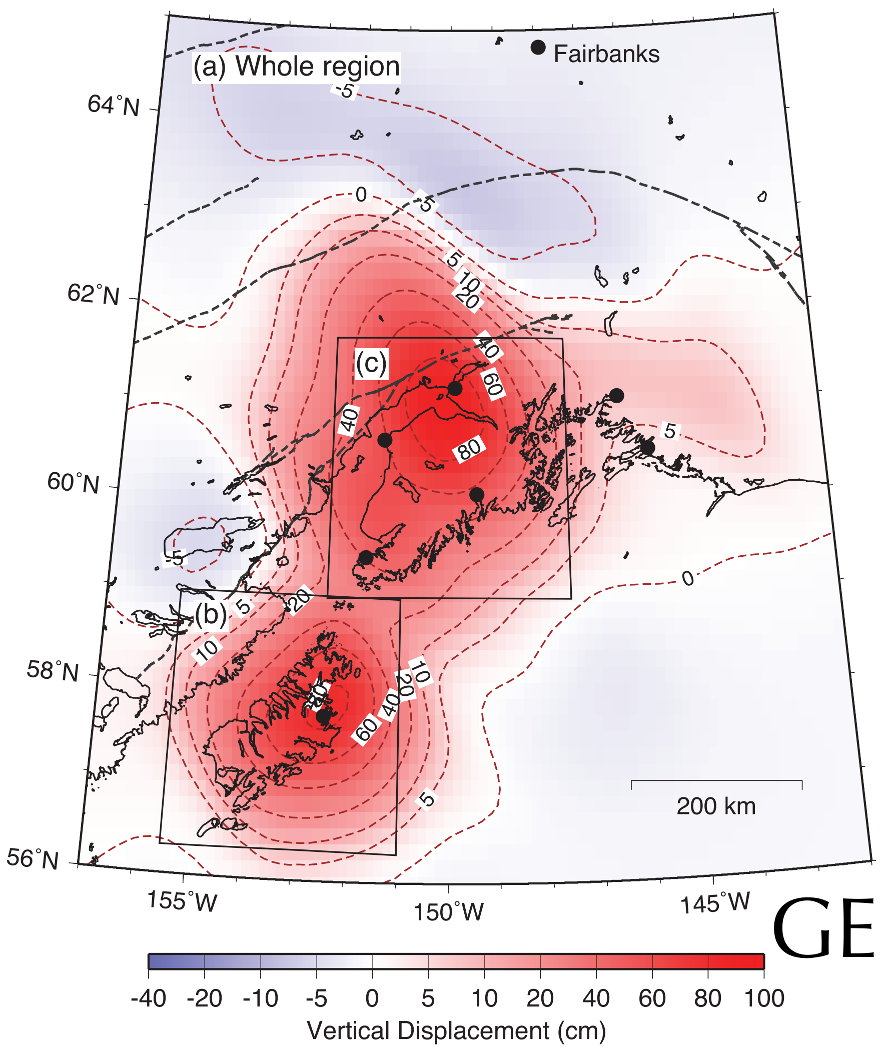
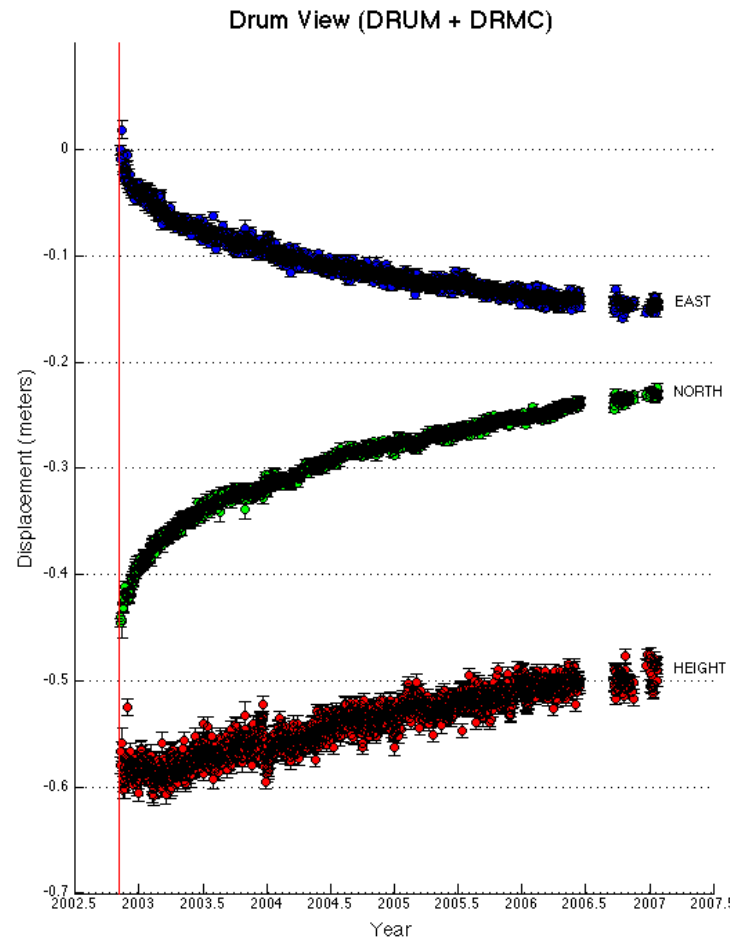
Lecture 17: Postseismic Deformation





GEOS 655 Tectonic Geodesy

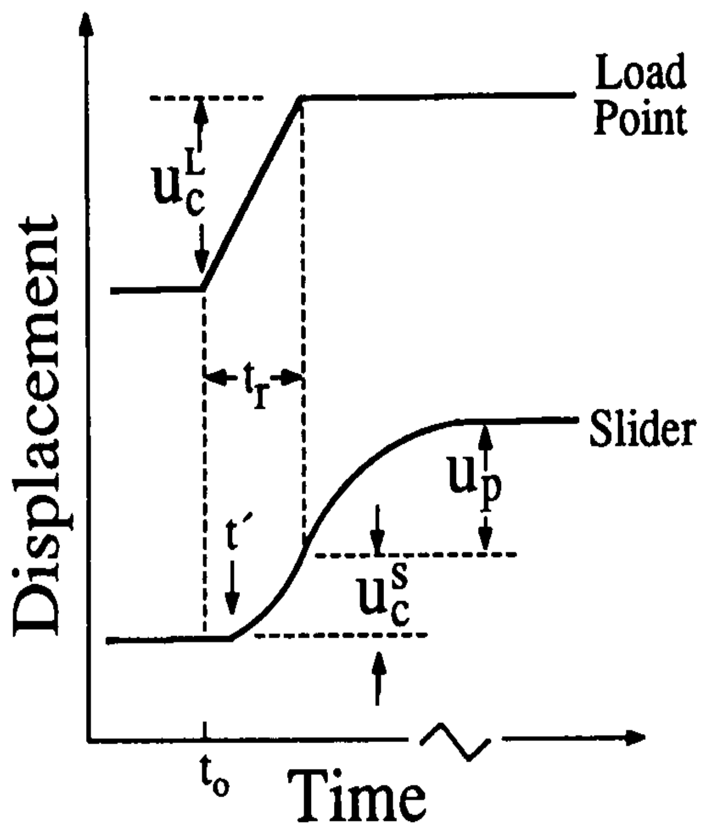
Jeff Freymueller

Mechanisms of Postseismic Deformation

Deformation following & triggered by an earthquake

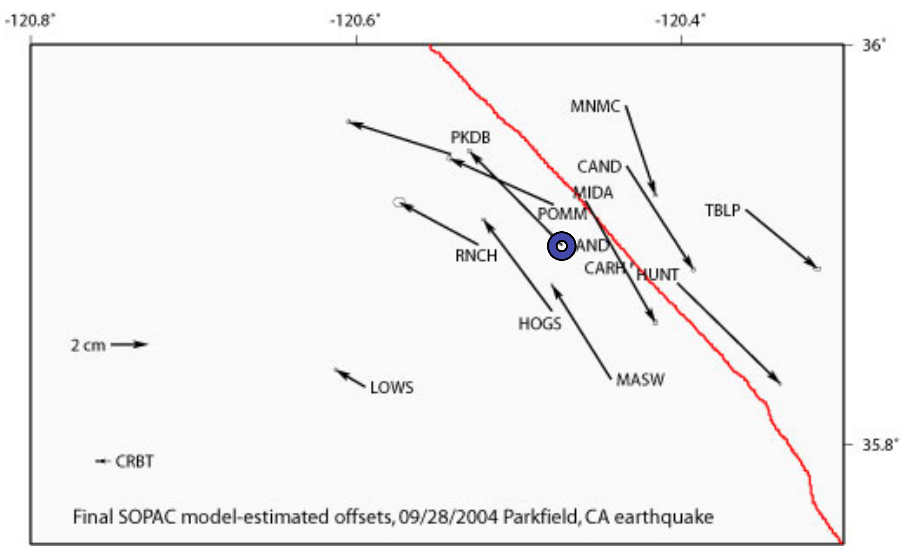
- Afterslip
  - Slow slip that follows the earthquake
  - On fault plane, above or below
- Viscoelastic Relaxation
  - Response of viscous material to stress change of earthquake
- Poroelastic Deformation
  - Generally local to fault zone

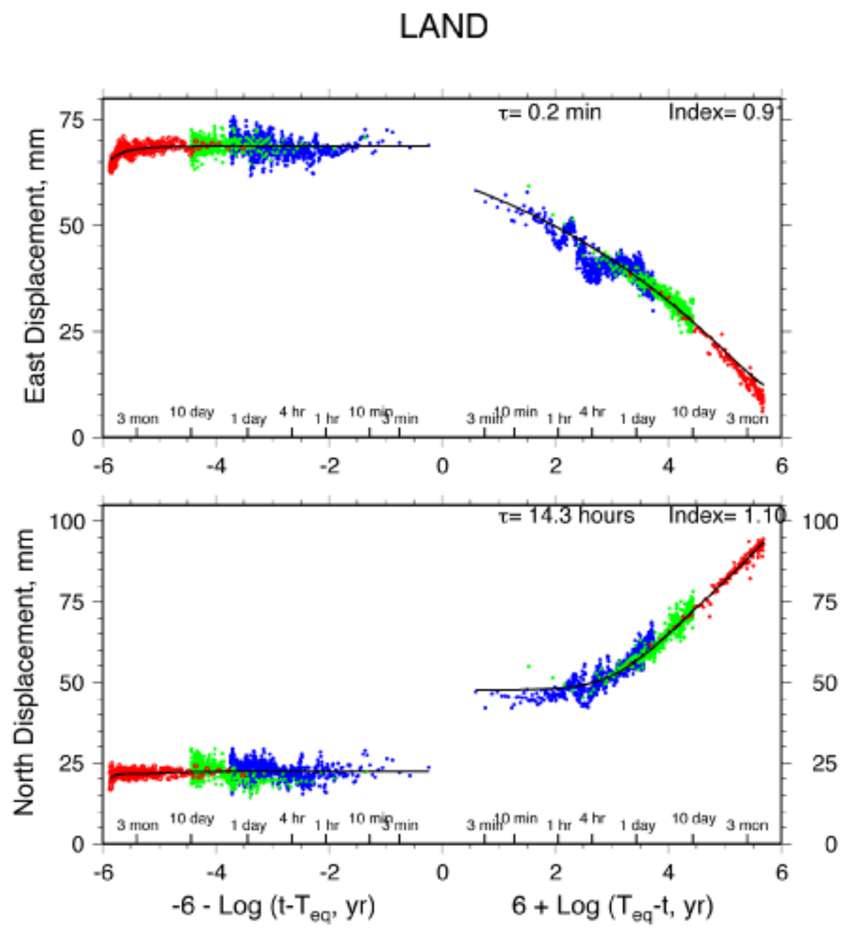
Afterslip



- Marone et al. (1991)
  - Fault with rate & state friction
  - Velocity strengthening
  - Subjected to sudden shear stress step
  - Displacement equivalent to displacement of spring slider
  - Displacement ~ log(time)

Shallow Afterslip at Parkfield





Shear Stress-Sliding Velocity Relation

- Rate and state friction predicts that at steady-state sliding there will be a balance between the driving shear stress and the sliding velocity

$$\tau^{ss} = \tau^{*} + (A - B)\ln(V / V^{*})$$

- τ^* is the strength at steady-state sliding velocity V^*.

Afterslip Constitutive Relations

- If there is a sudden jump in the sliding velocity due to coseismic slip in an earthquake, then this induces a stress jump:

$$\Delta\tau = (A - B)\ln(V_p / V_0)$$

- Further evolution of stress is determined by the interaction between the fault and the (elastic) medium in which it is embedded:

$$\frac{d\tau}{dt} = k(V^* - V)$$

Approximate Solution

- As the fault slips further, the driving force decreases

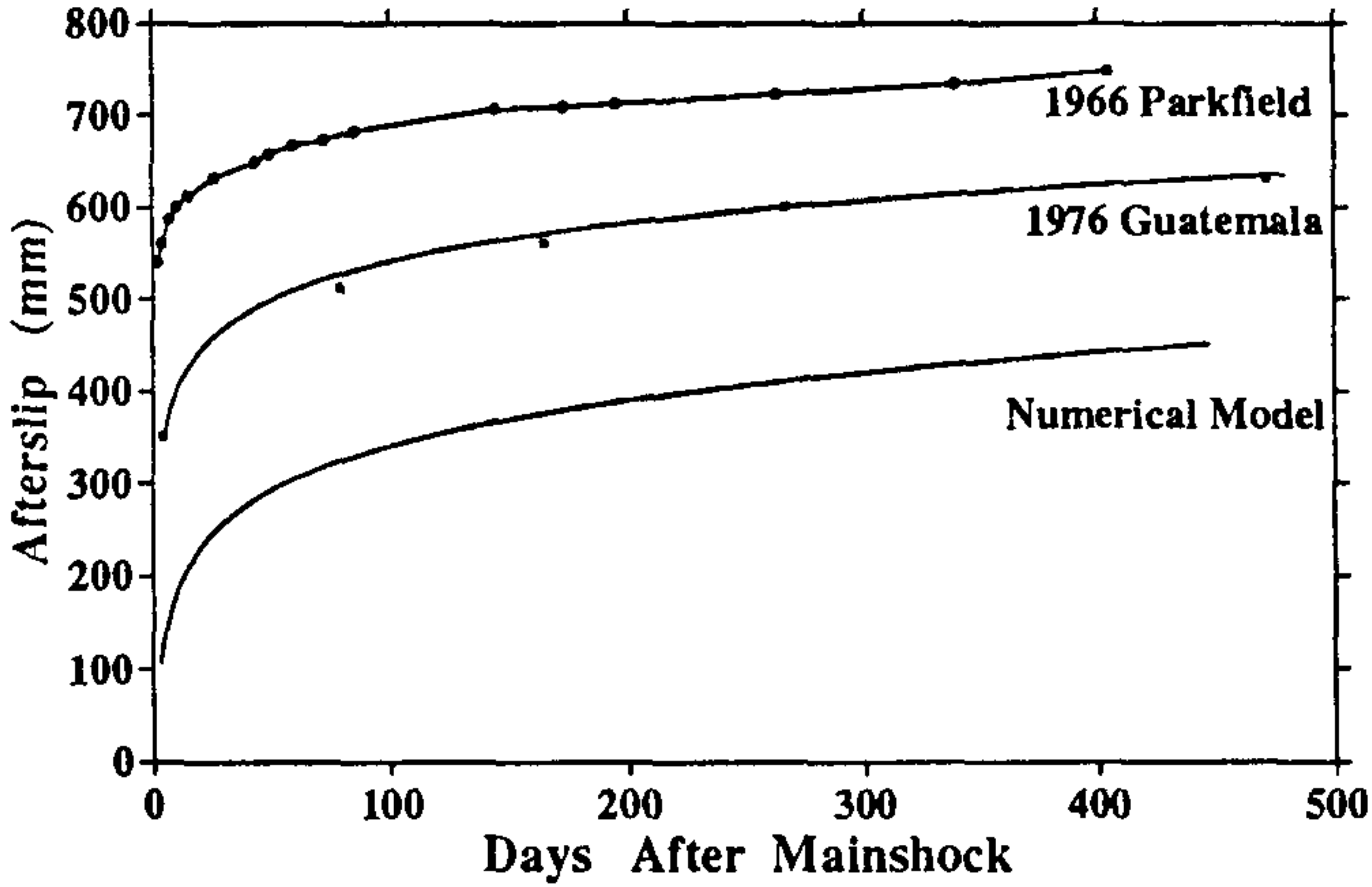
$$\Delta\tau = \tau_p - Uk$$

- With some substitution, this leads to

$$V = \frac{dU}{dt} = V_0 \exp\left(\frac{\tau_c - Uk}{A - B}\right)$$

$$U = \frac{A - B}{k} \ln\left[\left(\frac{kV_p}{A - B} t + 1\right)\right]$$

Comparison to Data



Marone et al., 1991

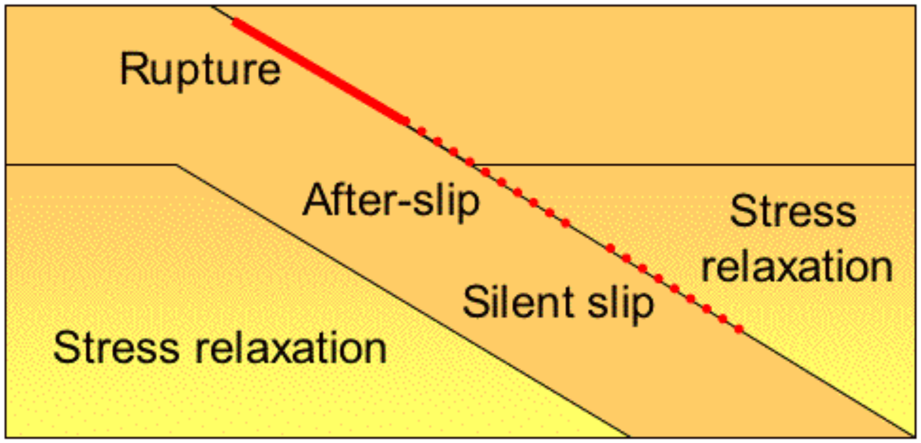
Notes on Marone et al. Model

- The model applies to shallow afterslip in a velocity-strengthening region, (A-B)>0, such as near-surface creep following an earthquake.
- It is often assumed that a similar expression will result for deep afterslip
- We don't generally know the constants, so we typically estimate them:

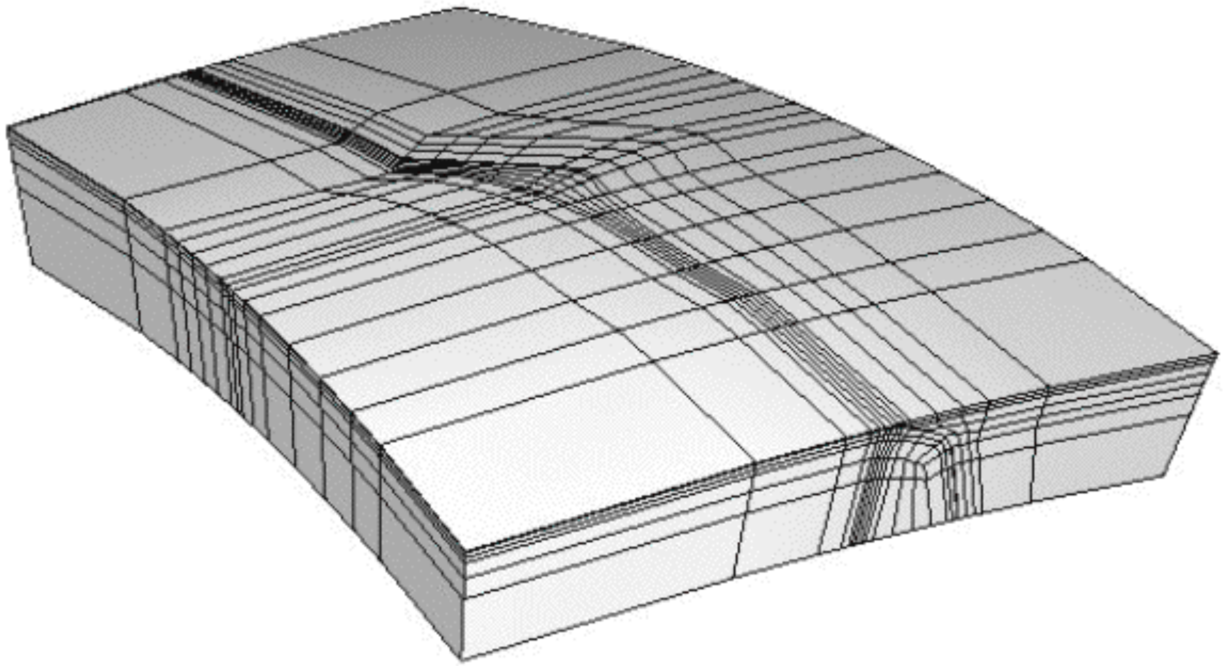
$$U = C \ln(\alpha t + 1)$$

  – $(1/\alpha)$ has the form of a relaxation time

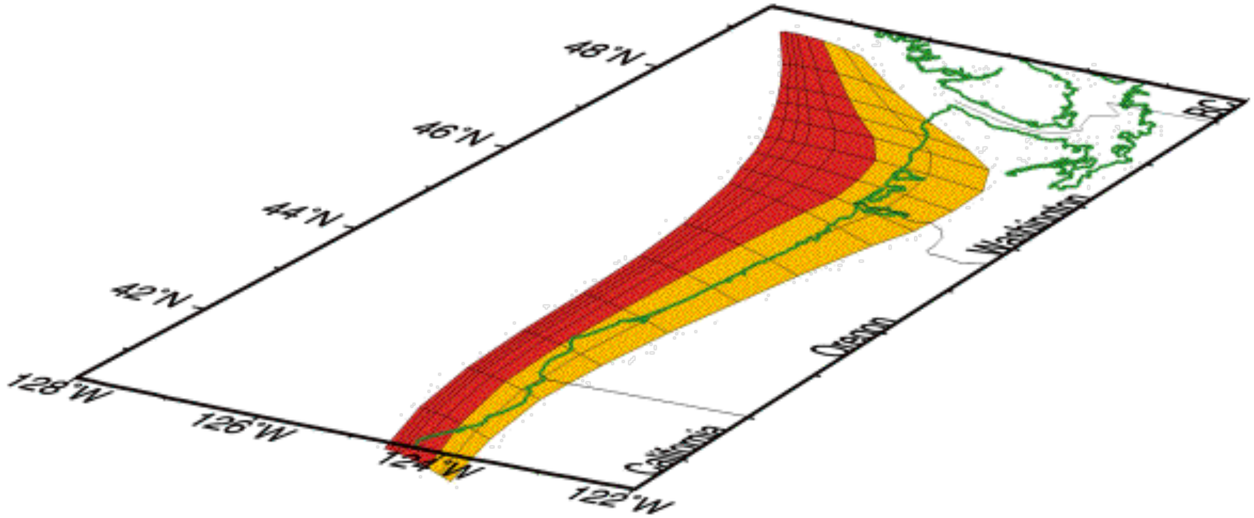
Viscoelastic Relaxation

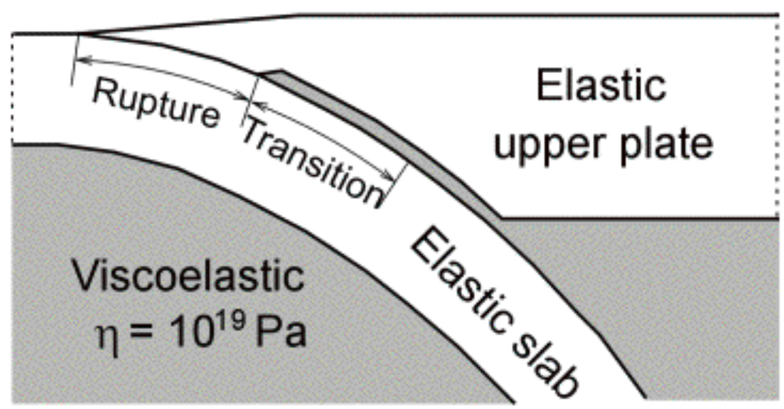


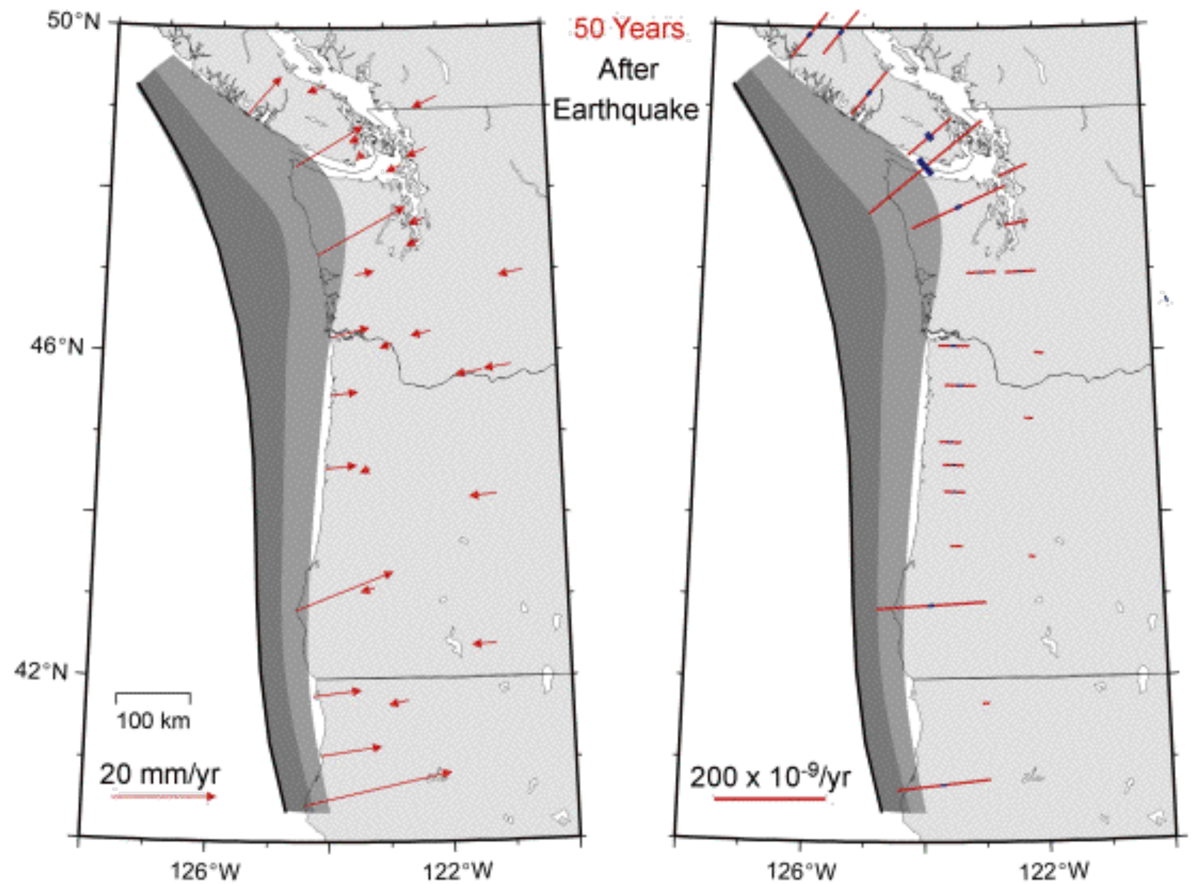
Viscoelastic deformation model for Cascadia
(3-D spherical finite element)



