Strain accumulation across strike-slip faults :
Investigation of the influence of laterally varying lithospheric properties

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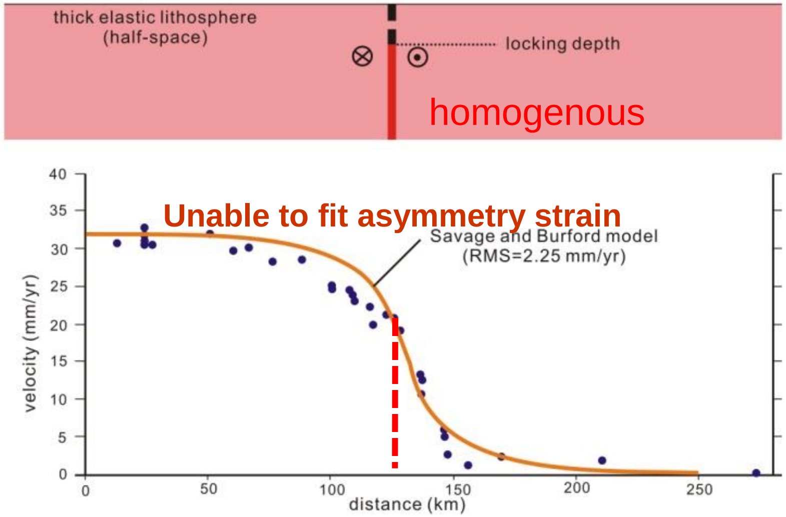
NCU

The Problem

Can we use geodetic data to infer lateral variation in rigidity ?

The Problem



(After Chery, 2008)

Use gradients in velocity field to identify where active faults are locked and accumulating stress.

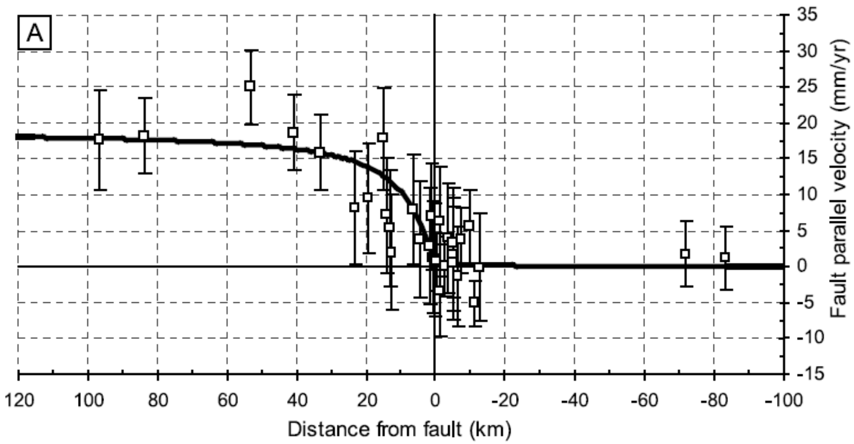
Gradients in velocity field can be attributed to:

1. Elastic distortion around locked faults
2. Lateral variations in lithospheric rigidity (thickness/stiffness)

Can we use geodetic data to infer lateral variation in rigidity ?

Inferred Lateral Variations in Crustal Rigidity

Great Sumatra Fault

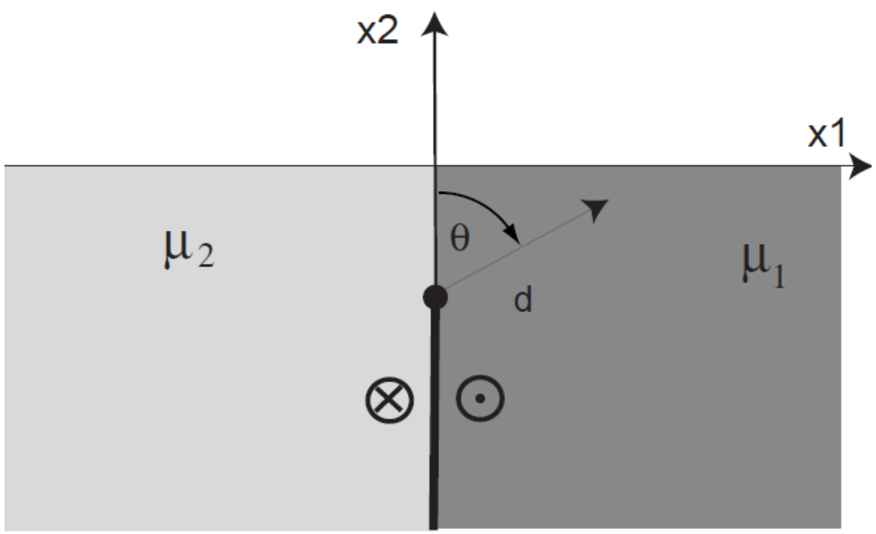


Elastic Half-Space Models

e.g., Le Pichon (2005)

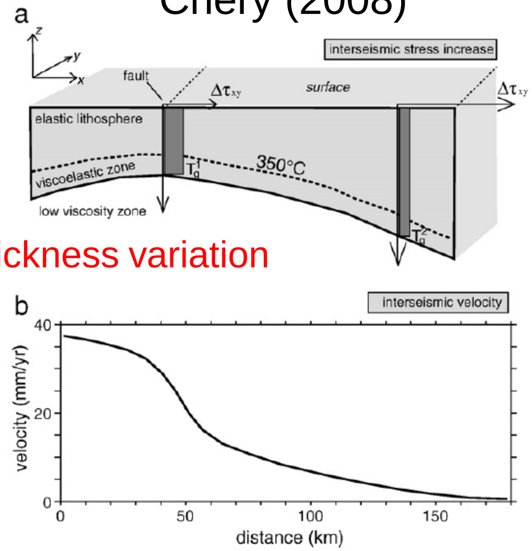
Inferred rigidity ratio (μ_1/μ_2): 30

Idealized bimaterial fault interface



Inferred Lateral Variations in Crustal Rigidity

Chéry (2008)



Lateral thickness variation

Jolivet et al. (2008)

Lateral stiffness variation

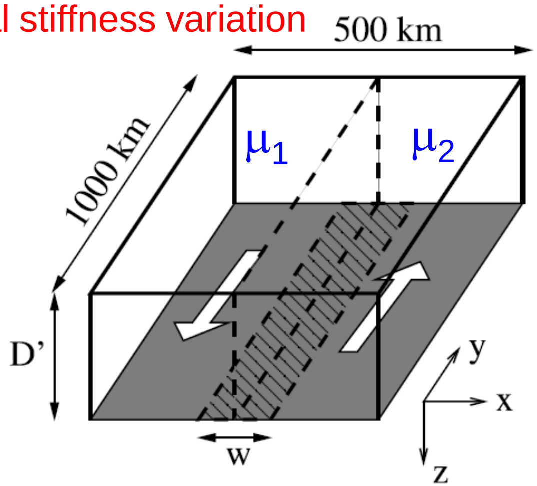


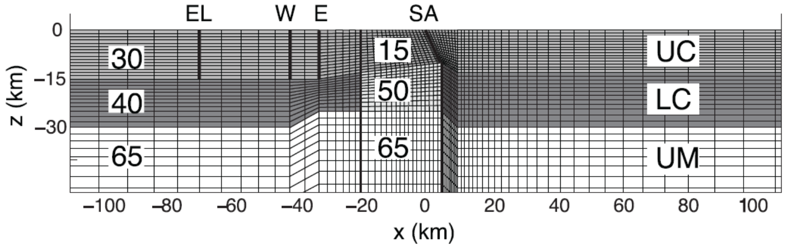
Plate Models

e.g., Chéry (2008), Jolivet et al. (2008)

Flow underneath plates is not considered.

Inferred Lateral Variations in Crustal Rigidity

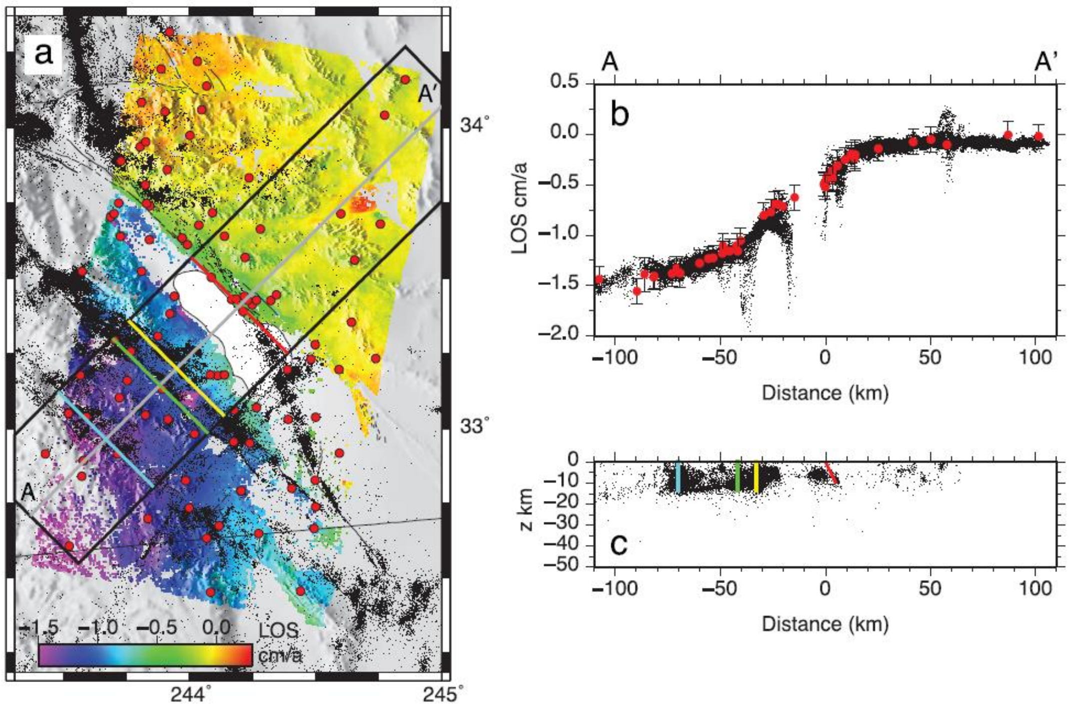
Lundgren et al. (2009)



Finite Element Models

e.g., Lundgren et al (2009), Schmalze et al. (2005)

Inversions are difficult because models are computationally expensive.



Why revisit this problem?

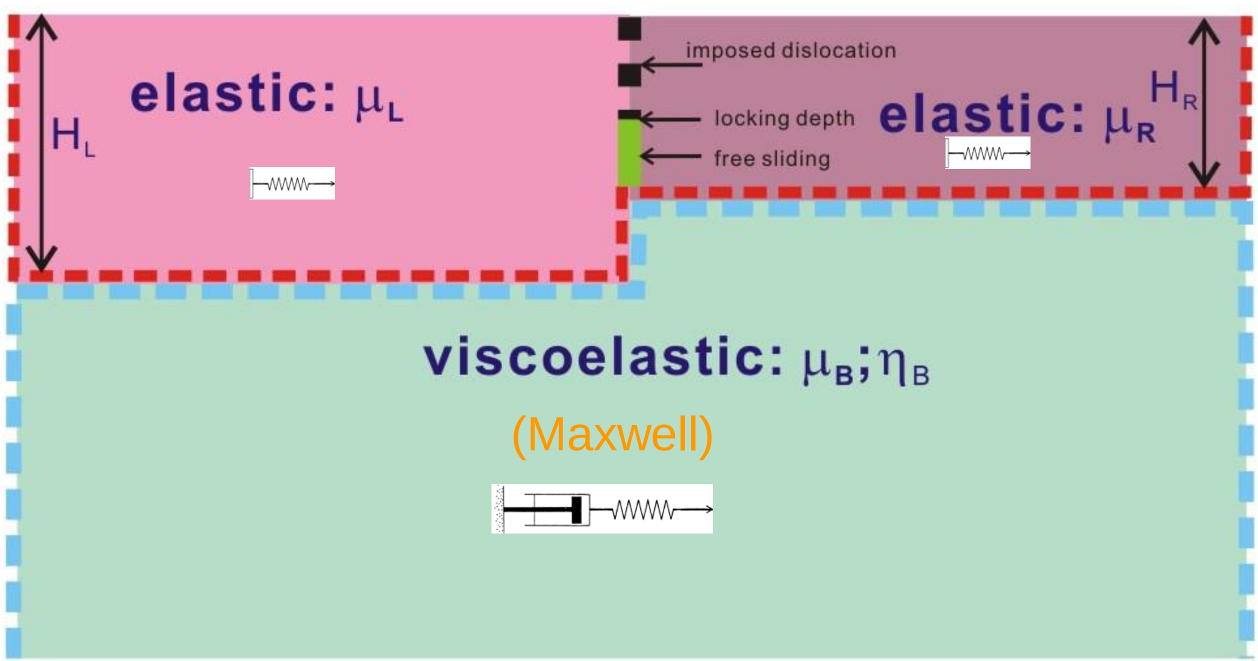
- Elastic half-space and plate models neglect viscous flow – we show that this is important

