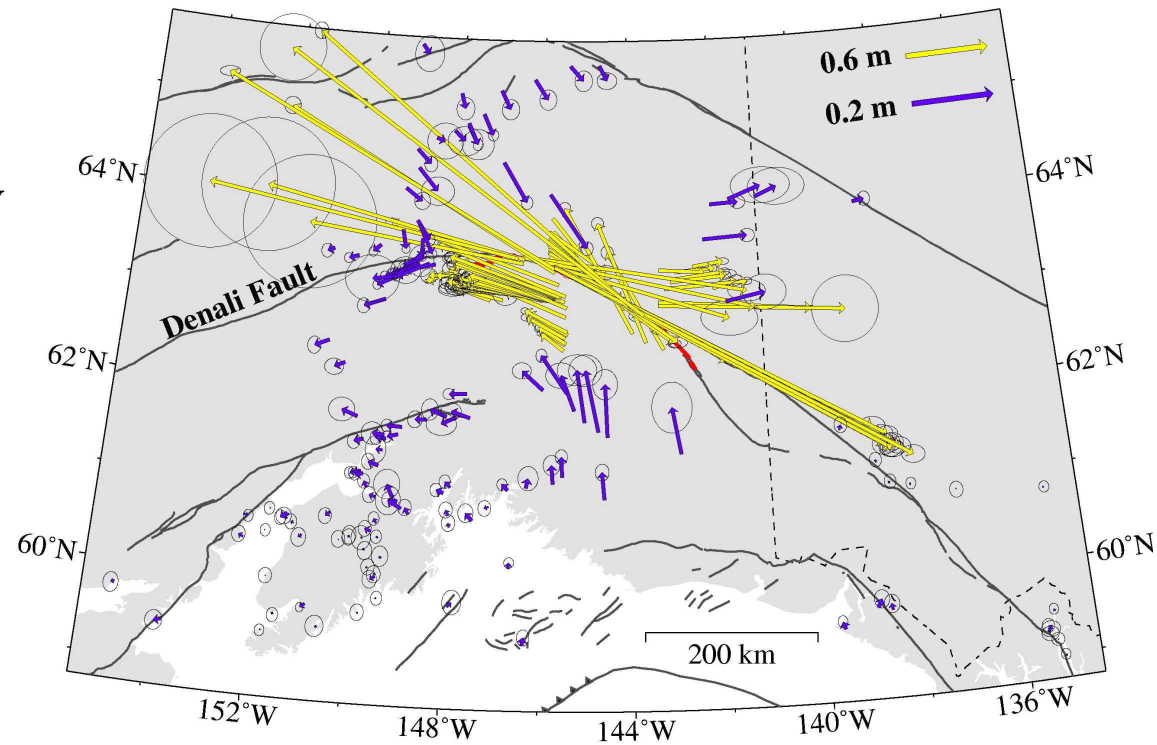
Lecture 15: Earthquakes



Tectonic Geodesy
GEOS 655
Jeff Freymueller

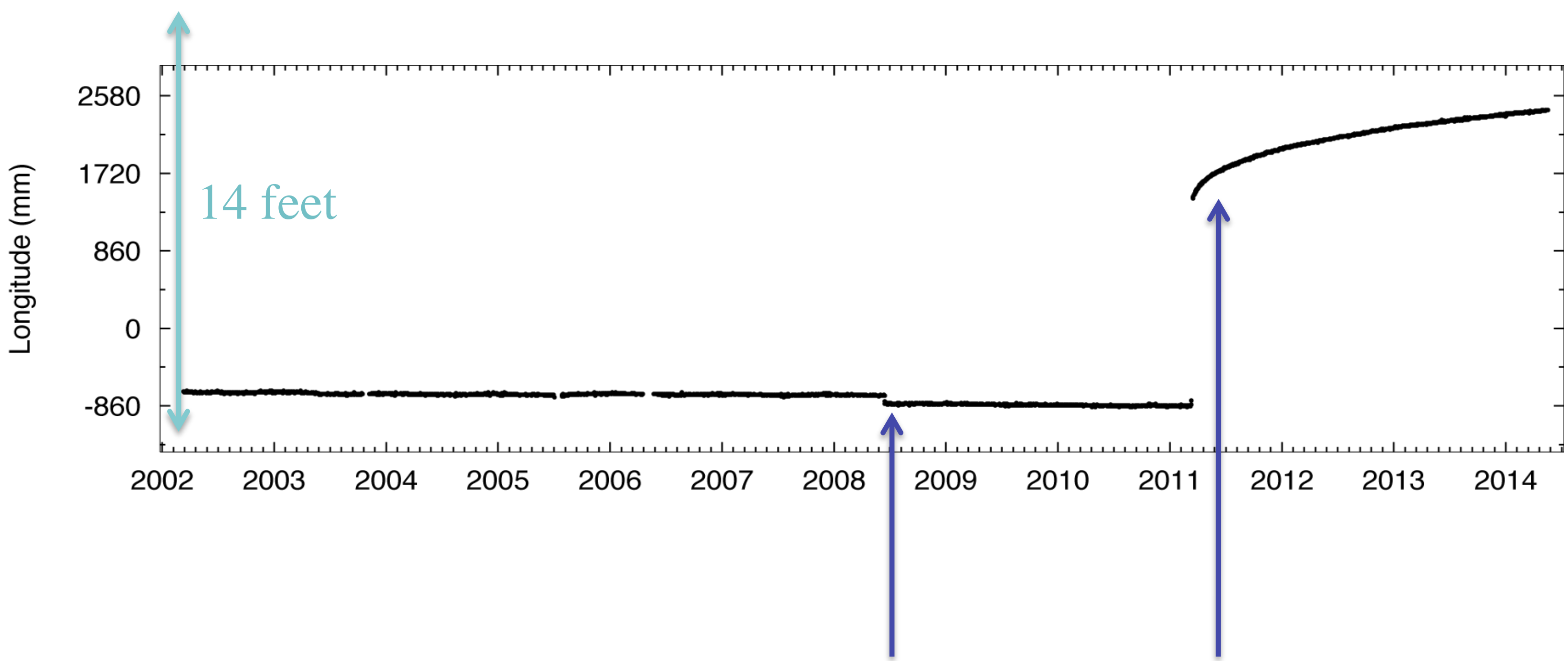
Where did slip occur on fault?

- The goal is to use displacements to determine where and how much slip occurred on the fault.
- The problem is non-linear in the fault geometry but linear in slip
- Geodetic data are complementary to seismic data; in theory both can be combined.

Steps to Study

- Collect post-earthquake data
- Identify displacements in time series
- How to estimate step?
  - Deformation between pre-earthquake and post-earthquake survey
  - Postseismic deformation
- What to do with displacements?
  - Elastic dislocation model(s) to relate slip on fault(s) to displacements

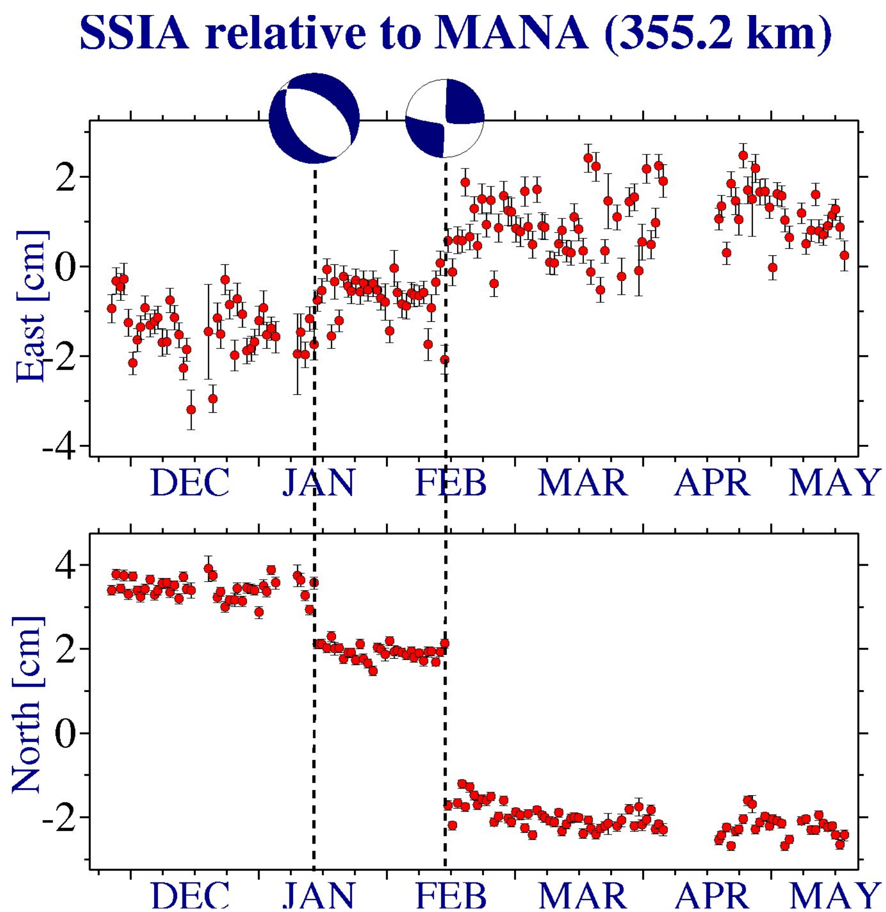
Great Earthquakes (Mizusawa, Japan)



earthquake

Tohoku Earthquake (11.5 feet eastward)

GPS Timeseries Reveal Coseismic Signals



Two clear offsets in SSIA timeseries:

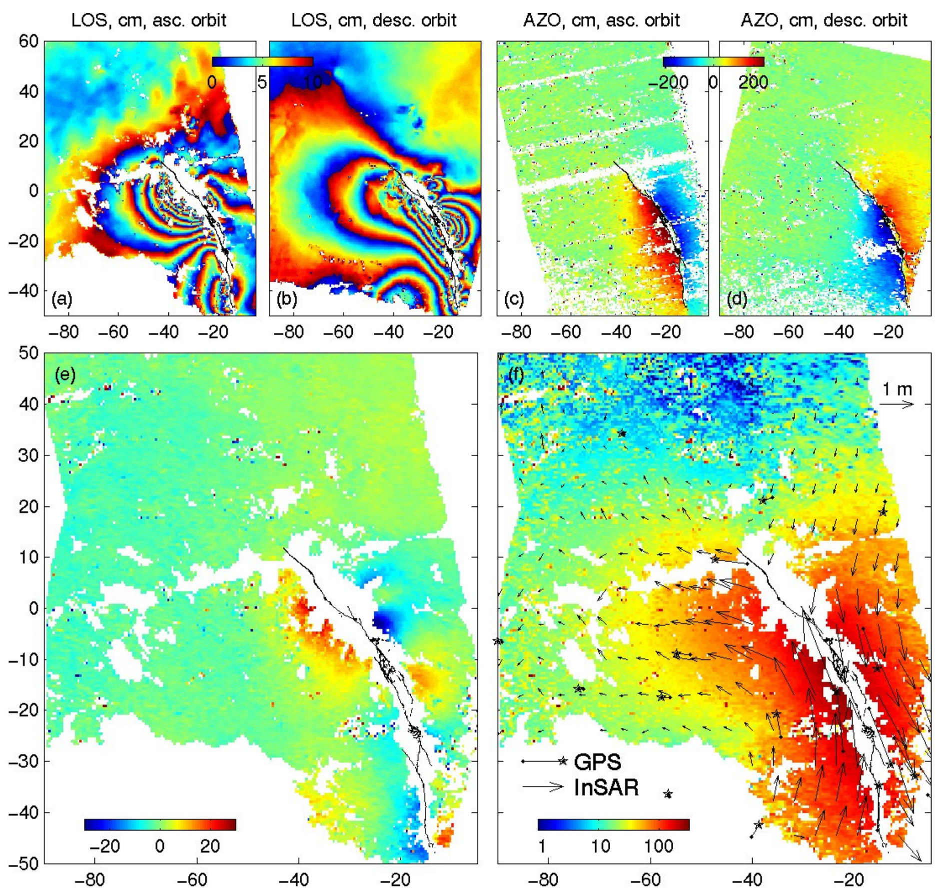
- January 13: 15+/-3 mm
- February 13: 39+/-3 mm

Can we use the GPS data to learn something about the earthquakes?

