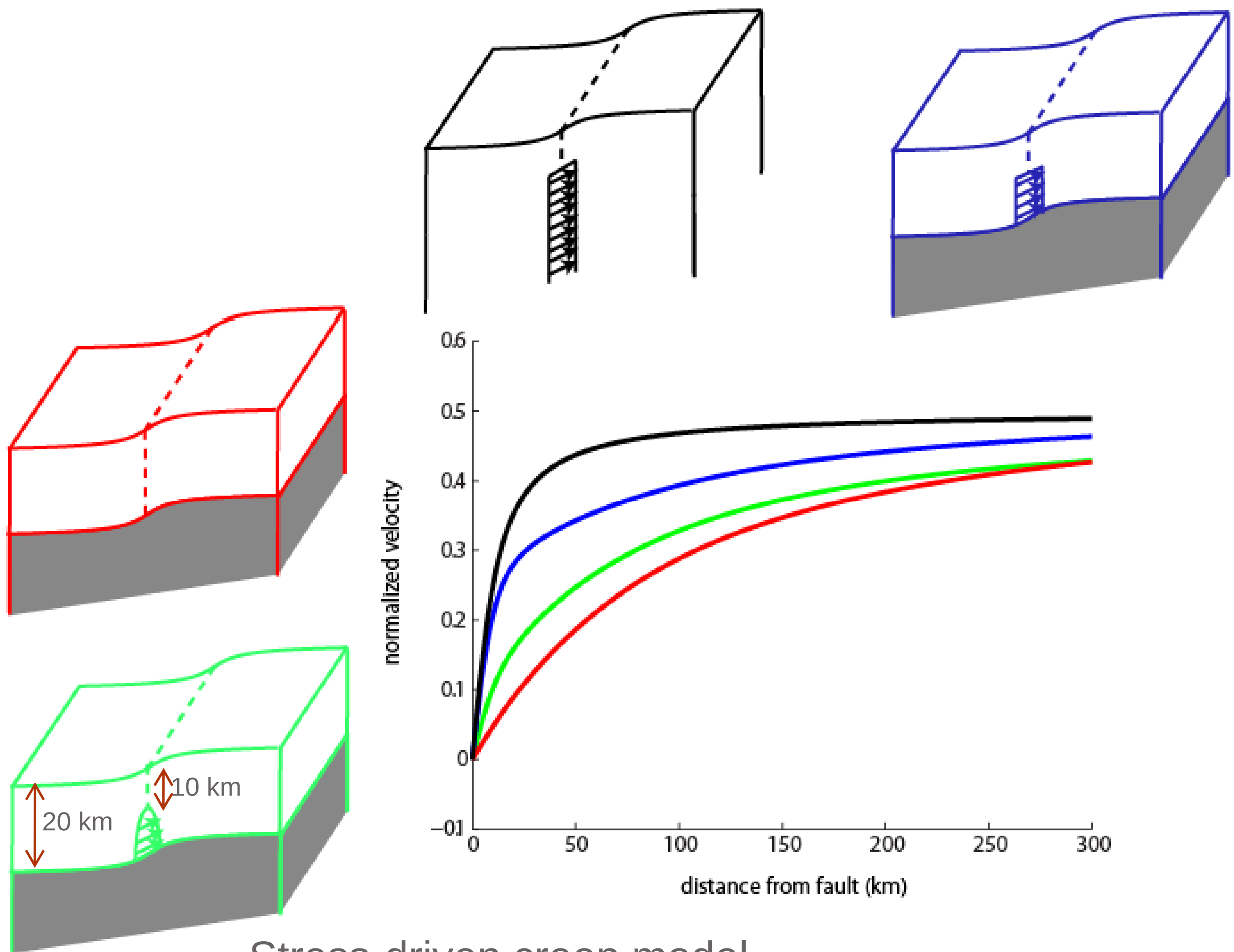
2D Models of Interseismic Deformation



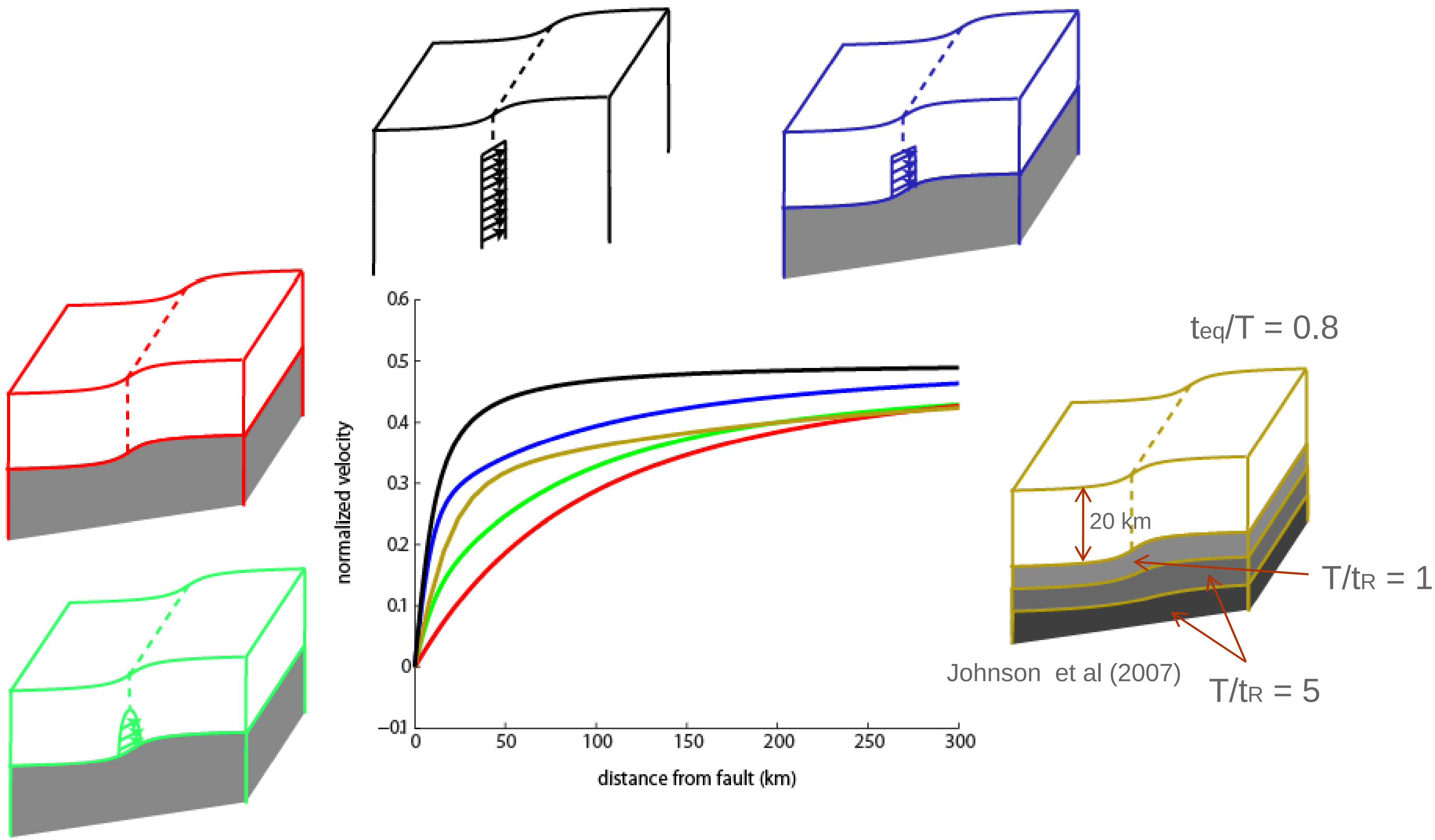
$T/t_R = 5$

$T_{eq}/T = 0.8$

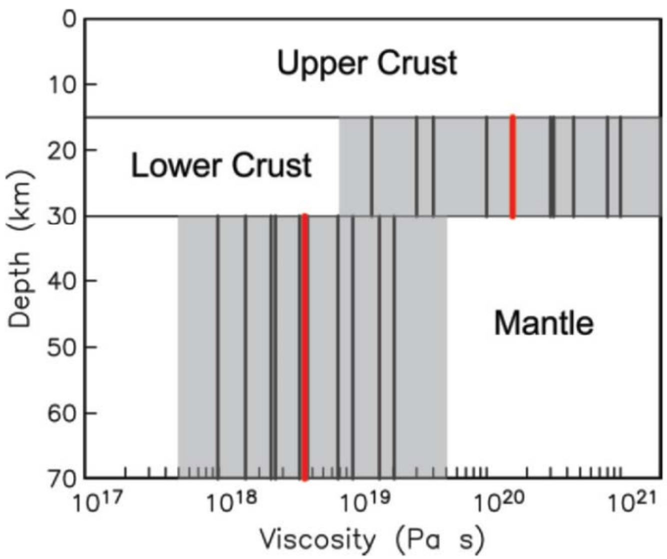
Stress-driven creep model

Johnson and Segall (2004)

2D Models of Interseismic Deformation

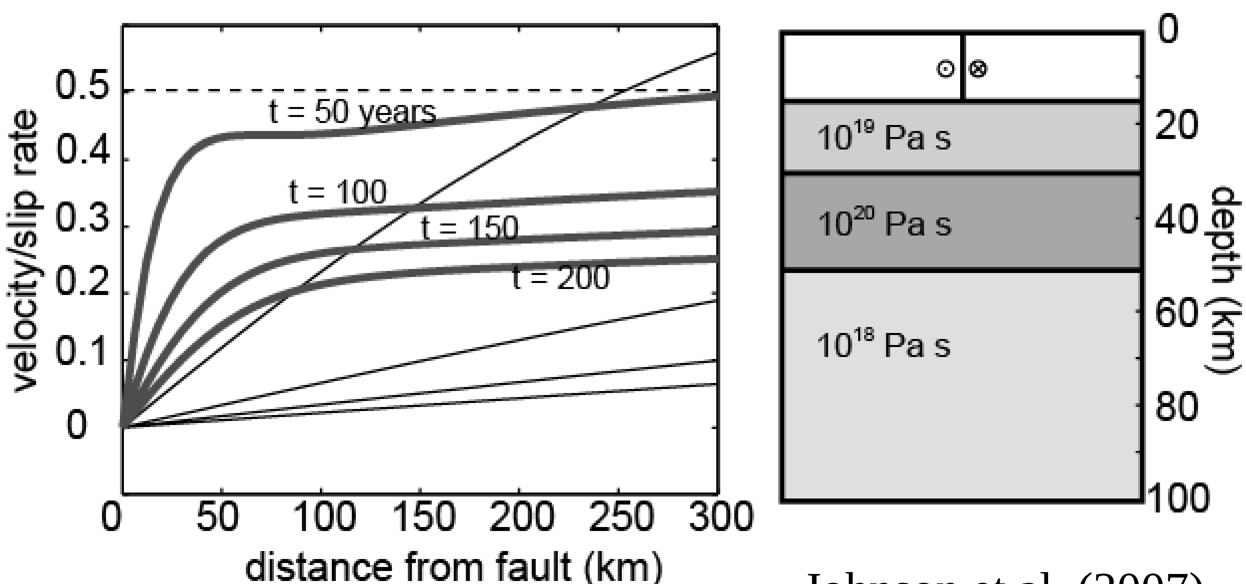


Viscosity Varies with Depth



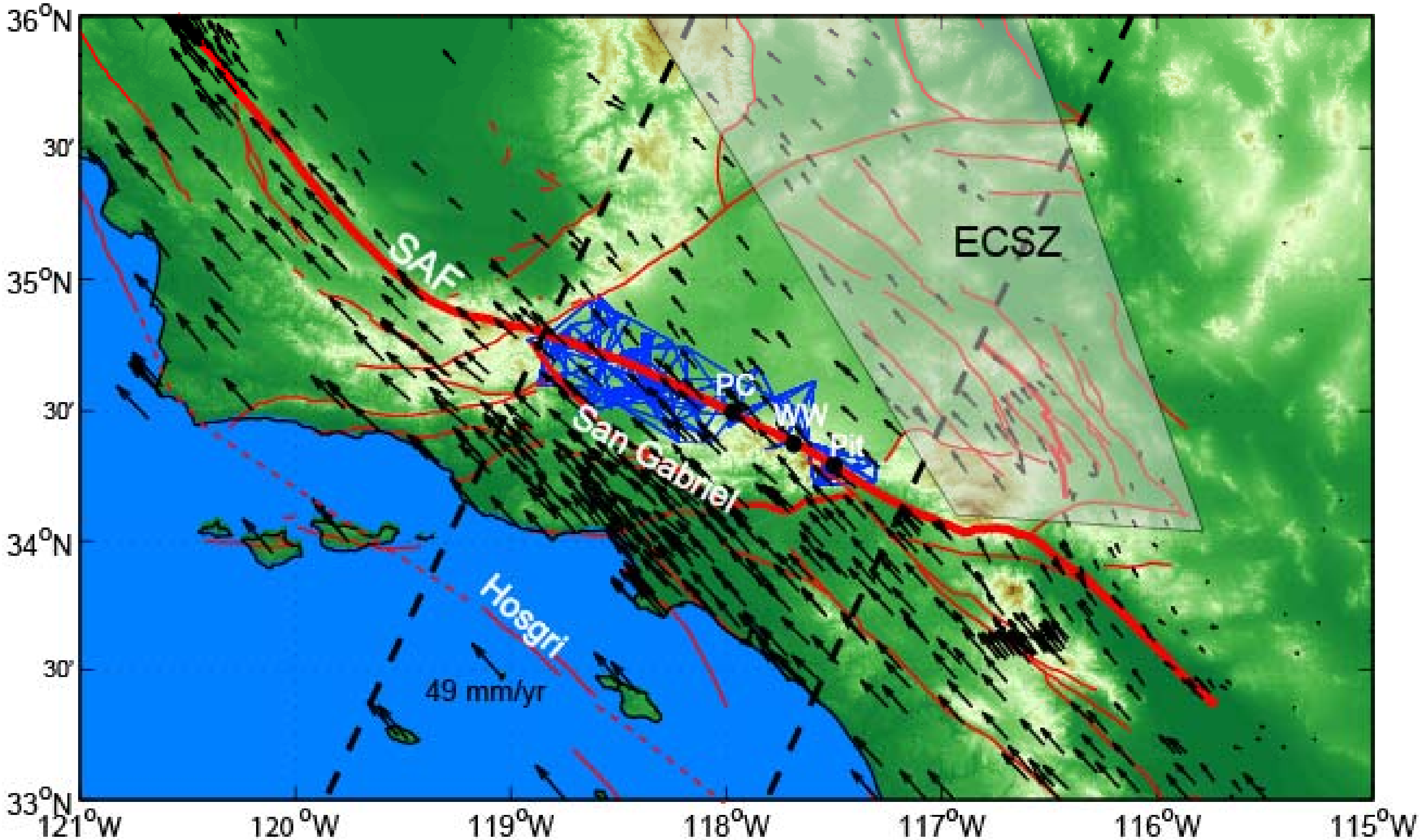
Thatcher and Pollitz (2008)

T = 250 yrs



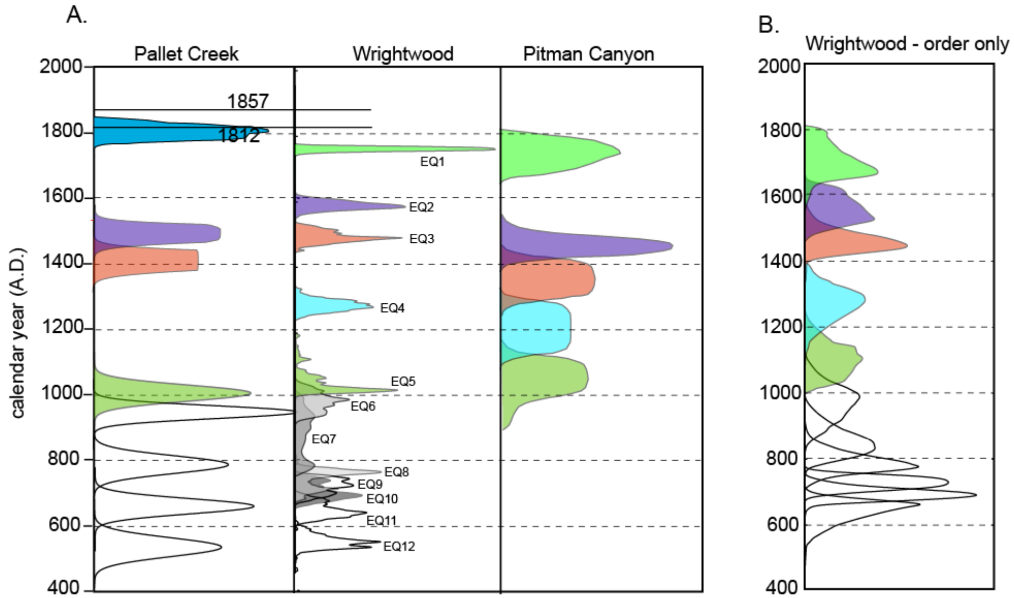
Johnson et al. (2007)

Fault Slip Rates and Interseismic Deformation: Mojave Region



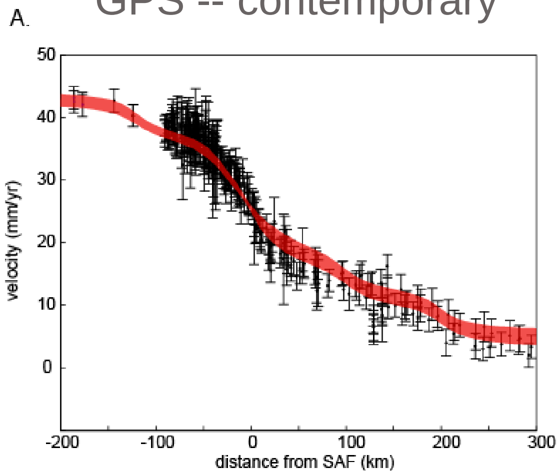
Johnson et al. (2007)

Data

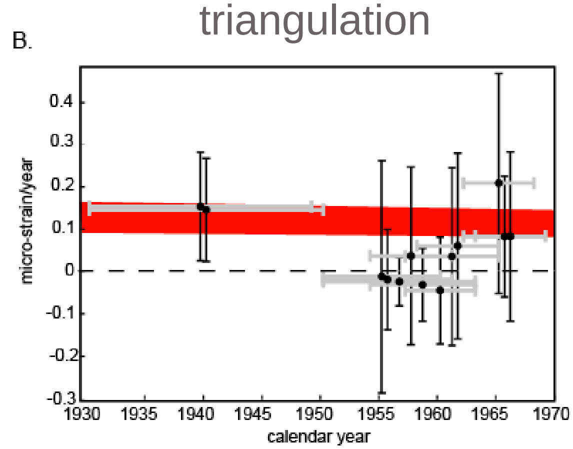


Paleoseismic record

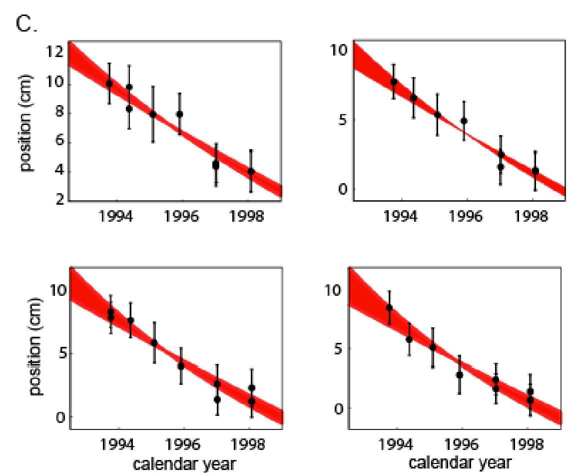
GPS -- contemporary



triangulation

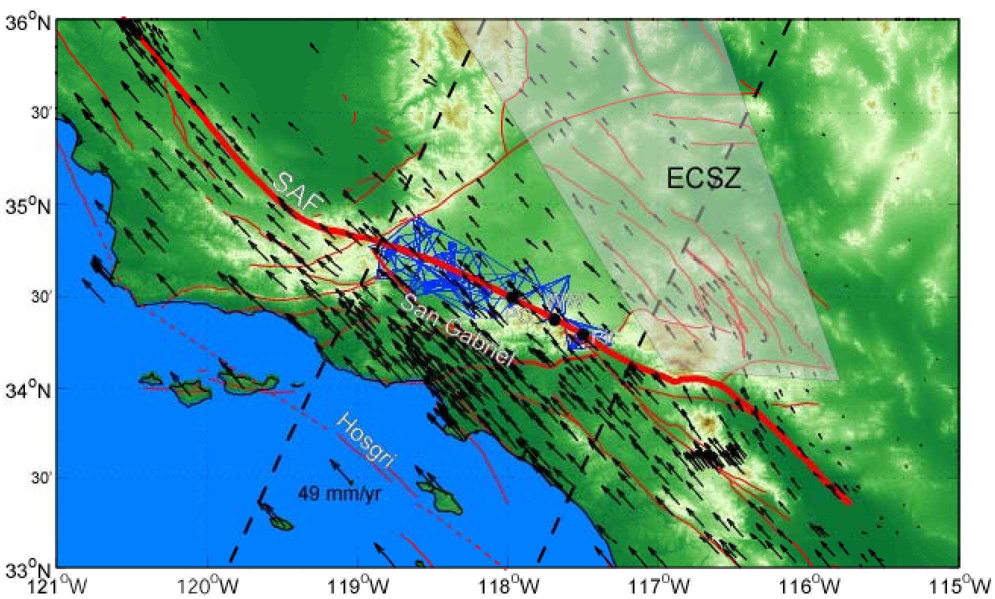


Landers postseismic GPS



2D Viscoelastic Earthquake Cycle Model

Mojave segment of SAF system



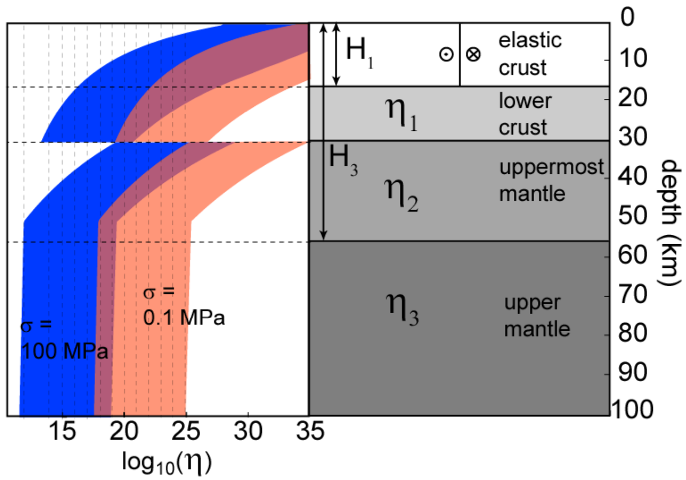
Data:

GPS

Historical triangulation

Paleoseismic data

Landers postseismic



Inversion →

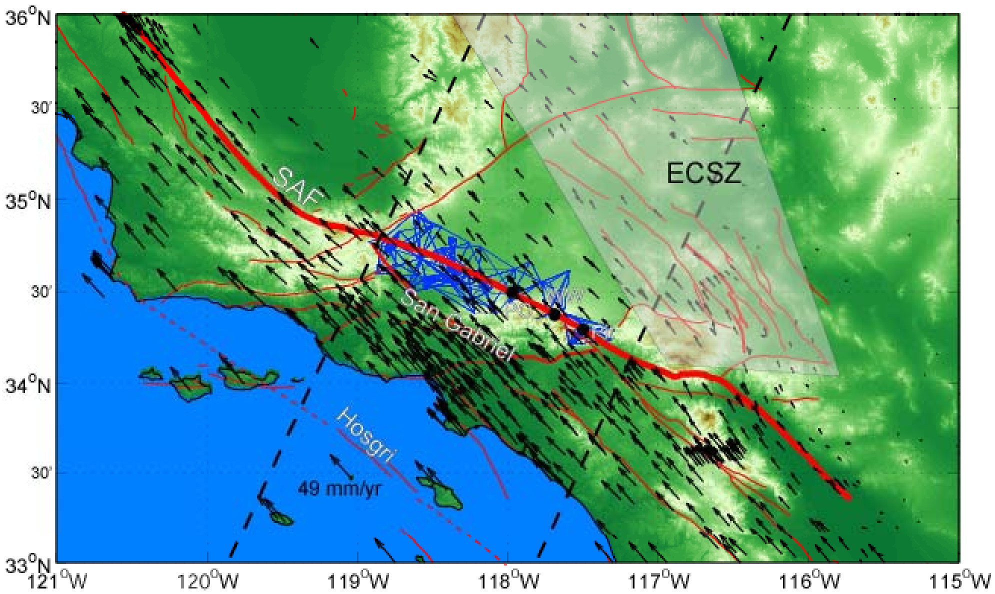
Estimate:

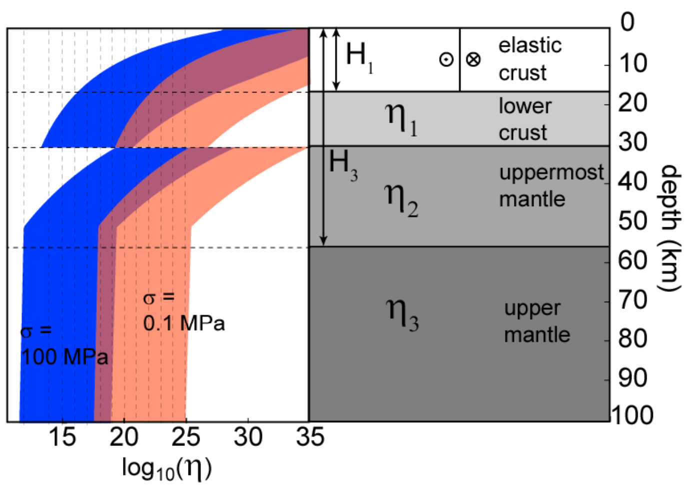
- slip rates
- viscosity

Johnson, Hilley, and Bürgmann (2007)

2D Viscoelastic Earthquake Cycle Model

Mojave segment of SAF system





Data:

GPS

Historical triangulation

Paleoseismic data

Landers postseismic

Inversion

Result:

slip rate: 23-32 mm/yr

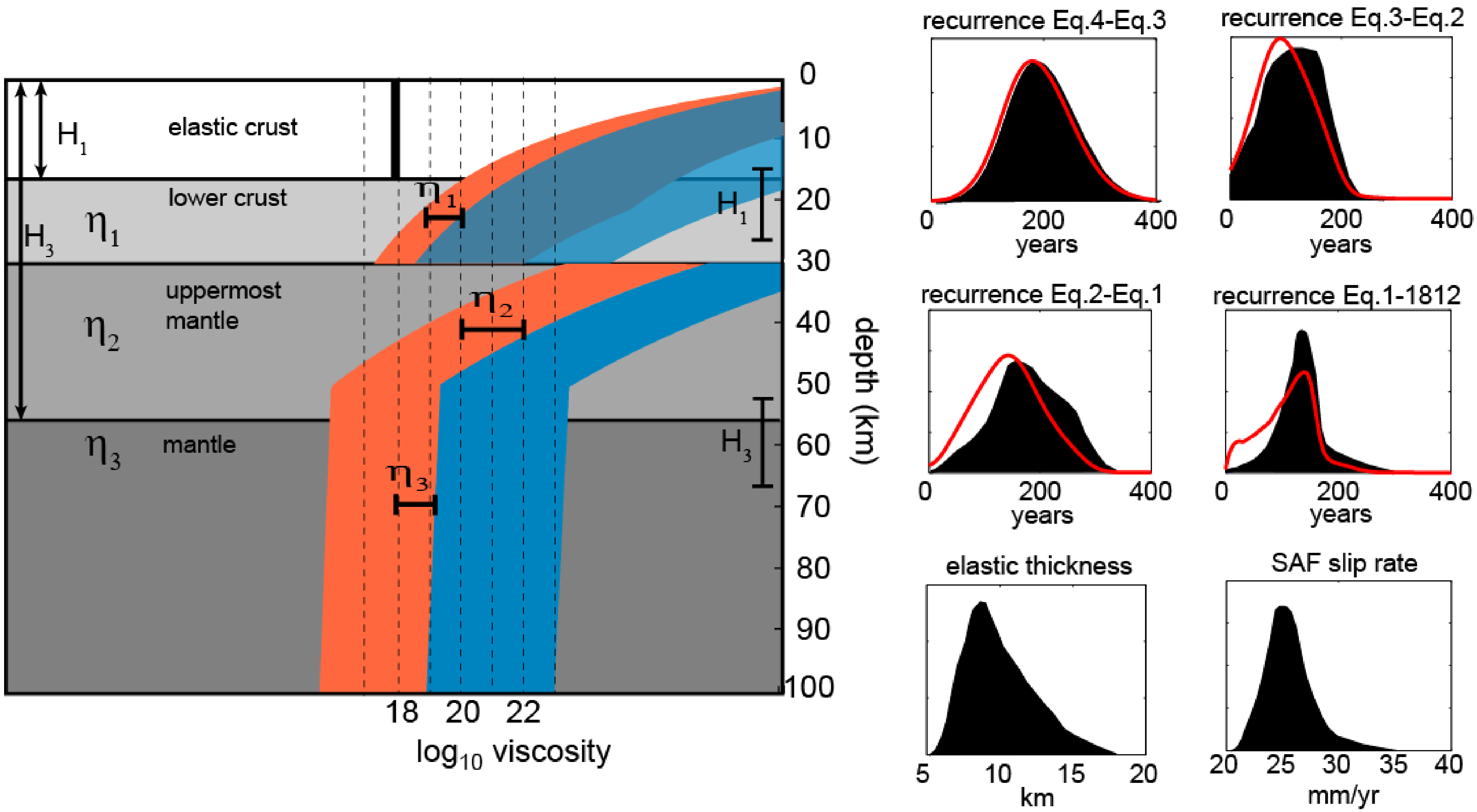
geology: 25-30 mm/yr

Elastic block models: 10-15 mm/yr

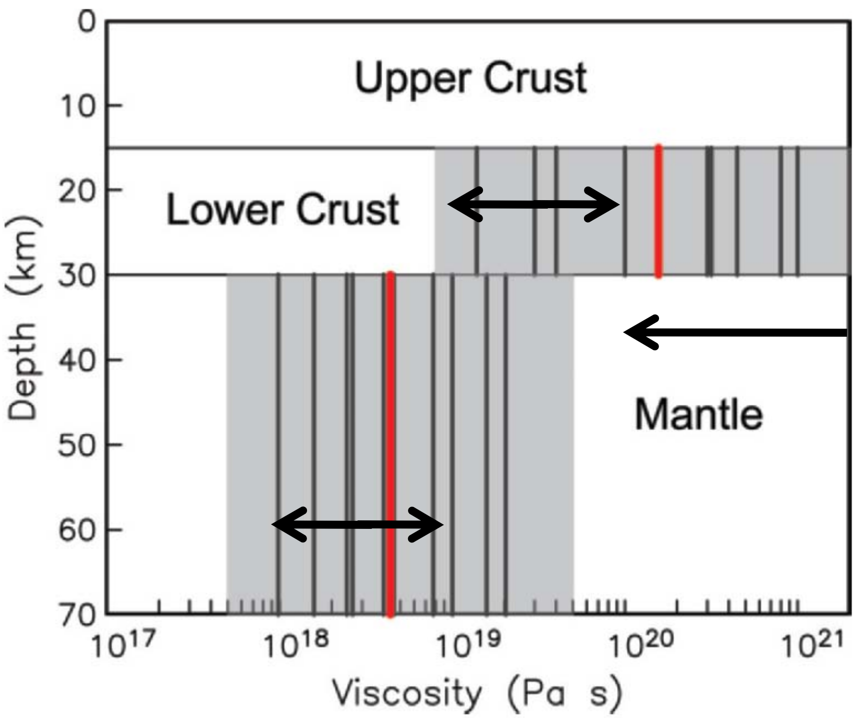
Johnson, Hilley, and Bürgmann (2007)

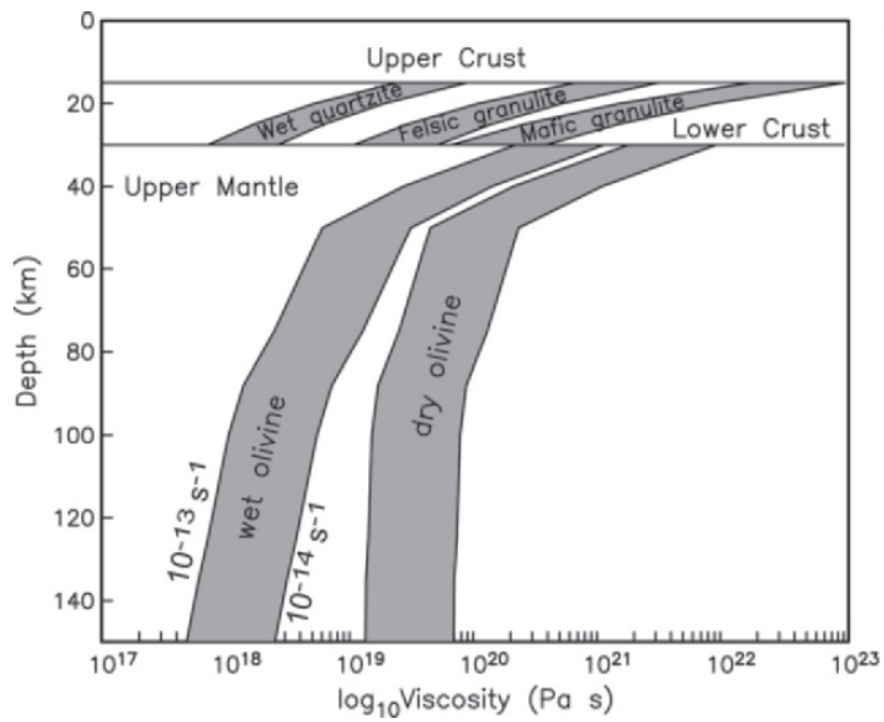
2D Viscoelastic Earthquake Cycle Model

Inversion Results



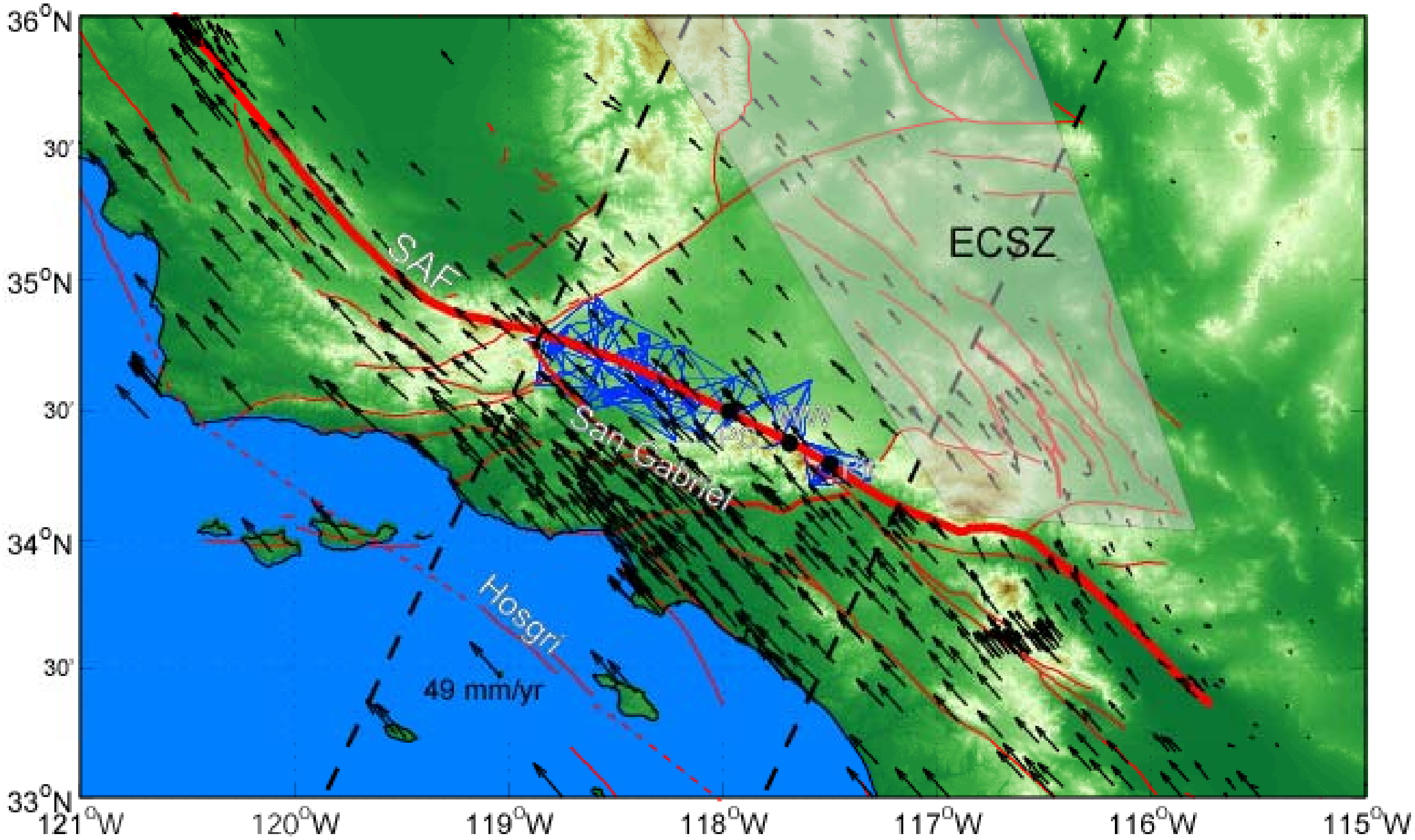
Lithosphere Viscosity



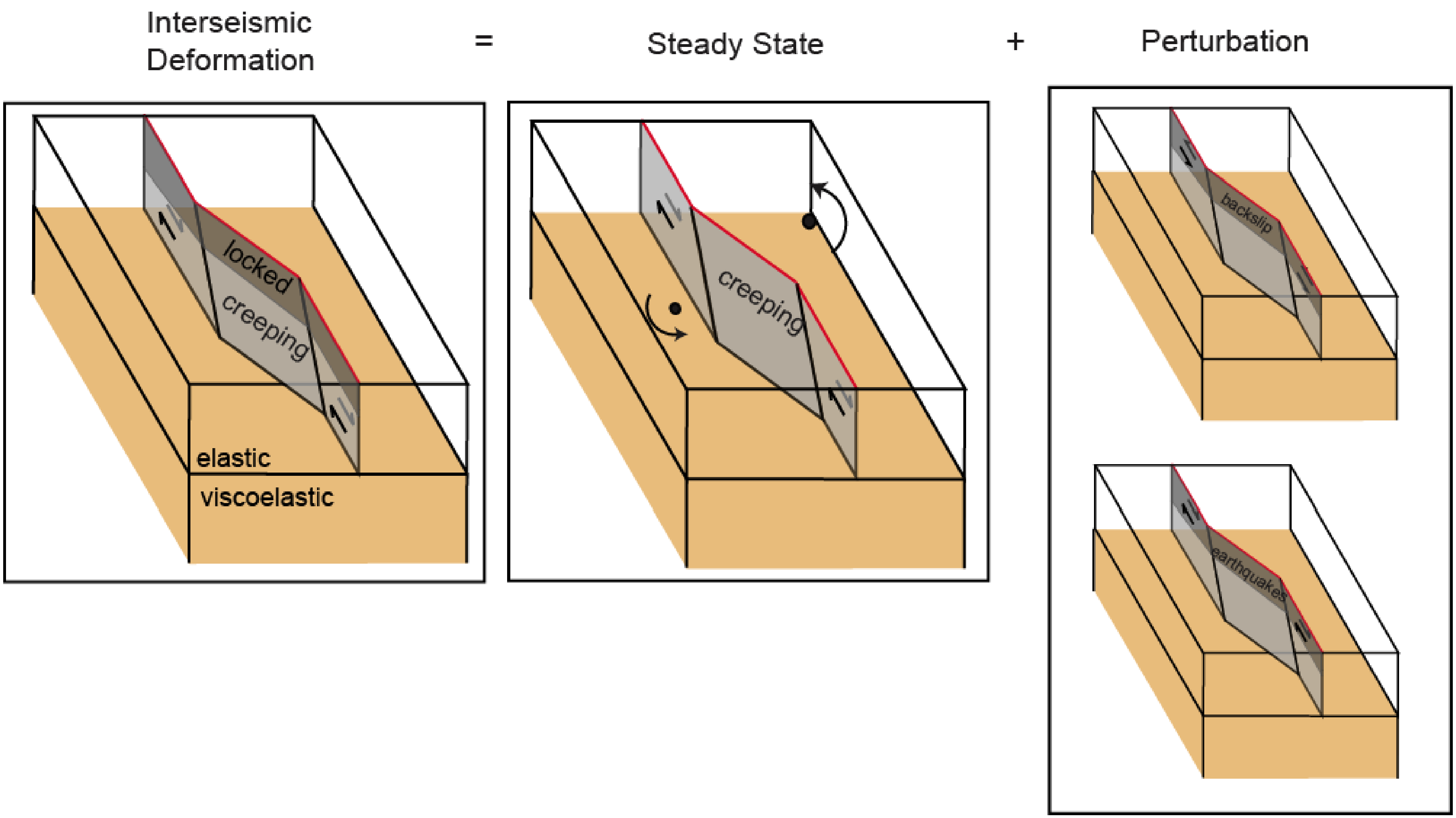


Thatcher and Pollitz (2008)

Faults are not 2D!

