Modeling crustal deformation through the earthquake cycle in Southern Alaska

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Earthquakes at plate boundaries?

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  (caused by plate tectonics)

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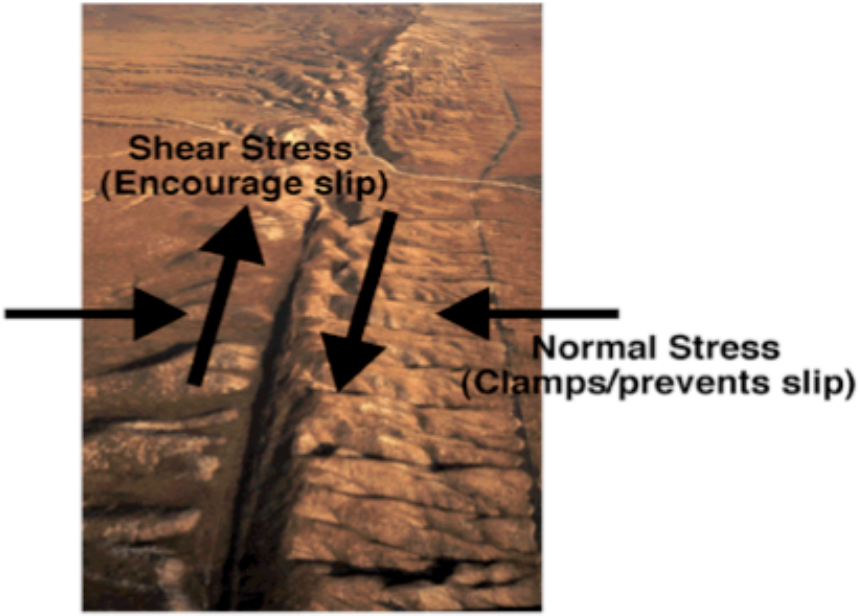

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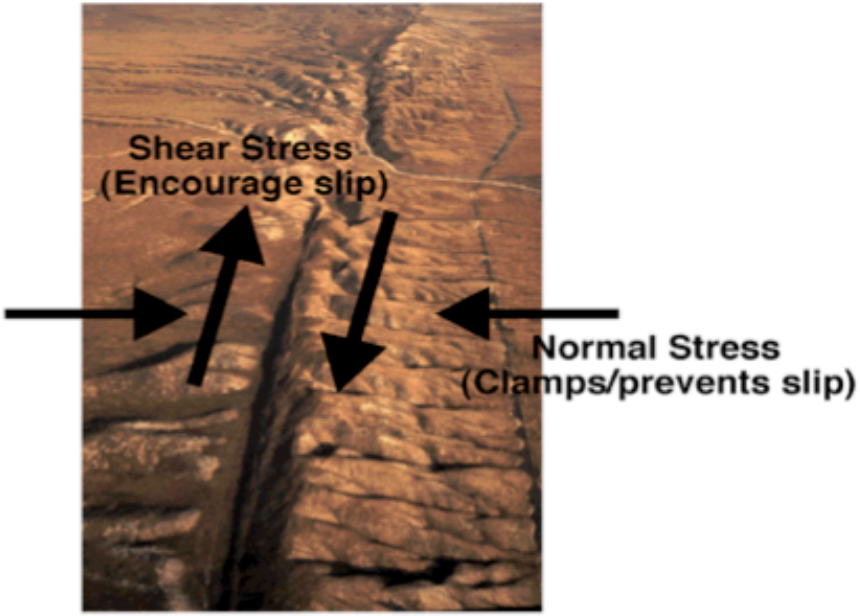

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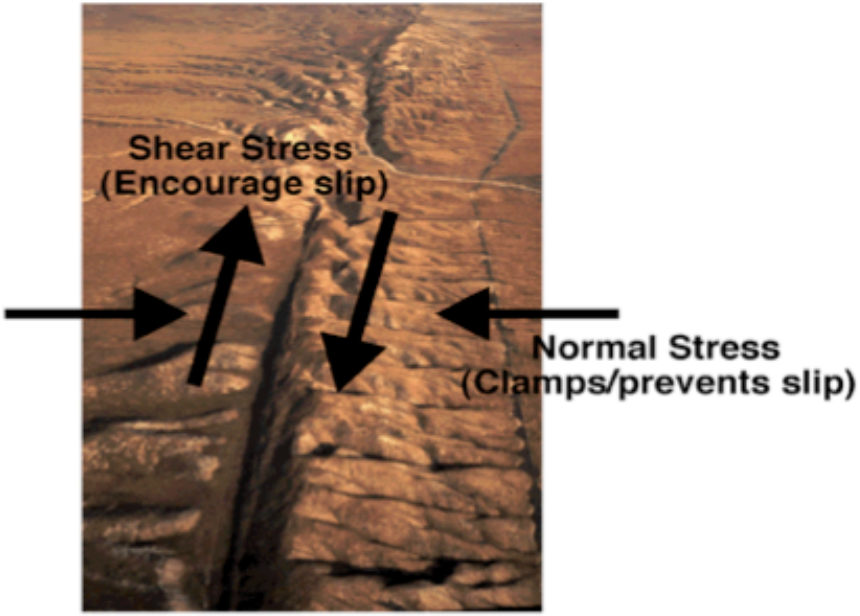

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(Coulomb stress change)

Crustal deformation => Stress on faults => Earthquakes

Crustal deformation

- Interseismic/Tectonic Loading
  - Deep slip
  - Virtual negative slip/Back slip
  - Invert/Calculate regional strain field from GPS observations
  - Model the plate dynamics

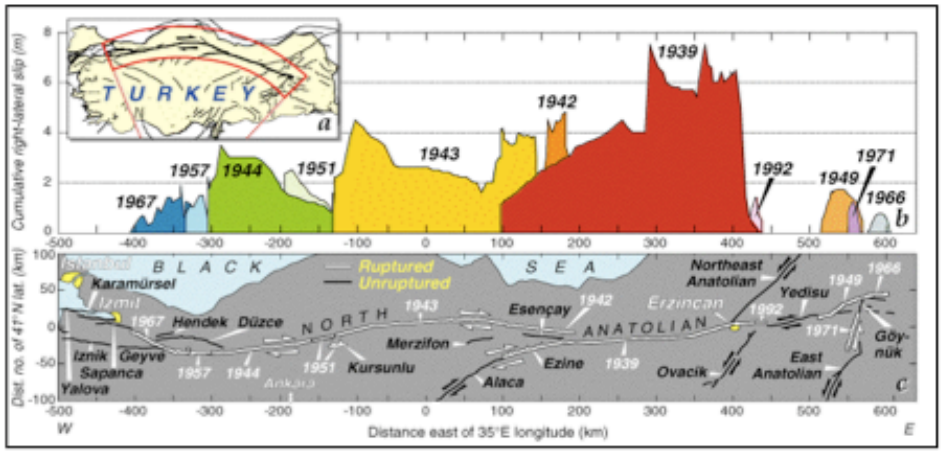
Kinematic

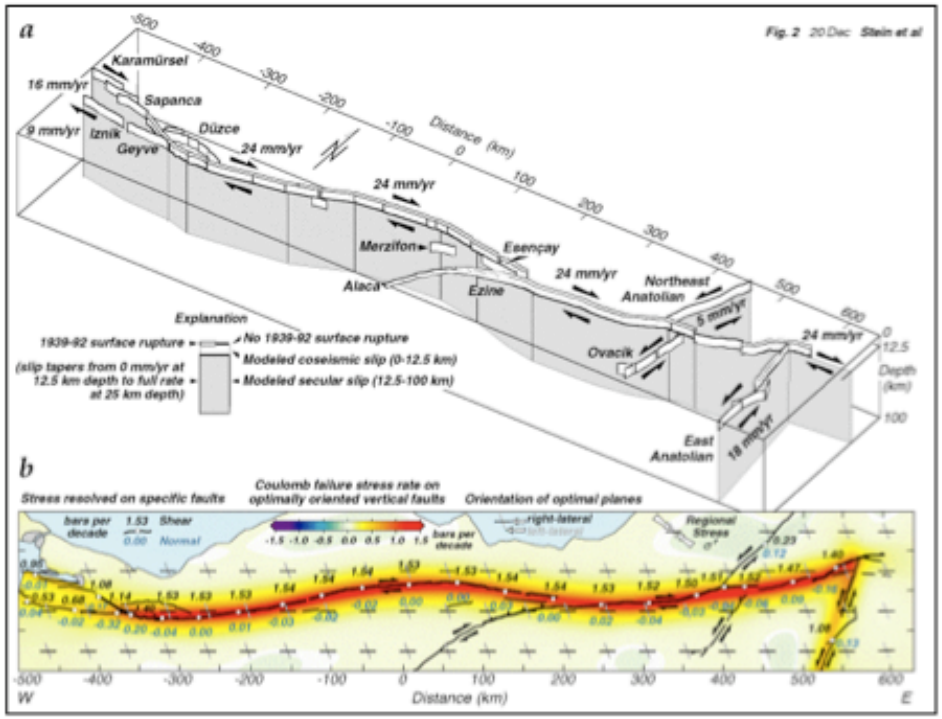
- Coseismic slip

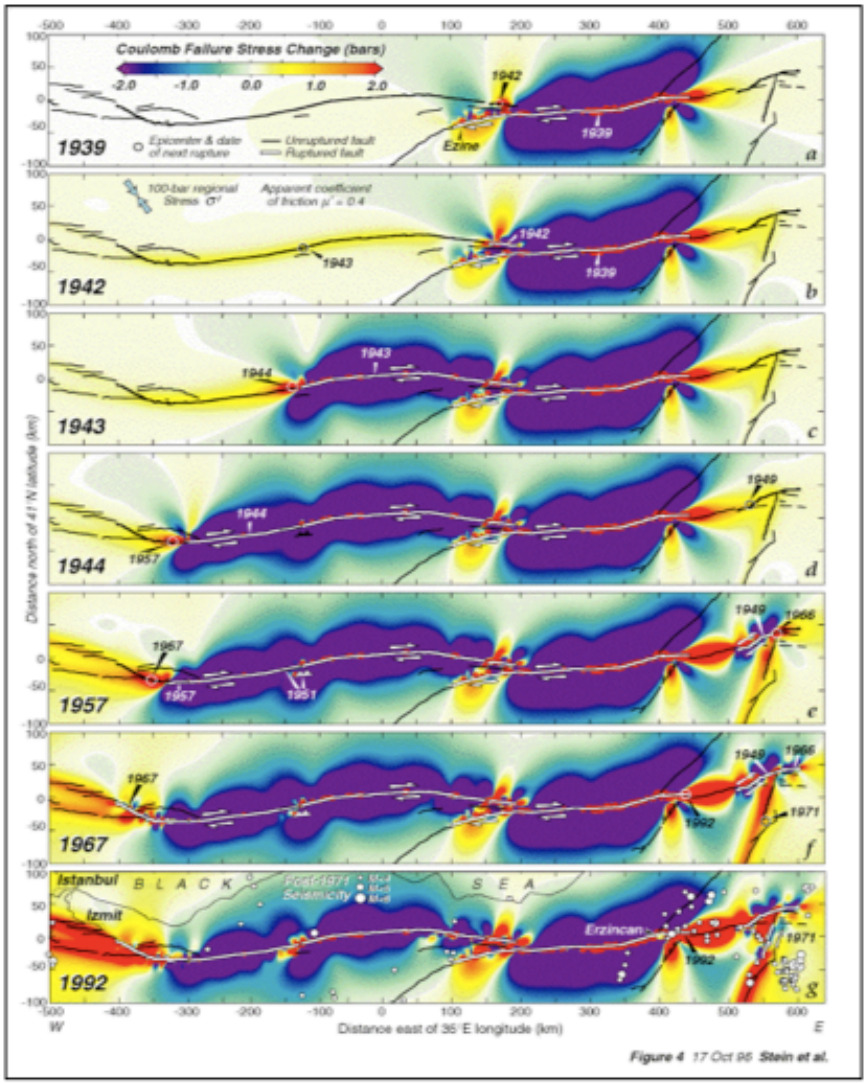
- Postseismic processes
  - Viscous relaxation
  - Afterslip
  - Poroelastic rebound

- Other processes
  - Ice unloading etc.

Stress evolution in Turkey 1939-1992



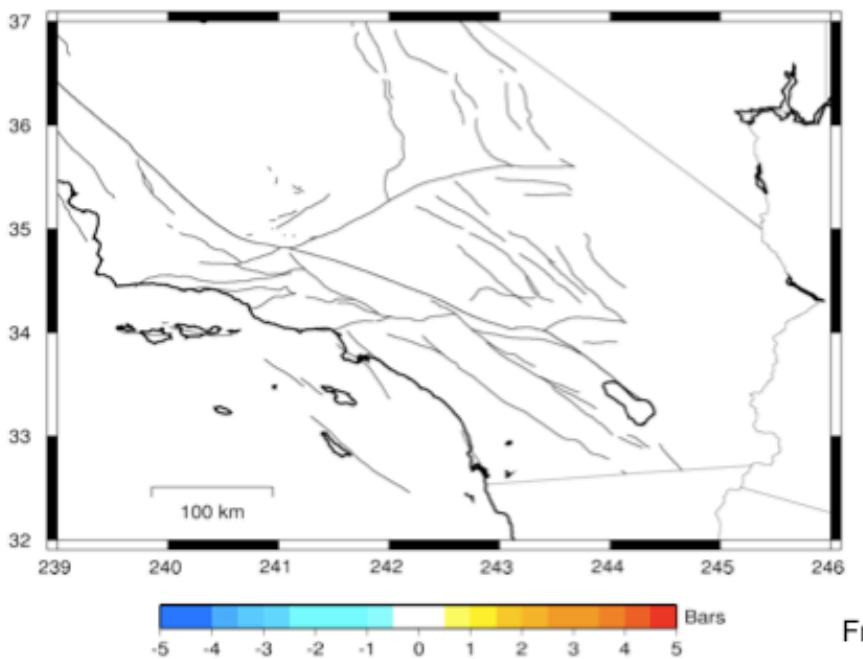




Stein, Barka and Dieterich

(GJI, 1997)

Stress evolution in Southern California 1812-2005



Freed, Ali and Burgmann

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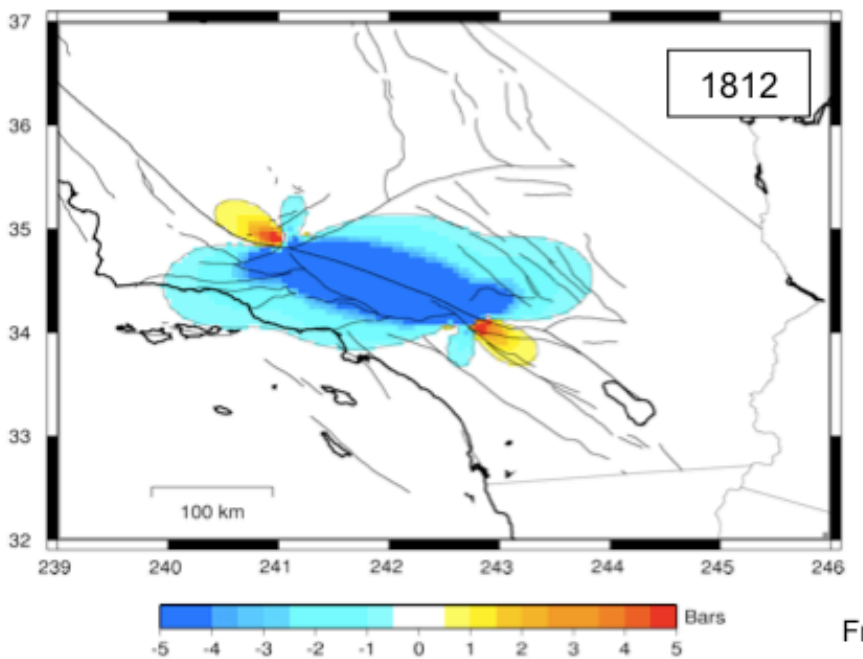

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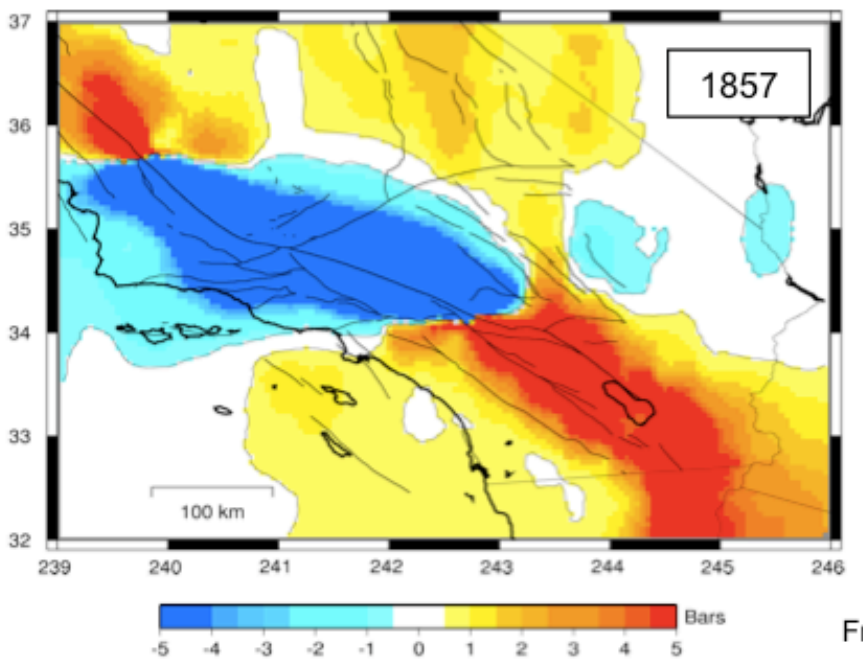

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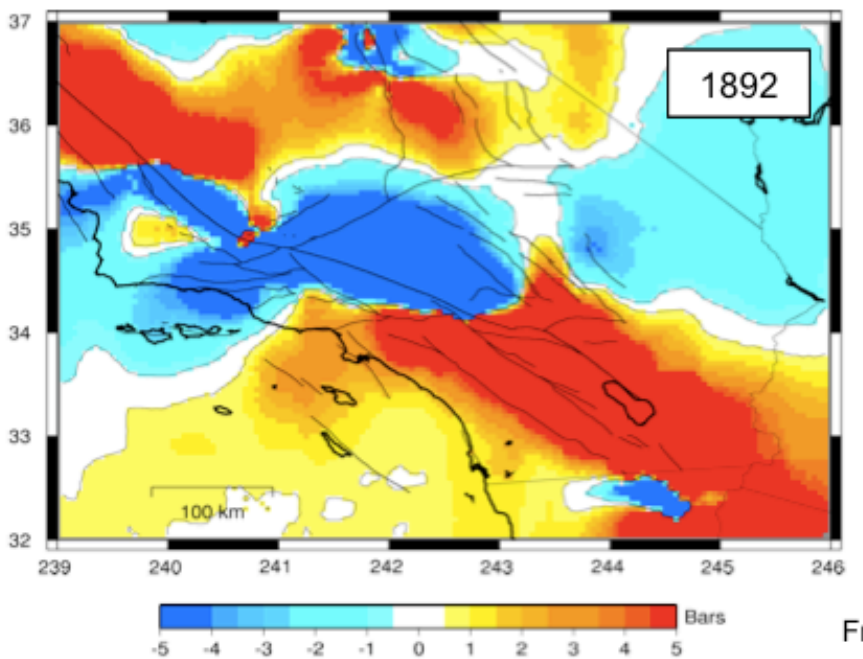

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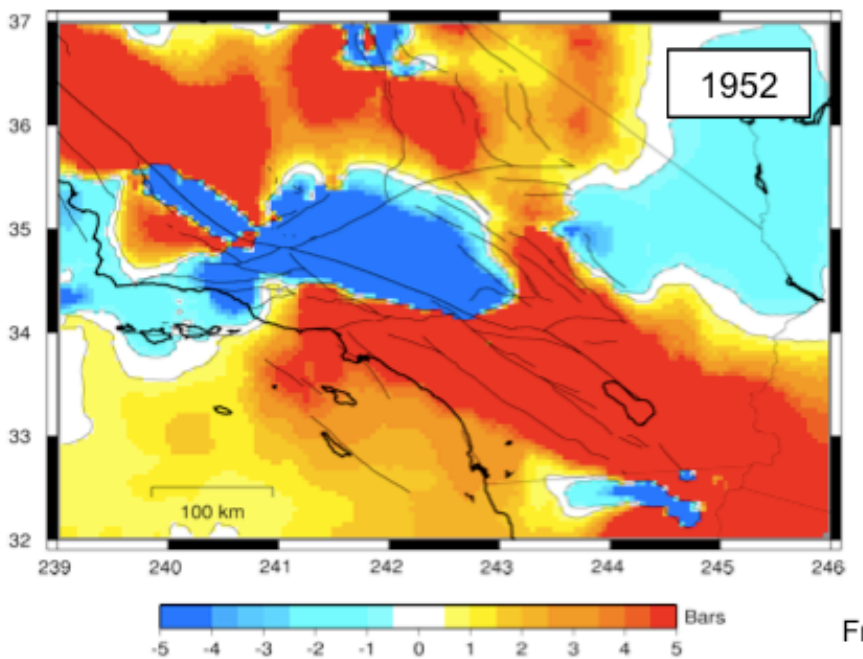

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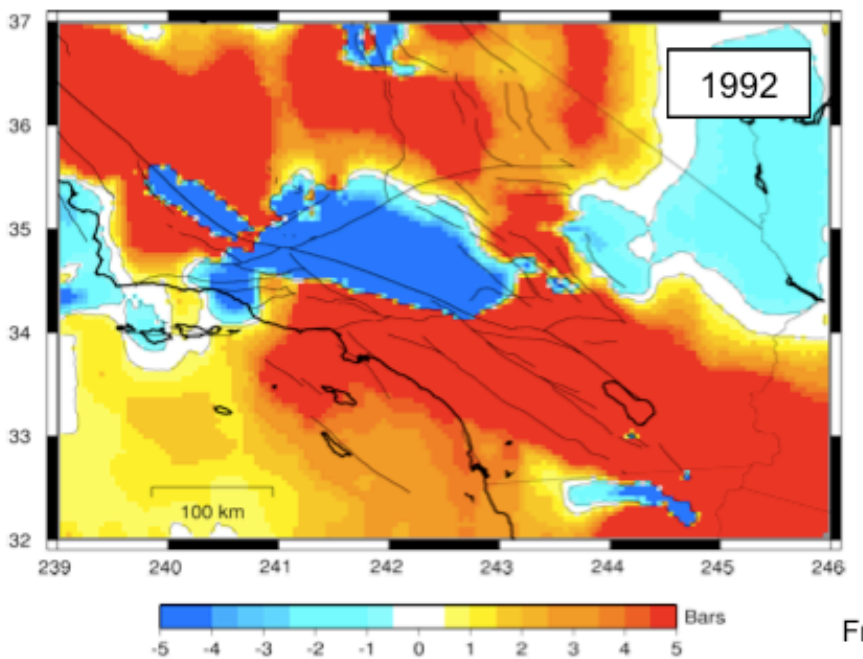

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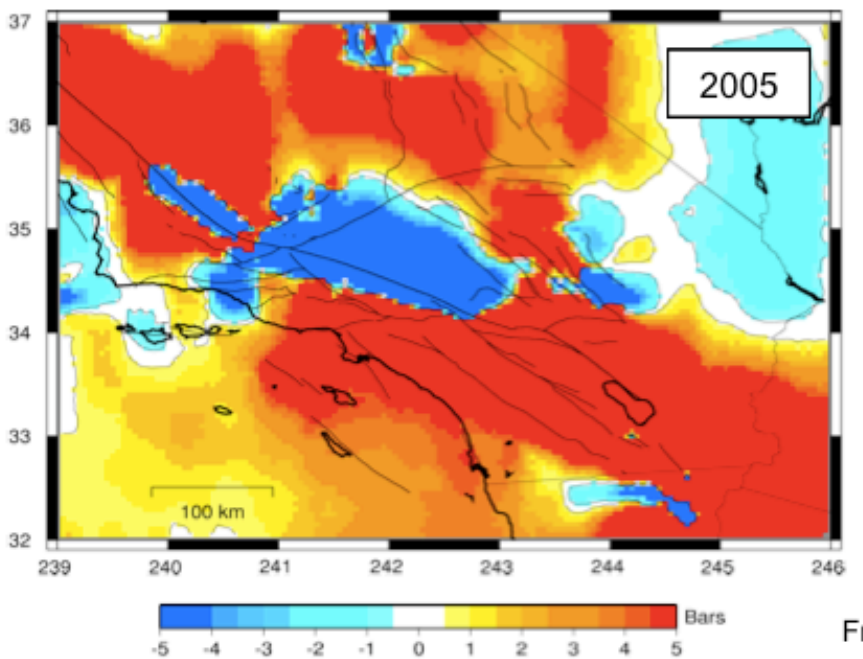

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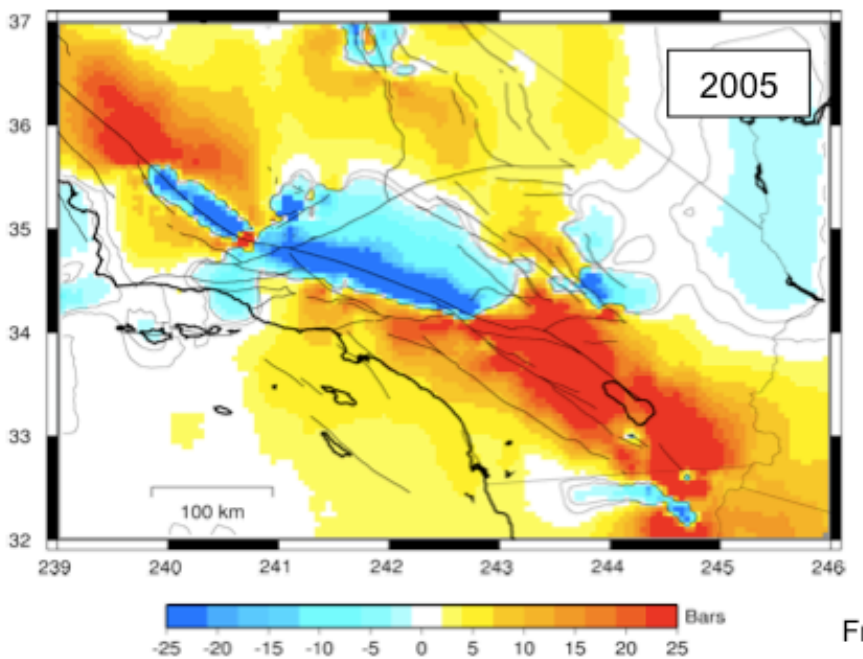

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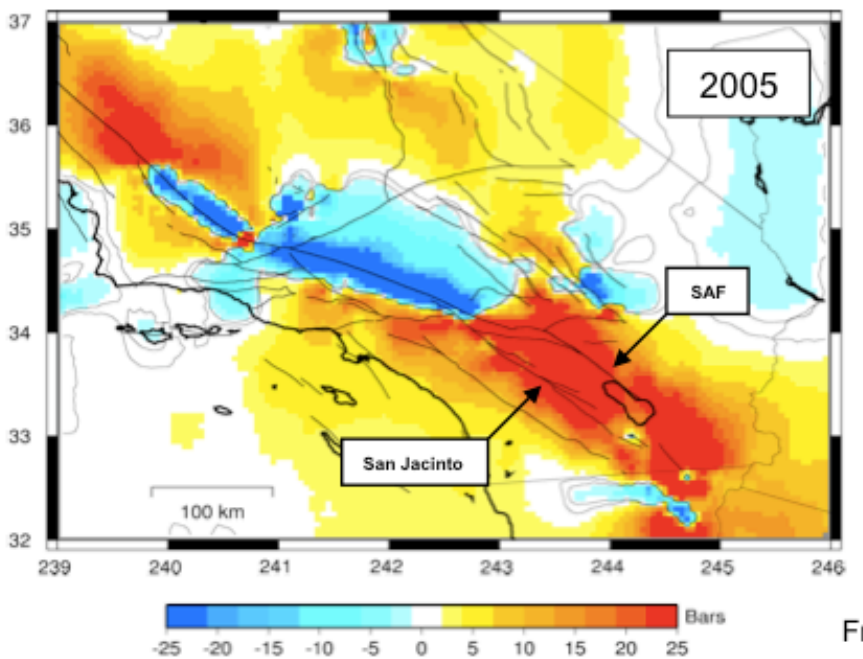

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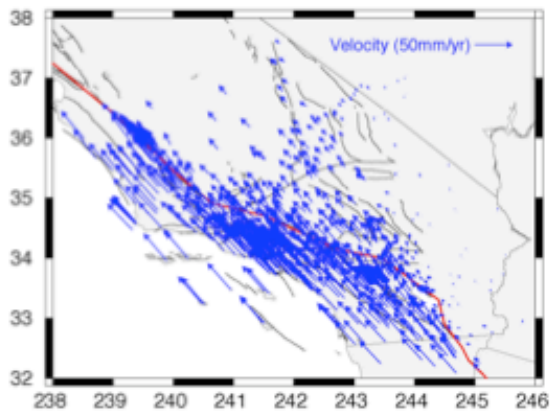

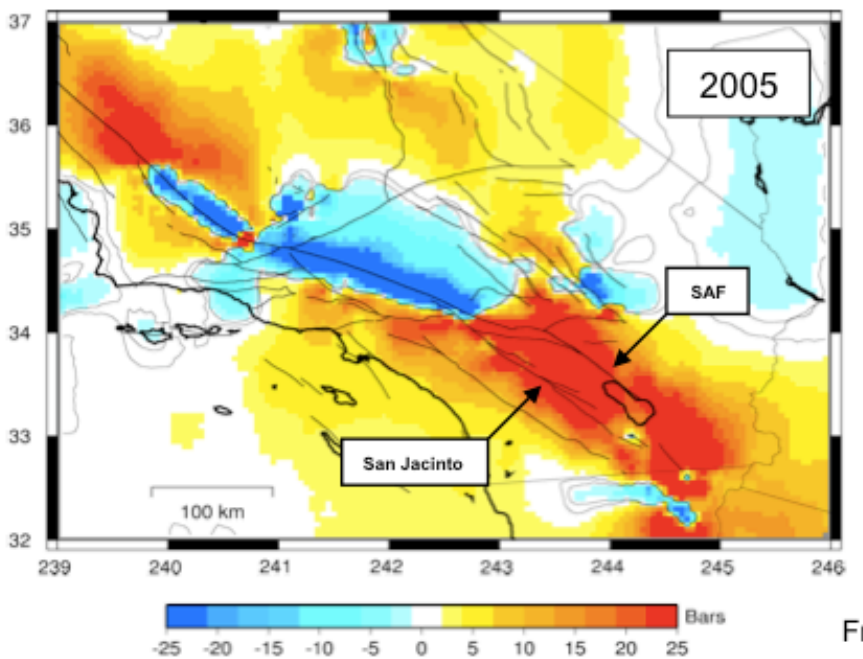

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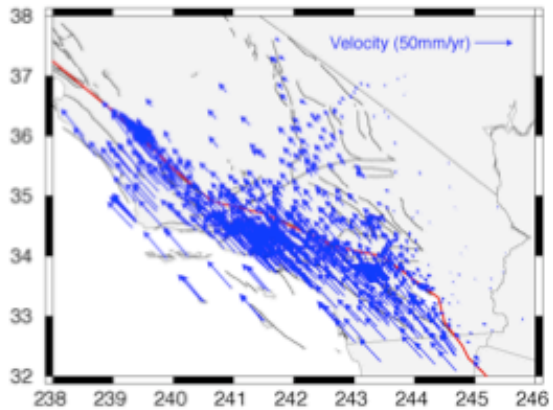