- Finite Element models too slow to fully explore model space

Our Model:

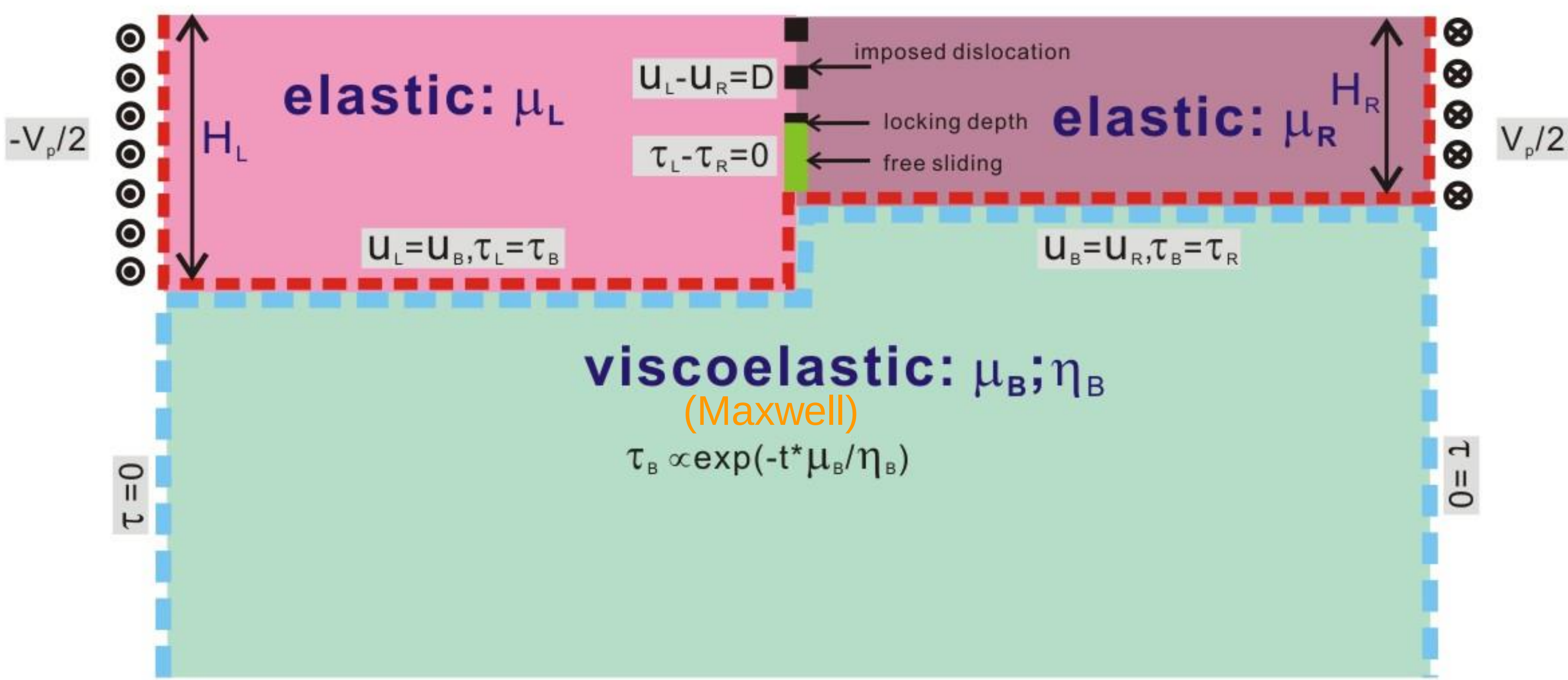
- Displacement-discontinuity Boundary Element Method
- Elastic layers overlying viscoelastic half-space
- Lateral variation of rigidity: e.g. stiffness and thickness
- Earthquake cycle model

Analytical solution of an finite-width screw dislocation [e.g. *Okada*, 1992]



Our Model

Boundary conditions



Stress Relaxation time, $t_R=2(\eta_B/\mu_B)$

Our Model:

For a purely elastic problem,

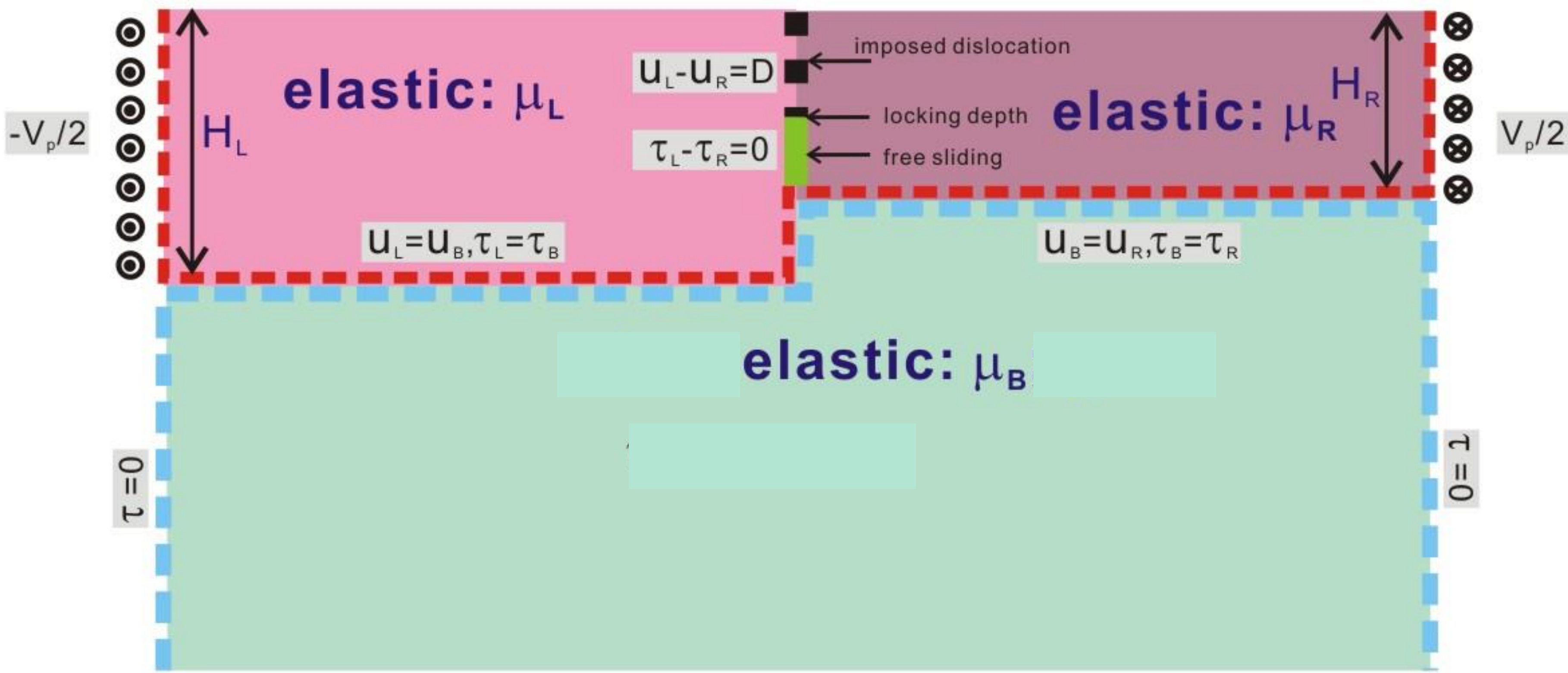
$$\boldsymbol{b} = \boldsymbol{G}^*\boldsymbol{s}$$

$$\Rightarrow \boldsymbol{s} = \boldsymbol{G}^{-1}\boldsymbol{b}$$

b : a vector of boundary conditions

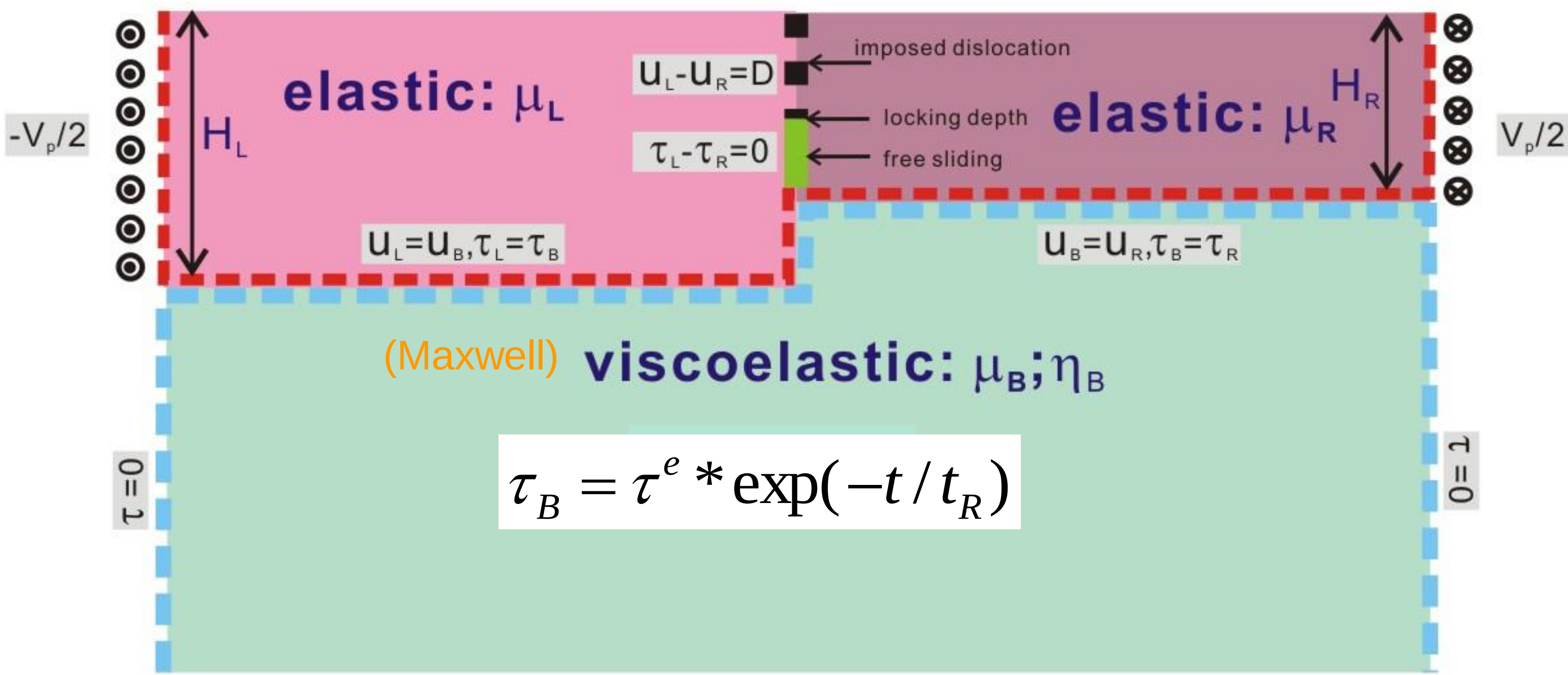
s : a vector of corresponding displacements

G : a matrix of Green's functions,



Our Model

Stresses vary with time, so do ***s*** and ***b***.



$$\tau_B = \tau^e * \exp(-t / t_R)$$

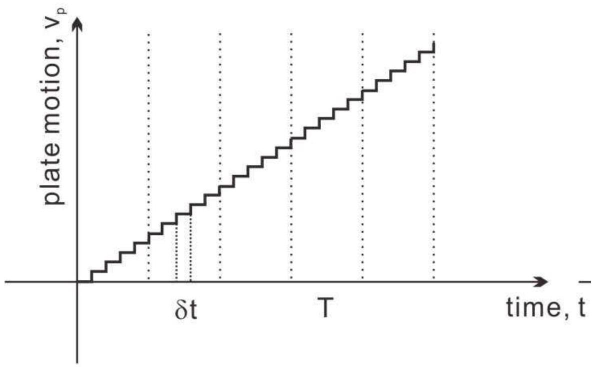
Stress Relaxation time, $t_R=2(\eta_B/\mu_B)$

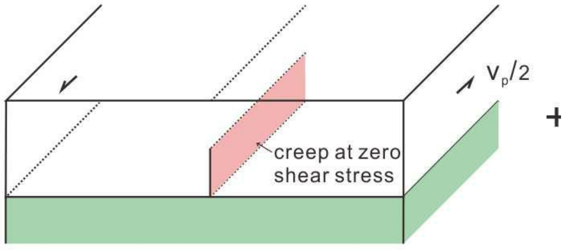
Our Model:

Stresses vary with time, so do ***s*** and ***b***.