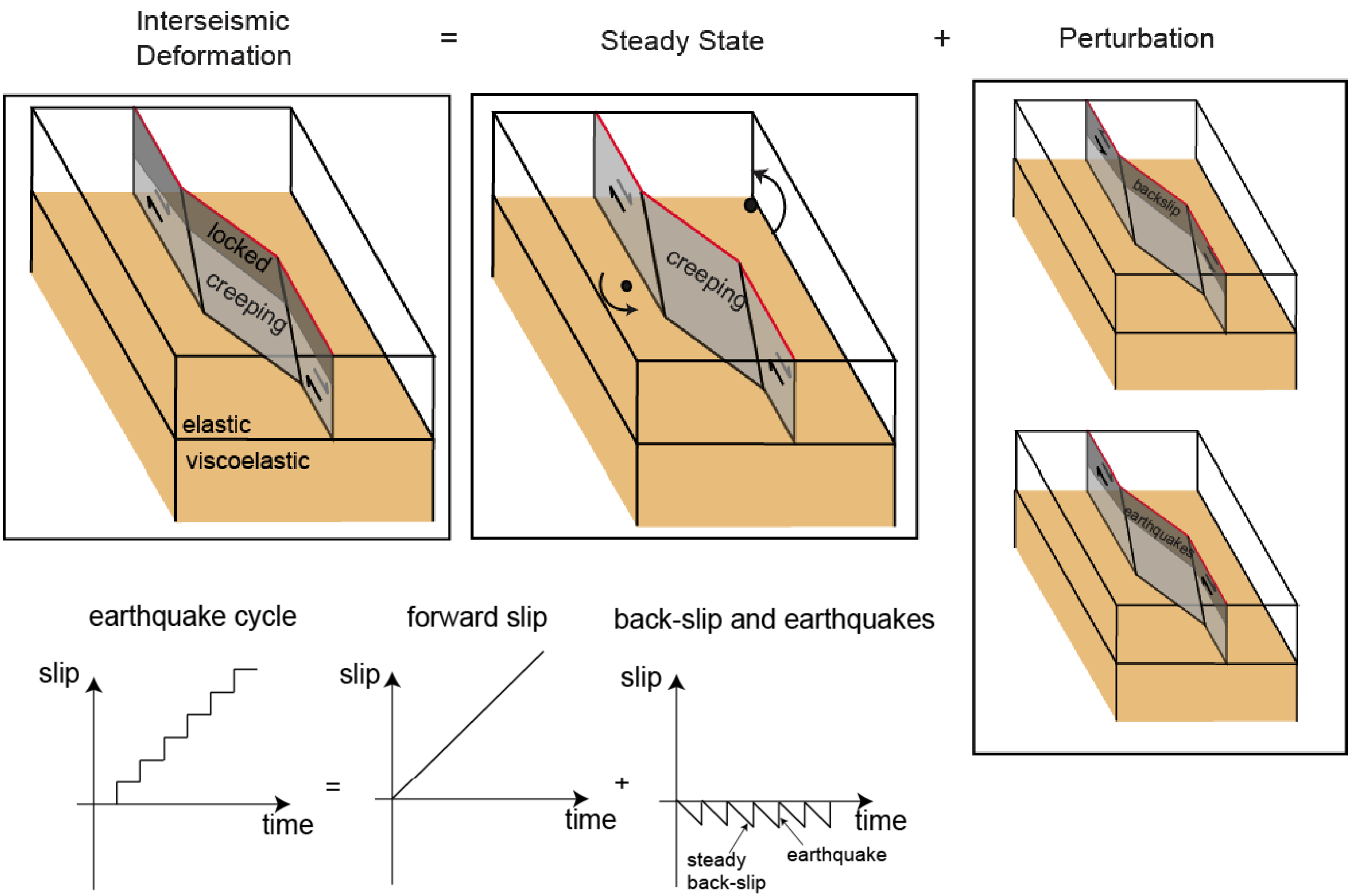


3D Earthquake Cycle Block Model

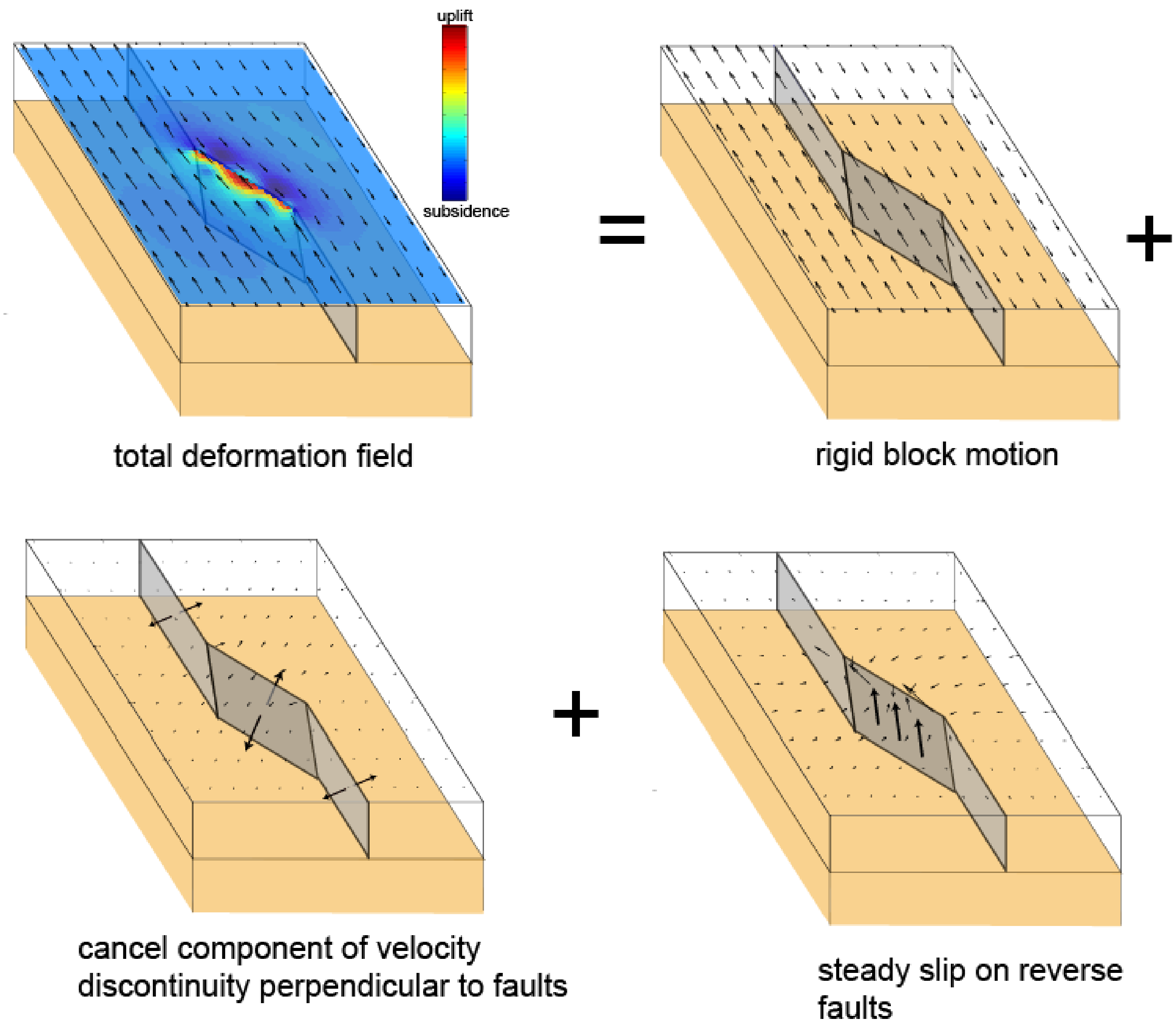


paper in prep.

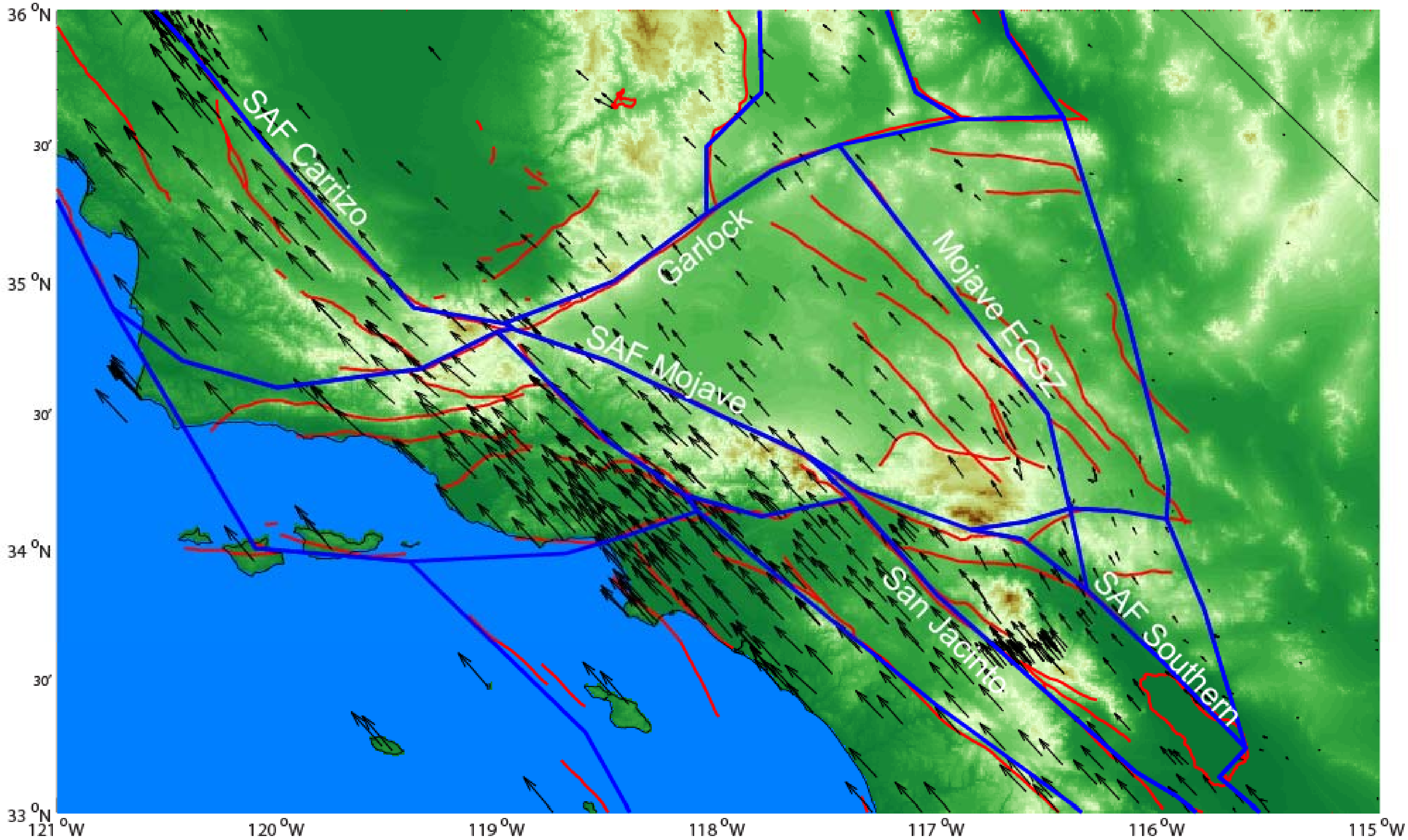
3D Earthquake Cycle Block Model



Construction of Steady State Velocity Field

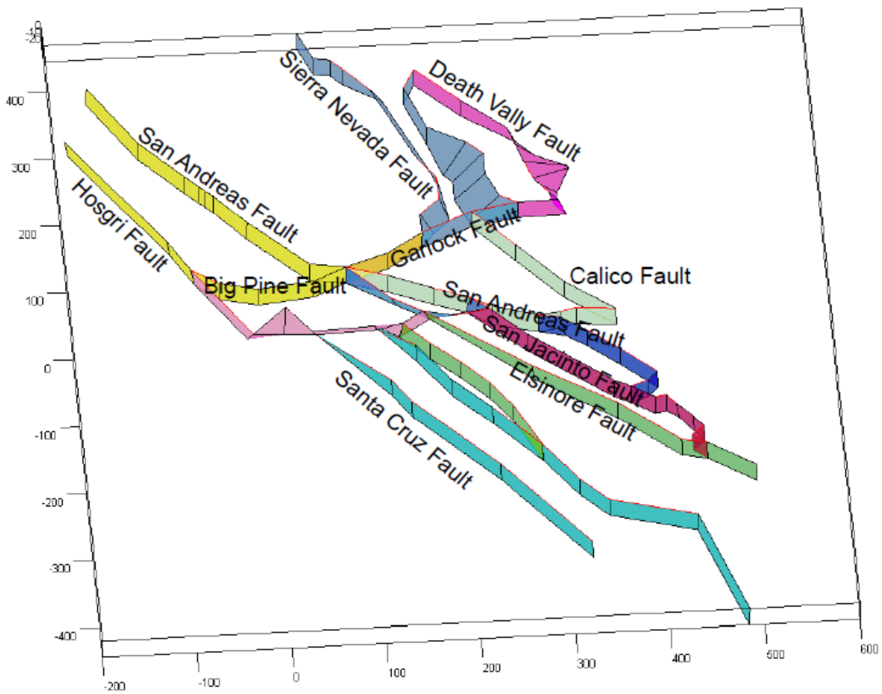


3D Cycle Block Model for Southern California

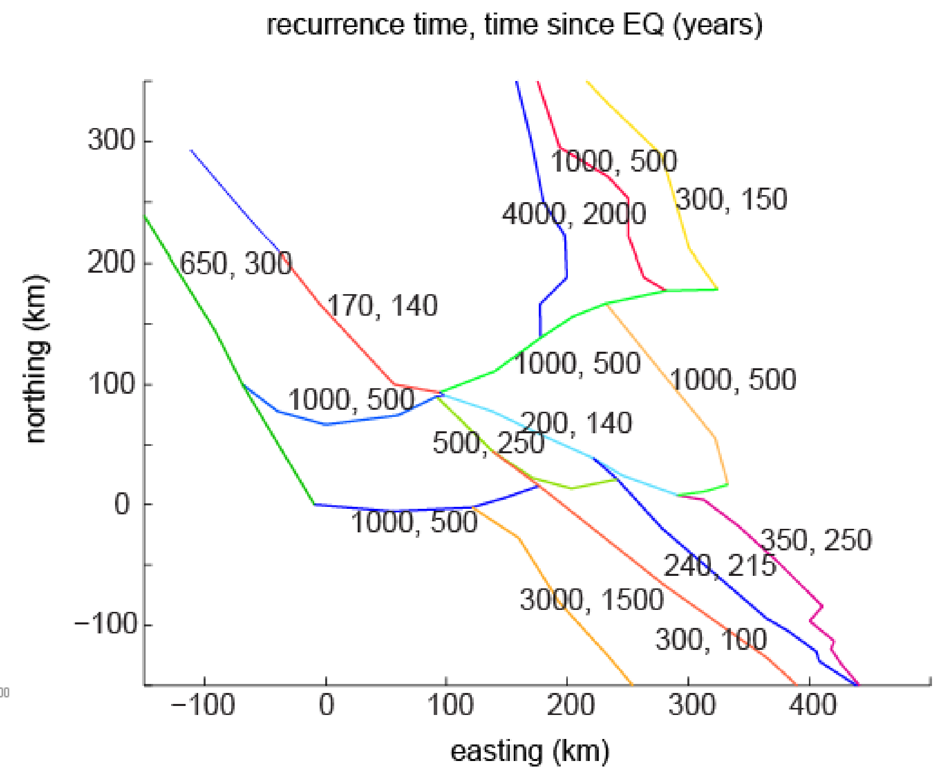


Fault Geometry

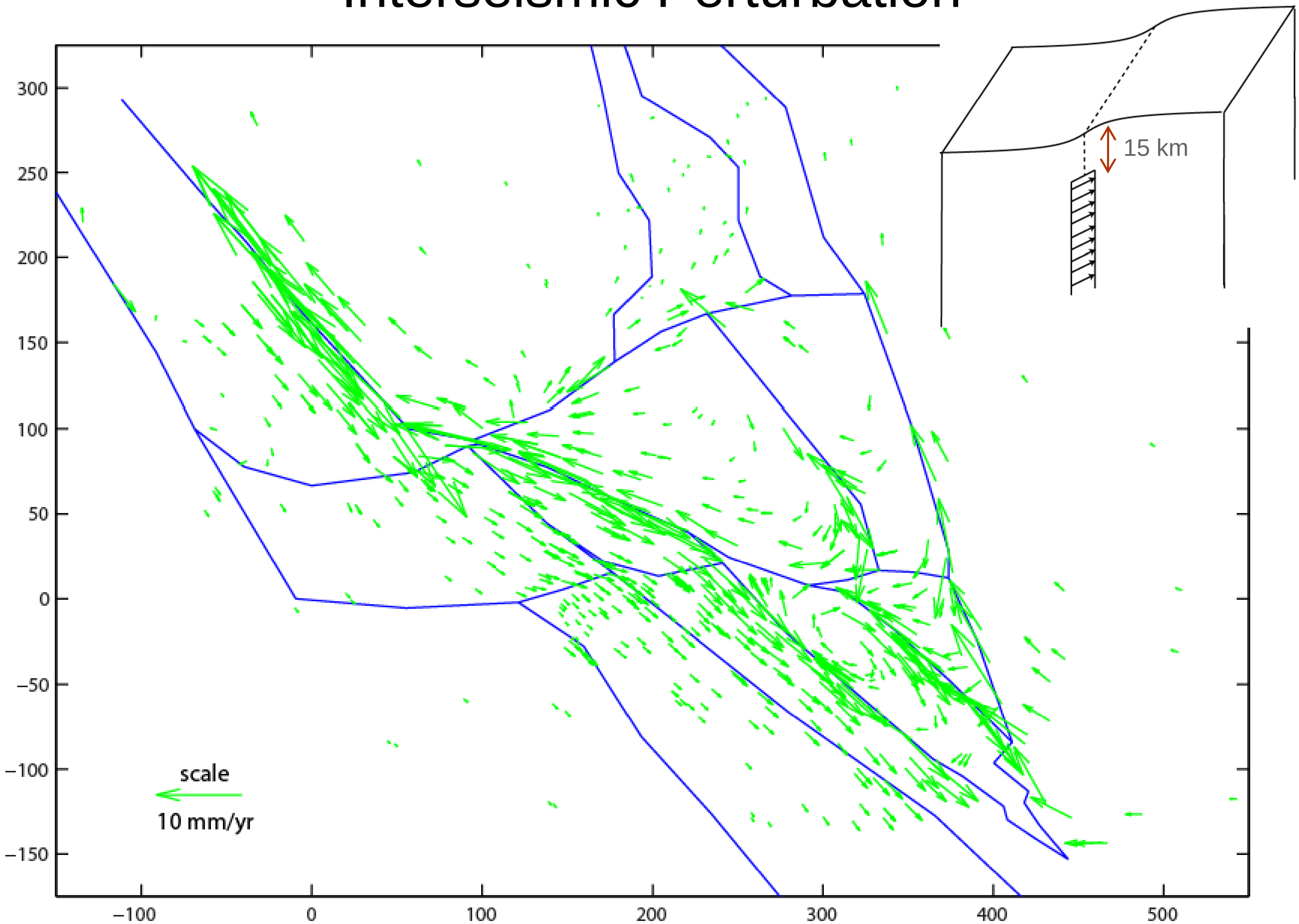
Based on SCEC Community Fault Model



Rupture Segments



Interseismic Perturbation



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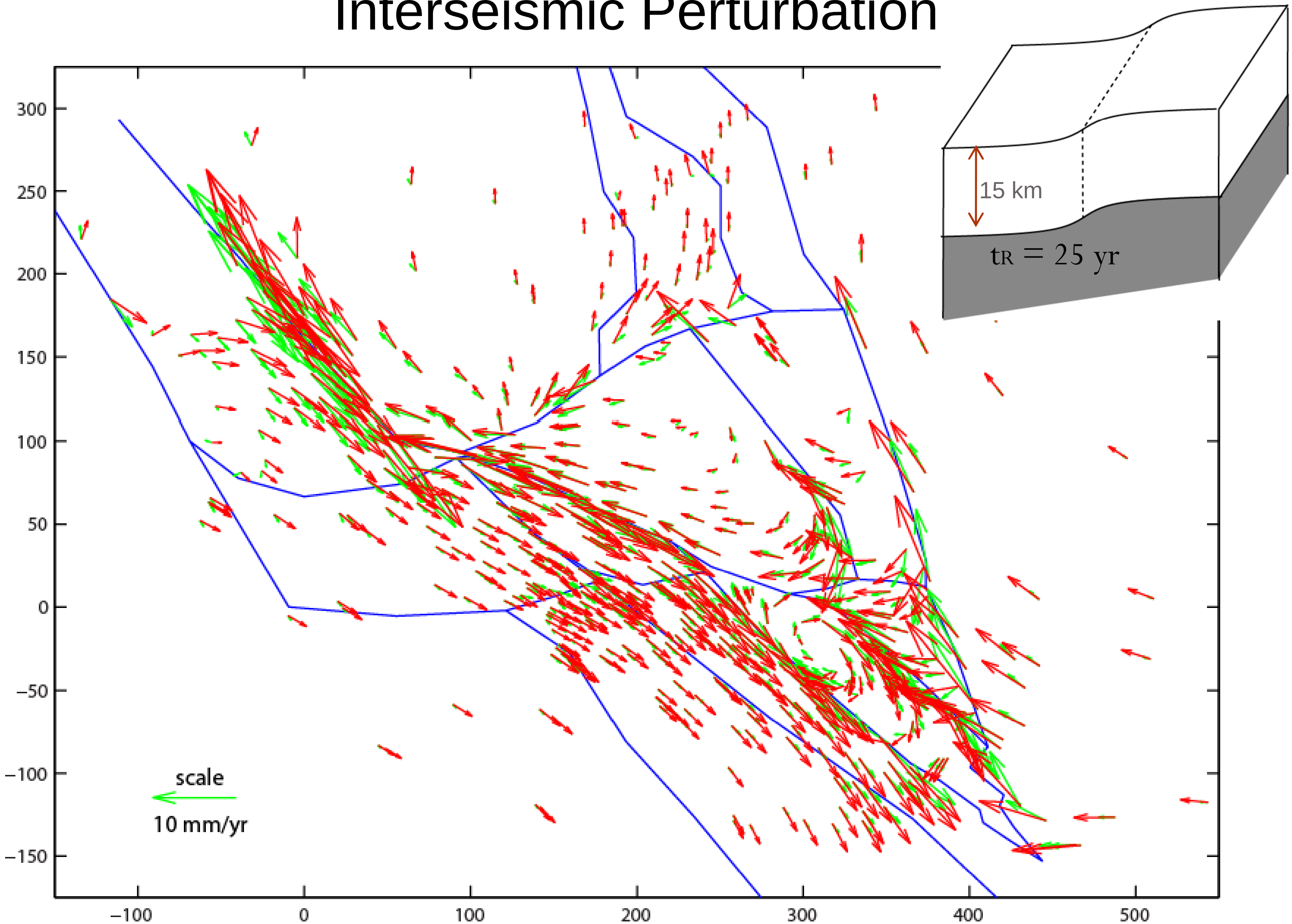