SSIA- El Salvador (closest to the seismic activity)

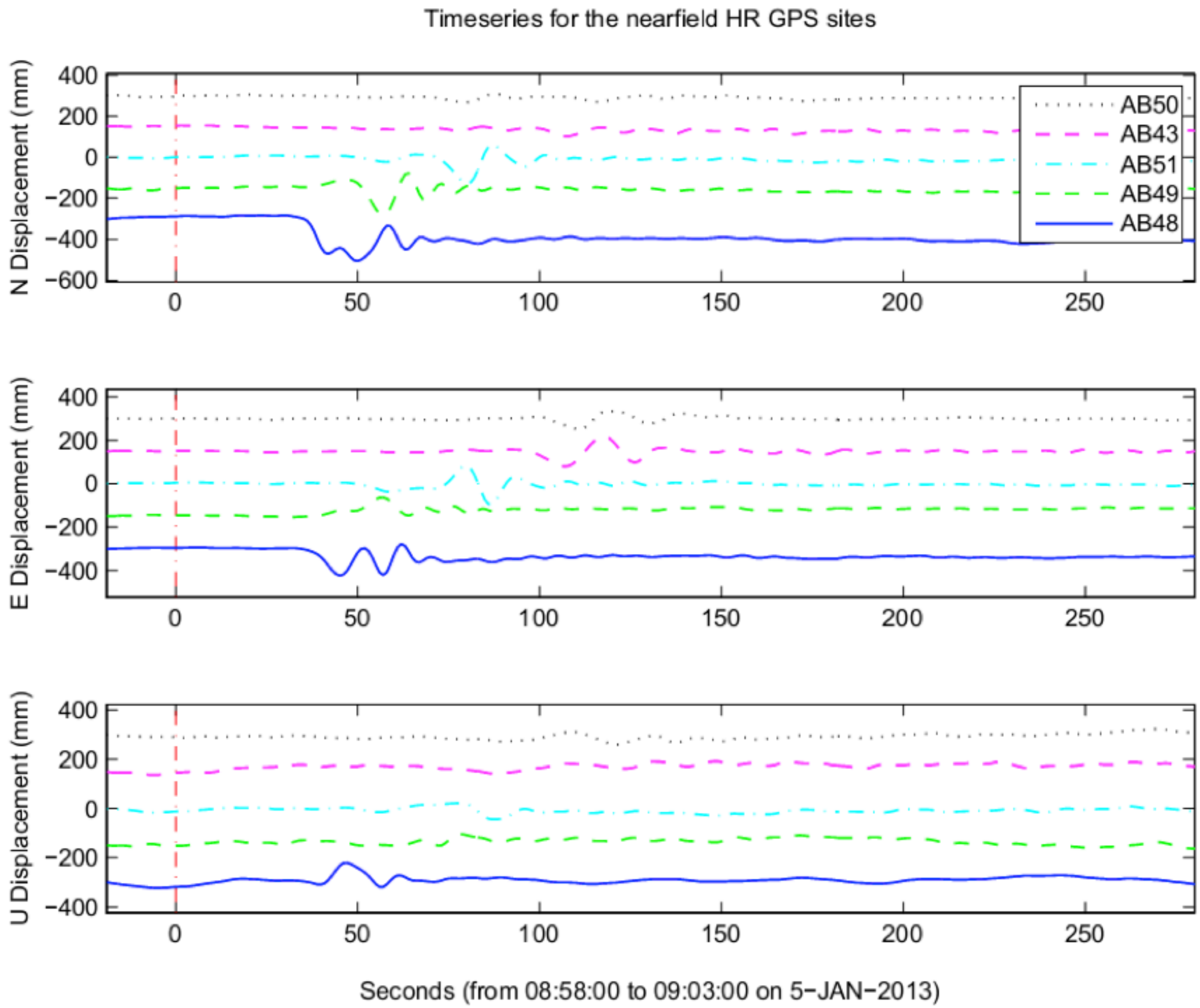
MANA-Nicaragua (furthest from the seismic activity)

InSAR vs/+ GPS

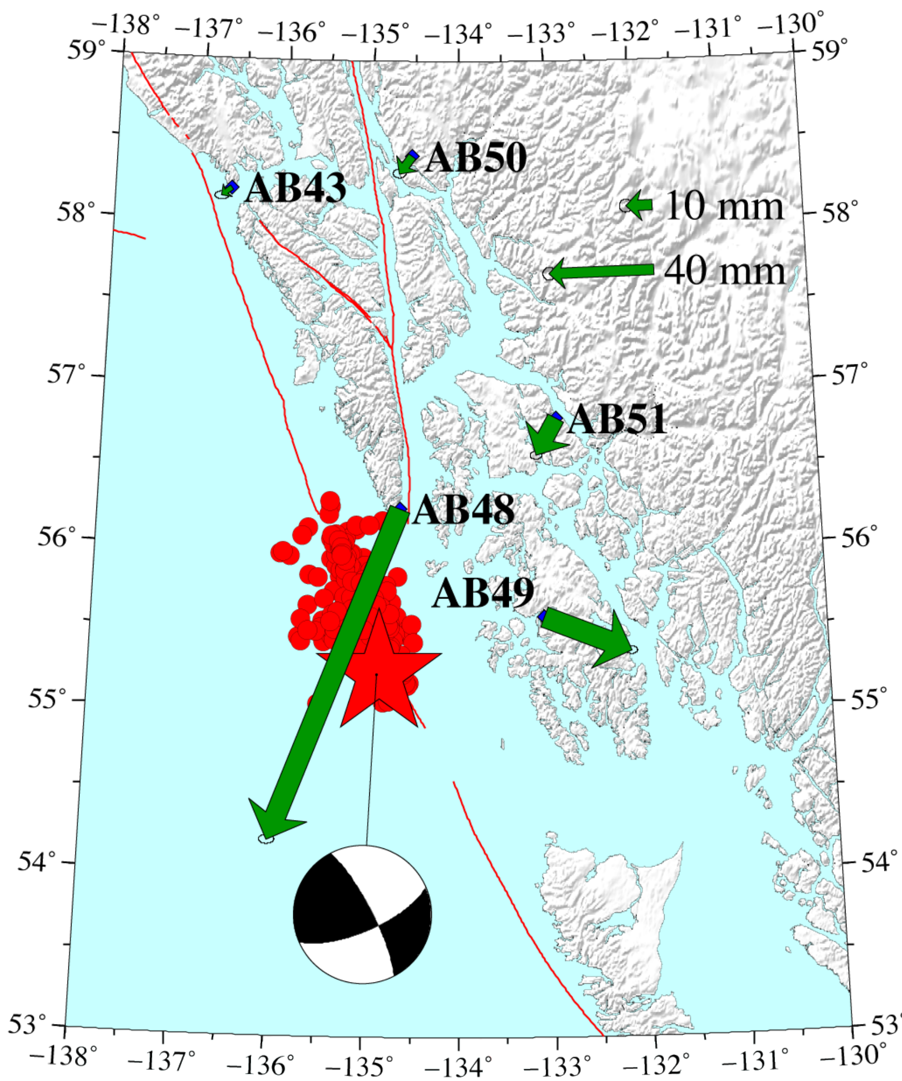


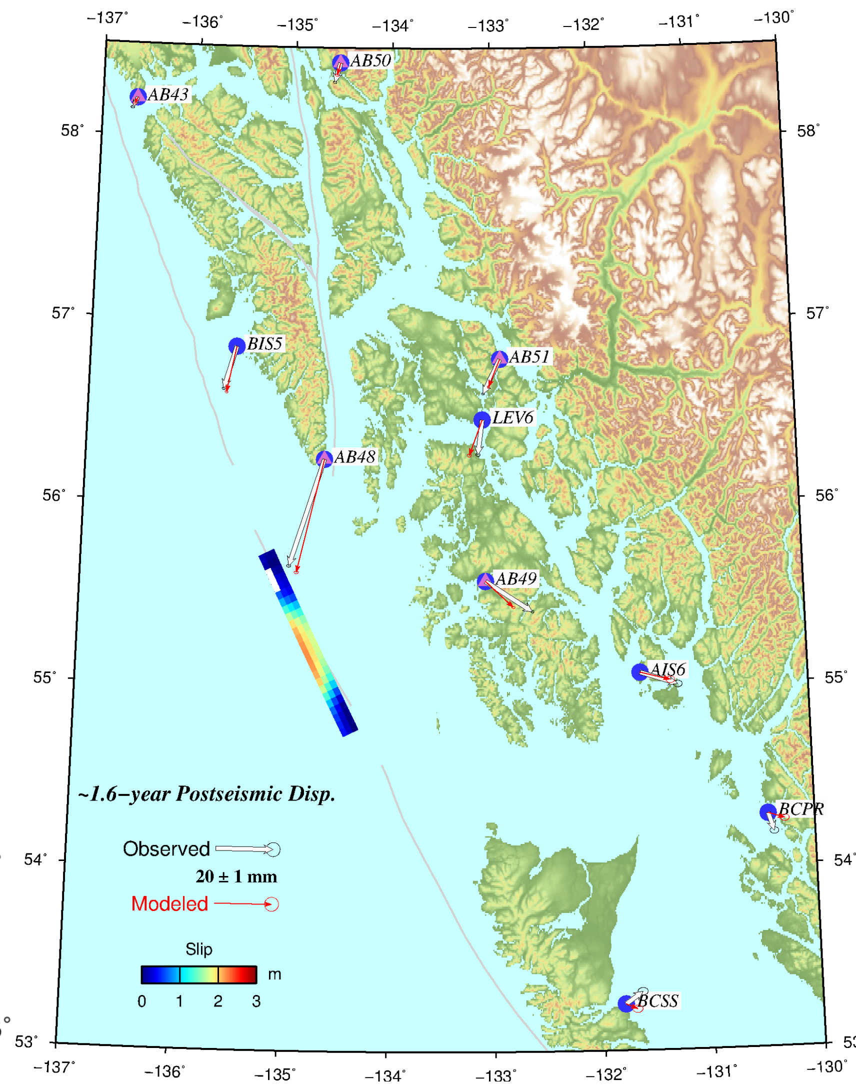
- InSAR does not require pre-earthquake field survey
- Spatially dense measurements
- But only one component, and the impact of the look angle makes for strange "look"
- Constrained by satellite repeat interval