At the *jth* increment, the displacement discontinuity distribution is

$$\boldsymbol{s_j} = \sum^{j-1} \boldsymbol{G}(t, t_R, s_1, s_2, \ldots, s_{j-1})^{-1}\, \boldsymbol{b}$$



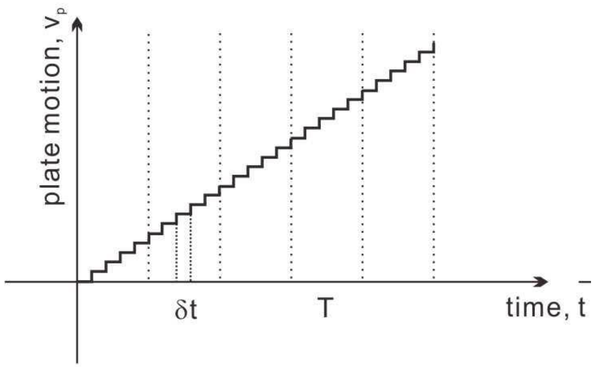


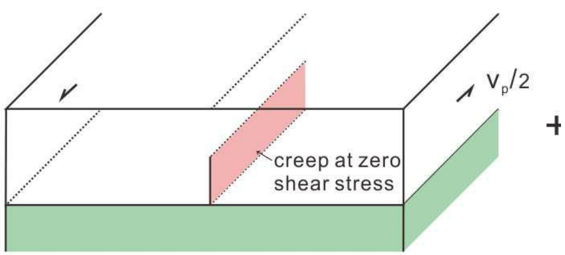
steady plate motion

Our Model: EQ cycle model

Scheme for computing an earthquake cycle-invariant velocity profile

$$\boldsymbol{s_j} = \sum_{k=0}^{j-1} \boldsymbol{G}(t, t_R, s_1, s_2, ..., s_{j-1})^{-1} \, \boldsymbol{b}$$





steady plate motion

Our Model: EQ cycle model

Scheme for computing an earthquake cycle-invariant velocity profile

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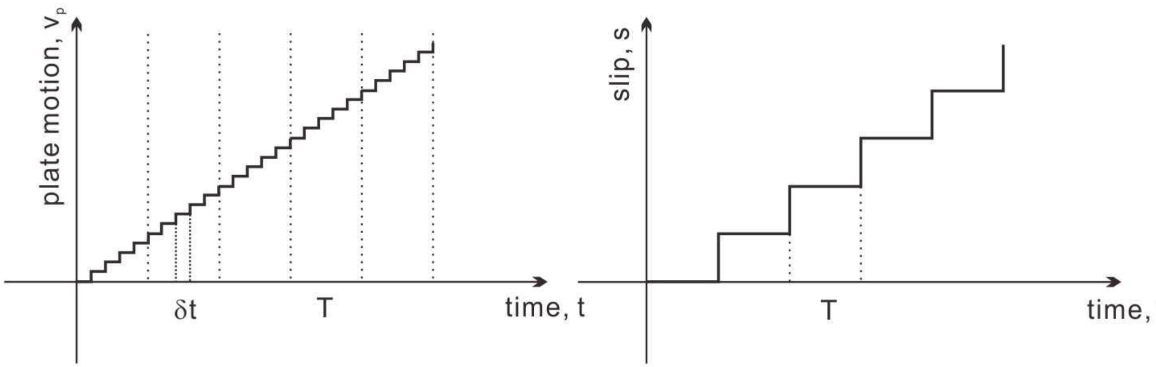
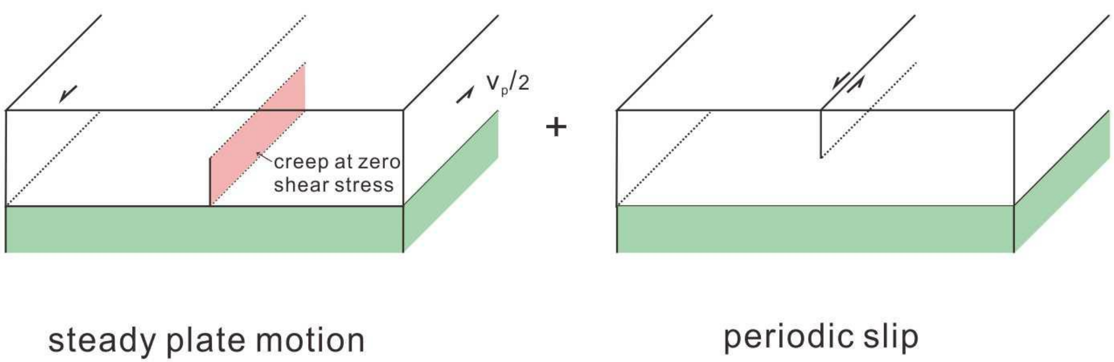


T: earthquake recurrence interval



Our Model: EQ cycle model

Scheme for computing an earthquake cycle-invariant velocity profile

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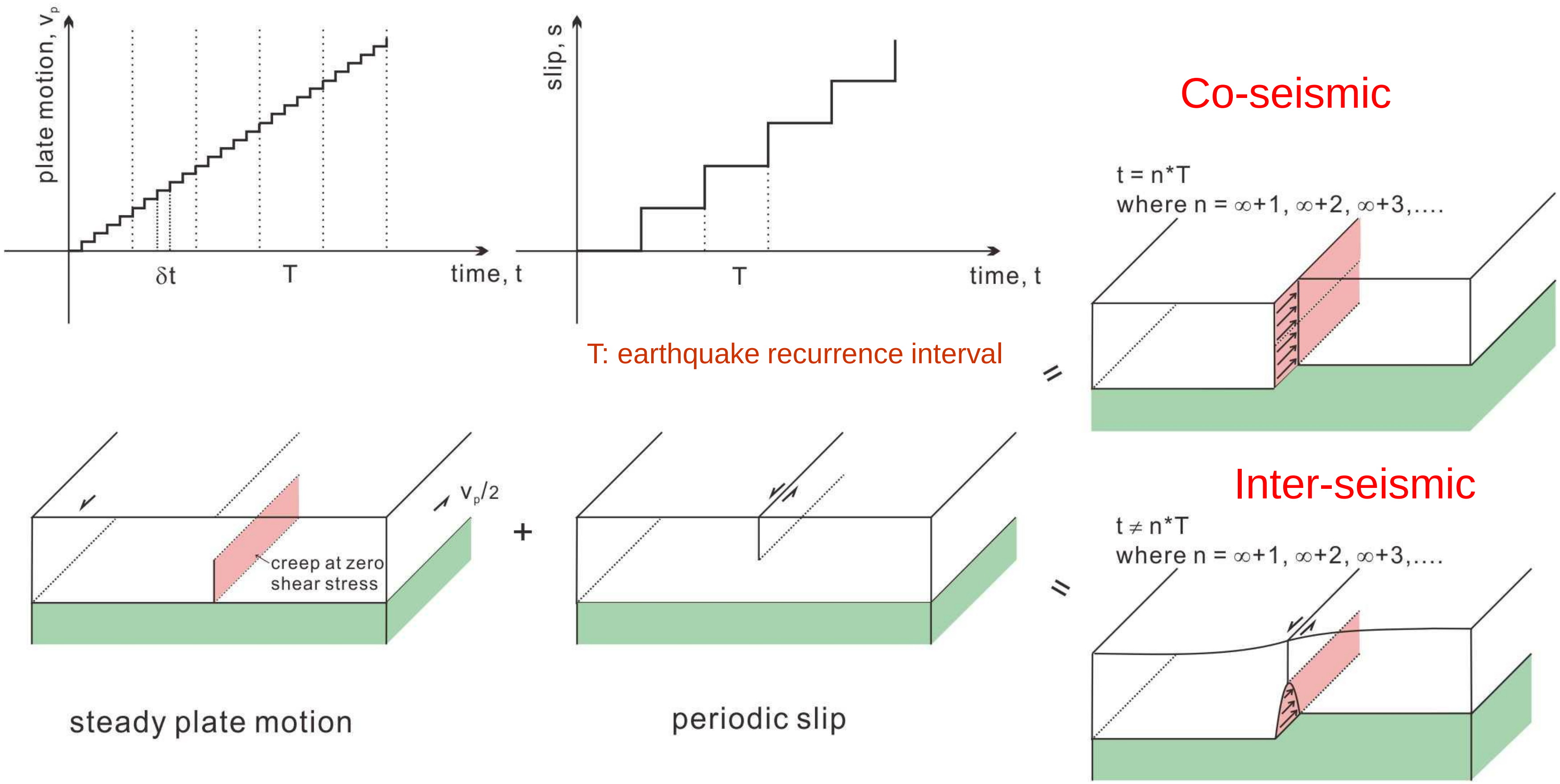
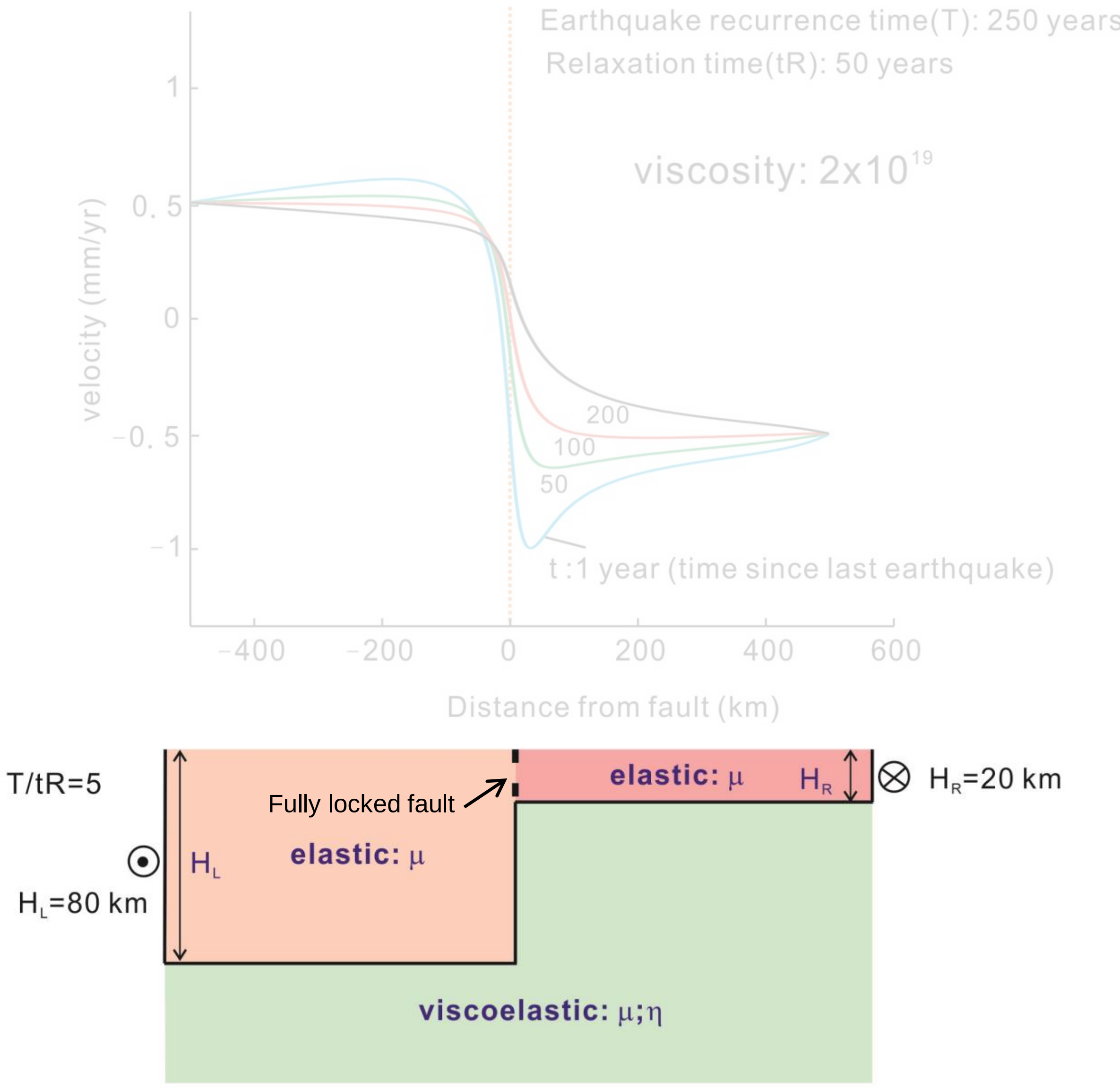