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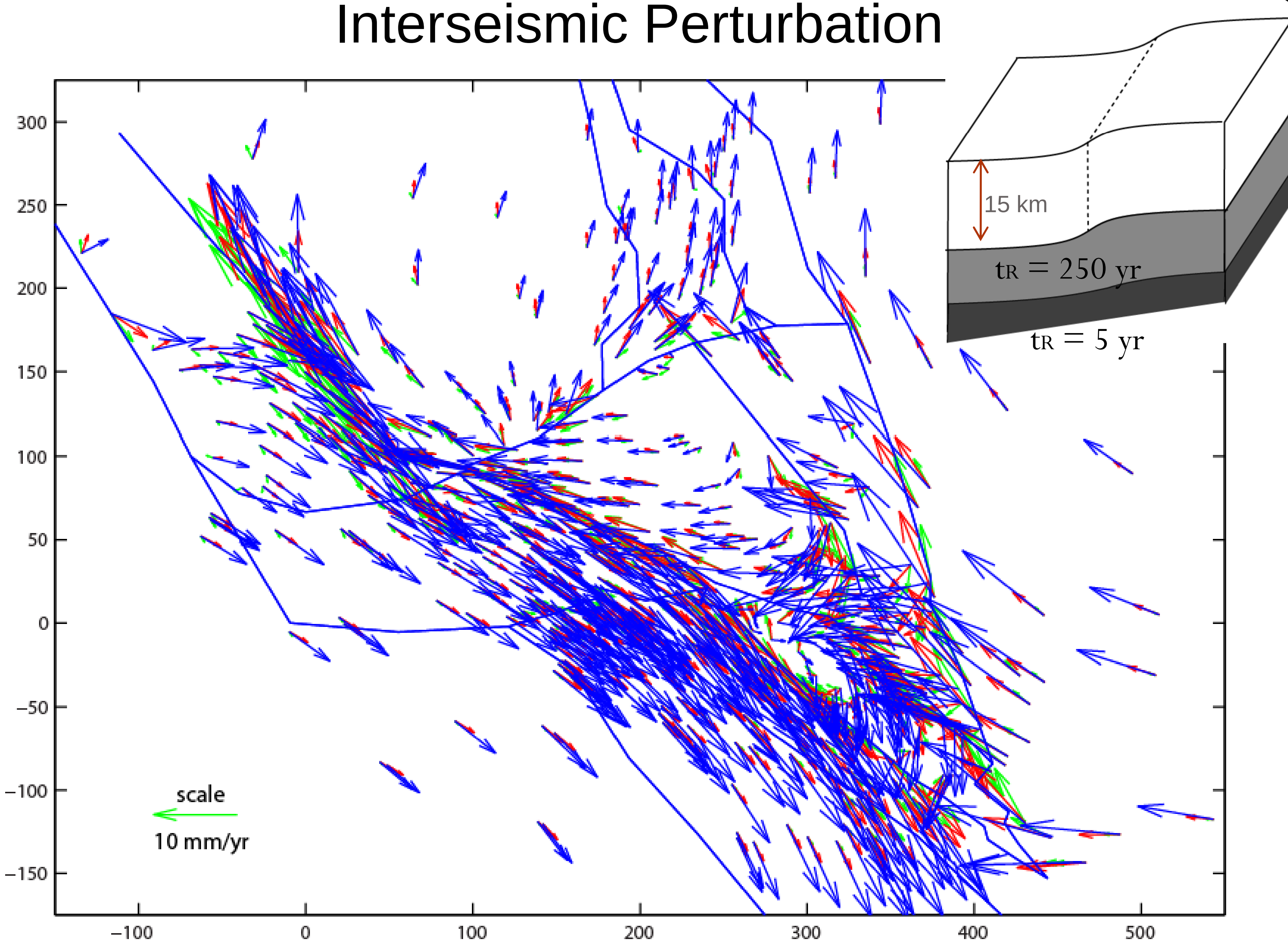
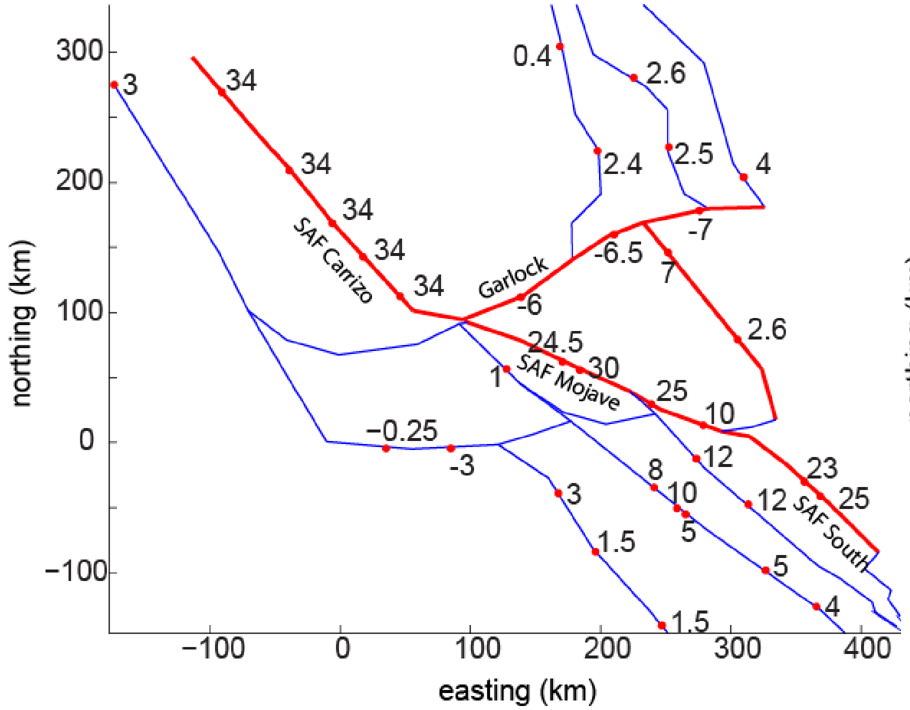
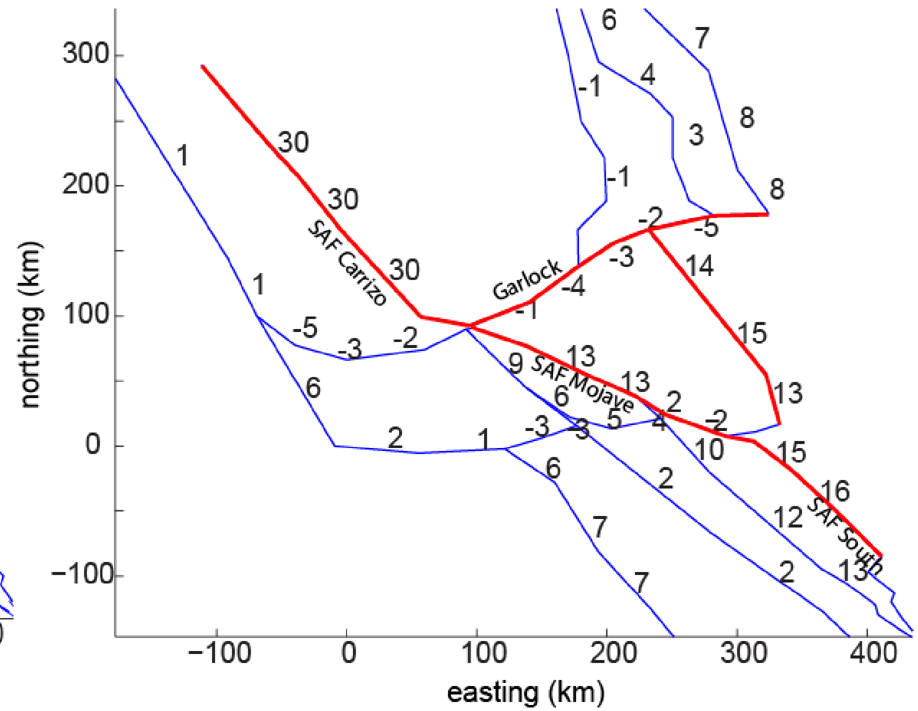


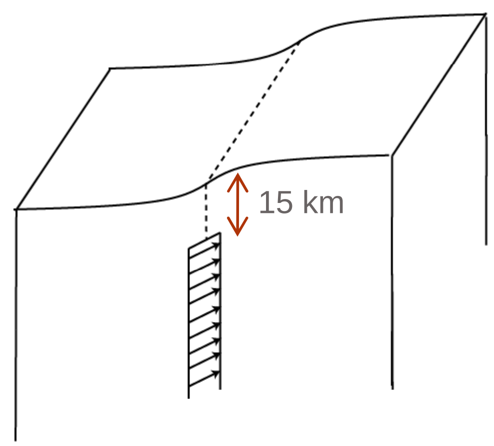
Inversion Results: strike-slip rate (mm/yr)

Geologic rates



Elastic block model





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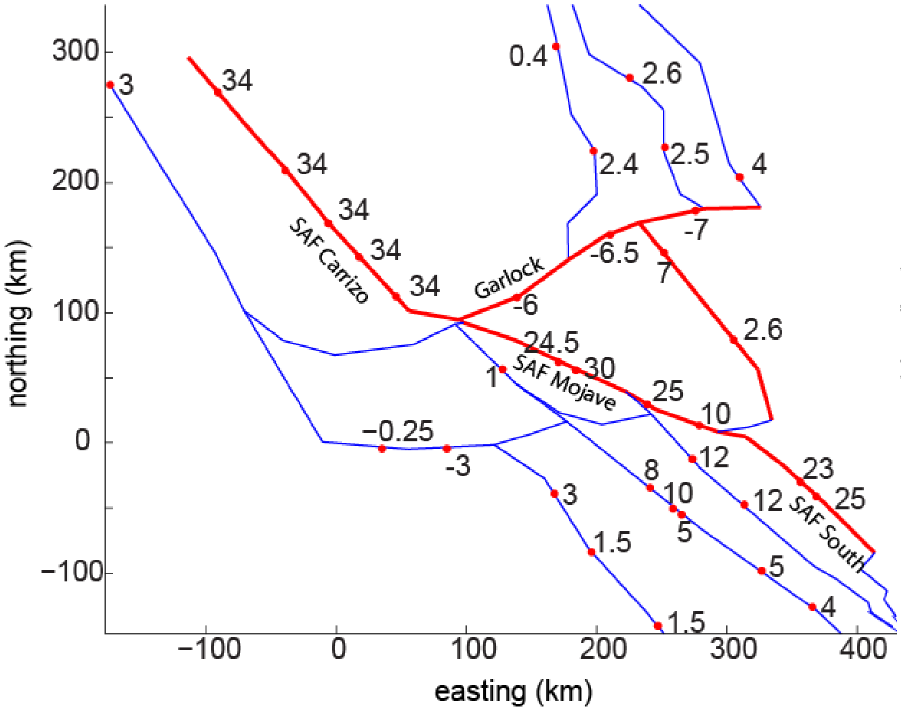
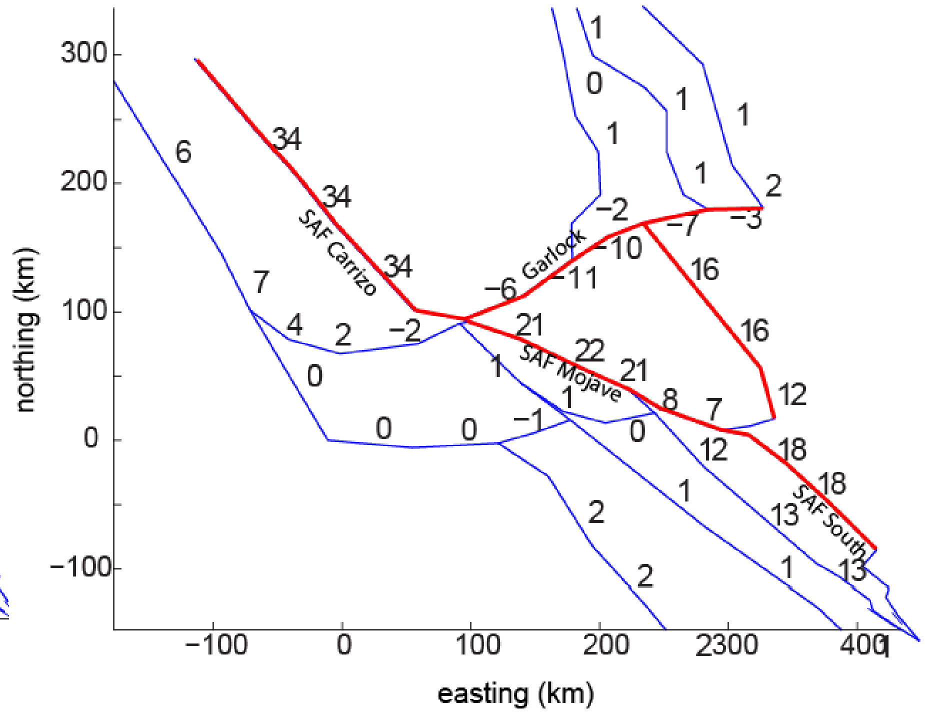
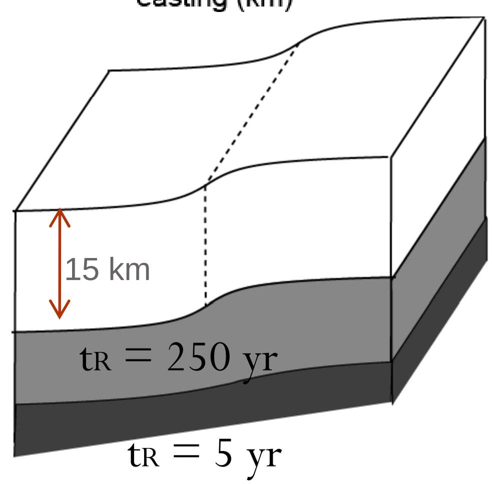
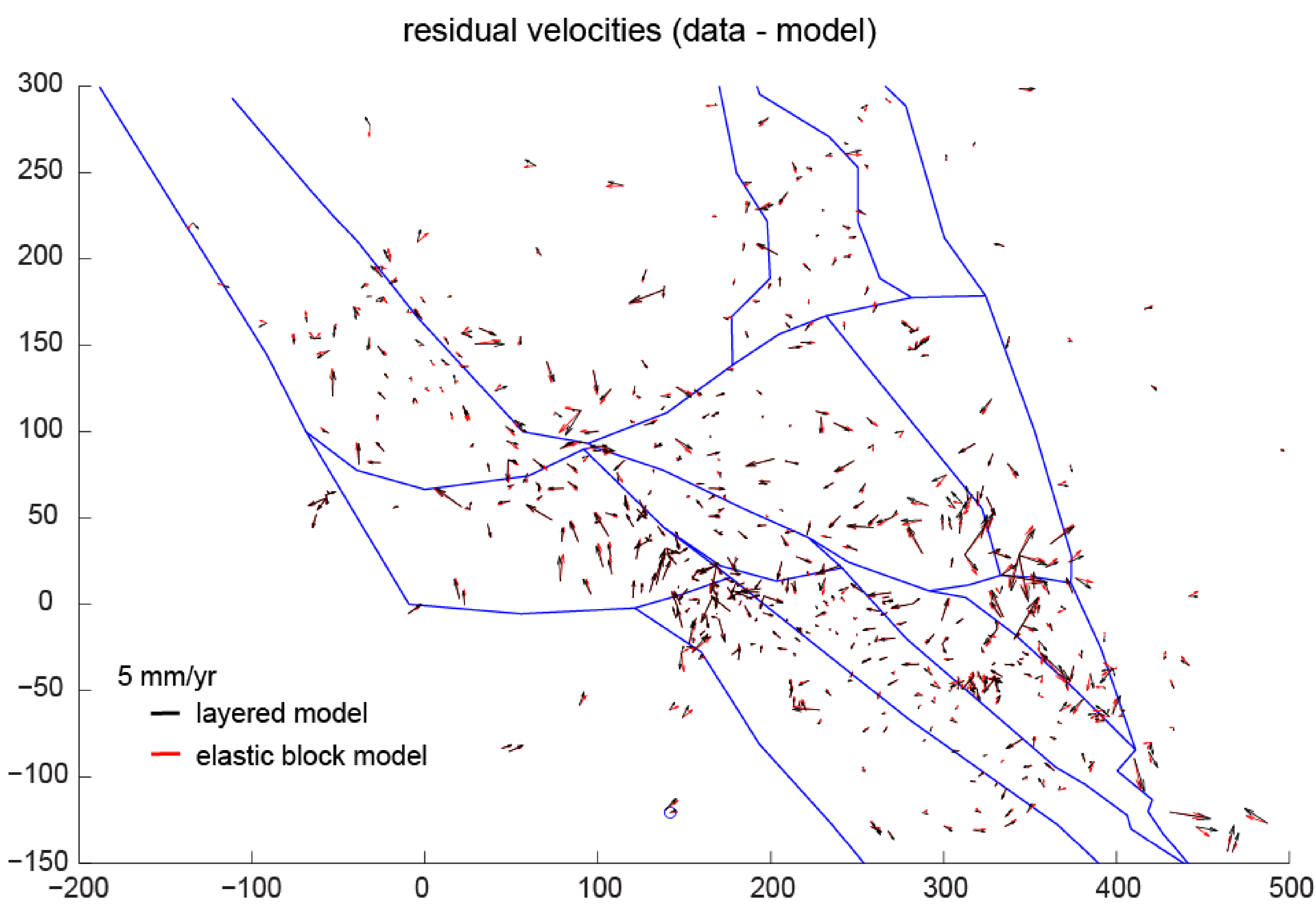


Viscoelastic block model



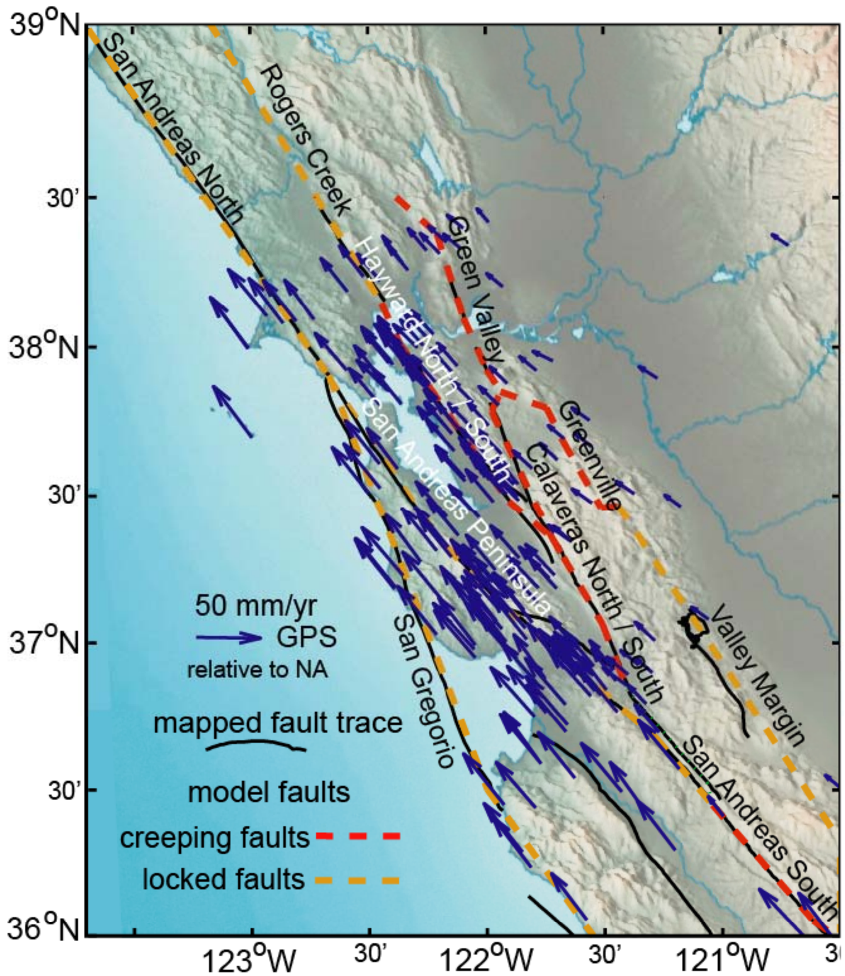


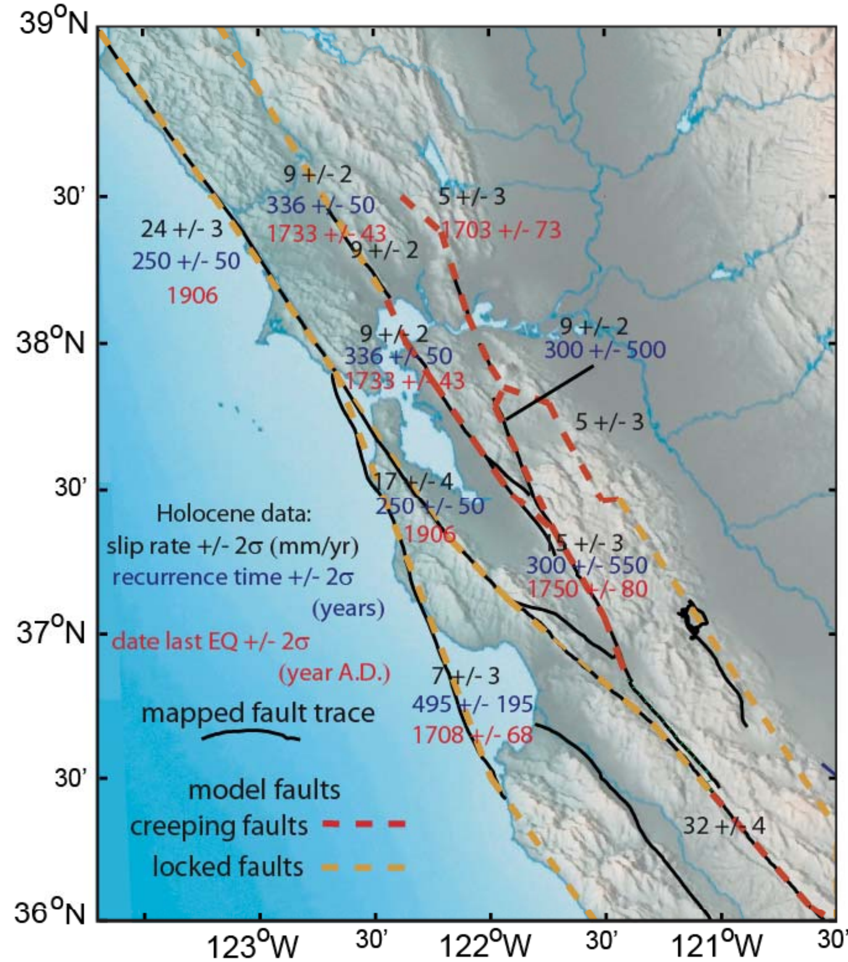


residual velocities (data - model)
300
250
200
150
100
50
0
−50
−100
−150
−200
−100
0
100
200
300
400
500
5 mm/yr
layered model
elastic block model