Kinematic Records

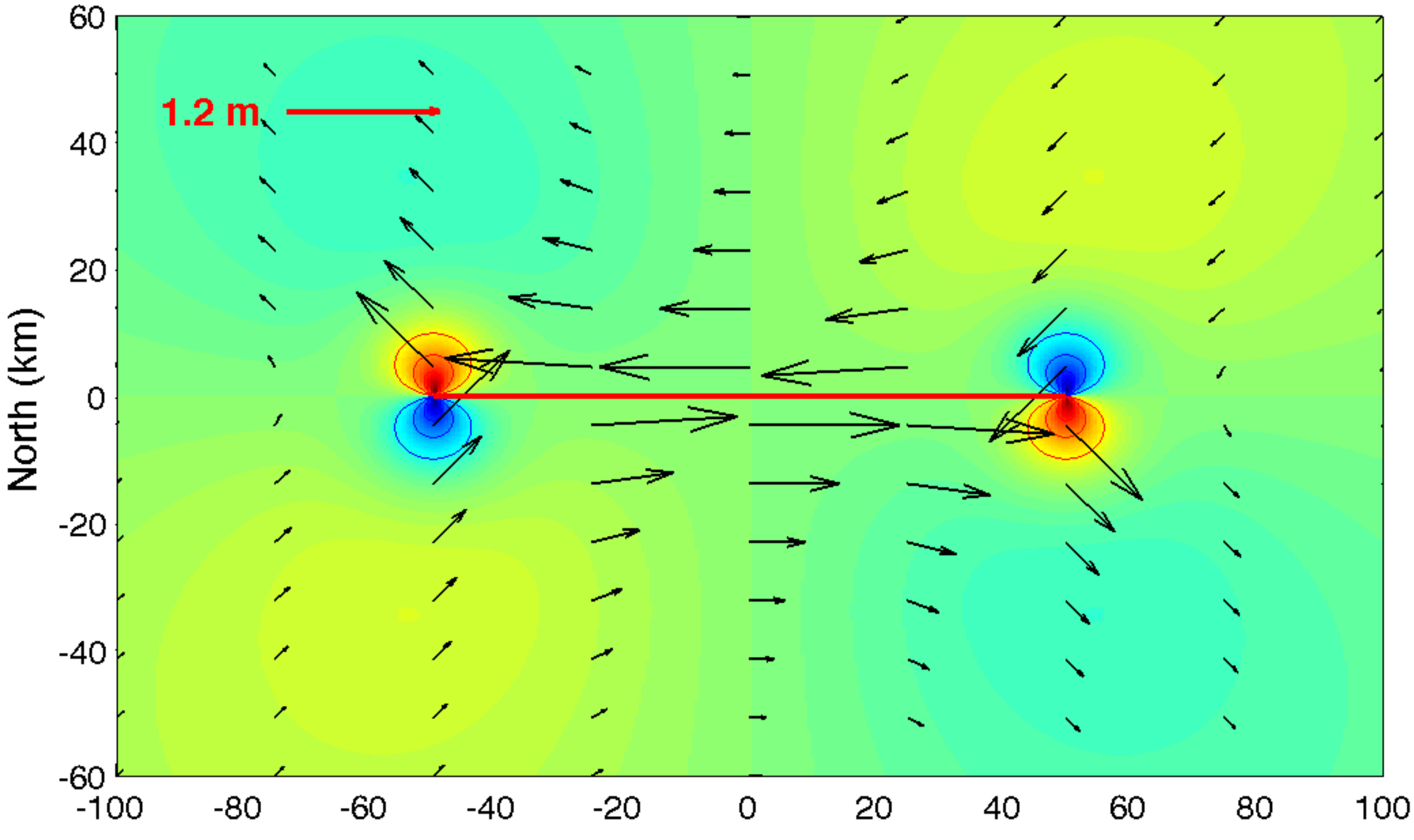


2013 Craig earthquake

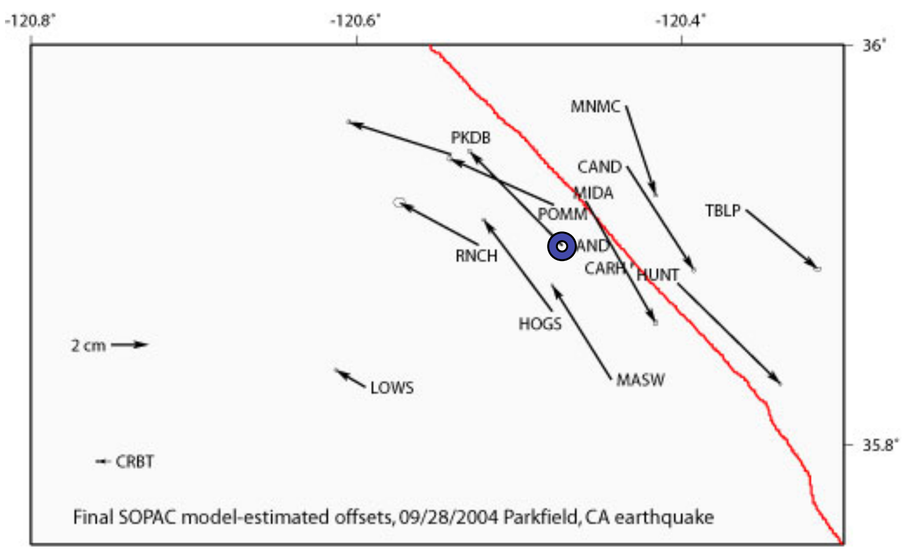


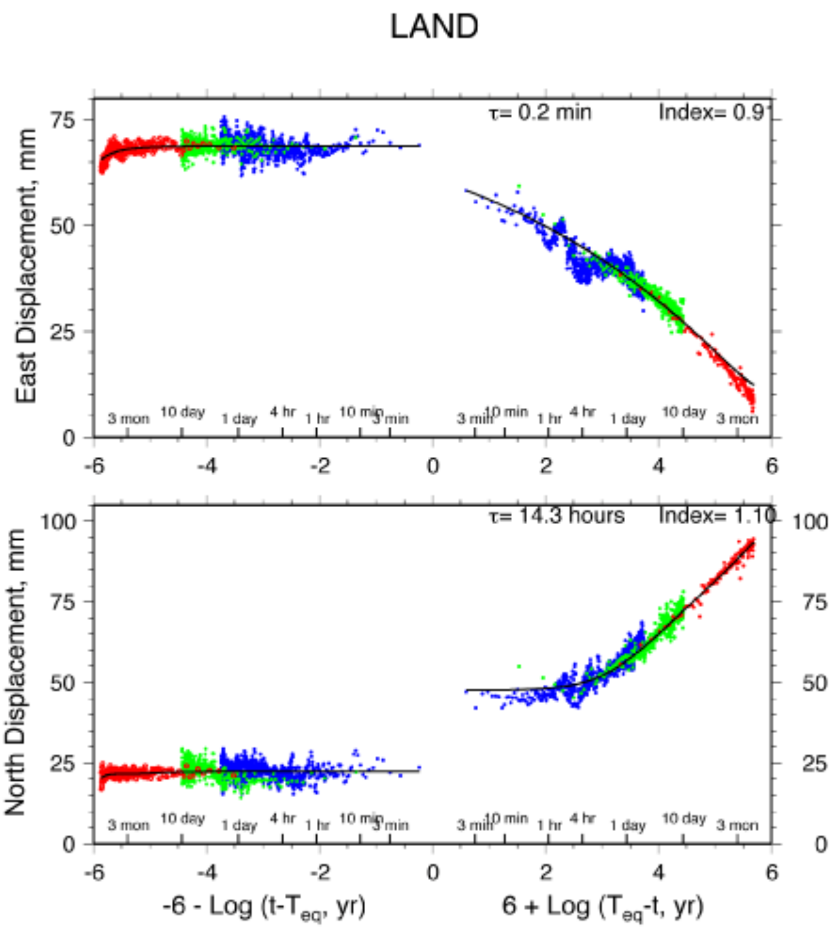


Elastic Dislocation Model

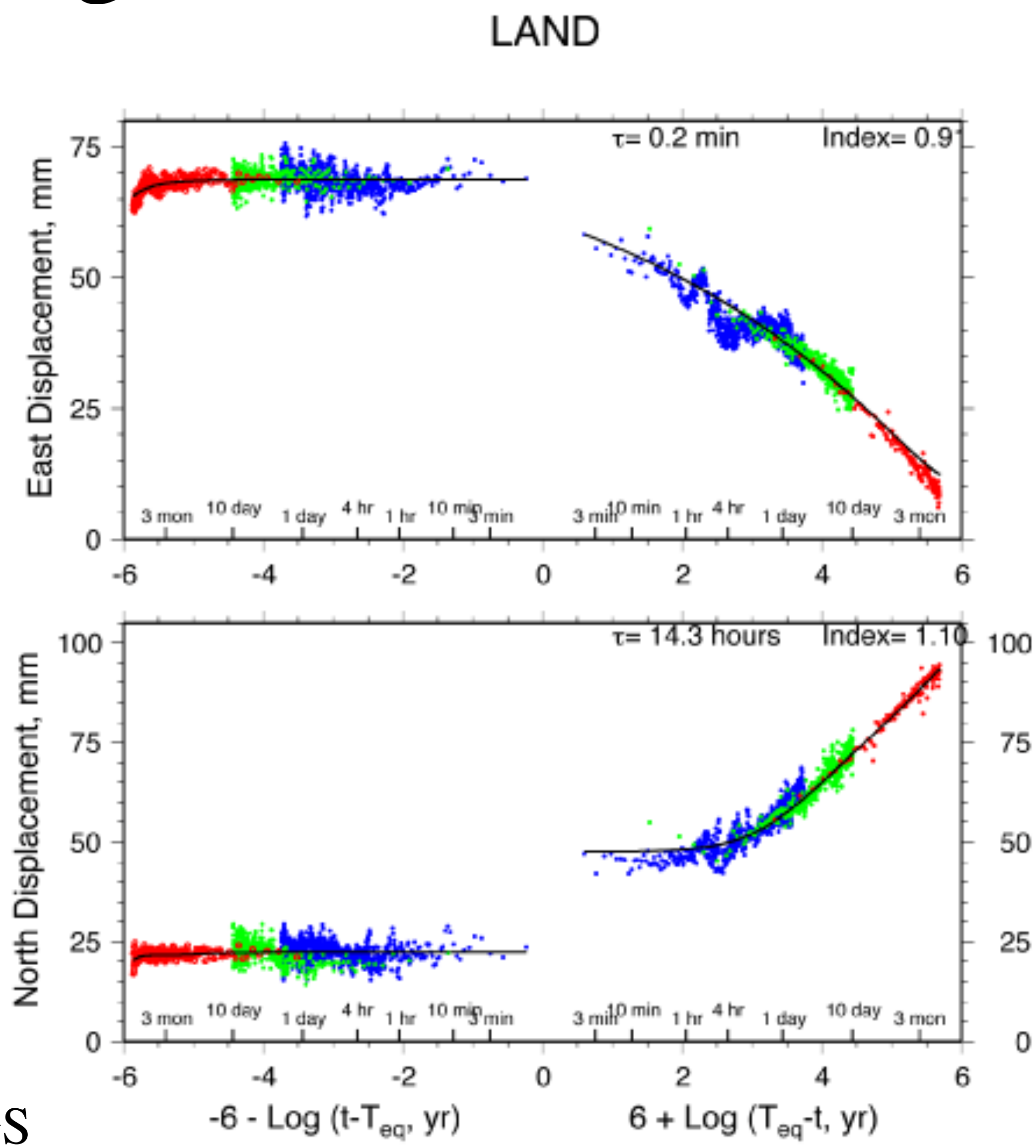


Parkfield Earthquake



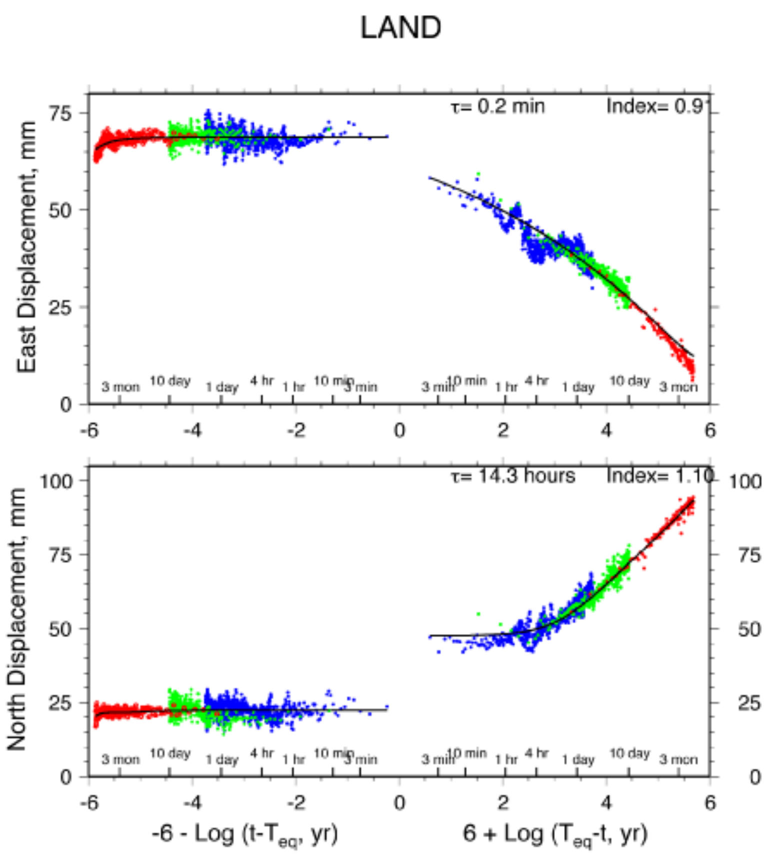


Separating Coseismic and Postseismic