Asymmetry of Deformation

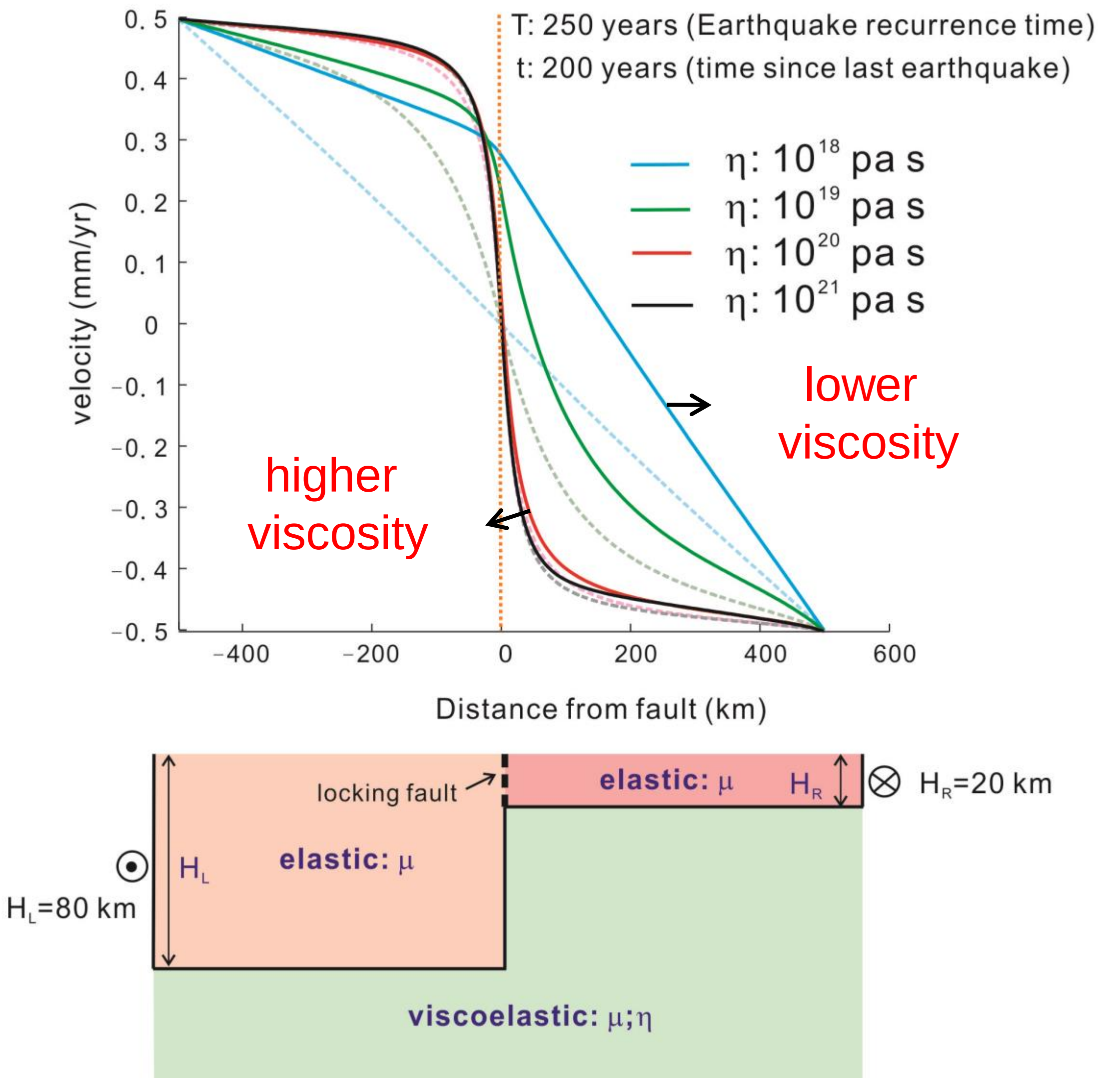


Contrast in Elastic Thickness

Asymmetry varies with the time since last earthquake (t)

Asymmetry is more pronounced at early times

Asymmetry of Deformation

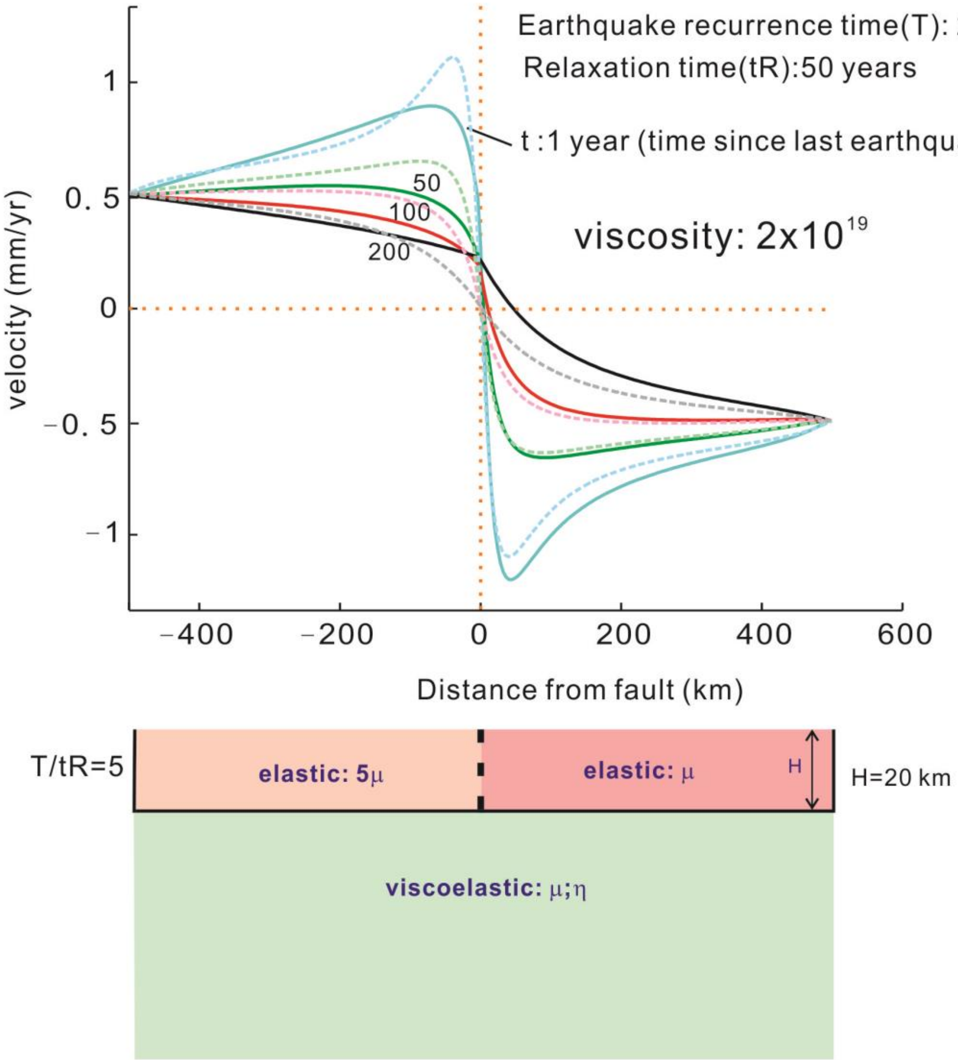


Contrast in Elastic Thickness

Asthenosphere viscosity is important:

Asymmetry is more pronounced for lower viscosities

Asymmetry of Deformation

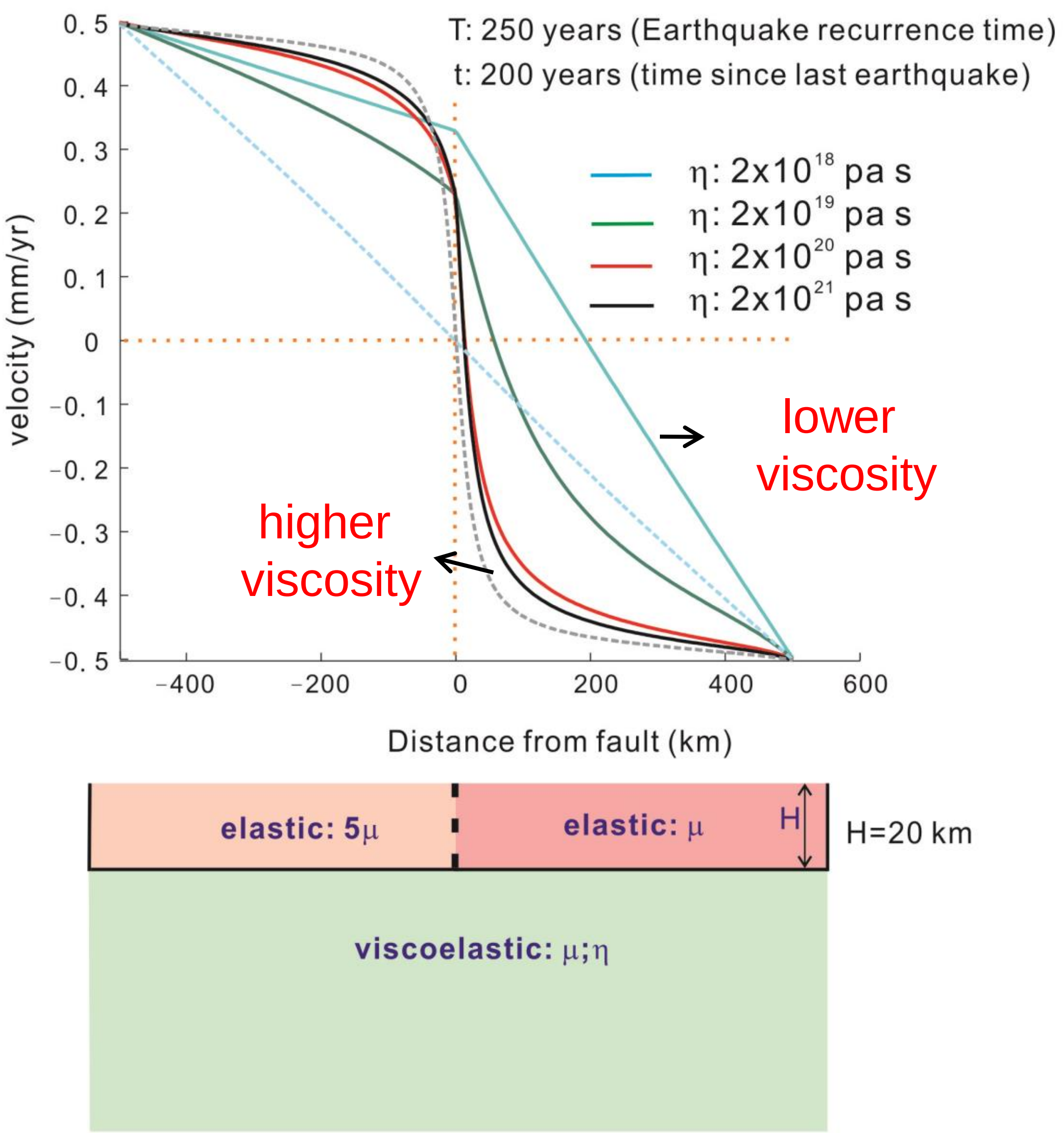


Contrast in Elastic stiffness

Asymmetry varies with the time since last earthquake (t)