San Francisco Bay Area

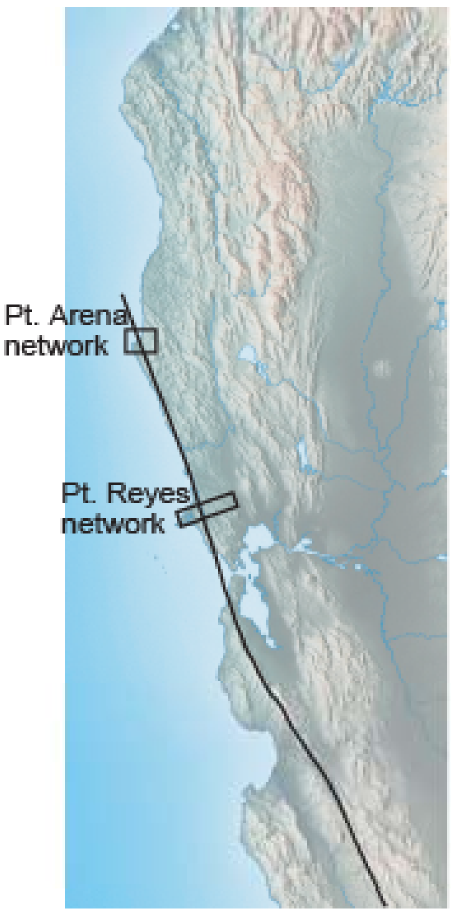
GPS and geologic data

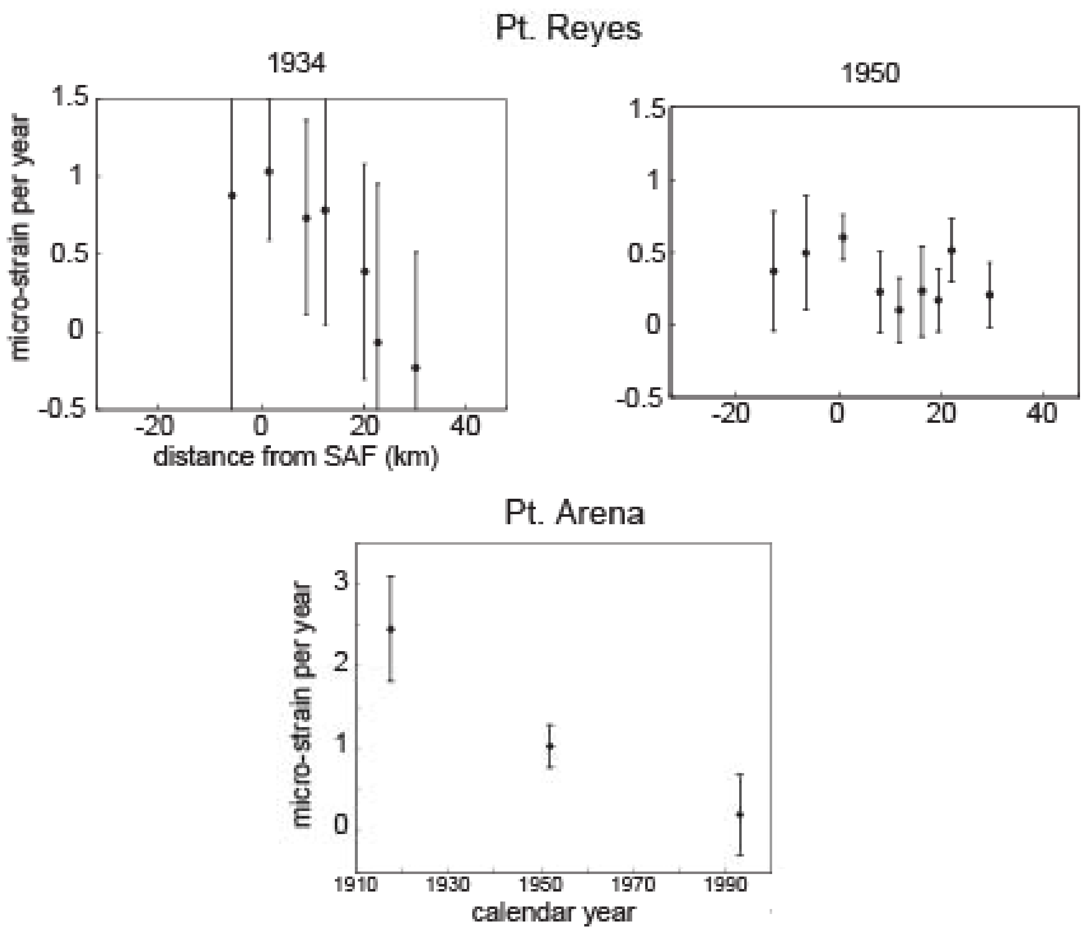




San Francisco Bay Area

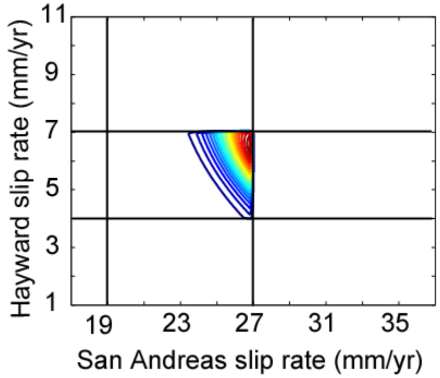
Triangulation data: post 1906 transient





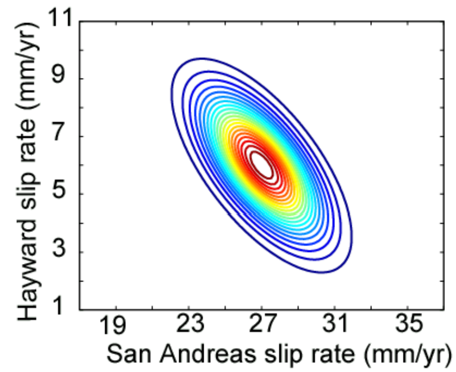
Probabilistic Bayesian Inversion

Posterior distribution



$= k \bullet$

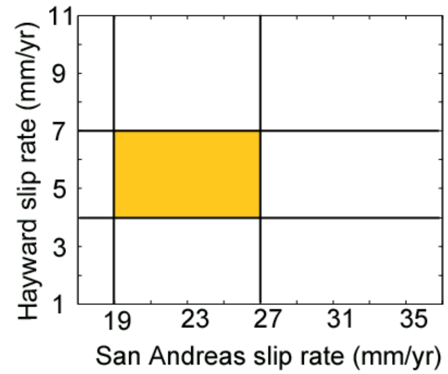
Likelihood



geodetic data & model

x

Prior distribution



geologic data

$$p(\boldsymbol{\Omega}, \mathbf{n}, \mathbf{w}_{GPS}, w_{TRI} \mid d) \quad = \quad p(d \mid \boldsymbol{\Omega}, \mathbf{n}, \mathbf{w}_{GPS}, w_{TRI}) \quad p(\boldsymbol{\Omega}, \mathbf{n}, \mathbf{w}_{GPS}, w_{TRI})$$

Euler poles (linear)

Nonlinear parameters

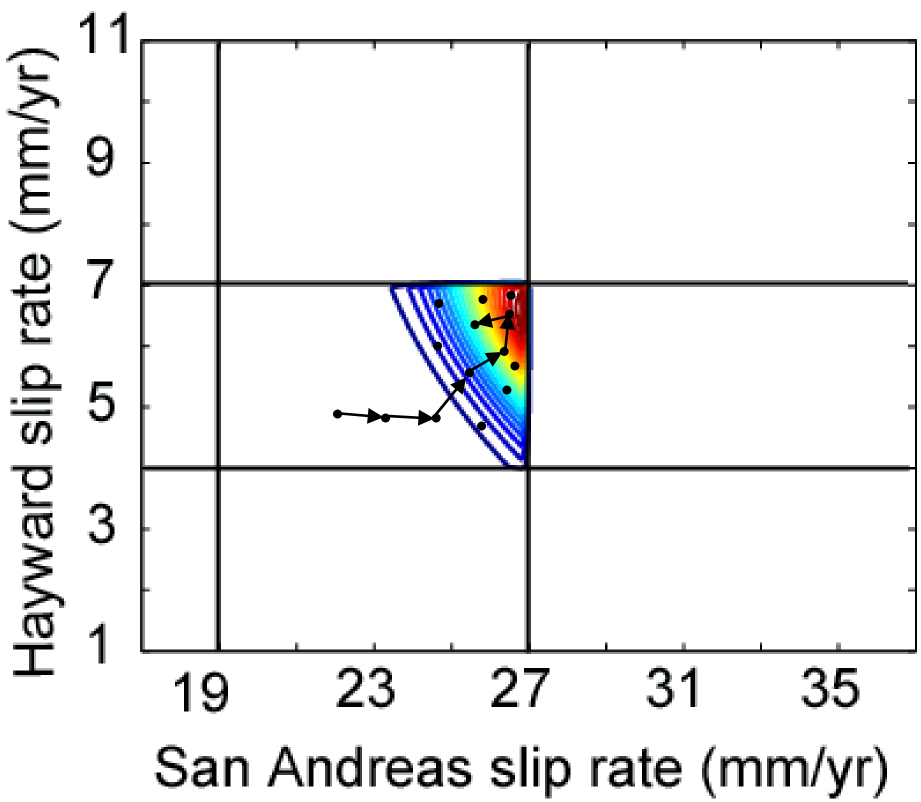
Relative weights on data

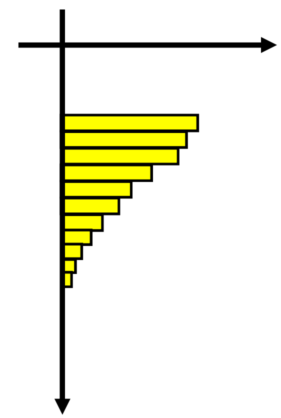
data

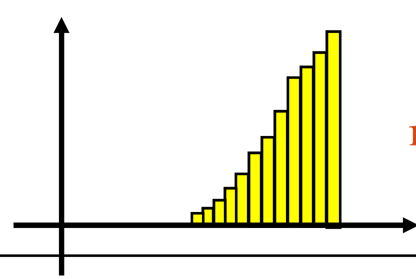
Algorithm

Monte Carlo with Metropolis Step

discrete samples







marginal

Mixed Linear/Nonlinear Inversion

$$p(\Omega, \mathbf{n}, \mathbf{w}_{GPS}, w_{TRI} \mid d) \quad = \quad p(\mathbf{\Omega} \mid d, \mathbf{n}, \mathbf{w}_{GPS}, w_{TRI}) \quad x \quad p(\mathbf{n}, \mathbf{w}_{GPS}, w_{TRI} \mid d)$$

data

Euler poles (linear)

Relative weights on data

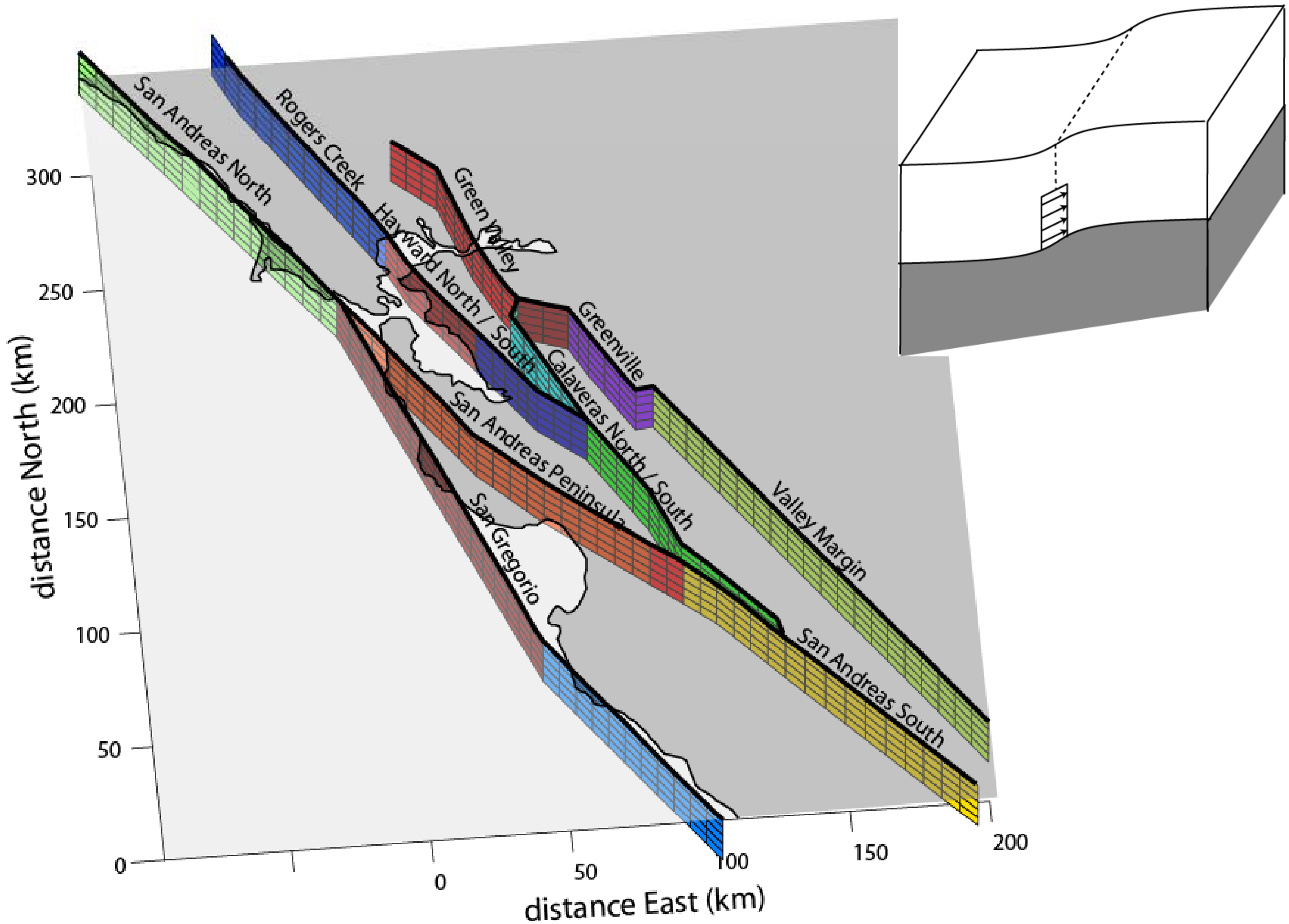
Nonlinear parameters

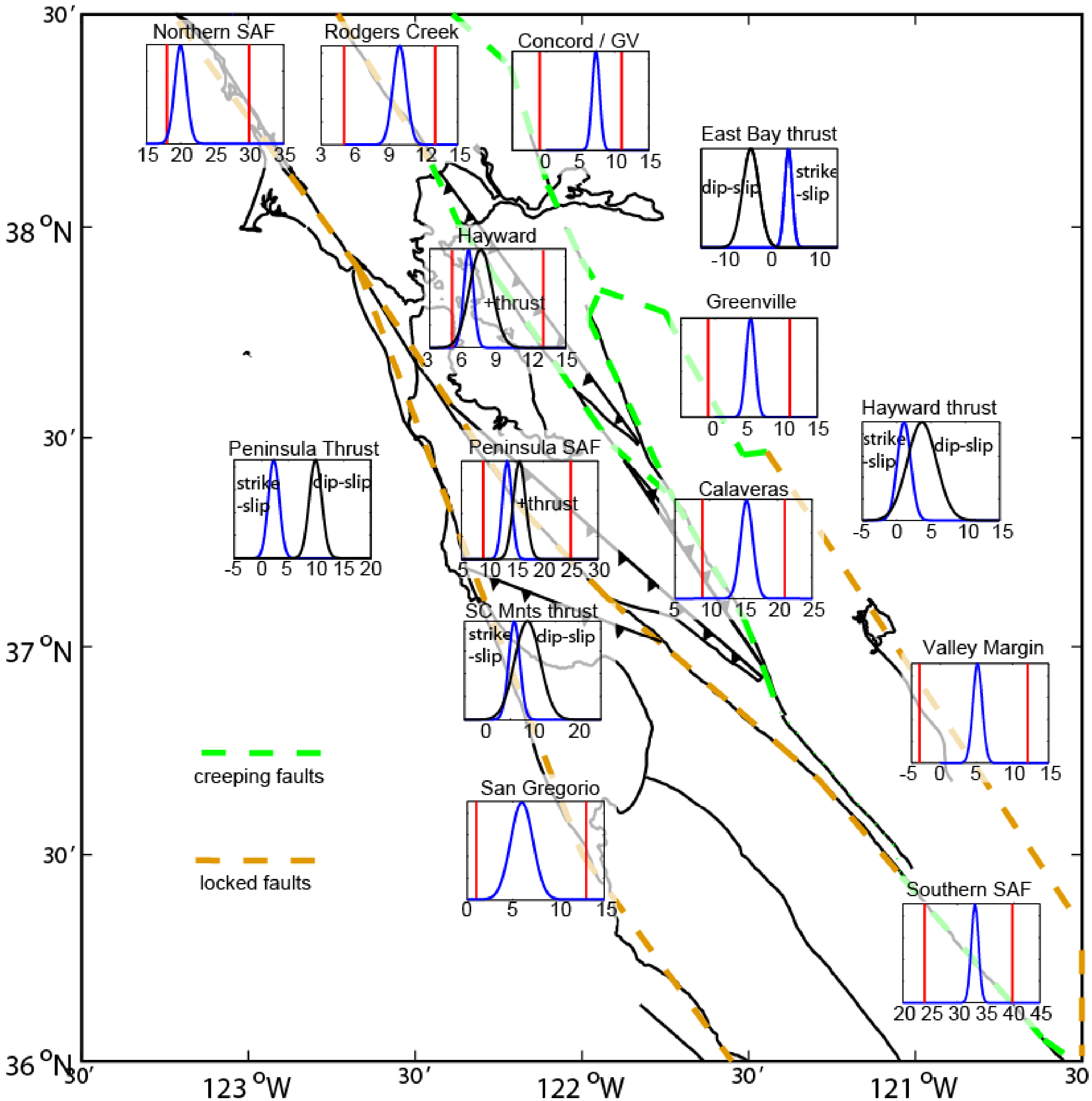
obtain with least squares

obtain analytical expression

sample with Monte Carlo algorithm

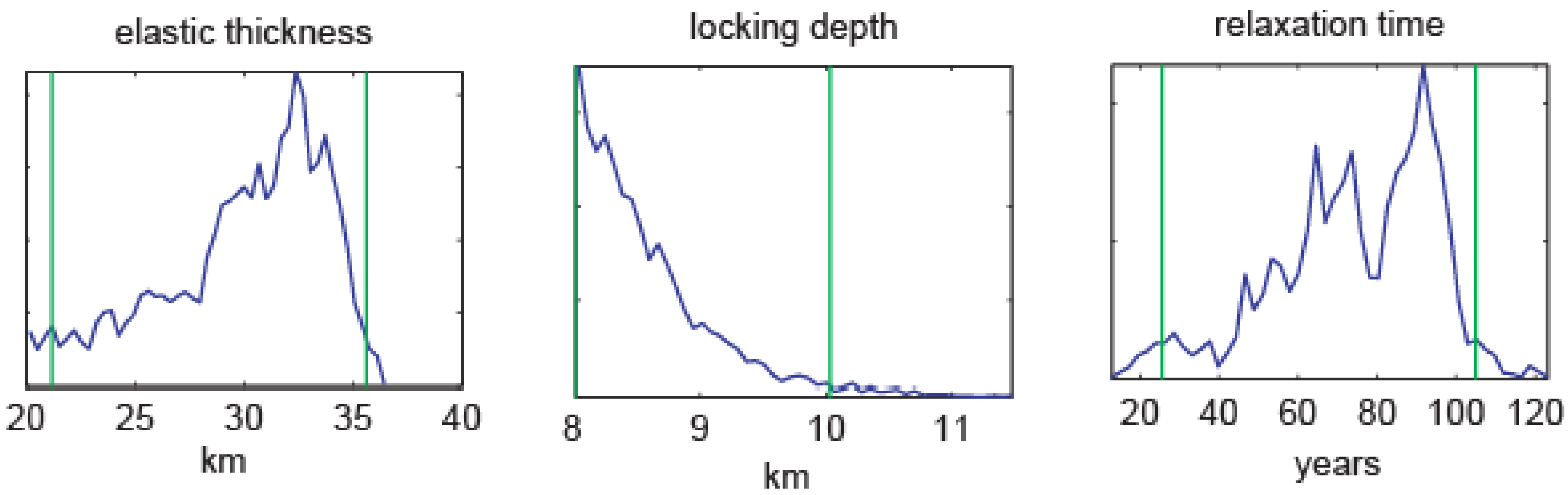
3D Viscoelastic Cycle Model

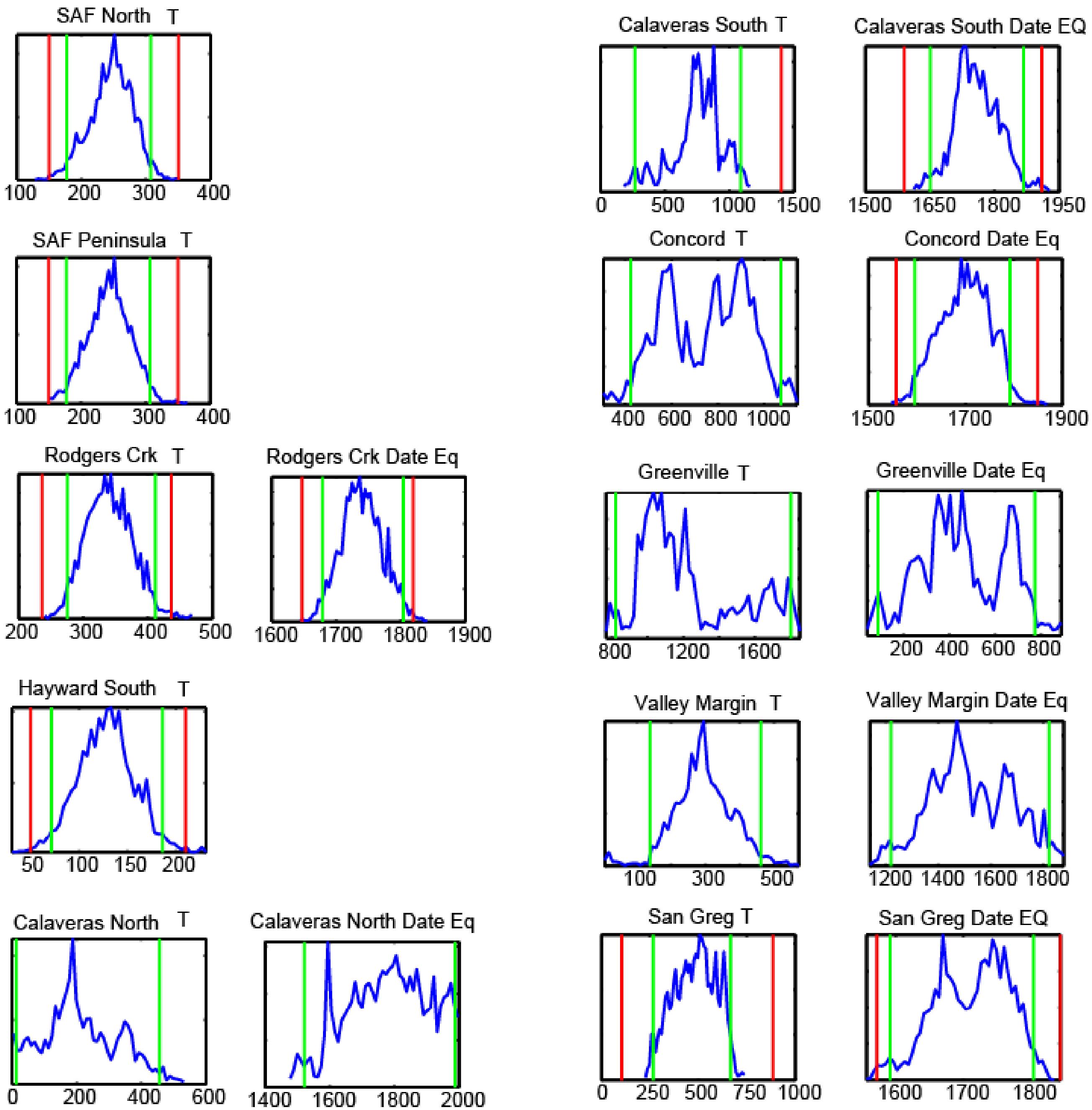




Inversion Result: Fault slip rates

Inversion Results:

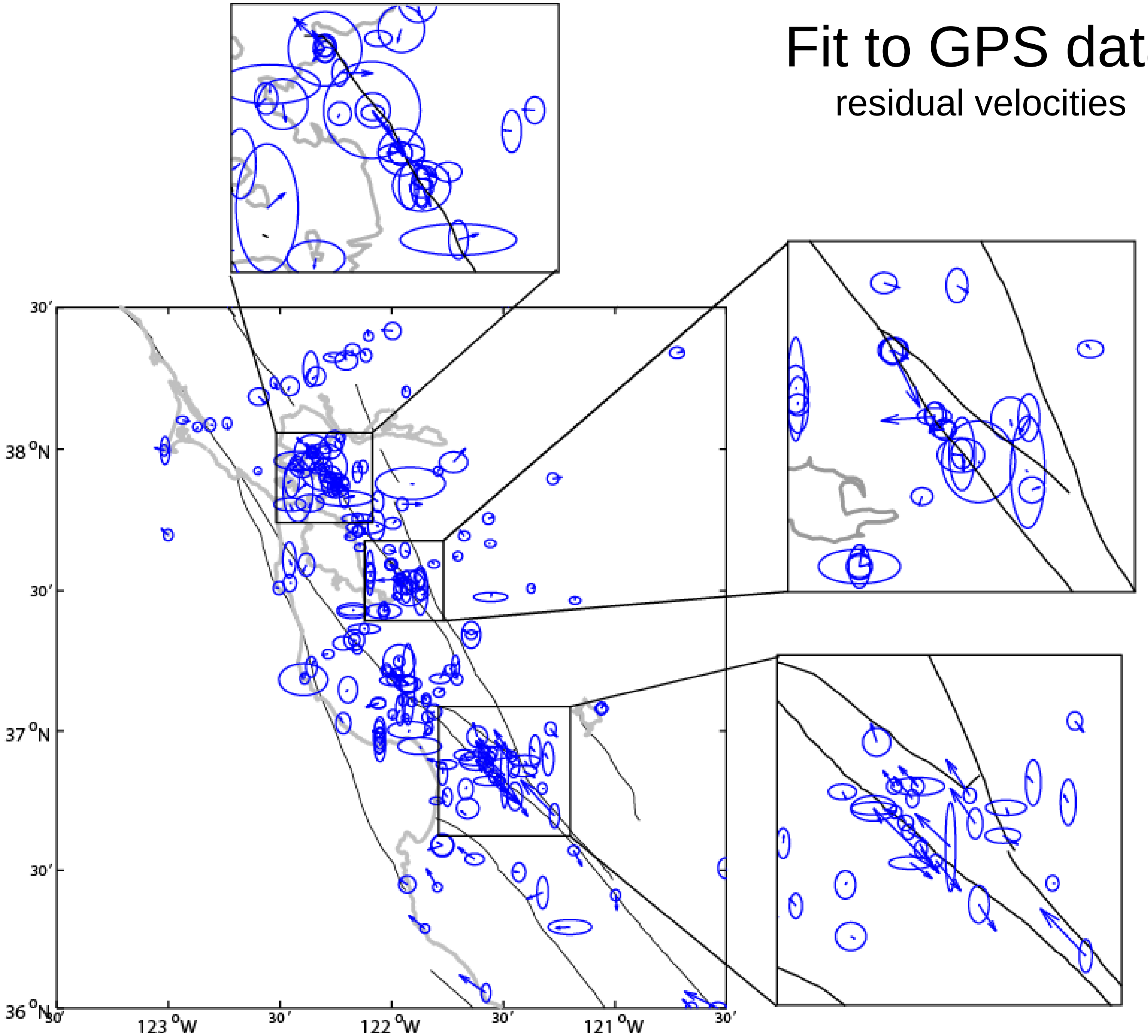




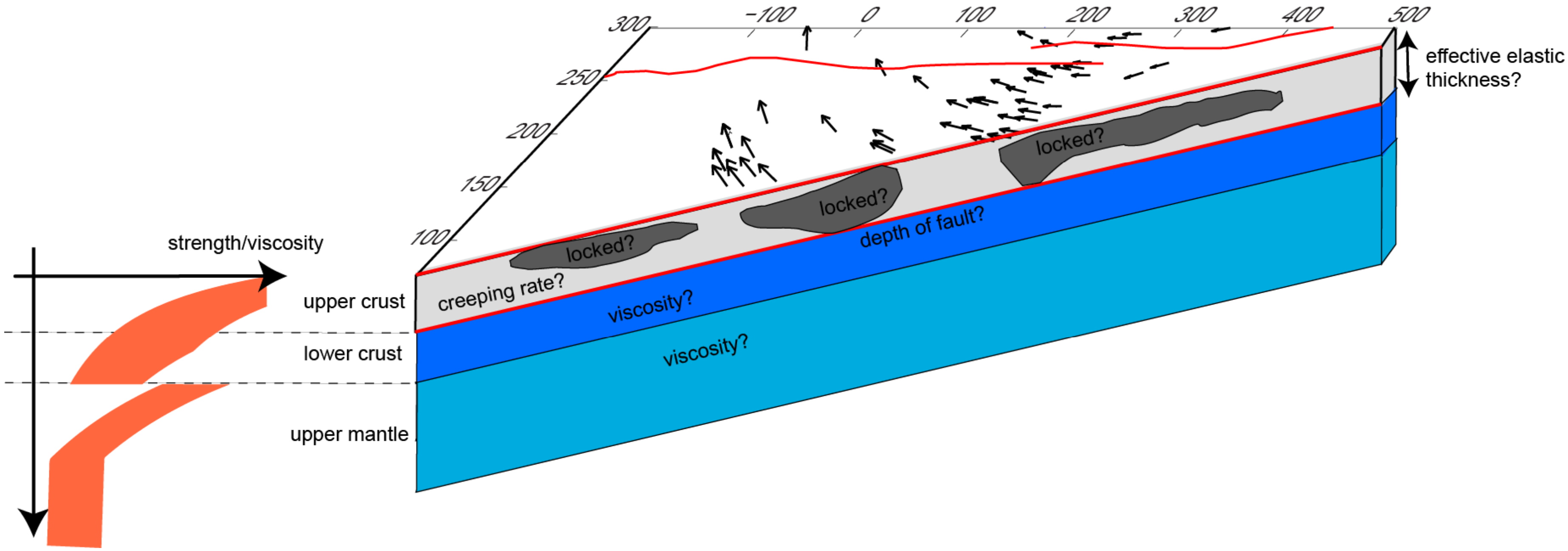
Inversion Result: Earthquake Recurrence Times

Fit to GPS data

residual velocities



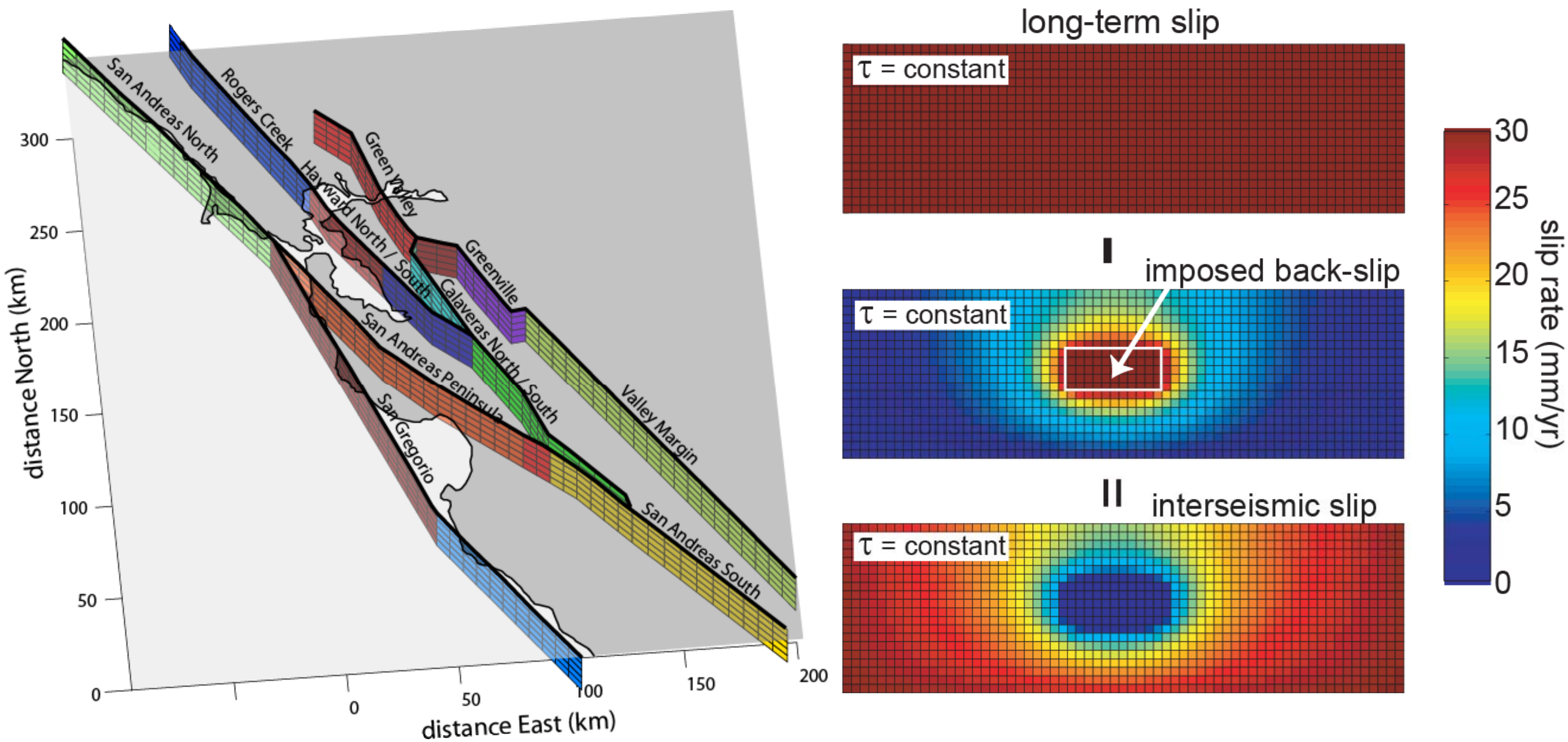
Conceptual Model of Lithosphere



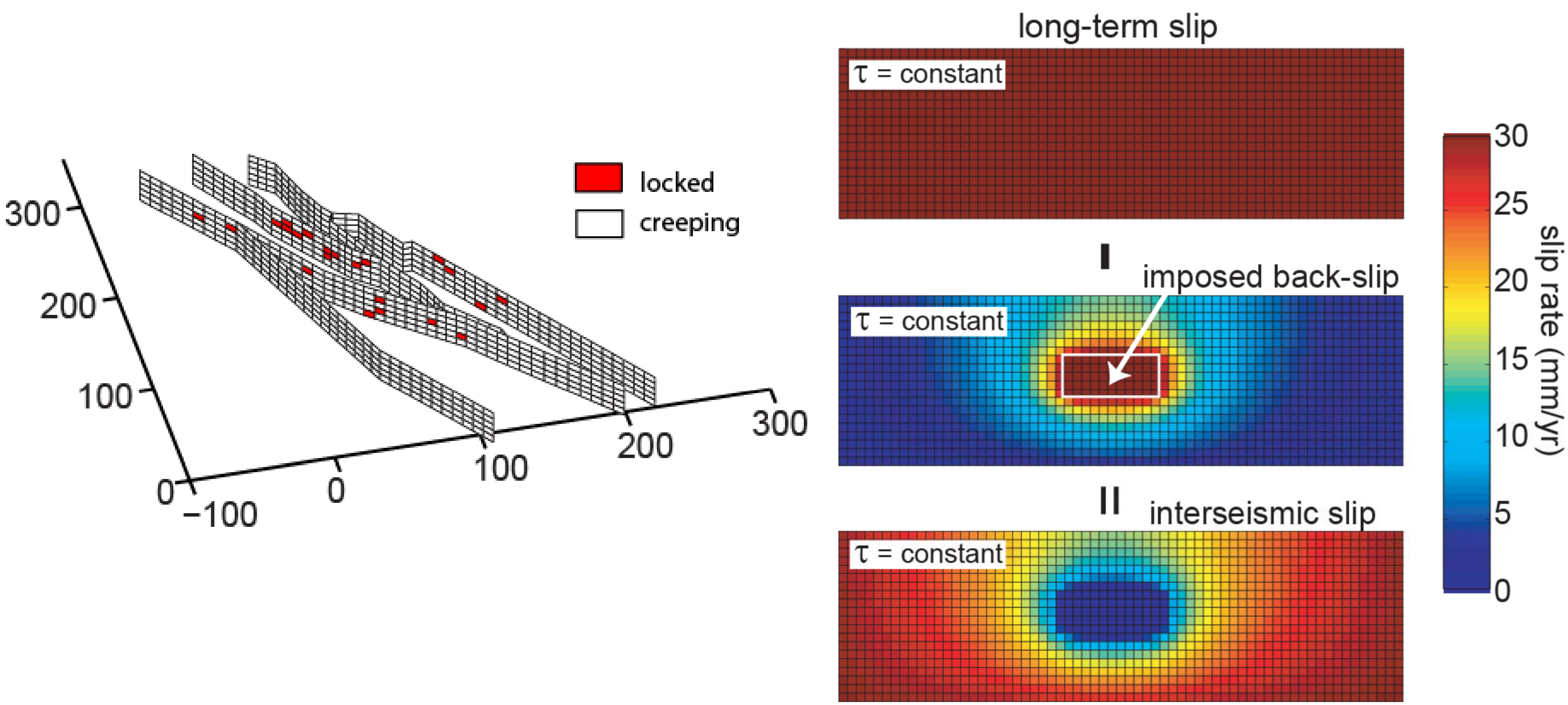
Approach: develop forward model and inverse method to obtain joint estimation of

(1) long-term fault slip rates
(2) Interseismic creep rates
(3) Location of locked patches
(4) Lithosphere viscosity
(5) Elastic thickness

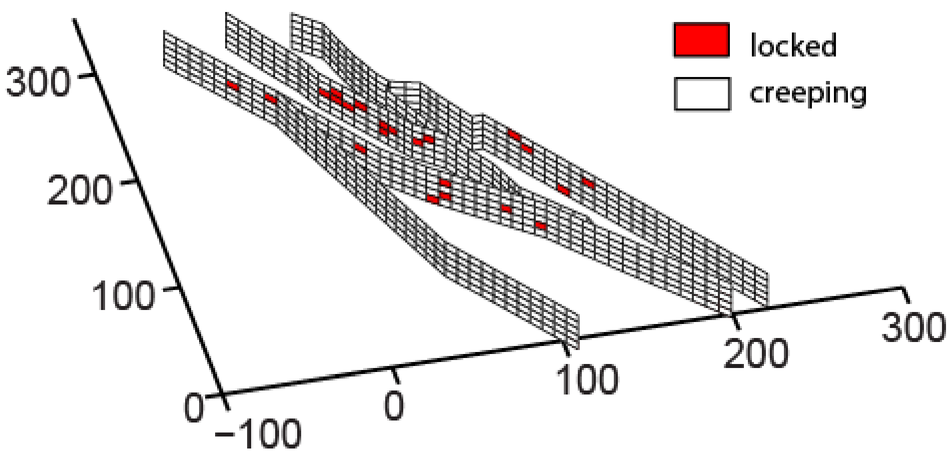
Simultaneous Estimation of Long-term Slip Rates and Locking Distribution

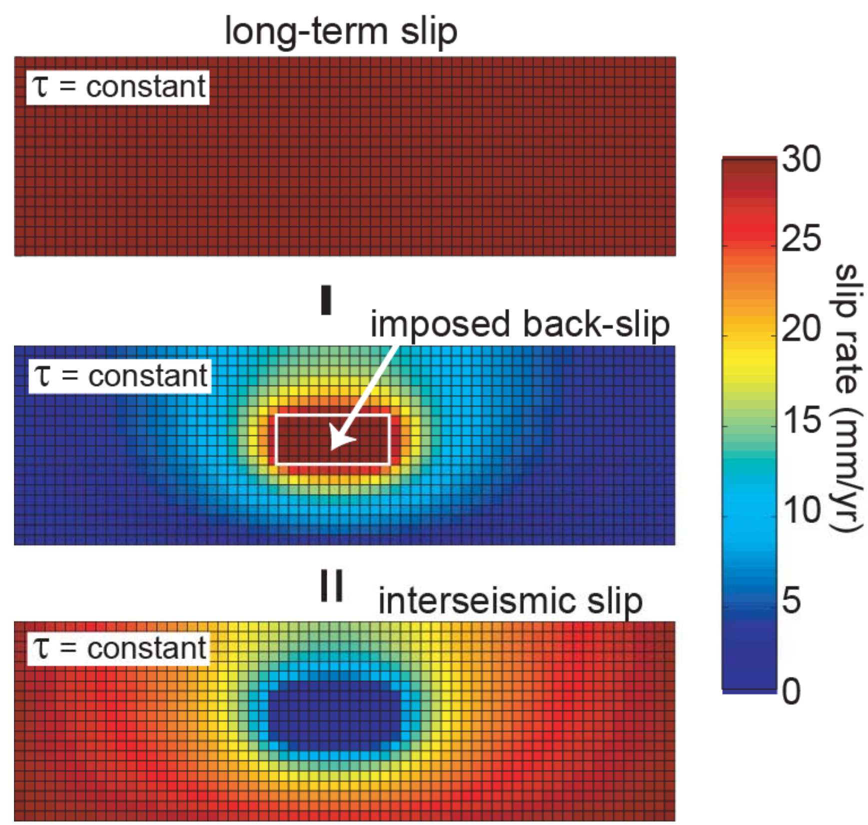


Simultaneous Estimation of Long-term Slip Rates and Locking Distribution



Simultaneous Estimation of Long-term Slip Rates and Locking Distribution





assume steady asthenosphere flow – fault stressing rate is constant

Creep Rate Linearly Related to Euler Poles

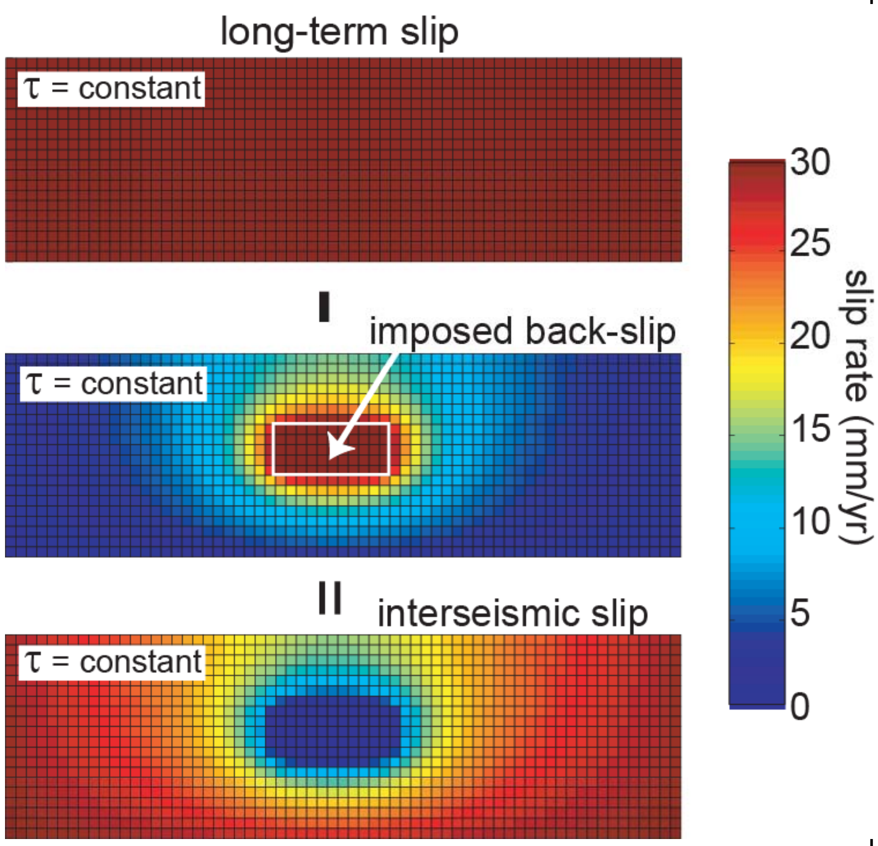
surface velocities — creep rate — long-term slip rate

$$\mathbf{d} = \mathbf{d}_c + \mathbf{d}_\ell = \mathbf{G}_c \dot{s}_c + \mathbf{G}_\ell \dot{s}_\ell$$