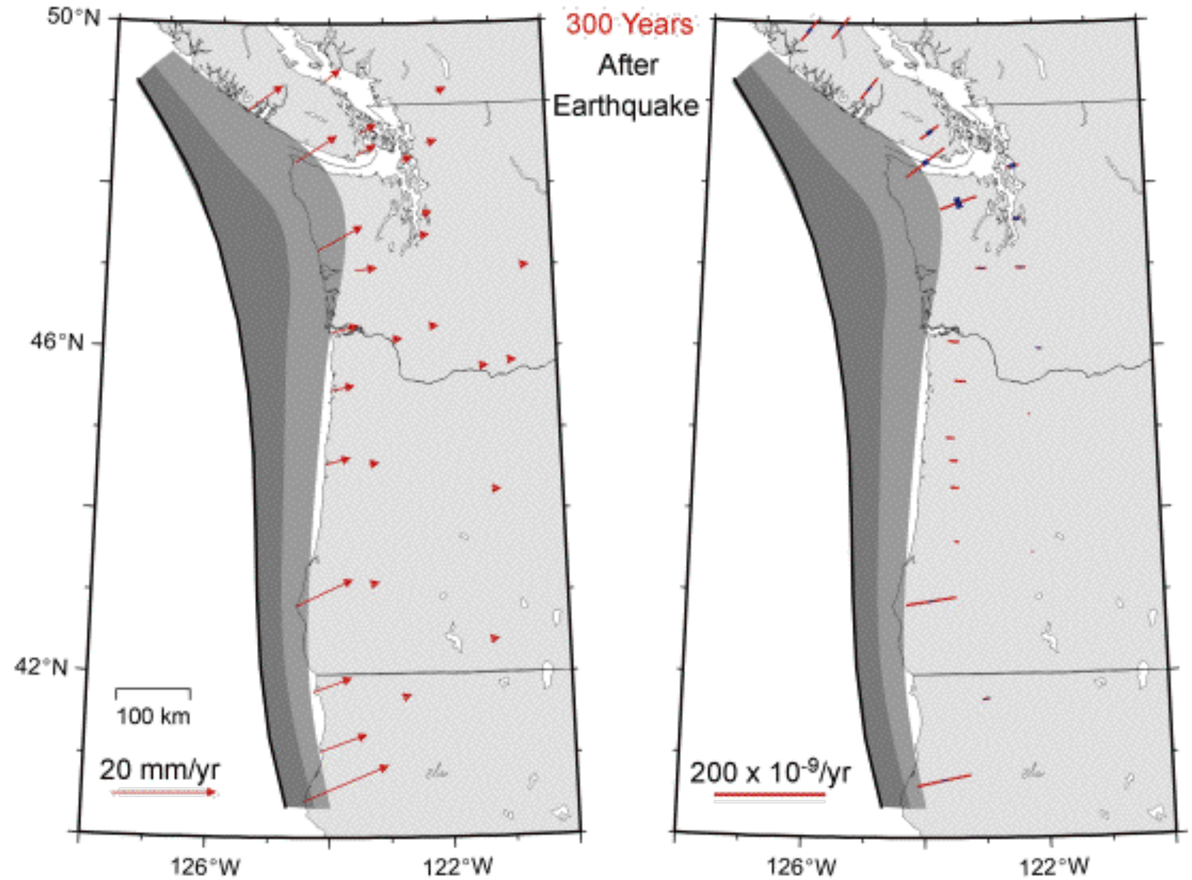
Model by J. He


48°N
46°N
44°N
42°N
128°W
126°W
124°W
122°W
BC
Washington
Oregon
California


Rupture
Transition
Elastic
upper plate
Elastic slab
Viscoelastic
η = 10¹⁹ Pa



(a) Velocities (b) Strain Rates

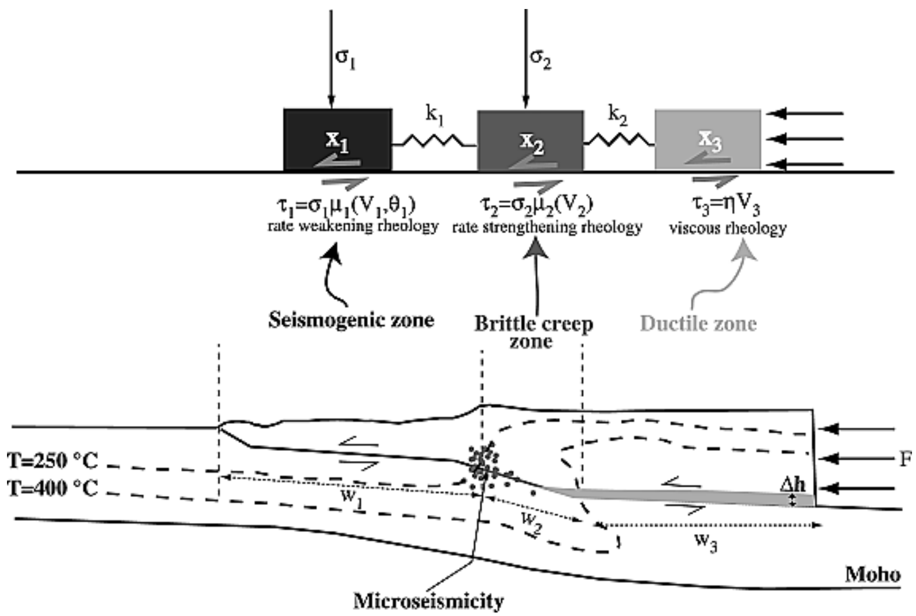


(a) Velocities (b) Strain Rates

Viscoelastic ± Afterslip

- Like afterslip, viscoelastic relaxation also can produce postseismic motion toward trench.
- Different spatial pattern
  - Deeper = longer wavelength
- Different temporal decay
  - In general, longer decay time
  - Relaxation time proportional to mantle viscosity, expected to be years to decades.
  - Exponential relaxation for viscoelastic

Perfettini Model



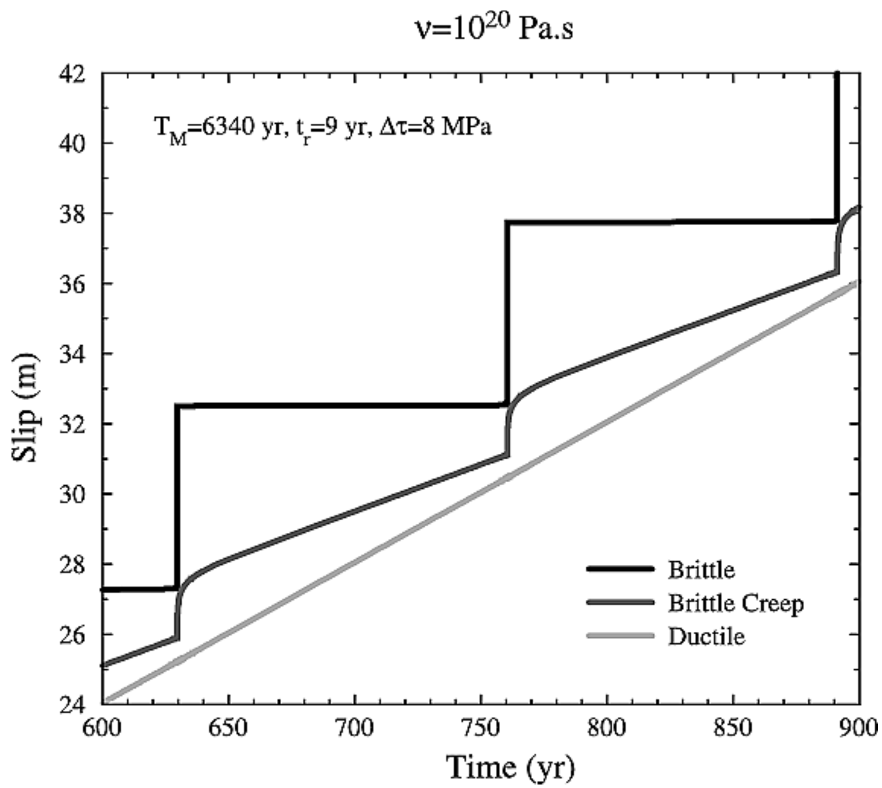
- Model history of slip using three linked "spring-sliders"
  - *Seismogenic: rate and state friction*
  - *Brittle creep zone: rate and state, stable*
  - *Ductile shear zone: viscous*
- Perfettini and Avouac (2004), Perfettini et al. (2005)

Key Assumptions

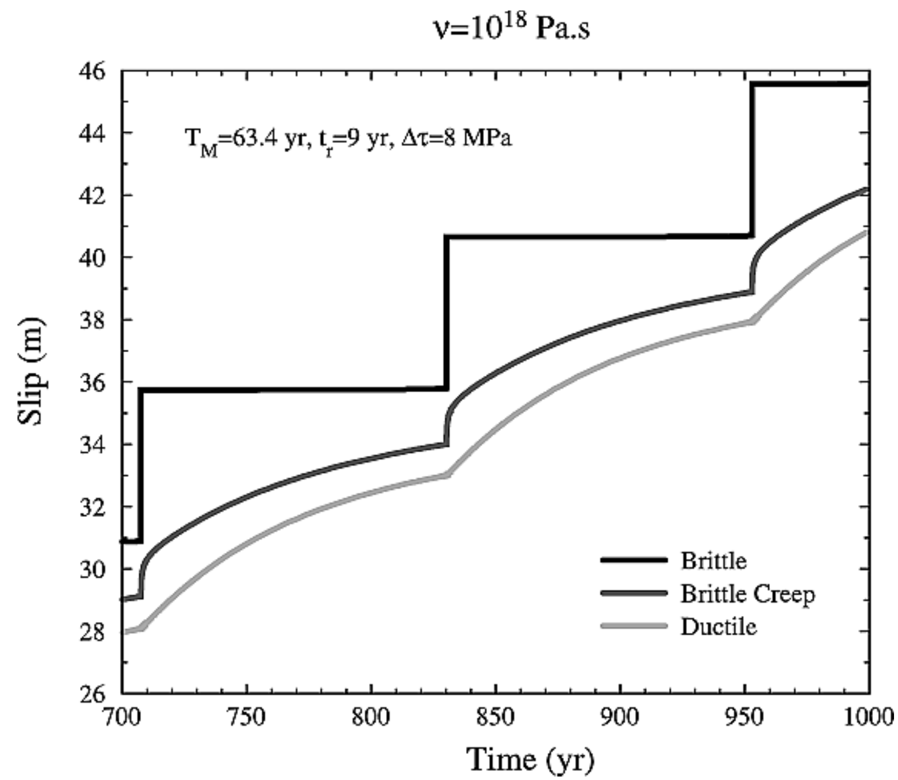
- System is driven by steady displacement at depth (viscous zone end of problem)
- Coupling between spring sliders is elastic, simulates response of surrounding medium
- Frictional failure results in repeated earthquakes
- This is a 1D model – predicts only the time dependence

Behavior

depends on viscosity of ductile zone

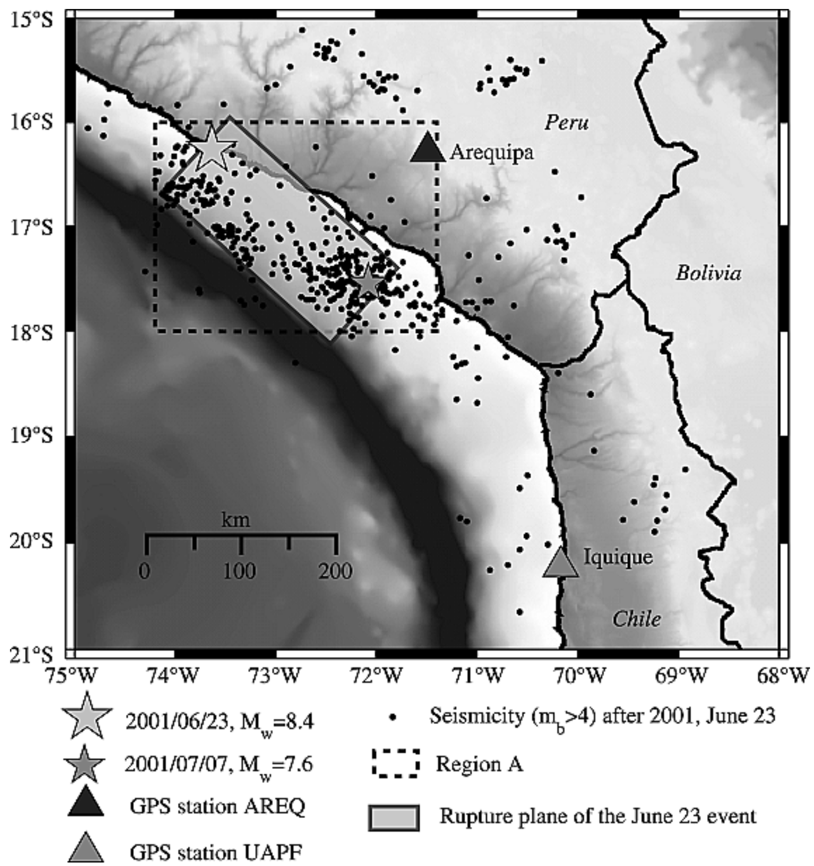


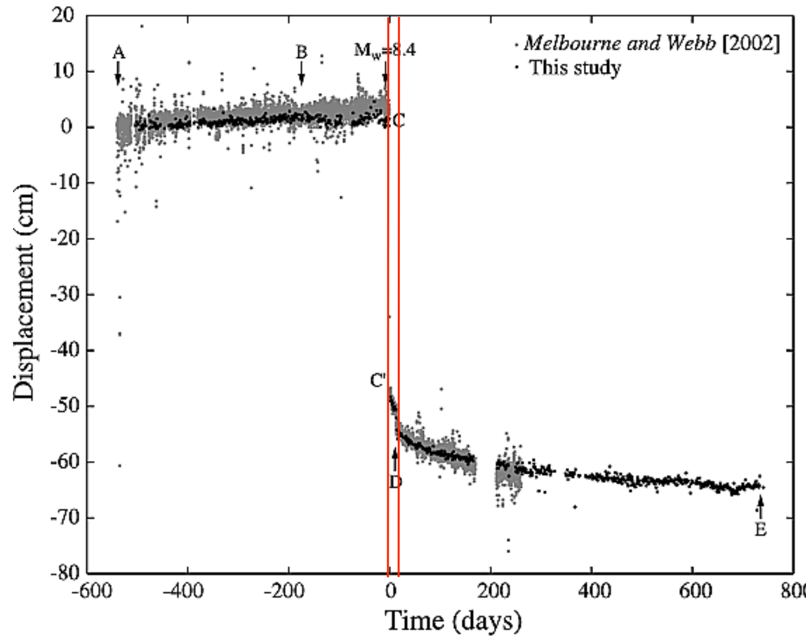
High viscosity



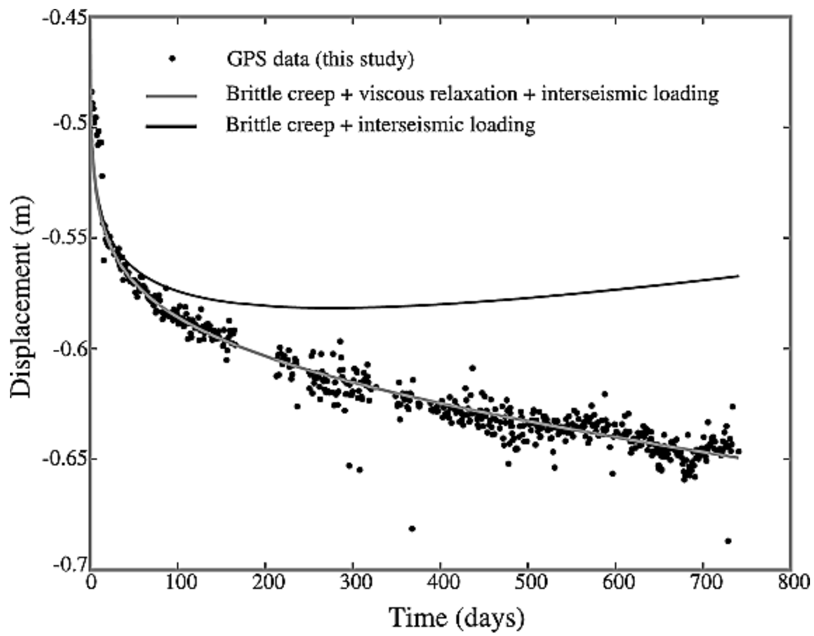
Low viscosity

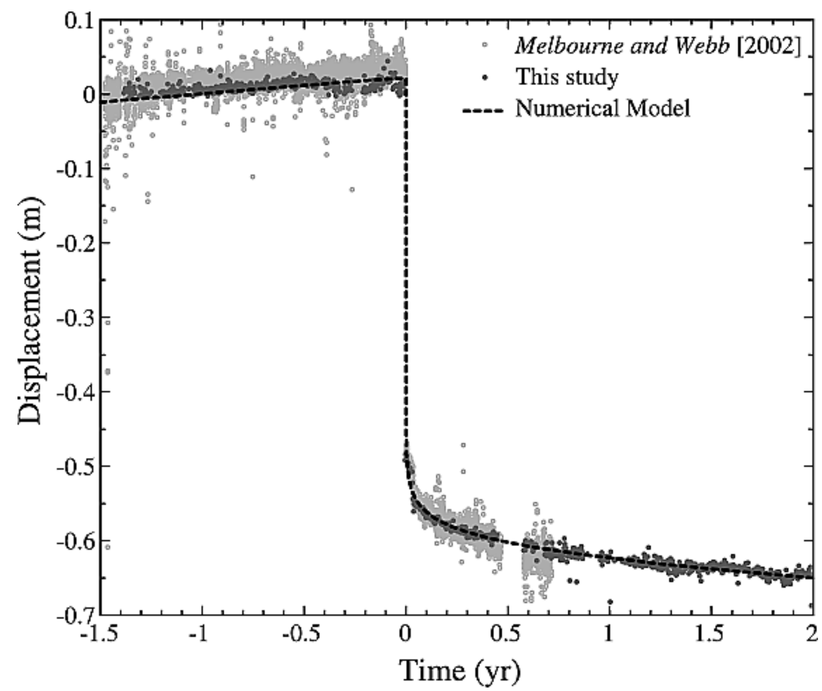
An Example – Arequipa, Peru



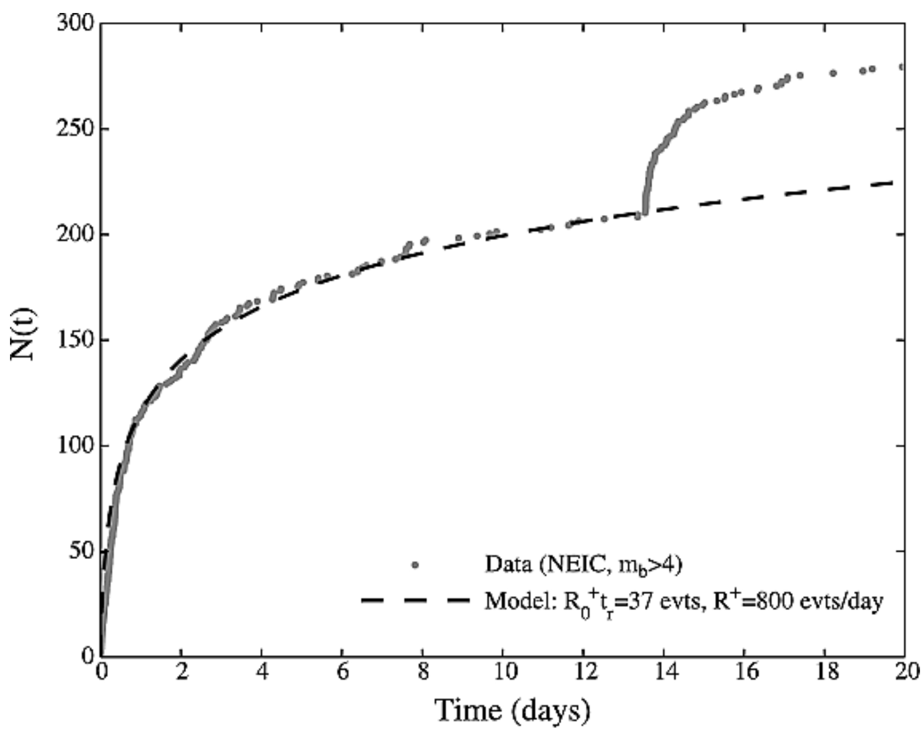


Fit to GPS Data





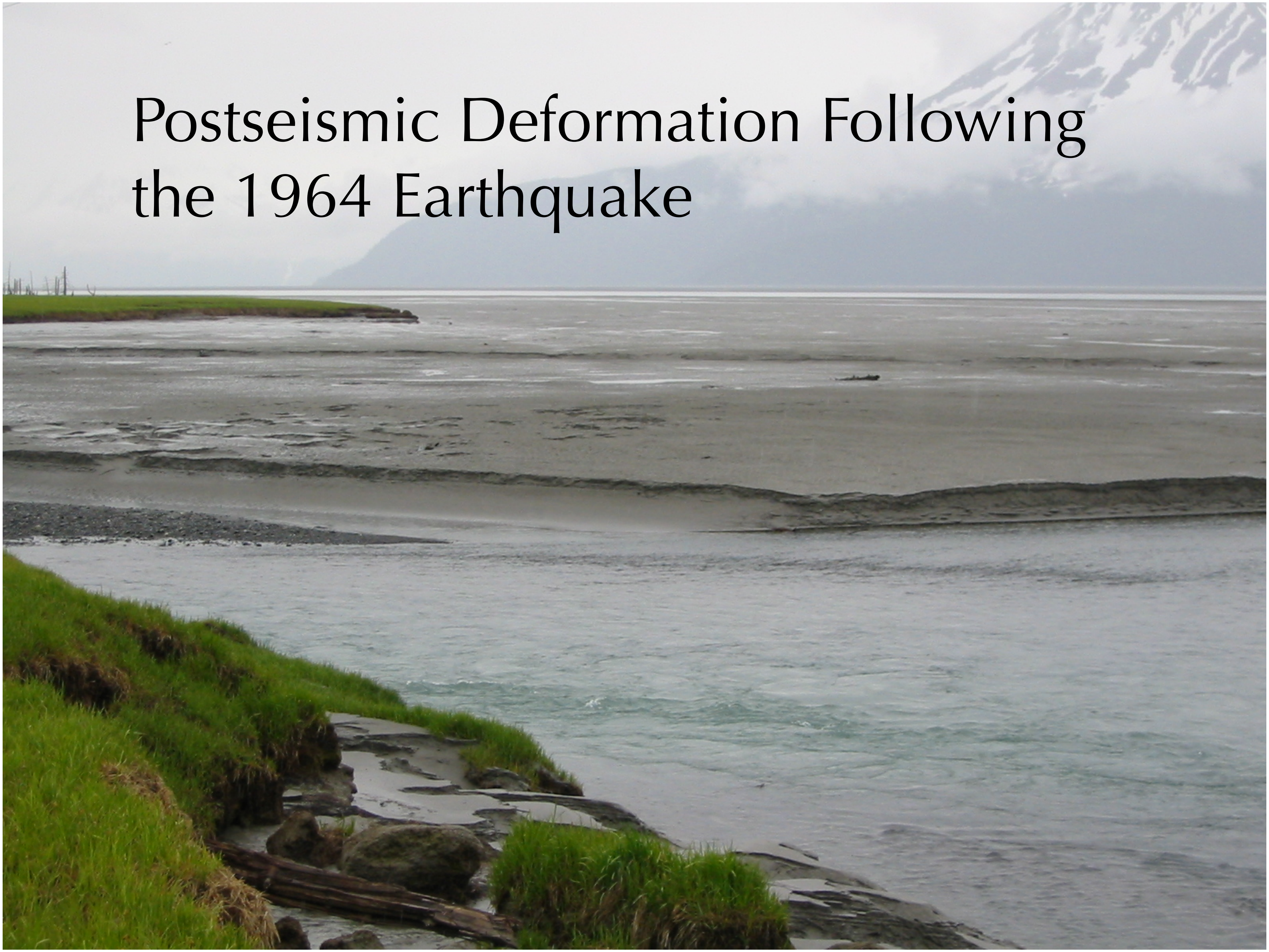
Relation of Slip, Aftershocks



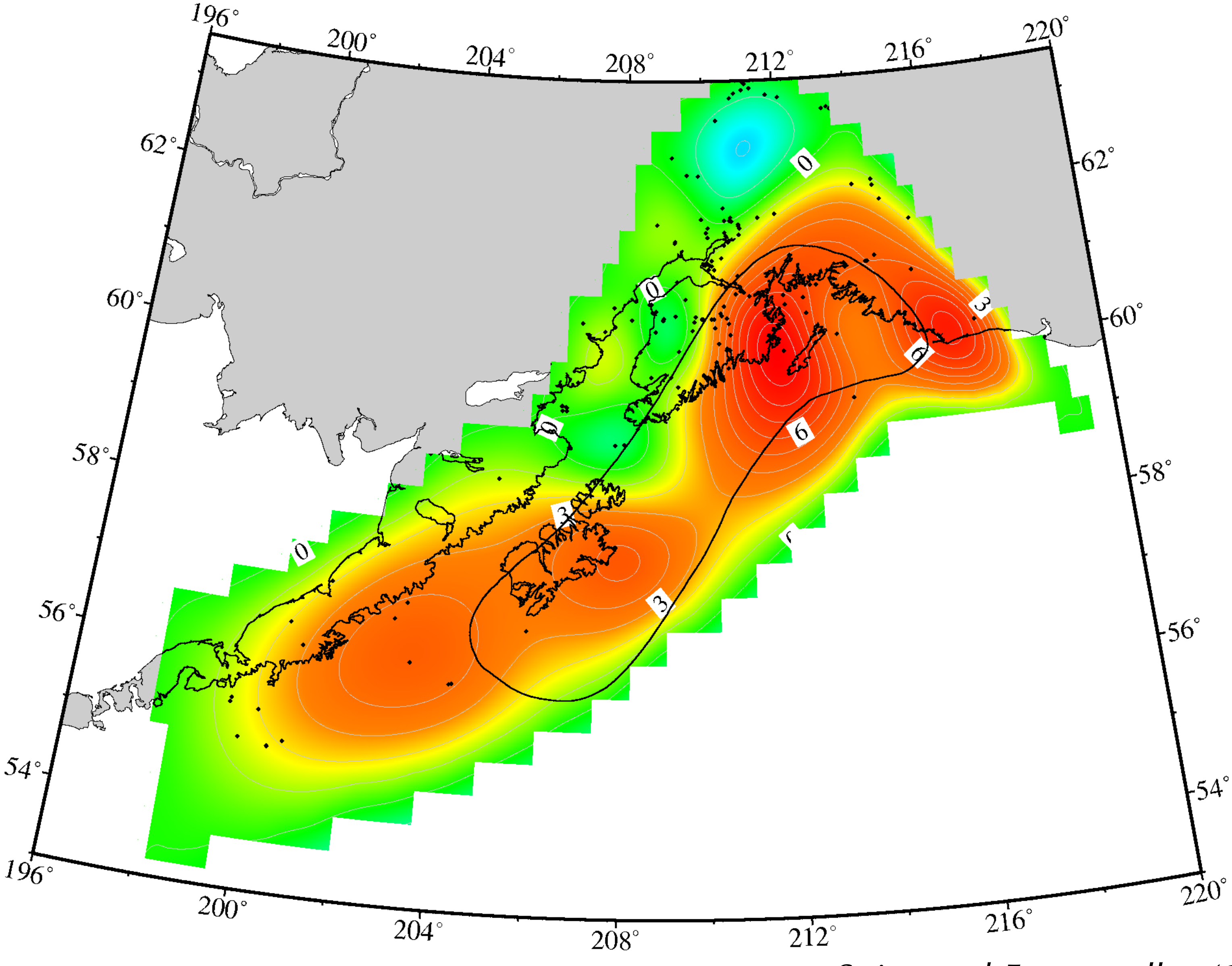
- The model also predicts that the aftershock rate and afterslip creep rate are related.

$$\frac{R_0^+}{R_0^-} = \frac{(V_2^0)^+}{(V_2^0)^-} = \frac{V_3^+}{V_3^-} = \exp(\alpha),$$

- The parameter α also controls the time evolution of the GPS data.