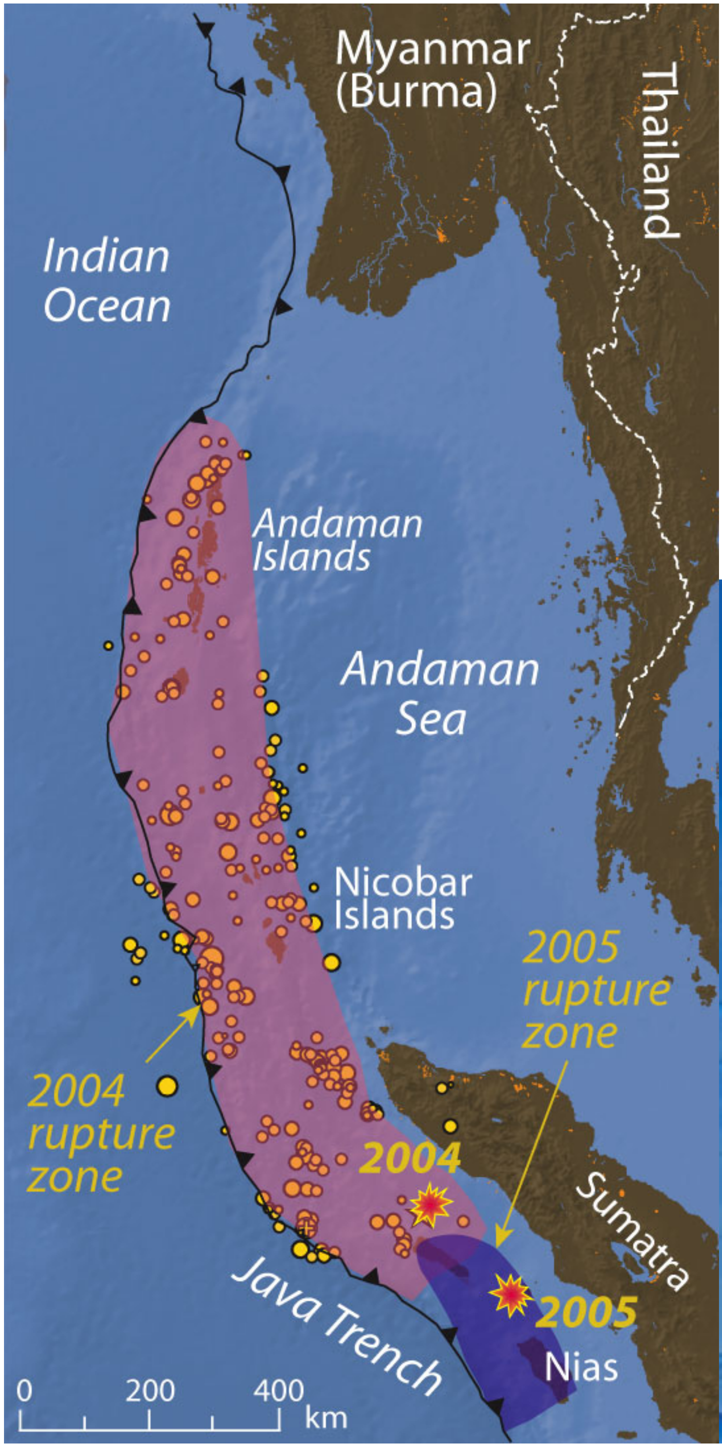
Parkfield eq
J. Langbein, USGS

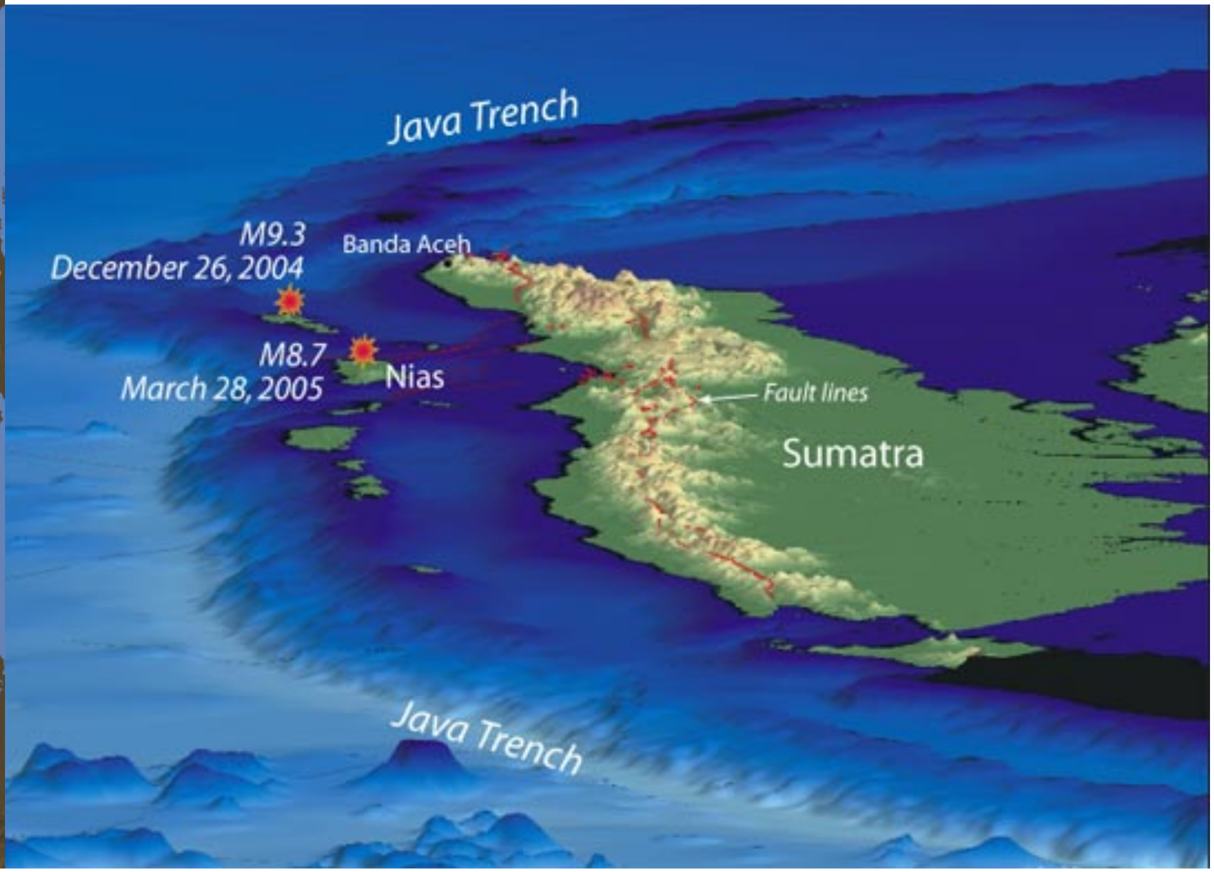
Lessons from Parkfield



- Postseismic deformation appears to begin immediately after earthquake
- Coseismic and postseismic mechanisms are different
- Almost all "coseismic" estimates include postseismic deformation