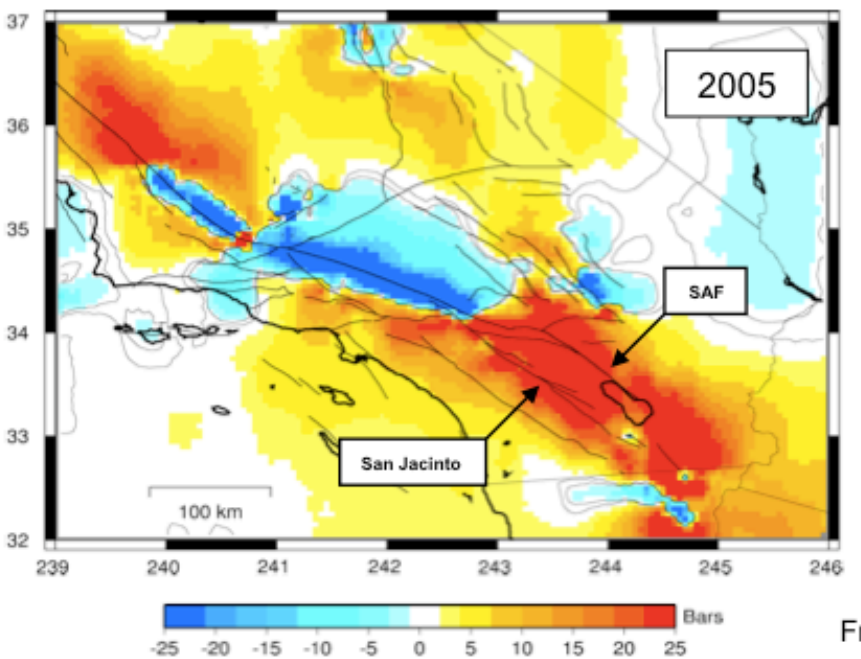

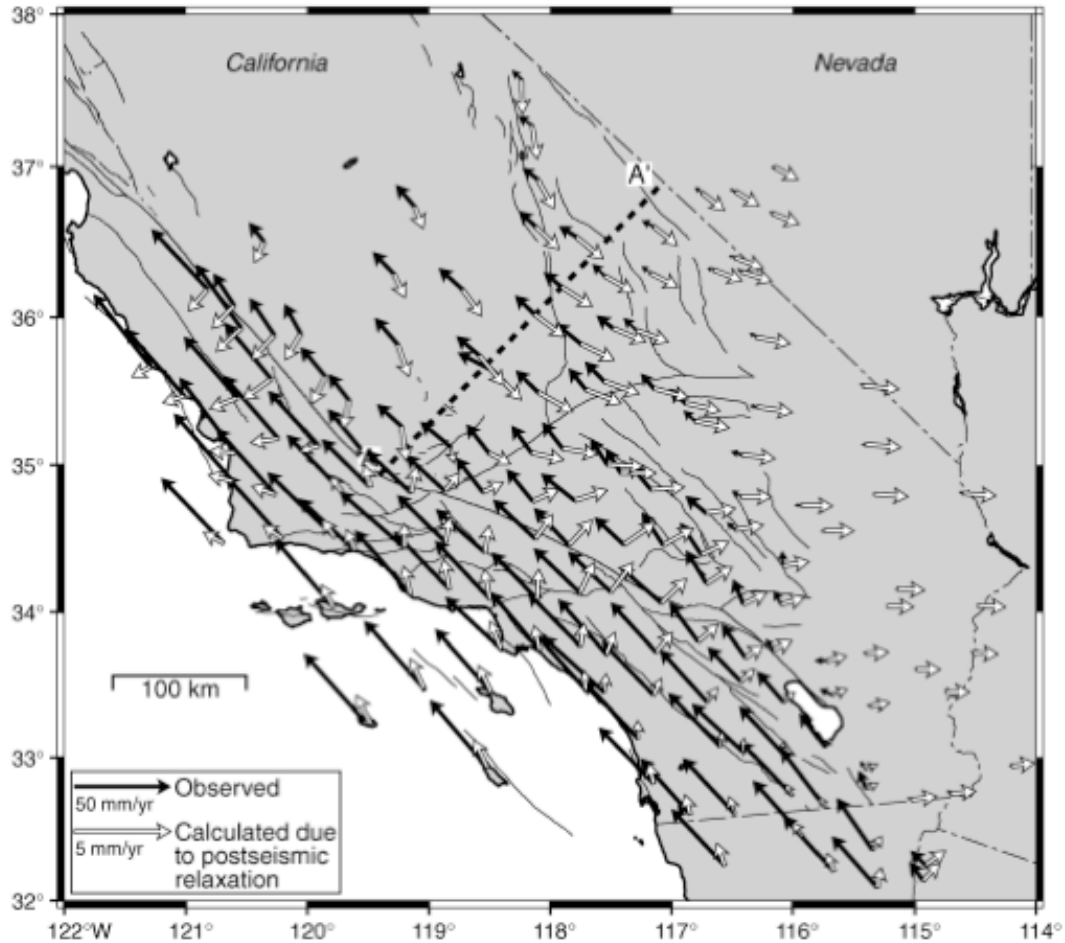

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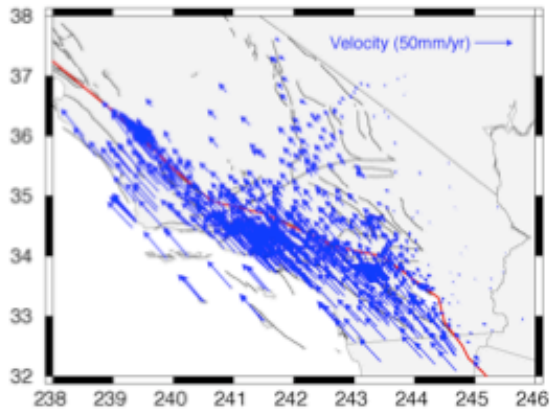

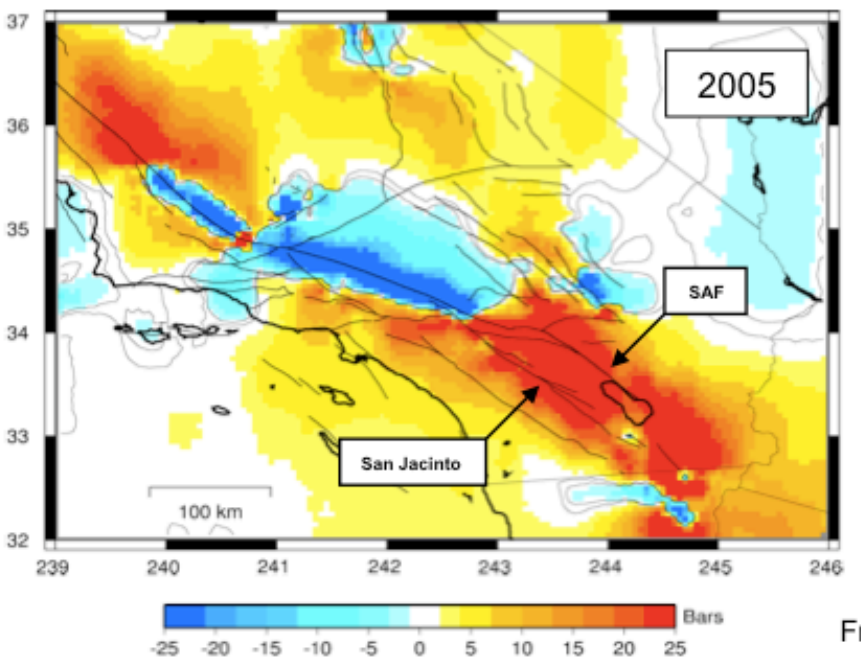

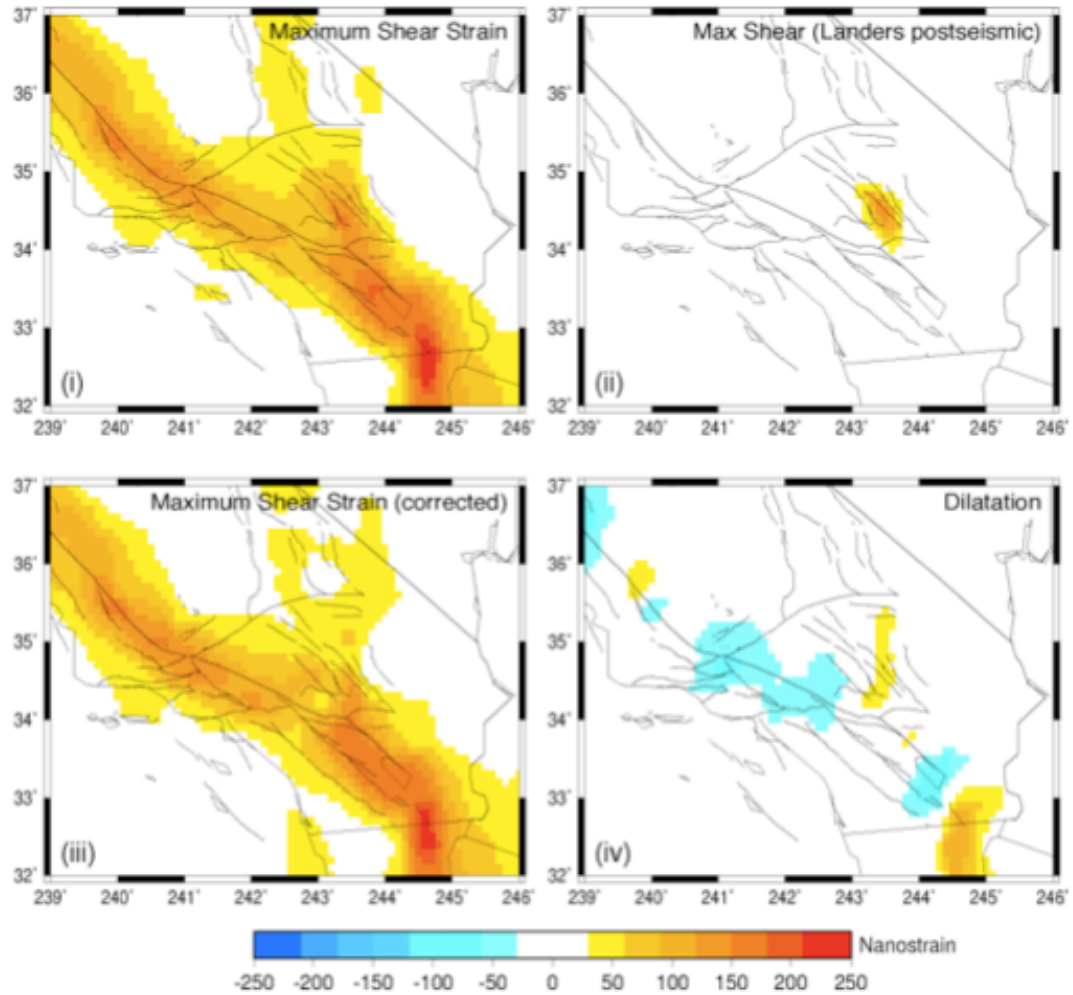

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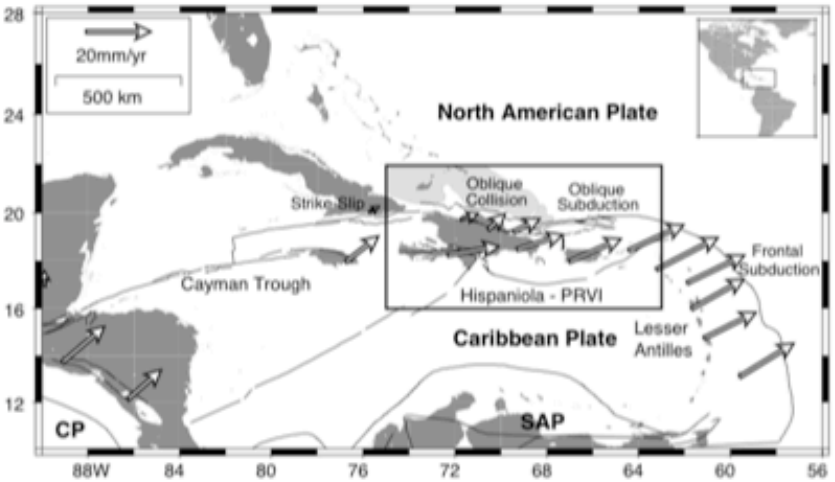
Stress evolution in NE Caribbean 1751-2003



Ali et al. (GJI, 2008)

Manaker et al. (GJI, 2008)

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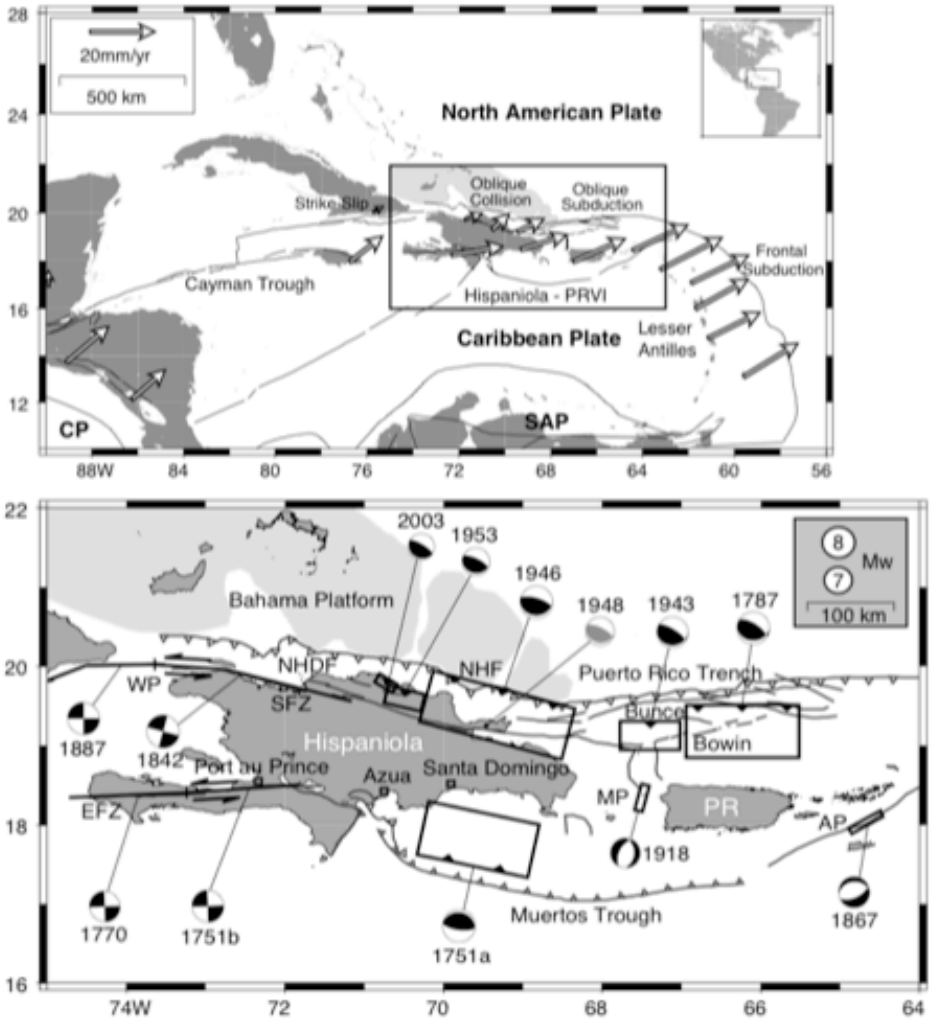

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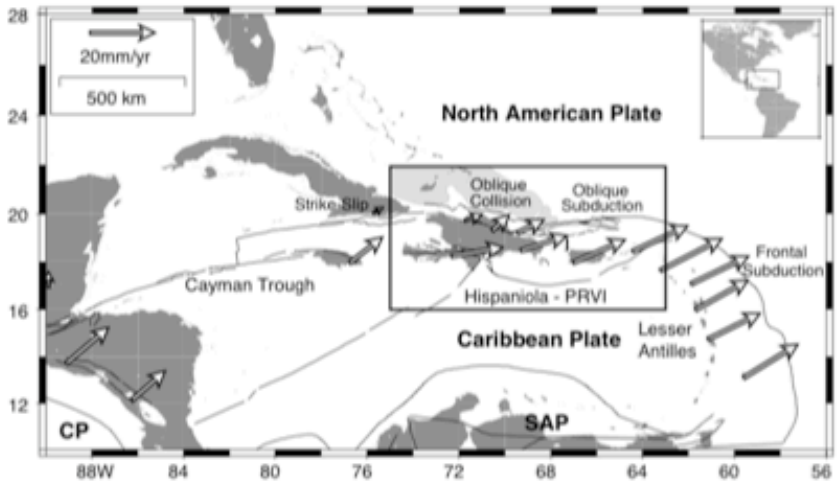

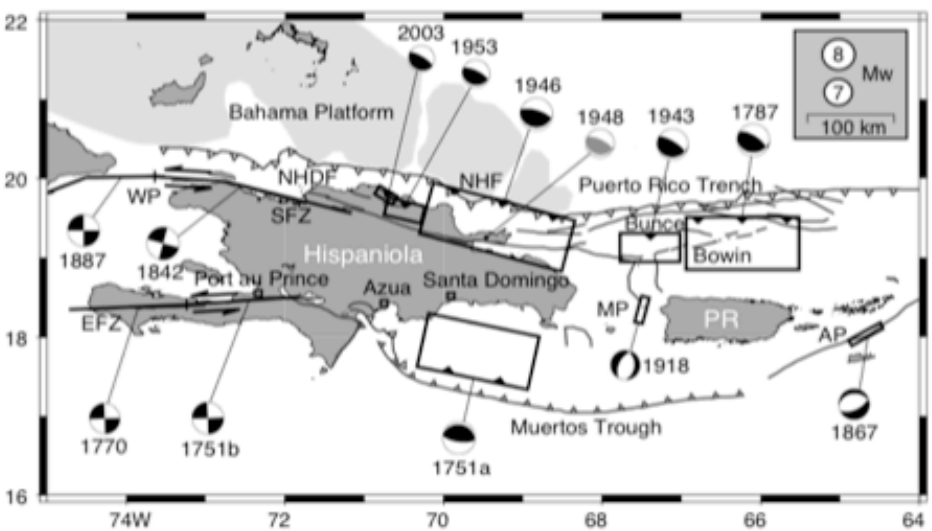

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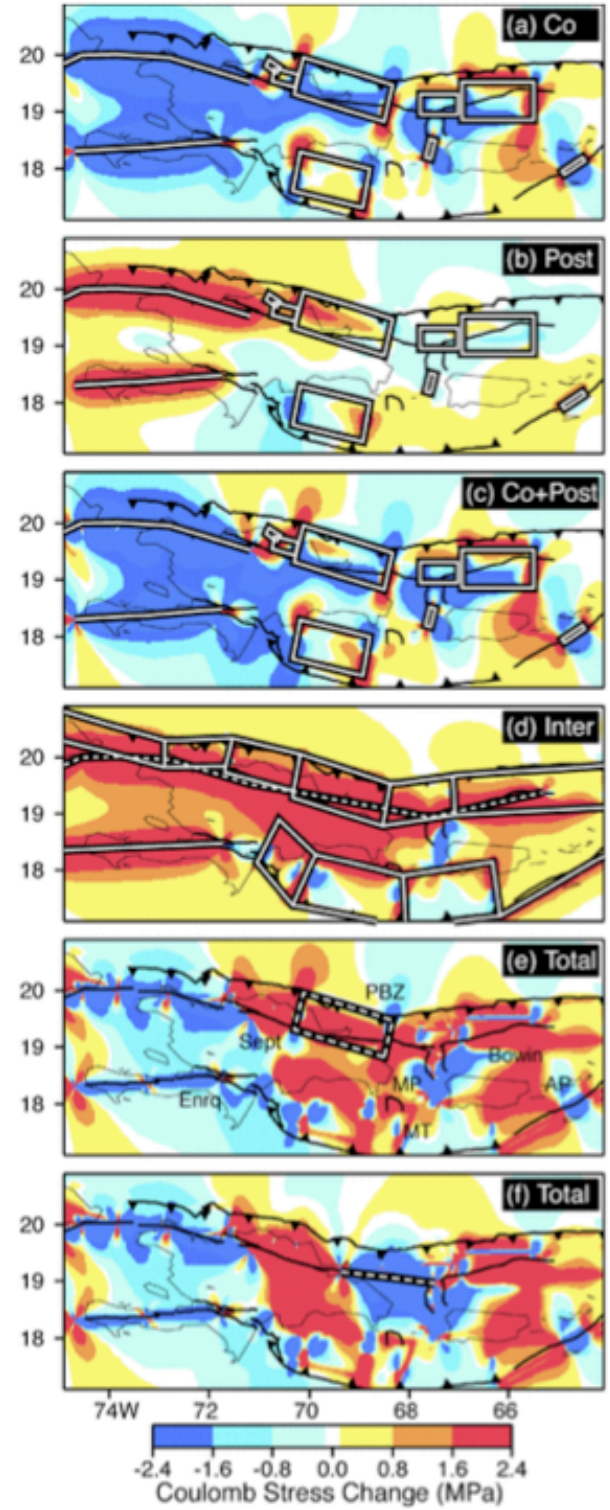
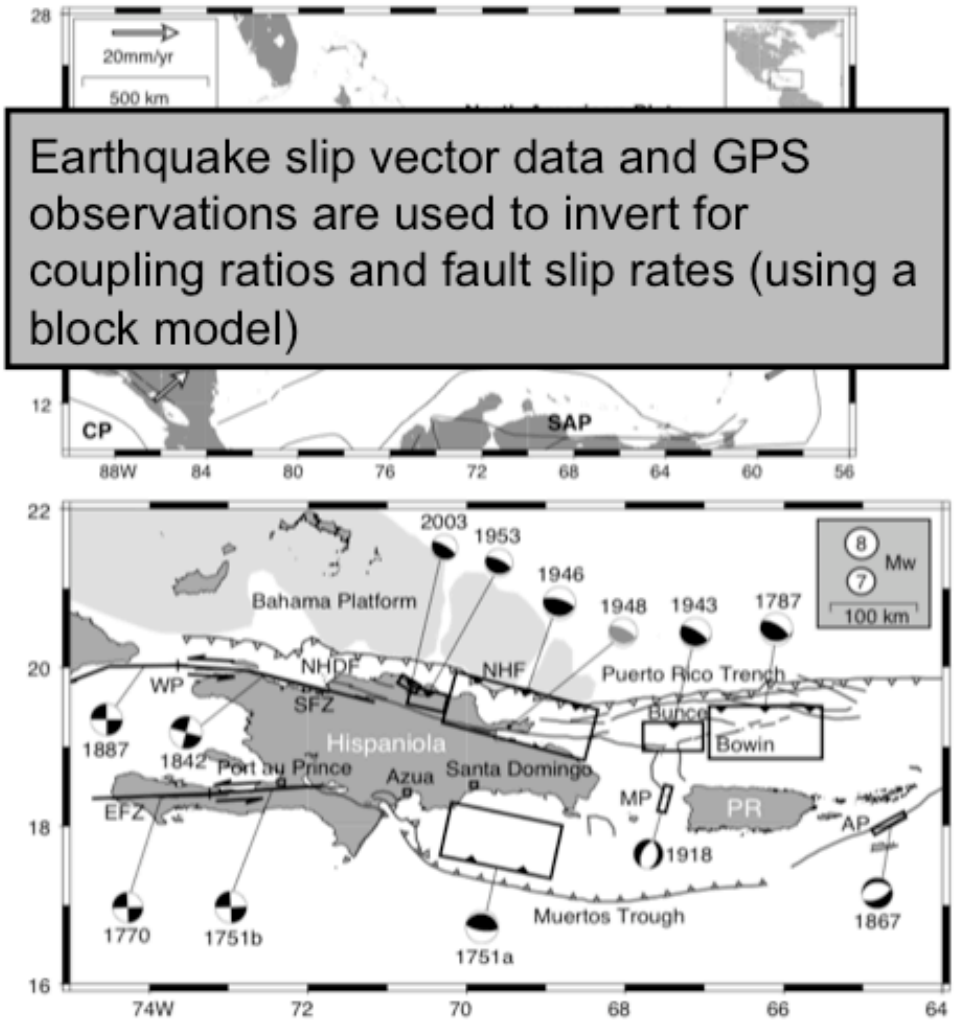


Stress evolution in NE Caribbean 1751-2003

Earthquake slip vector data and GPS observations are used to invert for coupling ratios and fault slip rates (using a block model)



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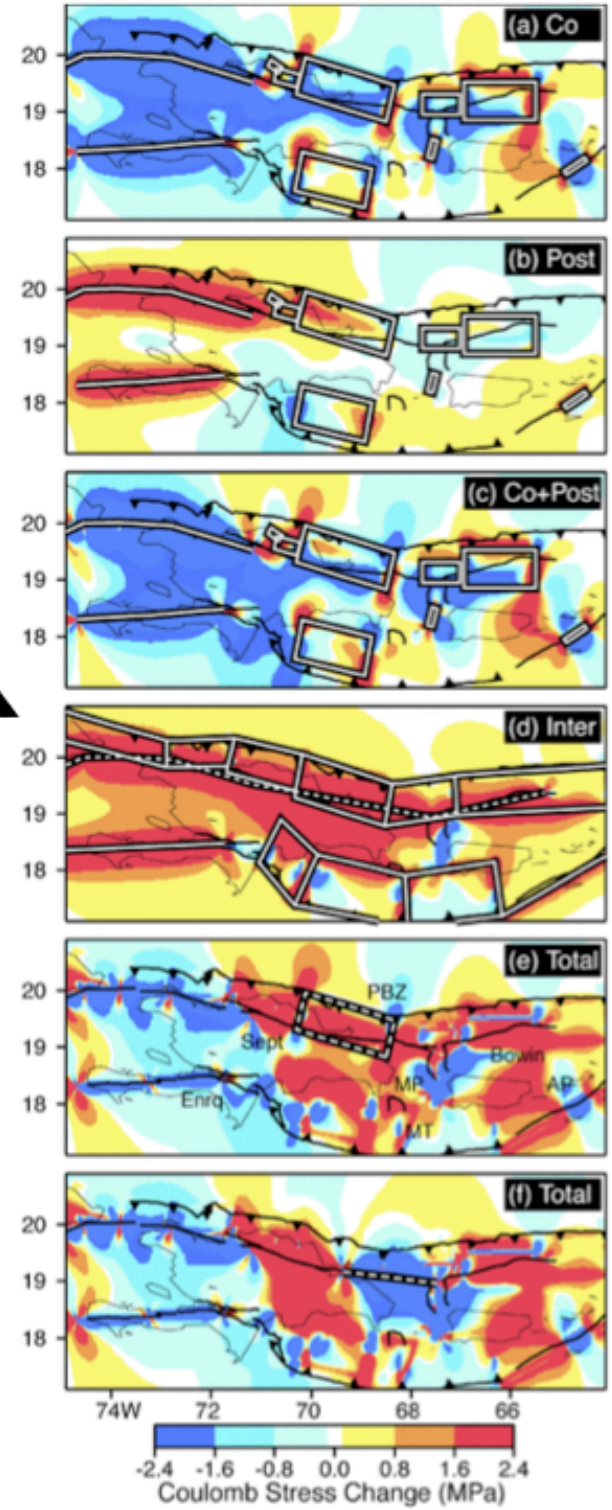

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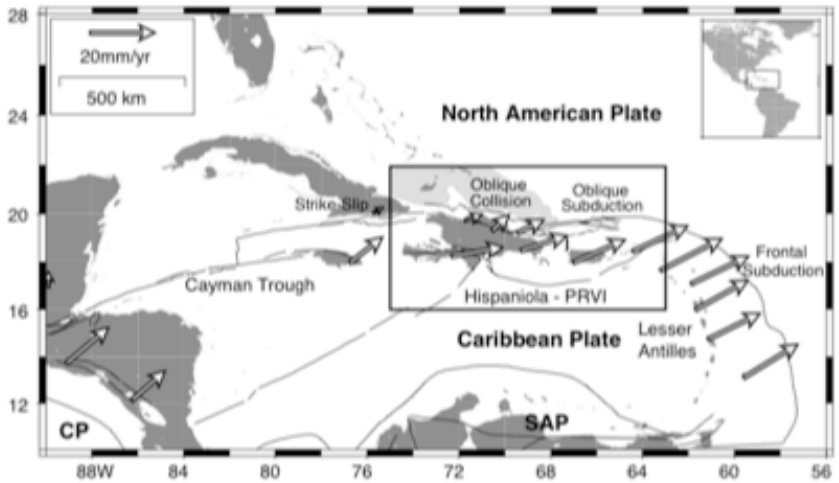