Asymmetry is more pronounced at later times

Asymmetry of Deformation



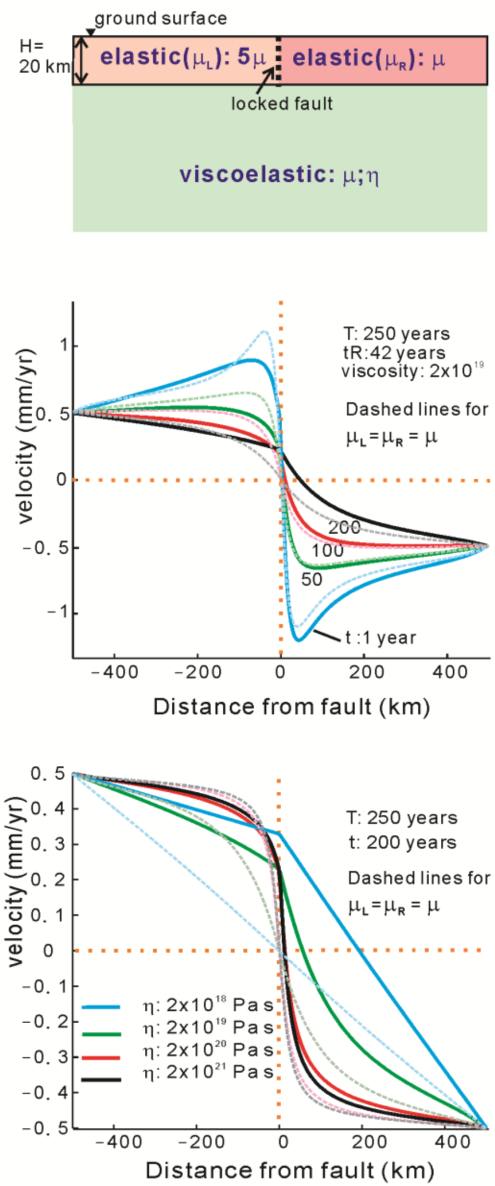
Contrast in Elastic stiffness

Asthenosphere viscosity is important:

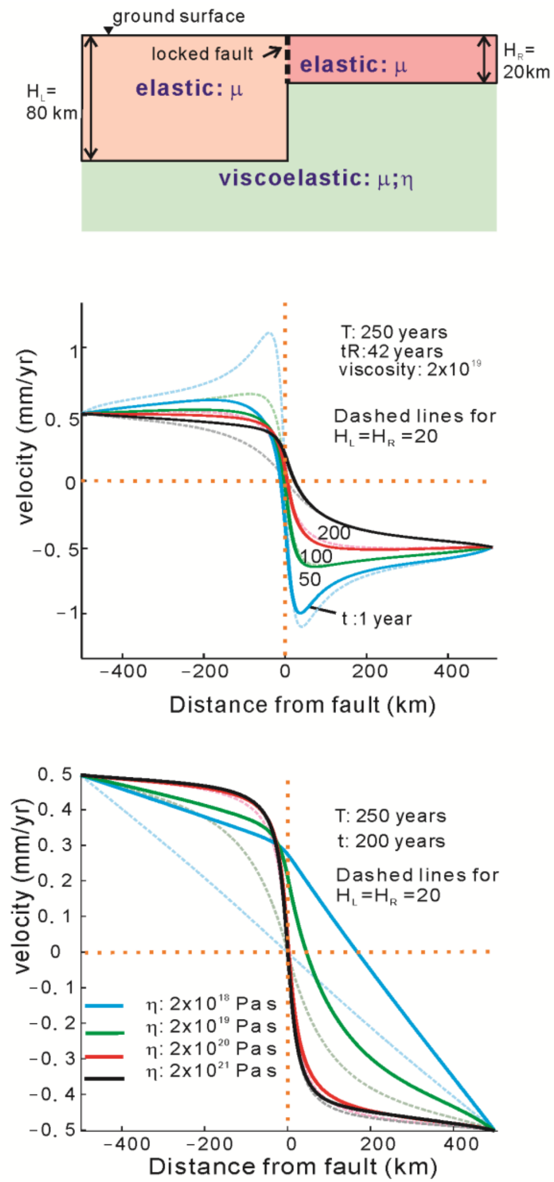
Asymmetry is more pronounced for lower viscosities

Asymmetry of Deformation

Contrast in Elastic stiffness



Contrast in Elastic Thickness



Monte Carlo Inversion

-- Metropolis method

To sample the posterior distribution, we initiate a random walk through the model space that samples the a priori distribution.

$$\underline{\boldsymbol{m}}_j = \underline{\boldsymbol{m}}_i + \sum_{k=1}^{d} \alpha_k \gamma_k \boldsymbol{e}_k$$

, *where* $\underline{\boldsymbol{m}} = [m^1\ m^2\ m^3\ m^4\ \ldots\ m^d]$

α_k : scale factor

γ_k : (-1, 1) uniform random deviate

$\boldsymbol{e}_k$: the unit vector along the kth axis in parameter space

Markov Chain random walk

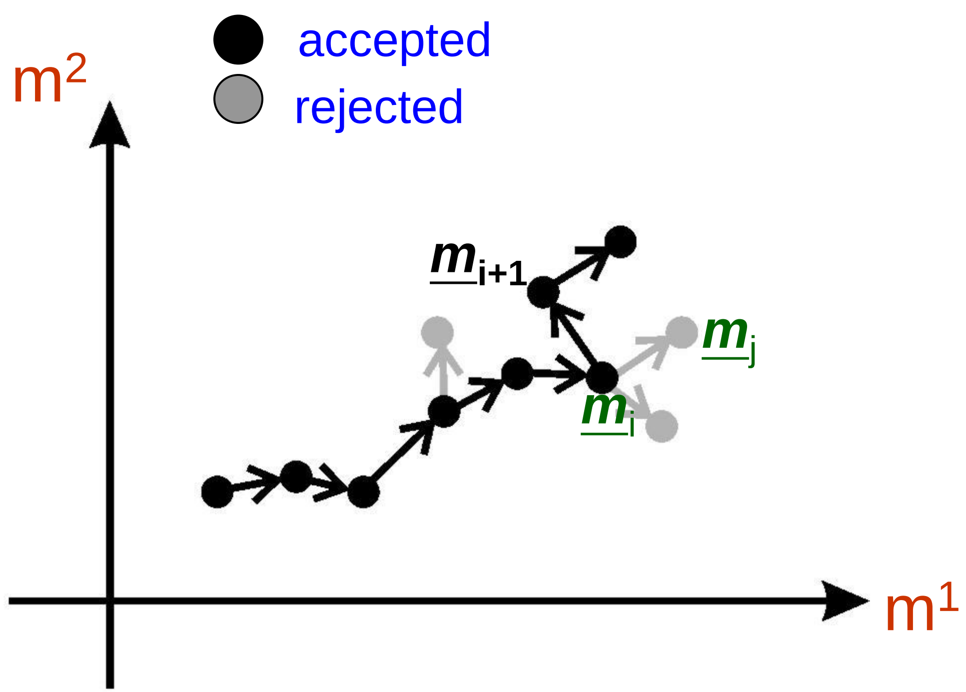
An example: samples projected to 2D

$$\underline{\boldsymbol{m}} = [m^1\ m^2\ m^3\ m^4\ \ldots\ m^d]$$

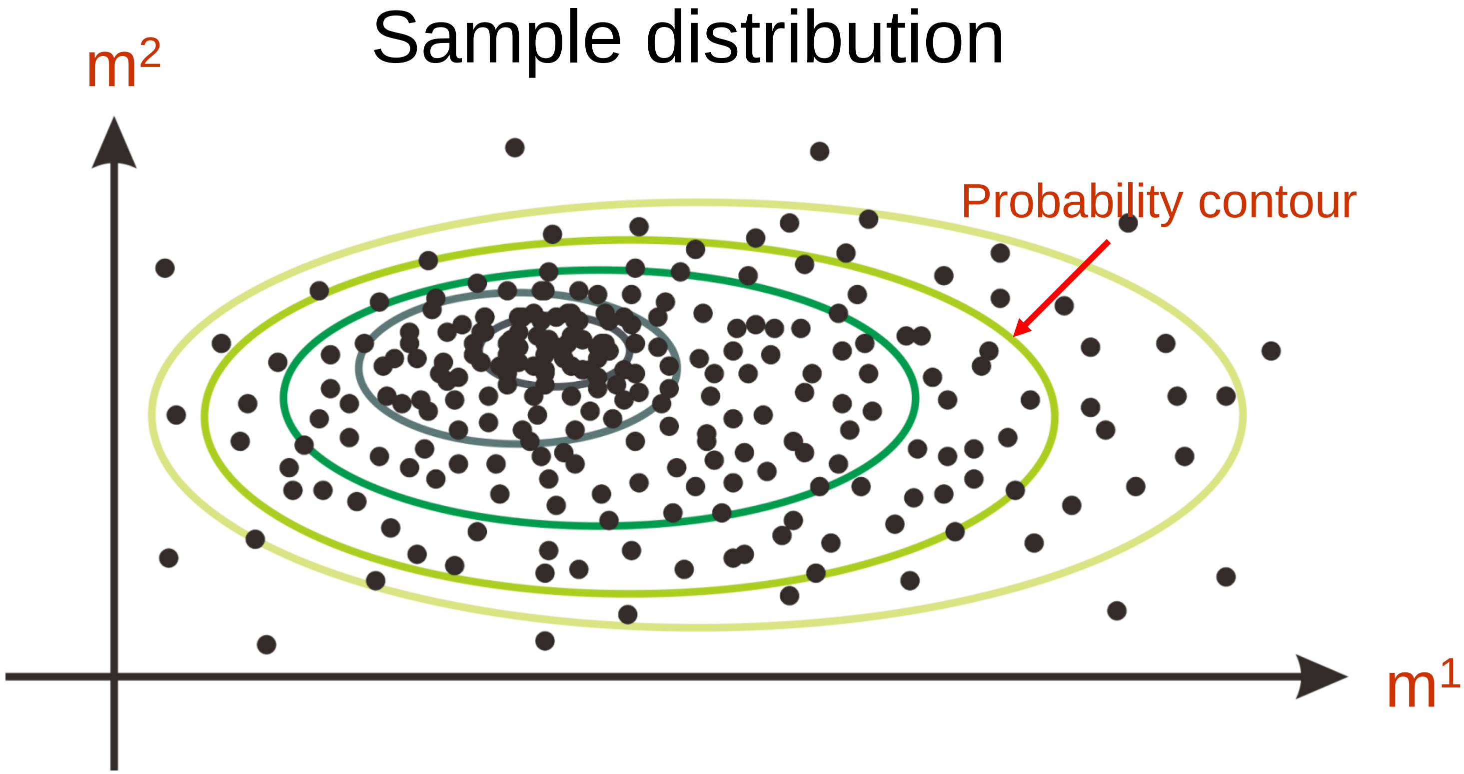
The walk moves to the next model with probability

$$P_{ij} = \min\left(1, \frac{\rho_D\left(g\left(\underline{\boldsymbol{m}}_j\right)\right)}{\rho_D\left(g\left(\underline{\boldsymbol{m}}_i\right)\right)}\right)$$

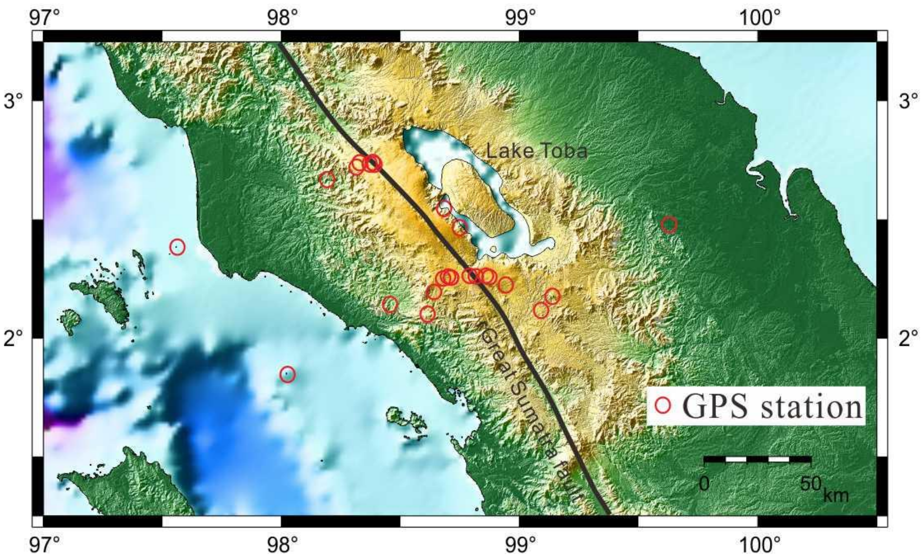
ρ_D: probability density function of the model parameters