Sumatra Sequence

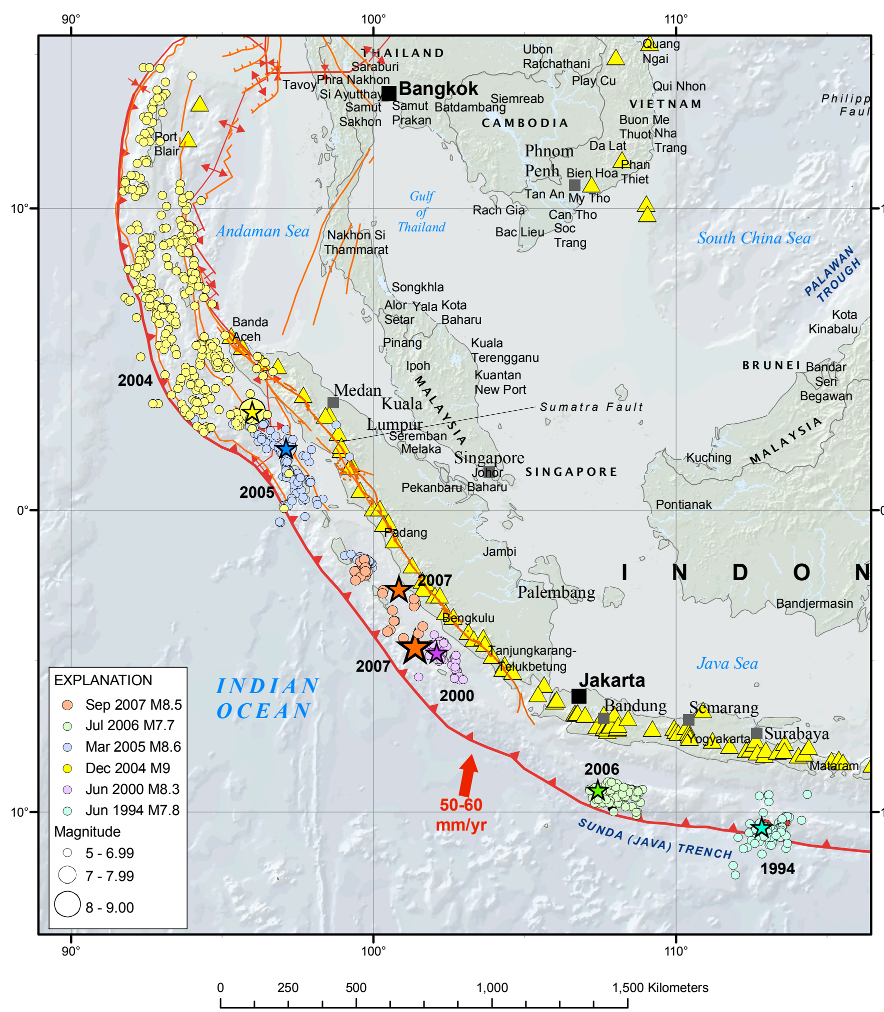




Several Ruptures this Decade

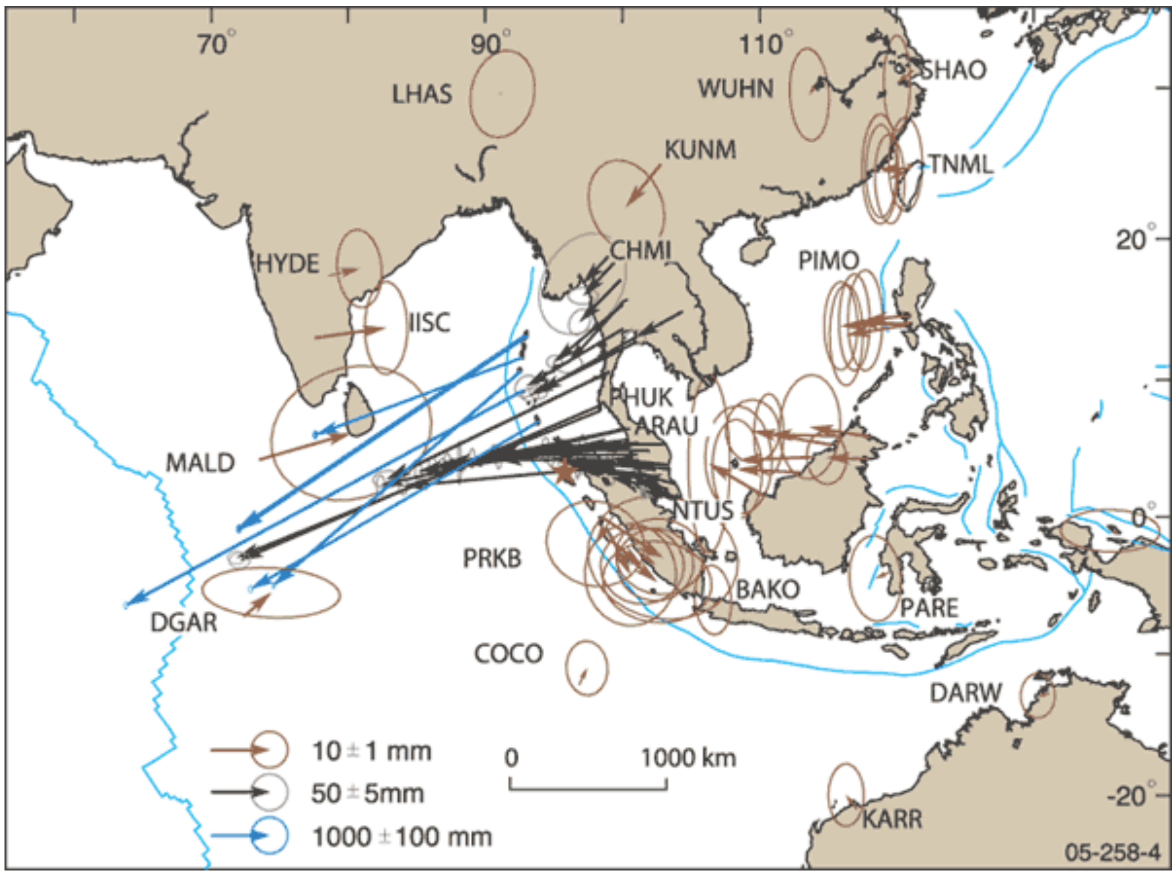
USGS

wo Decades of Ruptures in the Sumatra-Andaman Arcs



- 2002 M7.2
- 2004 M9.1 Sumatra-Andaman
- 2005 M8.6 Sumatra
- 2007 M8.5 Sumatra
- 2010 M7.7 Sumatra

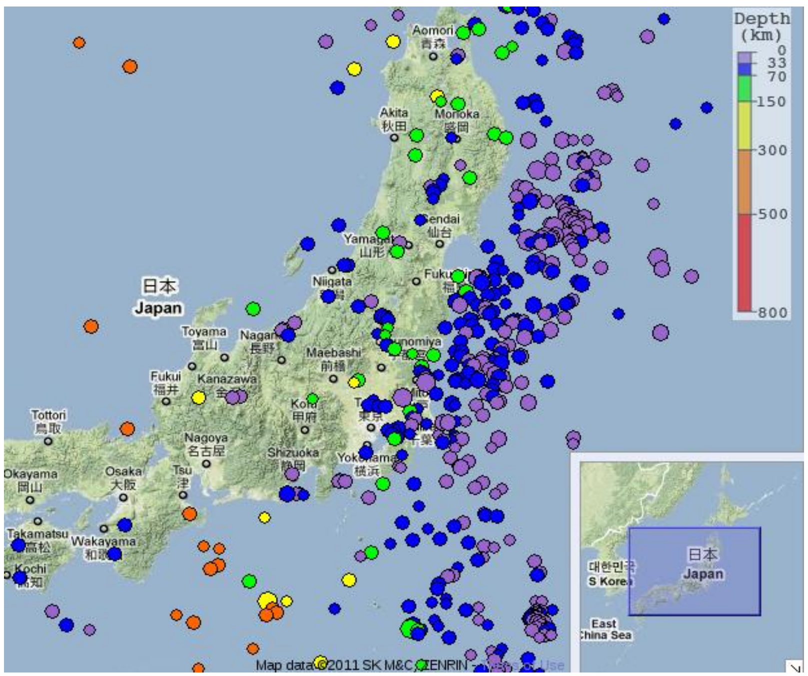
2004 Sumatra-Andaman



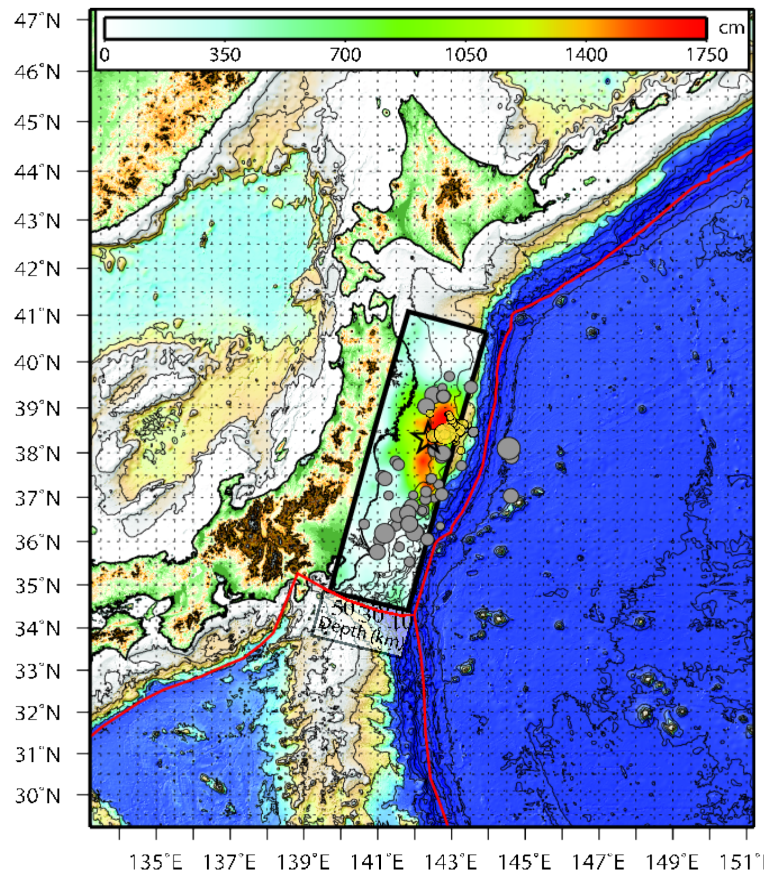
Banerjee et al. (2005)