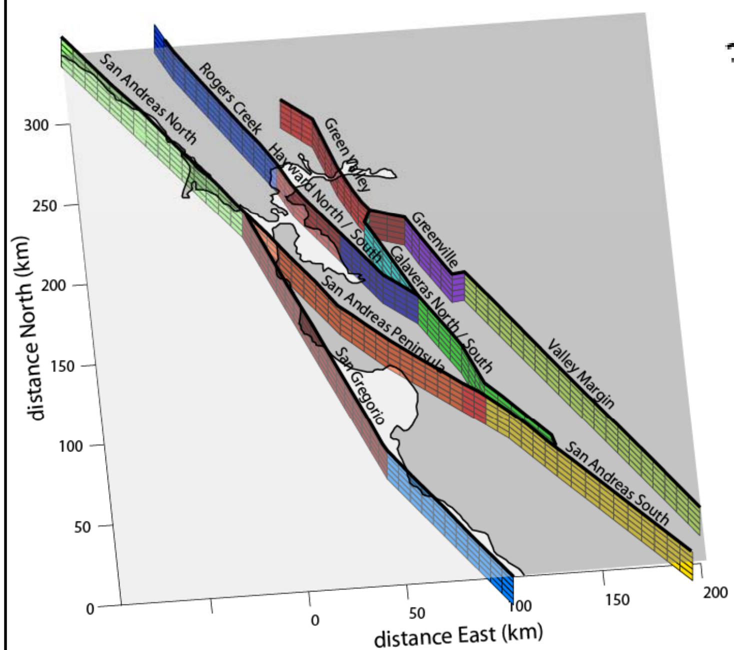
$$\dot{s}_c = \underbrace{(\mathbf{G}'_\sigma)^{-1} \mathbf{G}''_\sigma}_{\text{boundary element}} \dot{s}_\ell$$

$$\dot{s} = \mathbf{V}\Omega$$

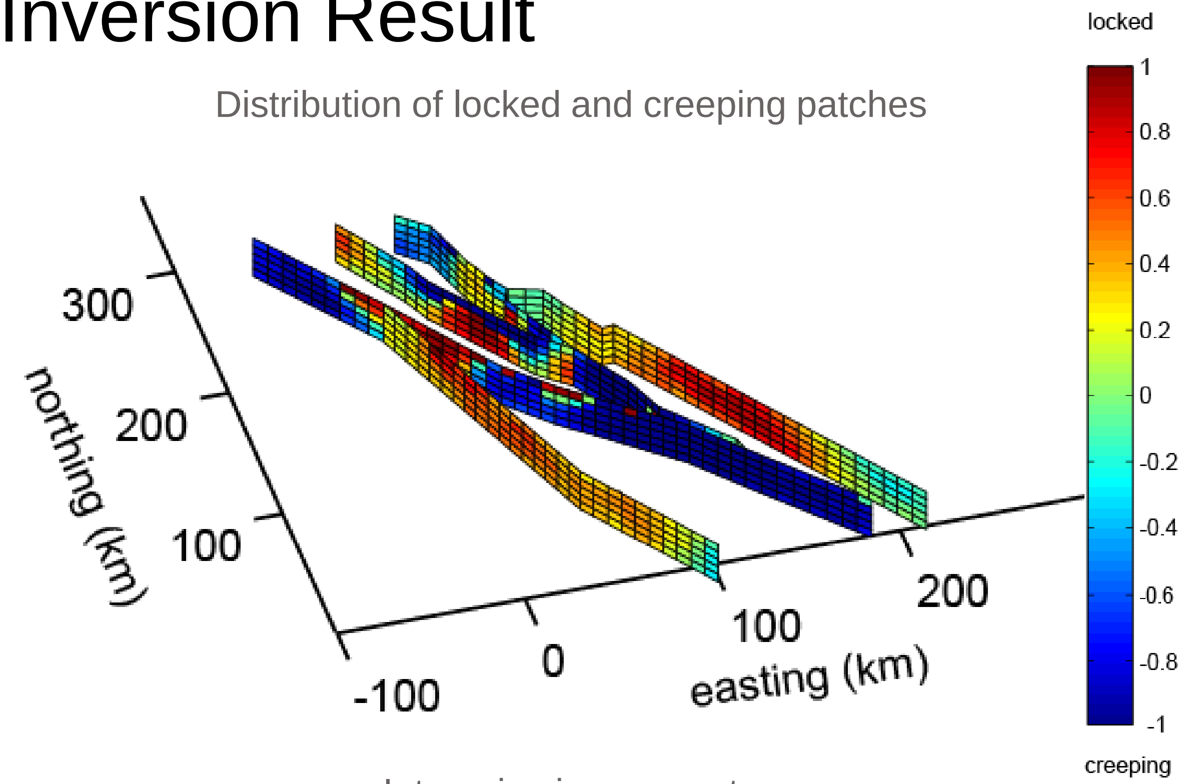
$$\mathbf{d} = \Big[\underbrace{\mathbf{G}_c (\mathbf{G}'_\sigma)^{-1} \mathbf{G}''_\sigma \mathbf{V}_c}_{\text{creeping contribution}} + \underbrace{\mathbf{G}_\ell \mathbf{V}_\ell}_{\text{locked contribution}}\Big] \Omega$$



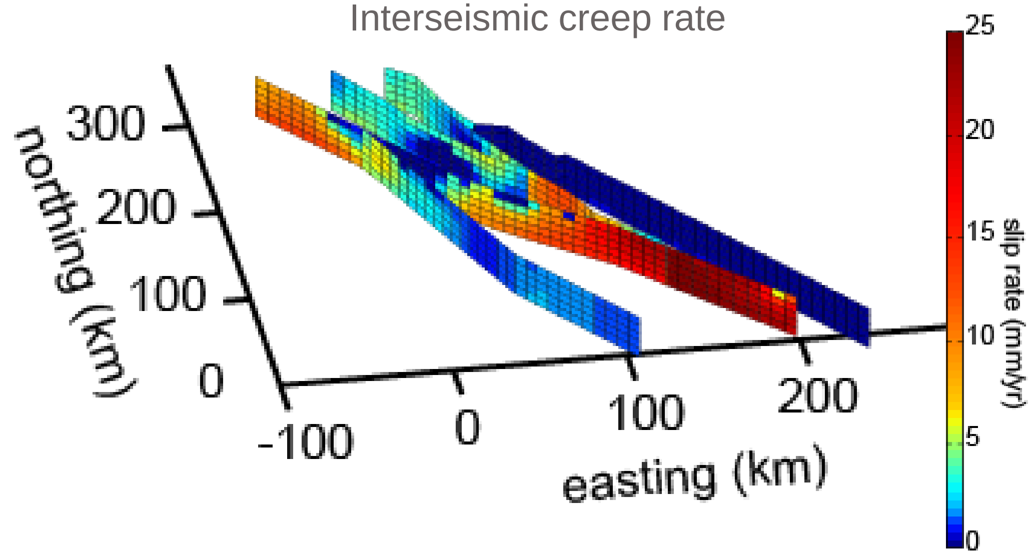
Inversion Result

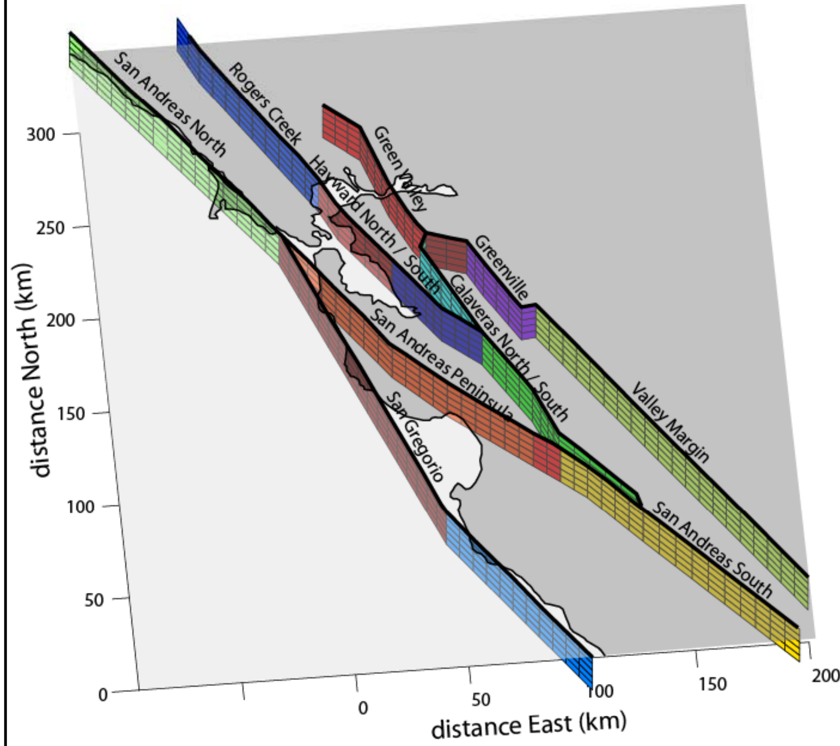


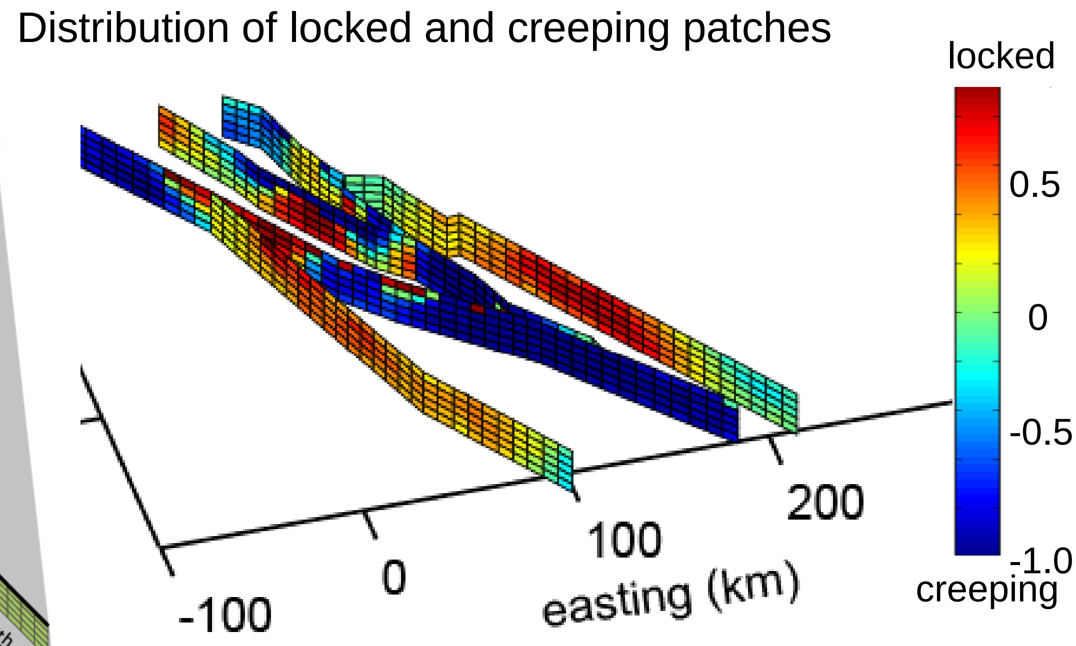
Distribution of locked and creeping patches

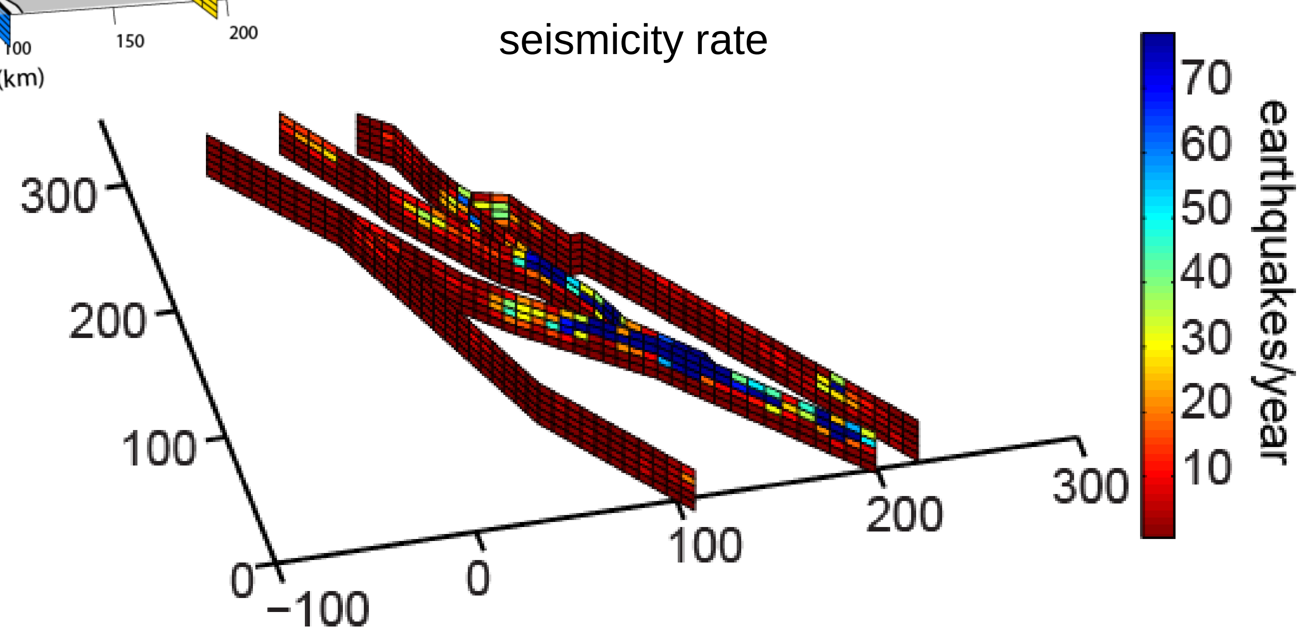


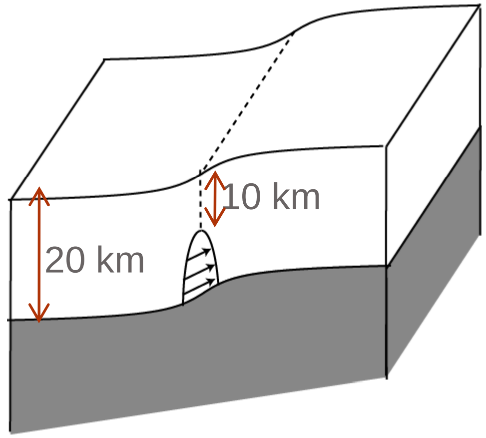
Interseismic creep rate




San Andreas North
Rogers Creek
Green Valley
Hayward North / South
Greenville
Calaveras North / South
San Andreas Peninsula
San Gregorio
Valley Margin
San Andreas South
distance North (km)
distance East (km)
300
250
200
150
100
50
0
50
100
150
200

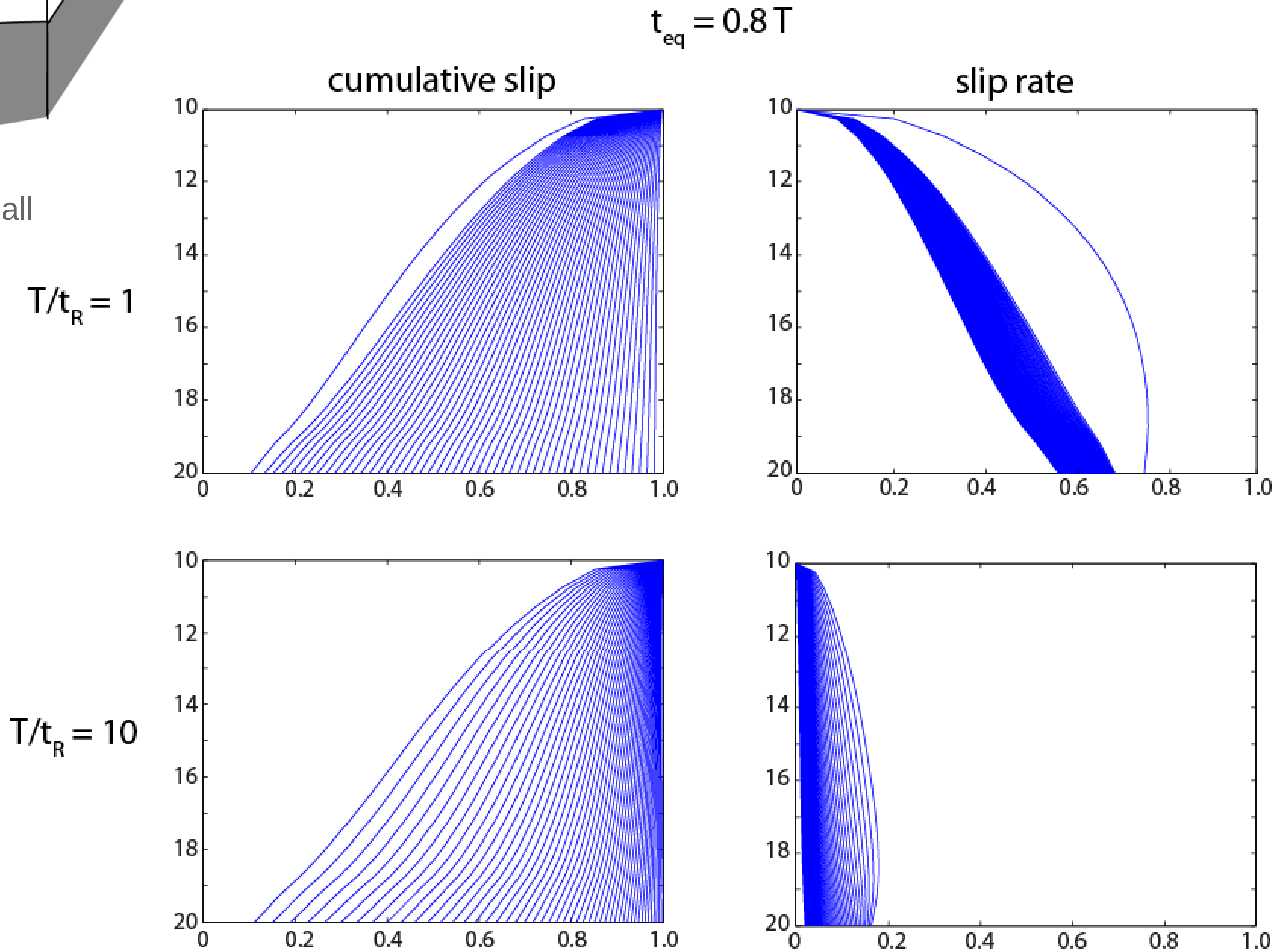

Distribution of locked and creeping patches
locked
0.5
0
-0.5
-1.0
creeping
-100
0
100
200
easting (km)


seismicity rate
300
200
100
0
-100
0
100
200
300
70
60
50
40
30
20
10
earthquakes/year

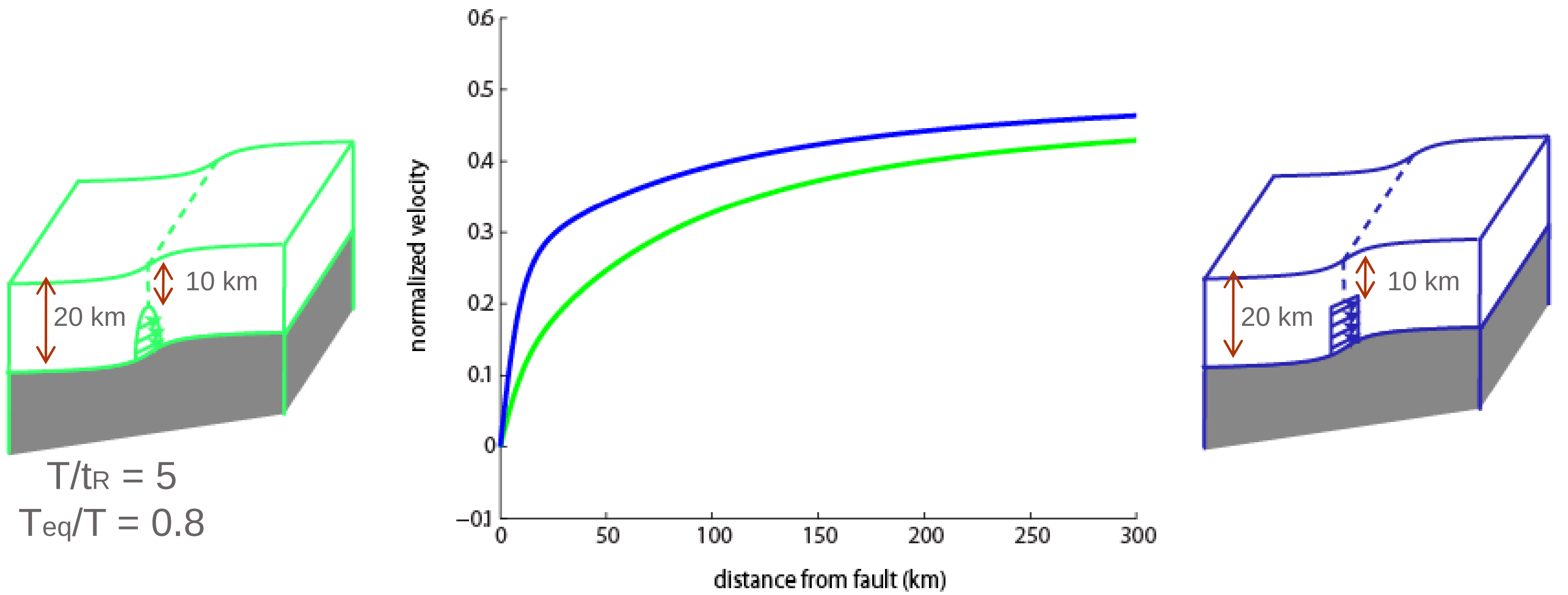


Johnson and Segall
(2004)

Creep Rate Varies with Time



Creep Rate Below Locking Depth



$T/t_R = 5$

$T_{eq}/T = 0.8$

different locking depths would be inferred

Incorporating Stress-driven Creep in Cycle Model

boundary condition: creep at constant stress (zero stressing rate)