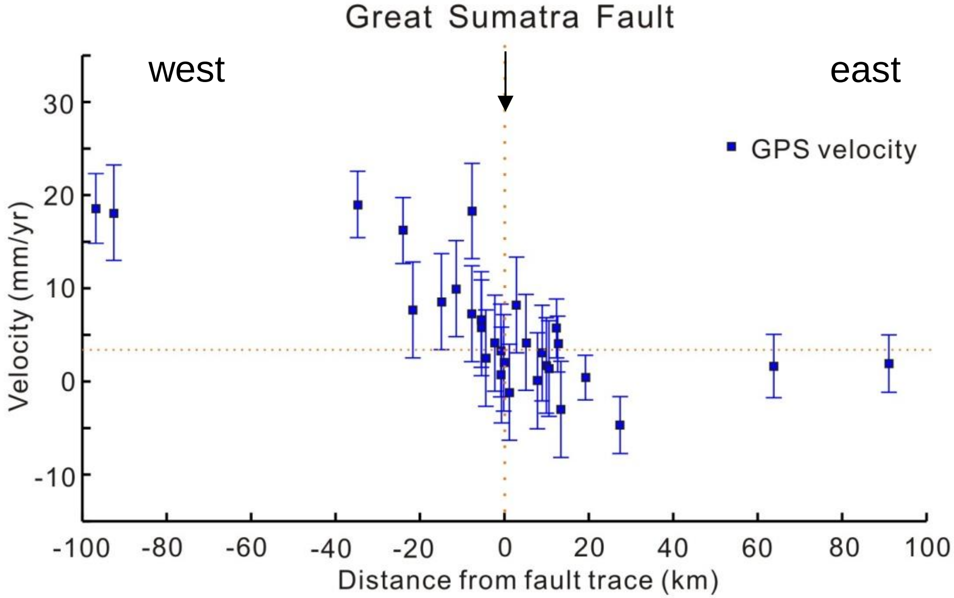
Markov Chain random walk



Great Sumatra Fault, Indonesia

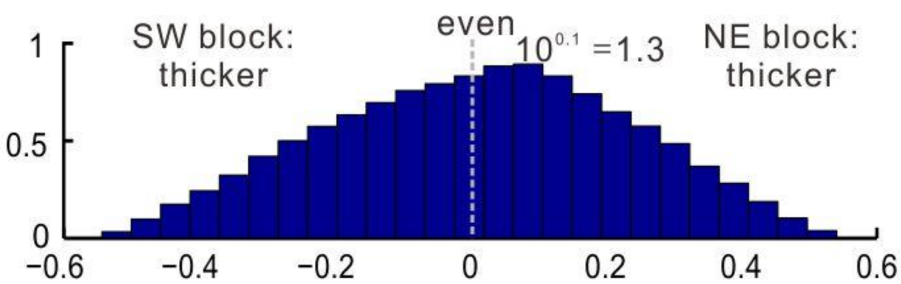


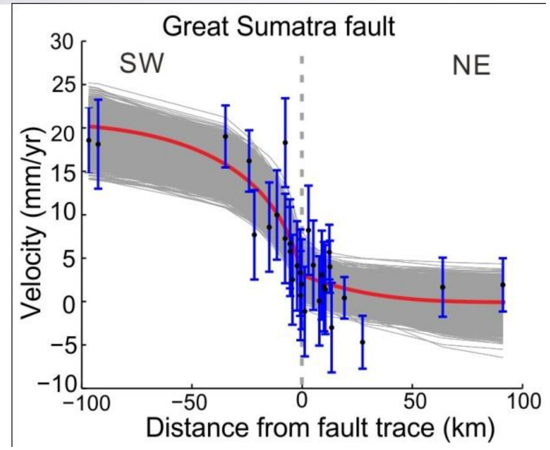
(Genrich et al., 2000; Le Pichon, 2005)

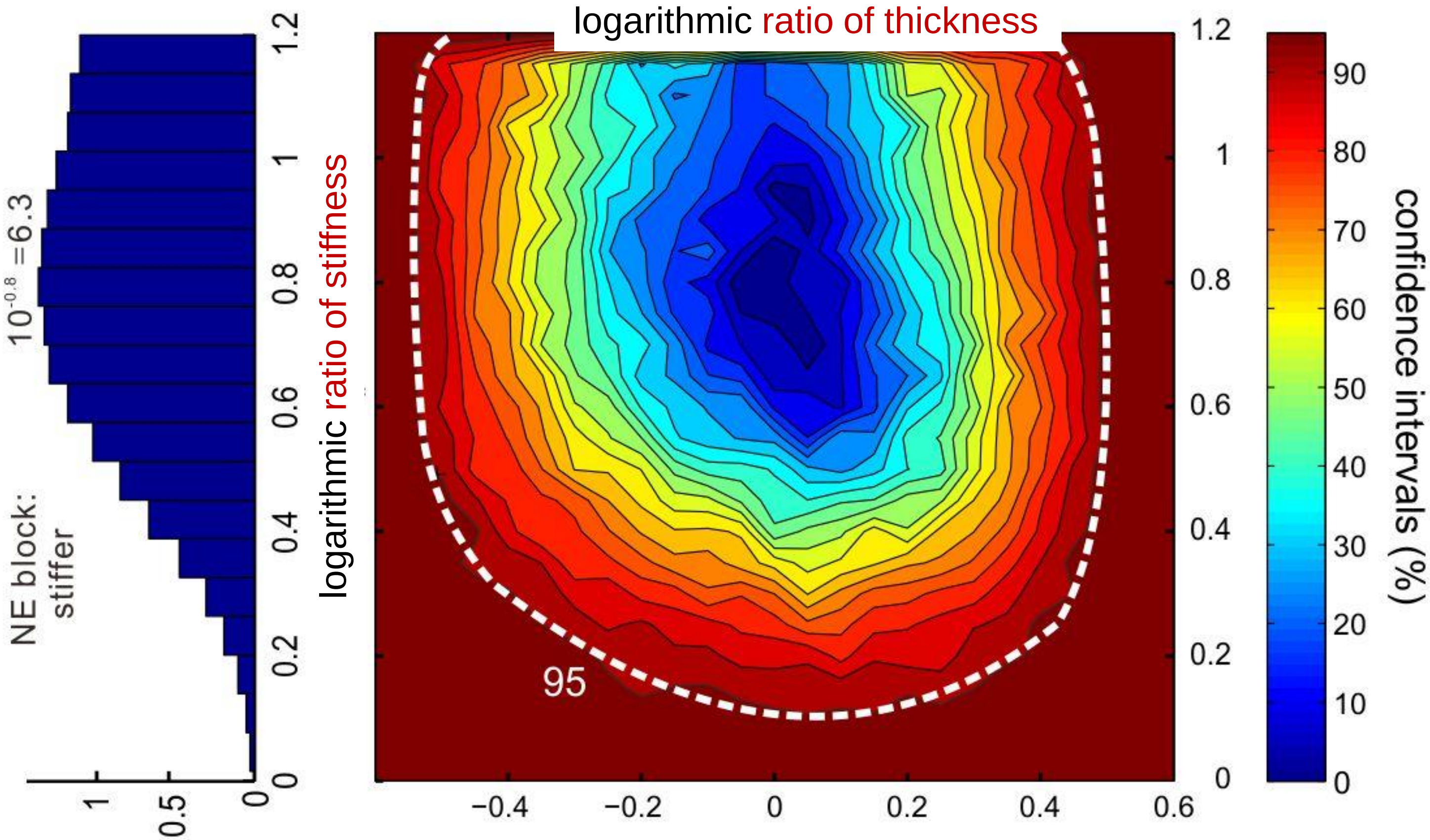


Component of velocity parallel to the fault trace

Results


SW block:
thicker
even
$10^{0.1}$ =1.3
NE block:
thicker
1
0.5
0
−0.6
−0.4
−0.2
0
0.2
0.4
0.6

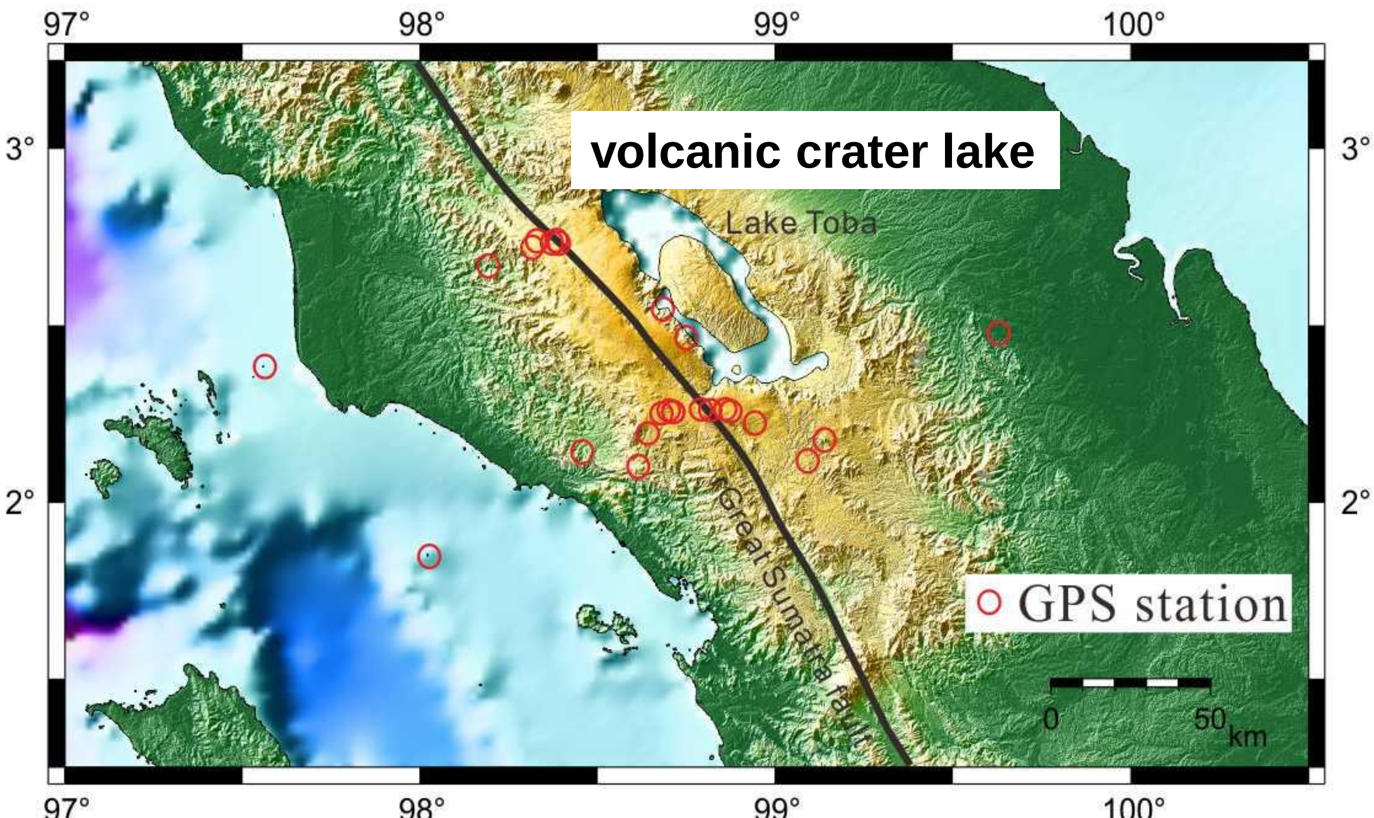

Great Sumatra fault
SW
NE
Velocity (mm/yr)
Distance from fault trace (km)
30
25
20
15
10
5
0
−5
−10
−100
−50
0
50
100


logarithmic ratio of thickness
logarithmic ratio of stiffness
$10^{-0.8}$ =6.3
NE block:
stiffer
95
confidence intervals (%)
0
10
20
30
40
50
60
70
80
90
1.2
1
0.8
0.6
0.4
0.2
0
−0.4
−0.2
0
0.2
0.4
0.6
1
0.5
0