2011 Tohoku-oki Earthquake

Seismology



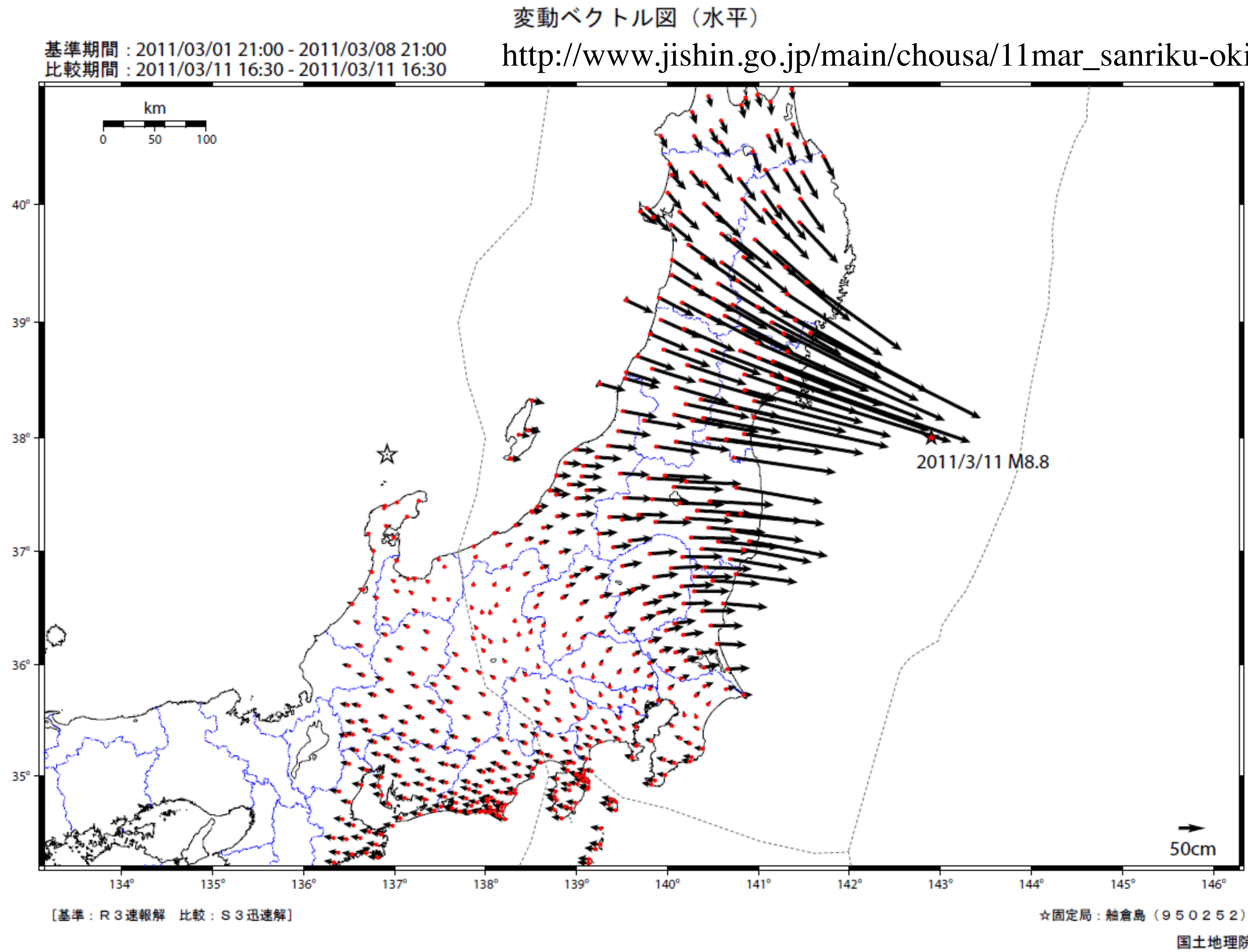
IRIS



USGS Slip Model from Gavin Hayes

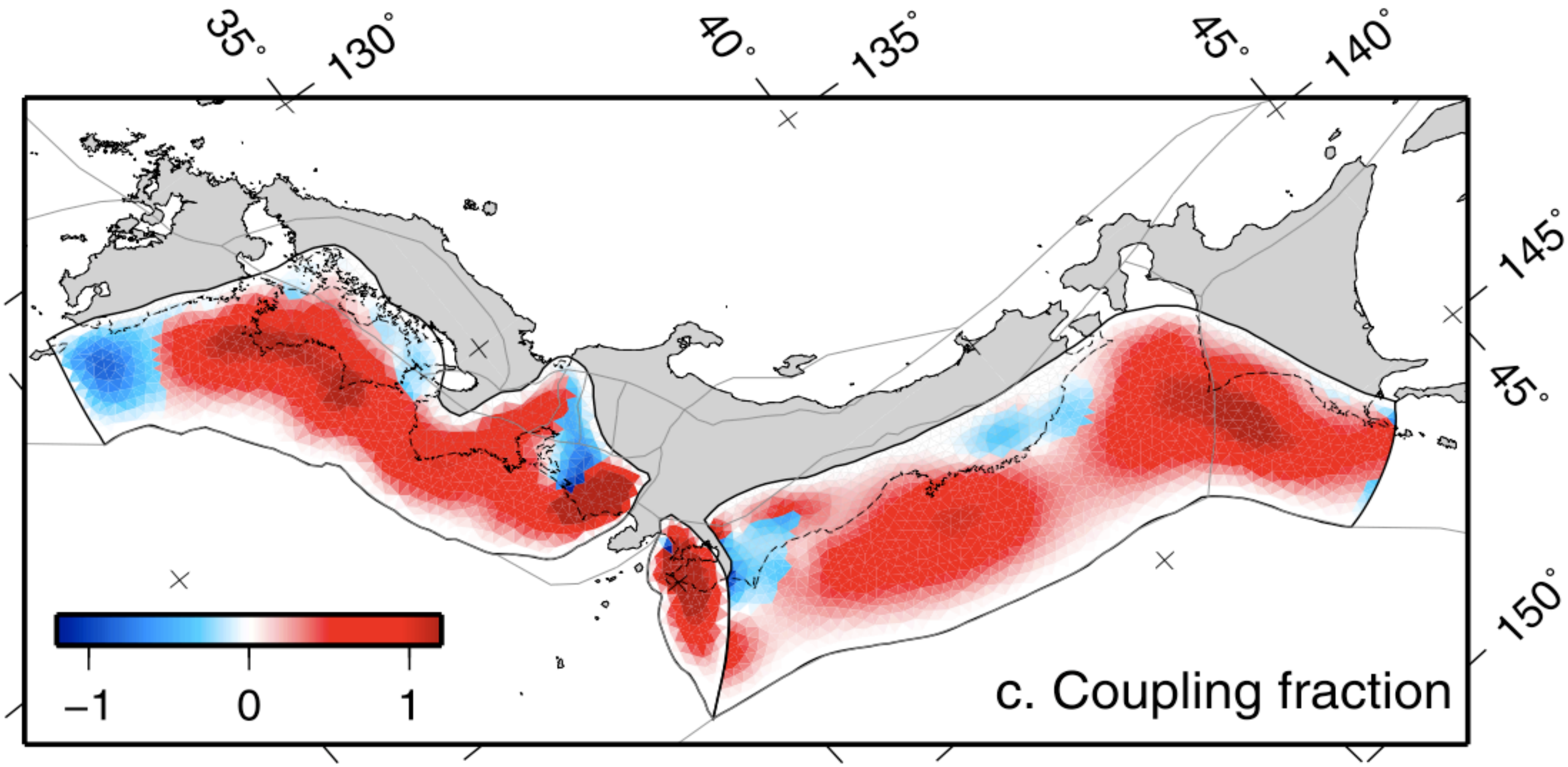
Observed GPS Displacements

http://www.jishin.go.jp/main/chousa/11mar_sanriku-oki/



Estimated Plate Coupling

from GPS data 1995-2000

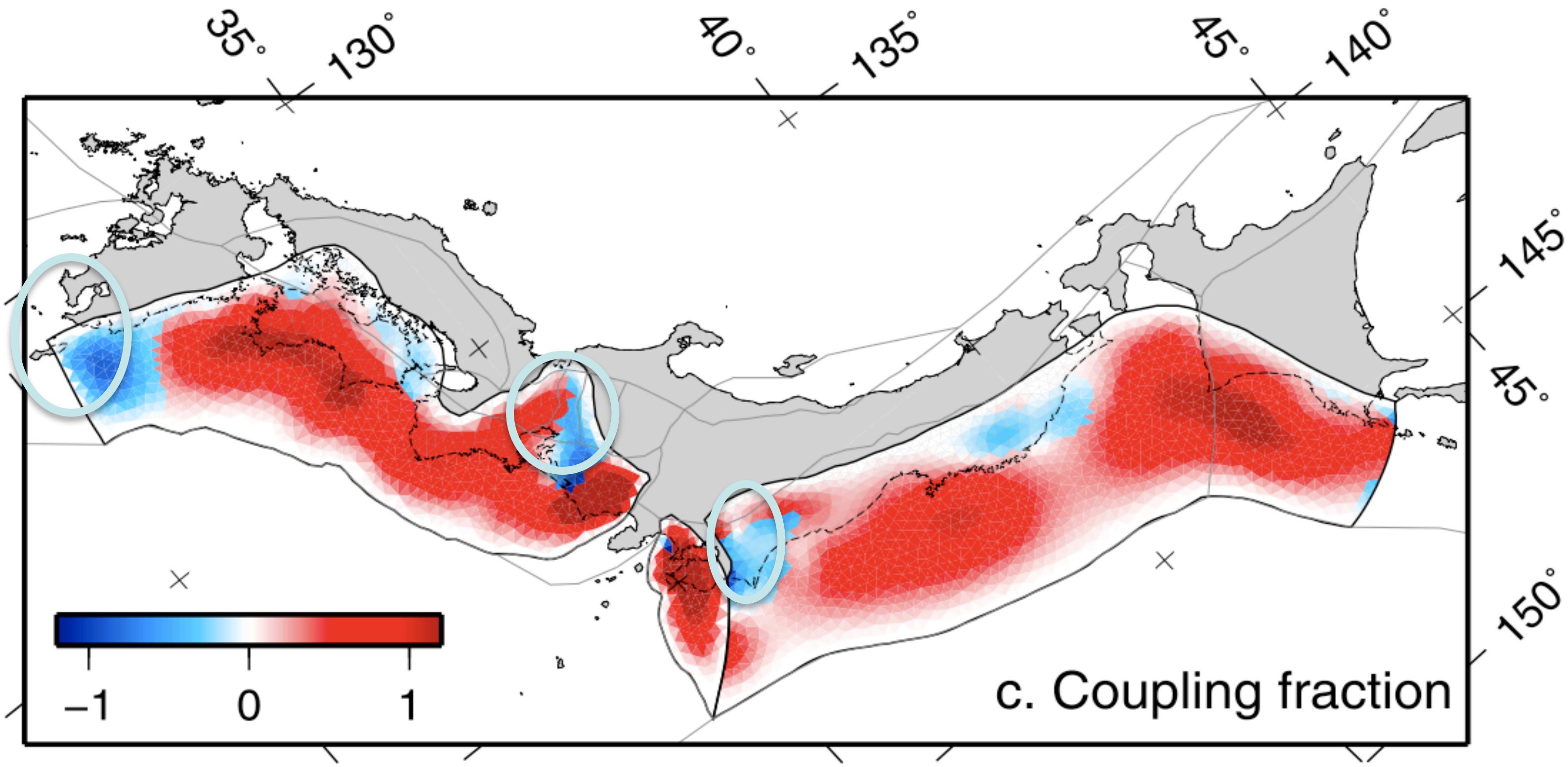


Meade and Loveless (2010)

Estimated Plate Coupling

from GPS data 1995-2000

Slow Slip Events



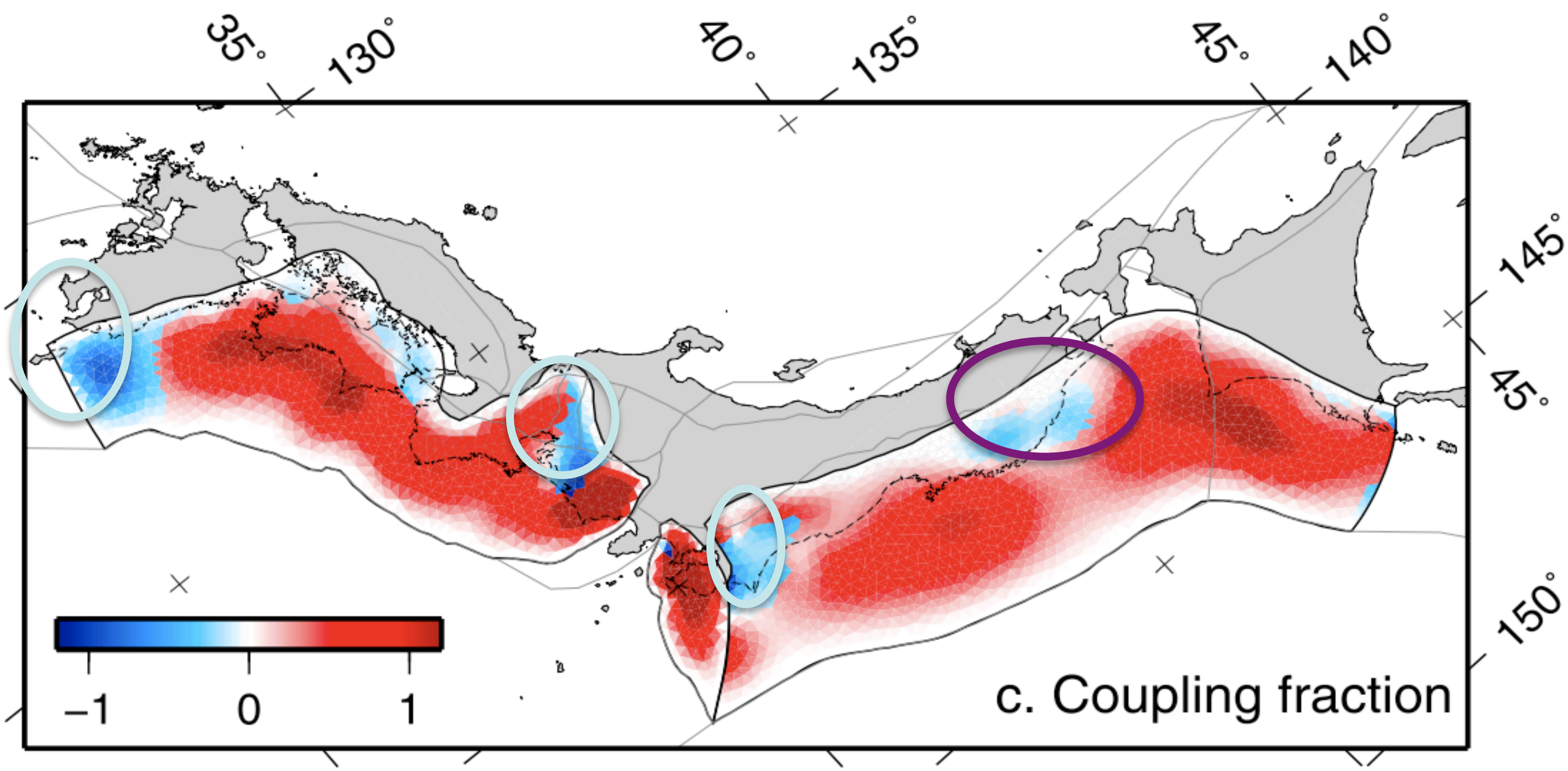
Meade and Loveless (2010)