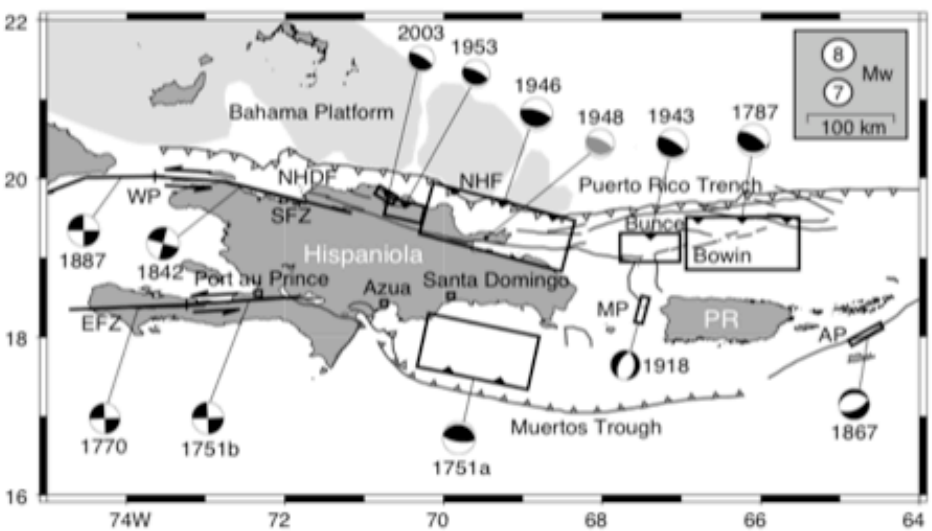

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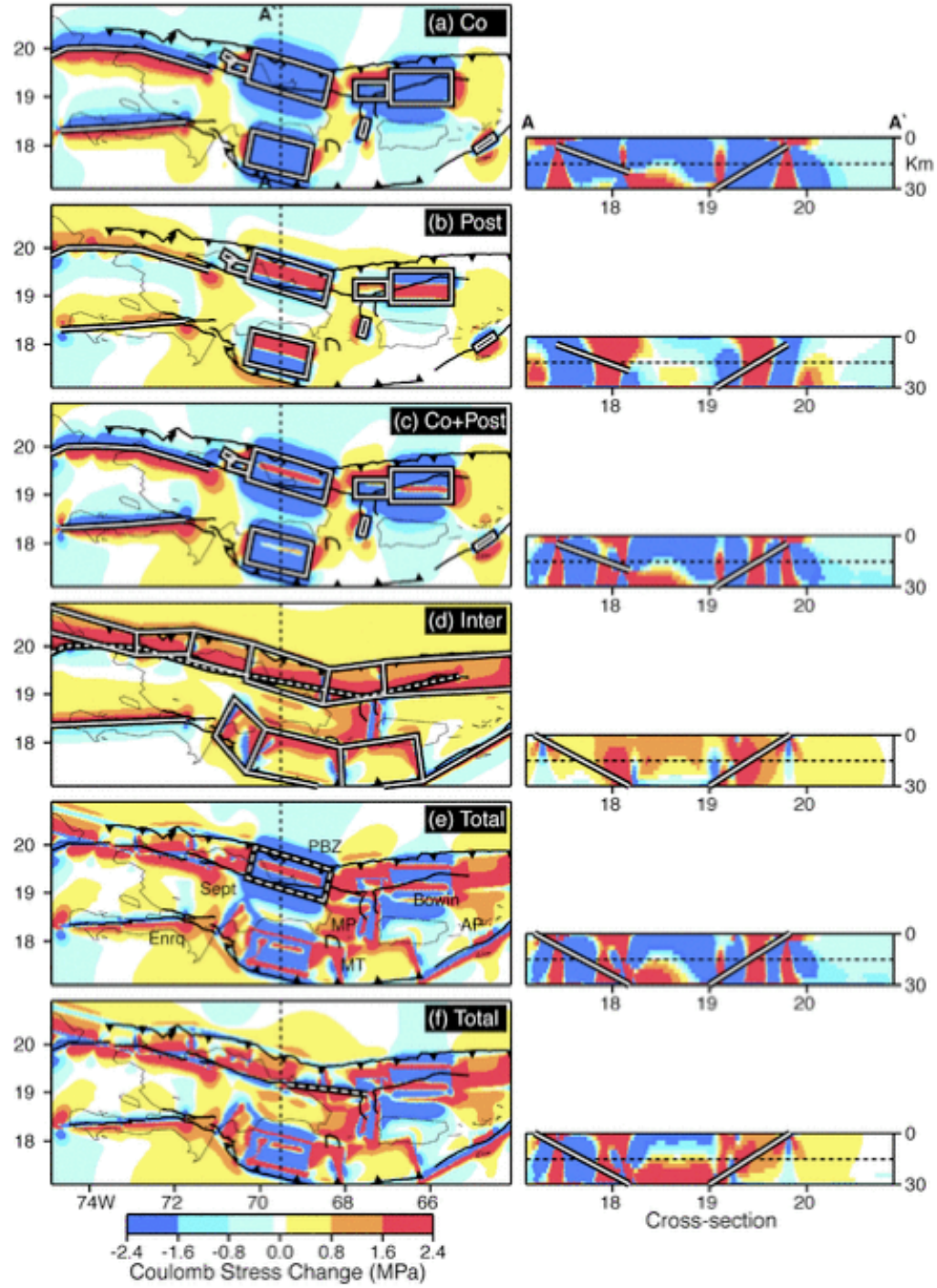
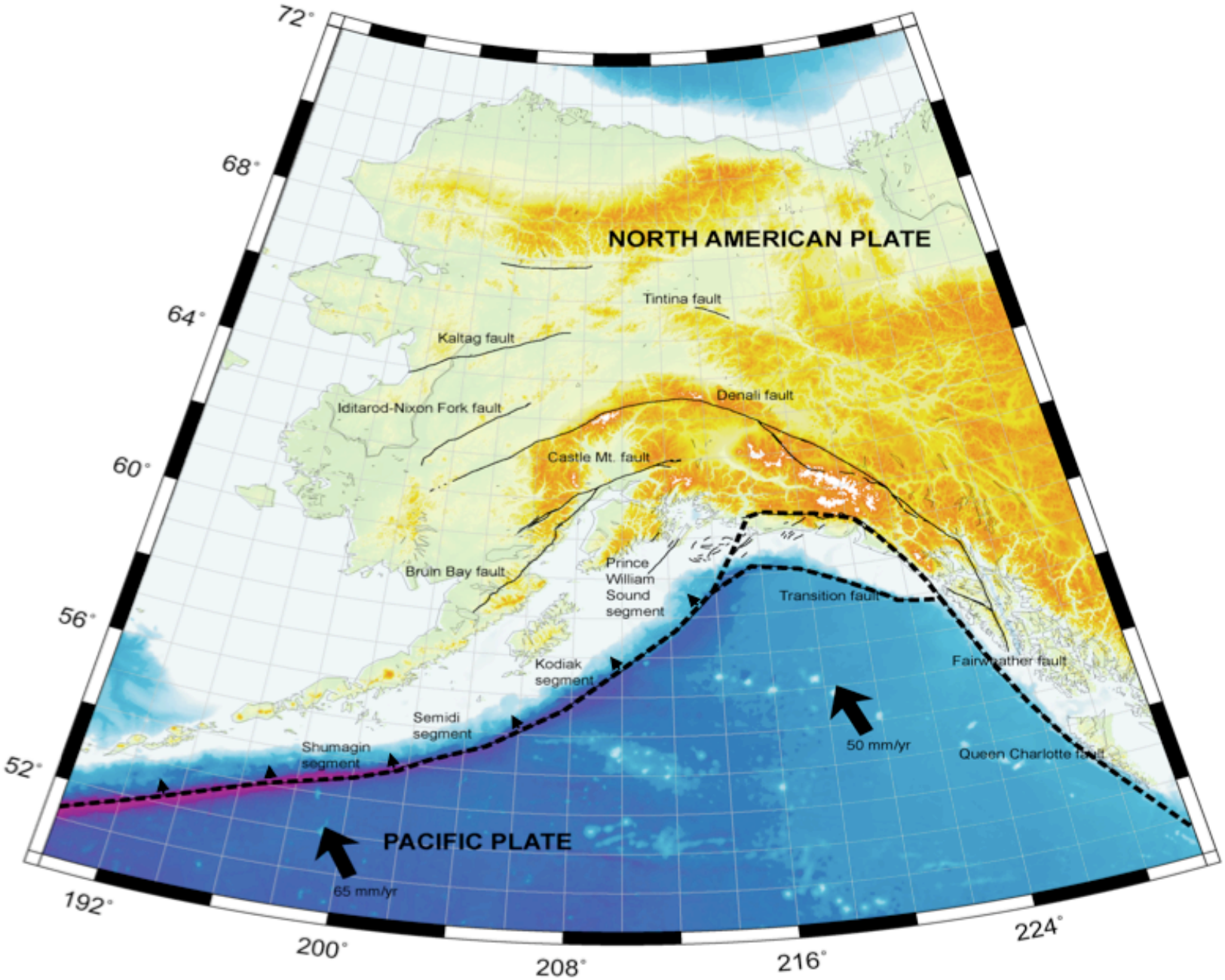
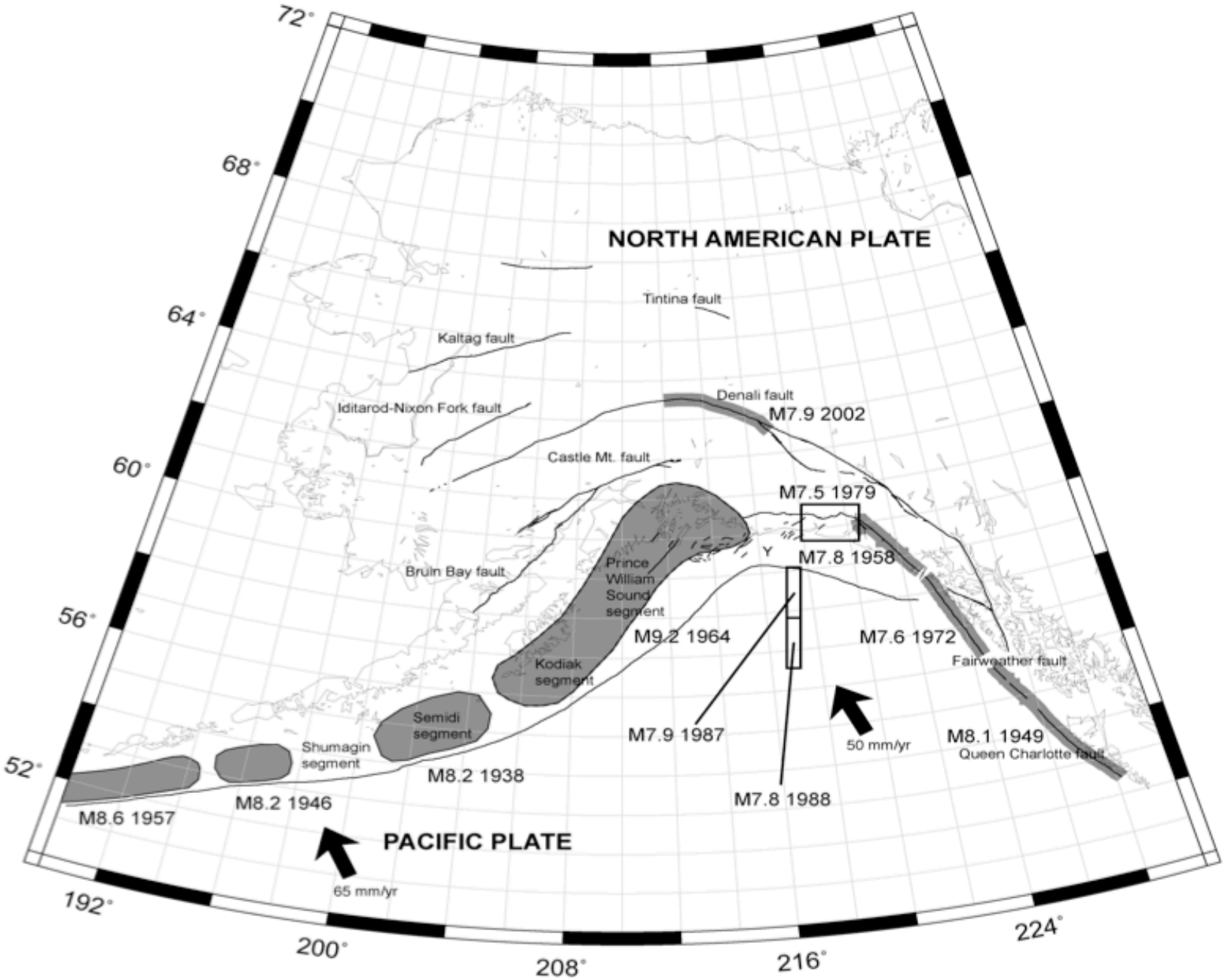
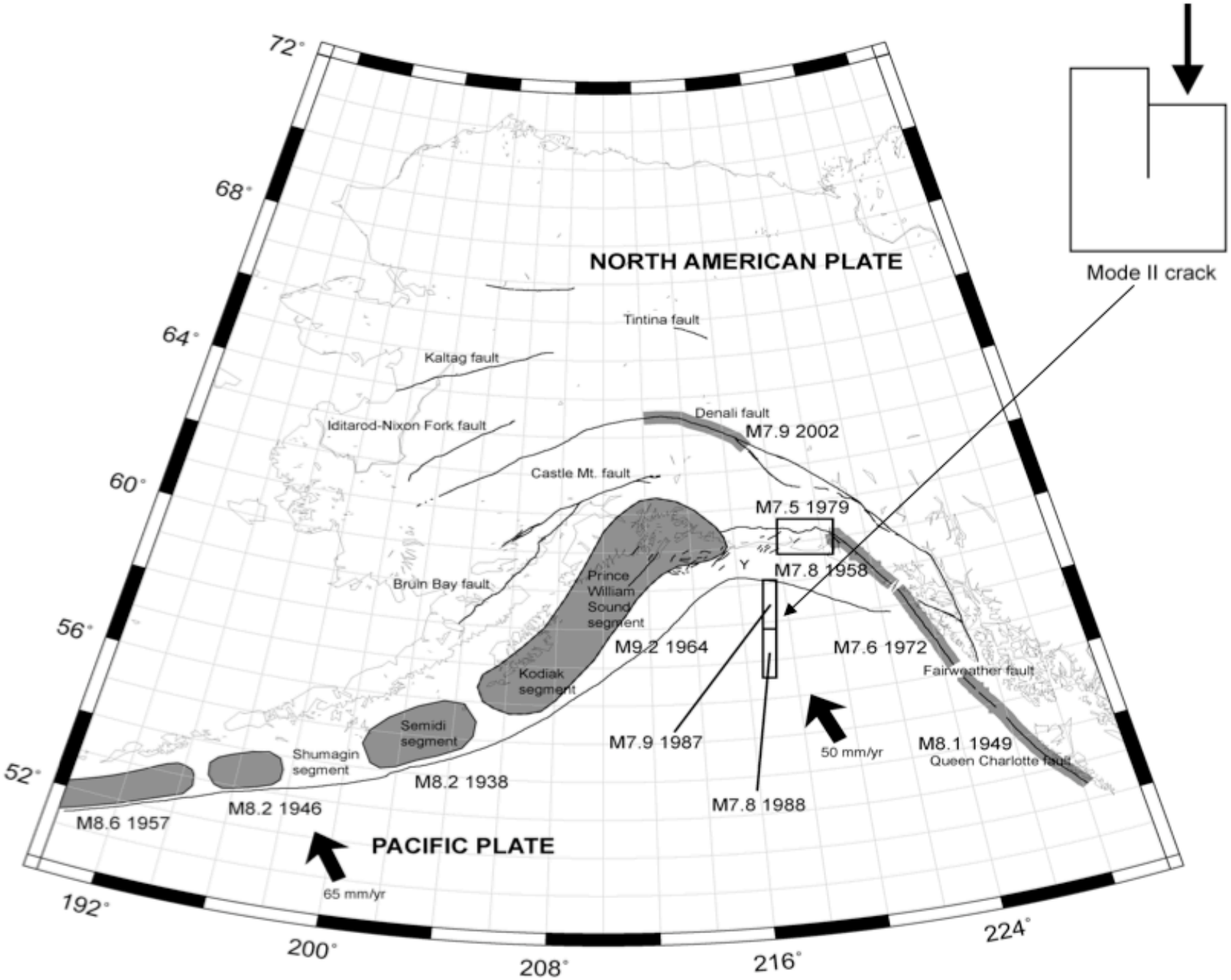


Outline for Southern Alaska

- Objective
  - Model contemporary deformation
  - Decompose the observed GPS velocities into secular and transient components
  - Calculate the evolution of stress over the past few decades
- Constraints
  - GPS
  - Geologic
- Numerical models
  - Interseismic deformation
  - Postseismic viscous relaxation


72°
68°
64°
60°
56°
52°
192°
200°
208°
216°
224°
NORTH AMERICAN PLATE
Tintina fault
Kaltag fault
Denali fault
Iditarod-Nixon Fork fault
Castle Mt. fault
Bruin Bay fault
Prince William Sound segment
Transition fault
Kodiak segment
Fairweather fault
Semidi segment
Shumagin segment
50 mm/yr
Queen Charlotte fault
PACIFIC PLATE
65 mm/yr


72°
68°
64°
60°
56°
52°
192°
200°
208°
216°
224°
NORTH AMERICAN PLATE
Tintina fault
Kaltag fault
Iditarod-Nixon Fork fault
Denali fault
M7.9 2002
Castle Mt. fault
M7.5 1979
M7.8 1958
Y
Bruin Bay fault
Prince William Sound segment
M9.2 1964
M7.6 1972
Fairweather fault
Kodiak segment
Semidi segment
Shumagin segment
M7.9 1987
50 mm/yr
M8.1 1949
Queen Charlotte fault
M8.2 1938
M7.8 1988
M8.6 1957
M8.2 1946
PACIFIC PLATE
65 mm/yr


72°
68°
64°
60°
56°
52°
192°
200°
208°
216°
224°
NORTH AMERICAN PLATE
Mode II crack
Tintina fault
Kaltag fault
Iditarod-Nixon Fork fault
Denali fault
M7.9 2002
Castle Mt. fault
M7.5 1979
M7.8 1958
Bruin Bay fault
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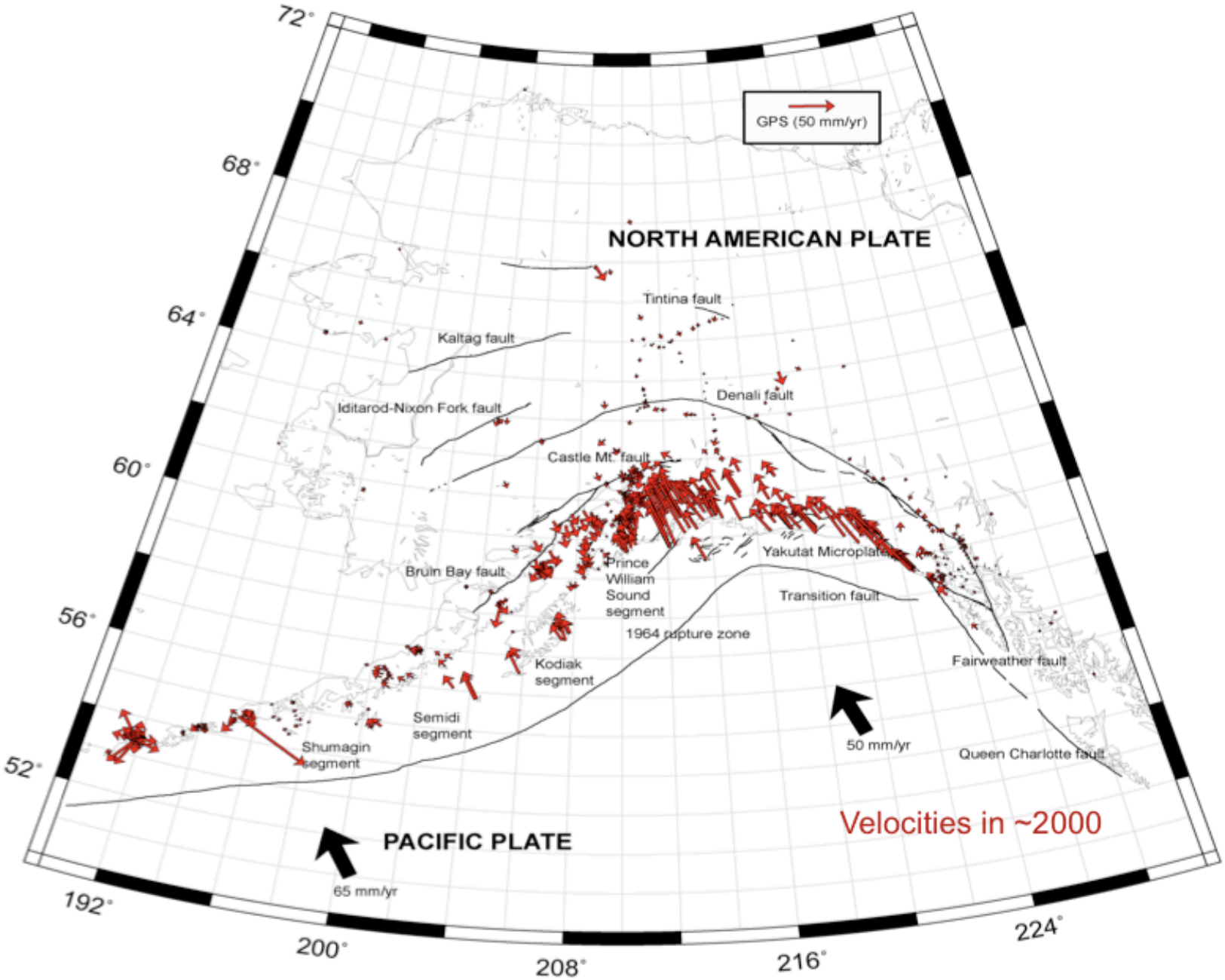
GPS (50 mm/yr)
NORTH AMERICAN PLATE
Tintina fault
Kaltag fault
Denali fault
Iditarod-Nixon Fork fault
Castle Mt. fault
Yakutat Microplate
Bruin Bay fault
Prince William Sound segment
Transition fault
1964 rupture zone
Kodiak segment
Fairweather fault
Semidi segment
Shumagin segment
50 mm/yr
Queen Charlotte fault
Velocities in ~2000
PACIFIC PLATE
65 mm/yr
72°
68°
64°
60°
56°
52°
192°
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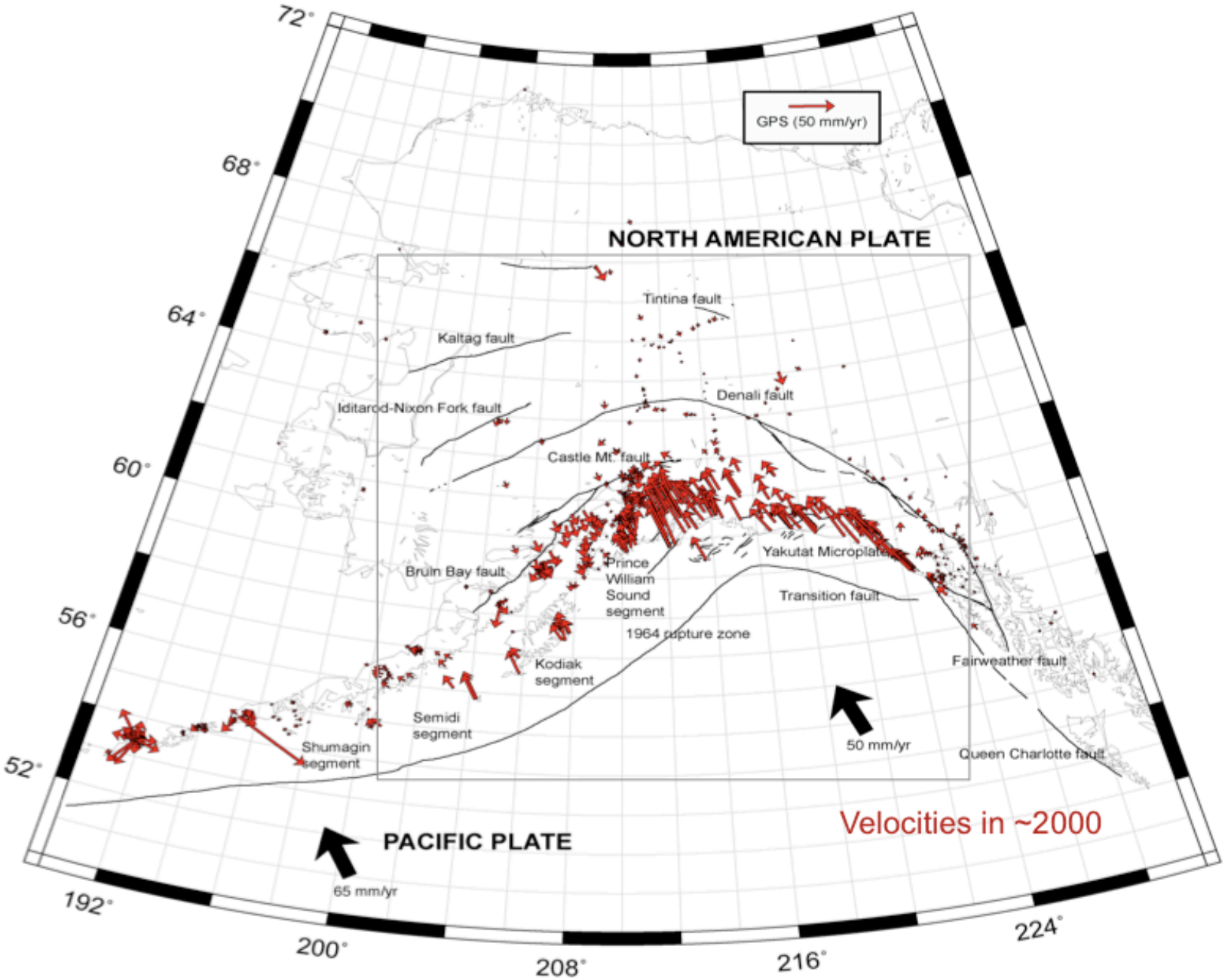
208°
216°
224°


GPS (50 mm/yr)
NORTH AMERICAN PLATE
Tintina fault
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Velocities in ~2000
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72°
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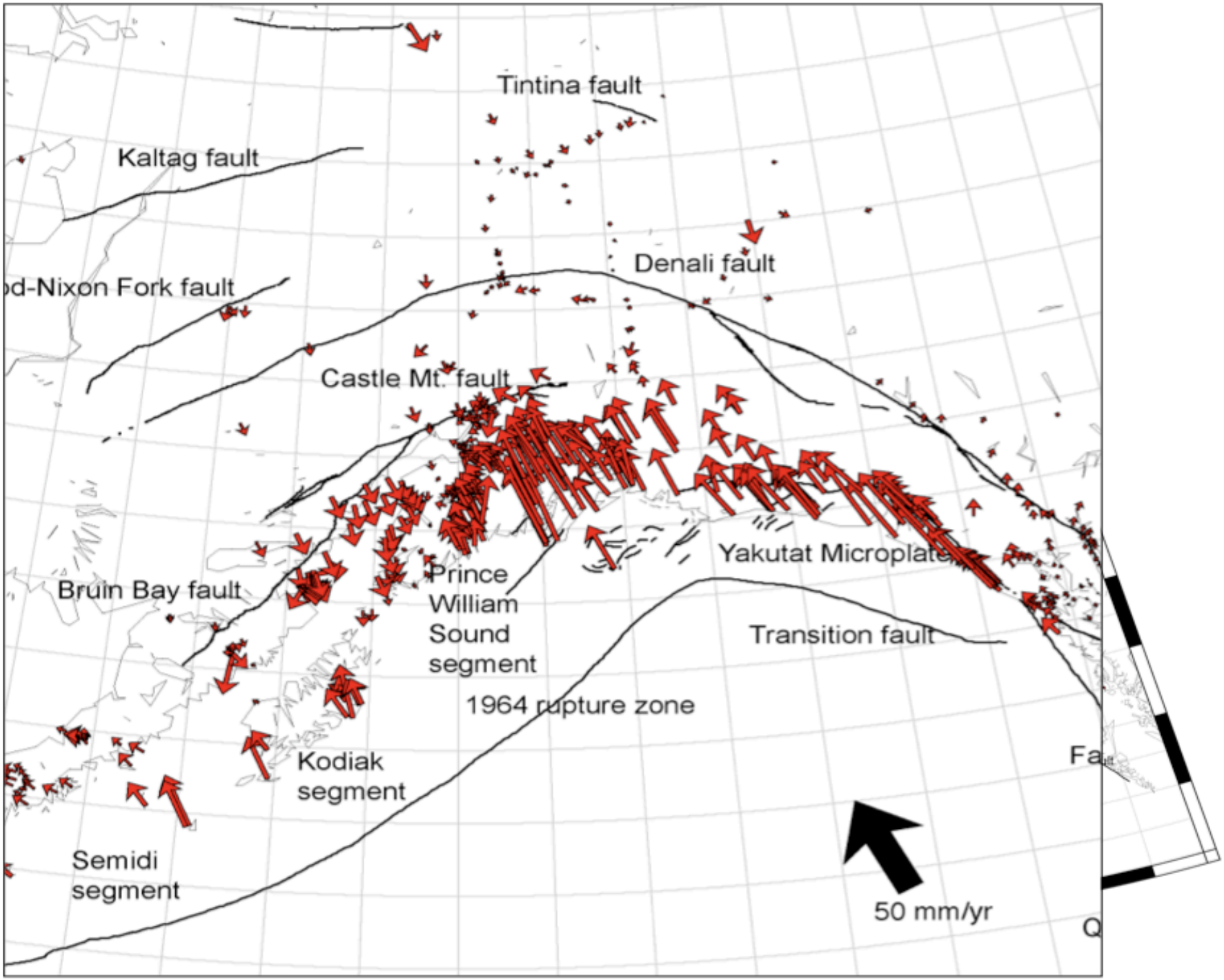
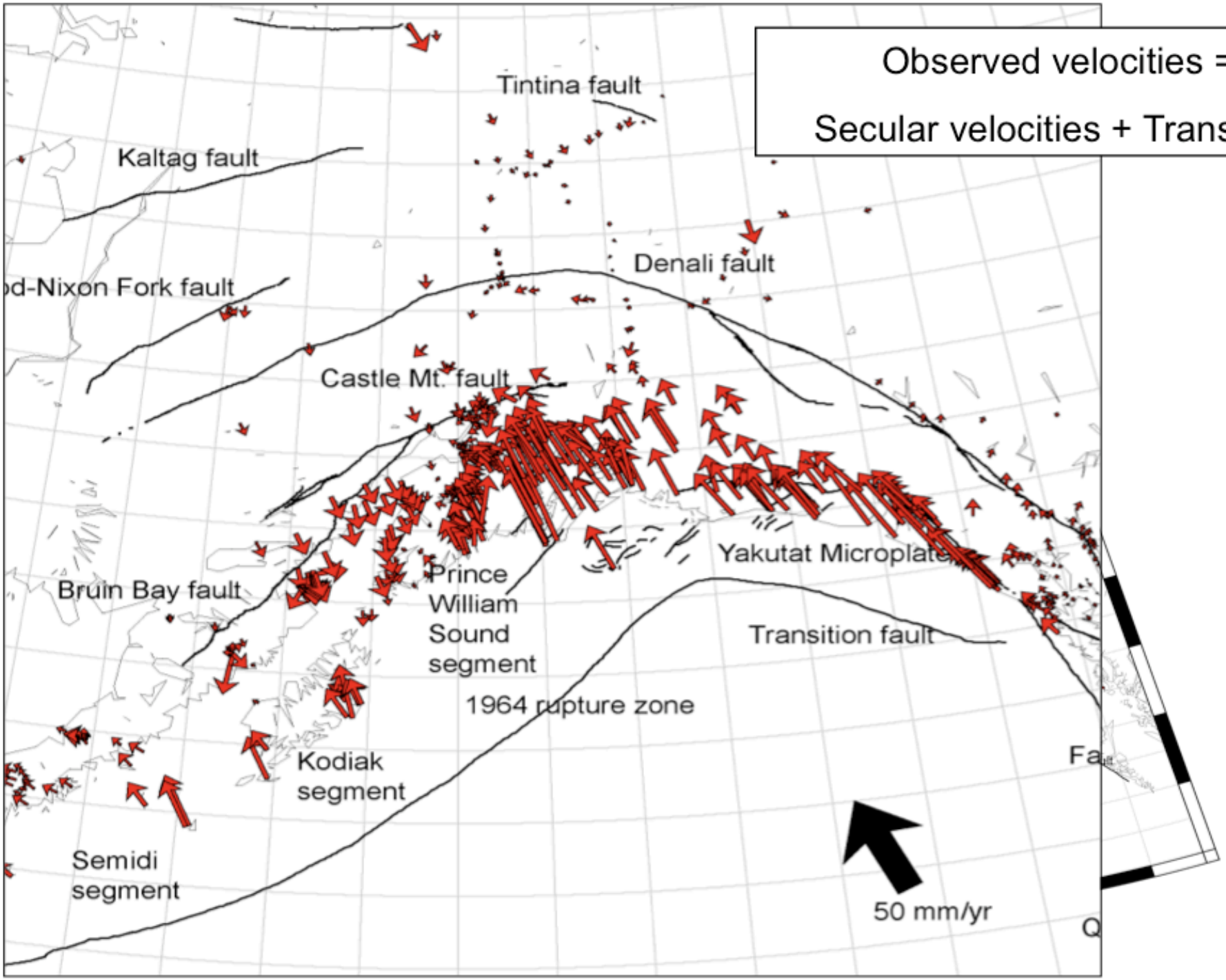

Tintina fault
Kaltag fault
Denali fault
d-Nixon Fork fault
Castle Mt. fault
Yakutat Microplate
Bruin Bay fault
Prince
William
Sound
segment
Transition fault
1964 rupture zone
Kodiak
segment
Semidi
segment
50 mm/yr


Observed velocities =
Secular velocities + Transients
Tintina fault
Kaltag fault
Denali fault
d-Nixon Fork fault
Castle Mt. fault
Yakutat Microplate
Bruin Bay fault
Prince
William
Sound
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Transition fault
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segment
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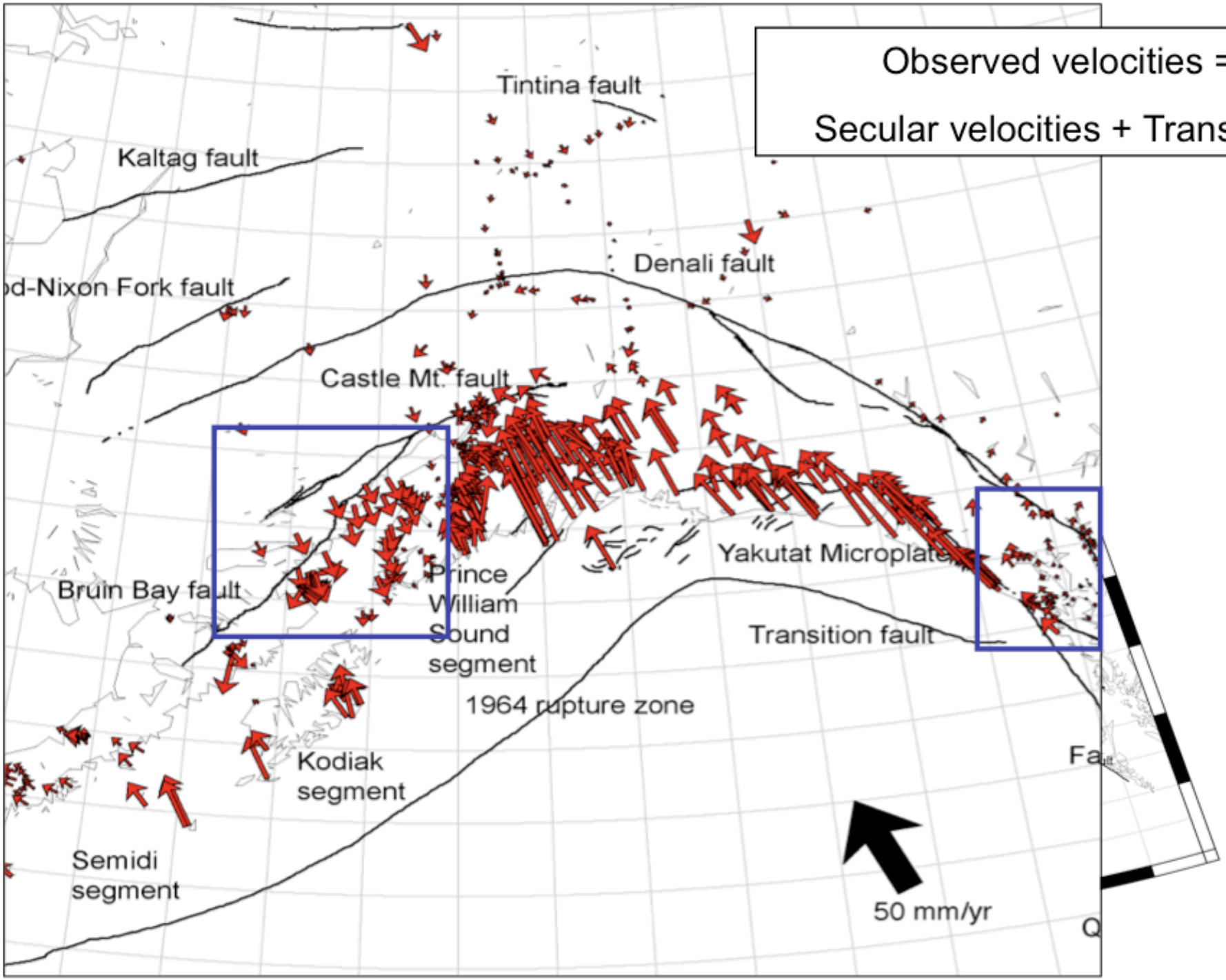
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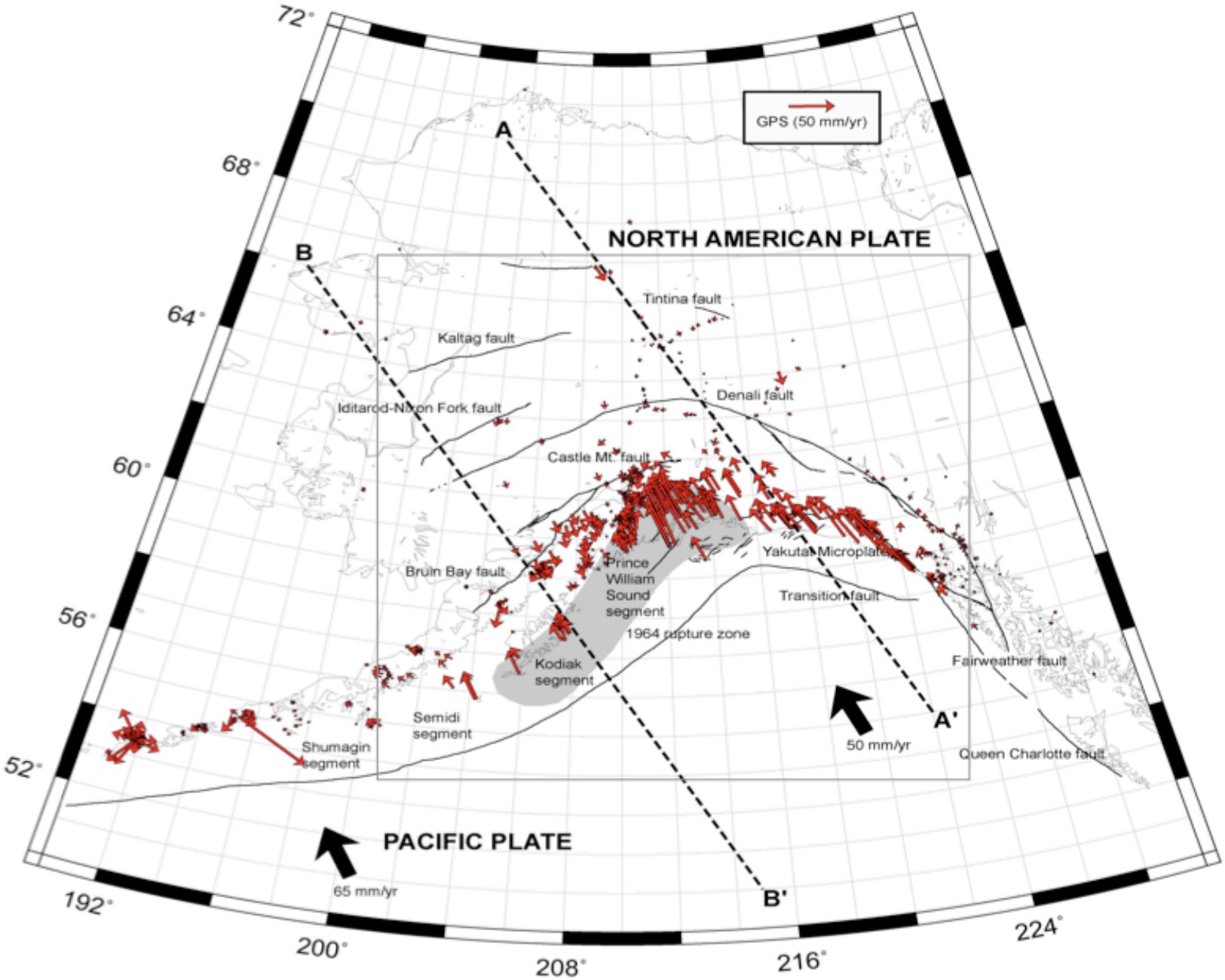
50 mm/yr