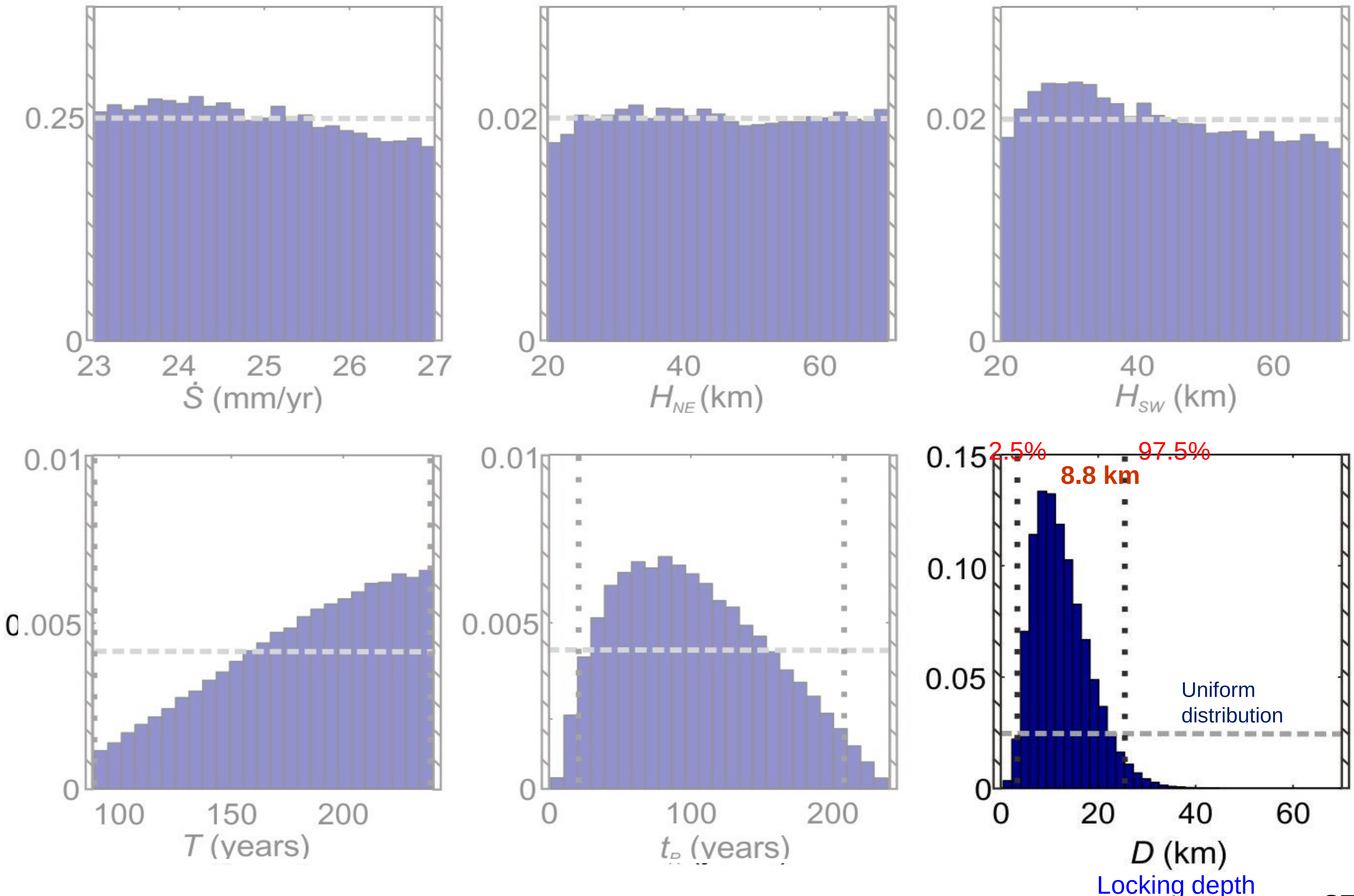
Results

- For Great Sumatra fault, the inversion result shows eastern elastic layer must be stiffer than western one but there is no resolved a contrast in elastic thickness.

Consistent with the manifestion of geology

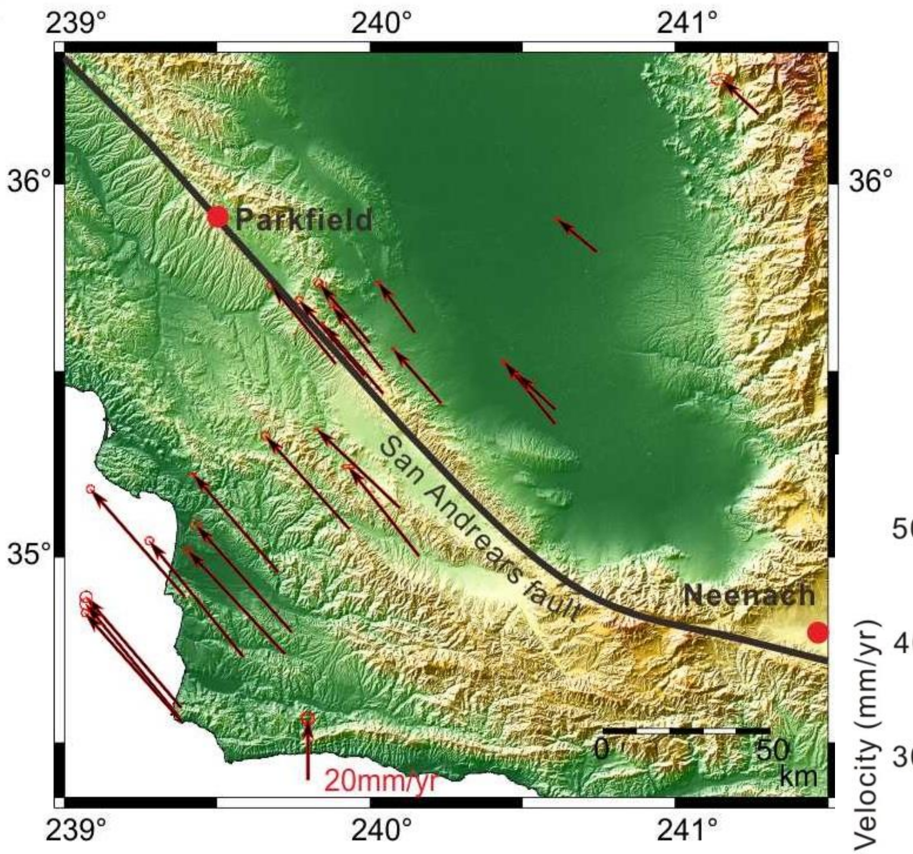


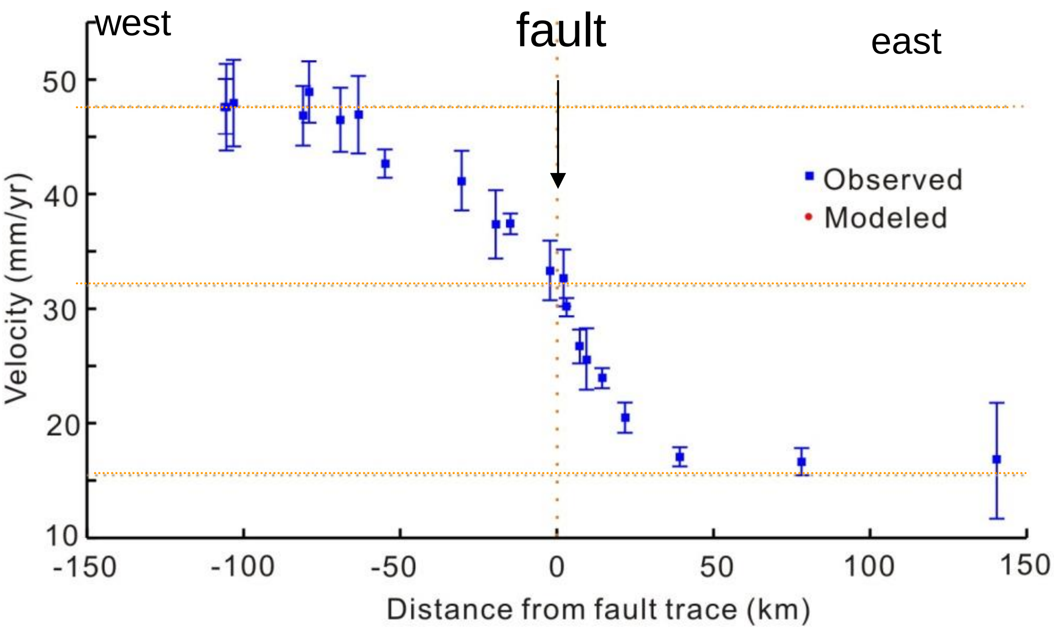
Results



0.25
0
23
24
25
26
27
Ṡ (mm/yr)
0.02
0
20
40
60
H_NE (km)
0.02
0
20
40
60
H_SW (km)
0.01
0.005
0
100
150
200
T (years)
0.01
0.005
0
0
100
200
0.15
0.10
0.05
0
2.5%
97.5%
8.8 km
Uniform
distribution
0
20
40
60
D (km)
Locking depth

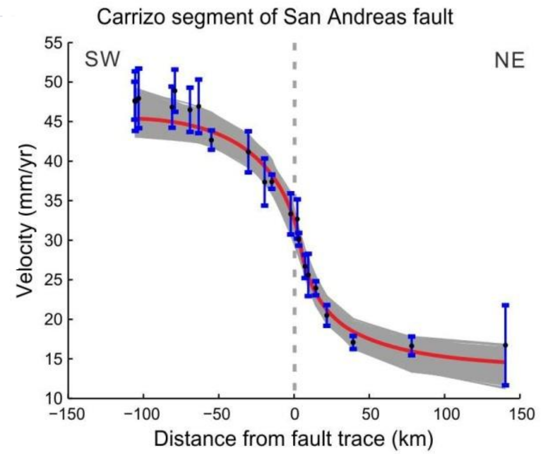
Carrizo segment of San Andreas Fault, USA

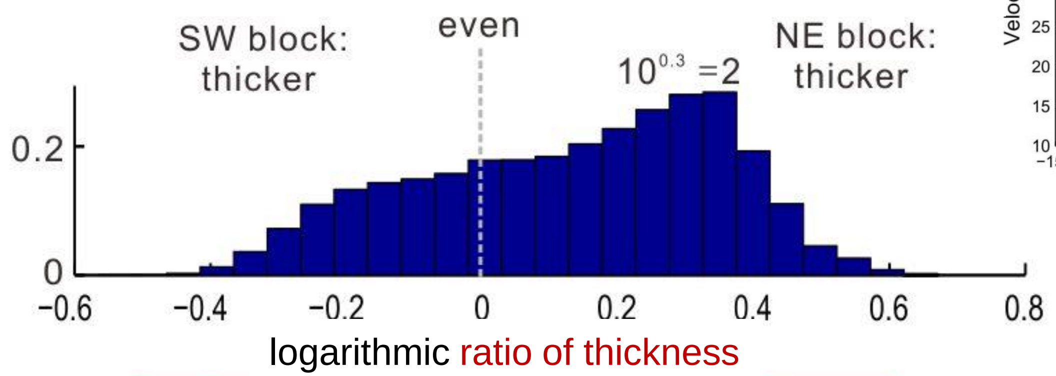


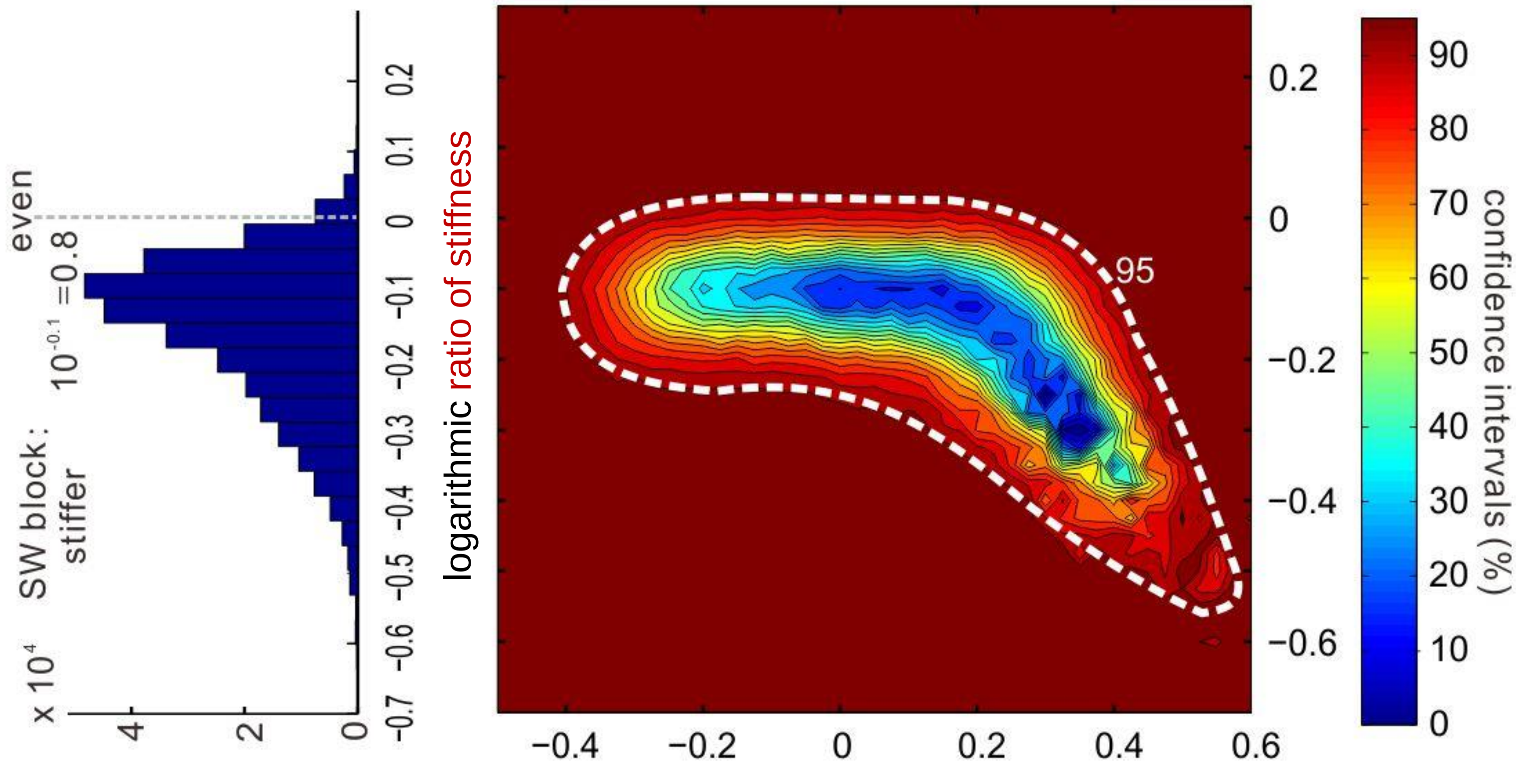


Results

- the inversion favors a thicker layer on east side (2 times) but stiffer layer on west side (1.2 times); however, uniform thickness and stiffness cannot be ruled out.