Estimated Plate Coupling

from GPS data 1995-2000

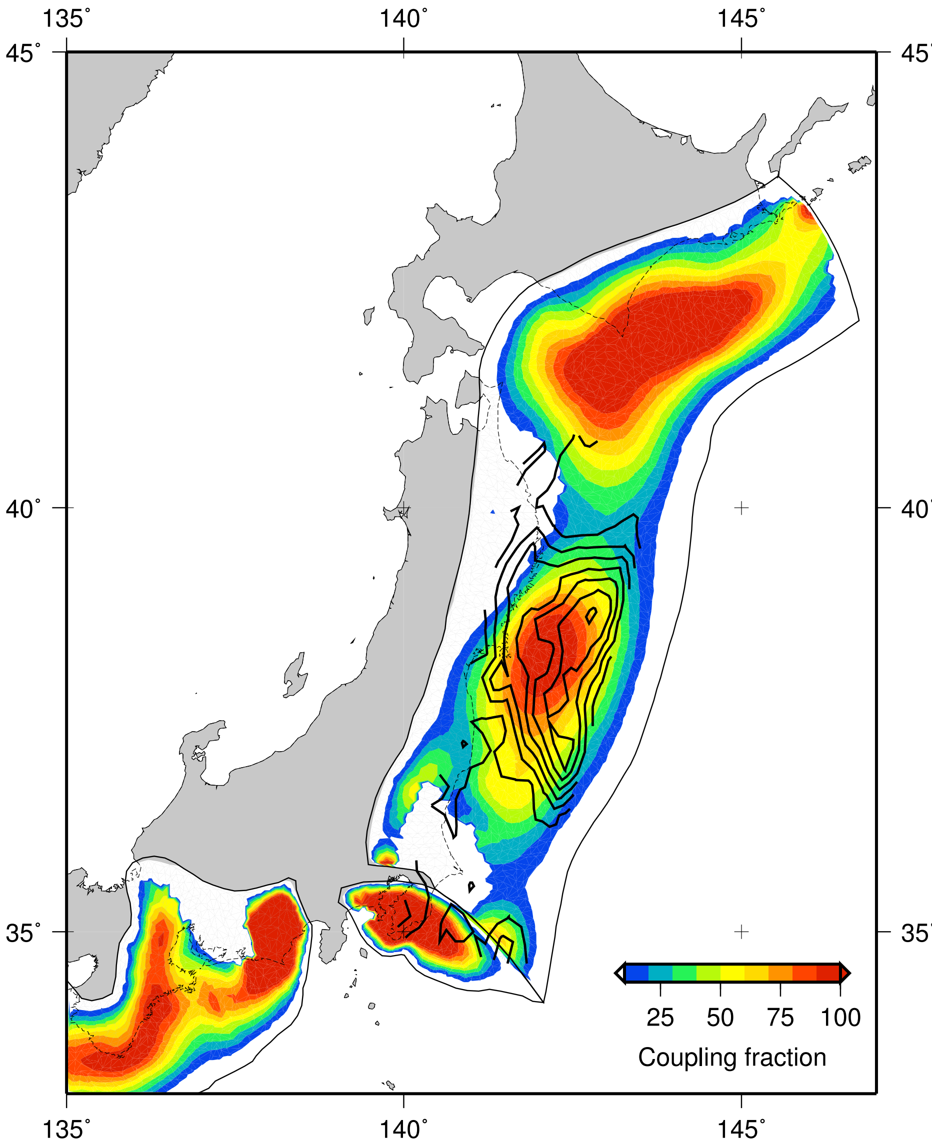
Slow Slip Events

Afterslip from 1994 quake



Meade and Loveless (2010)

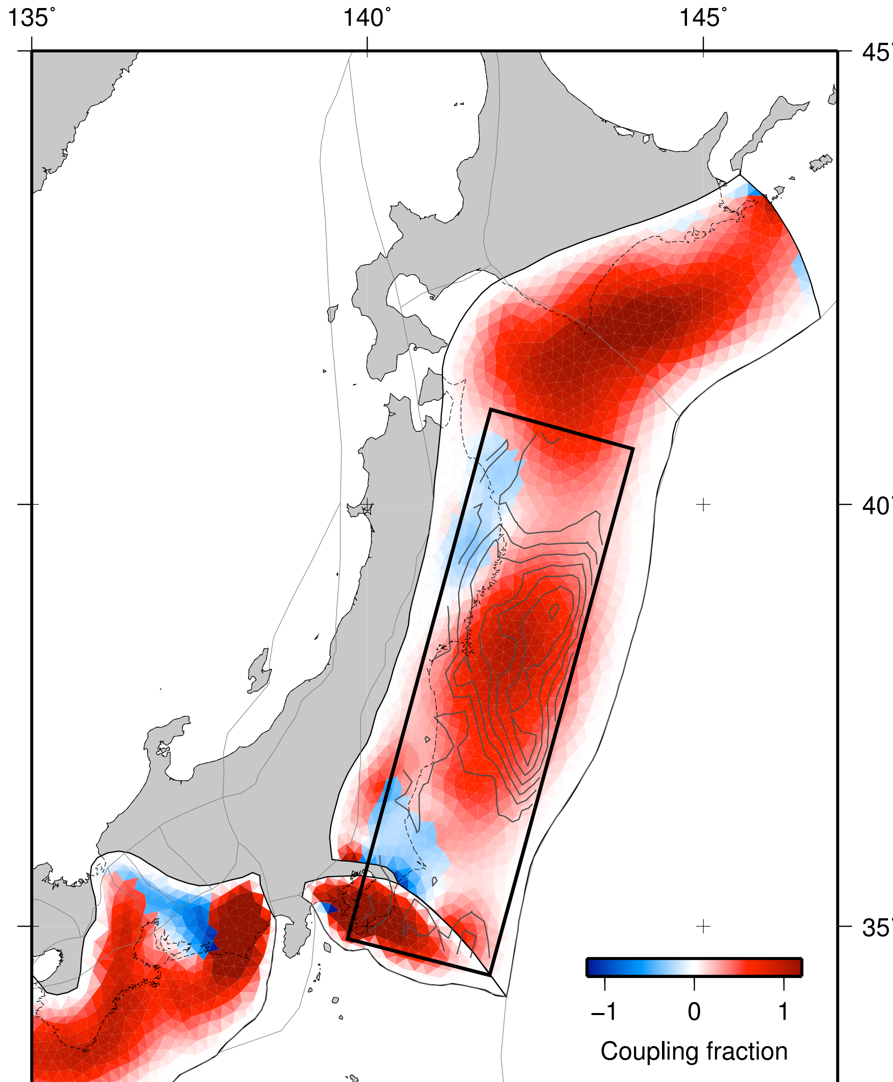
Comparison of Locked Zone to Slip



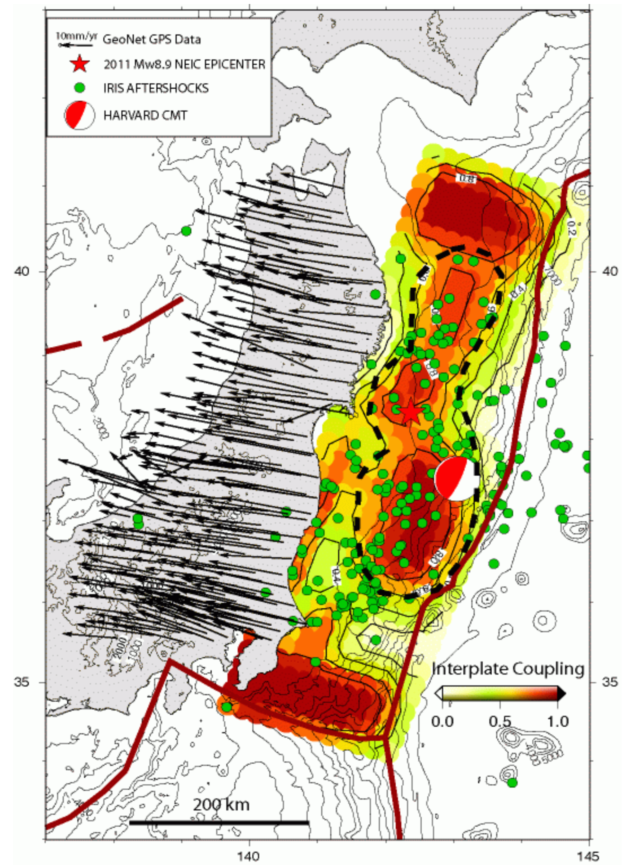
- Colors: Loveless and Meade (2010) interseismic model
- Contours: USGS slip model contours
- To first order, the rupture area of the earthquake is the same as the interseismic locked zone

Loveless and Meade, 3/14/11

Two Inversions



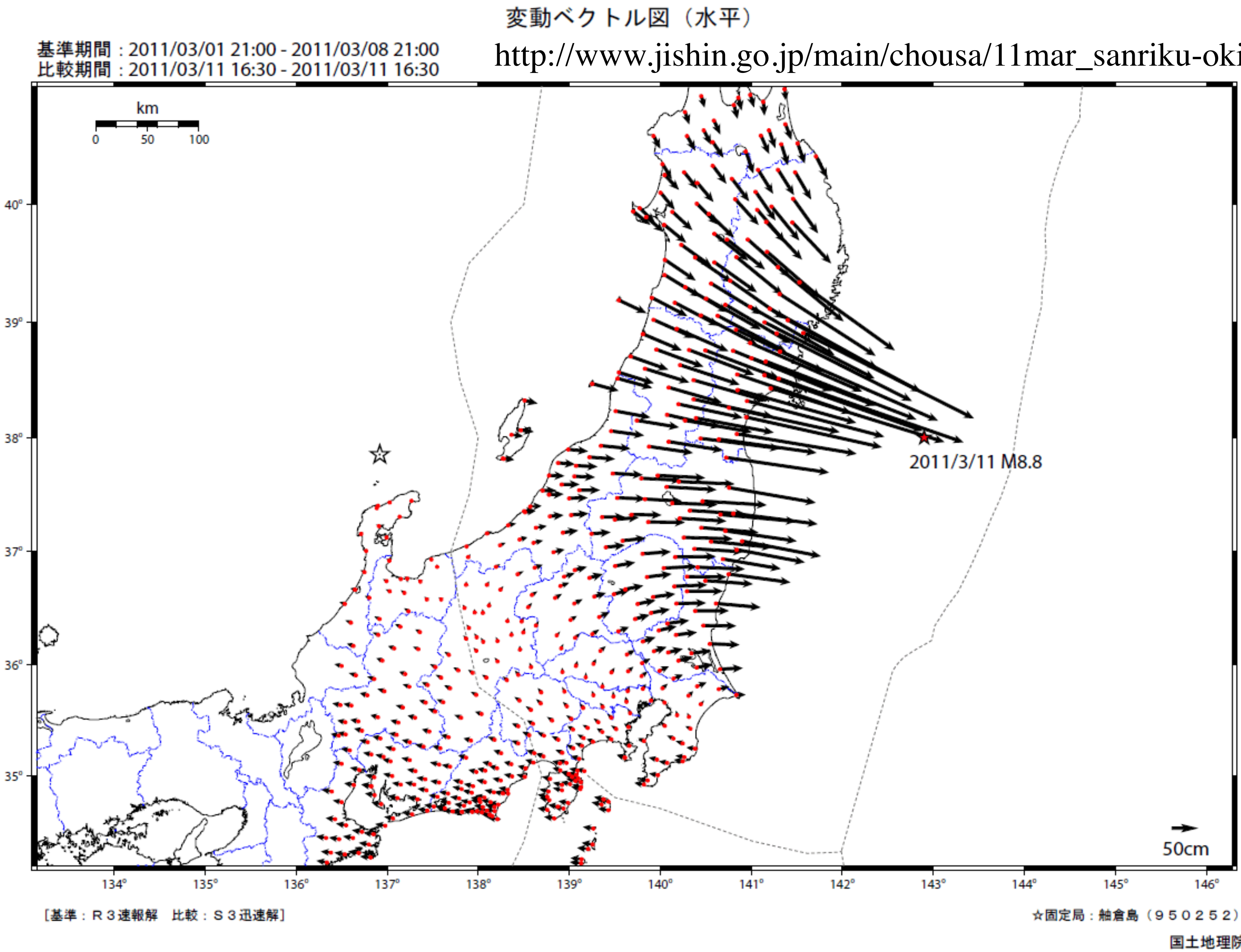
Loveless and Meade (2010)