GPS (50 mm/yr)
NORTH AMERICAN PLATE
PACIFIC PLATE
A
A'
B
B'
Tintina fault
Kaltag fault
Denali fault
Iditarod-Nixon Fork fault
Castle Mt. fault
Bruin Bay fault
Prince William Sound segment
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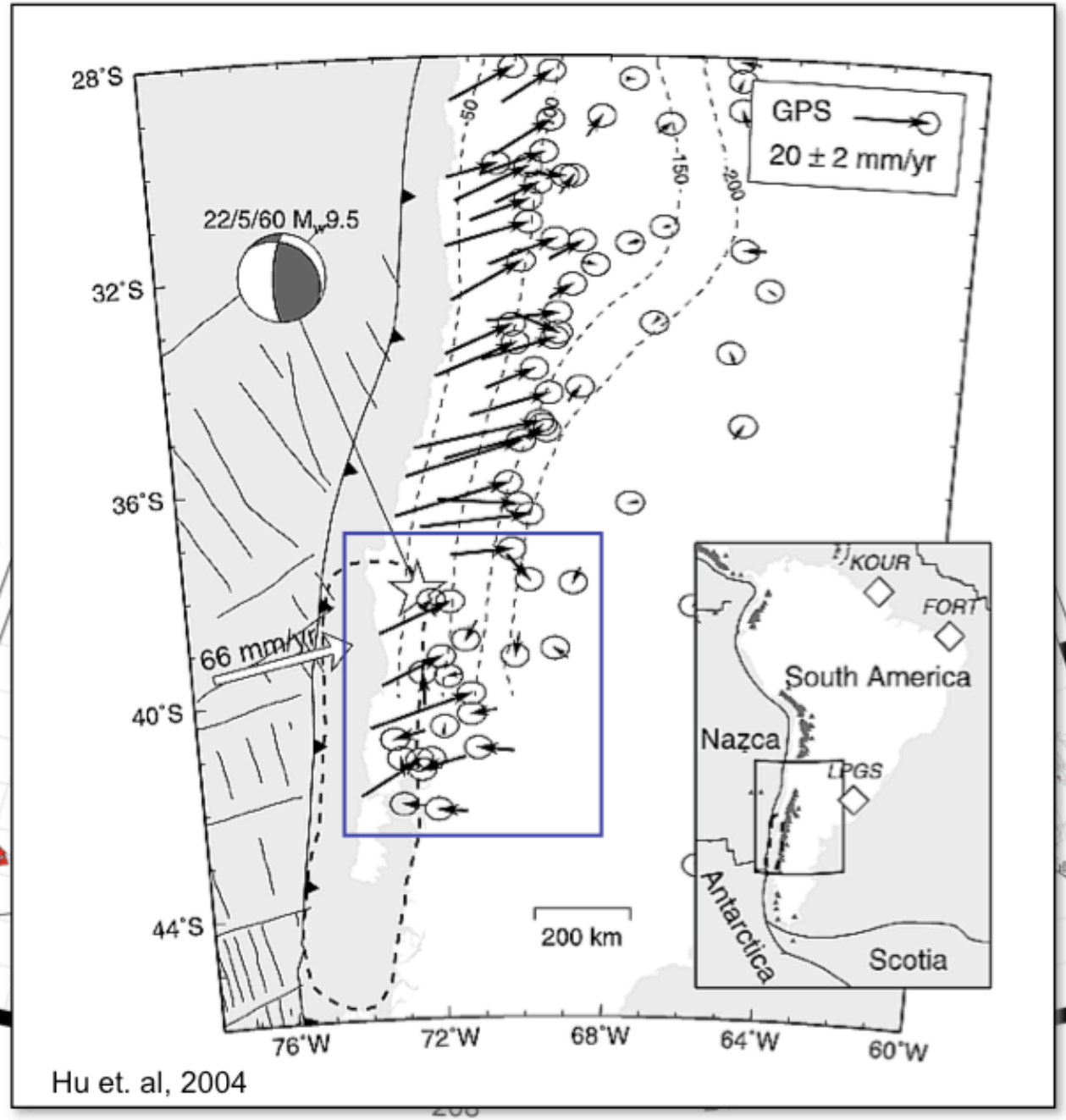

28°S
32°S
36°S
40°S
44°S
76°W
72°W
68°W
64°W
60°W
GPS
20 ± 2 mm/yr
22/5/60 M_w 9.5
66 mm/yr
200 km
KOUR
FORT
South America
Nazca
LPGS
Antarctica
Scotia

Hu et. al, 2004

Modeling Approach

Objective: Calculate the elastostatic response of an earthquake in a viscoelastic medium

- Initial BVP

$$\sigma_{ij,j} + f_i = 0 \tag{1}$$

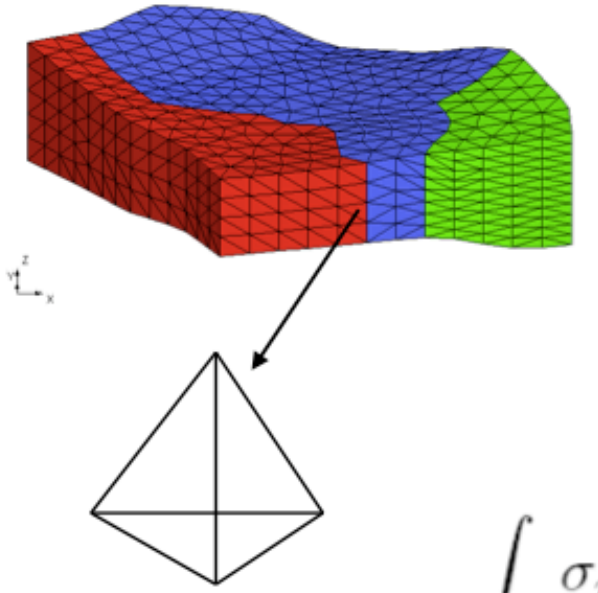
$$\epsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{2}$$

$$\epsilon_{ij} = \epsilon_{ij}^E + \epsilon_{ij}^V$$

$$\dot{\epsilon_{ij}} = \frac{\dot{\sigma_{ij}}}{2\mu} + A\sigma_{ij}^n exp^{-\frac{Q}{RT}}$$

$$\dot{\epsilon_{ij}} = \frac{\dot{\sigma_{ij}}}{2\mu} + \frac{\sigma_{ij}}{2\eta} \tag{3}$$

- We want to find the displacement $u(\boldsymbol{x}, t)$ and a stress tensor field $\sigma_{ij}(\boldsymbol{x}, t)$ which satifies the above given some initial and boundary conditions



Finite Element Formulation

$$\int_V (\sigma_{ij,j} + f_i)\, \phi_i dV = 0$$

$$\int_V \sigma_{ij,j}\phi_i dV + \int_V \sigma_{ij}\phi_{i,j} dV = \int_S \sigma_{ij}\phi_i n_i dS$$

$$\sum_{elements} \left(\int_{V^e} \frac{1}{2}\sigma_{ij}(\phi_{i,j} + \phi_{j,i}) dV - \int_{S_T^e} T_i \phi_i dS - \int_{V^e} f_i \phi_i dV \right) = 0$$

$$K_e^{n+1} U_e^{n+1} = F_e^{n+1}$$

K_e^{n+1} depends on Δt and F_e^{n+1} depends on Δt and σ^n where

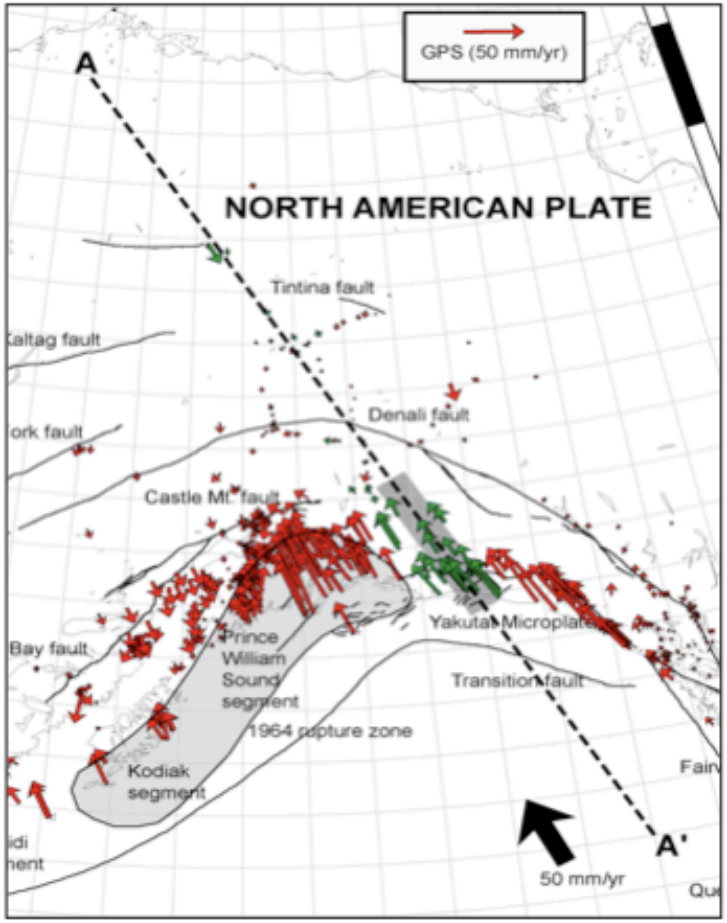
$$\sigma^{n+1} = f(\Delta t, \epsilon^{n+1}, \epsilon^n, \sigma^n)$$

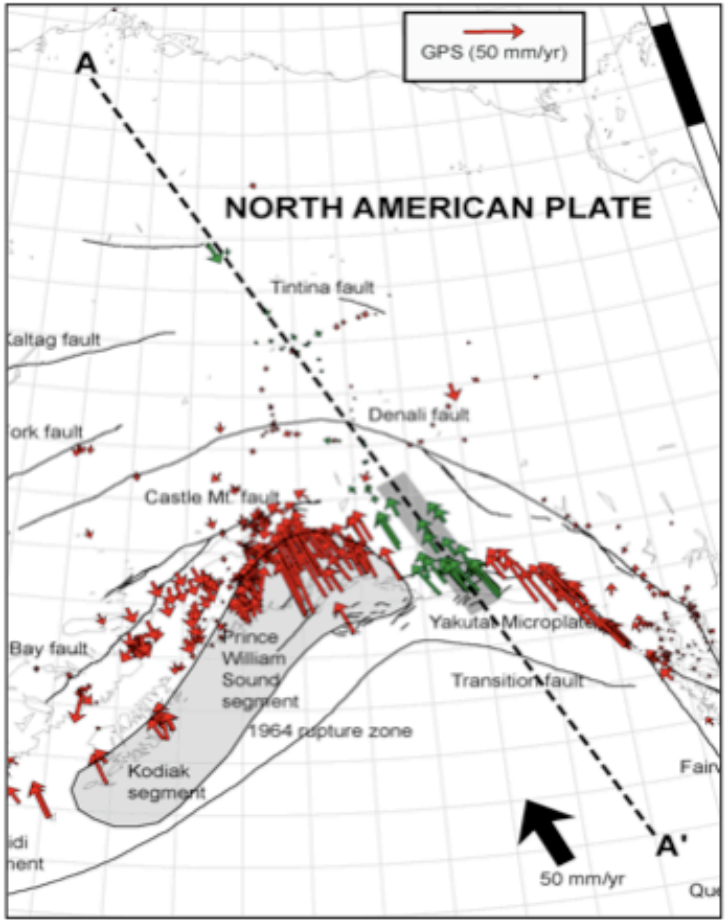
Faults

- Split nodes (Melosh and Raefsky, 1981)
  - Adds additional terms to the RHS (i.e., [K] doesn't change and remains SPD)
  - Conjugate gradient works well

- Cohesive (zero volume) elements and Lagrange Multipliers (to enforce constraints)
  - $$\begin{bmatrix} K & C^T \\ C & 0 \end{bmatrix} \begin{bmatrix} \vec{u} \\ \vec{L} \end{bmatrix} = \begin{bmatrix} \vec{b} \\ \vec{D} \end{bmatrix}$$
  - C is the matrix of direction cosines; D is the magnitude of fault slip and L is the force required to impose the slip
  - System is indefinite
  - GMRES and variants

- Penalty Method (e.g. nodes connected to each other via springs)
  - Matrix is ill conditioned


GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt. fault
Prince
William
Sound
segment
1964 rupture zone
Kodiak
segment
Yakutat Microplate
Transition fault
A'
50 mm/yr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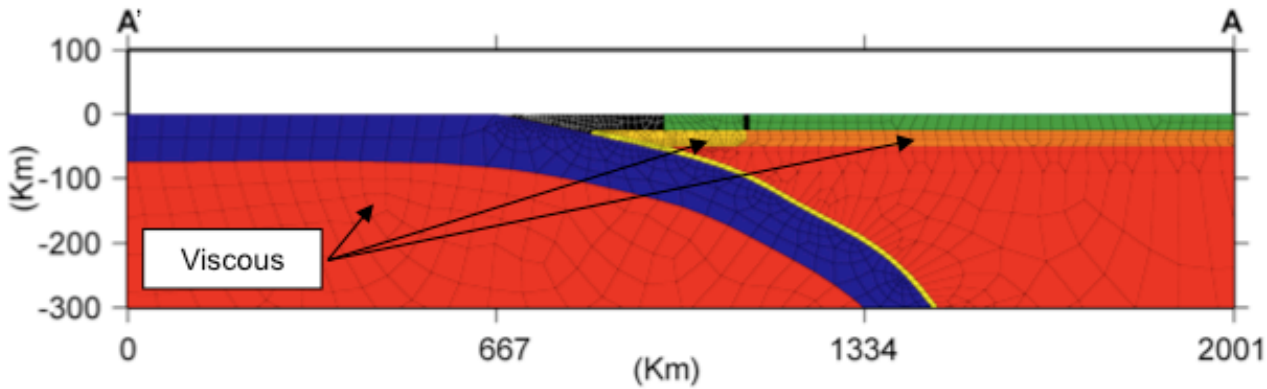
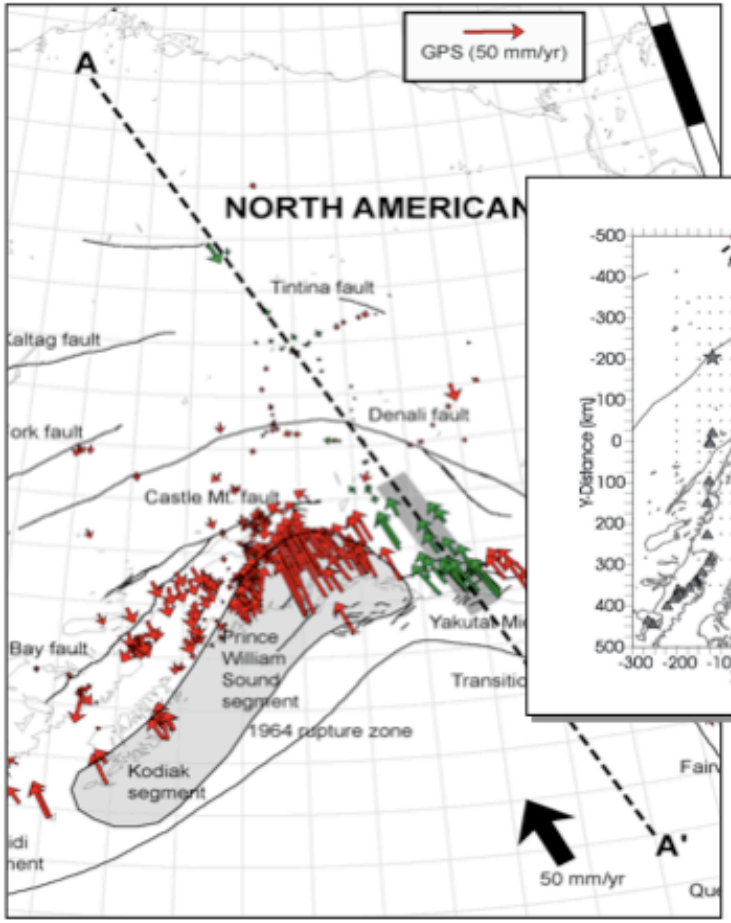
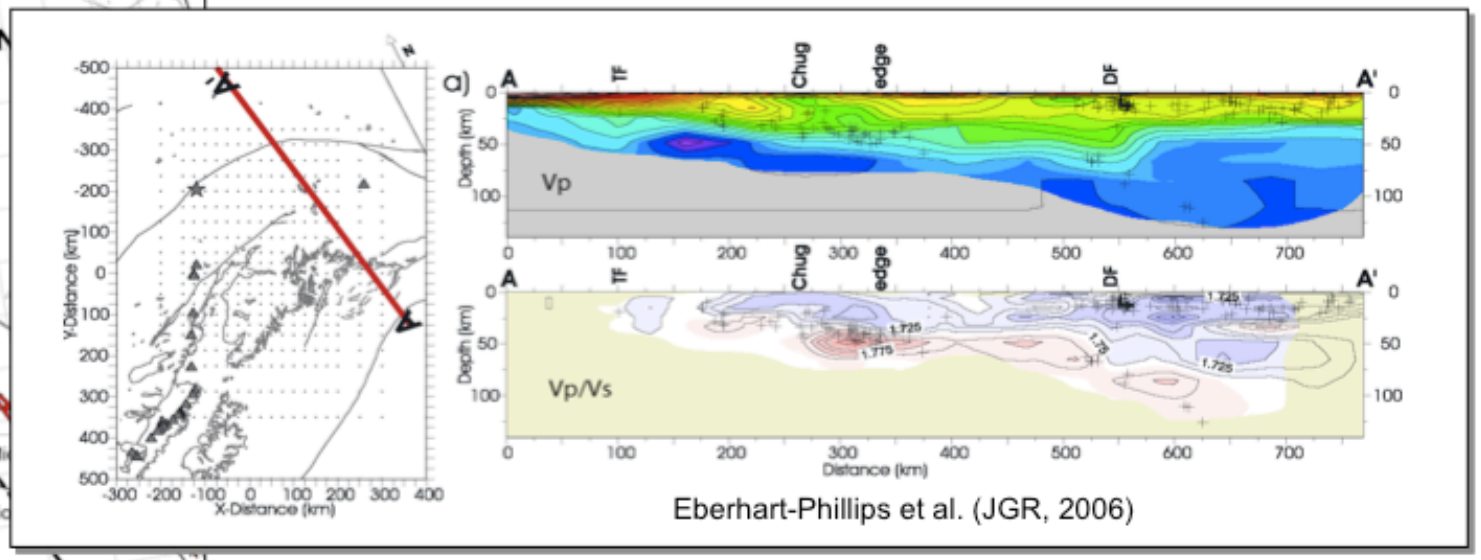
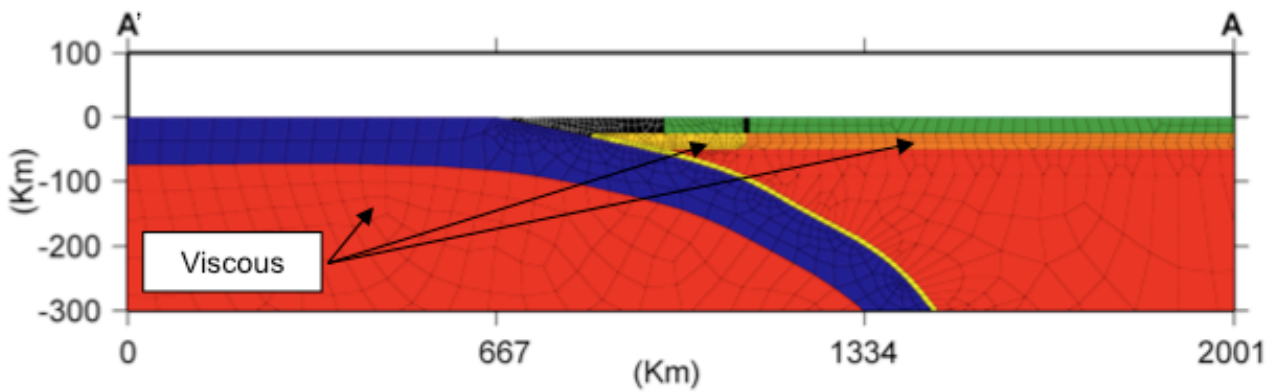
1964 rupture zone
Kodiak
segment
Yakutat Microplate
Transition fault
A'
50 mm/yr

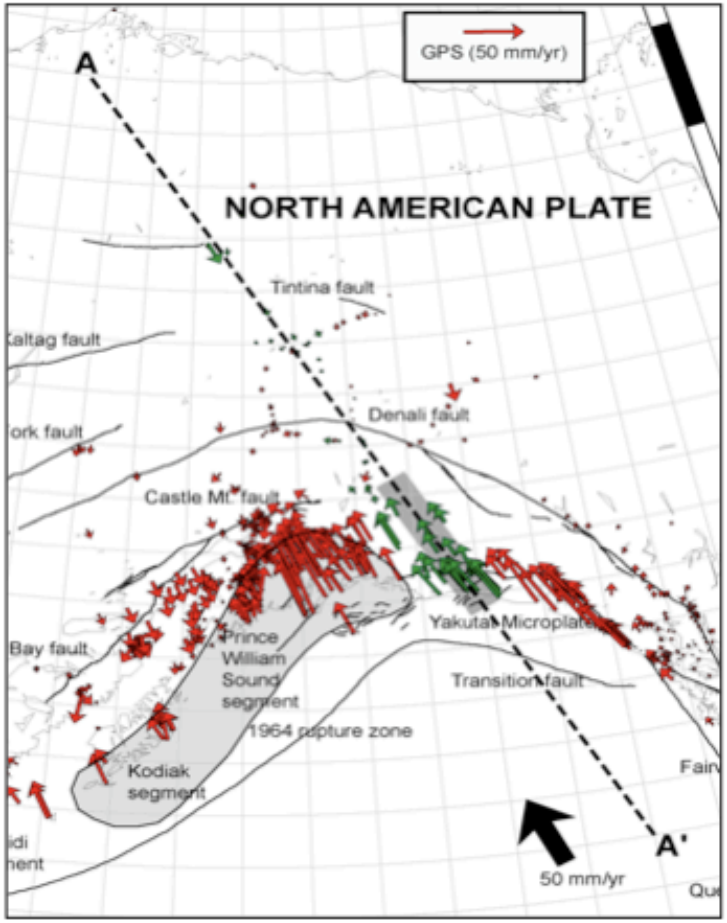

A'
A
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)

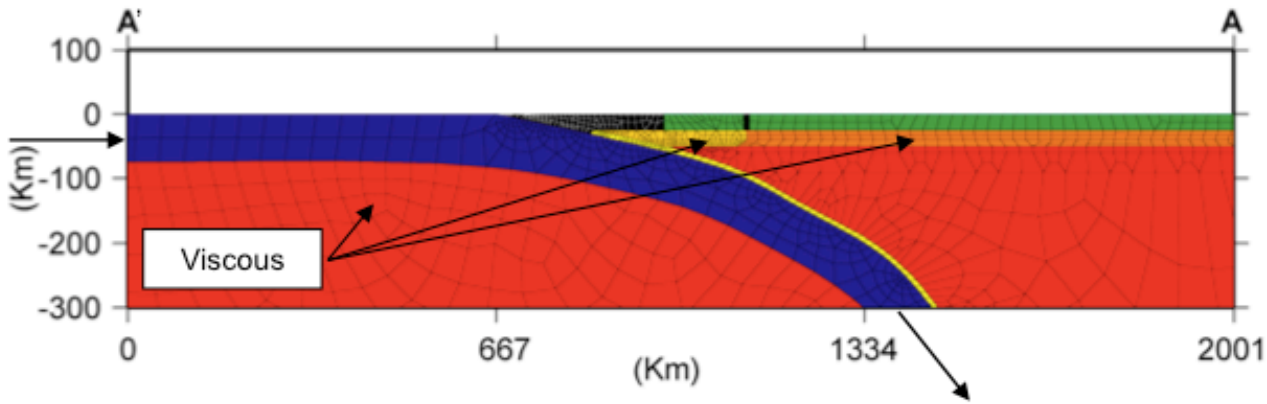


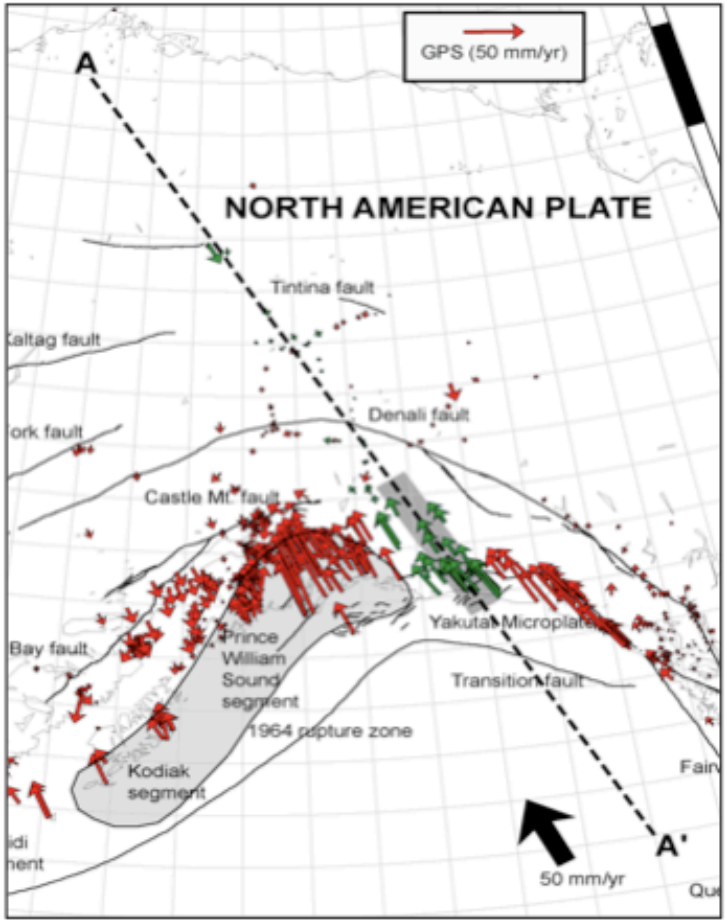


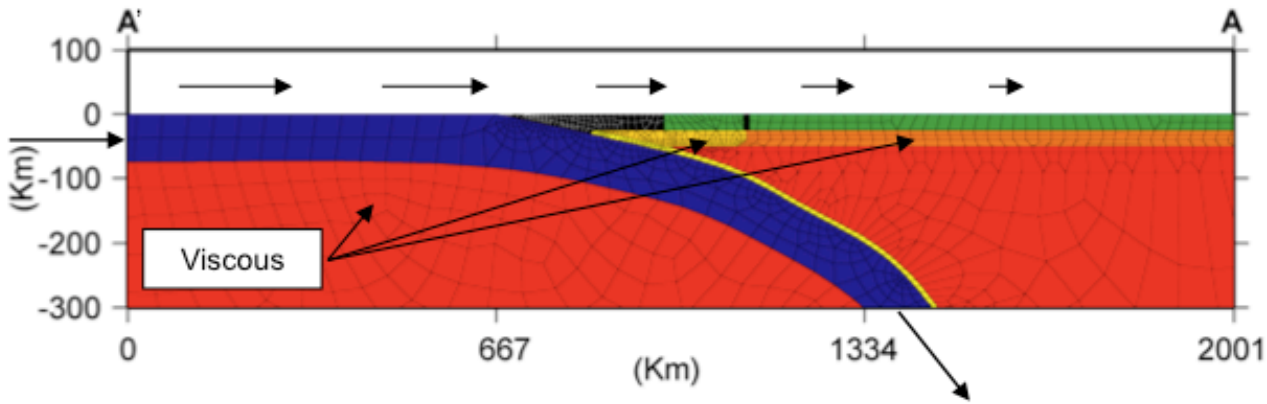
Eberhart-Phillips et al. (JGR, 2006)




GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt. fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Yakutat Microplate
Transition fault
A'
50 mm/yr


A'
A
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)


GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt. fault
Prince
William
Sound
segment
1964 rupture zone
Kodiak
segment
Transition fault
A'
50 mm/yr


A'
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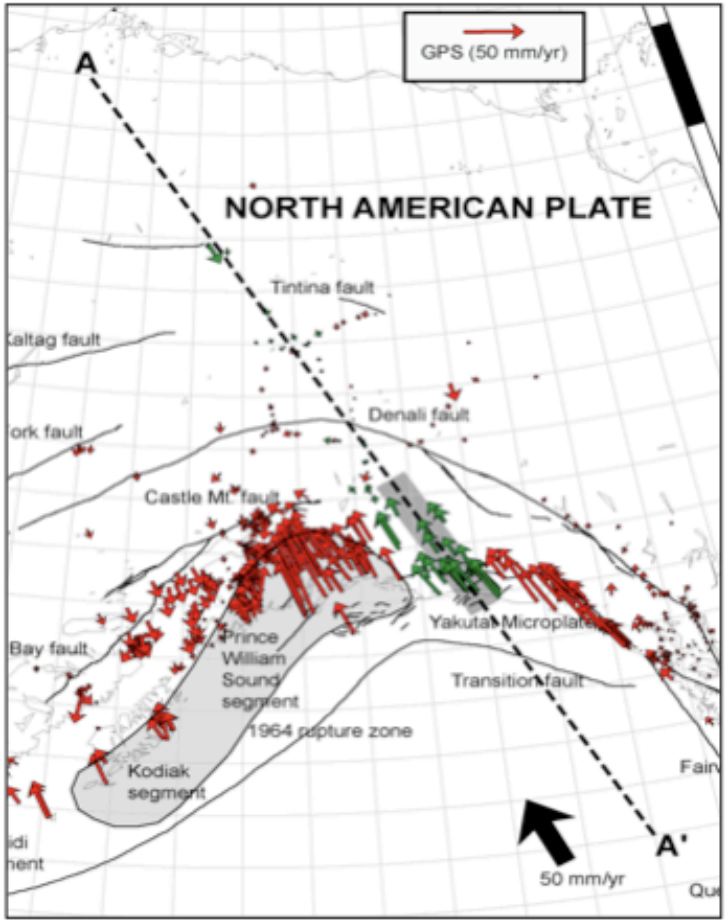
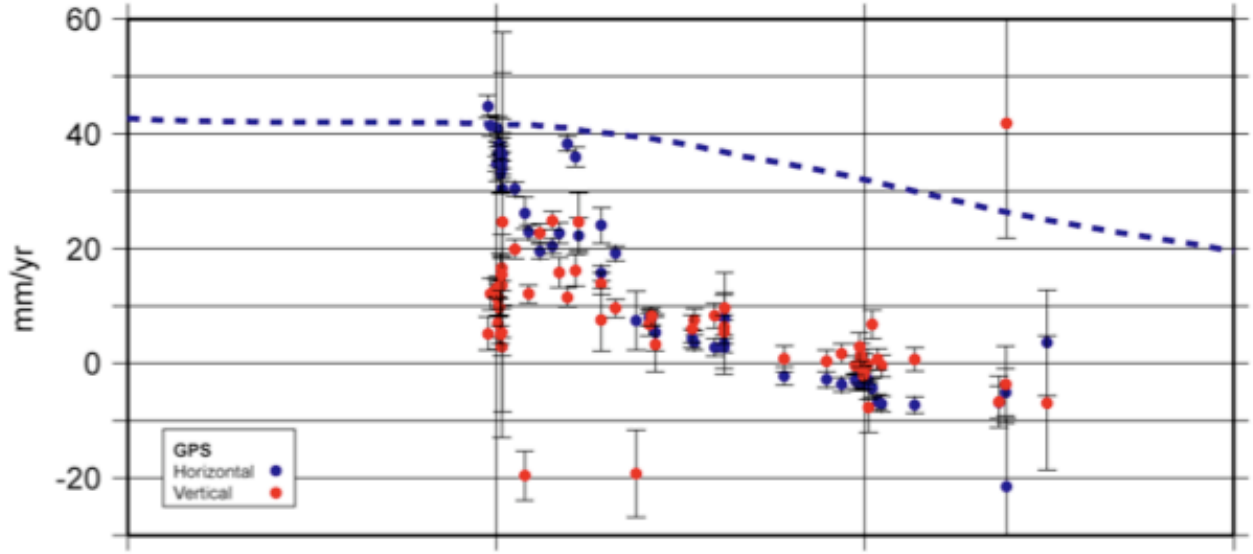
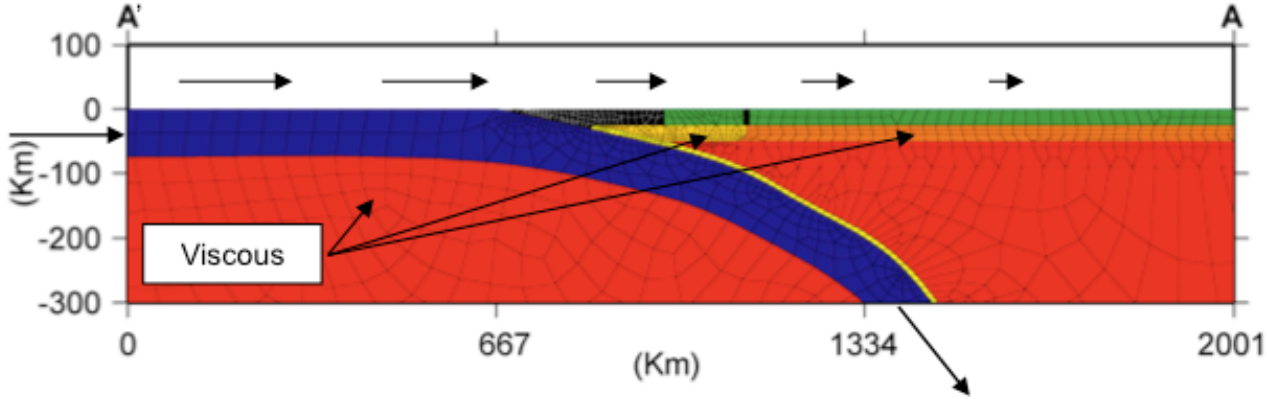
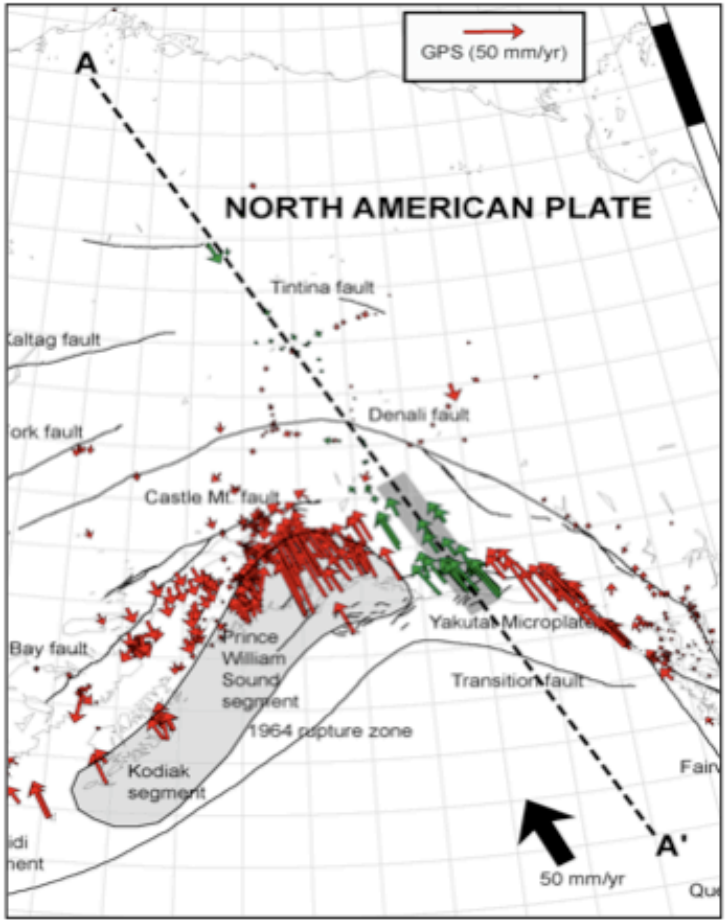
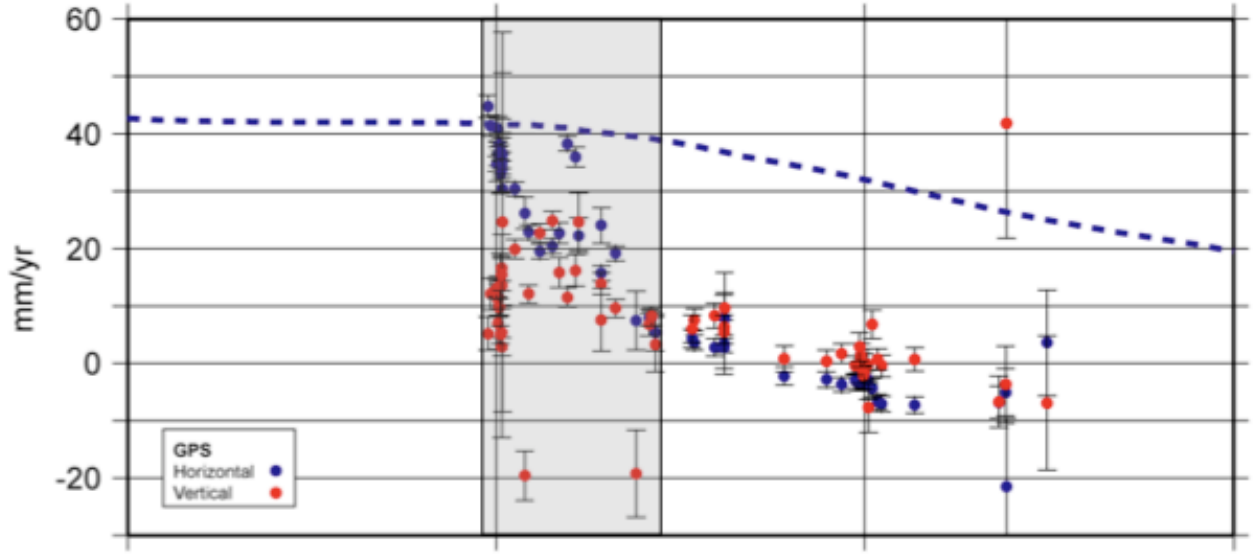
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)