Postseismic Deformation Following
the 1964 Earthquake

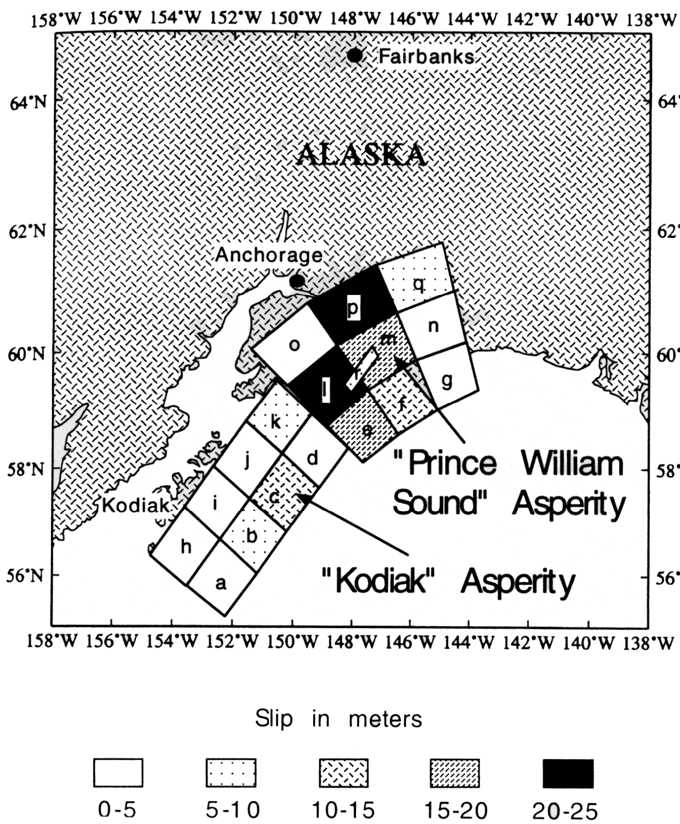
Regional Plate Coupling



Suito and Freymueller (2009)

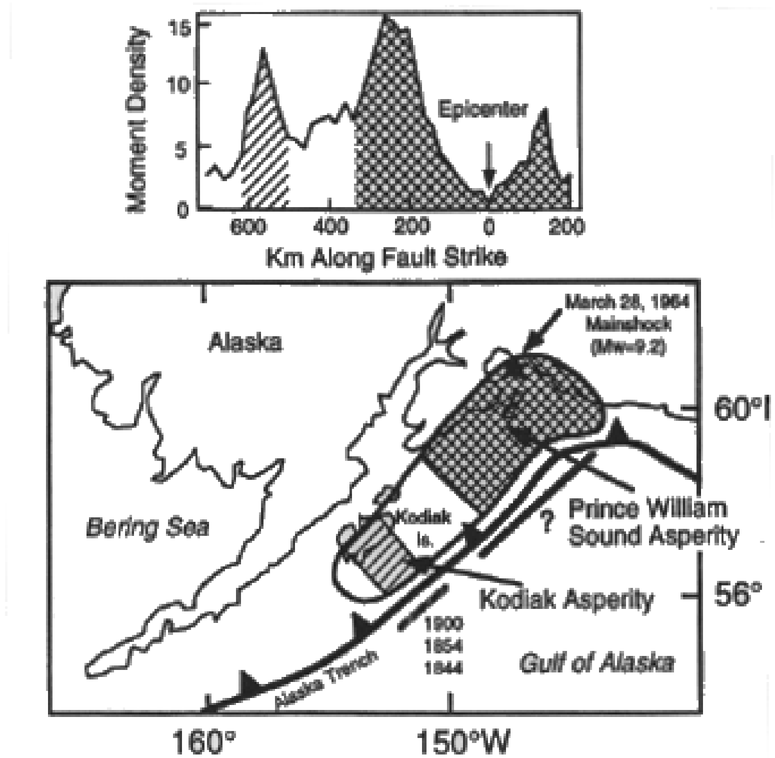
Slip Distributions

Geodetic



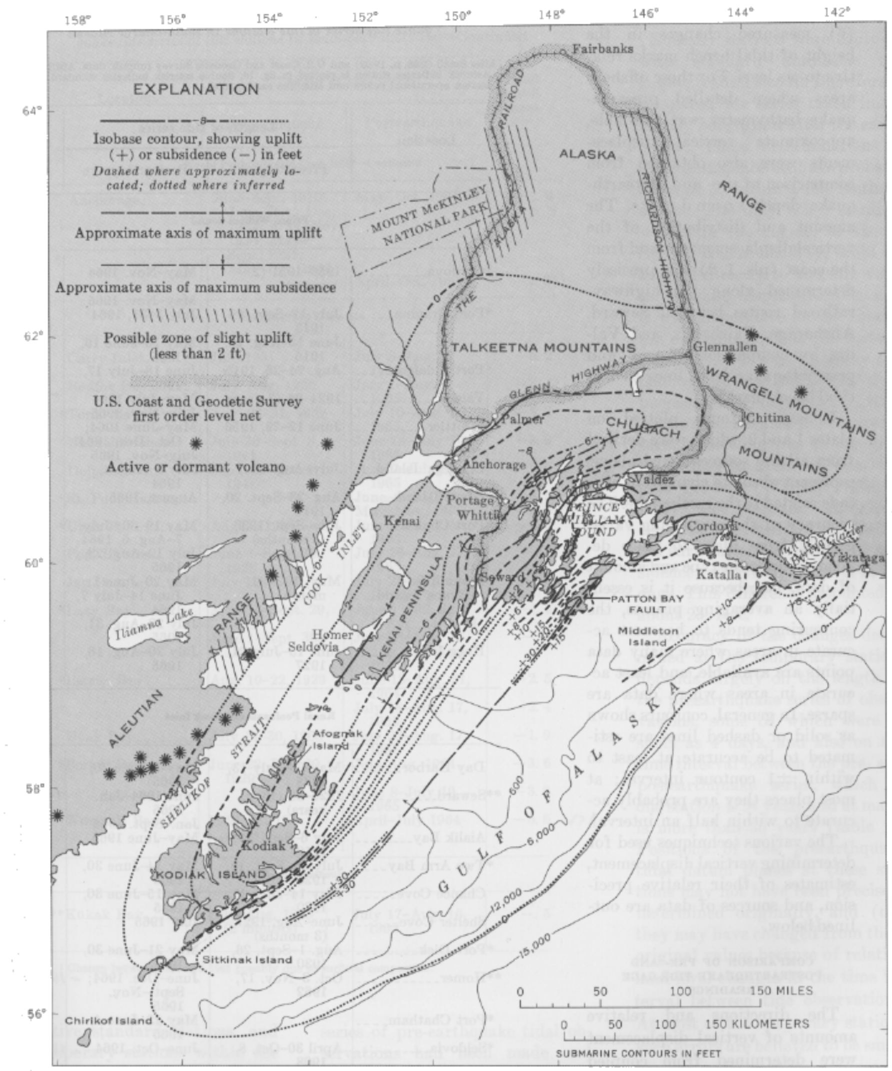
Johnson et al. (1996)

Seismic

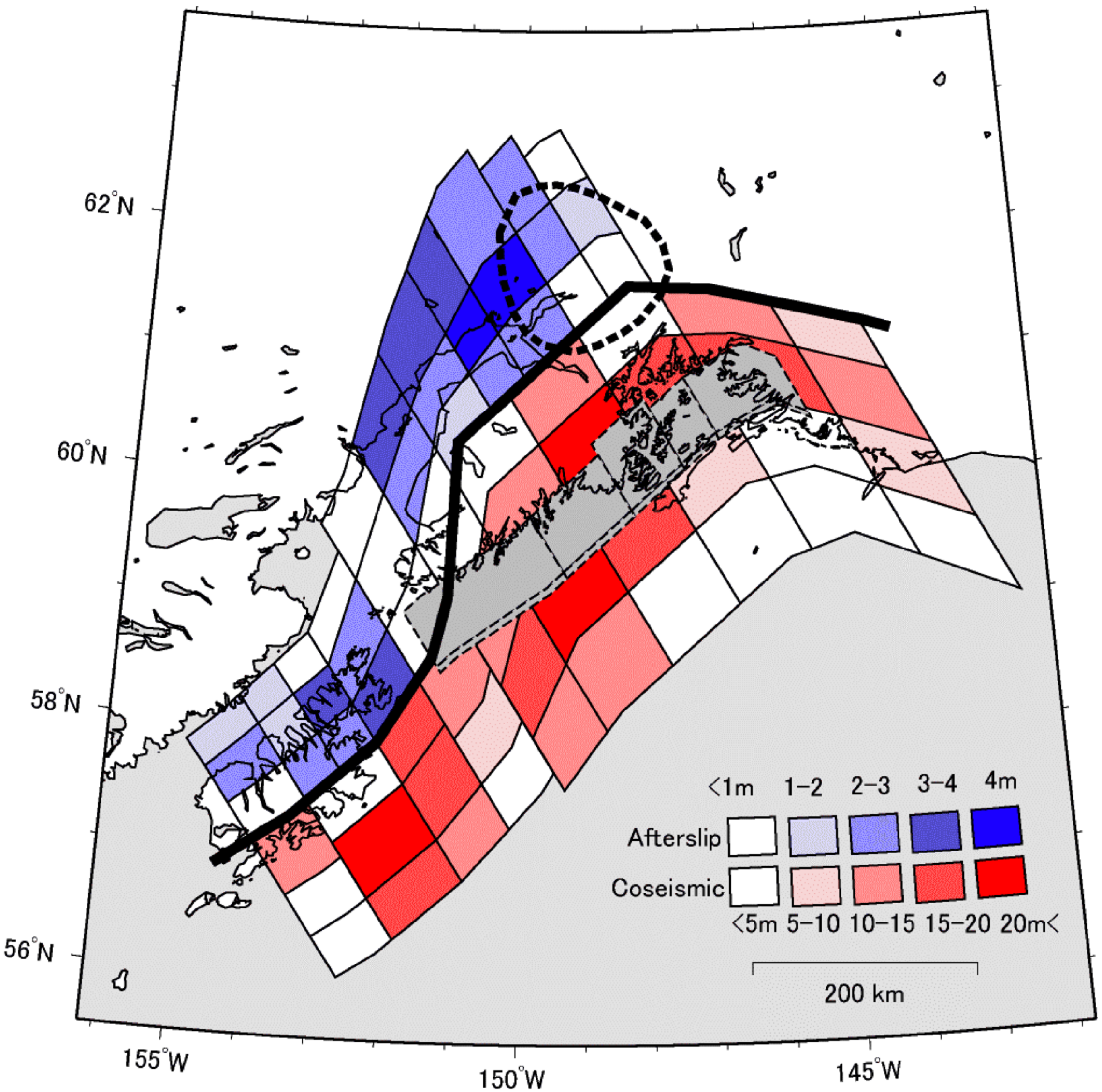


Christensen and Beck (1994)

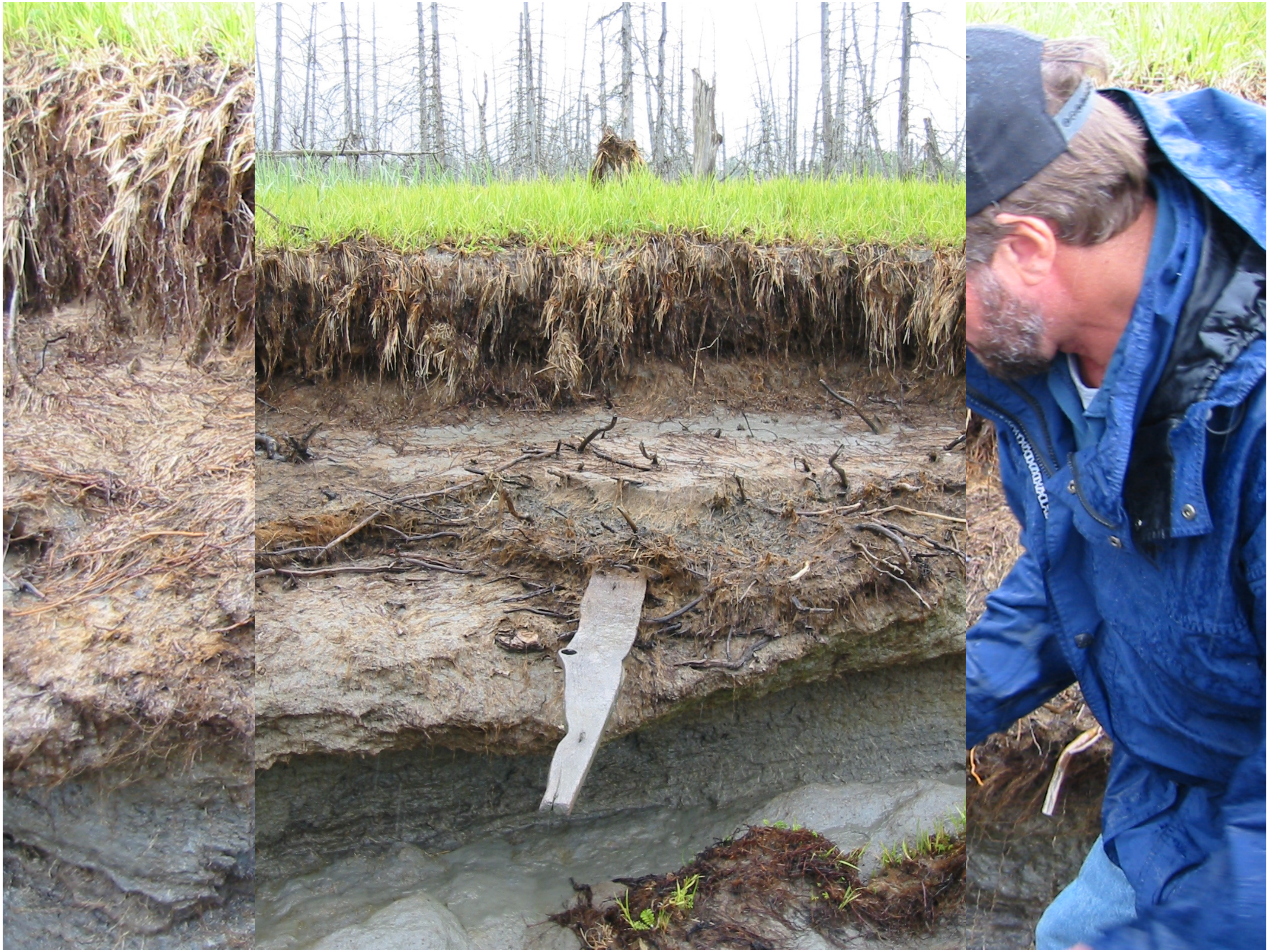
Coseismic Vertical Displacements



Newly Estimated Slip Distribution



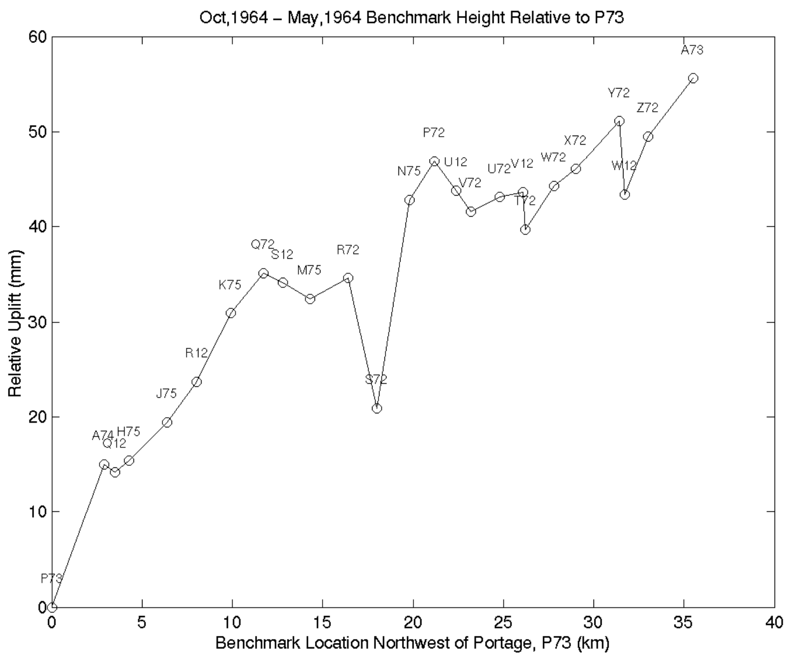
- Important new feature is longer splay fault (gray fault)
- We also estimated the (postseismic) afterslip distribution (blue)

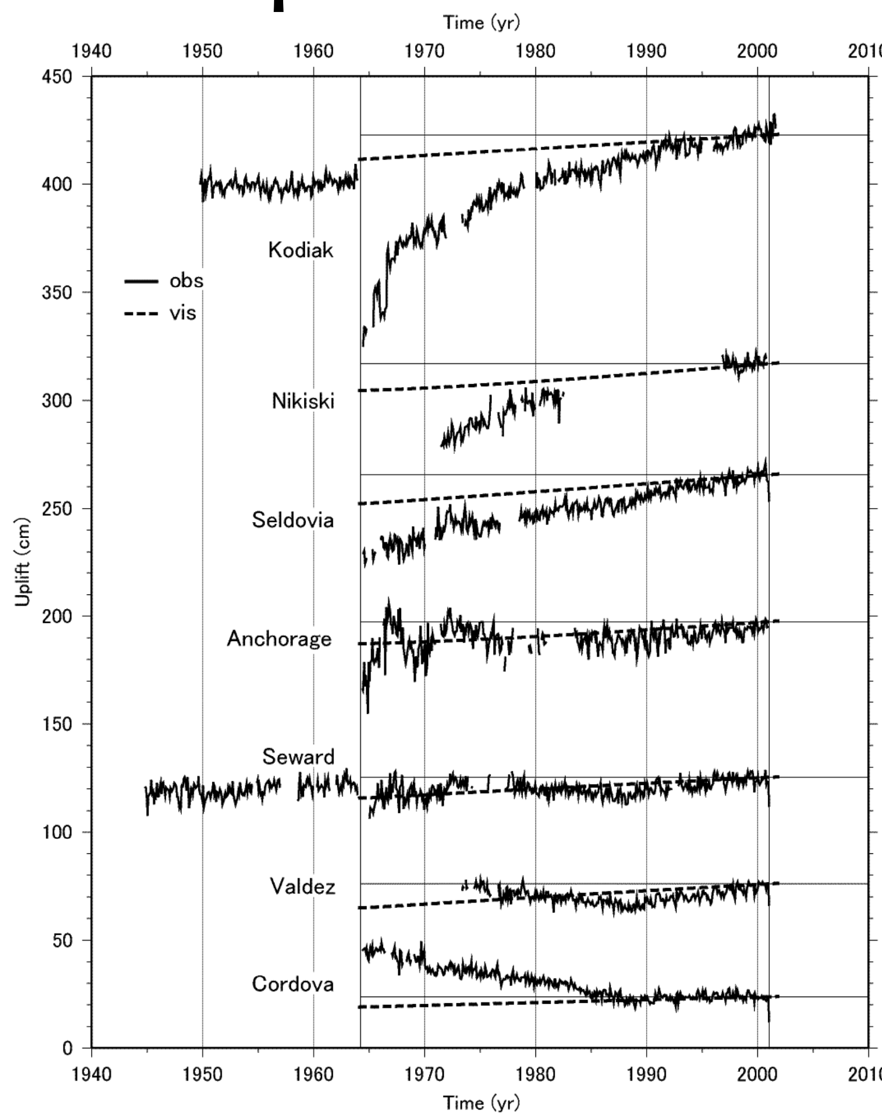


Data for Alaska 1964 Postseismic

- Cumulative uplift and angle changes
  - Tide gauge observations
  - Leveling marks resurveyed with GPS
  - Triangulation marks resurveyed with GPS
- Present-day velocities (3D)
  - Based on GPS observations 1992-2007
  - Many new sites on road started 1995-96
  - Most sites off road system started in 1998+

Postseismic Uplift

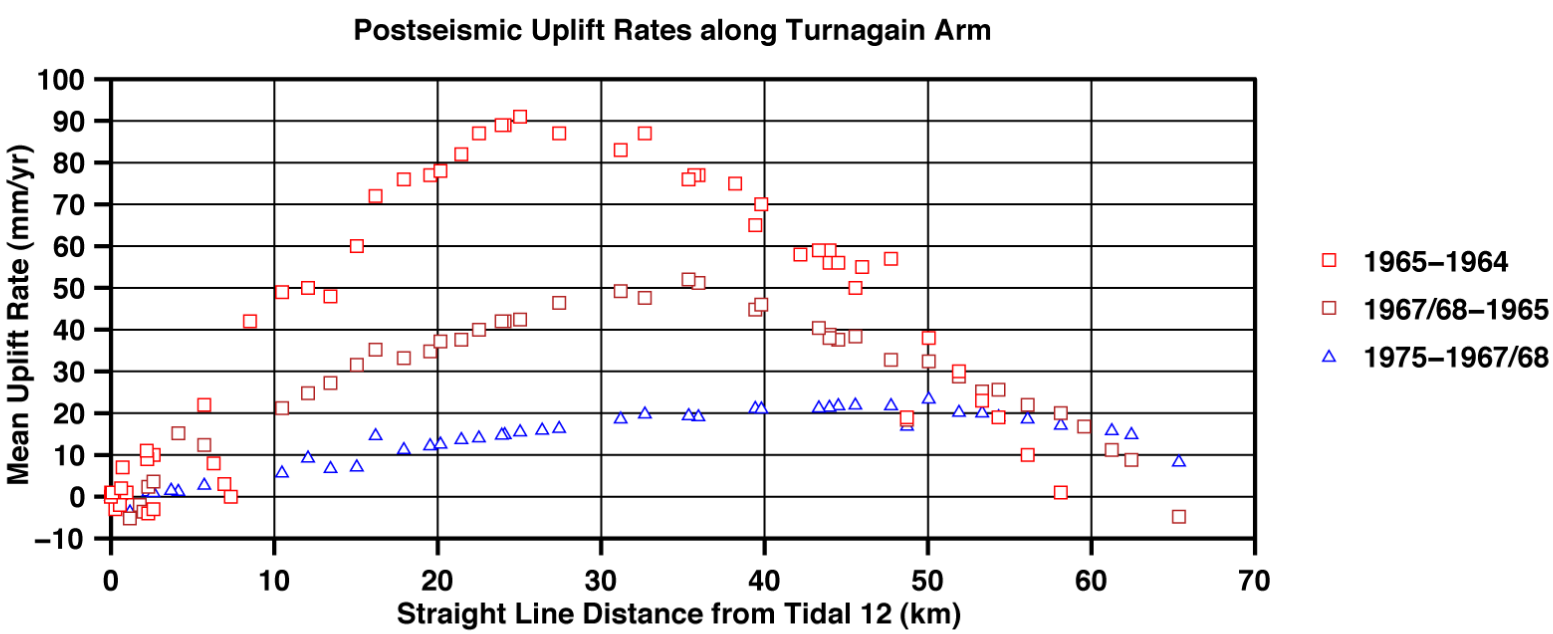




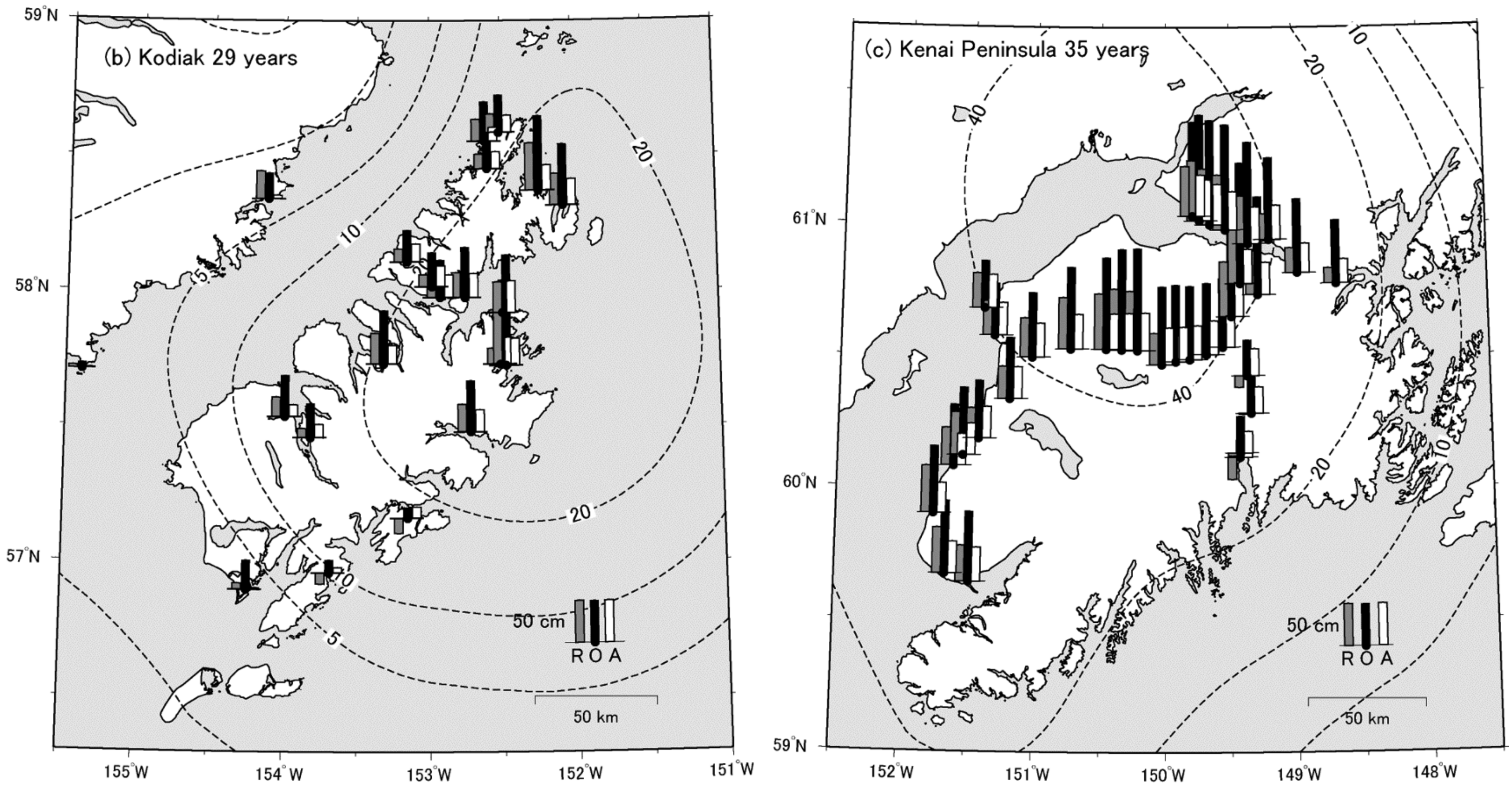
General Character of Postseismic

- Rapid uplift was observed following 1964 earthquake (precise horizontal data were not available)
- Uplift rate declined over time
- Long-term (decadal) uplift rate still faster than before earthquake
- Postseismic deformation concentrated near downdip end of locked zone.

Decline in Postseismic Uplift Rate

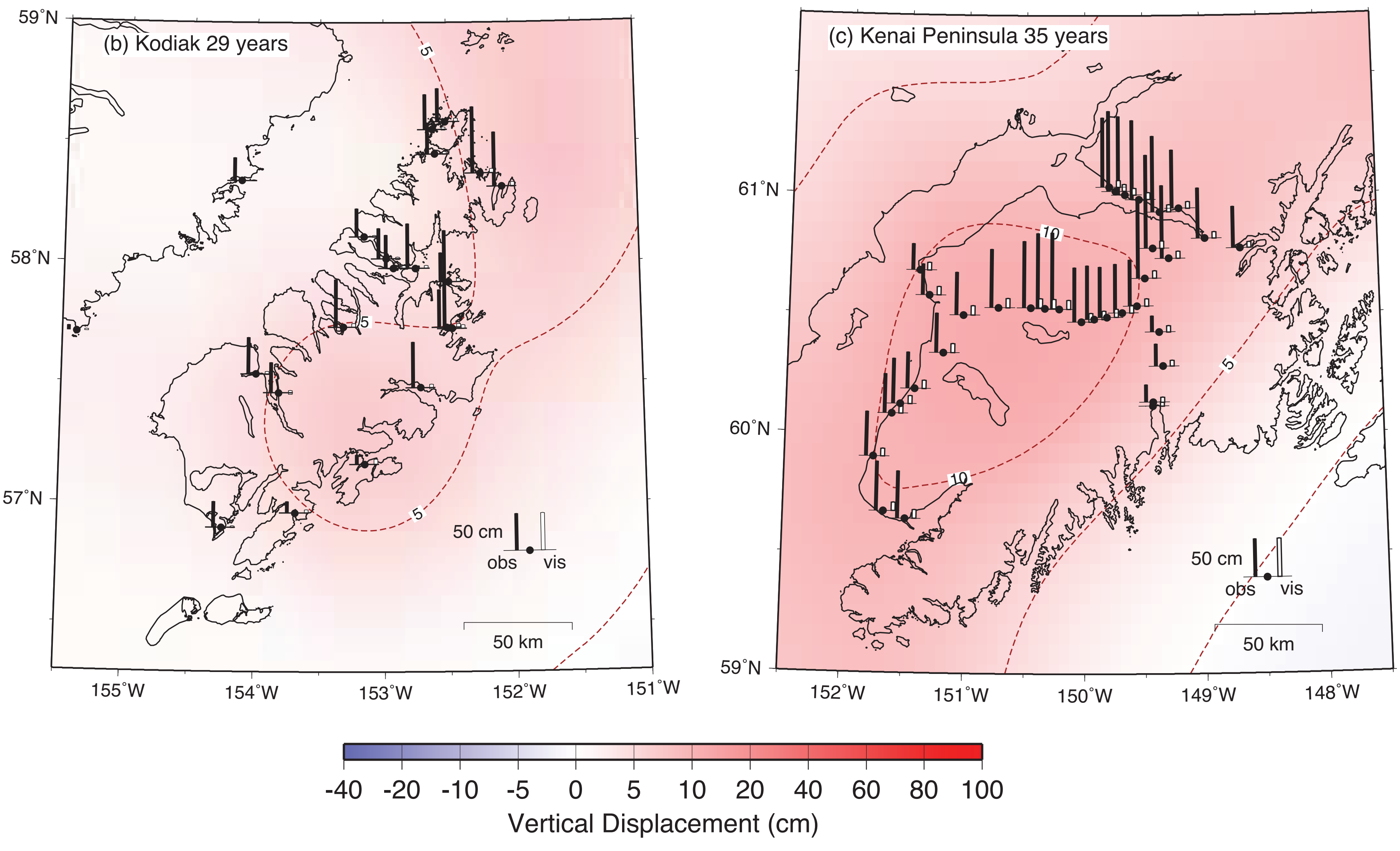


Cumulative Postseismic Uplift



1964 to present (cm)