Results

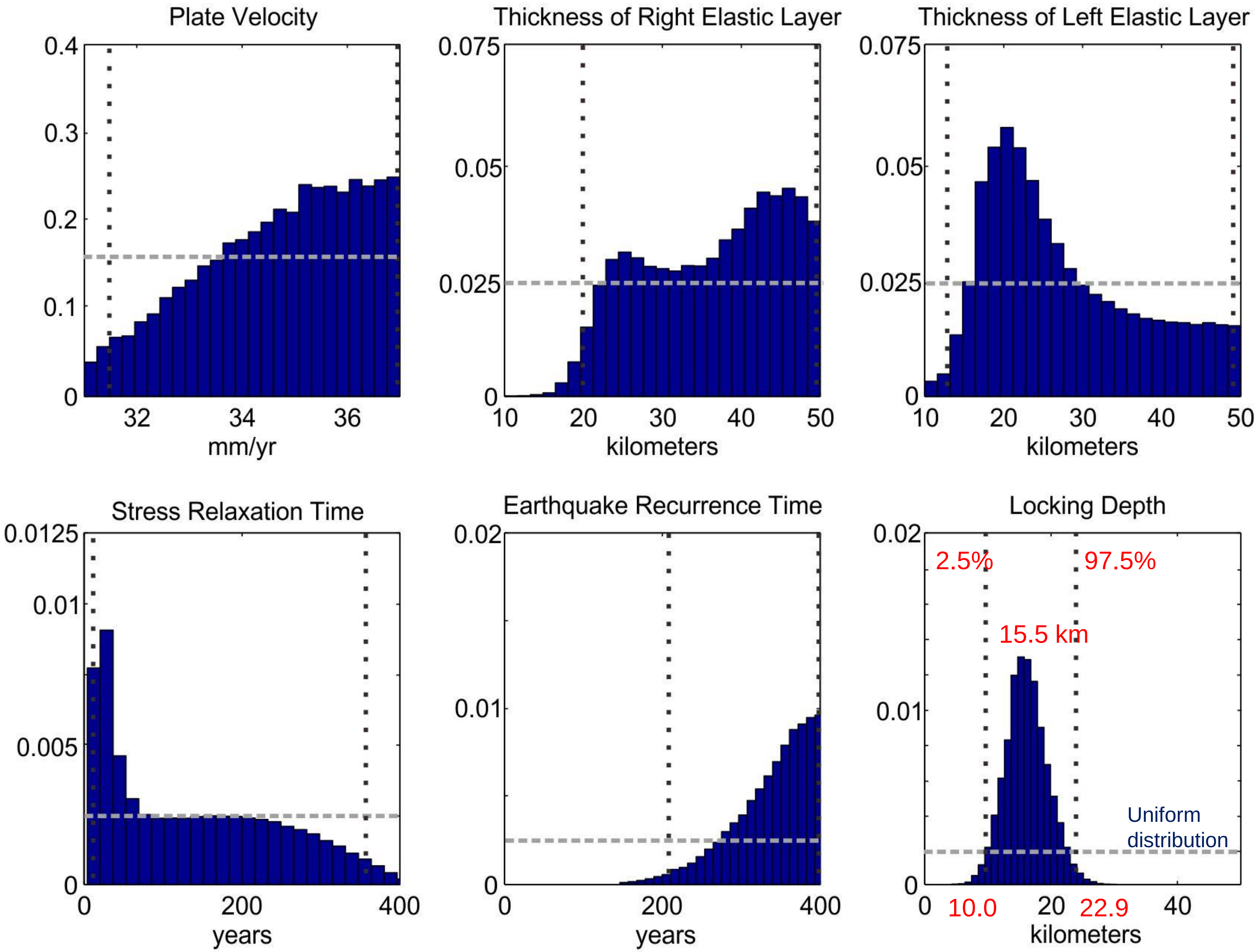


Plate Velocity
0.4
0.3
0.2
0.1
0
32
34
36
mm/yr
Thickness of Right Elastic Layer
0.075
0.05
0.025
0
10
20
30
40
50
kilometers
Thickness of Left Elastic Layer
0.075
0.05
0.025
0
10
20
30
40
50
kilometers
Stress Relaxation Time
0.0125
0.01
0.005
0
0
200
400
years
Earthquake Recurrence Time
0.02
0.01
0
0
200
400
years
Locking Depth
0.02
0.01
0
2.5%
97.5%
15.5 km
Uniform distribution
0
10.0
20
22.9
40
kilometers

Conclusions

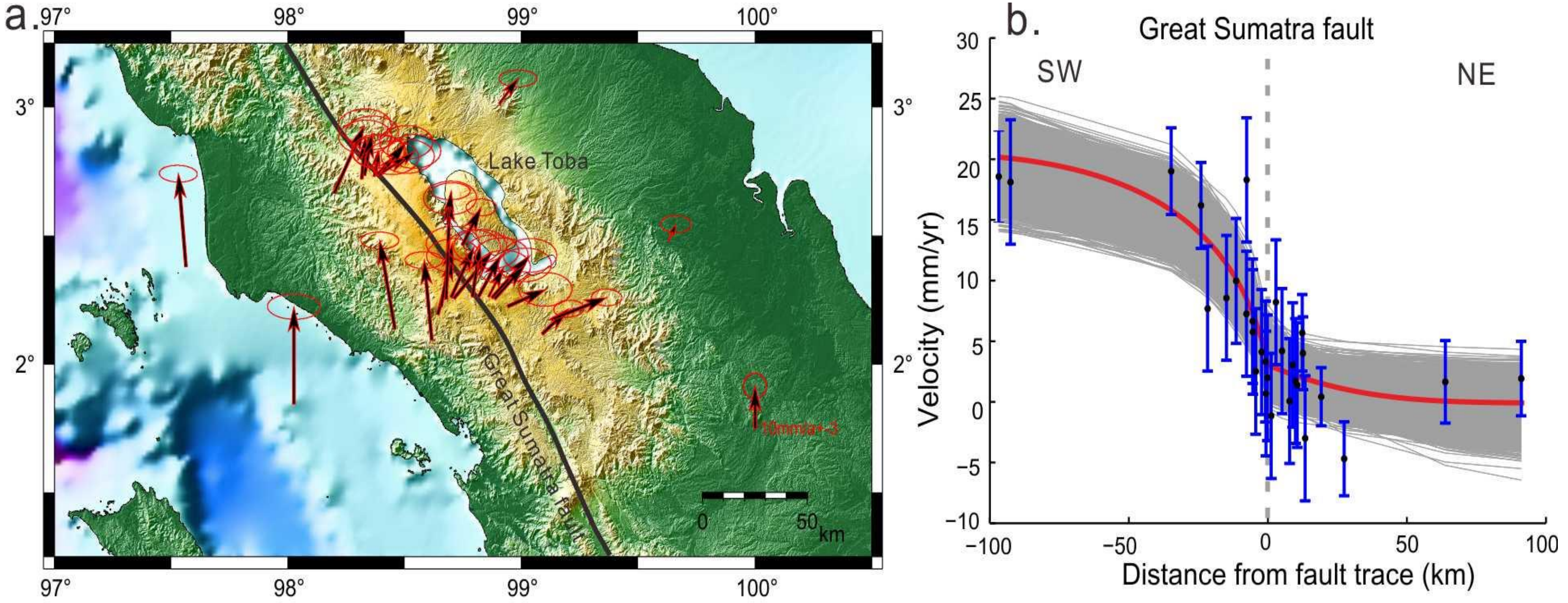
Can we use geodetic data to infer lateral variation in rigidity ?

Yes, we can

(up to some degree).

Thank you for your attention!

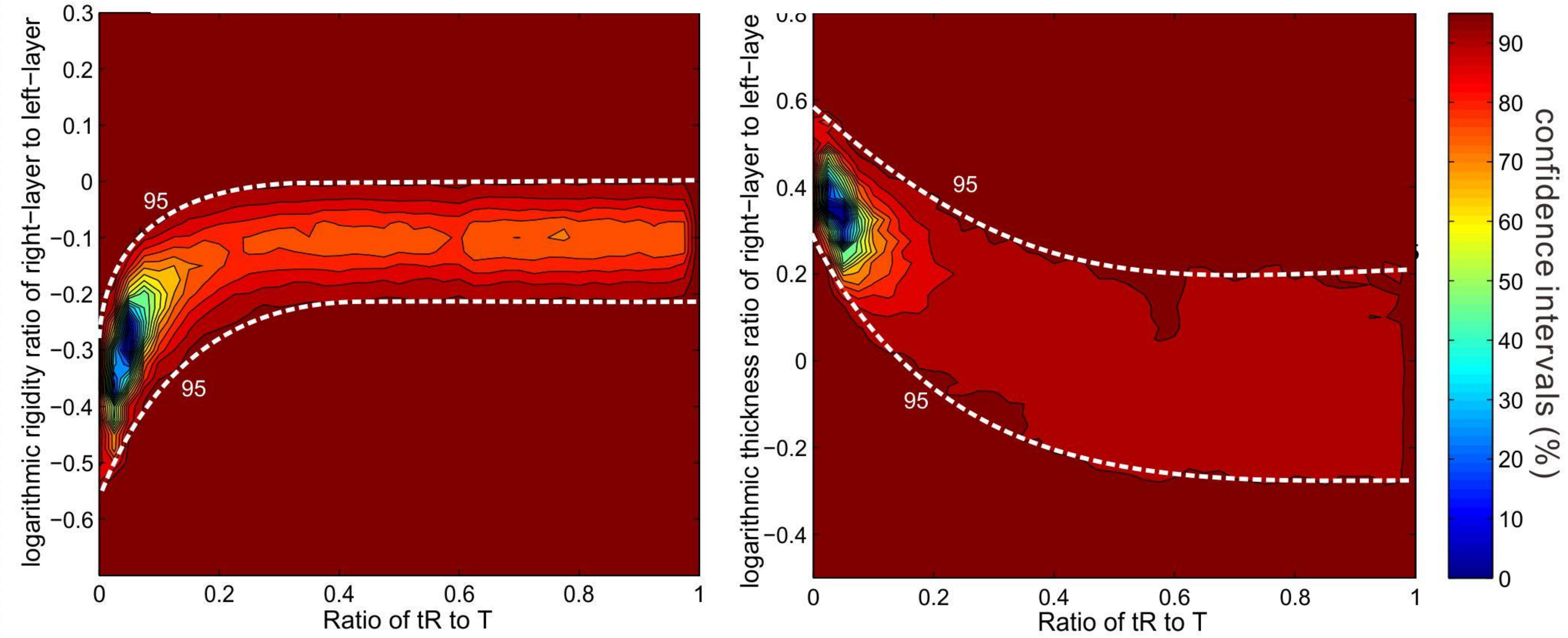
Great Sumatra Fault



Results

ratio of t_R to T vs. rigidity ratio

ratio of t_R to T vs. thickness ratio



t_R: Stress relaxation time
T: earthquake recurrence time