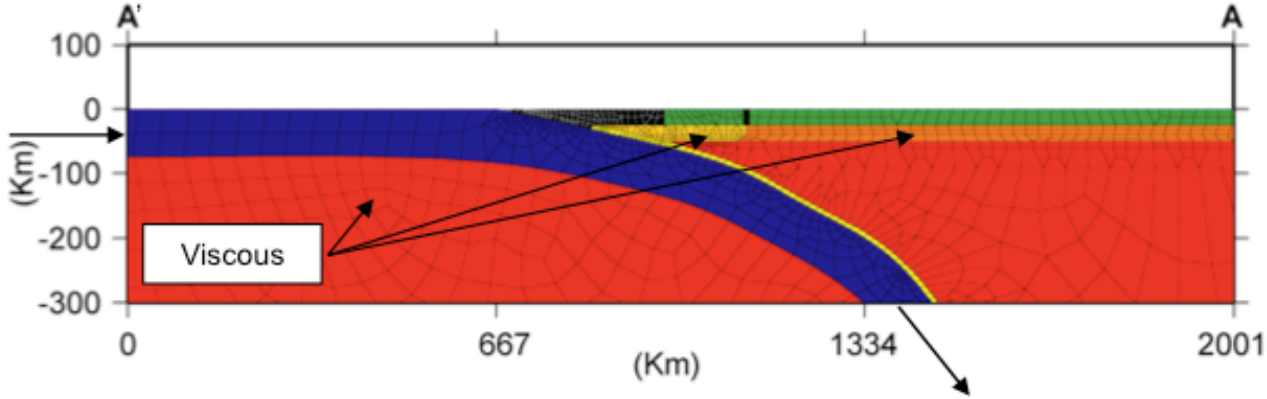

GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Yakutat Microplate
Transition fault
A'
50 mm/yr

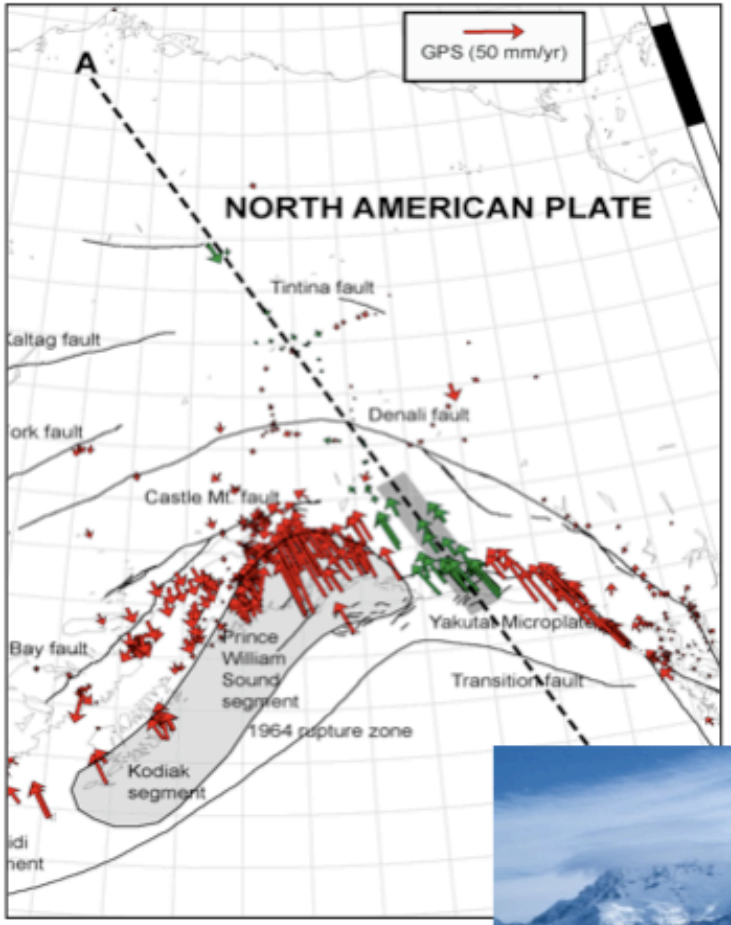

60
40
20
0
-20
mm/yr
GPS
Horizontal
Vertical

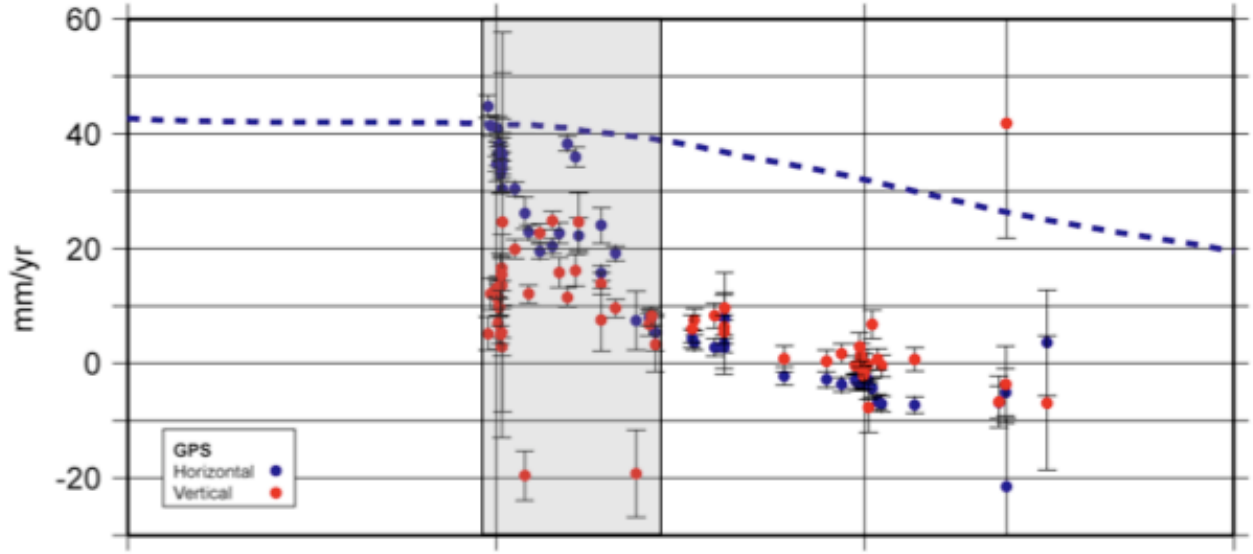

A'
A
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)

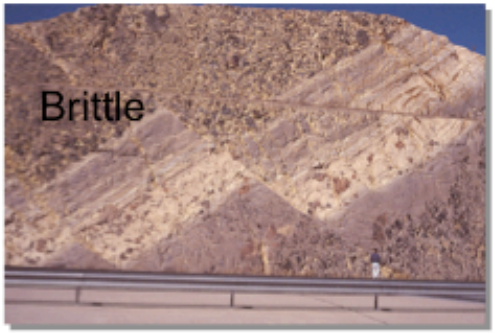

GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt. fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Yakutat Microplate
Transition fault
A'
50 mm/yr


60
40
20
0
-20
mm/yr
GPS
Horizontal
Vertical

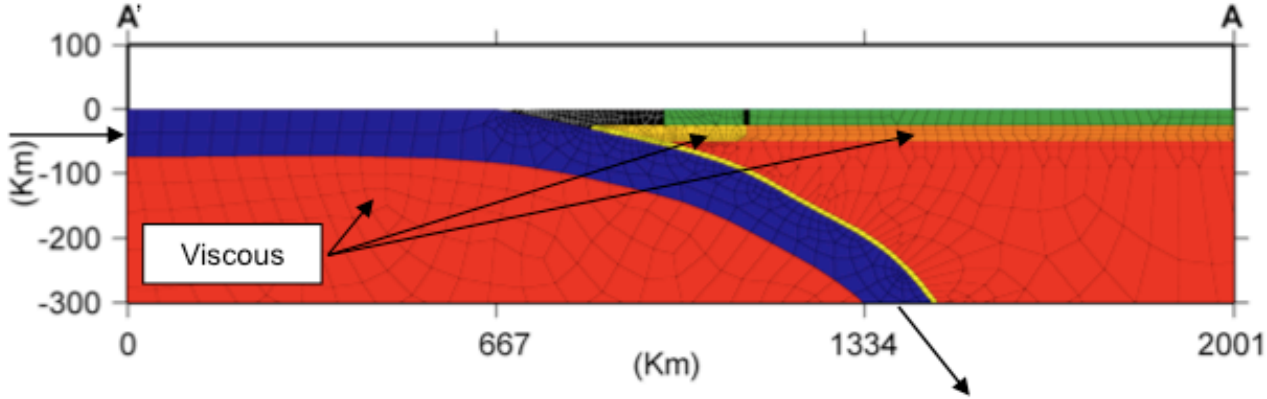

A'
A
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)

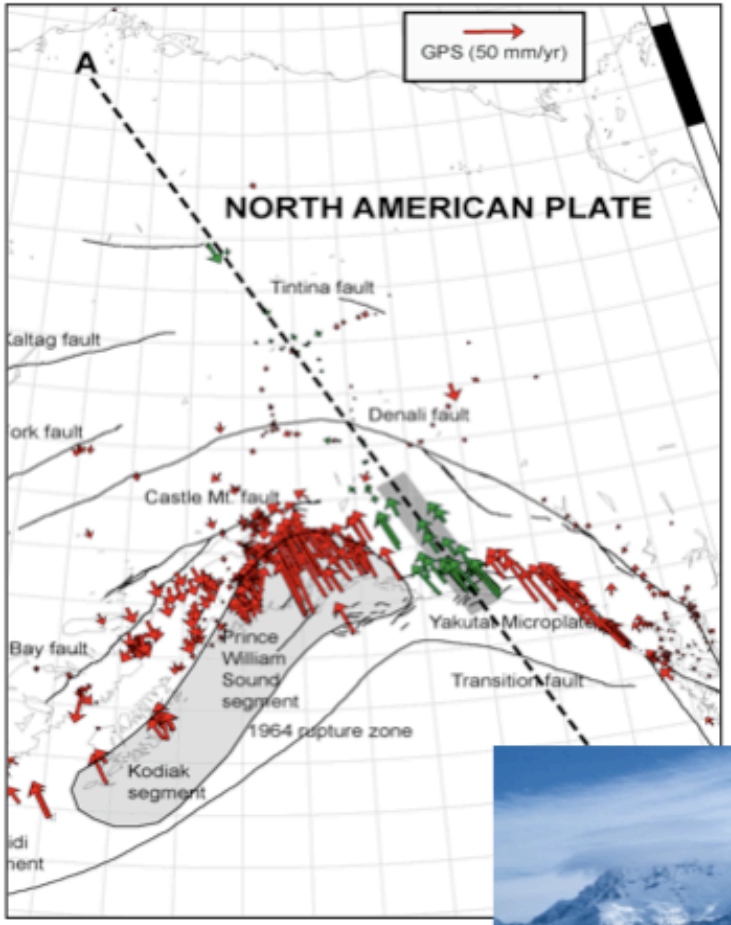

GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt. fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Yakutat Microplate
Transition fault
Bay fault

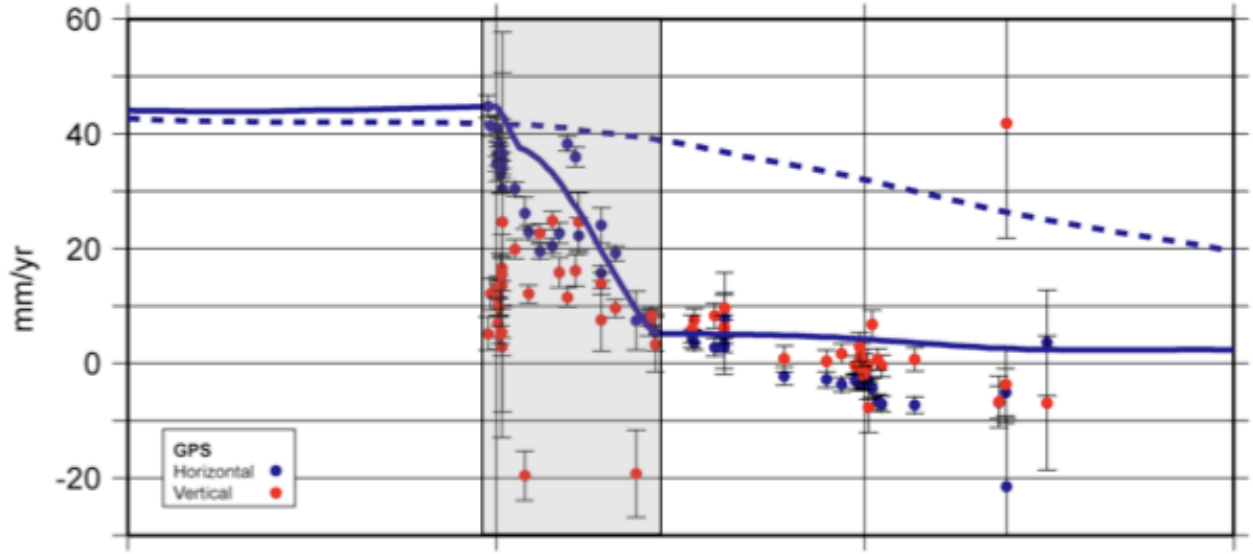

60
40
20
0
-20
mm/yr
GPS
Horizontal
Vertical

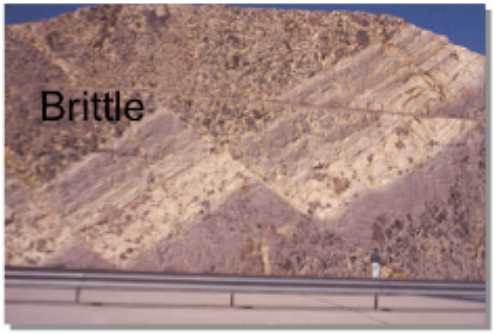

Brittle


Ductile

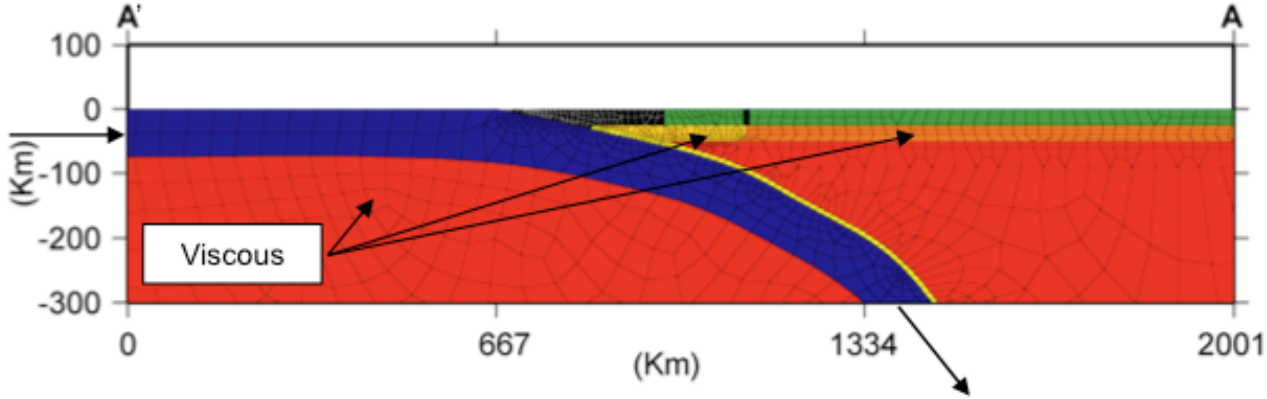

A'
A
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)

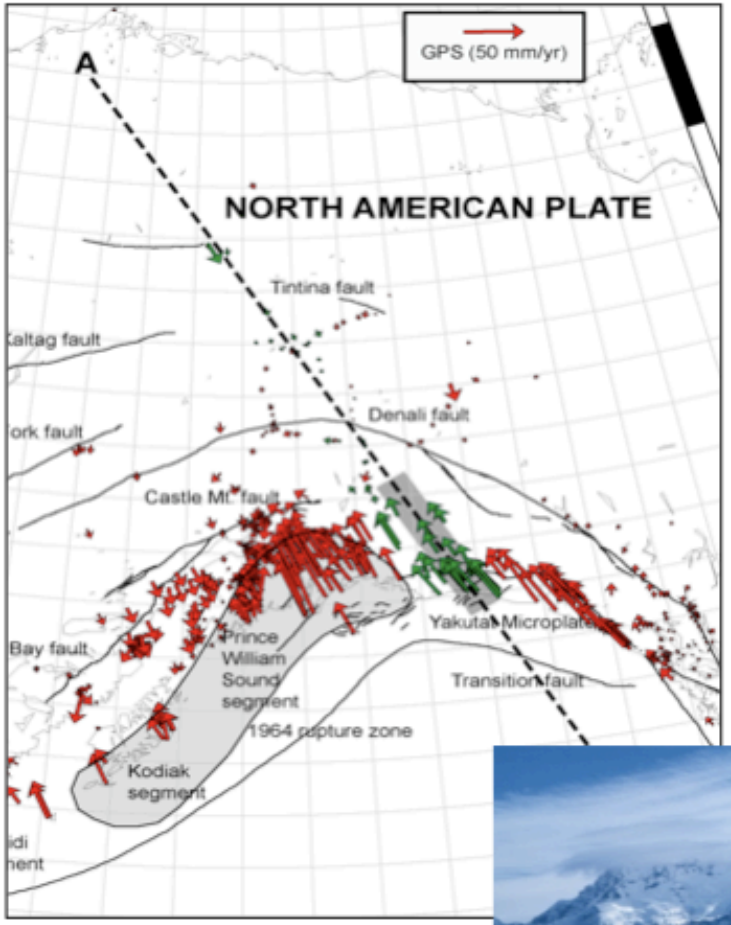

GPS (50 mm/yr)
A
NORTH AMERICAN PLATE
Tintina fault
Denali fault
Castle Mt. fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Yakutat Microplate
Transition fault

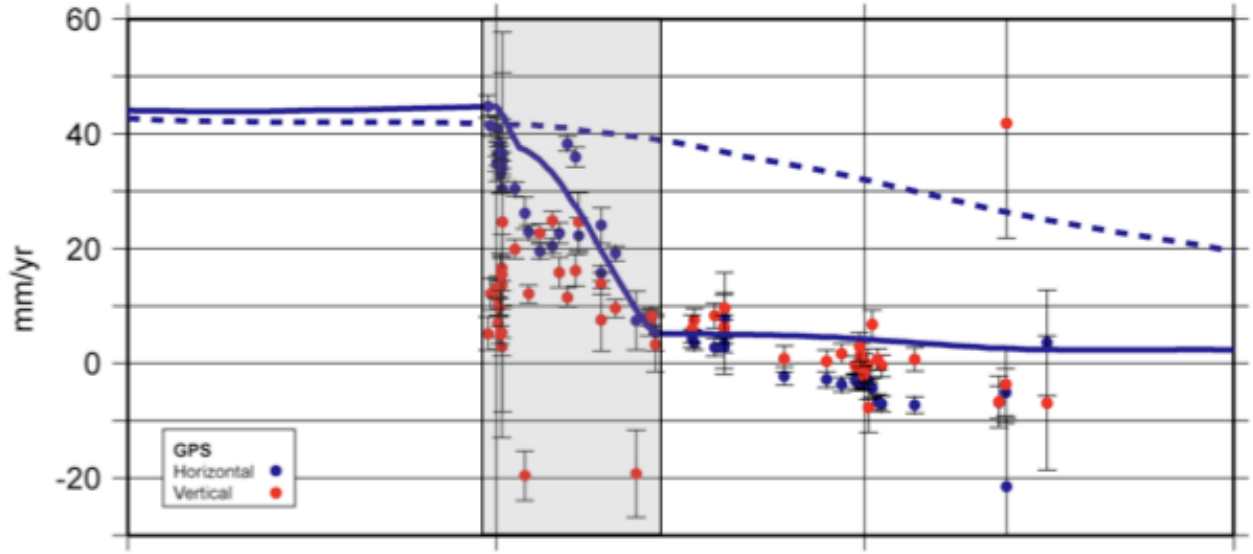

60
40
20
0
-20
mm/yr
GPS
Horizontal
Vertical

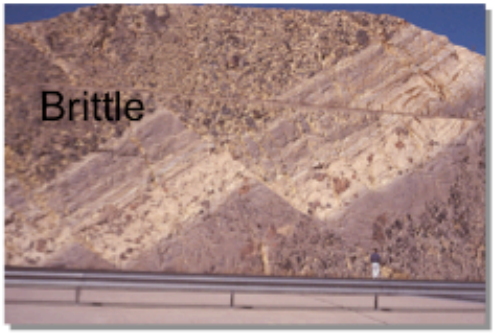

Brittle

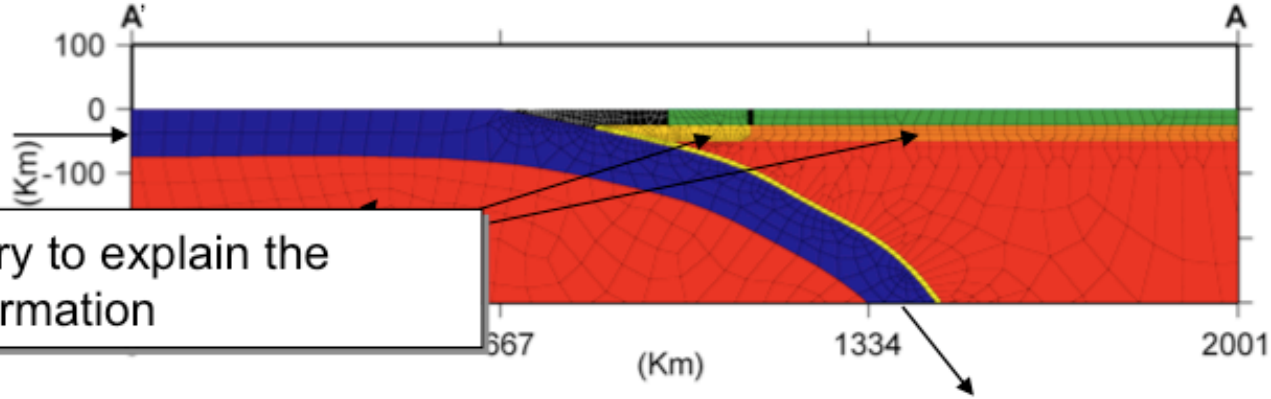

Ductile


A'
A
100
0
-100
-200
-300
(Km)
Viscous
0
667
1334
2001
(Km)

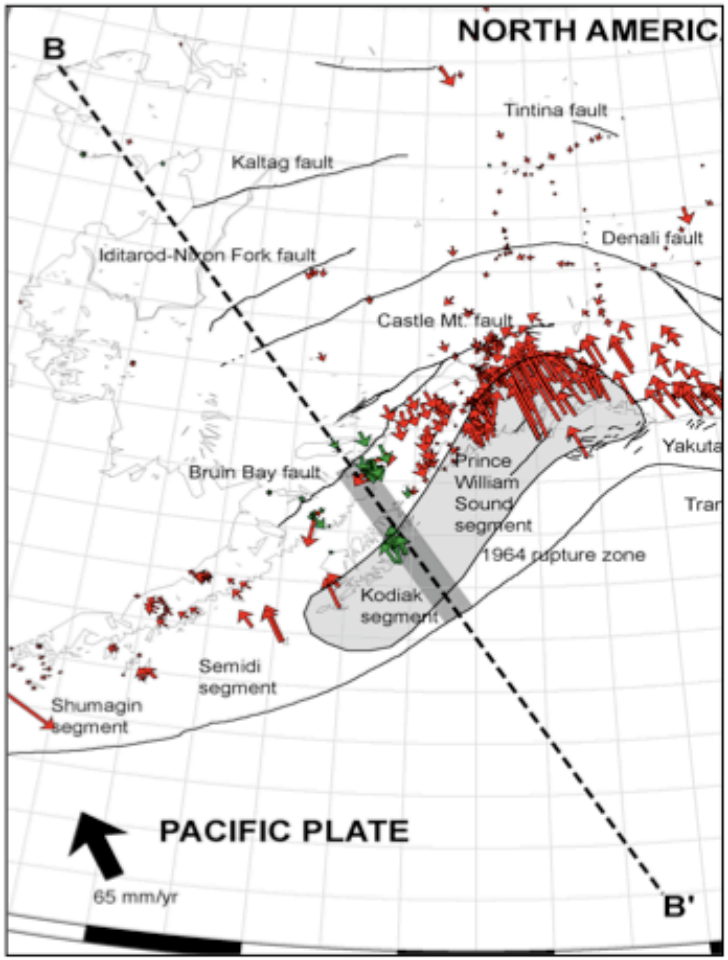


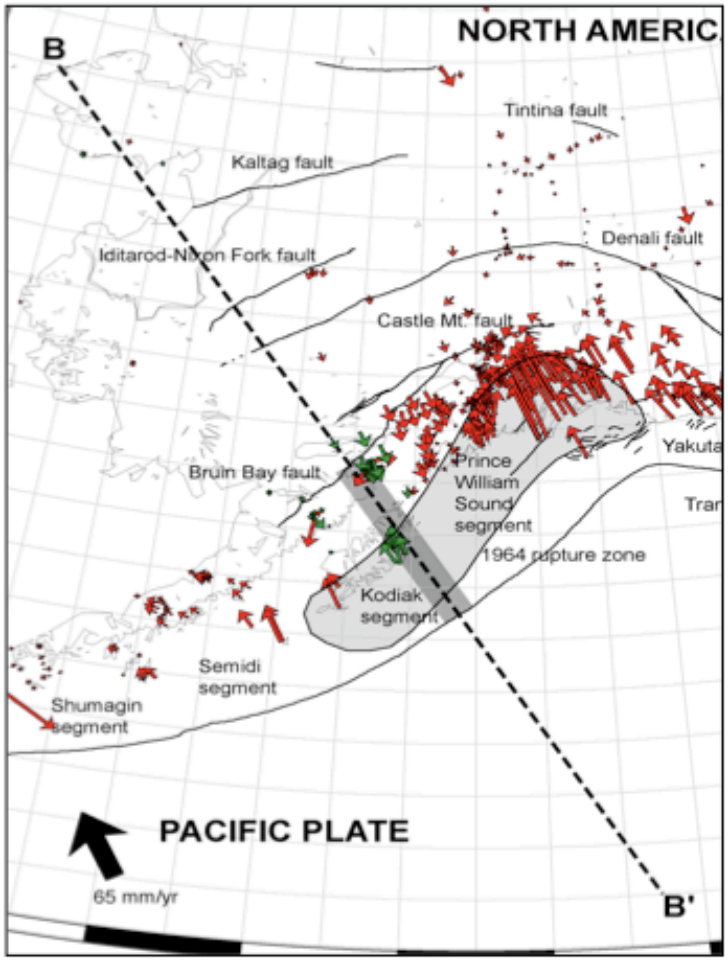






A "weak zone" is necessary to explain the interseismic deformation


NORTH AMERIC
B
Tintina fault
Kaltag fault
Denali fault
Iditarod-Nixon Fork fault
Castle Mt. fault
Yakuta
Bruin Bay fault
Prince
William
Sound
segment
Tran
1964 rupture zone
Kodiak
segment
Semidi
segment
Shumagin
segment
PACIFIC PLATE
65 mm/yr
B'