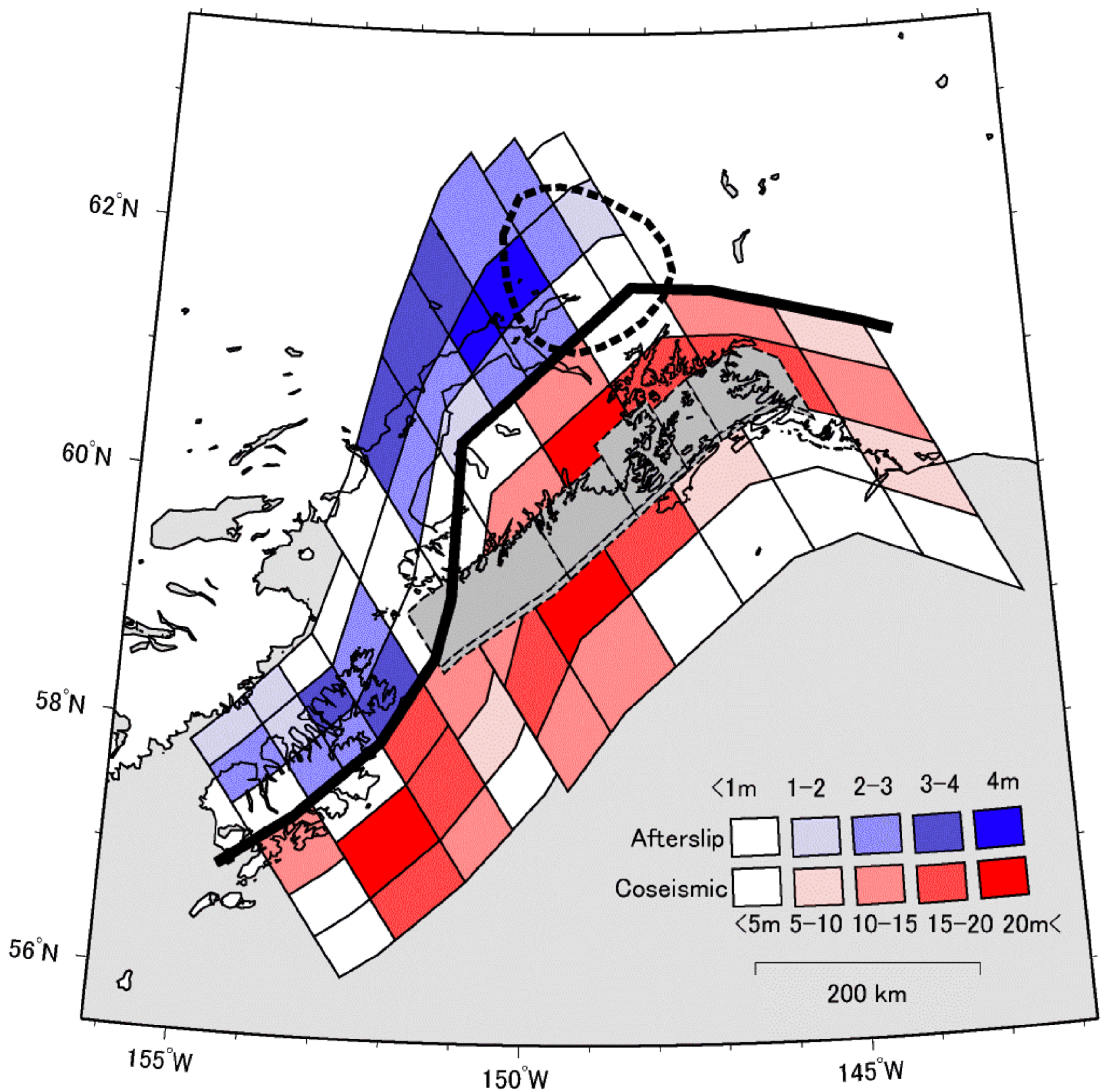
Viscoelastic Only Model



Estimating Afterslip

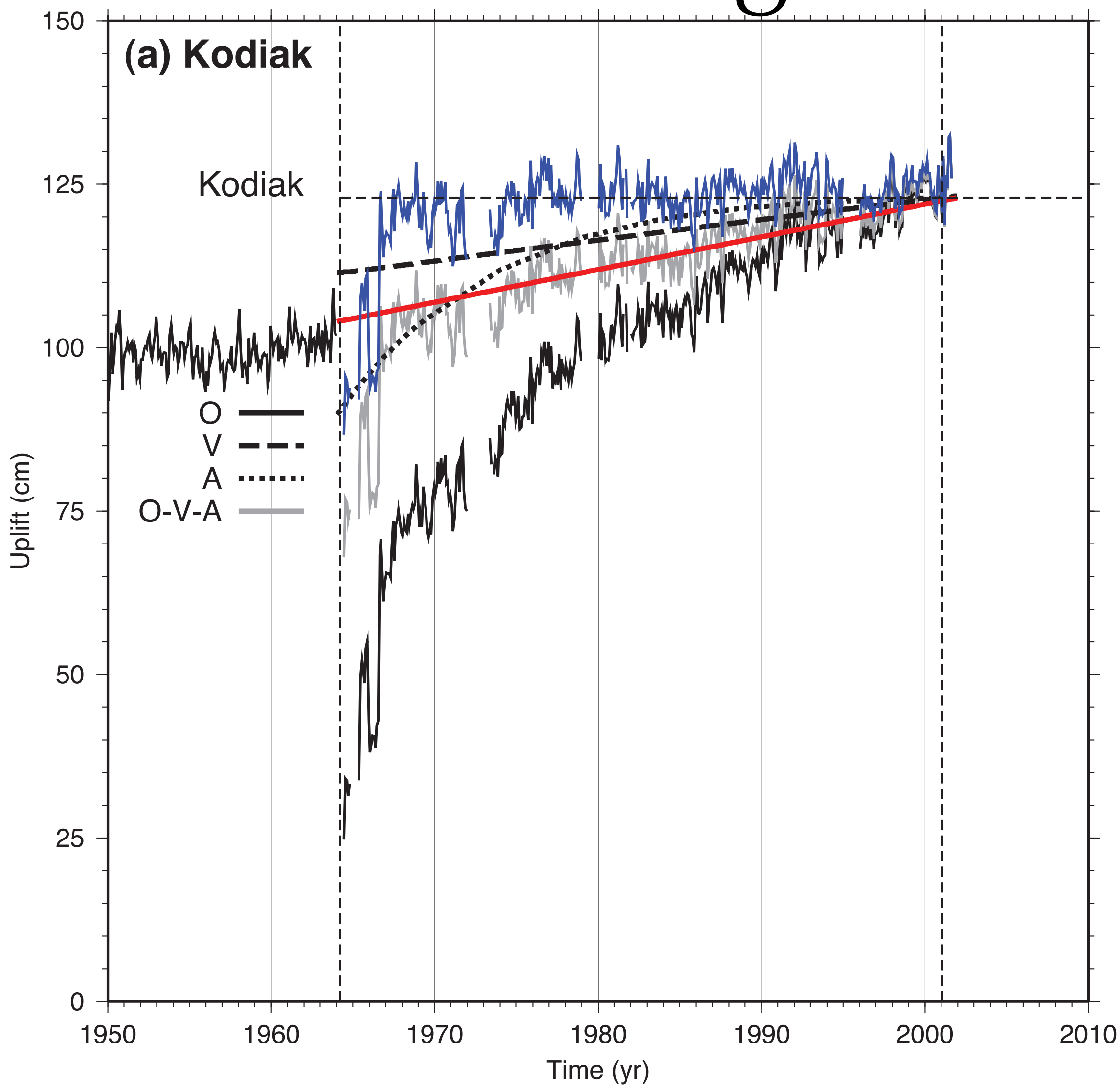
- Subtract the viscoelastic model predictions from the cumulative uplift data
- Estimate an afterslip distribution to fit the data.

Newly Estimated Slip Distribution



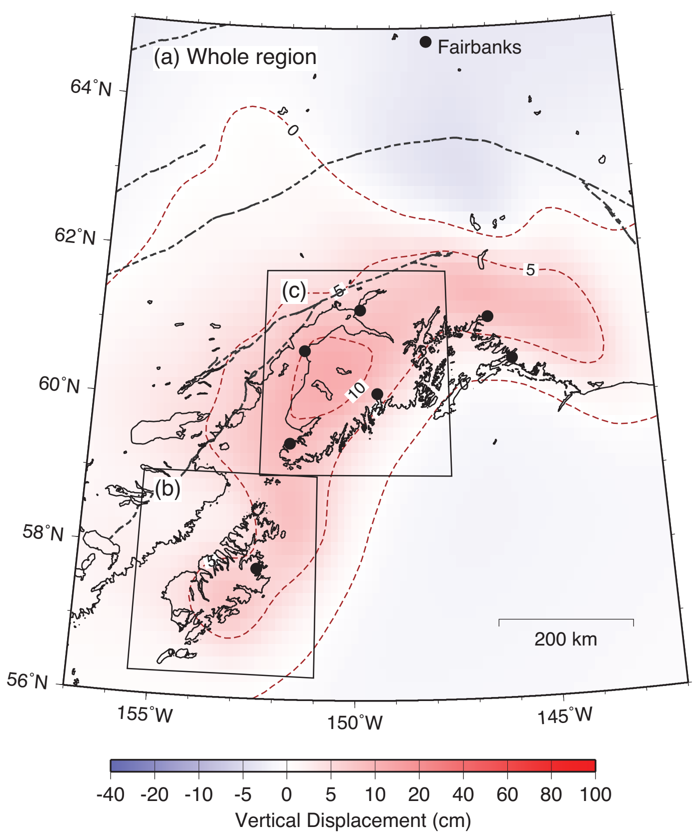
- Important new feature is longer splay fault (gray fault)
- We also estimated the (postseismic) afterslip distribution (blue)

Time Dependence from Kodiak Tide Gauge

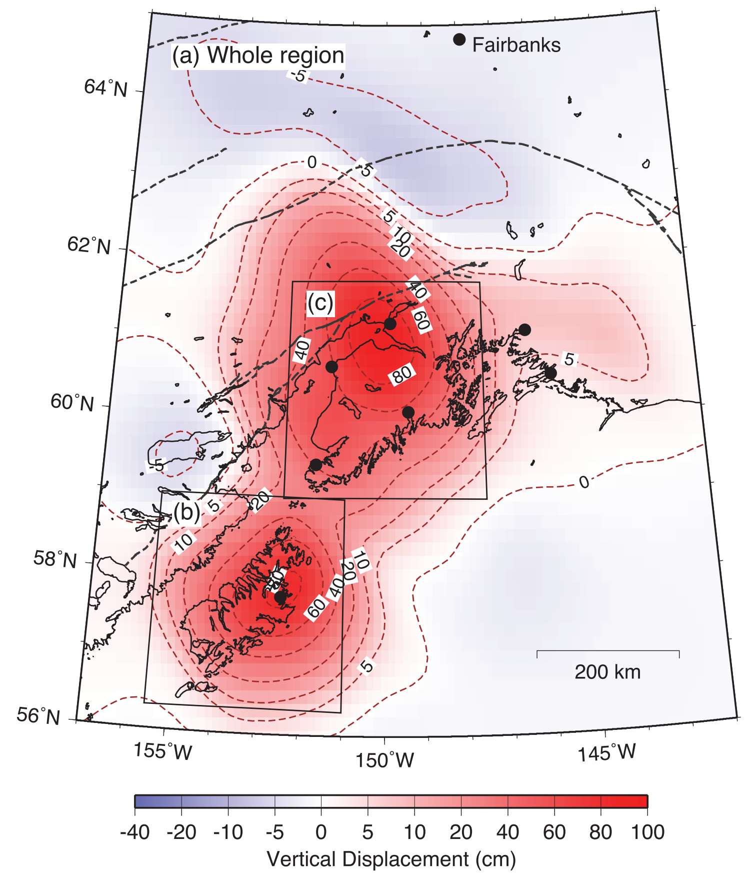


Models of Uplift Compared

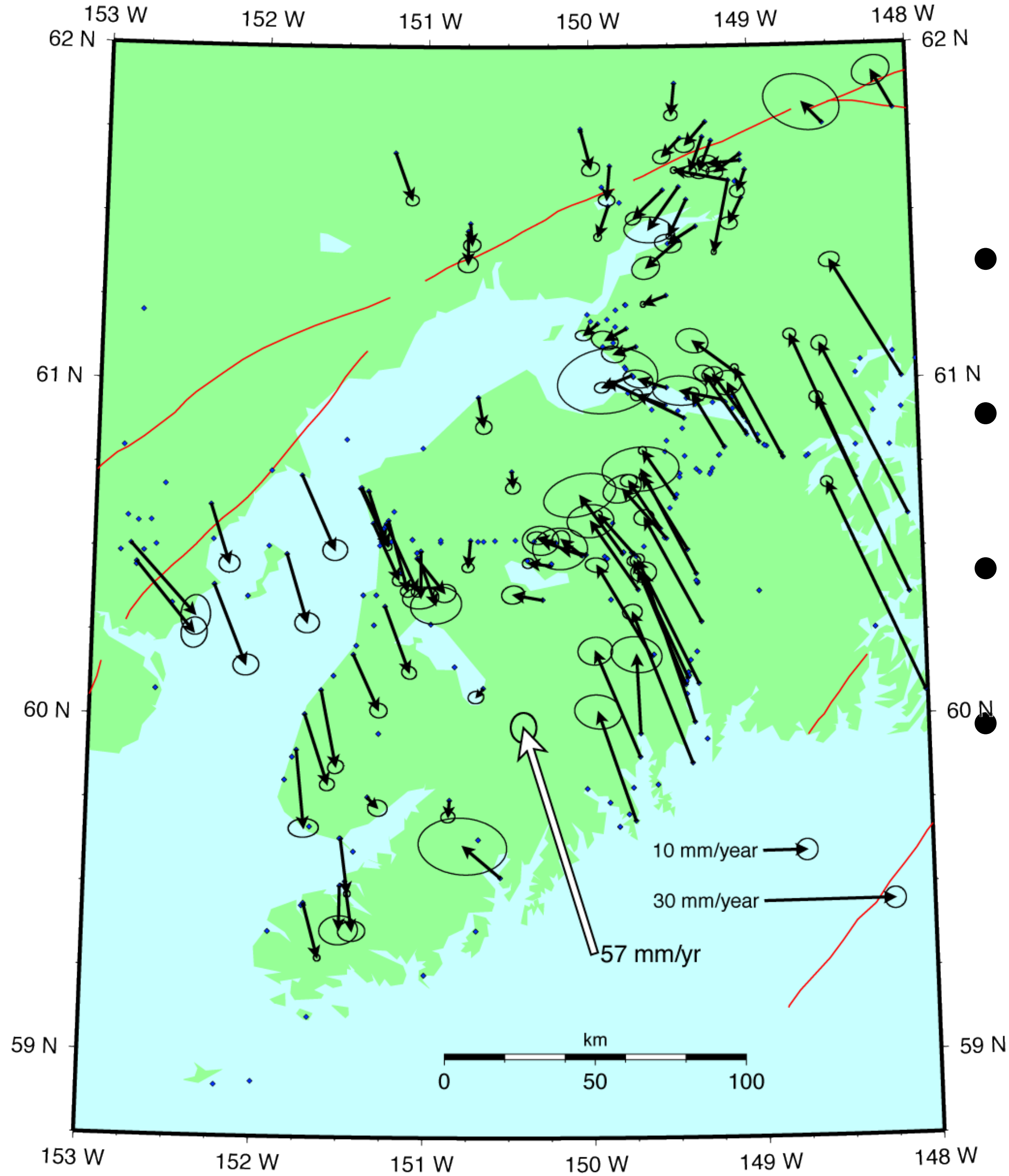
Viscoelastic Only



Viscoelastic + Afterslip

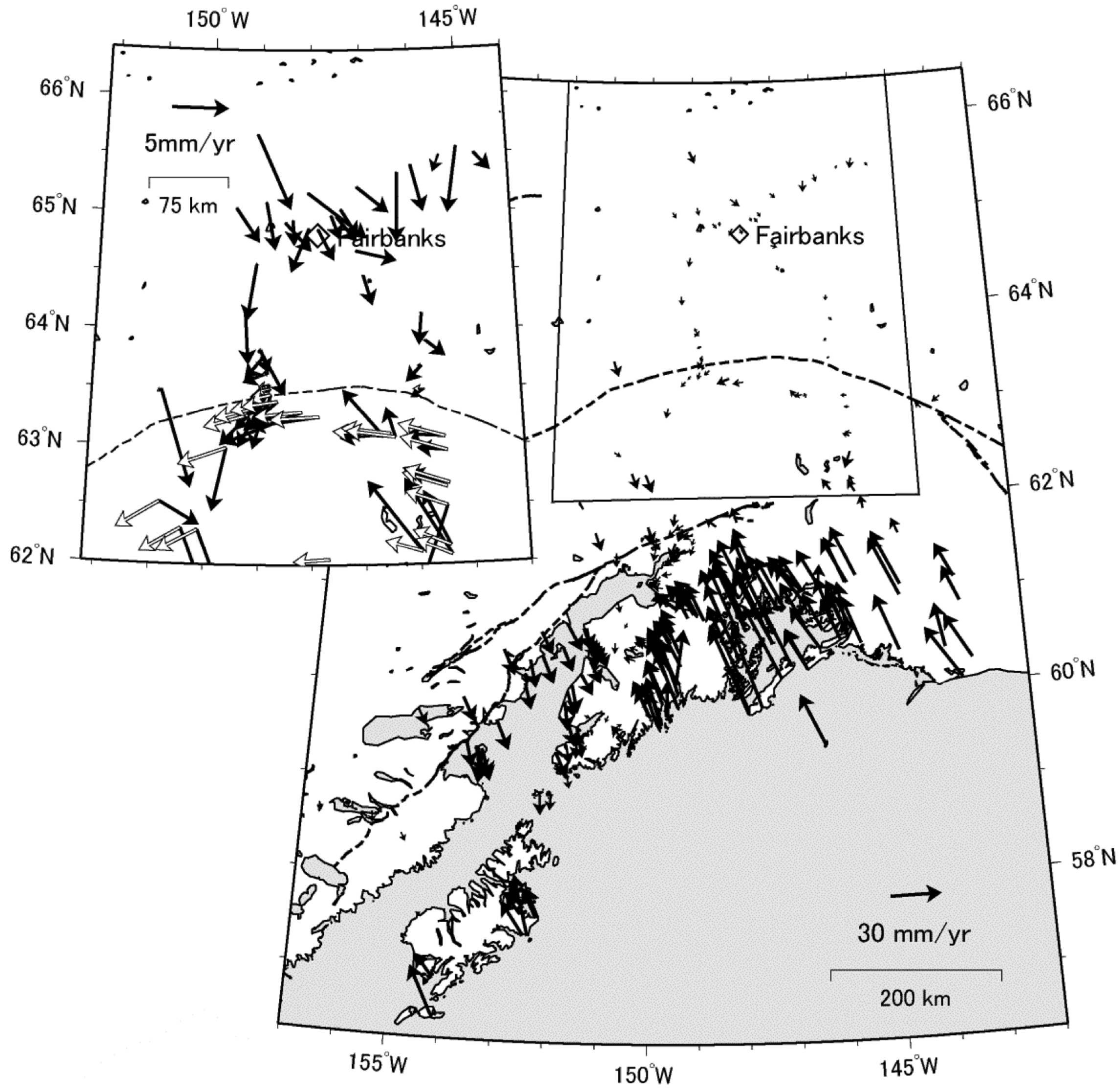


Horizontal

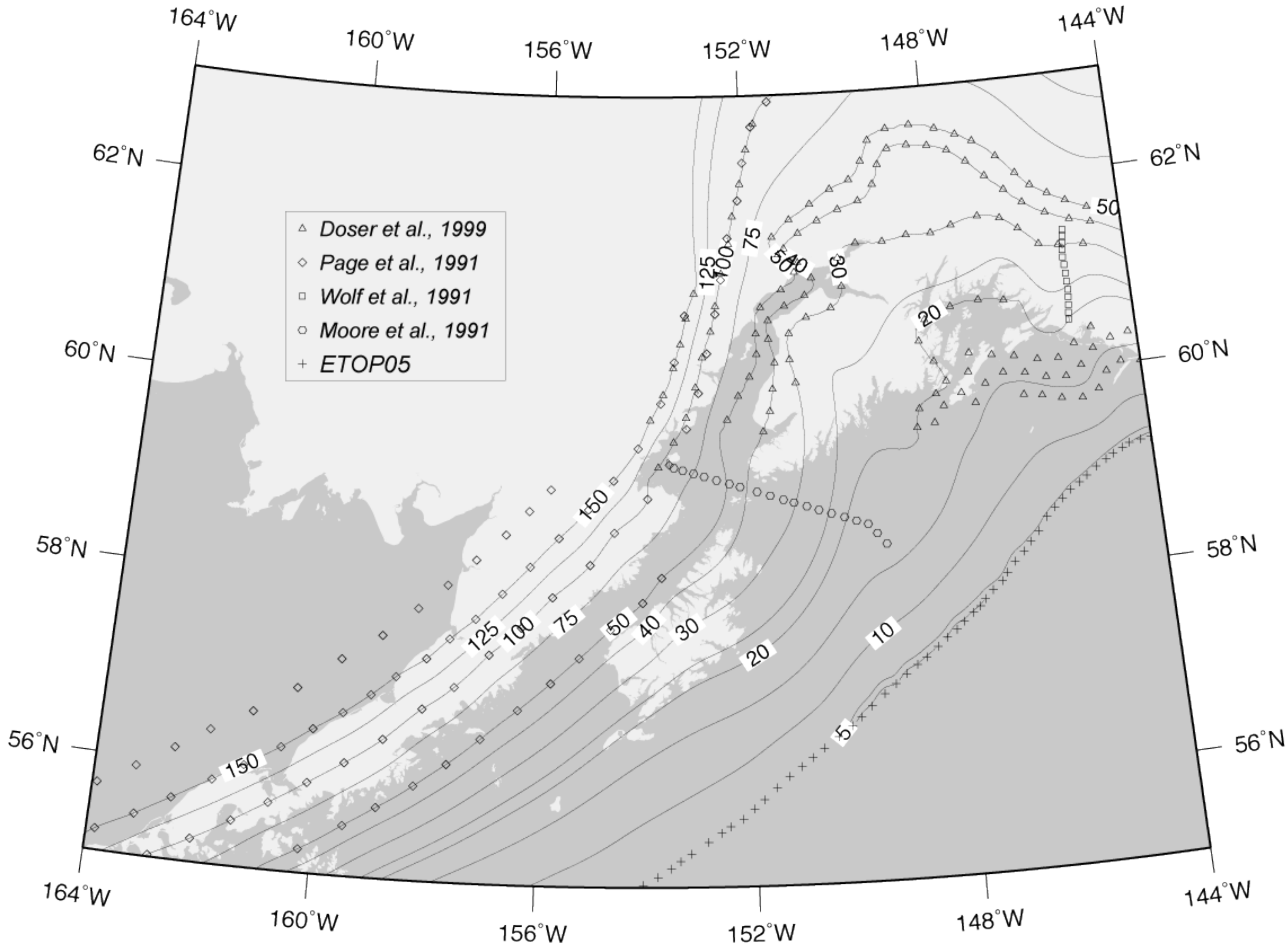


- NNW motion from shallow coupling
- SSE motion from postseismic
- Not quite in opposite directions
- Variations in slip deficit along-strike
  - Nearly zero slip deficit at SW Kenai Peninsula

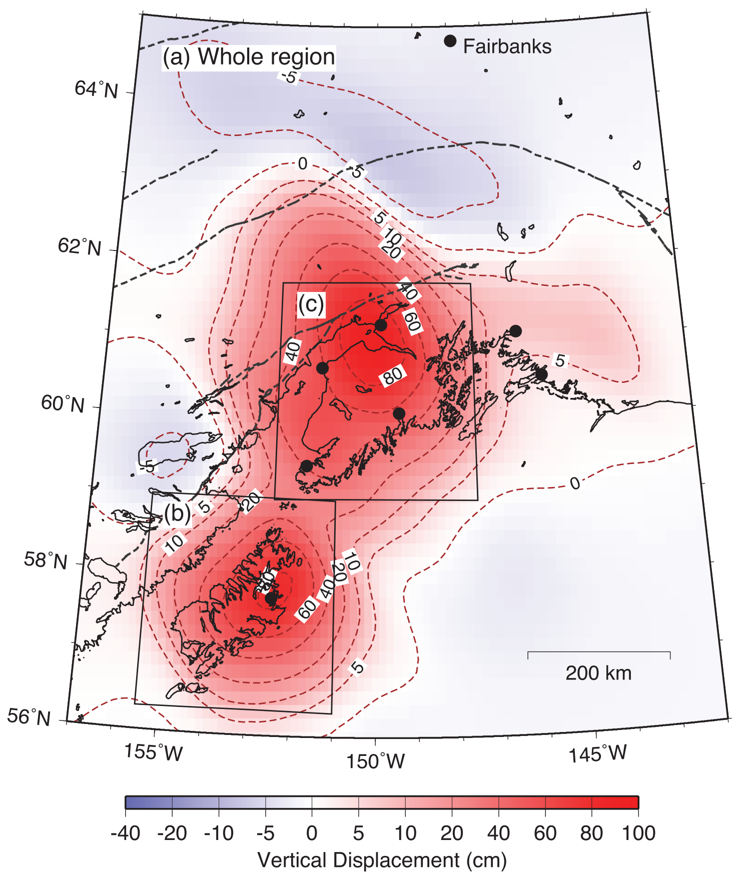
Observed Present Day Velocities

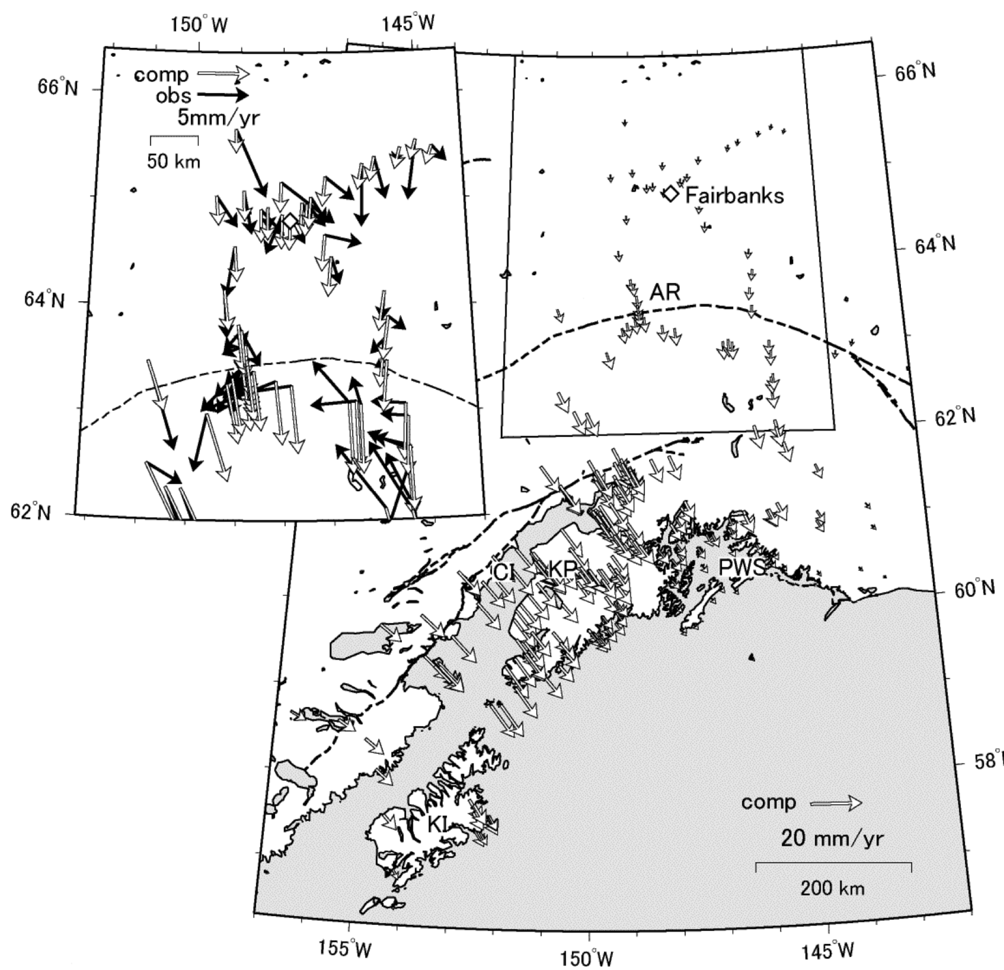


Geometry of Subducting Slab



Postseismic Model Predictions

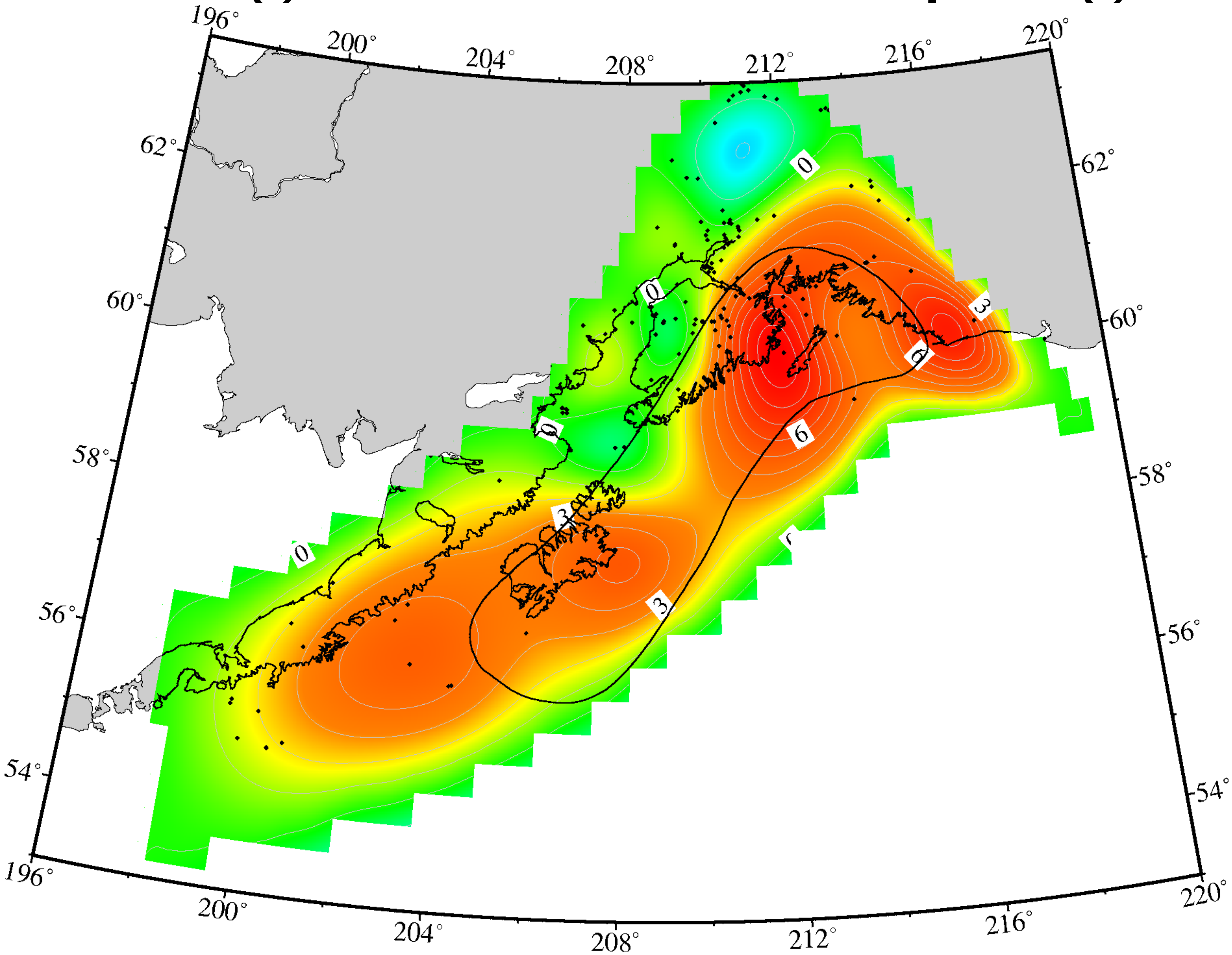




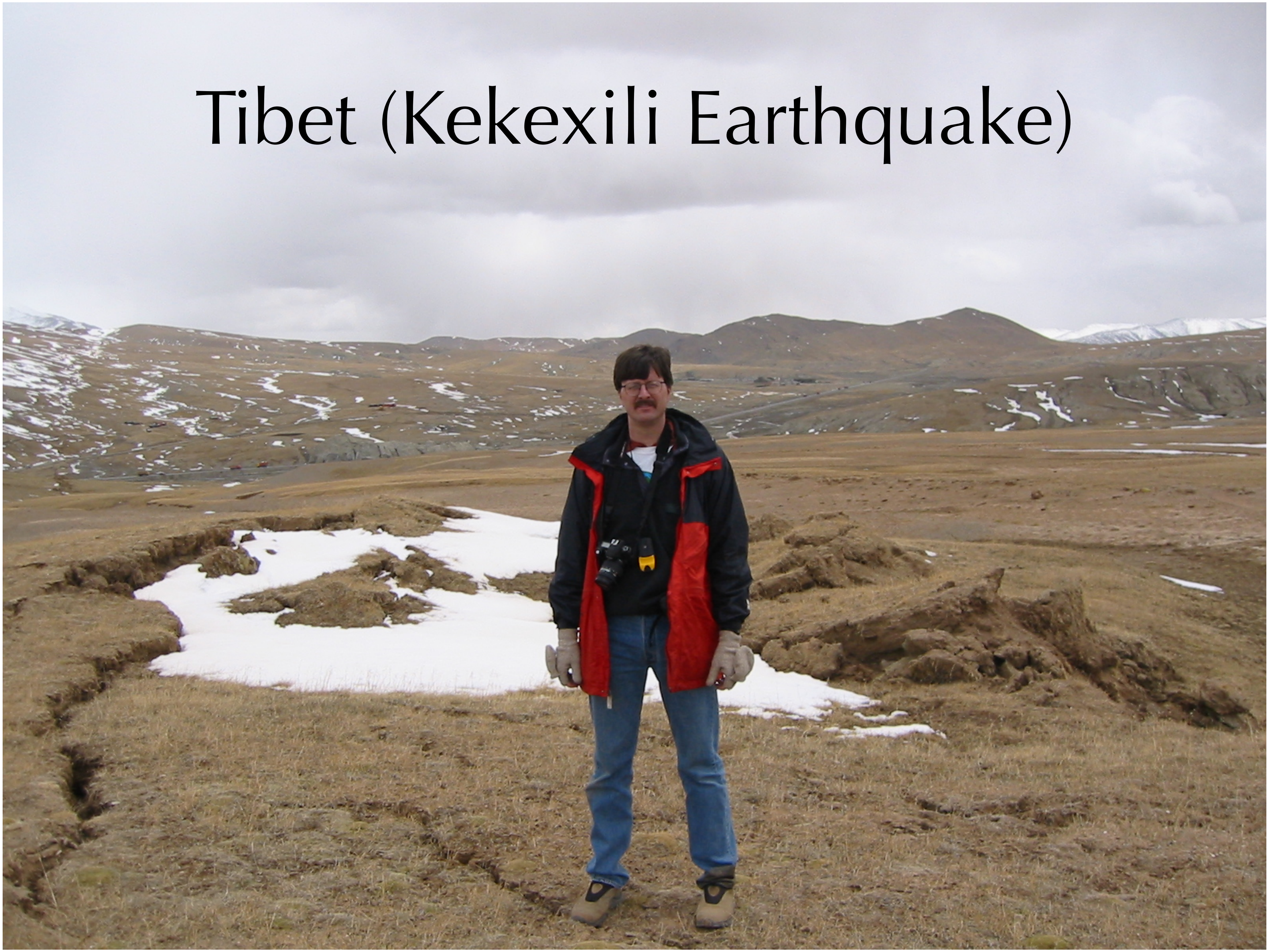
Summary: 1964 Earthquake

- Rapid postseismic deformation continues >40 years after earthquake
  - ~15-20 mm/yr postseismic signal
  - Postseismic uplift centered farther from trench than coseismic subsidence
  - Afterslip dominates the cumulative postseismic uplift
  - Viscoelastic relaxation largest postseismic component in present day velocities
- Present day velocities require model for along-strike variations in plate coupling & postseismic
  - Shallow plate coupling either ~100% or ~0%
  - Distribution consistent with asperities as persistent features