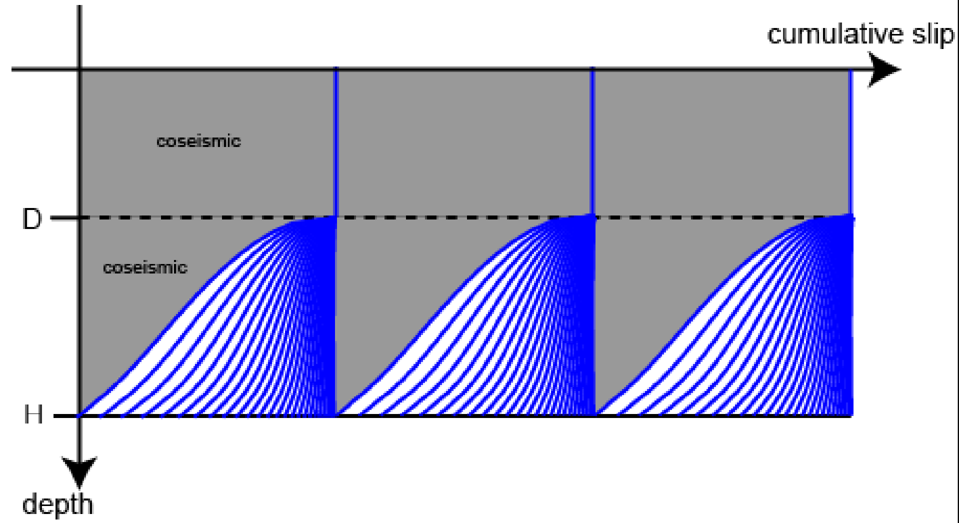
$$g_e^U(z,t)\overbrace{\dot{s}_L T}^{\text{coseismic slip}} + g_e^L(z,t)\overbrace{(\dot{s}_L-\dot{s}_i)}^{\text{deep coseismic slip}}T + g_c^L(z)\dot{s}_i = 0$$

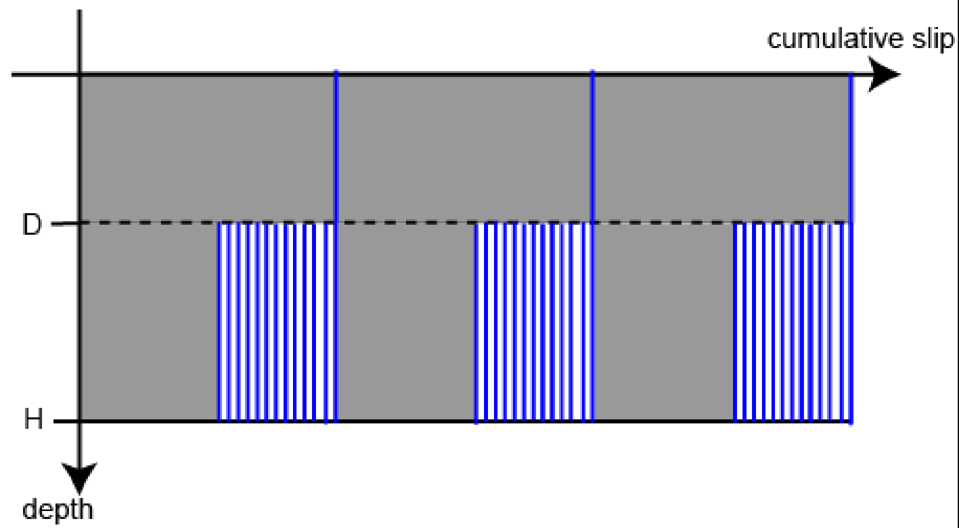
g ~ Green's functions

$\dot{s}_L$ ~ long-term slip rate

$\dot{s}_i$ ~ interseismic creep rate

$$g_e^U(z,t)\dot{s}_L T + g_e^L(z,t)(\dot{s}_L-\dot{s}_i)T + g_c^L(z)\dot{s}_i T = 0$$





Incorporating Stress-driven Creep in Cycle Model

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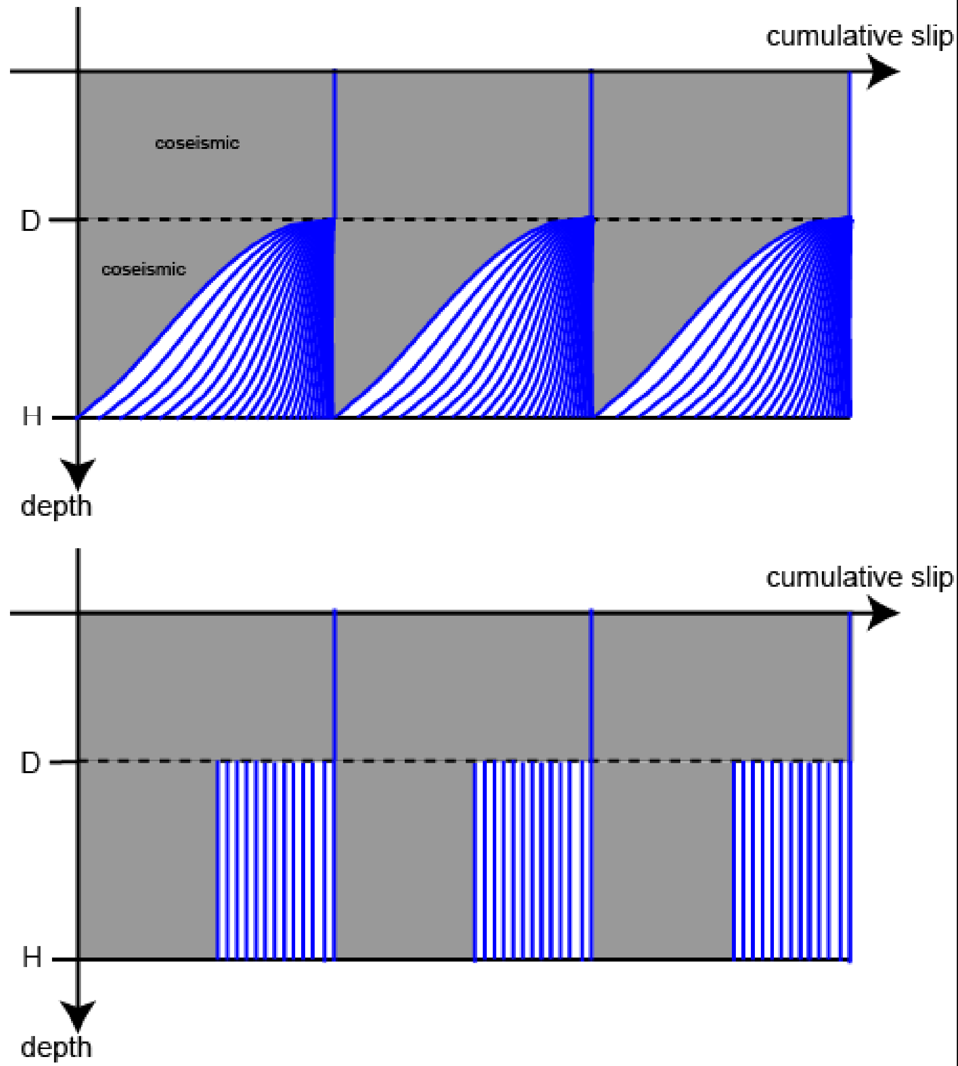
$$g_e^U(z,t)\dot{s}_L T + g_e^L(z,t)(\dot{s}_L-\dot{s}_i)T + g_c^L(z)\dot{s}_i T = 0$$

$$\dot{s}_i = \dot{s}_L \frac{T[g_e^U(z,t) + g_e^L(z,t)]}{g_c^L(z) - g_e^L(z,t)T}$$

$$\overbrace{(\dot{s}_L-\dot{s}_i)T}^{\text{deep coseismic slip}} = \overbrace{\dot{s}_L T}^{\text{coseismic slip}} \left\{ 1 - \frac{T[g_e^U(z,t) + g_e^L(z,t)]}{g_c^L(z) - g_e^L(z,t)T} \right\}$$



Incorporating Stress-driven Creep in Cycle Model

boundary condition: creep at constant stress (zero stressing rate)

$$g_e^U(z,t)\overbrace{\dot{s}_L T}^{\text{coseismic slip}} + g_e^L(z,t)\overbrace{(\dot{s}_L-\dot{s}_i)T}^{\text{deep coseismic slip}} + g_c^L(z)\dot{s}_i = 0$$

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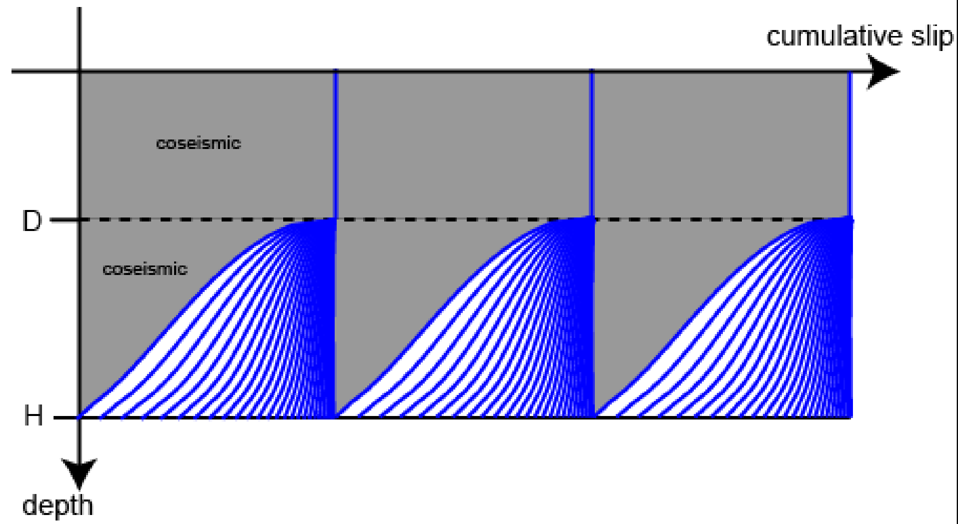

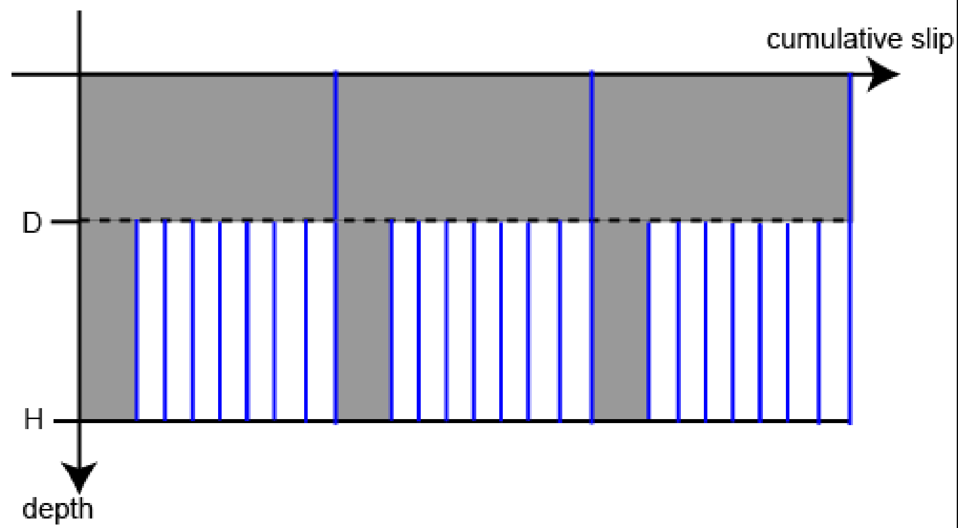

boundary condition: creep at constant stress (zero stressing rate)

$$g_e^U(z,t)\overbrace{\dot{s}_L T}^{\substack{\text{coseismic}\\ \text{slip}}} + g_e^L(z,t)\overbrace{(\dot{s}_L-\dot{s}_i)T}^{\substack{\text{deep}\\ \text{coseismic}\\ \text{slip}}} + g_c^L(z)\dot{s}_i = 0$$

g ~ Green's functions

$\dot{s}_L$ ~ long-term slip rate

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$$g_e^U(z,t)\dot{s}_L T + g_e^L(z,t)(\dot{s}_L-\dot{s}_i)T + g_c^L(z)\dot{s}_i T = 0$$

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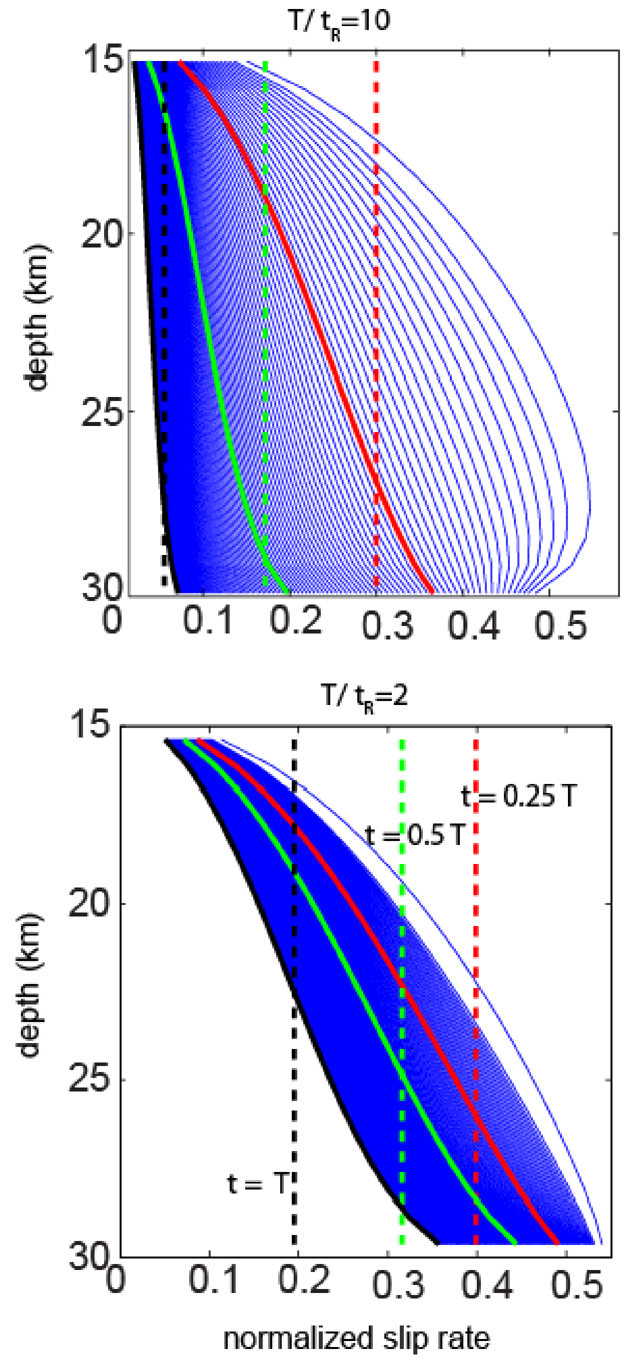
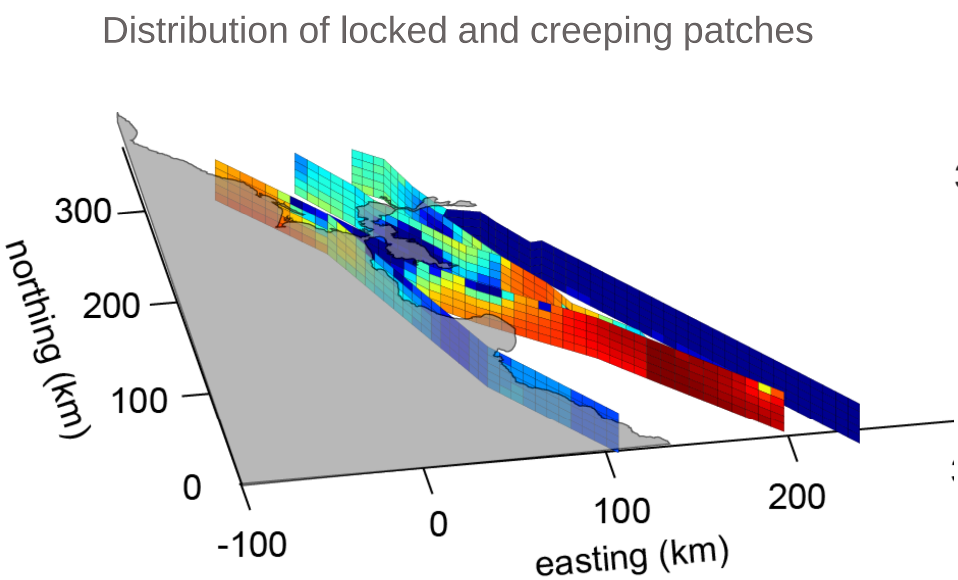
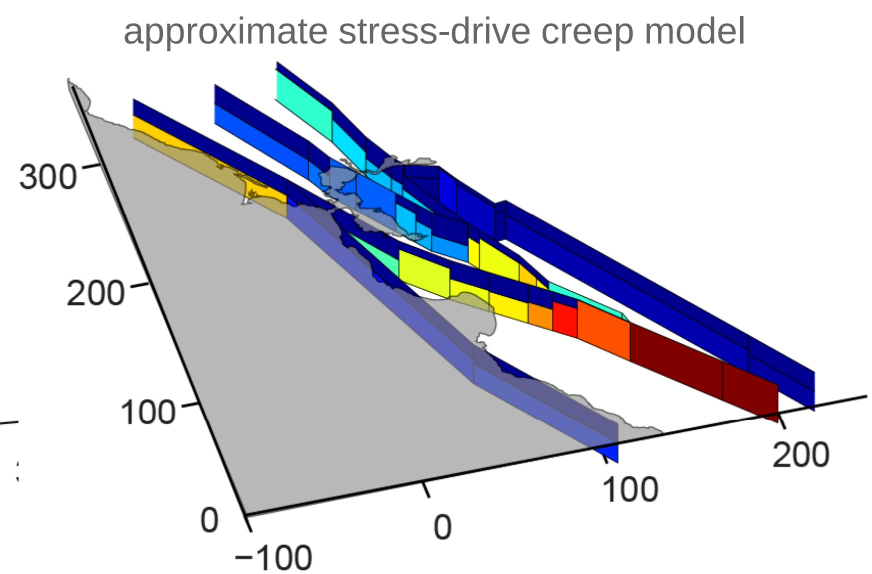
$$\overbrace{(\dot{s}_L-\dot{s}_i)T}^{\substack{\text{deep}\\ \text{coseismic}\\ \text{slip}}} = \overbrace{\dot{s}_L T}^{\substack{\text{coseismic}\\ \text{slip}}} \left\{1 - \frac{T[g_e^U(z,t) + g_e^L(z,t)]}{g_c^L(z) - g_e^L(z,t)T}\right\}$$

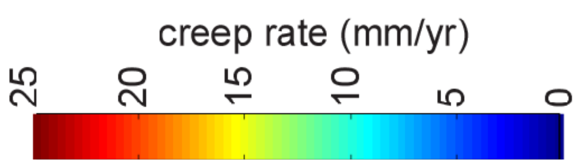


Stress-driven Interseismic Creep

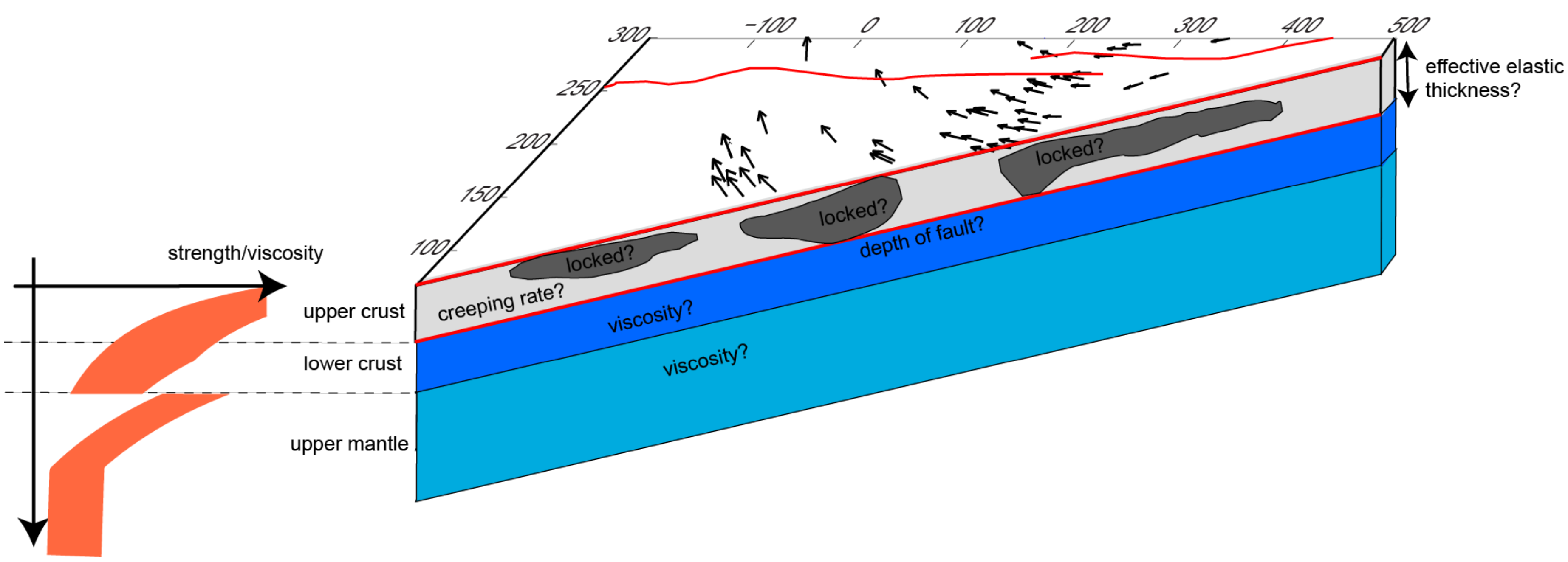
Inversion Result







Conclusion



We nearly have a method to simultaneously estimate:

(1) long-term fault slip rates
(2) Interseismic creep rates
(3) Location of locked patches
(4) Lithosphere viscosity
(5) Elastic thickness