NORTH AMERIC
B
Tintina fault
Kaltag fault
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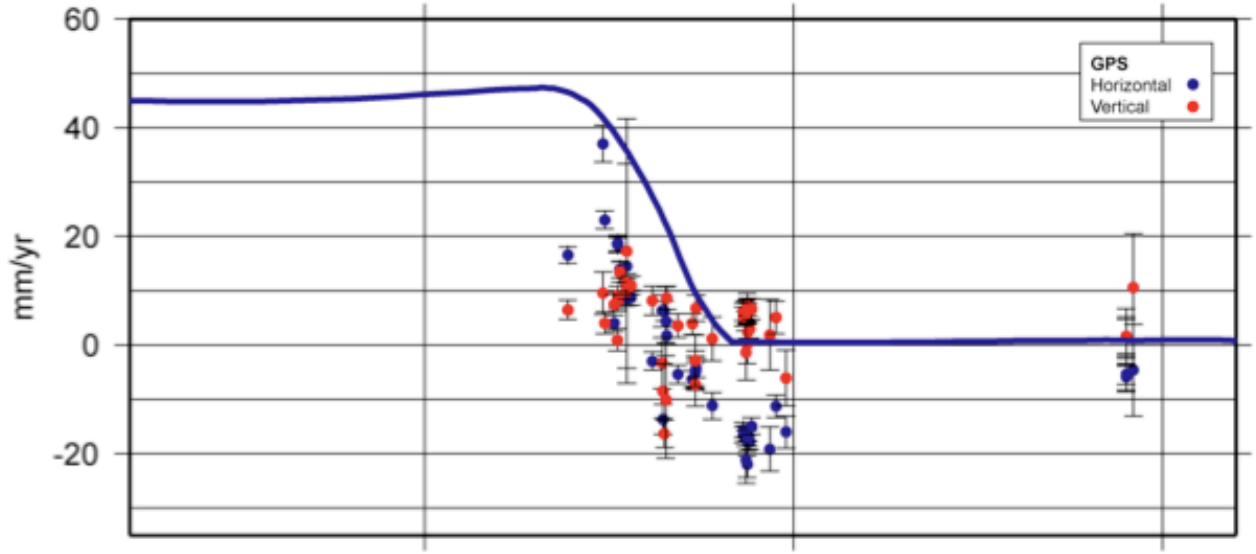
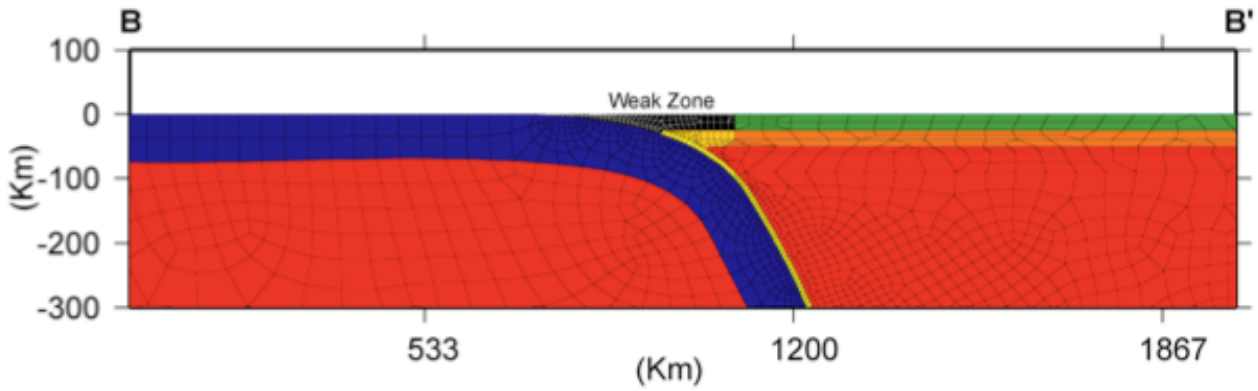
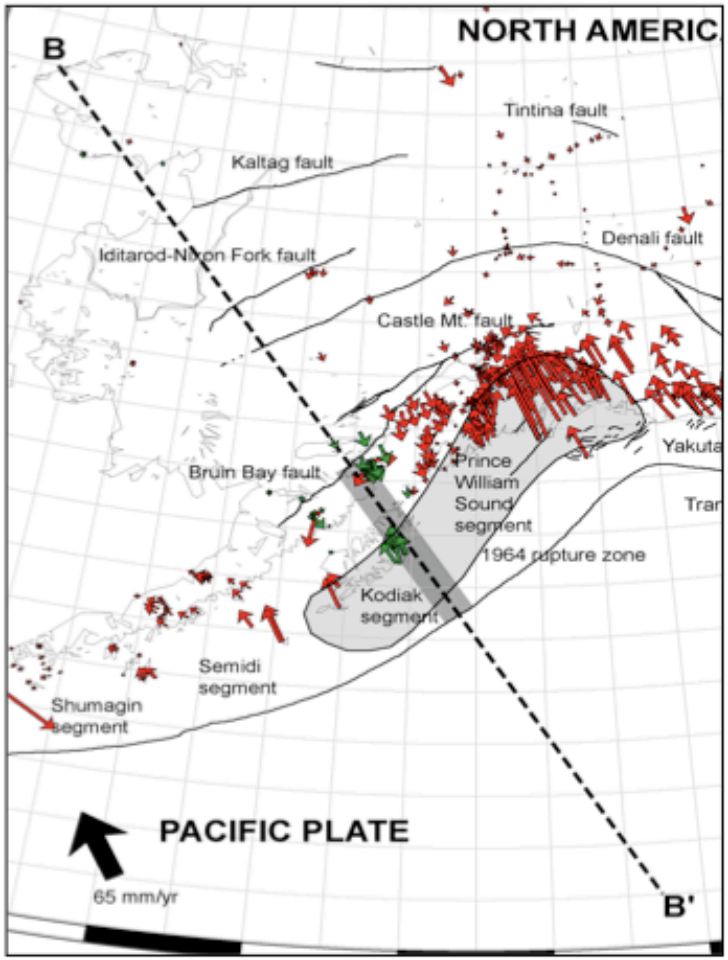
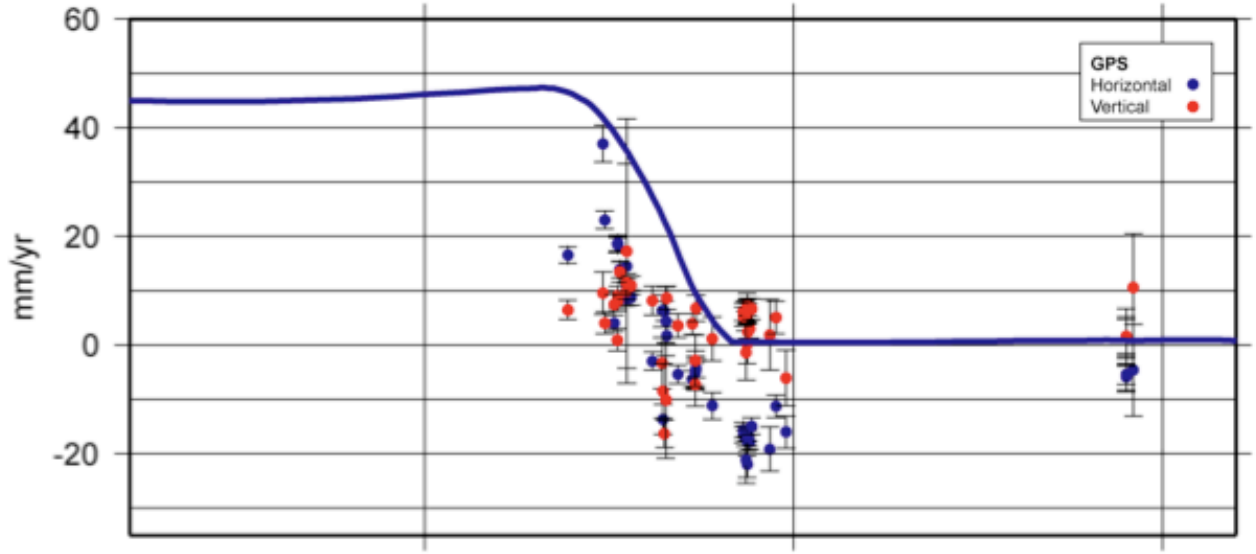
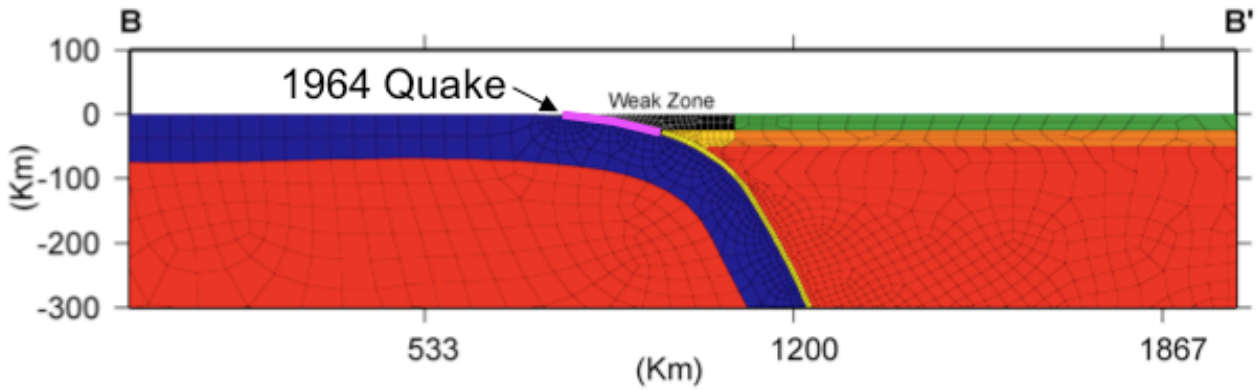
Castle Mt. fault
Bruin Bay fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Semidi segment
Shumagin segment
PACIFIC PLATE
65 mm/yr
B'

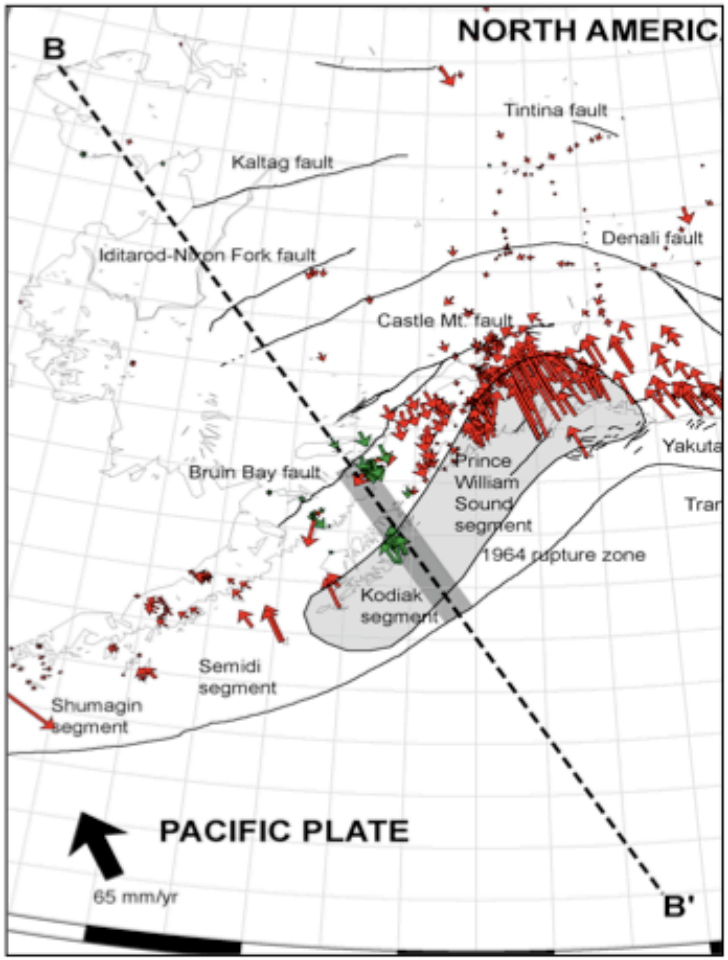

60
40
20
0
-20
mm/yr
GPS
Horizontal
Vertical

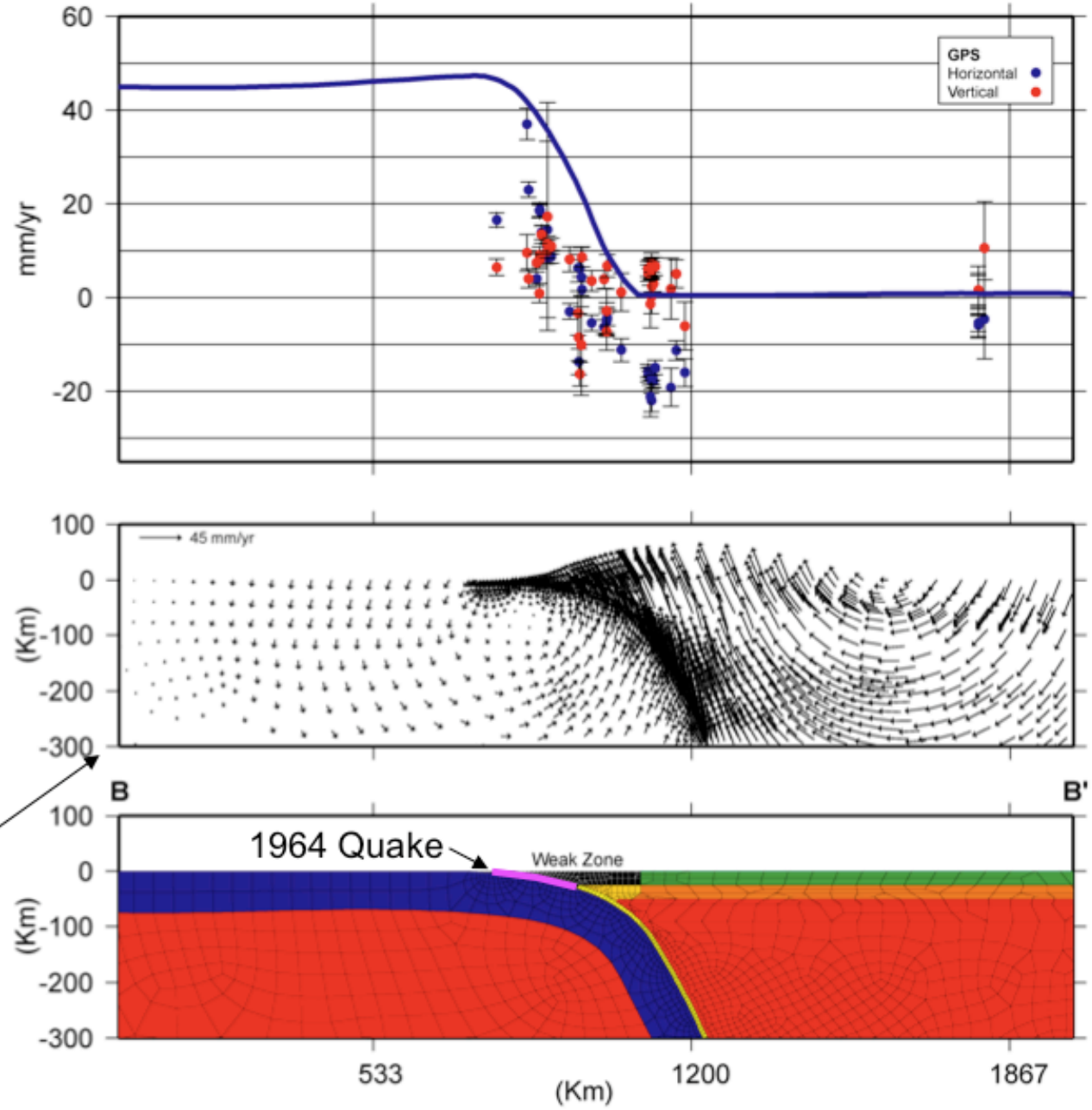

B
B'
100
0
-100
-200
-300
(Km)
Weak Zone
533
1200
1867
(Km)


NORTH AMERIC
B
Tintina fault
Kaltag fault
Denali fault
Iditarod-Nixon Fork fault
Castle Mt. fault
Bruin Bay fault
Prince William Sound segment
1964 rupture zone
Kodiak segment
Semidi segment
Shumagin segment
PACIFIC PLATE
65 mm/yr
B'

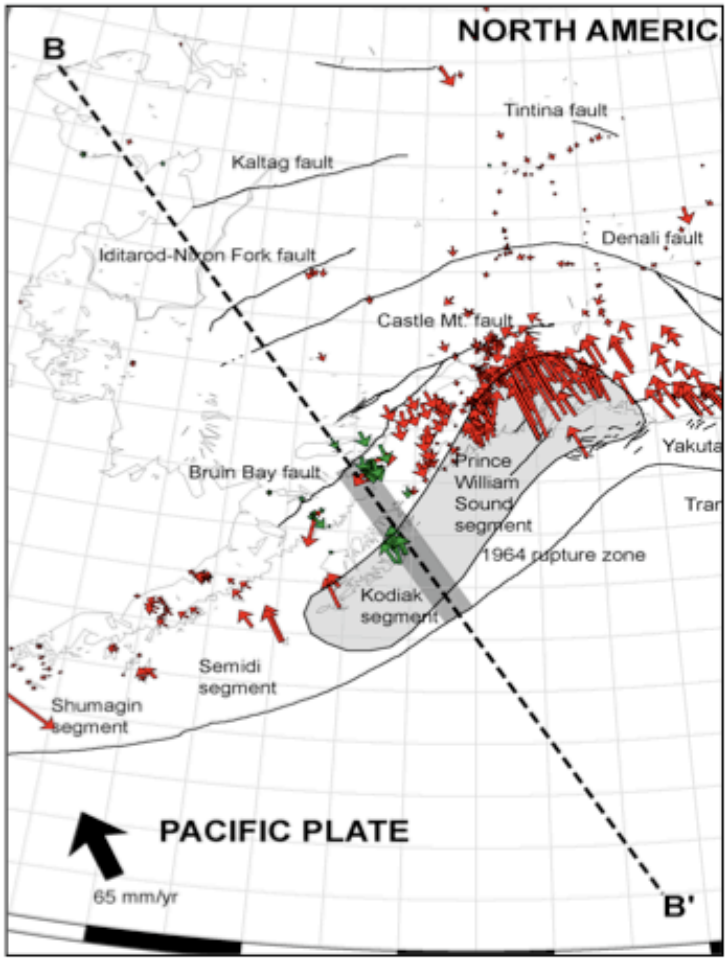

60
40
20
0
-20
mm/yr
GPS
Horizontal
Vertical

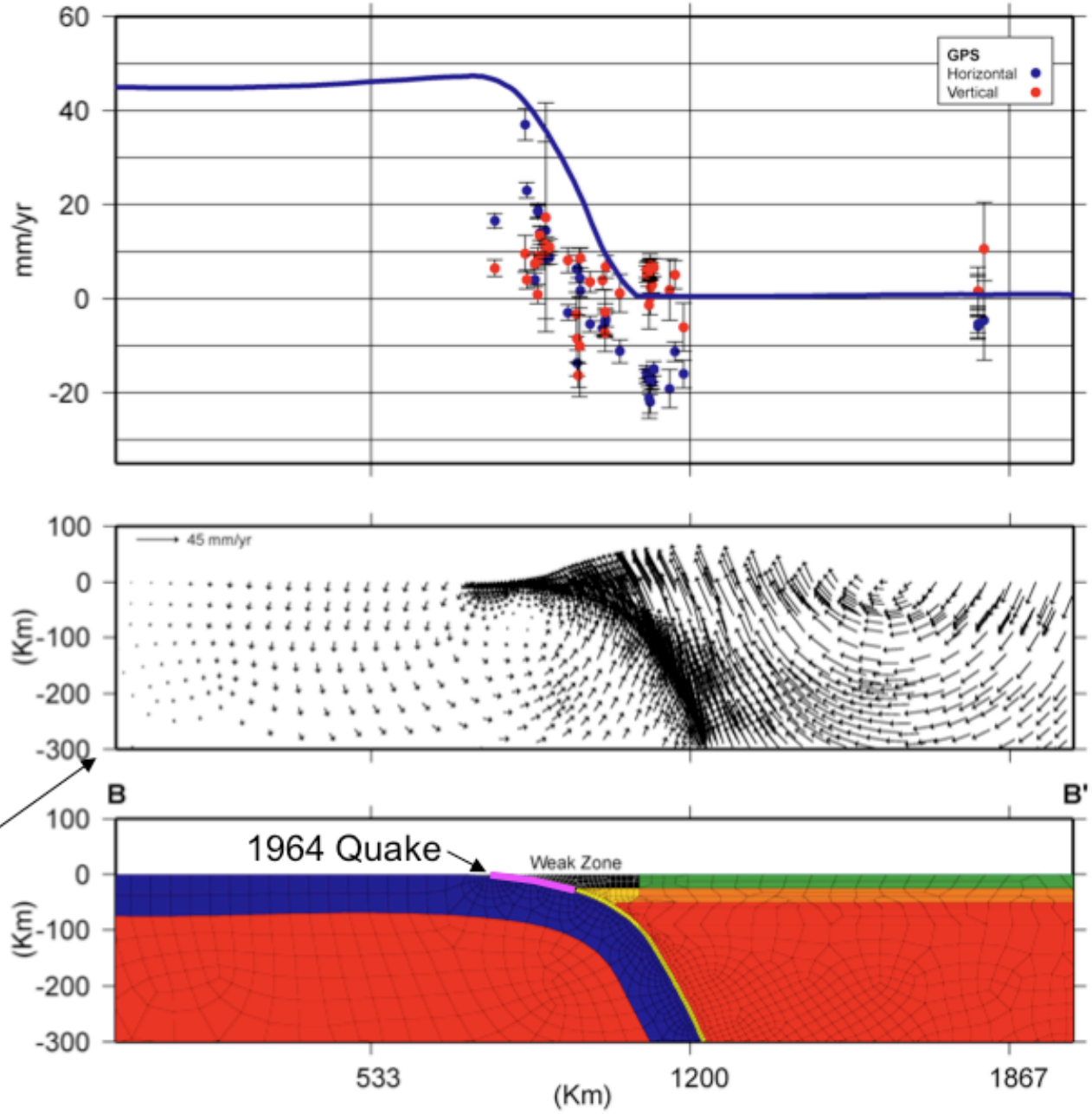

B
B'
1964 Quake
Weak Zone
100
0
-100
-200
-300
(Km)
533
1200
1867
(Km)



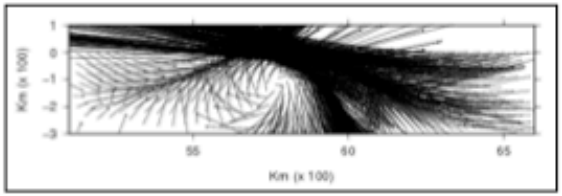


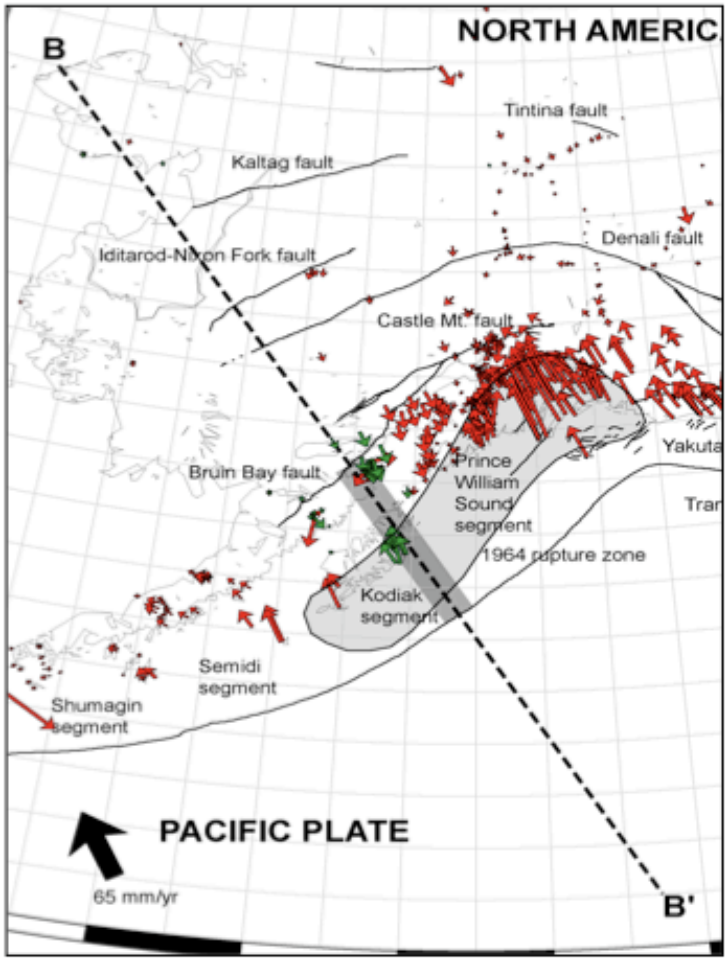
Postseismic signal from the 1964 Earthquake around ~2001

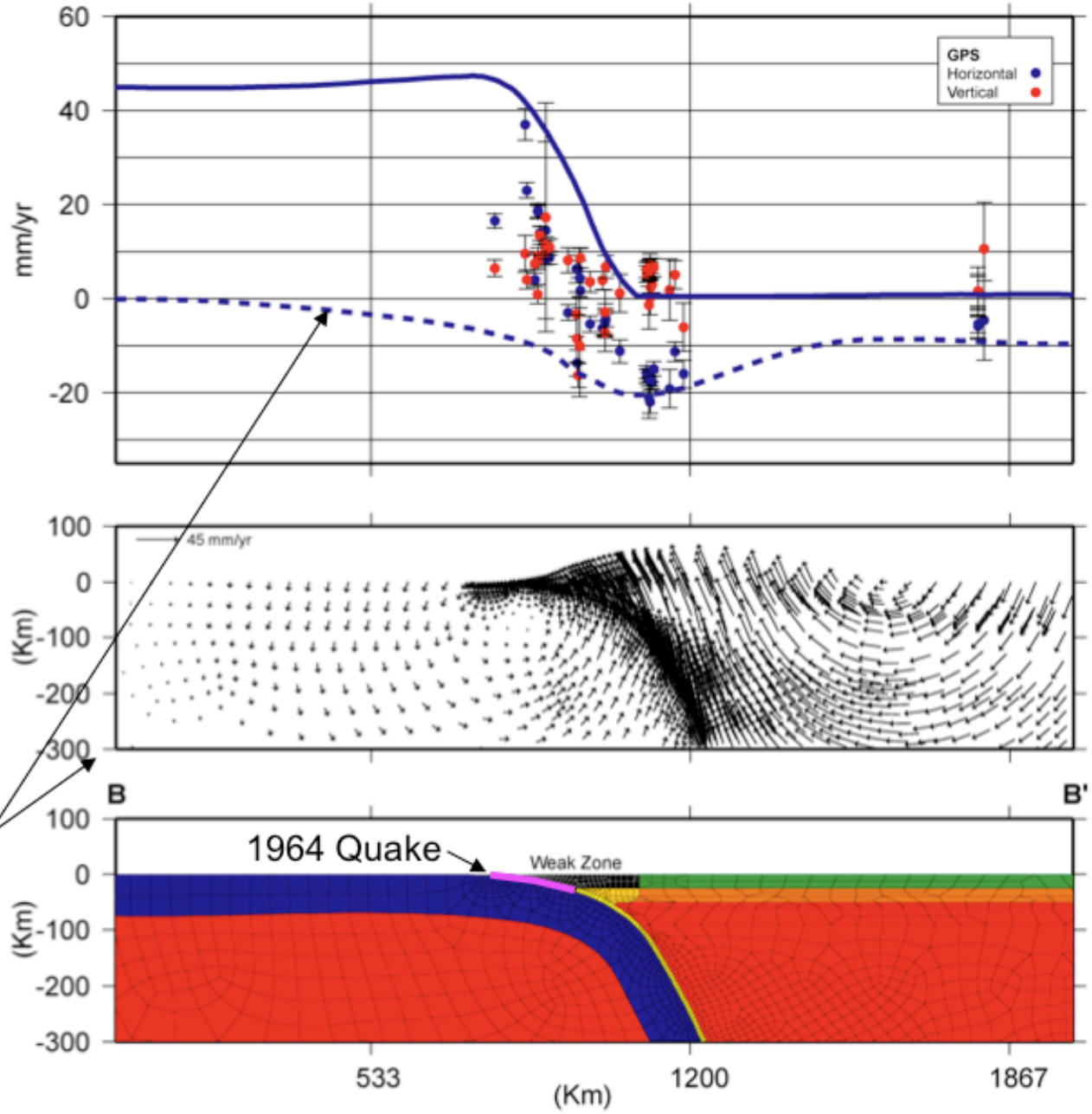




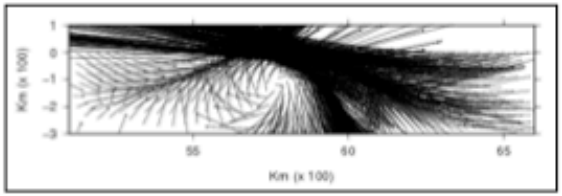
Postseismic signal from the 1964 Earthquake around ~2001

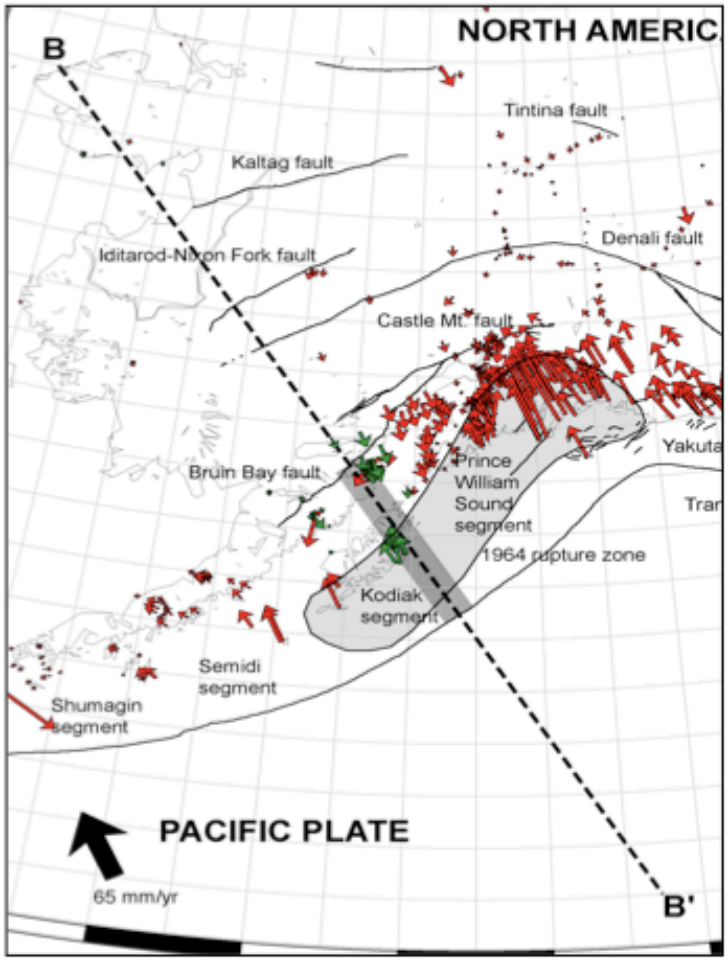


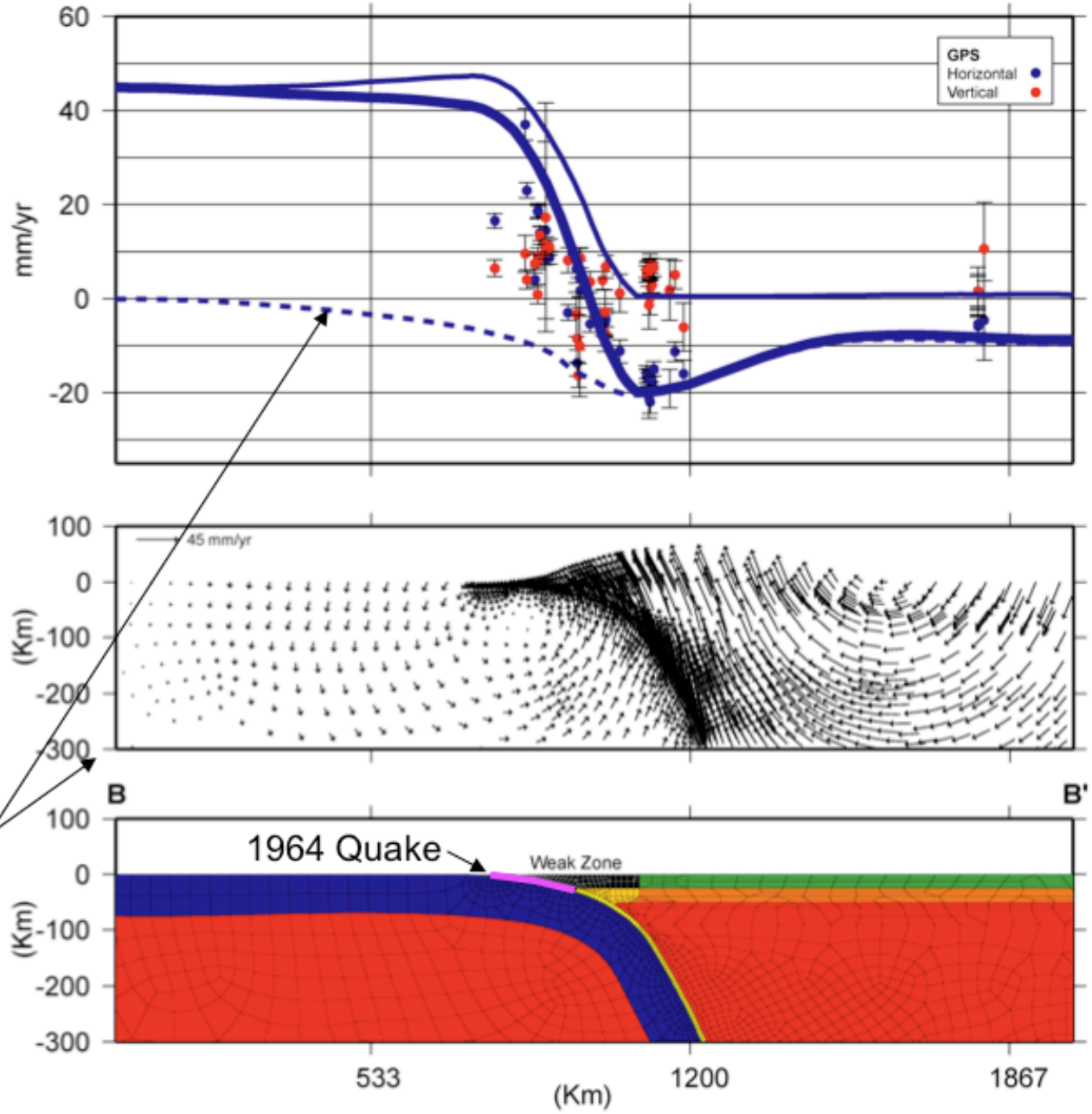




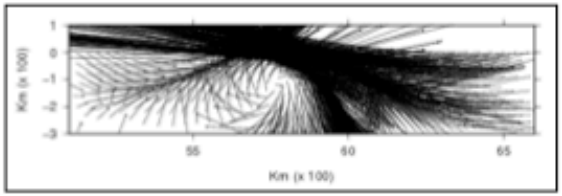
Postseismic signal from the 1964 Earthquake around ~2001