Regional Plate Coupling



Suito and Freymueller (2009)

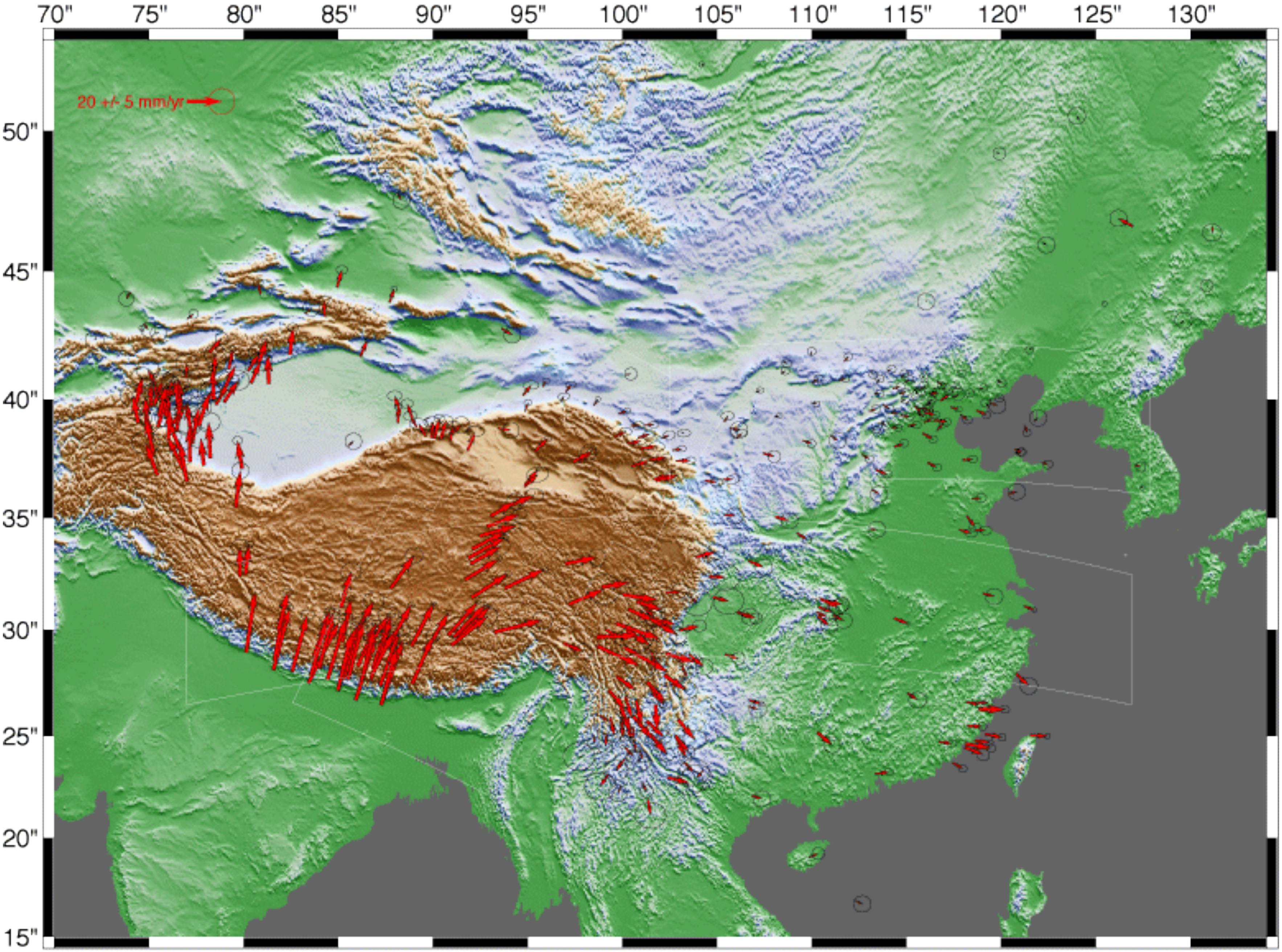

Tibet (Kekexili Earthquake)

Facts About the Earthquake

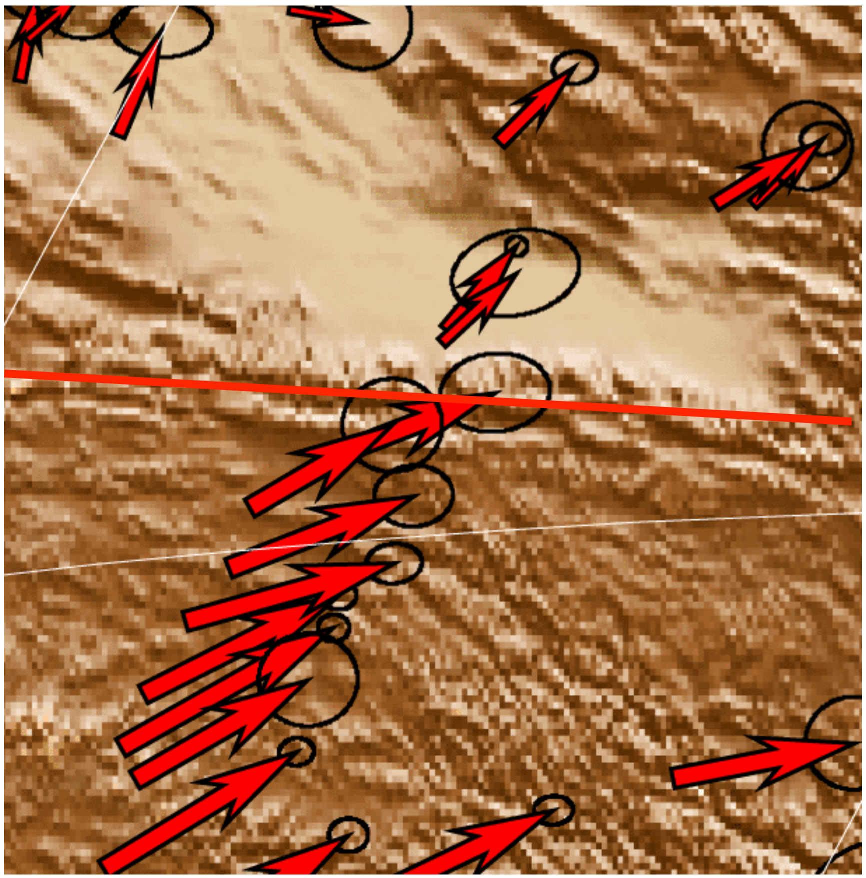
- November 14, 2001, M_W 7.9
  - Magnitude estimates from 7.9 to 8.1
- Ruptured the Kunlun fault for ~350-400 km
  - Longest earthquake rupture in Asia in last century
  - Pure left-lateral strike slip
  - Complex rupture in first few 10s of seconds
- Caused little damage and no deaths
  - But ruptured across a tunnel for Golmud-Lhasa railroad
- Extensive earthquake response made by China Seismological Bureau with some NSF support

Earthquake Response

- CEA made a rapid earthquake response
  - installed 4 continuous GPS sites
  - Measured coseismic displacements
  - GPS profile along Golmud-Lhasa highway
  - Repeated leveling, gravity, etc
- NSF supported a postseismic survey
  - Mostly off-road, very remote sites
  - Will provide detailed measurements of postseismic deformation across the most of the region

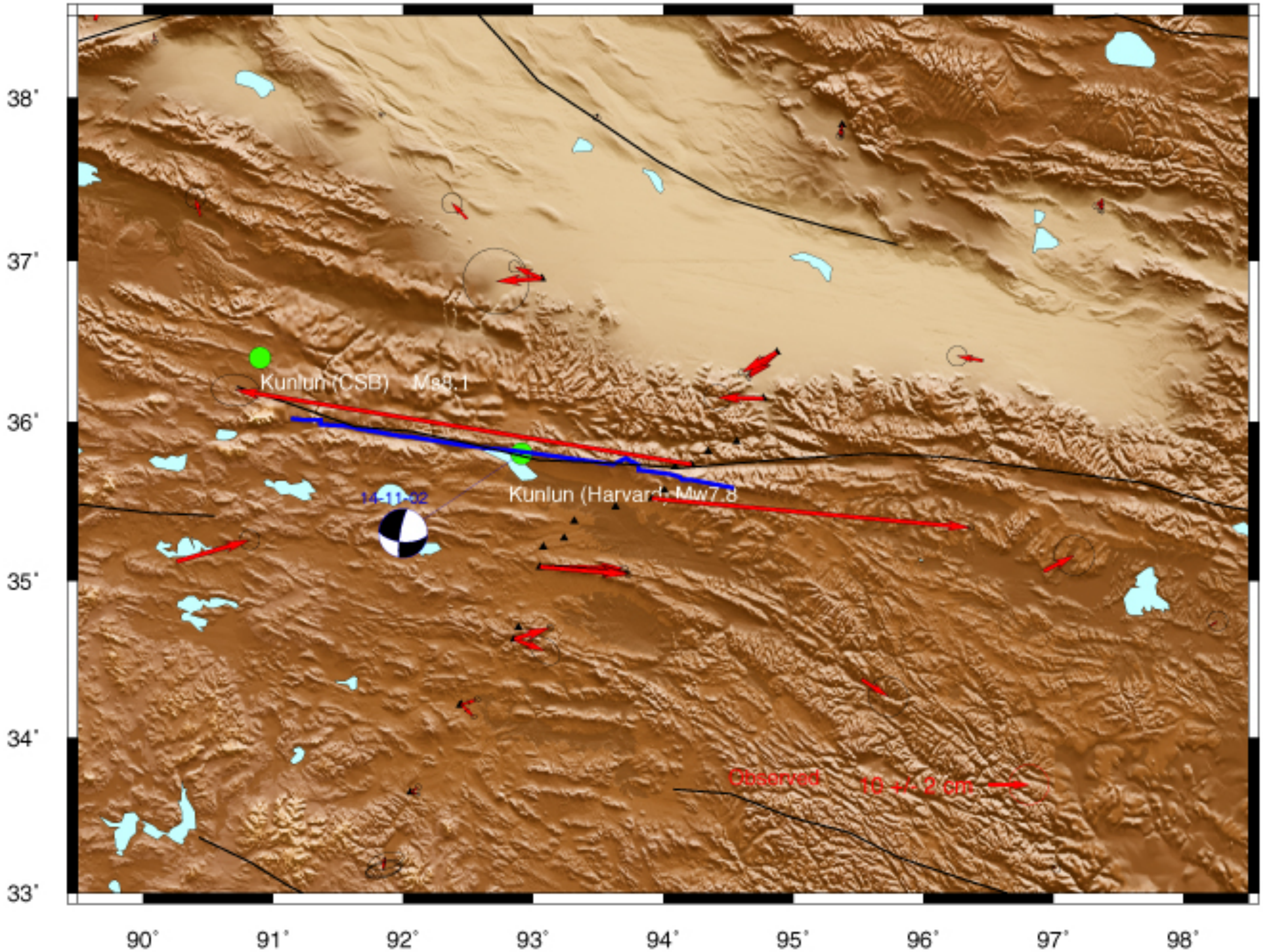

20 +/- 5 mm/yr
70" 75" 80" 85" 90" 95" 100" 105" 110" 115" 120" 125" 130"
50" 45" 40" 35" 30" 25" 20" 15"

Closeup of Kunlun fault

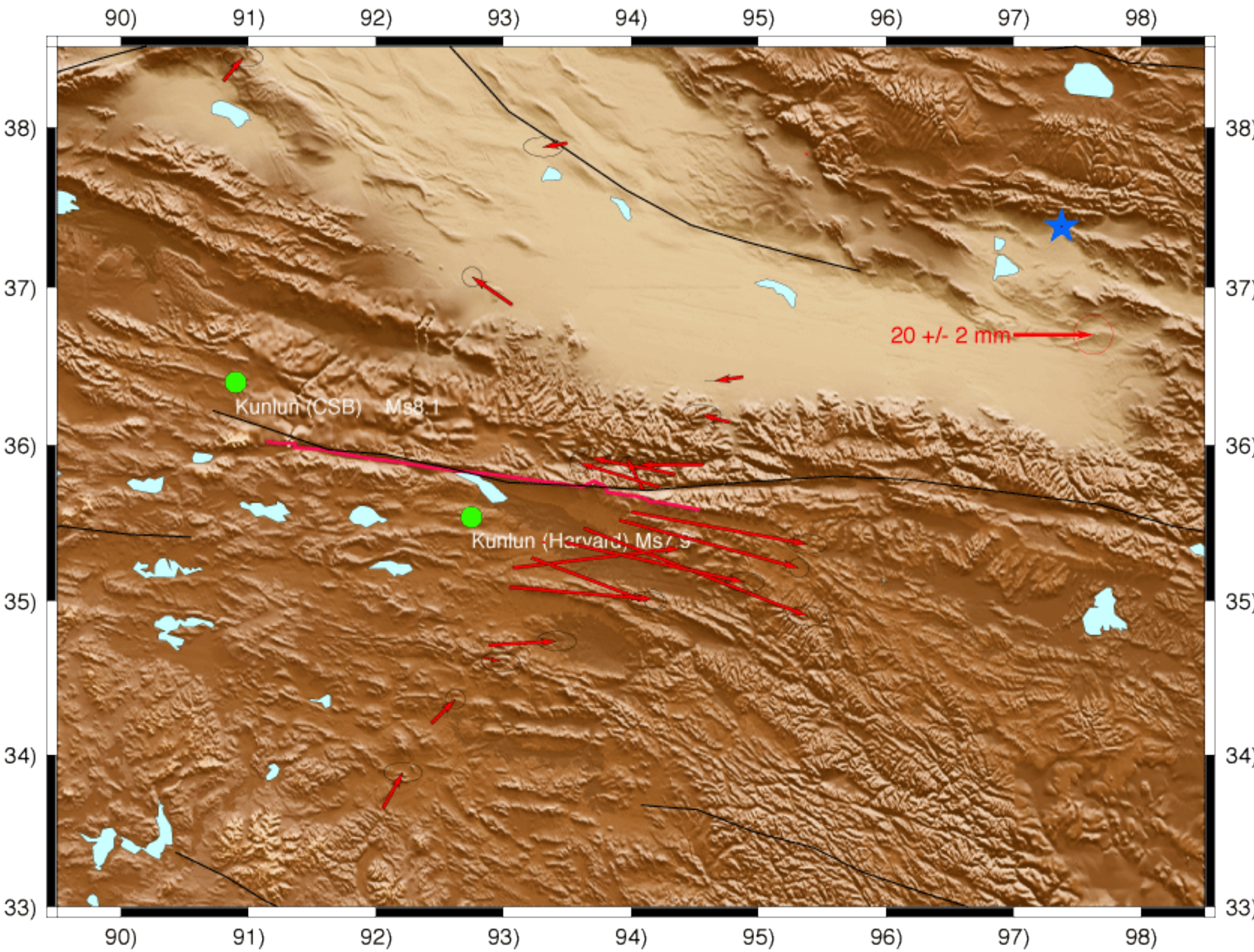


- ~10 mm/yr of left-lateral shear across Kunlun fault and area to south
- Slow and uniform contraction in N32°E component

Coseismic Deformation induced by the Kunlun Earthquake Ms 8.1



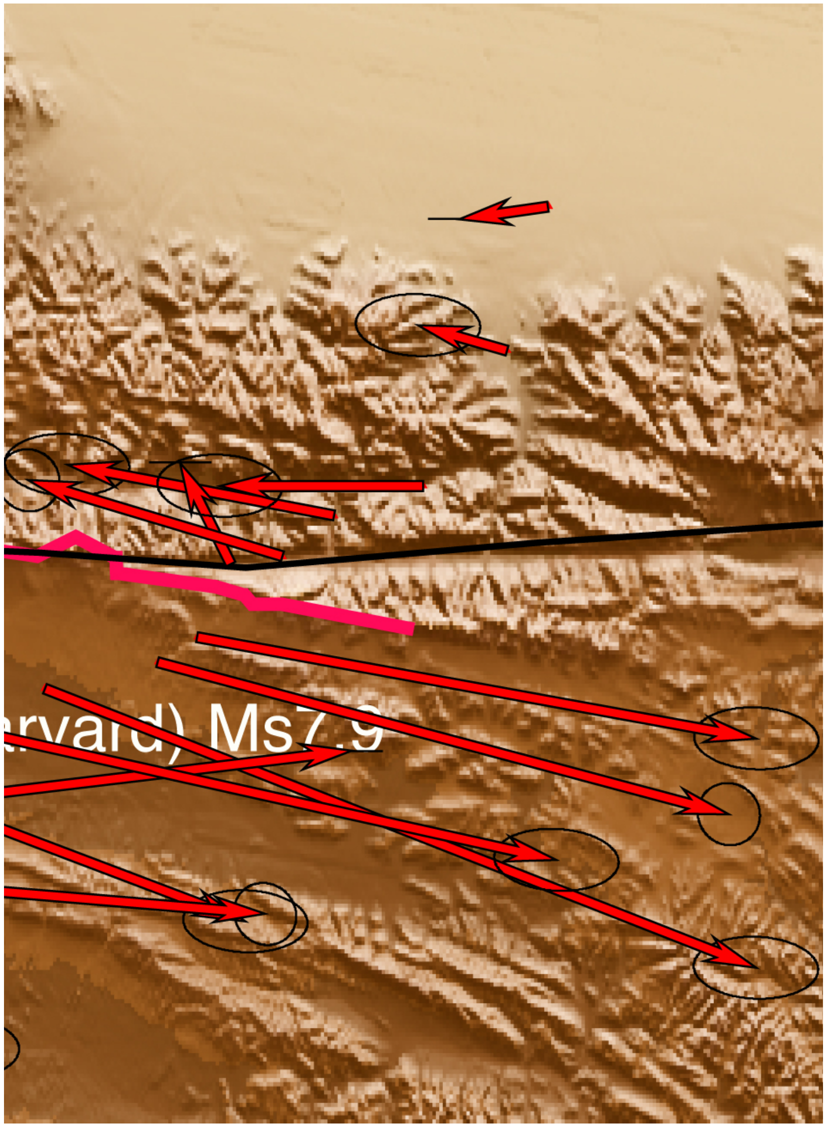
Postseismic Displacements December 2001 – March 2002



Magnitude of Displacements

- Up to 16 cm/yr rates if they persist for an entire year
  - 4-6 cm over 3-3.5 months
  - Sites resurveyed in August 2002, no data yet
- Significant postseismic displacements observed at least 300 km from rupture
  - At least 150 km from rupture to north
  - At least 300 km from rupture to south

Near East End of the Rupture



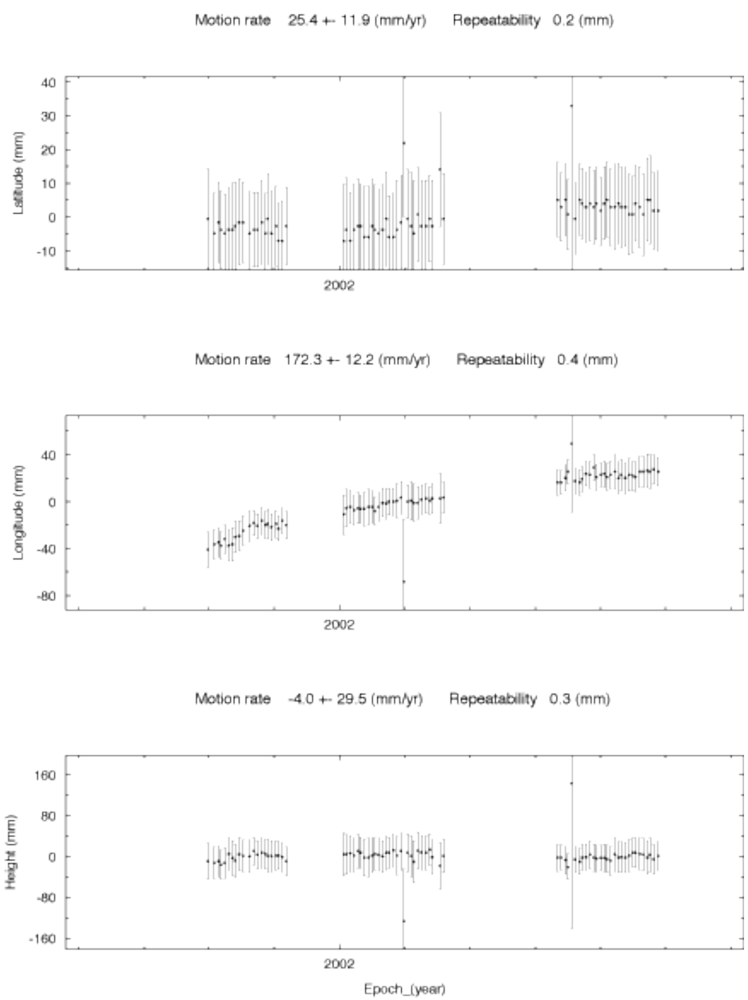
- Observation sites form a nearly fault-normal profile
- Pronounced asymmetry in displacements
  - 4-6 cm on south side
  - 2 cm or less on north
- Displacements may decrease more slowly to south side
  - But could be due to along-strike variations in slip
- Time dependence?

Station Time Series

Station : WDGD

E93.08(N35.21(4578.55 (m)

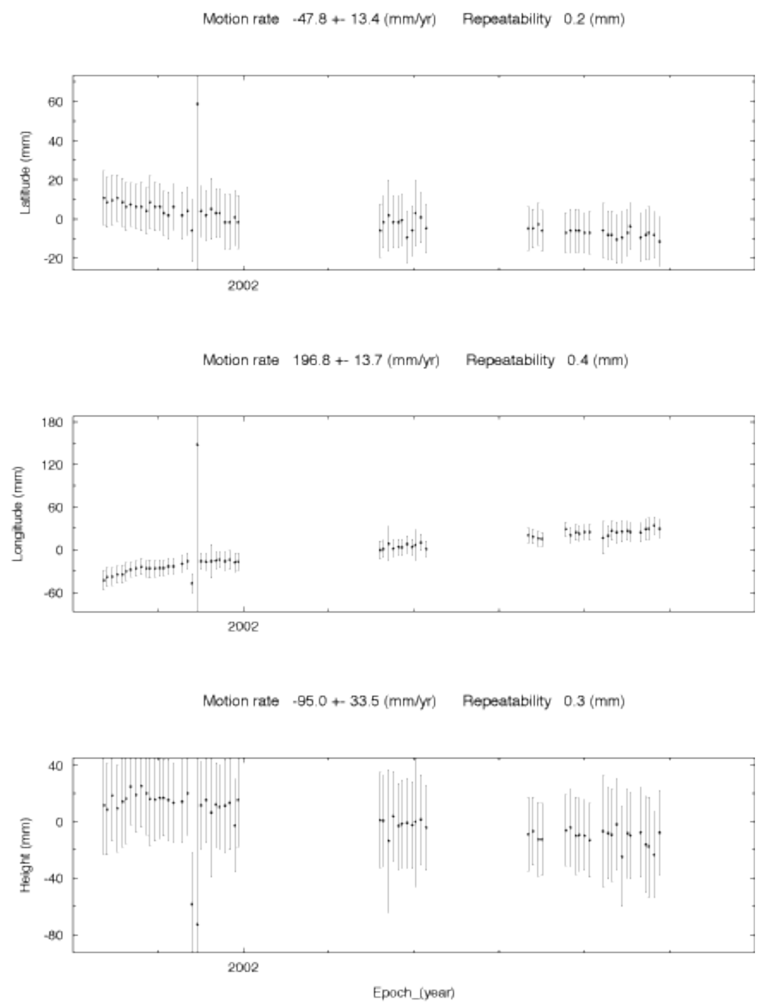
78 Daily Solutions (2001.9 - 2002.2)



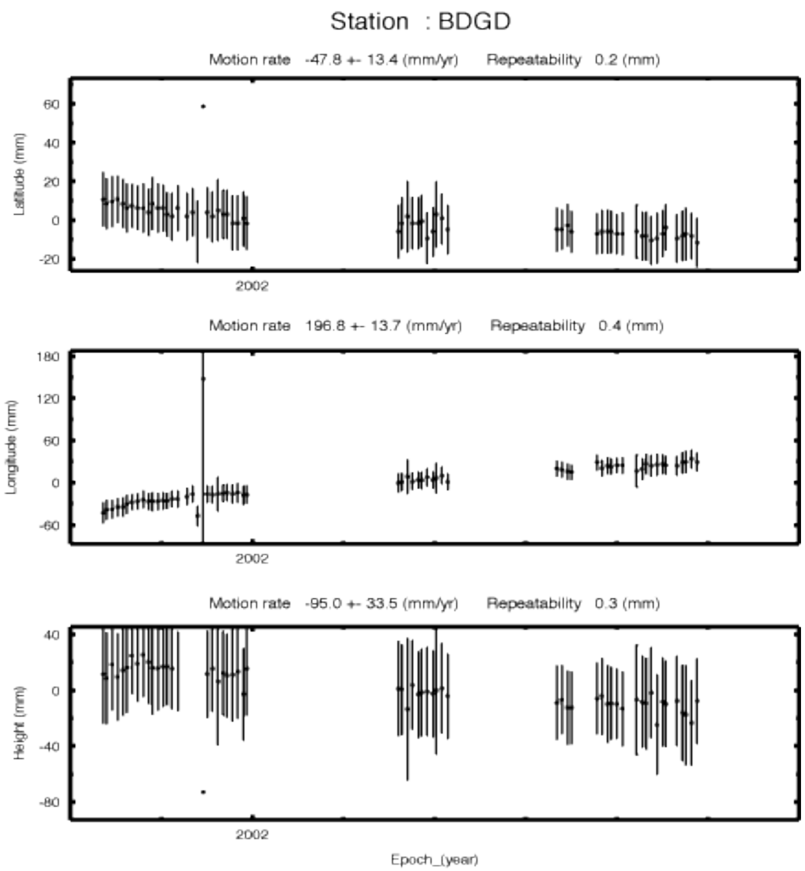
Station : BDGD

E93.91' N35.52' 4555.59 (m)