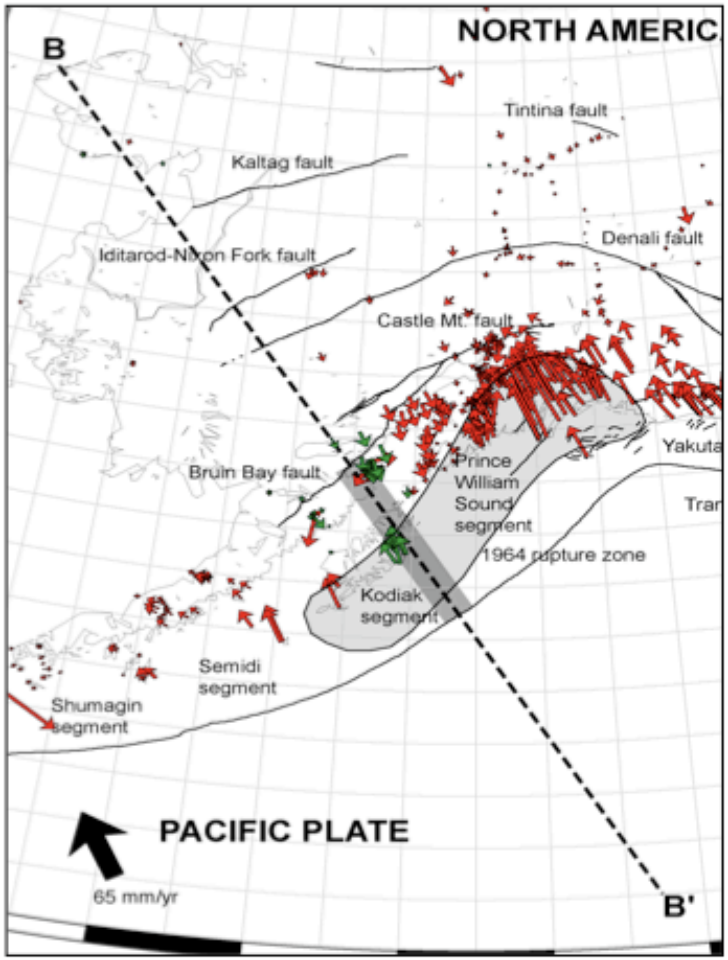


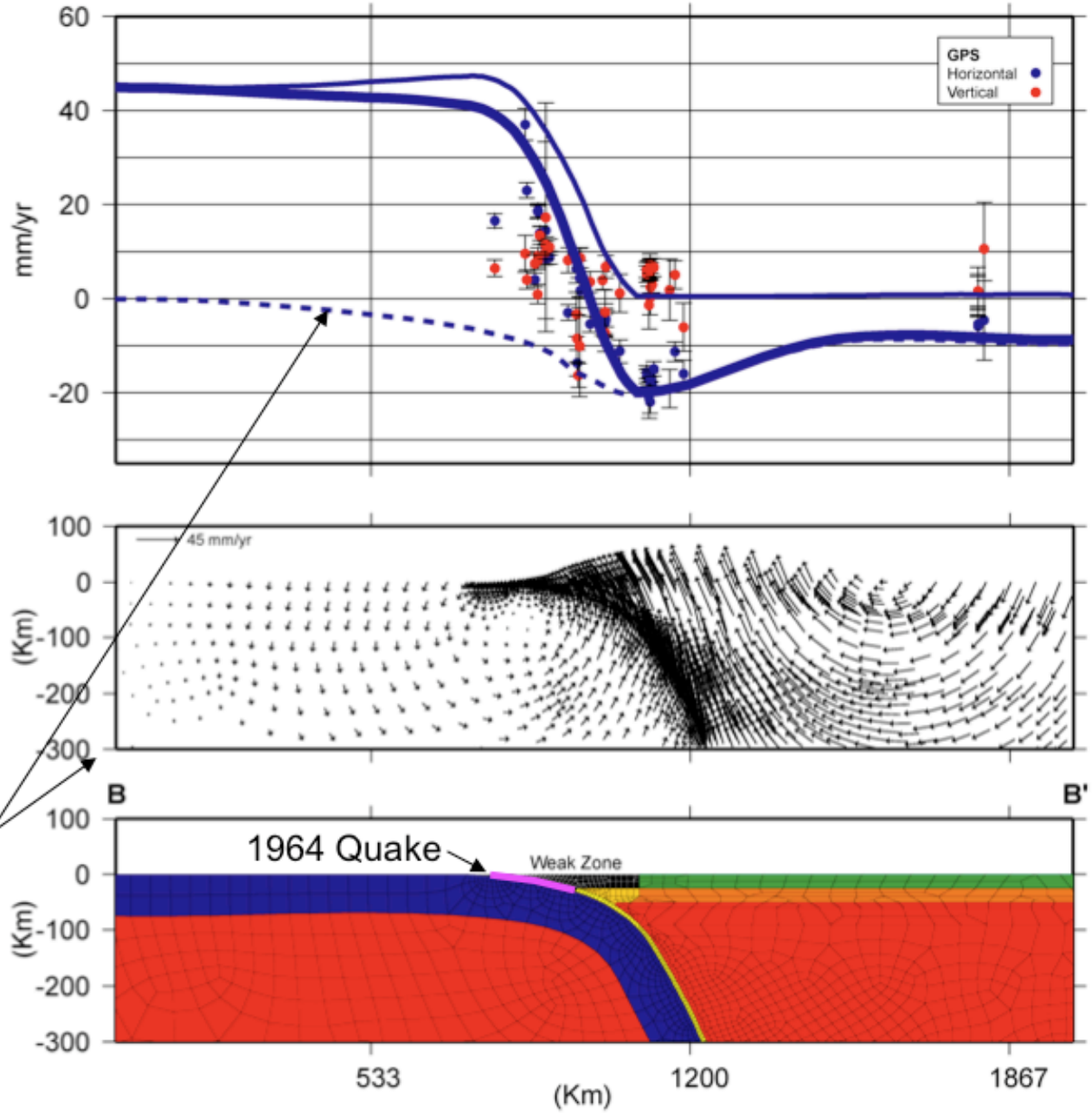


Postseismic signal from the 1964 Earthquake around ~2001

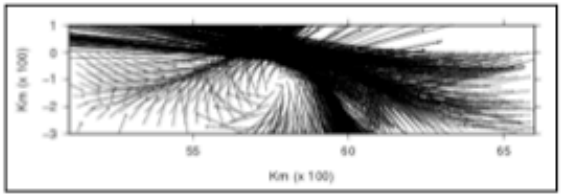


Transient (postseismic) processes are important

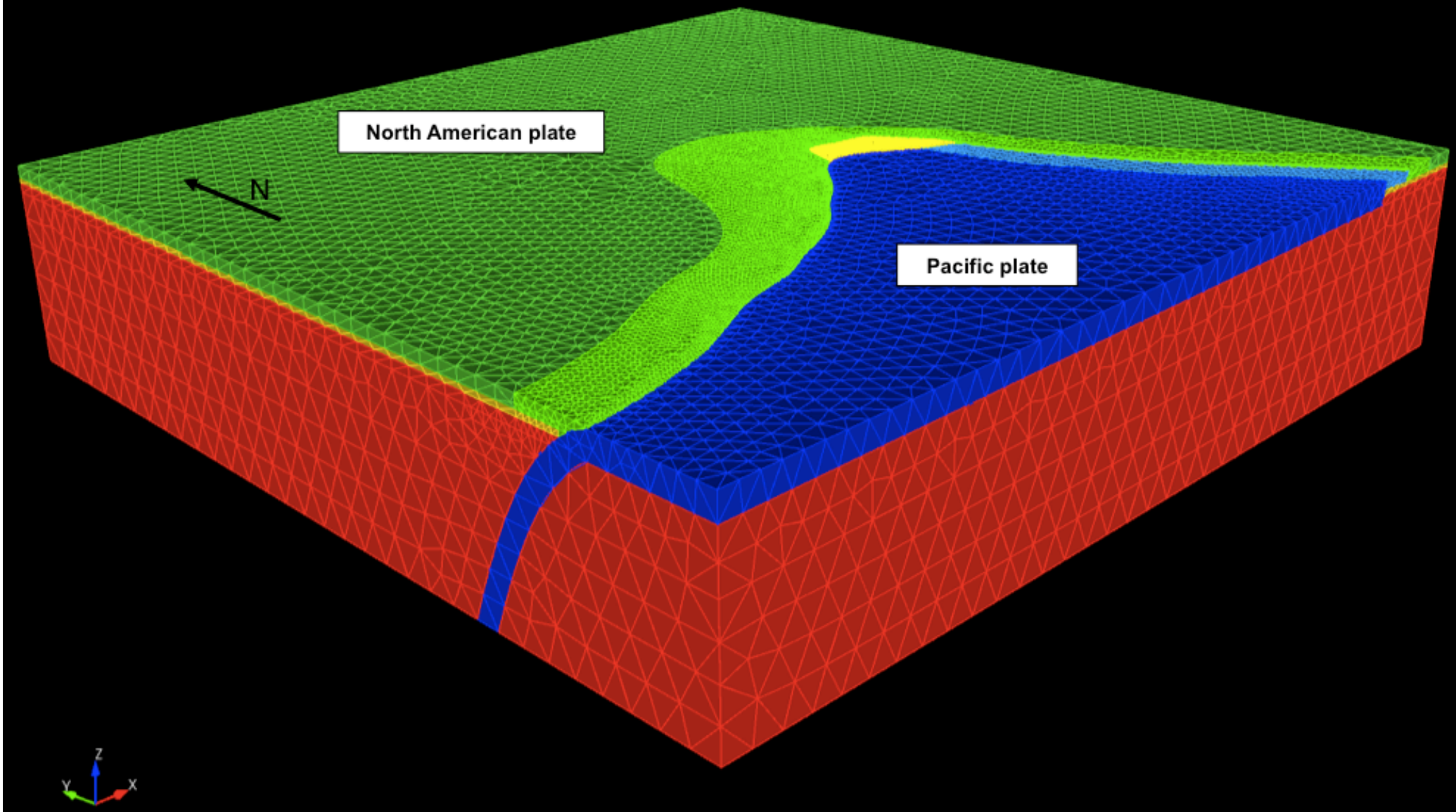




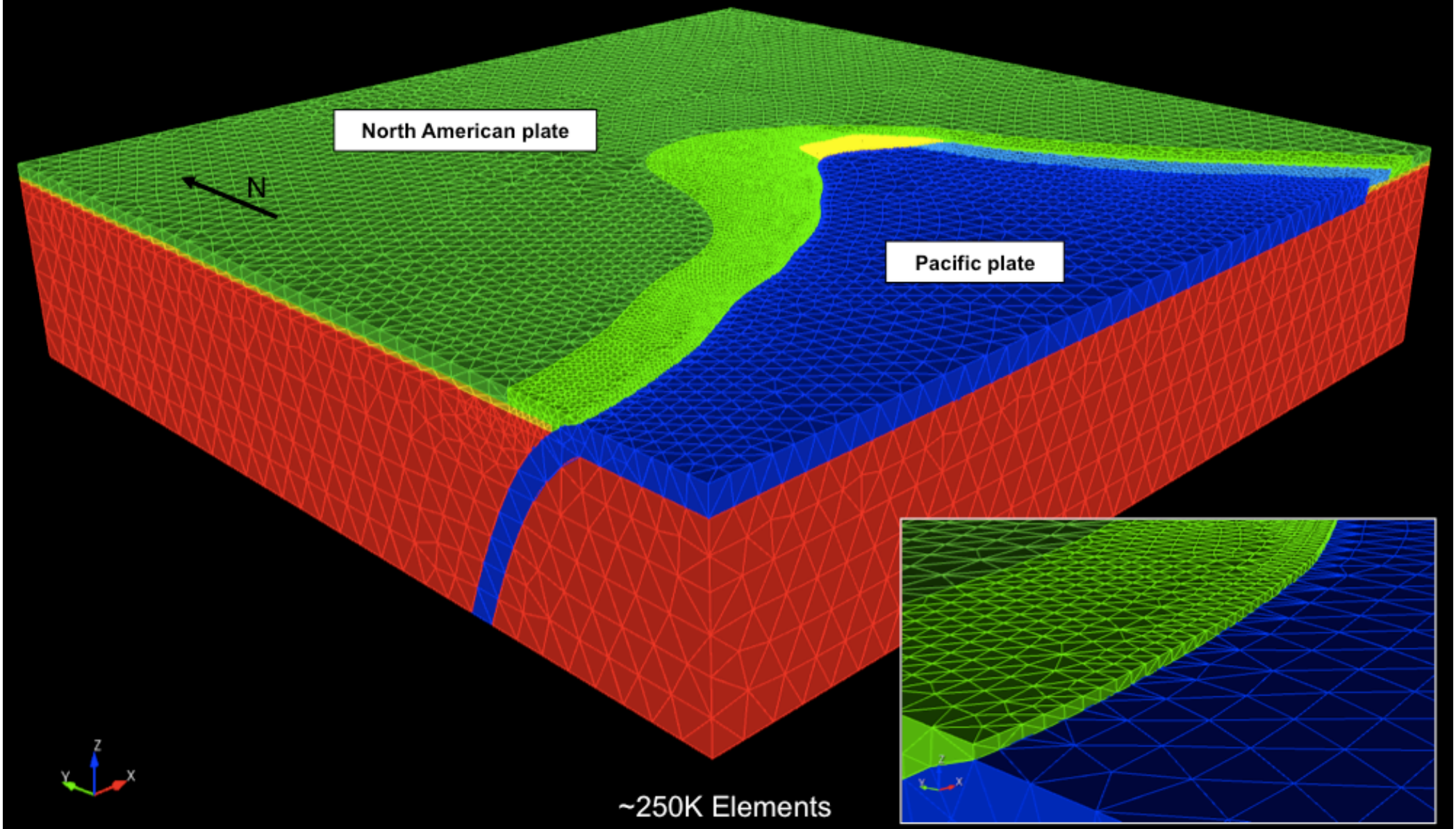
Postseismic signal from the 1964 Earthquake around ~2001



Discretized geometry

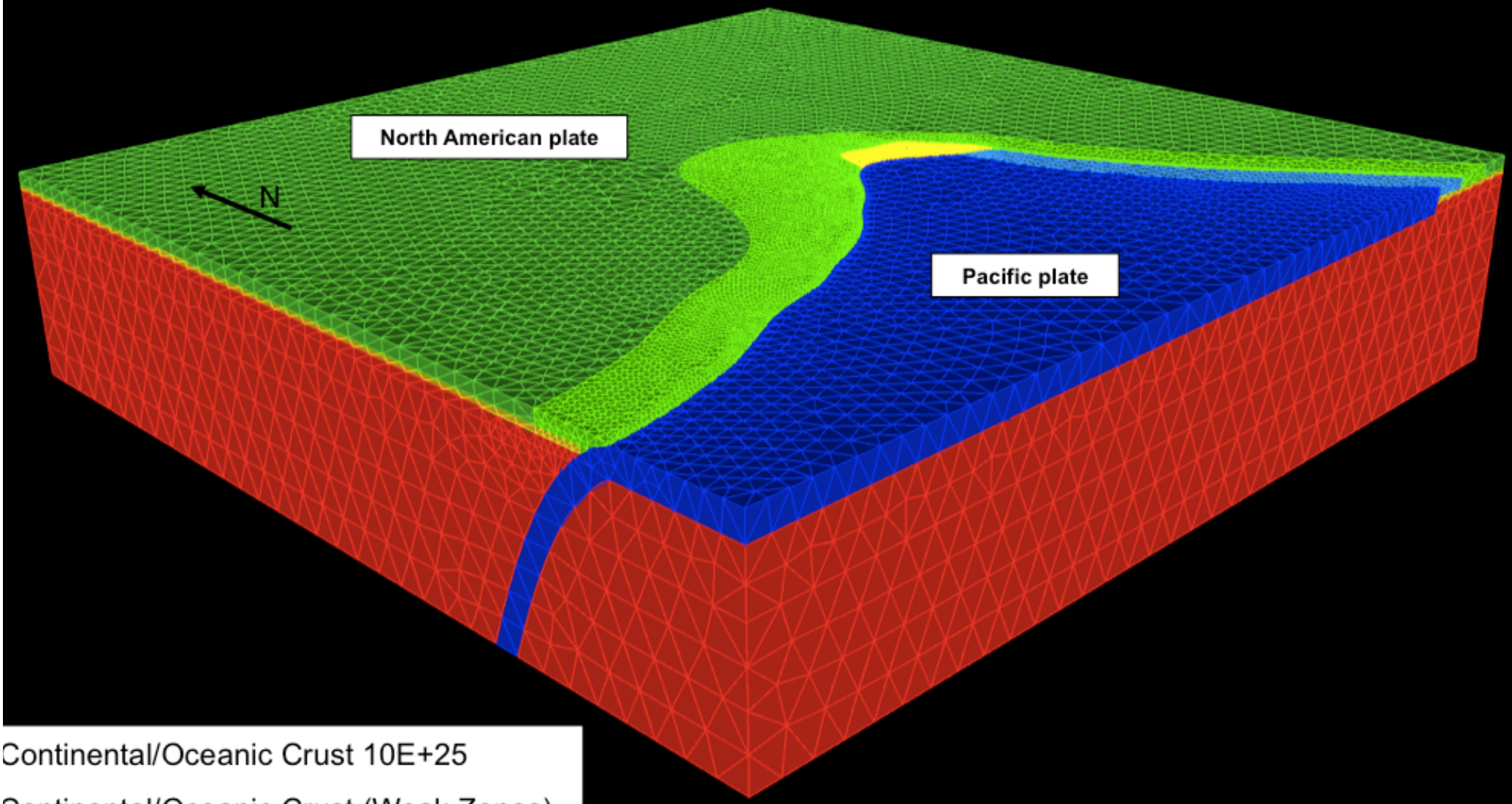


Discretized geometry



~250K Elements

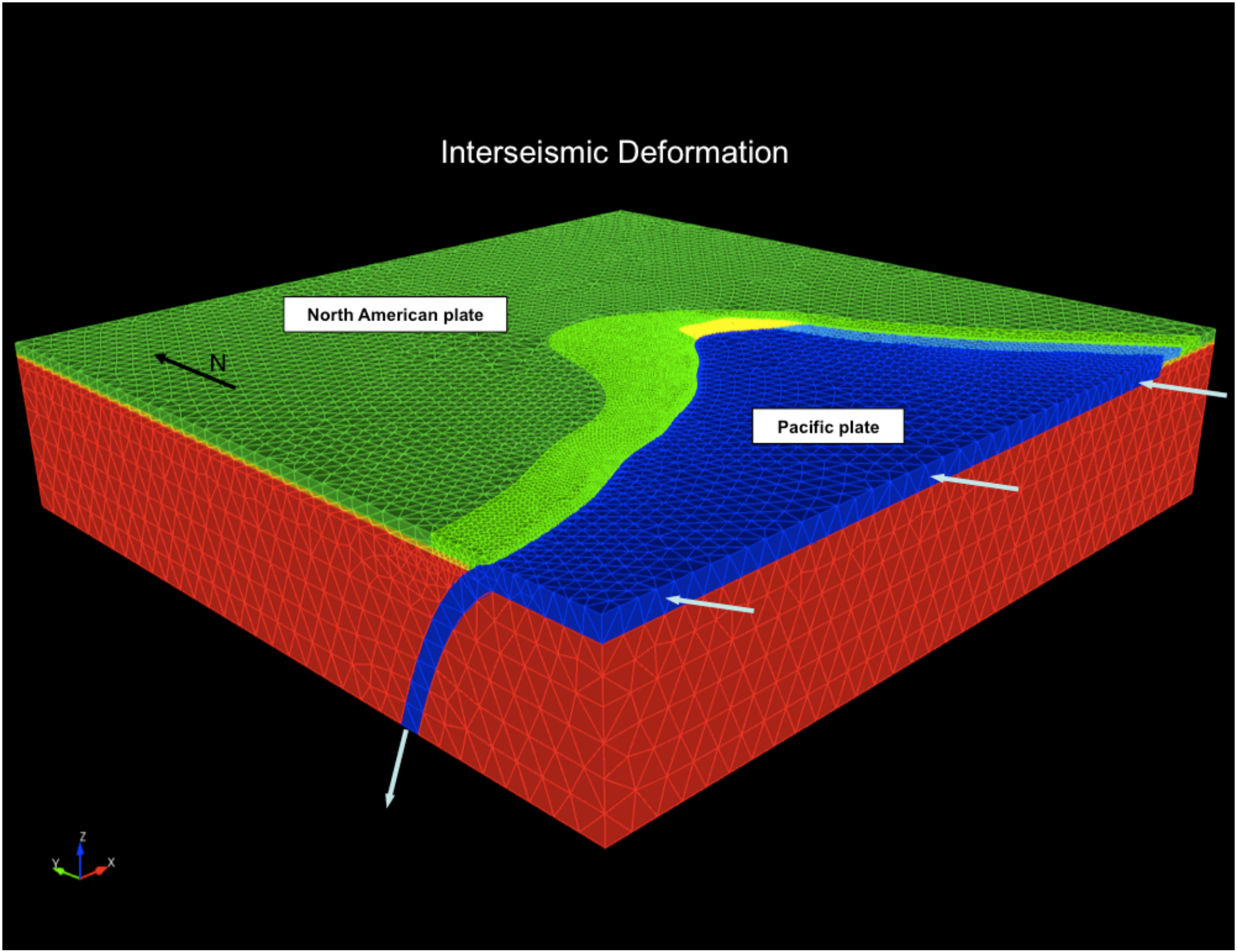
Discretized geometry

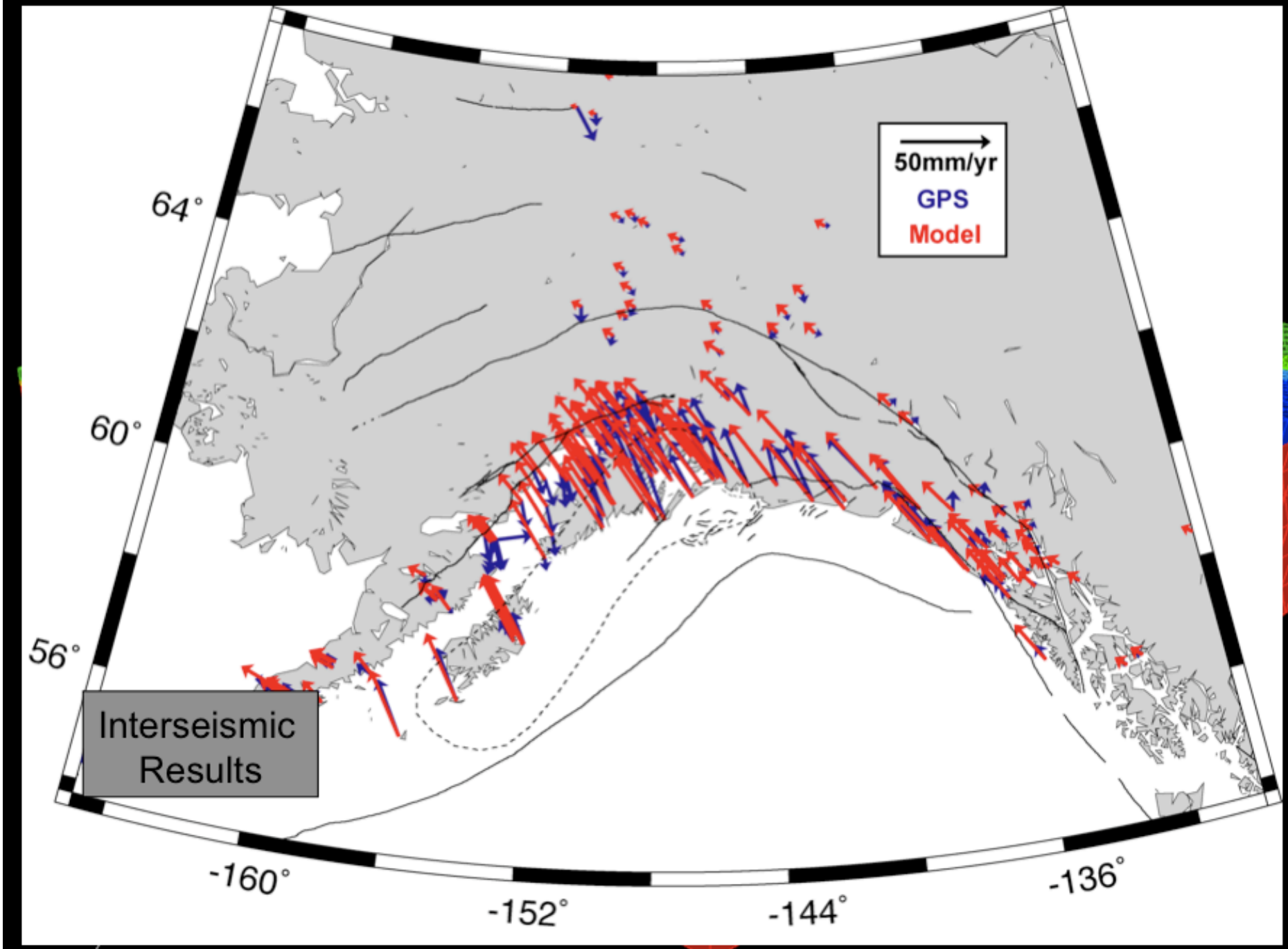


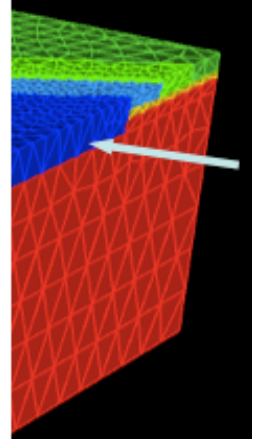
Continental/Oceanic Crust 10E+25

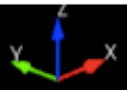
Continental/Oceanic Crust (Weak Zones) 10E+22

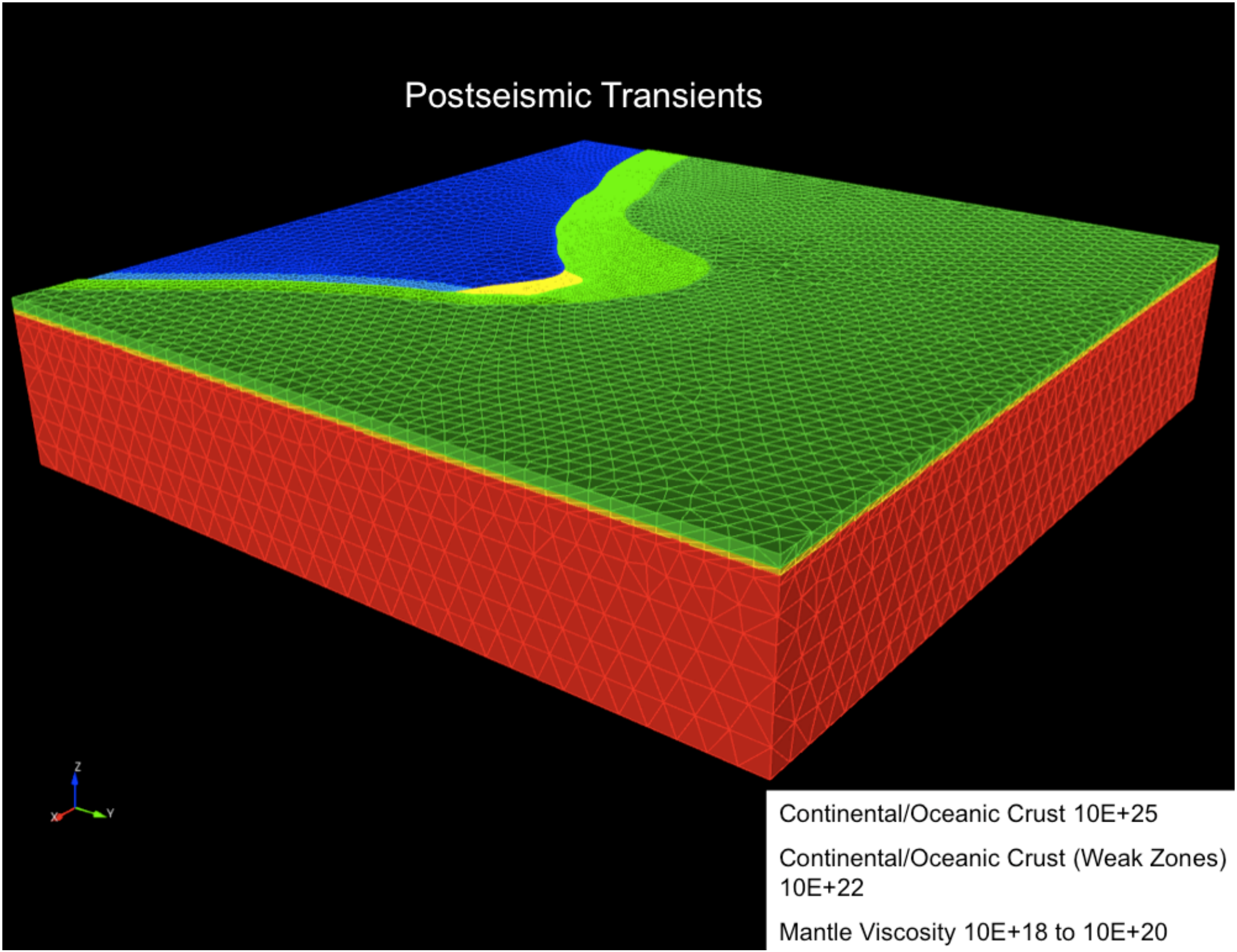
Mantle Viscosity 10E+18 to 10E+20


Interseismic Deformation
North American plate
N
Pacific plate
Z
Y
X

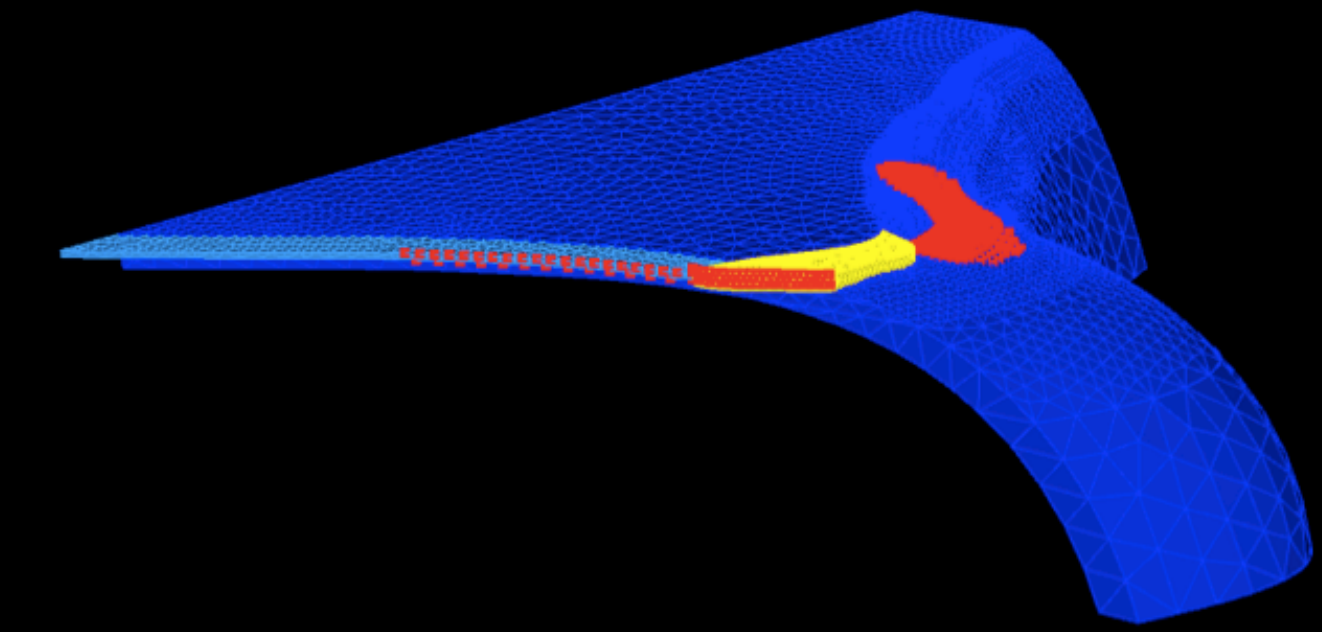

50mm/yr
GPS
Model
64°
60°
56°
-160°
-152°
-144°
-136°
Interseismic Results




Z
Y
X


Postseismic Transients
Z
X
Y
Continental/Oceanic Crust 10E+25
Continental/Oceanic Crust (Weak Zones) 10E+22
Mantle Viscosity 10E+18 to 10E+20