62 Daily Solutions (2001.9 - 2002.2)



Analysis of Time Dependence



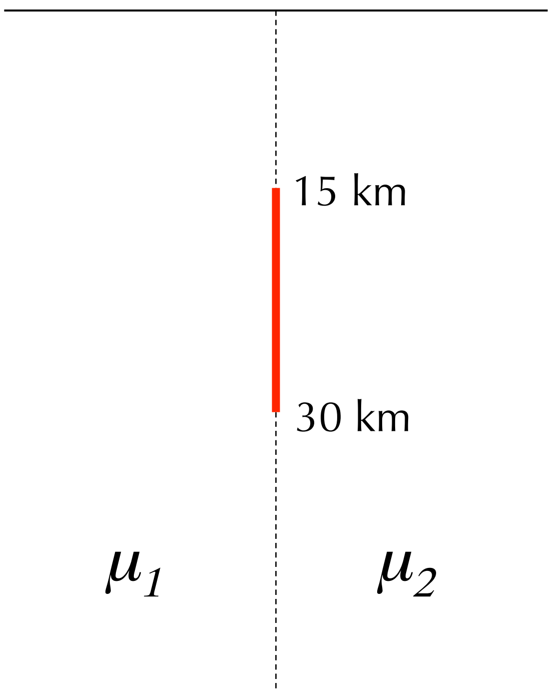
- Roughly linear over first ~3 months
- First ~2 weeks show higher rate
- Probably an early phase with time decay of ~days
- Longer phase with time decay of > ~months

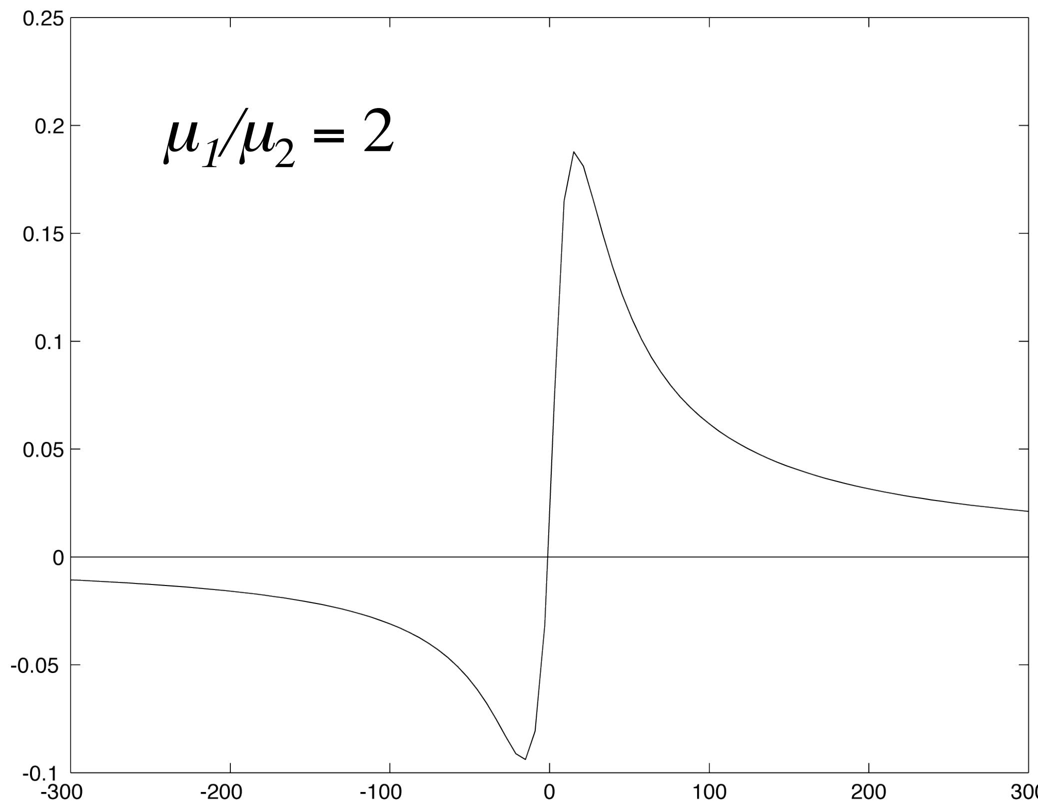
Cause of Asymmetric Deformation

Asymmetry in displacements can result from

- Reference frame bias
- Dipping fault
- Asymmetry in material properties
  - Lower rigidity to south for afterslip mechanism
  - Lower viscosity to south for viscoelastic mechanism
  - ~30 km crustal thickness change near fault

Inhomogeneous Afterslip Model

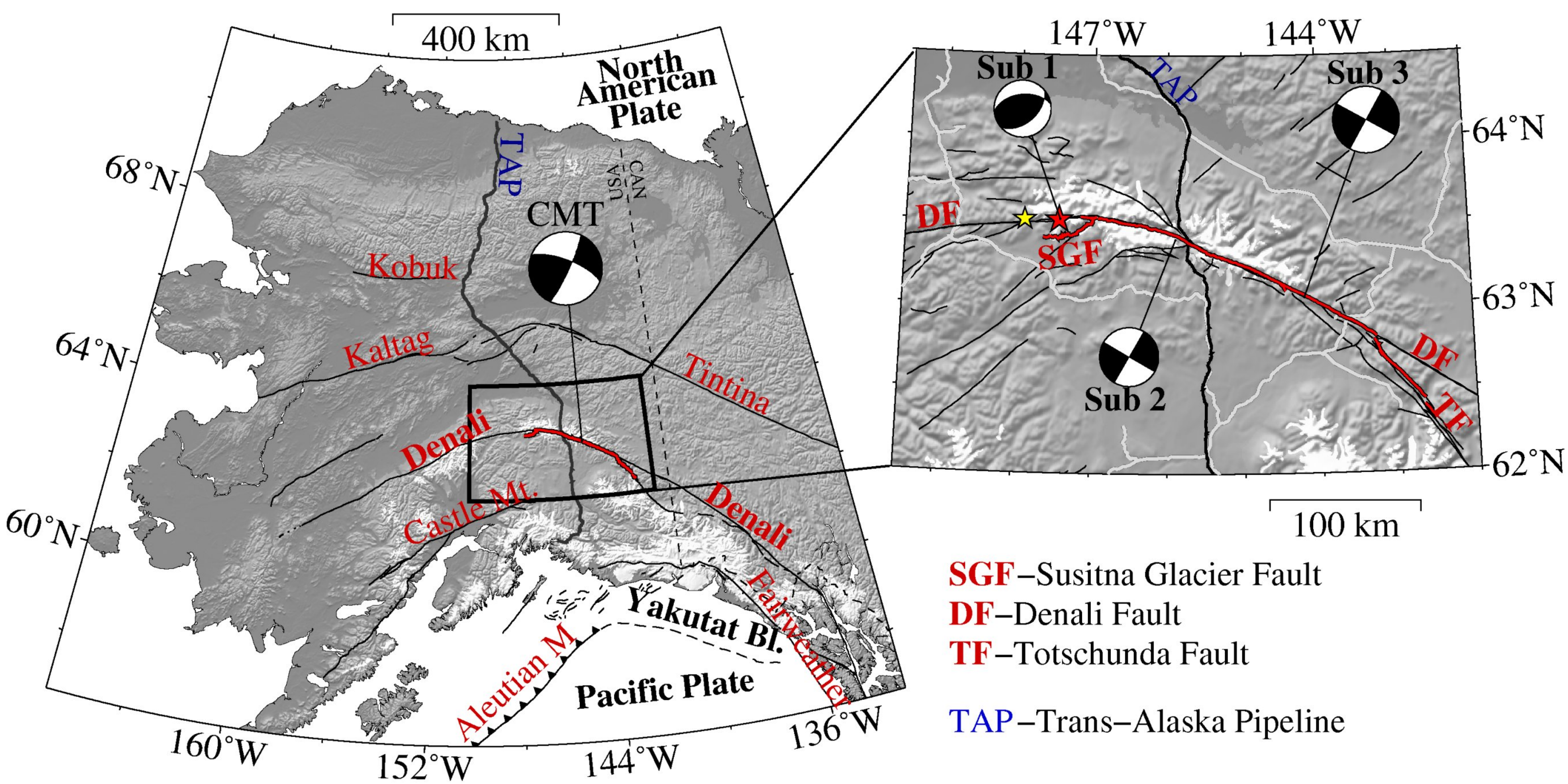




Summary: Kekexili Earthquake

- Very rapid postseismic deformation
  - Roughly 15x interseismic rate
- Strong apparent asymmetry in postseismic deformation
  - Never before observed anywhere
  - Displacements a factor of two larger on south
  - Asymmetry most likely caused by a material property contrast

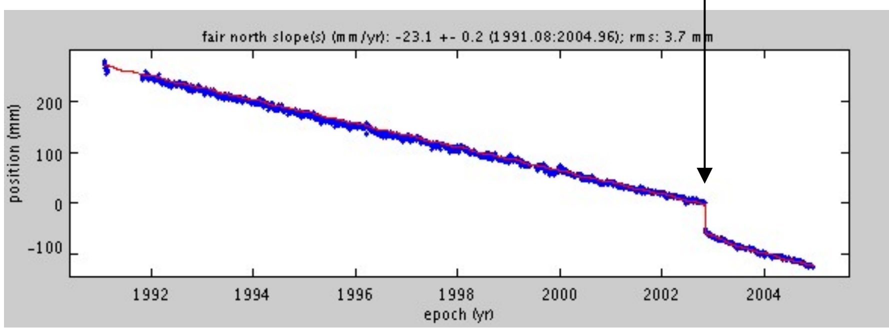
Tectonic setting

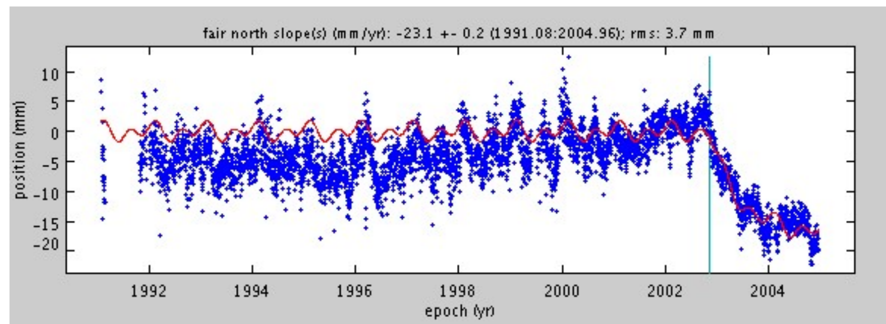


Fairbanks After Denali Earthquake

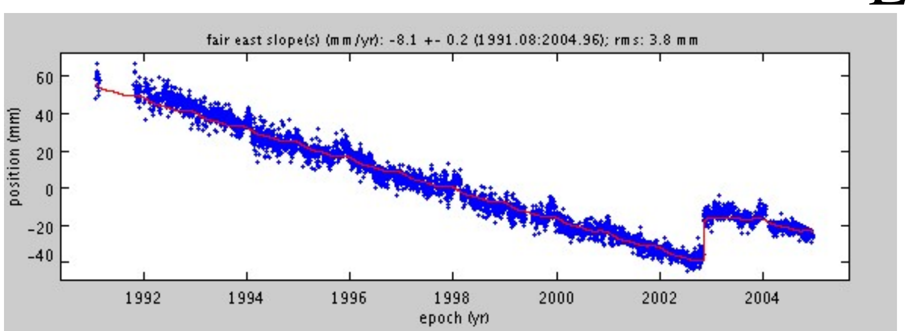
Mw7.9, 11/3/2002

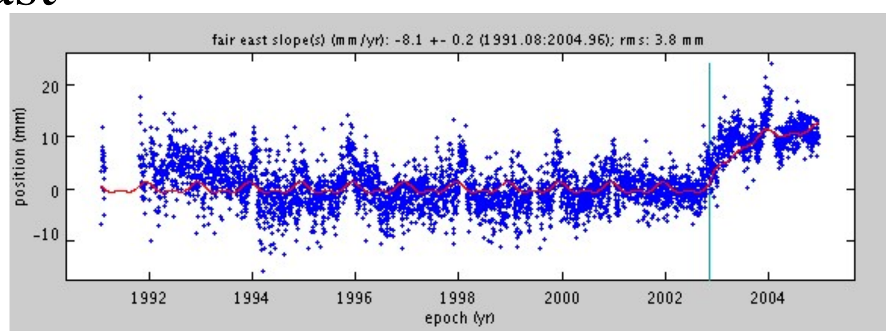
North





East



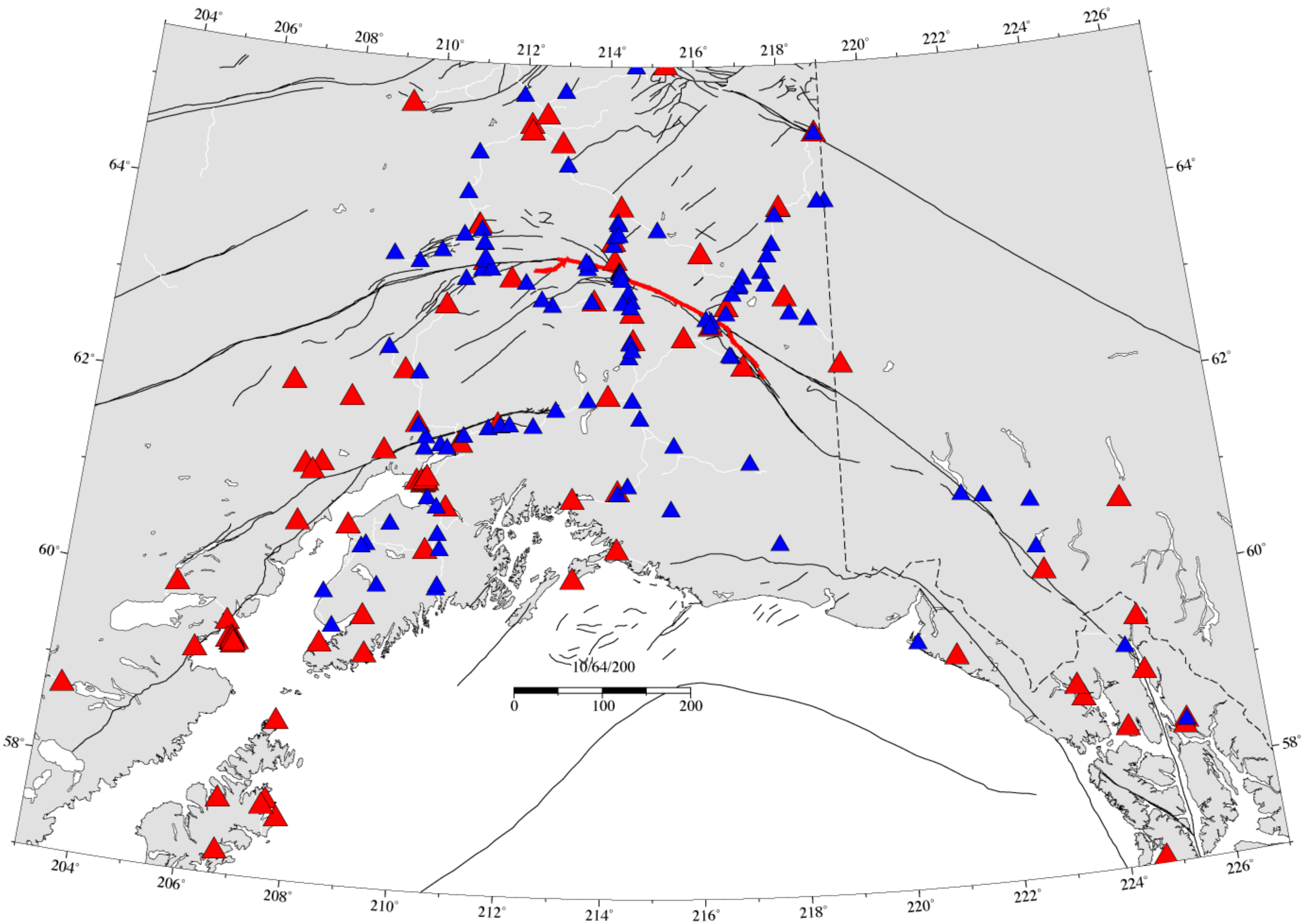


ITRF Time Series

De-trended, offsets removed

Time series from http://sopac.ucsd.edu

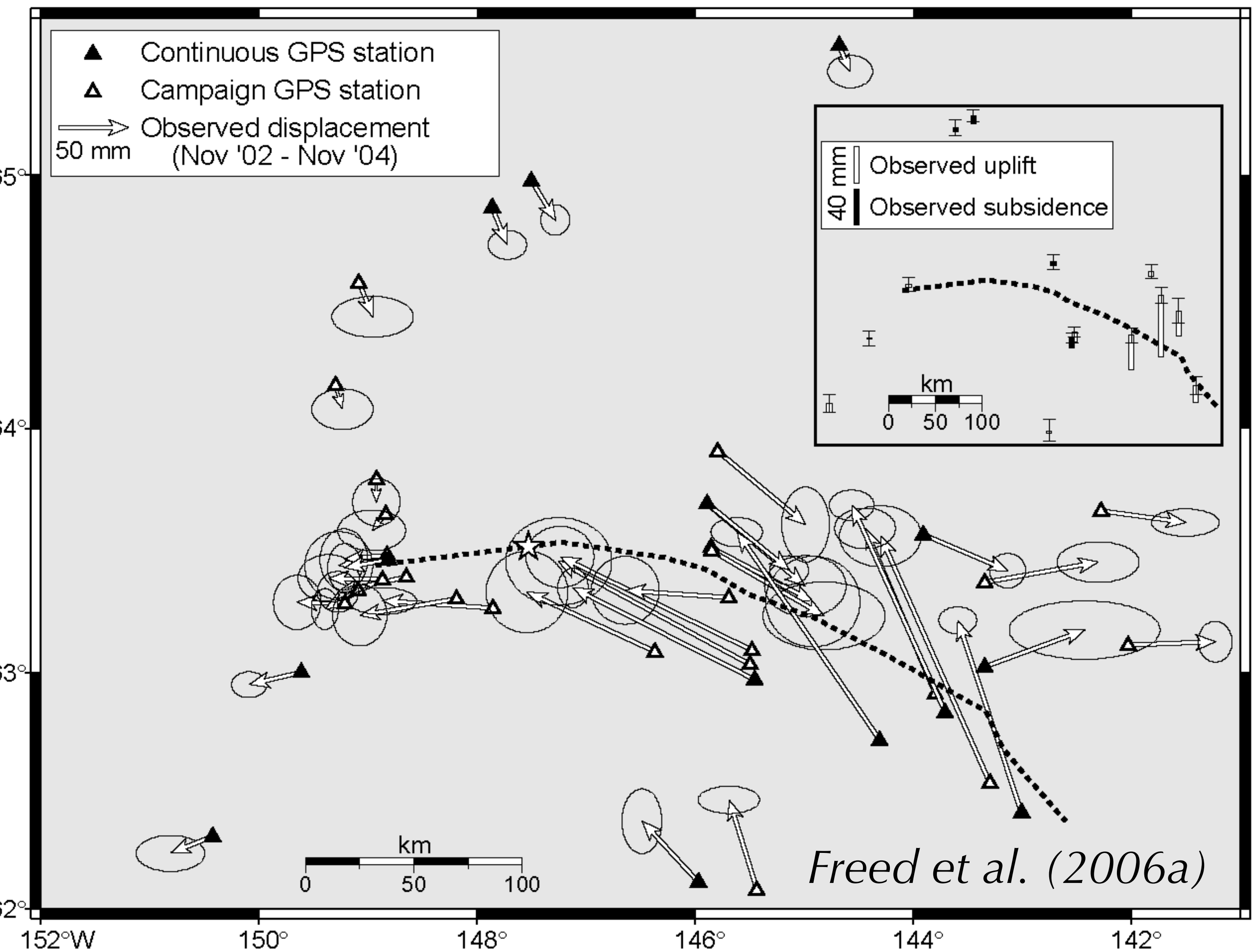
Postseismic GPS Network



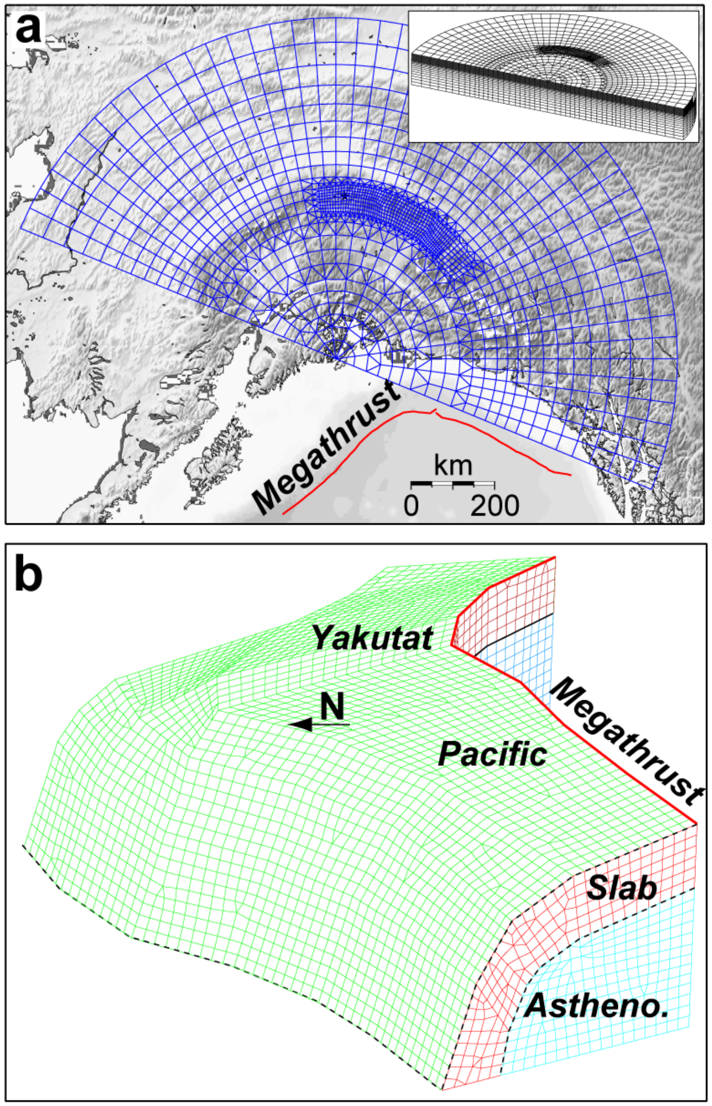
Red = CGPS

Blue = repeated surveys

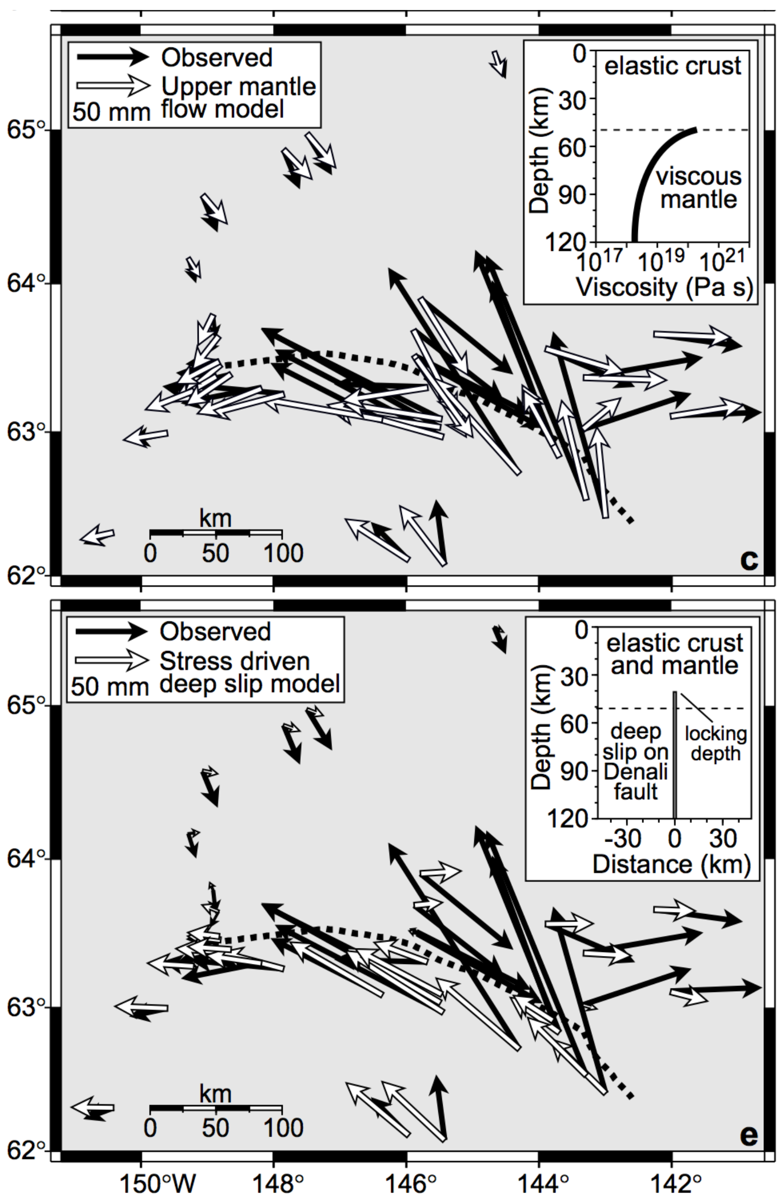
2-year Displacements



Model Mesh



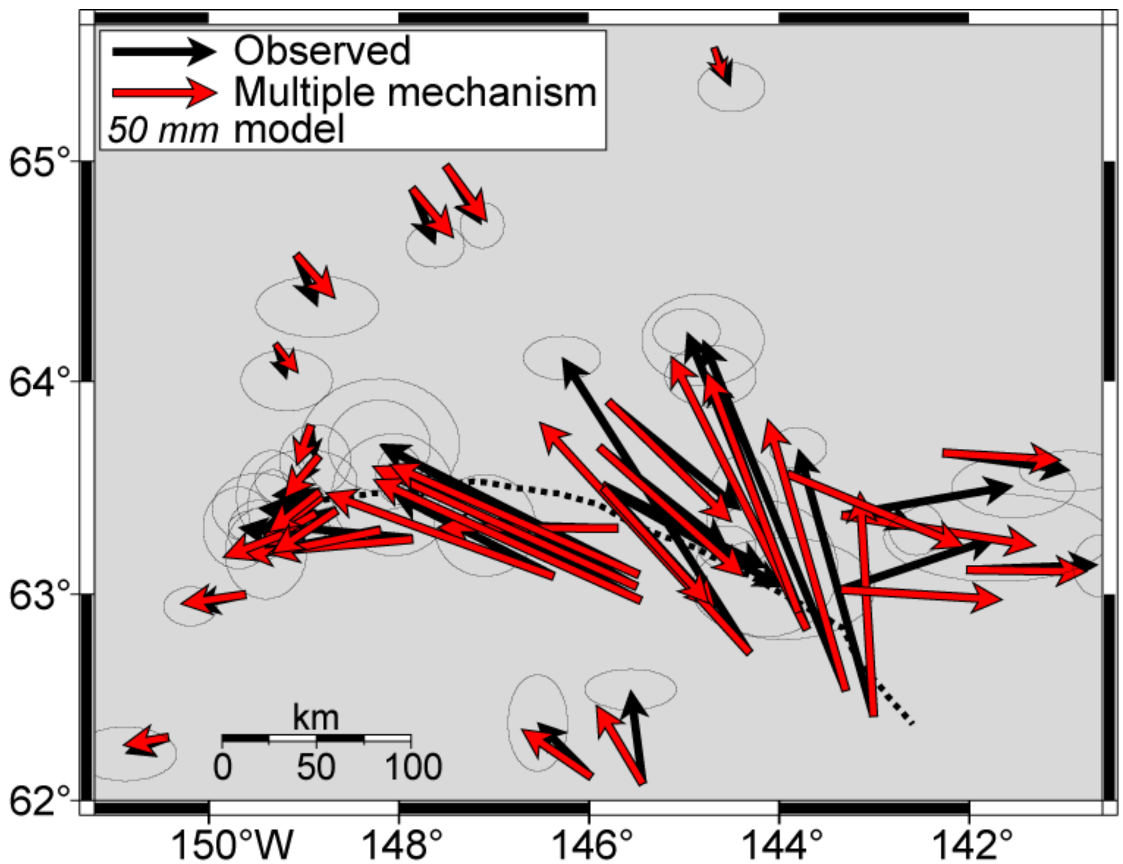
- Freed et al., 2006a,b
- Half-cylinder model domain
- Elastic layer over viscoelastic medium (viscosity varies with depth)
- Elastic moduli vary based on seismic velocities
- Can consider viscous lower crust and/or mantle
- Published models assume layered viscosity structure (depends only on depth). Future models will include 3D structure based on elastic slab (b).



Models

- Poroelastic relaxation is small except in vertical
- Viscoelastic-only models misfit data significantly
- Physically reasonable afterslip models do not fit the data well either
- **Try estimating afterslip after removing the viscoelastic model that fits far-field**

Best-fitting Multi-Mechanism Model



Postseismic Models

- **Pollitz (2005)**
  - Purely viscoelastic with transient rheology
- **Freed et al. (2006a)**
  - Two components required, linear viscoelastic + crustal component (afterslip or shear zone).
- Freed et al. (2006b)
  - Far-field time series support non-linear mantle rheology
- Biggs et al. (2009)
  - Linear viscoelastic model optimized to fit InSAR data
- **Johnson et al. (2009)**
  - Afterslip-dominated (based on rate and state friction) with significant linear viscoelastic component.

Comparing Models' Predictive Power

- How well do any of these models predict the time series of data collected after the models were developed?
  - Models used 1-4 years of data, various subsets of data
  - 7 years of data now available
  - Extensive campaign GPS data in addition to PBO
- What can we learn from the models' successes and failures?
- Compare model predictions to observed displacements over specific time intervals.

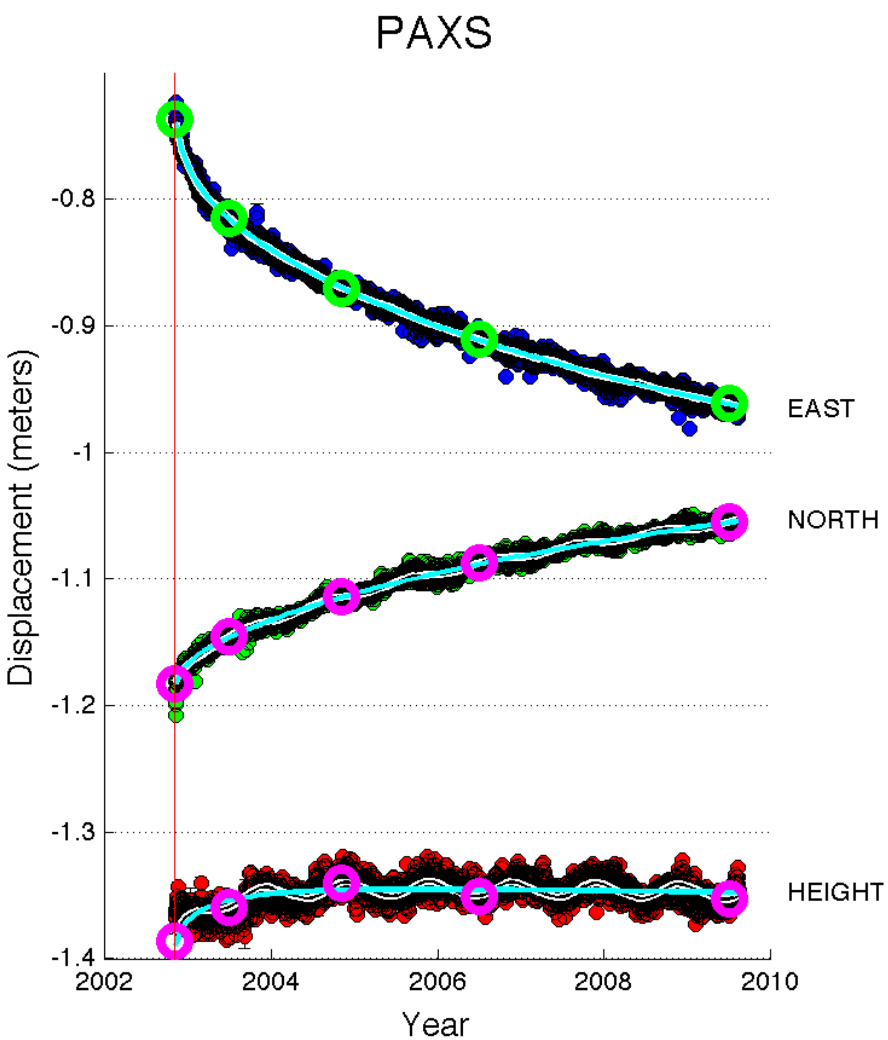
Characteristics of the Models

Model	Data Span Used	Viscoelastic	Afterslip	Notes
Pollitz, 2005	1 year	Transient viscosity	None	Used an early coseismic model
Freed, 2006 (approximated)	2 years	Linear, depth-variable	None*	Uses different software than original, slightly tweaked
Johnson, 2009	4 years	Linear, half-space below lithosphere	Rate-strengthening friction law	

✓ The Pollitz model assumed all deformation was from viscoelastic response, and estimated a low viscosity based on early rates.

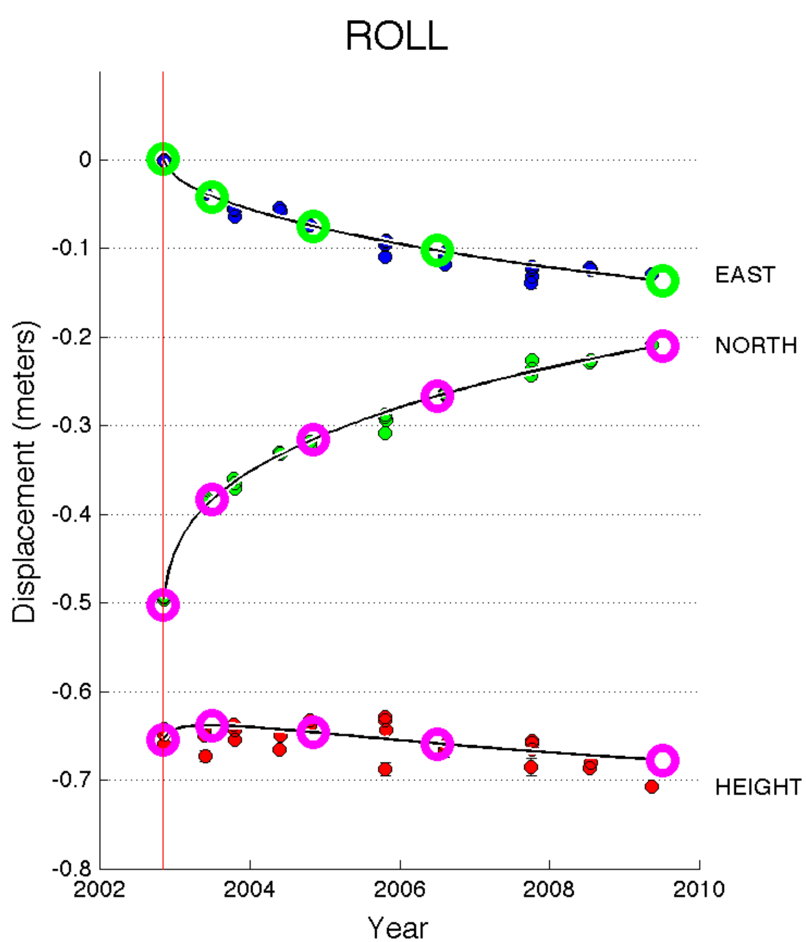
✓ The original Freed model included a shallow component (afterslip or shear in lower crust), but this replicated version includes only the viscoelastic part.

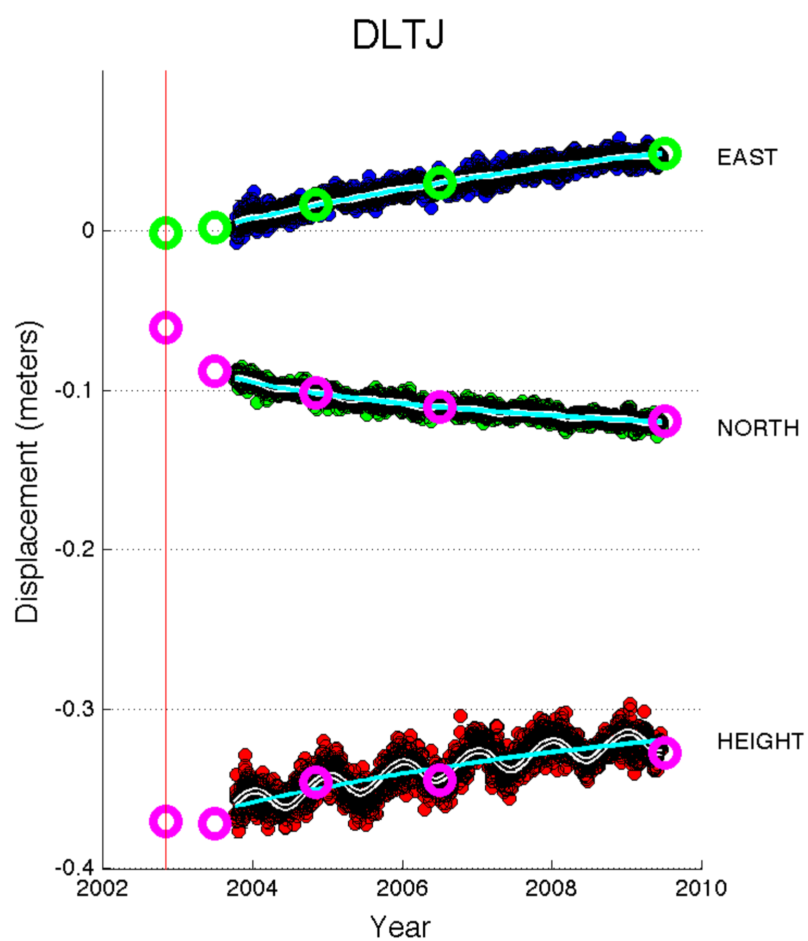
Fitting Postseismic Time Series

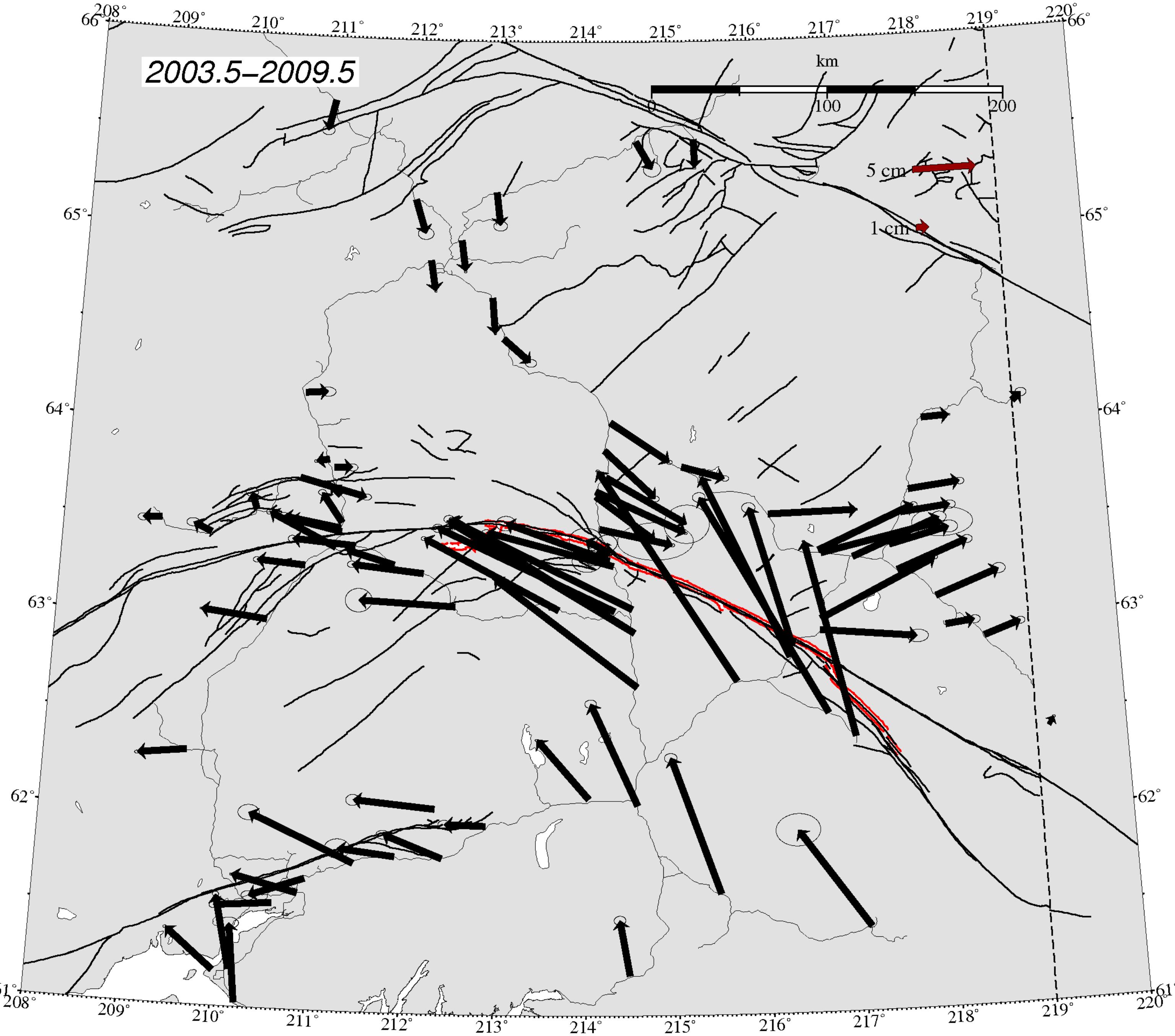


- Pre-earthquake trend removed ➔ transient only
- Time series fit using
  - Logarithmic 0.05 yr decay
  - Exponential decay 7.0 yr
    - Misfit improves as time constant is increased, up to at least 15 yr
  - Annual + semi-annual removed from CGPS
- Model sampled for
  - t=0 to t=+2yr
  - 2003.5-2006.5
  - 2006.5-2009.5
  - 2003.5-2009.5

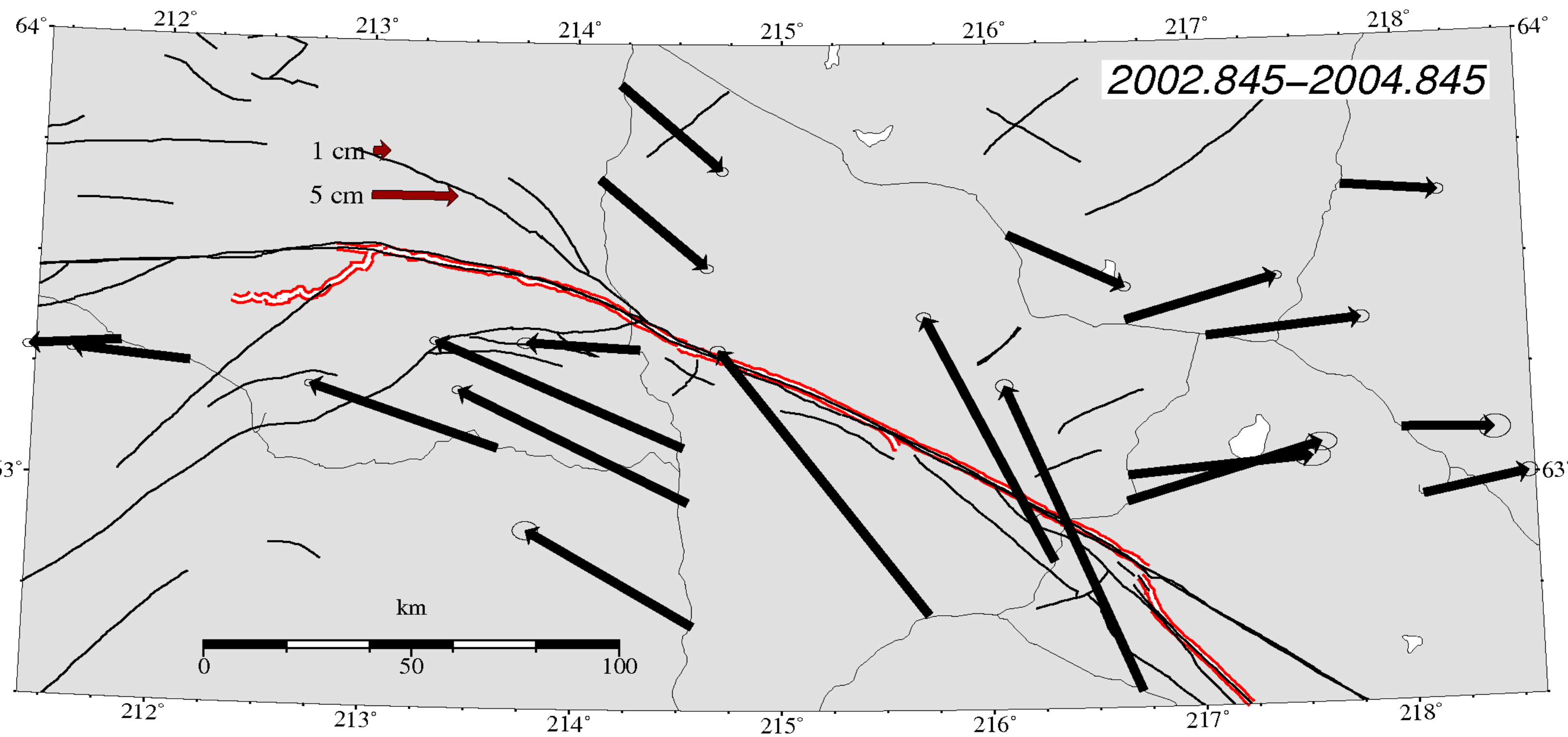
Sample Time Series



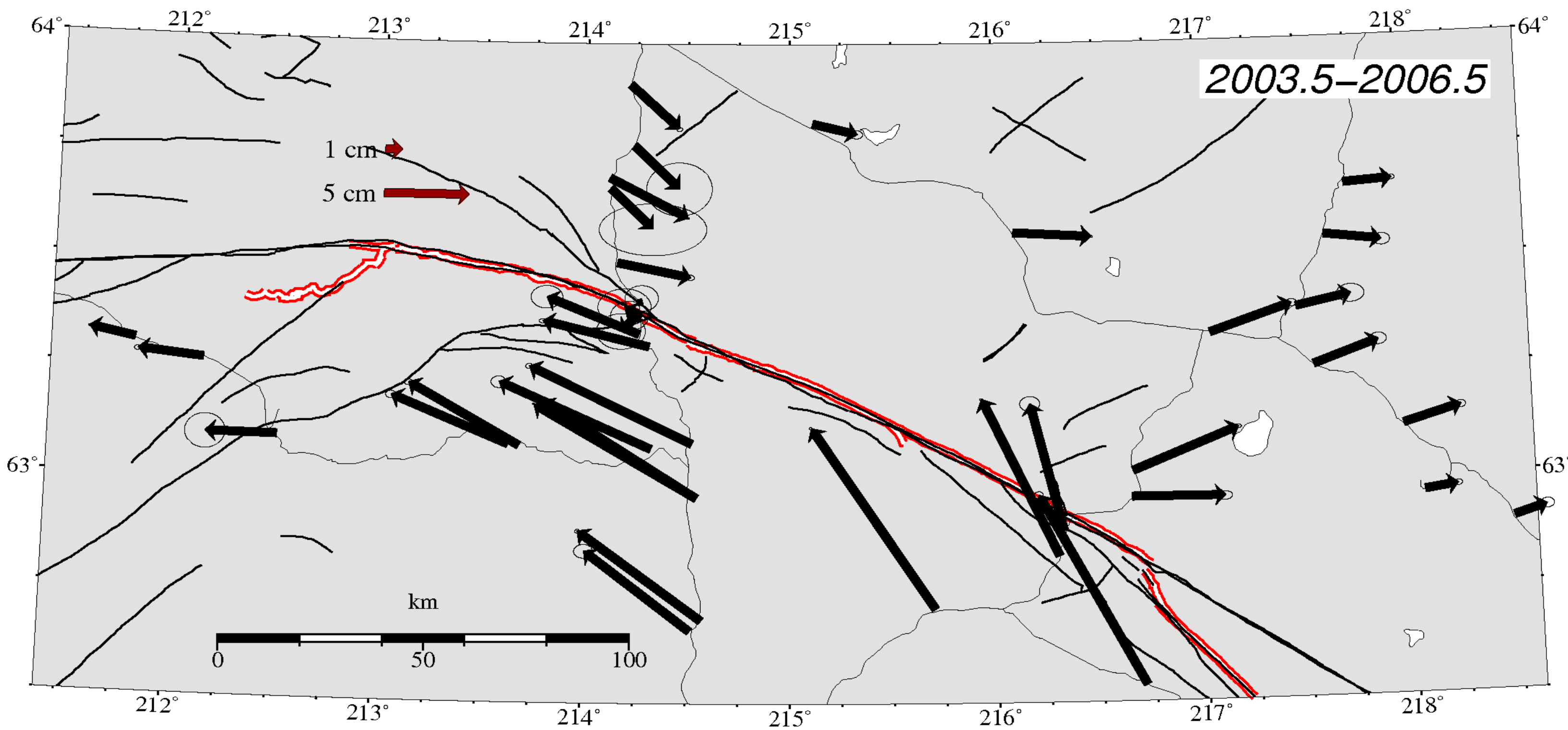



2003.5–2009.5
km
0
100
200
5 cm
1 cm
208°
209°
210°
211°
212°
213°
214°
215°
216°
217°
218°
219°
220°
66°
65°
64°
63°
62°
61°