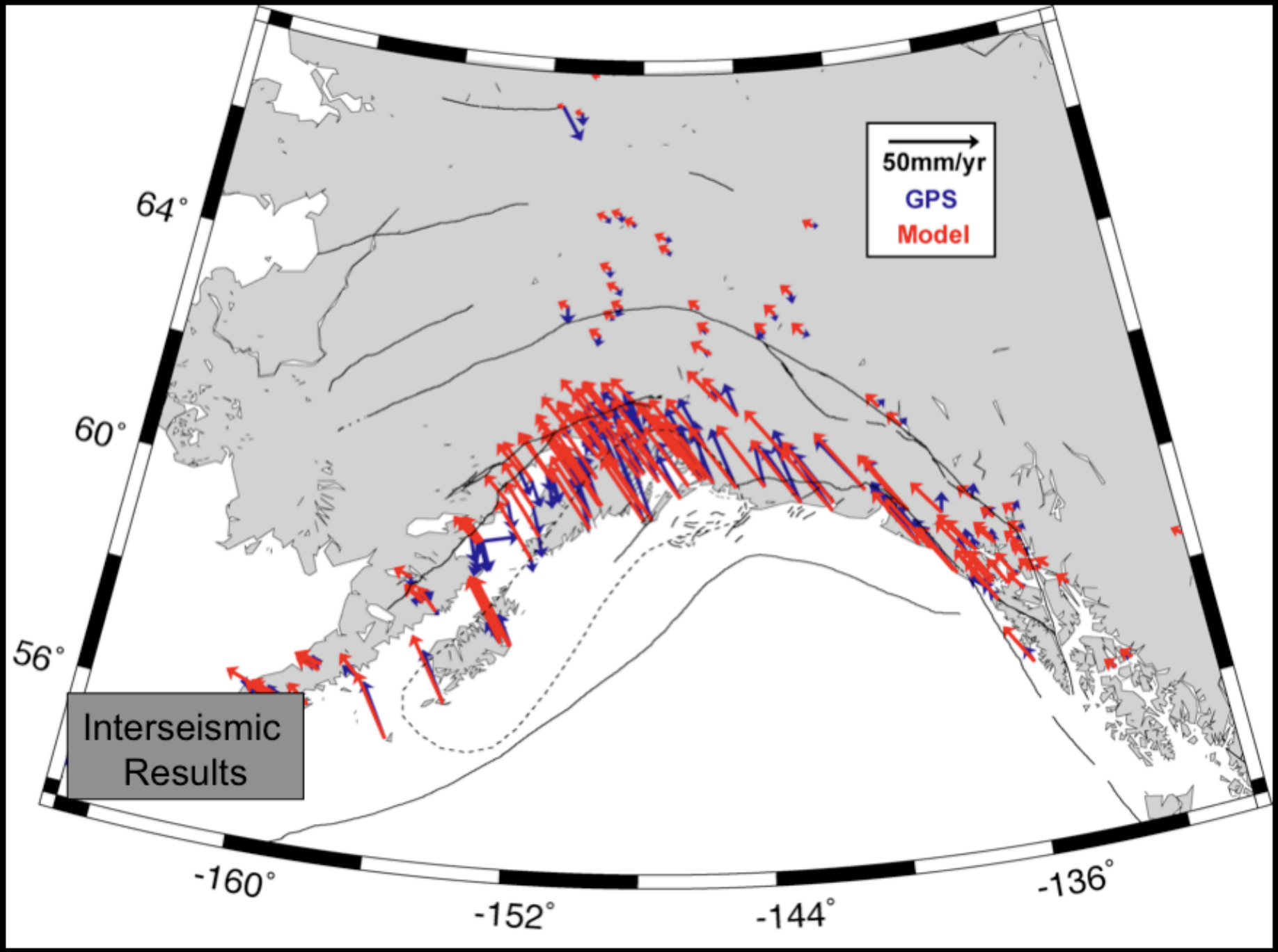
Postseismic Transients

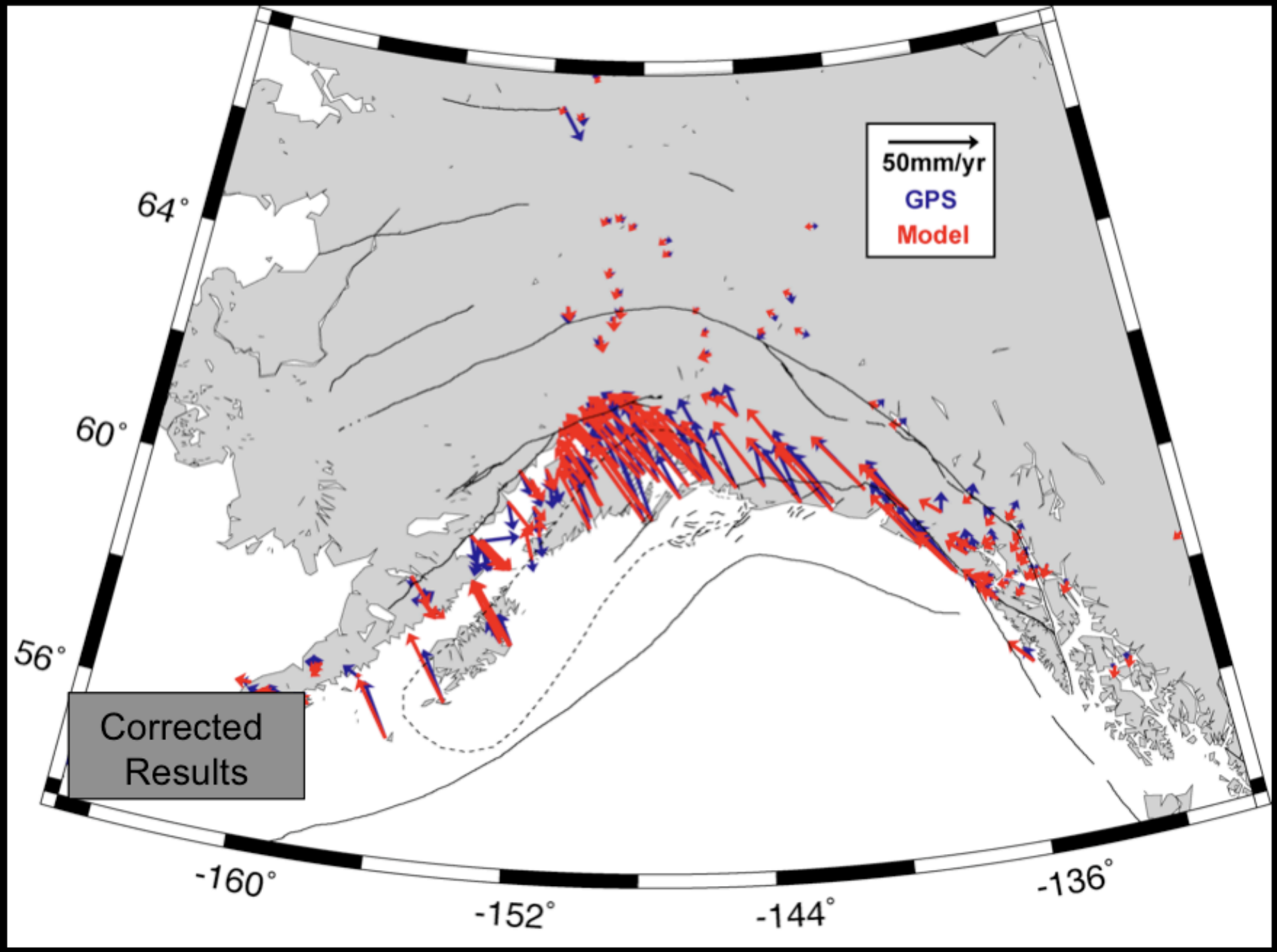


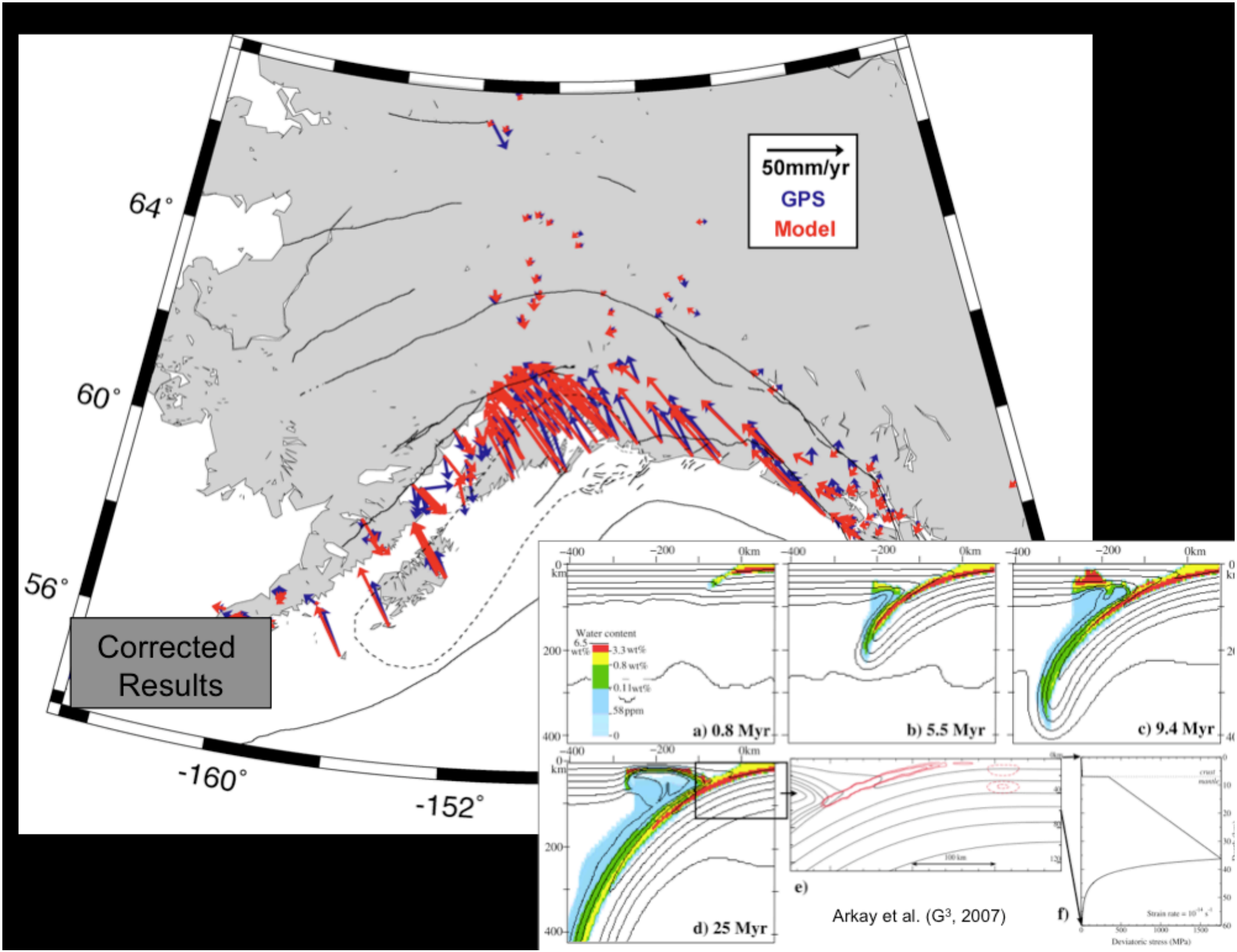
Continental/Oceanic Crust 10E+25

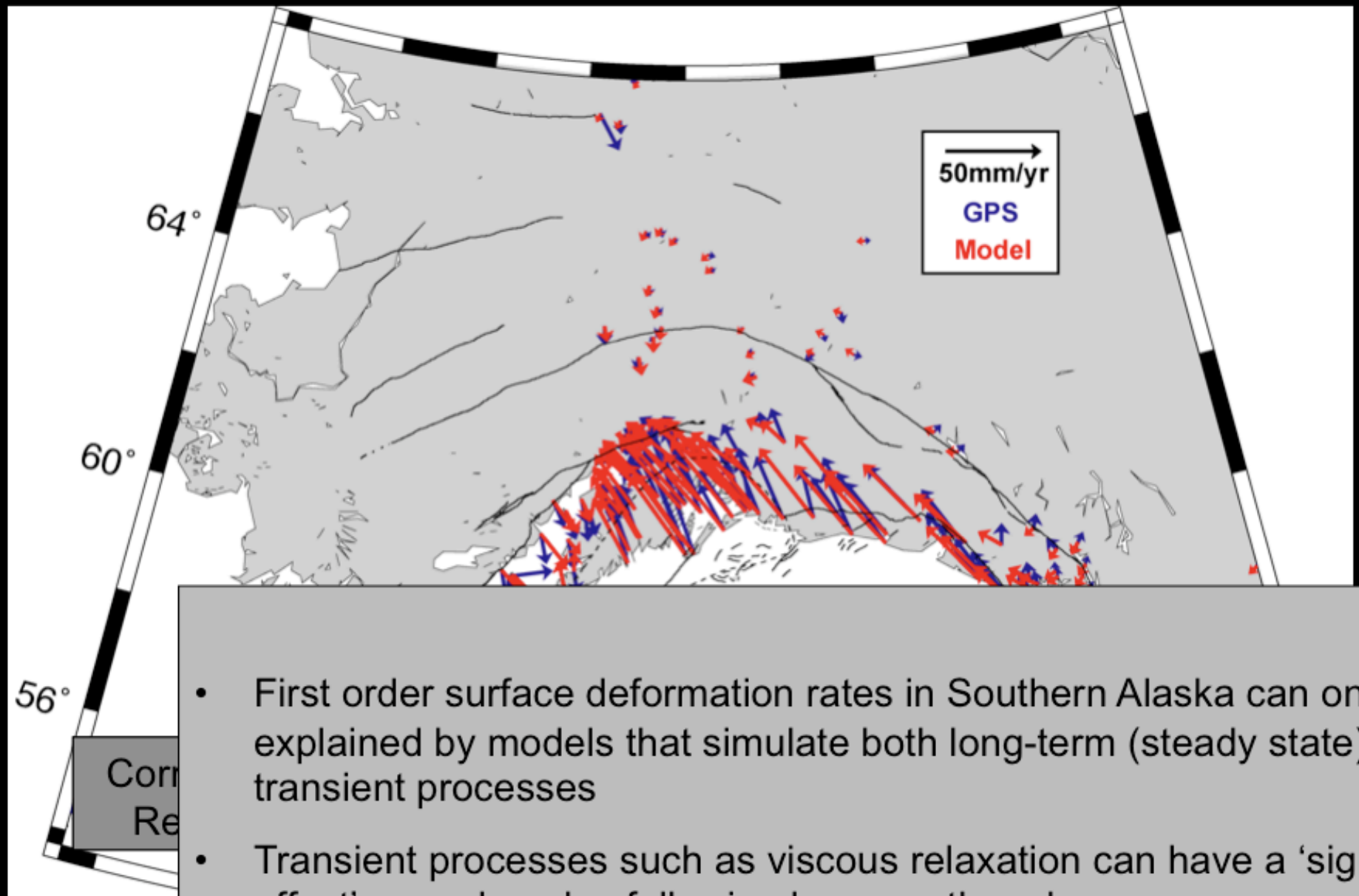
Continental/Oceanic Crust (Weak Zones) 10E+22

Mantle Viscosity 10E+18 to 10E+20


50mm/yr
GPS
Model
64°
60°
56°
-160°
-152°
-144°
-136°
Interseismic Results


50mm/yr
GPS
Model
64°
60°
56°
Corrected Results
-160°
-152°
-144°
-136°

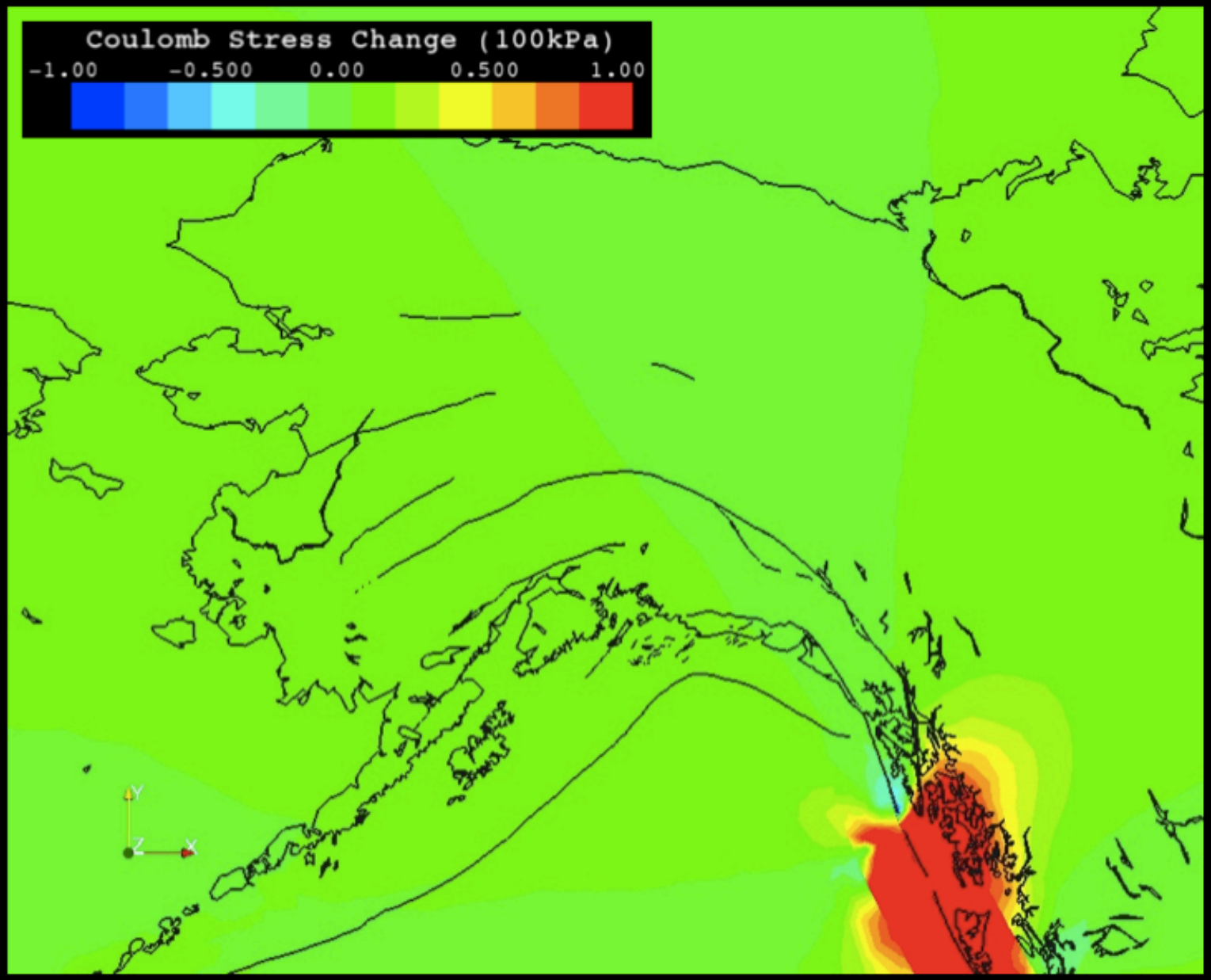

50mm/yr
GPS
Model
64°
60°
56°
-160°
-152°
Corrected Results
Water content
6.5 wt%
3.3 wt%
0.8 wt%
0.11wt%
58ppm
0
a) 0.8 Myr
b) 5.5 Myr
c) 9.4 Myr
d) 25 Myr
e)
f)
Arkay et al. (G3, 2007)



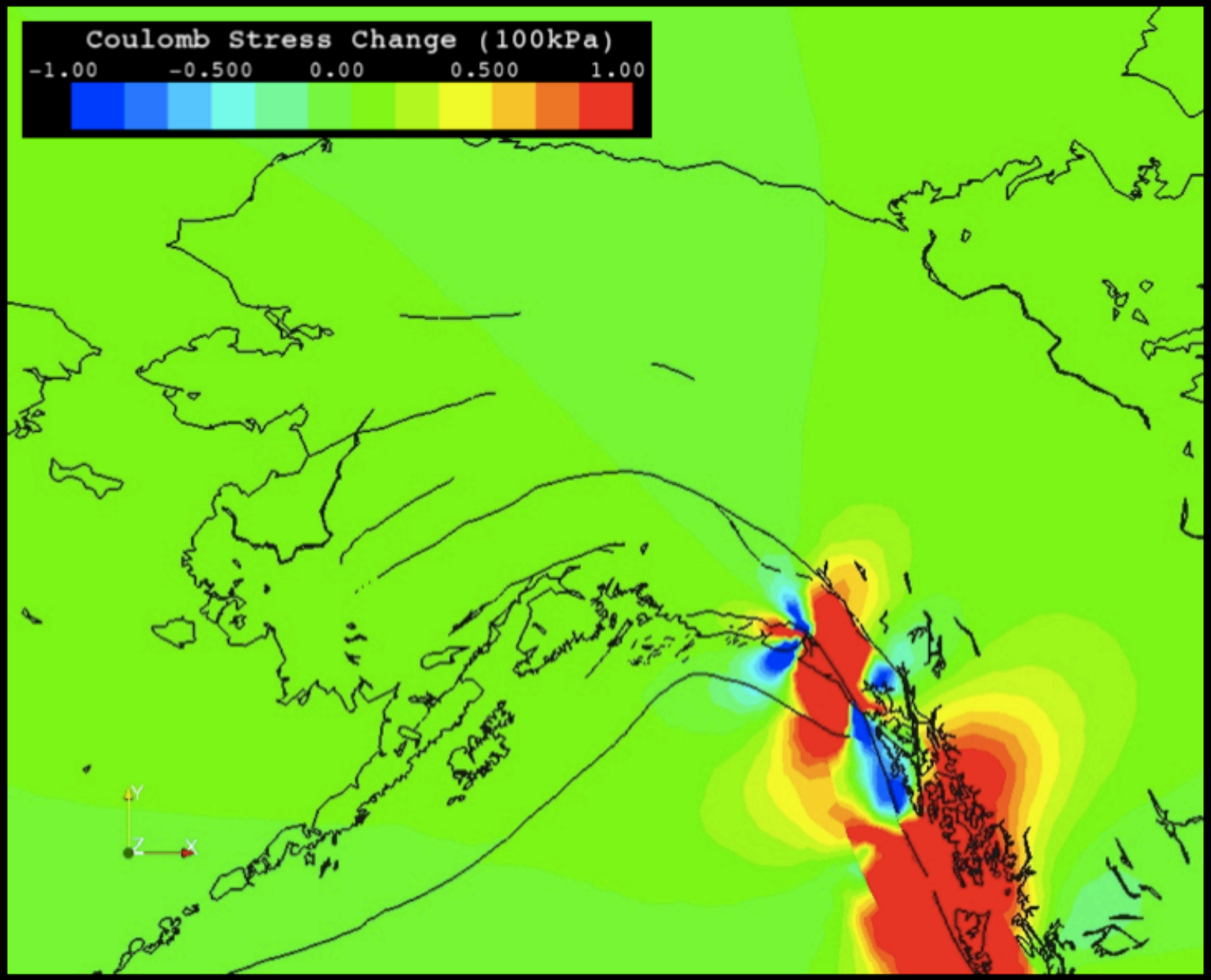
- First order surface deformation rates in Southern Alaska can only be explained by models that simulate both long-term (steady state) and transient processes
- Transient processes such as viscous relaxation can have a 'significant effect' even decades following large earthquakes
- Distribution of slip does not seem to have a significant effect on the postseismic signal ~36 years after the quake

Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake

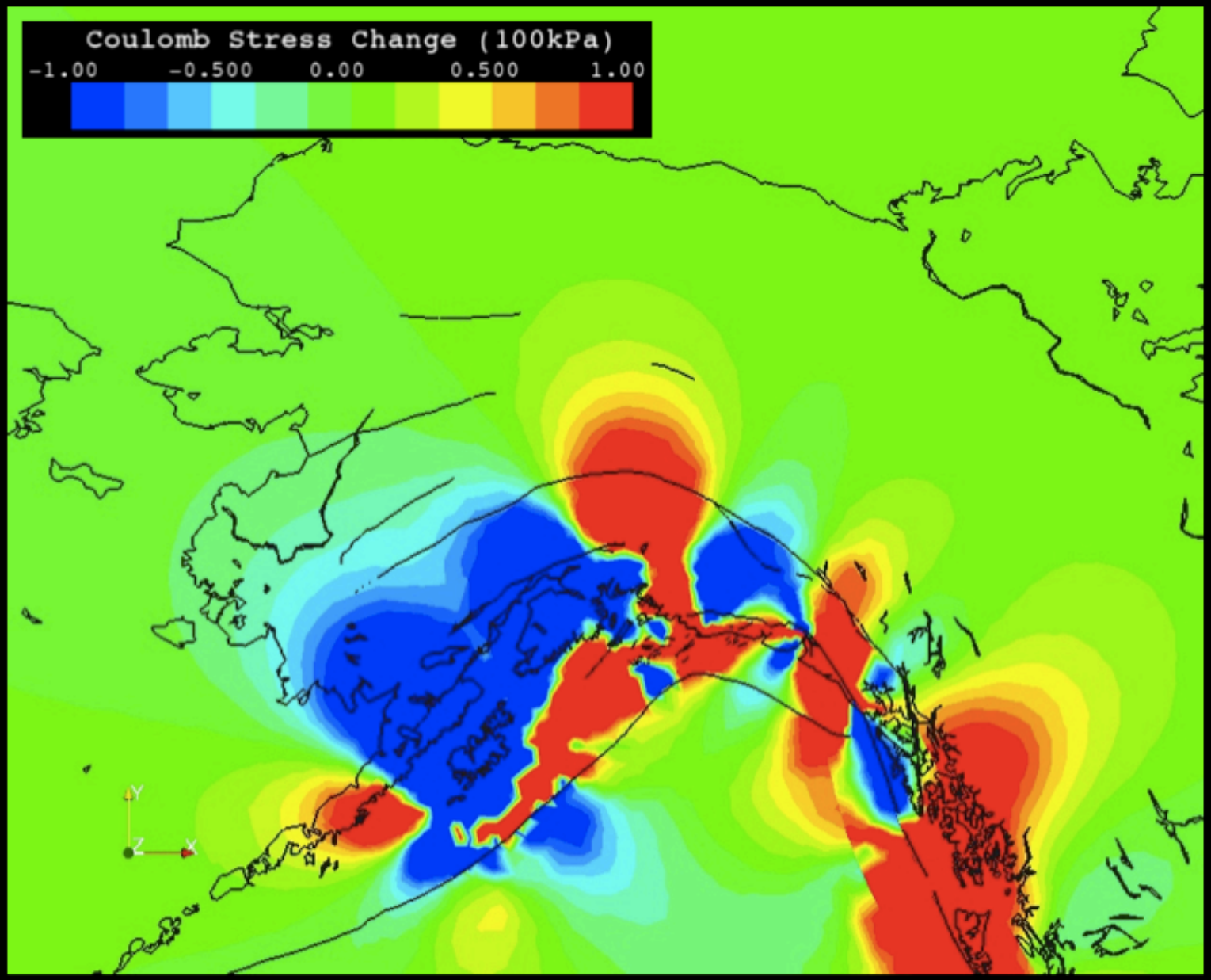
Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake



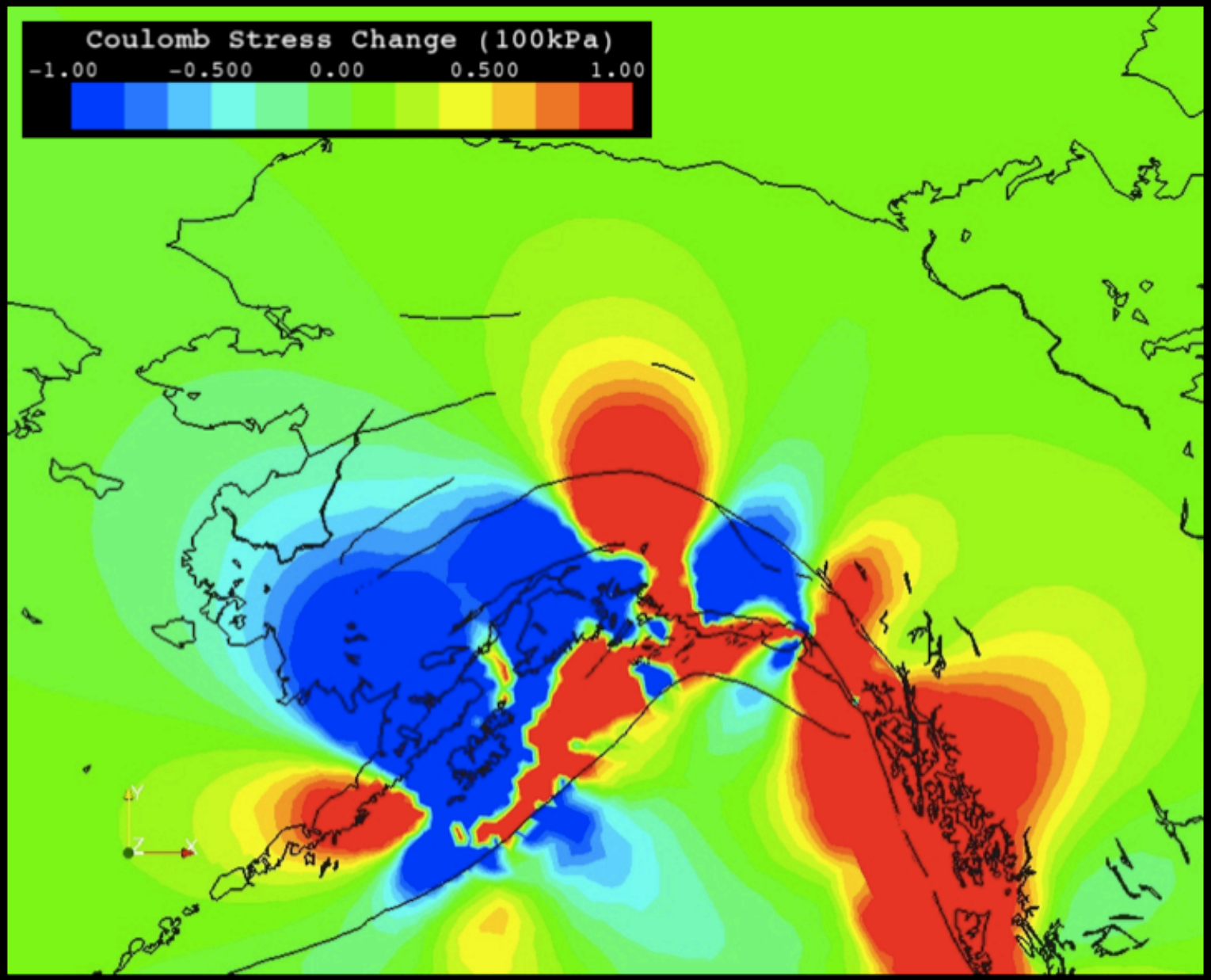
Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake



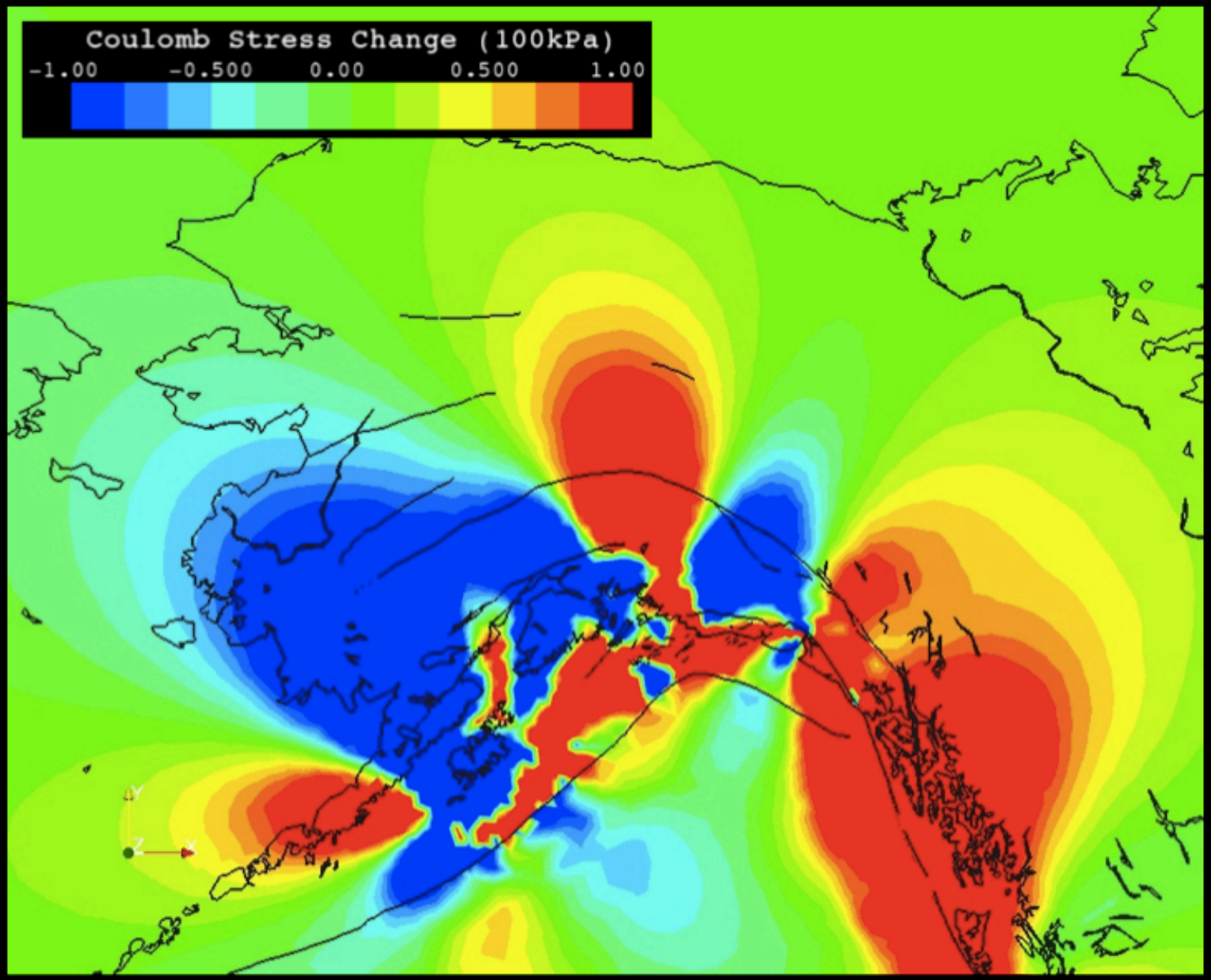
Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake



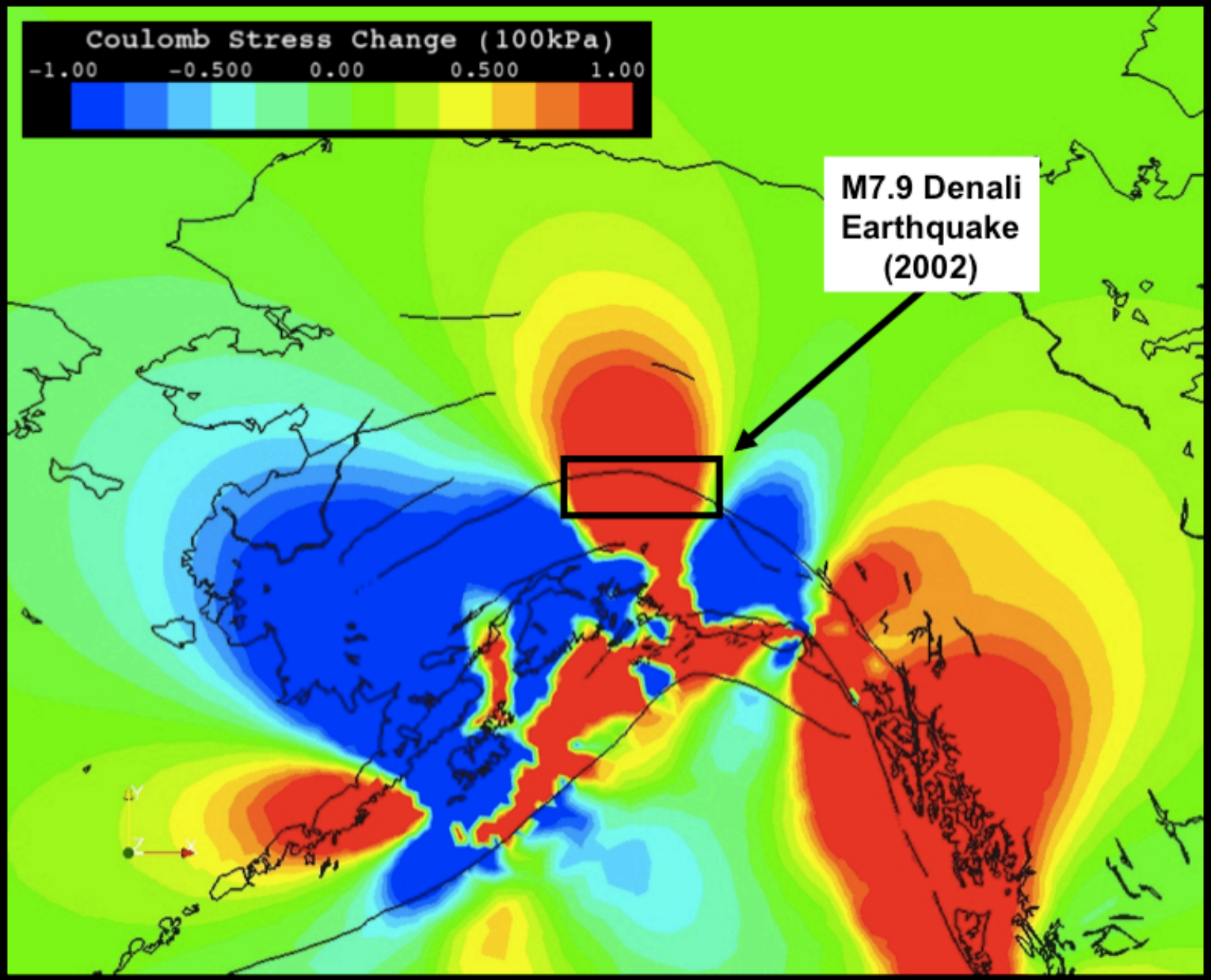
Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake



Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake



Coulomb stress change as experienced by right lateral faults (striking ~east) since 1949 until just prior the Denali earthquake




Thank You
Denali National Park