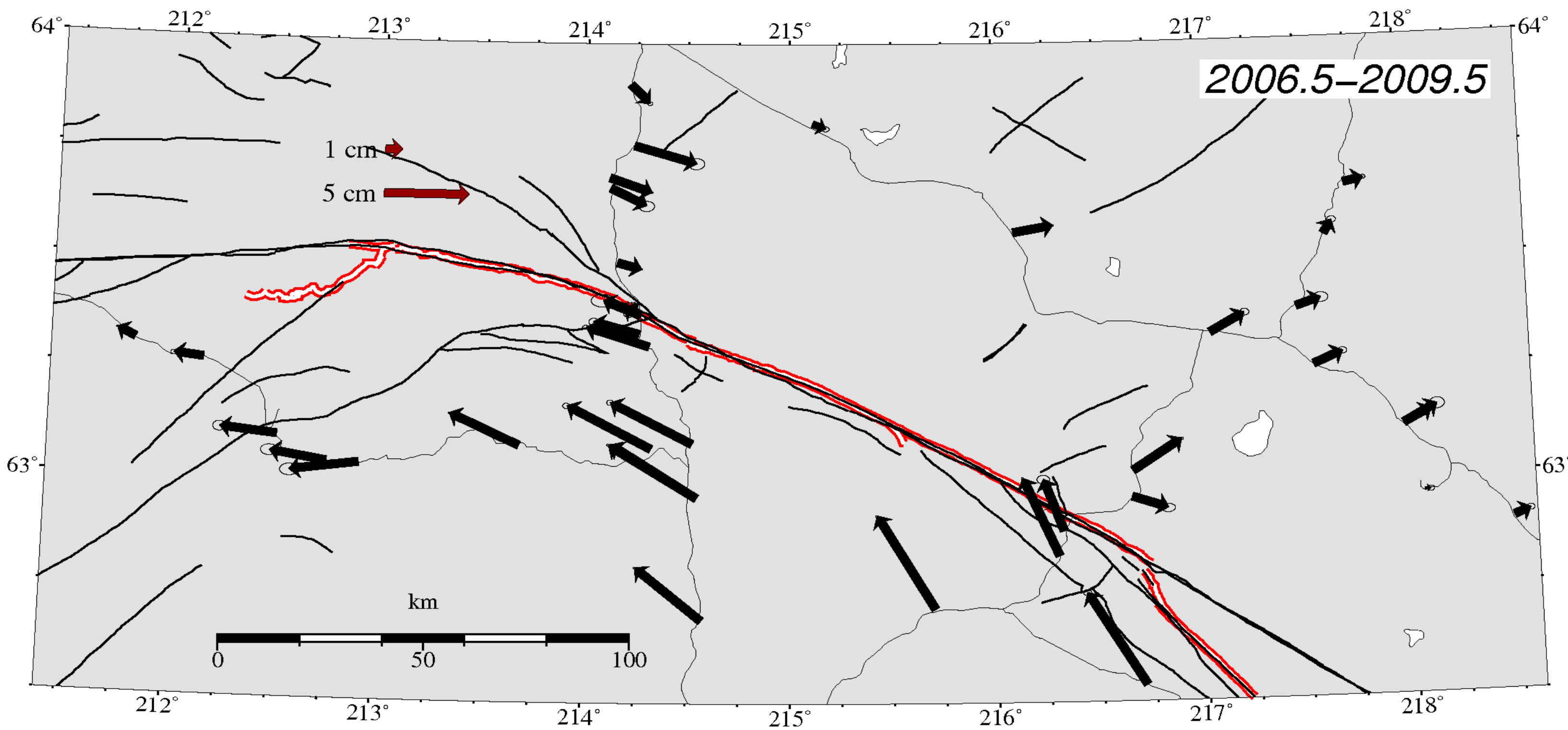
Time Progression



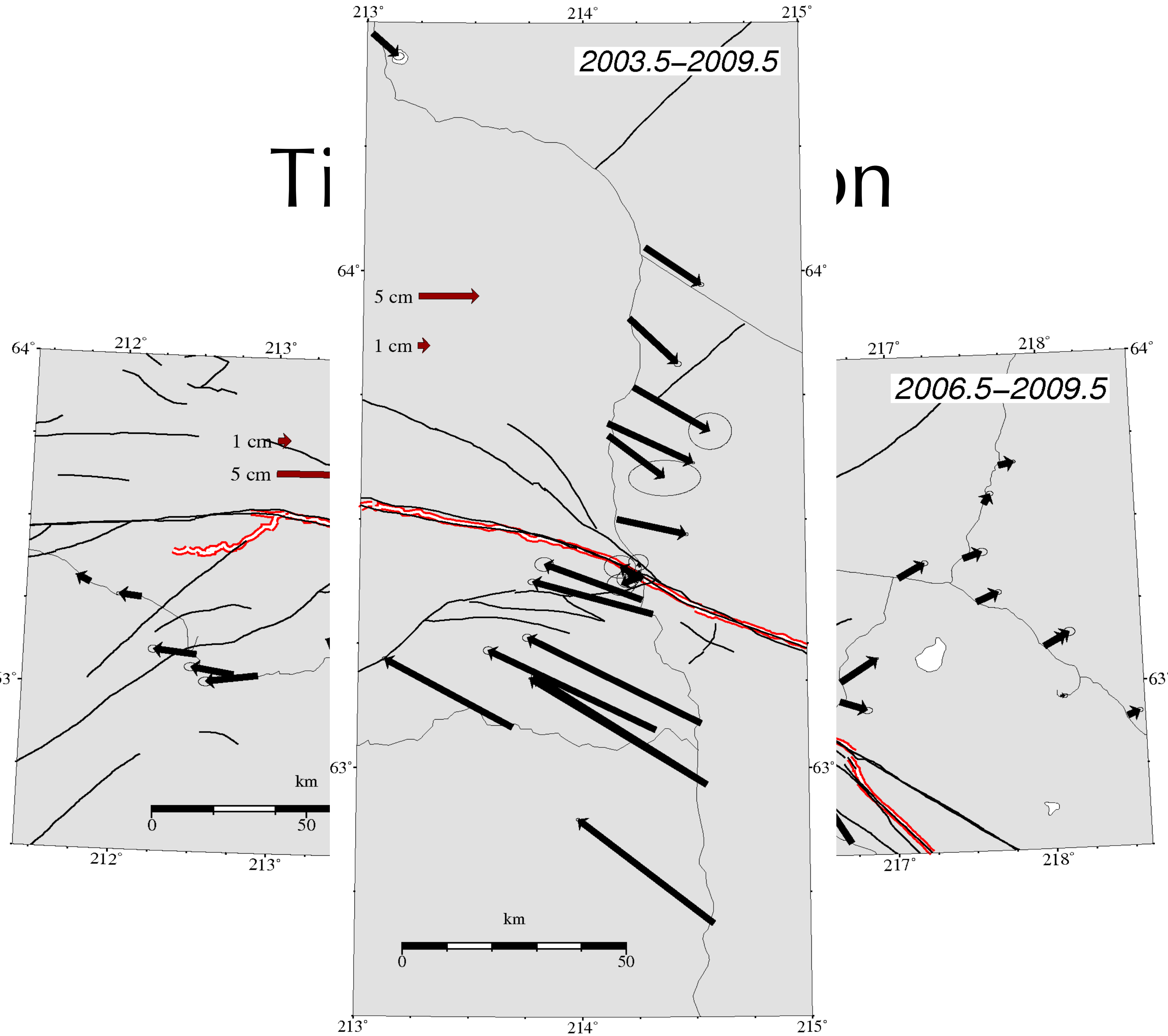
Time Progression



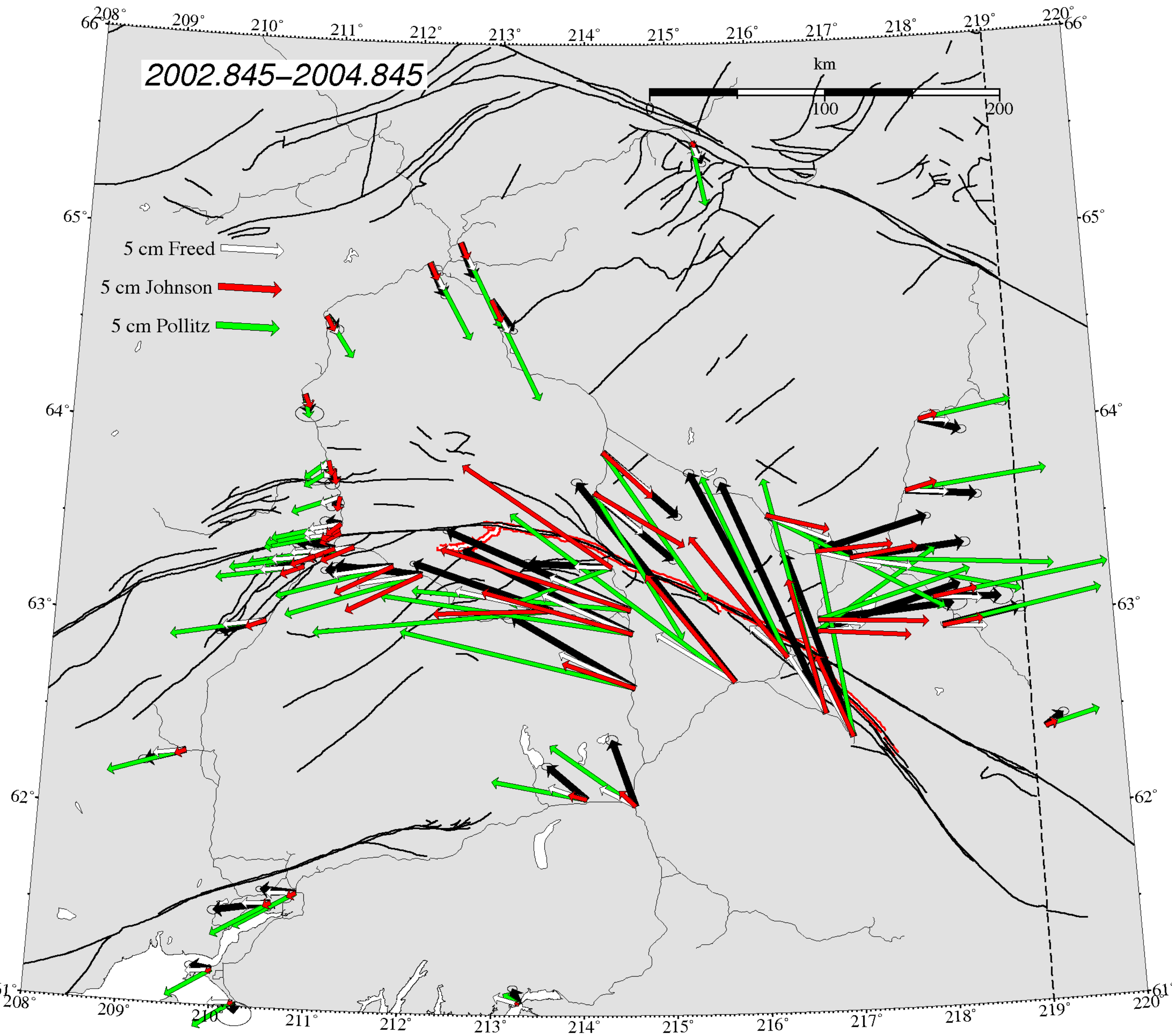
Time Progression



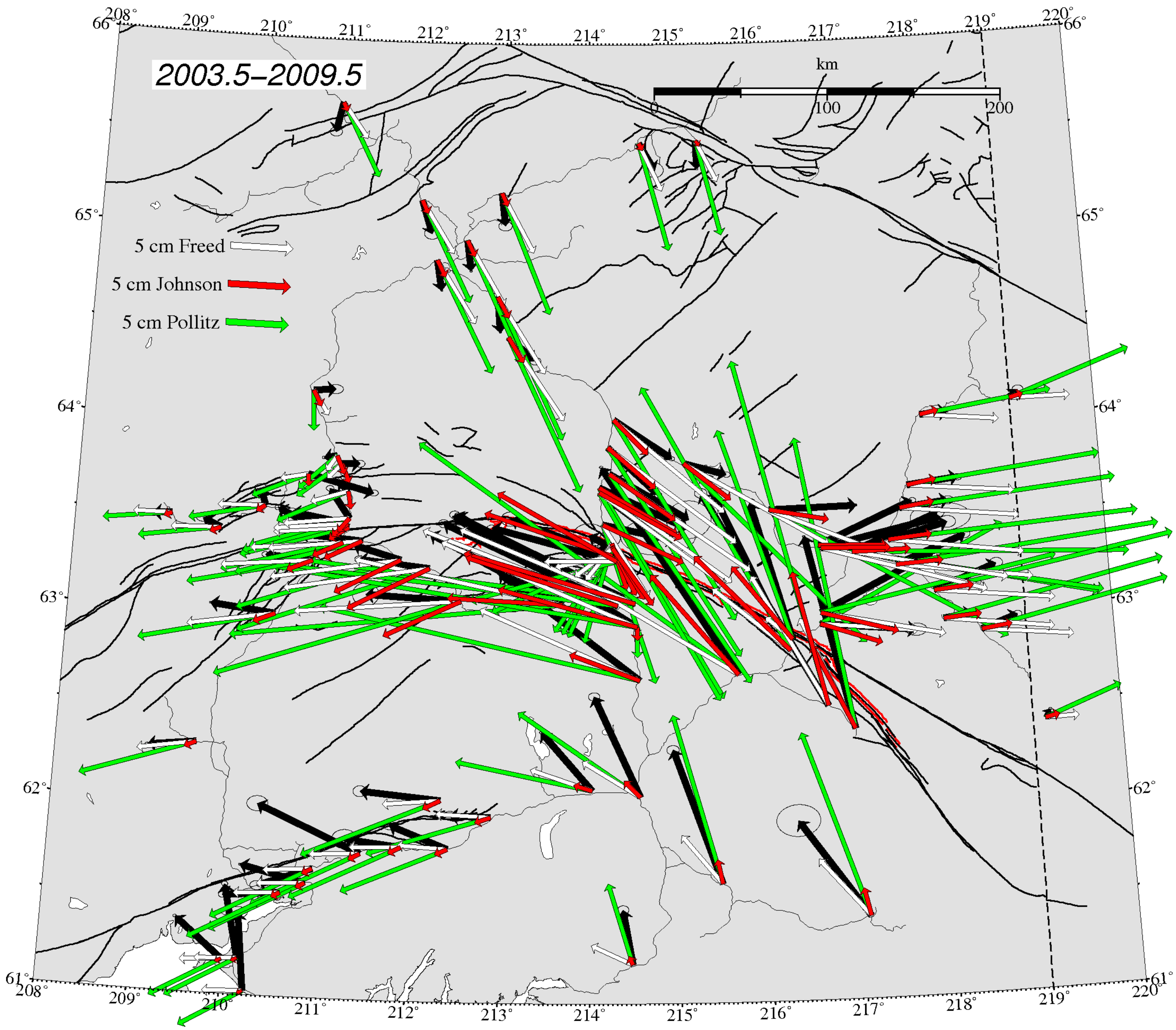
Ti on



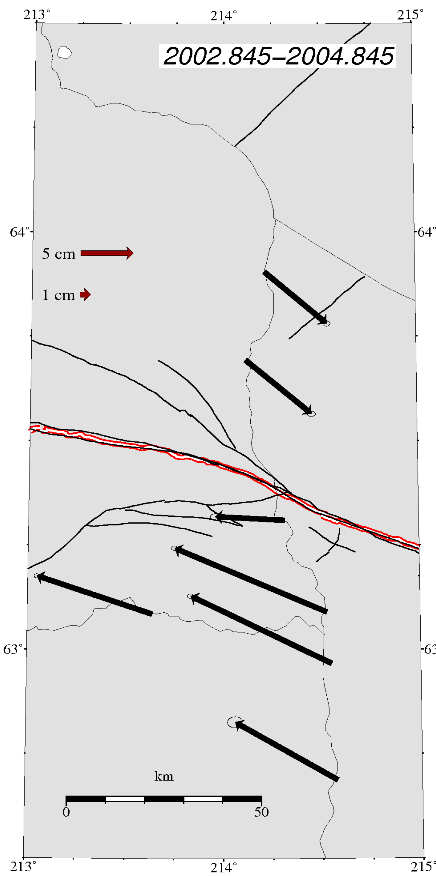
2003.5–2009.5
2006.5–2009.5
213°
214°
215°
64°
63°
212°
217°
218°
5 cm
1 cm
km
0
50

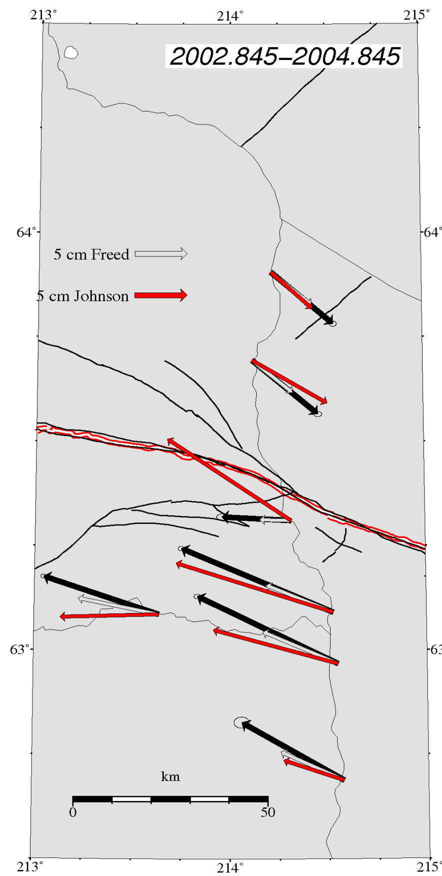


2002.845–2004.845
km
0
100
200
5 cm Freed
5 cm Johnson
5 cm Pollitz
208°
209°
210°
211°
212°
213°
214°
215°
216°
217°
218°
219°
220°
66°
65°
64°
63°
62°
61°

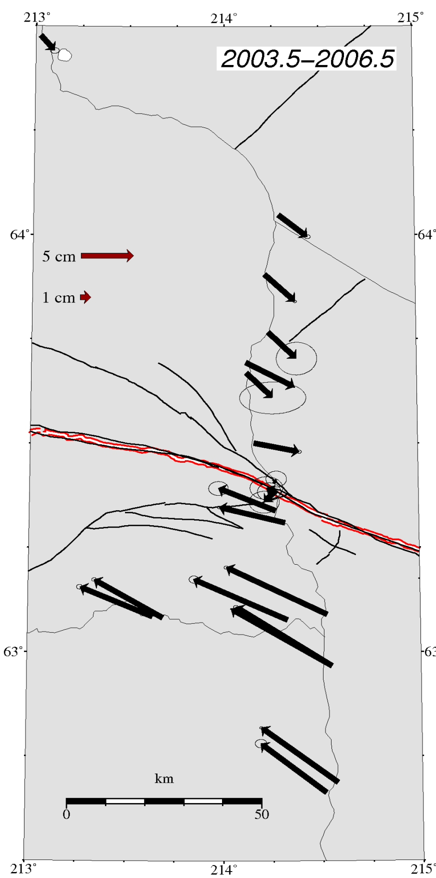

2003.5–2009.5
5 cm Freed
5 cm Johnson
5 cm Pollitz
km
0
100
200
208°
209°
210°
211°
212°
213°
214°
215°
216°
217°
218°
219°
220°
66°
65°
64°
63°
62°
61°

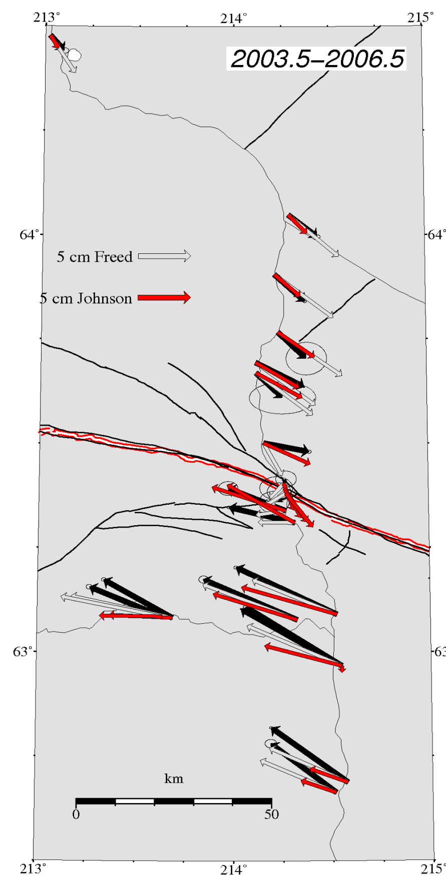
Detail of Near-Fault Data



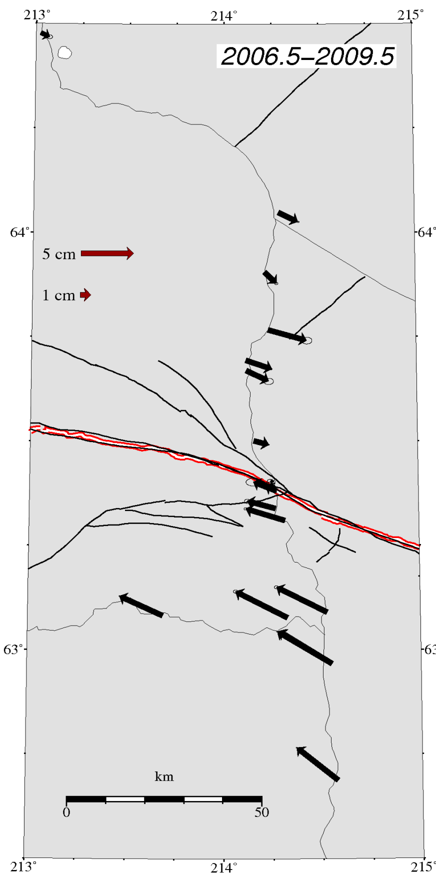


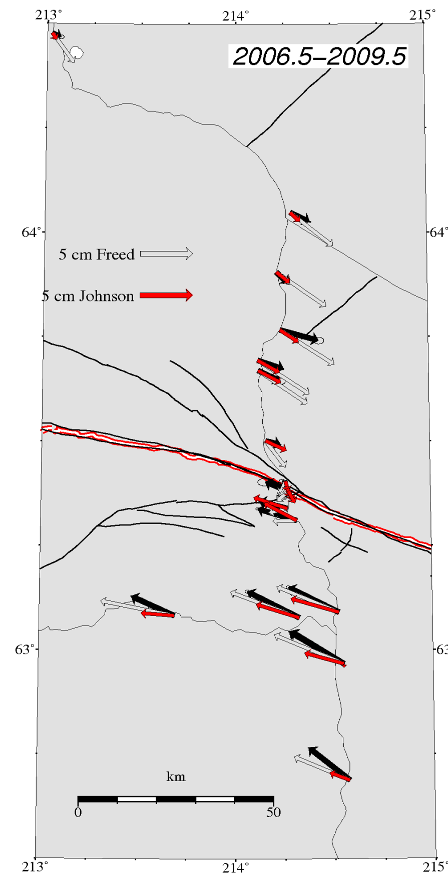
Detail of Near-Fault Data



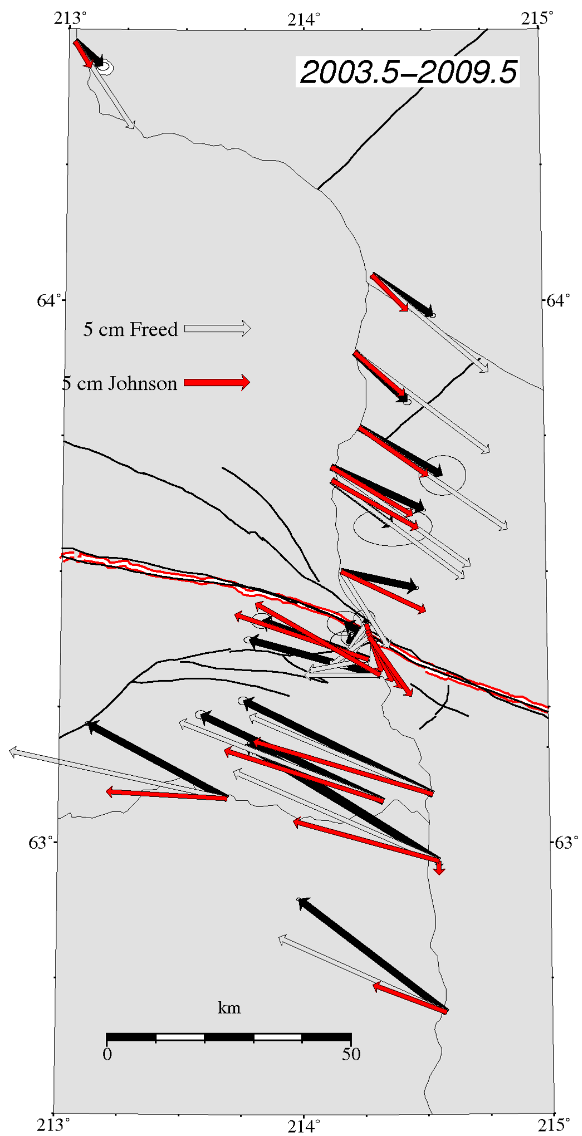


Detail of Near-Fault Data



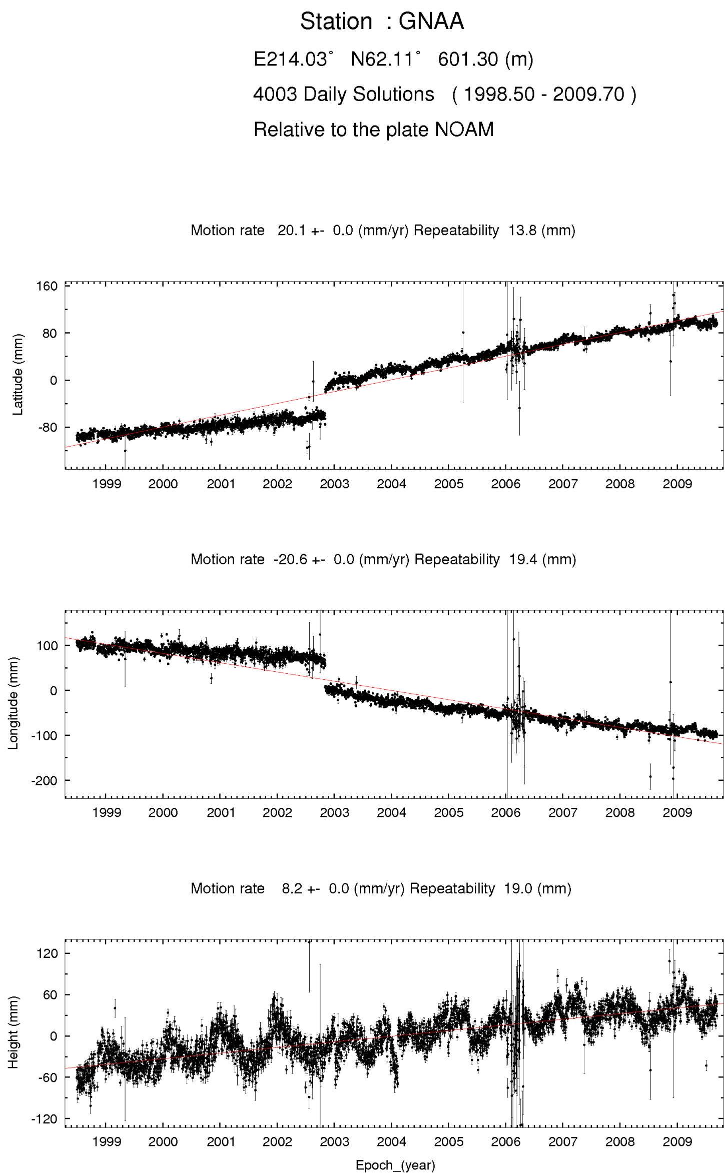


Key Observation 1



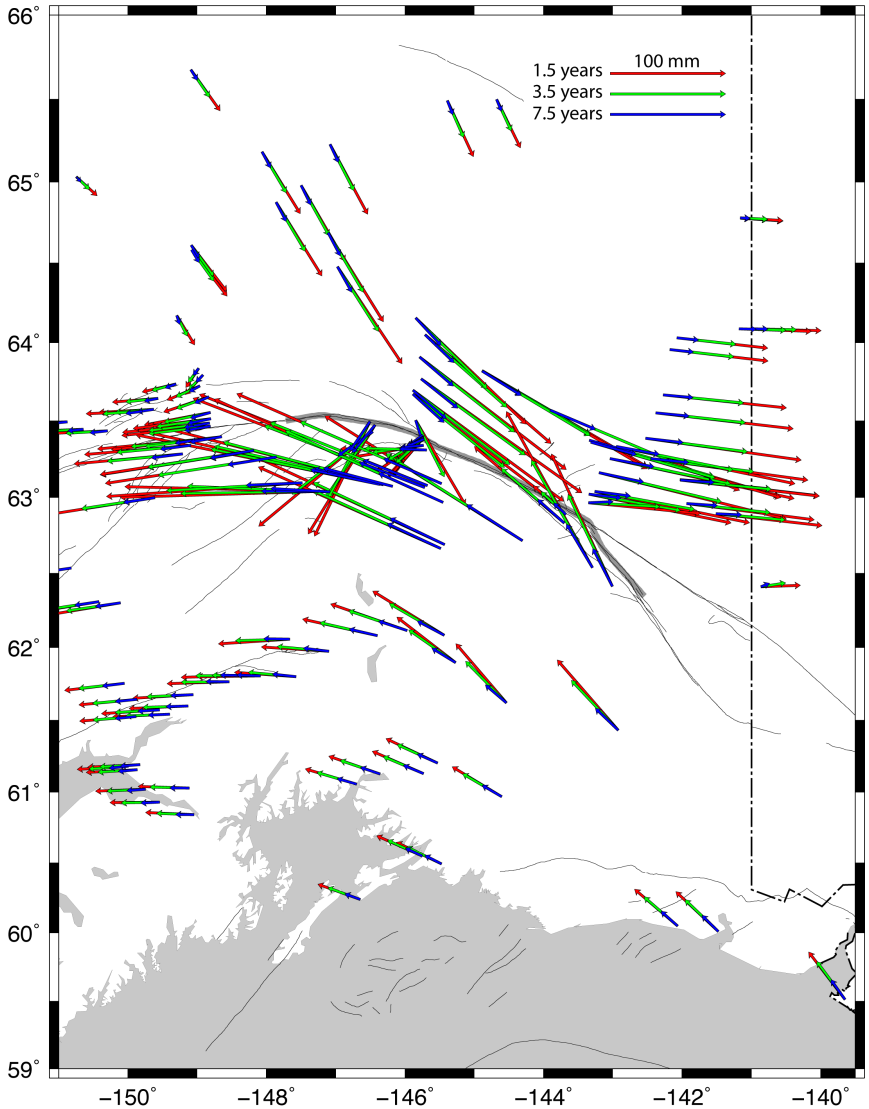
- *Afterslip in Johnson et al. (2008) model produces some of the observed asymmetry in displacements; viscoelastic-only models do not*
- But cannot predict motion in far south
  - Caused by interaction with subduction coupling?
  - Caused by significant inhomogeneity in mantle?
- Including effect of slab in viscoelastic models produces slower motion in south, not faster.

Key Observation 1



- Large change in velocity in roughly the direction of plate convergence
  - Horiz. velocity ~ doubles
- But NO strong curvature of the time series
- Change in velocity is roughly consistent with a significant expansion of locked zone on subduction interface (Johnson et al., 2008).

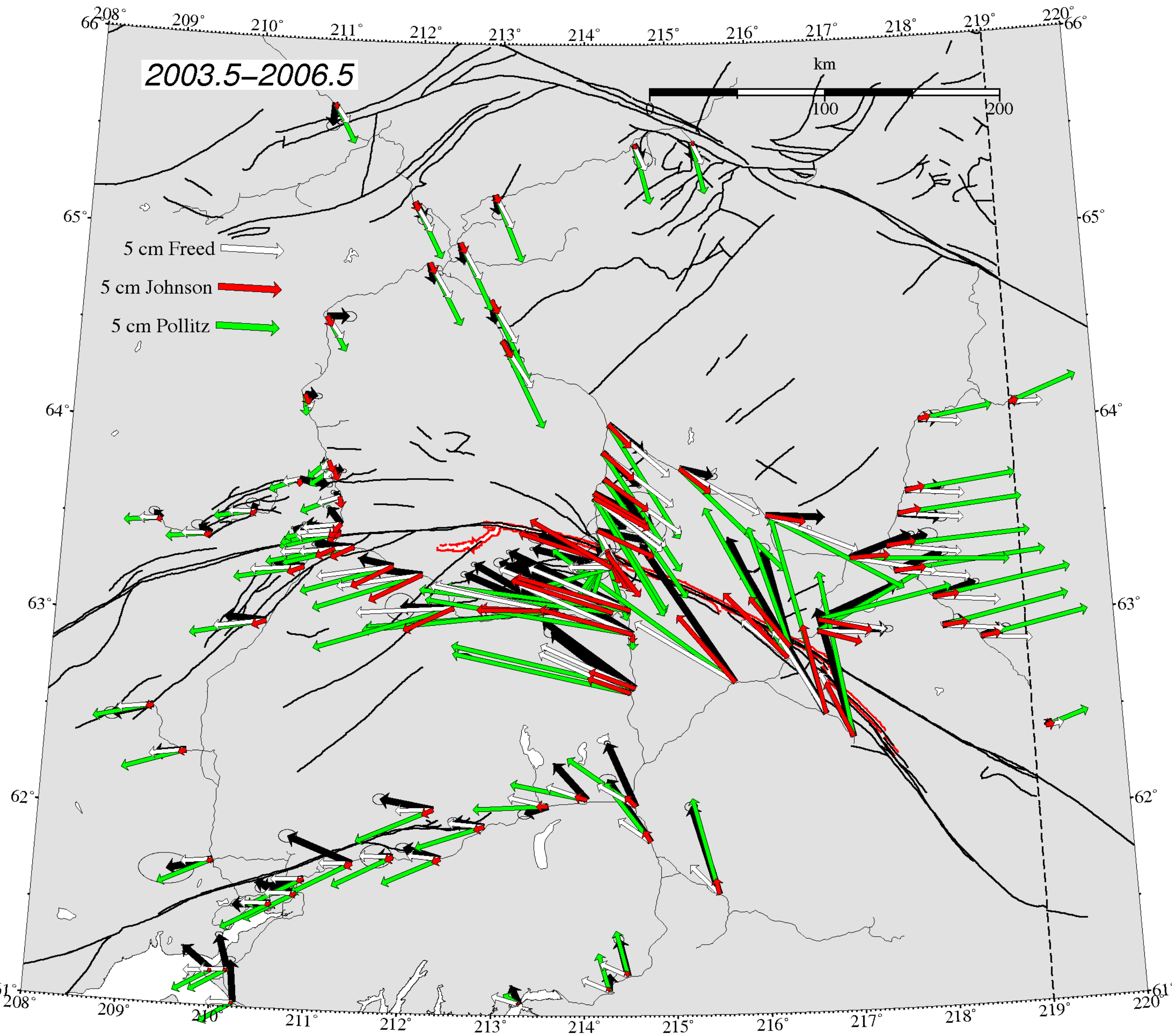
Key Observation 2

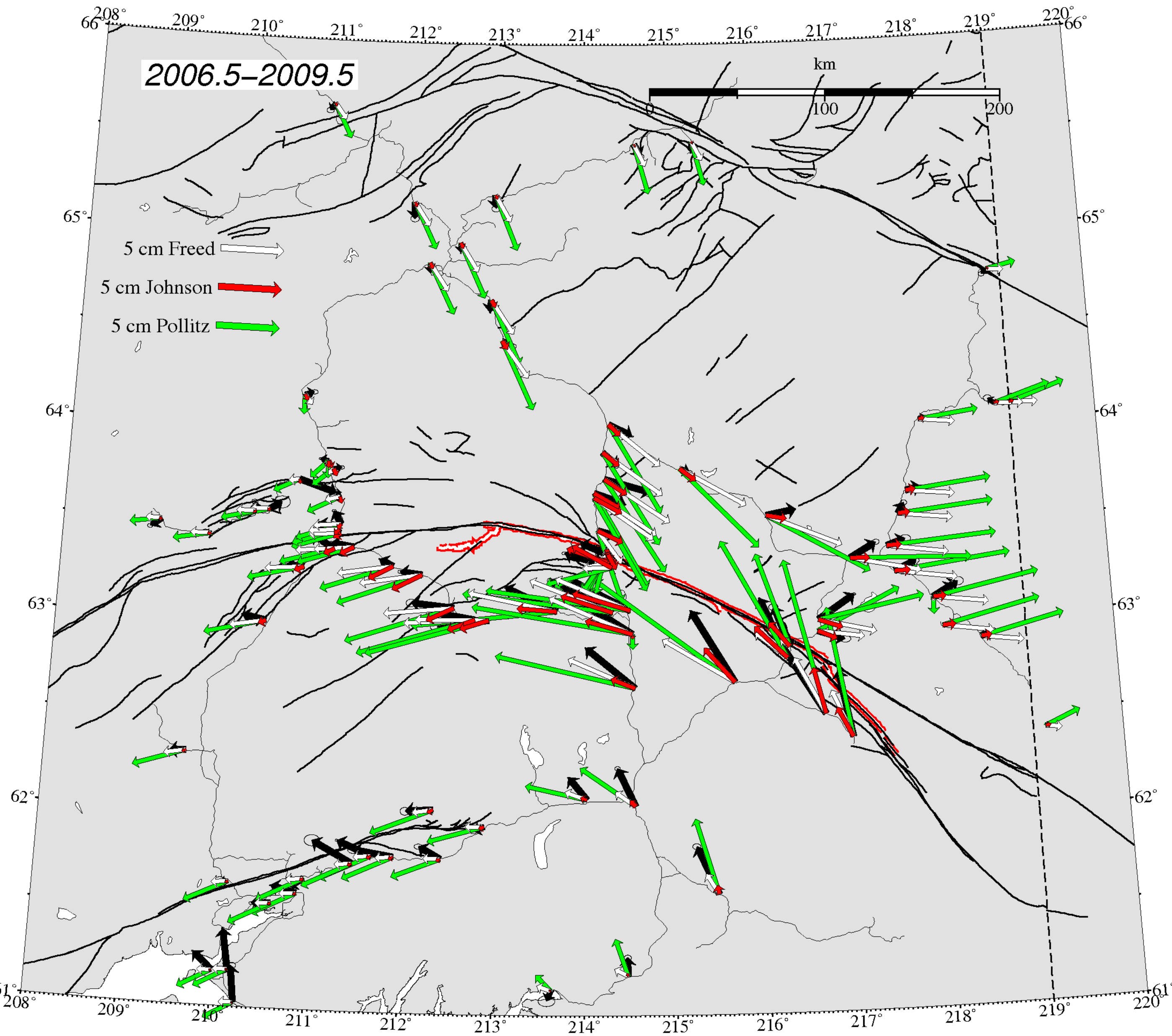


- *Linear viscous models do not predict the observed rotation of displacement vectors with time*
- Observations show a counter-clockwise rotation of vectors north of fault, clockwise rotation of vectors south of fault.

Conclusions

- Asymmetry of observed displacements is significant and difficult to explain
  - Near fault: afterslip can explain
  - Large displacements >100 km south may require change in behavior of locked zone on subduction thrust.
- No published model provides a good overall fit to observations.
  - Something fundamental seems to be missing.
- Spatially dense campaign data provide a significant augmentation to sparse continuous data.


2003.5–2006.5
5 cm Freed
5 cm Johnson
5 cm Pollitz
km
0
100
200
208°
209°
210°
211°
212°
213°
214°
215°
216°
217°
218°
219°
220°
61°
62°
63°
64°
65°
66°



2006.5–2009.5
5 cm Freed
5 cm Johnson
5 cm Pollitz
km
0
100
200
208°
209°
210°
211°
212°
213°
214°
215°
216°
217°
218°
219°
220°
66°
65°
64°
63°
62°
61°