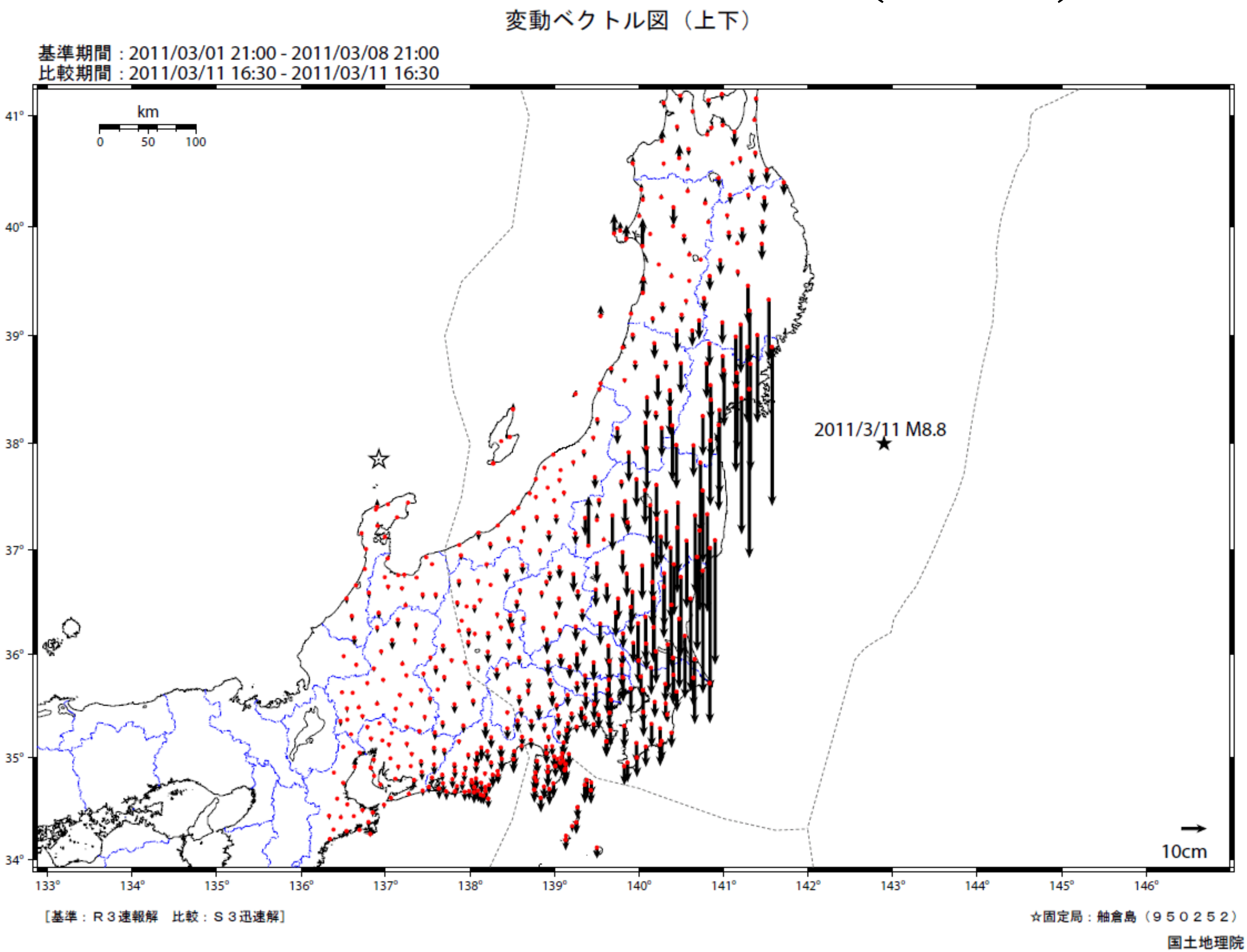
Mohamed Chlieh, GeoAzur, France

Observed GPS Displacements

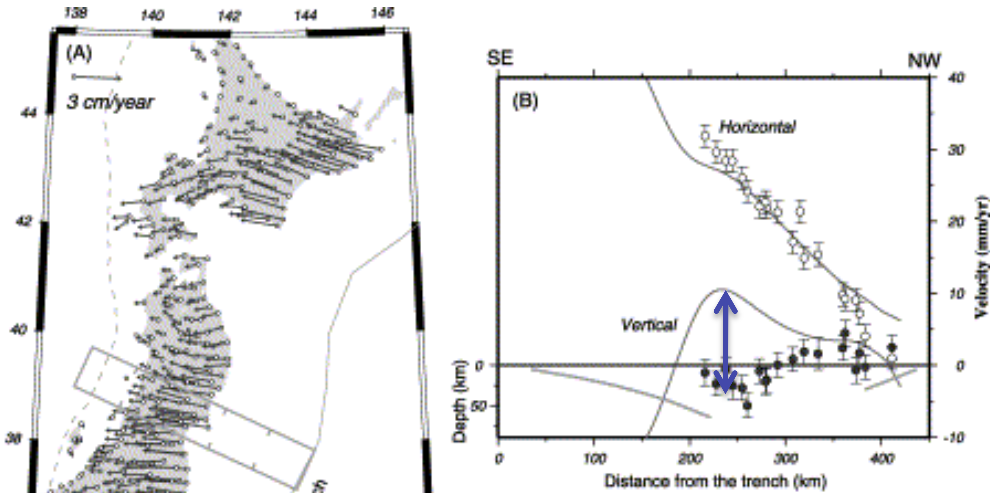
http://www.jishin.go.jp/main/chousa/11mar_sanriku-oki/



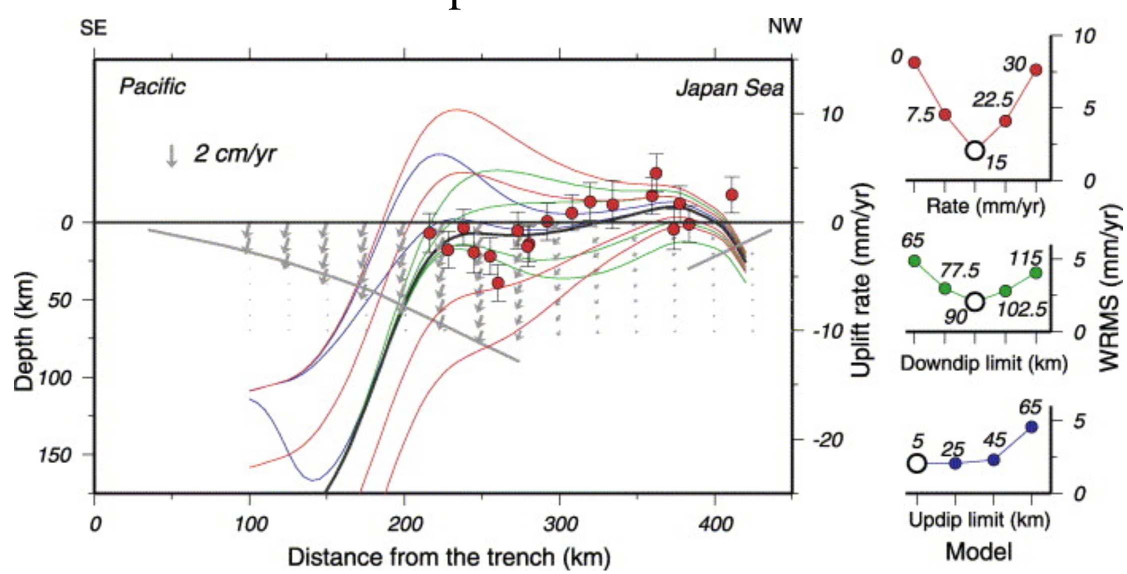
Observed Vertical (GPS)



Both Interseismic & Coseismic Subsidence?

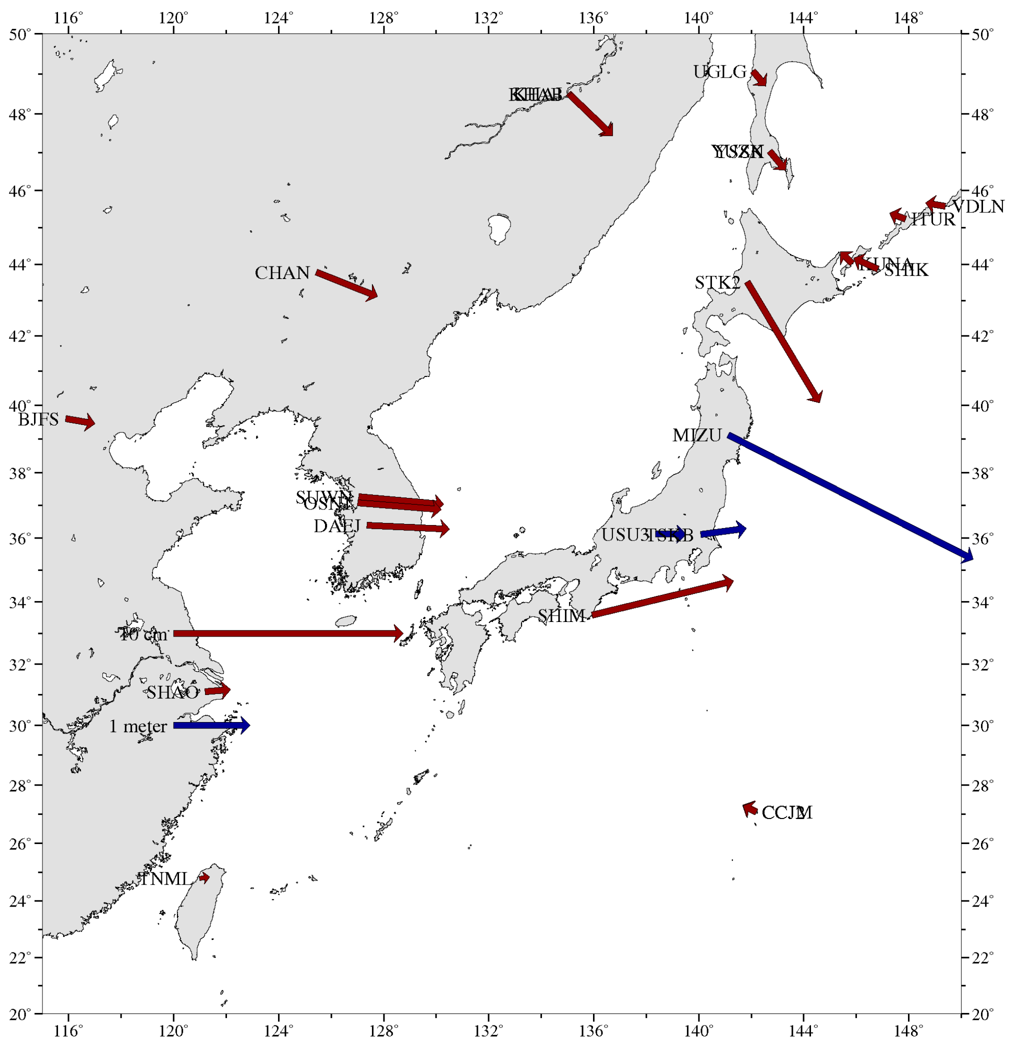


Heki explained this difference through a model of subsidence via subduction erosion. Aoki and Scholz (2004) instead assumed a wider locked zone, so that the coastal area was within the zone of subsidence. But the earthquake rupture area seems more consistent with Heki's explanation.



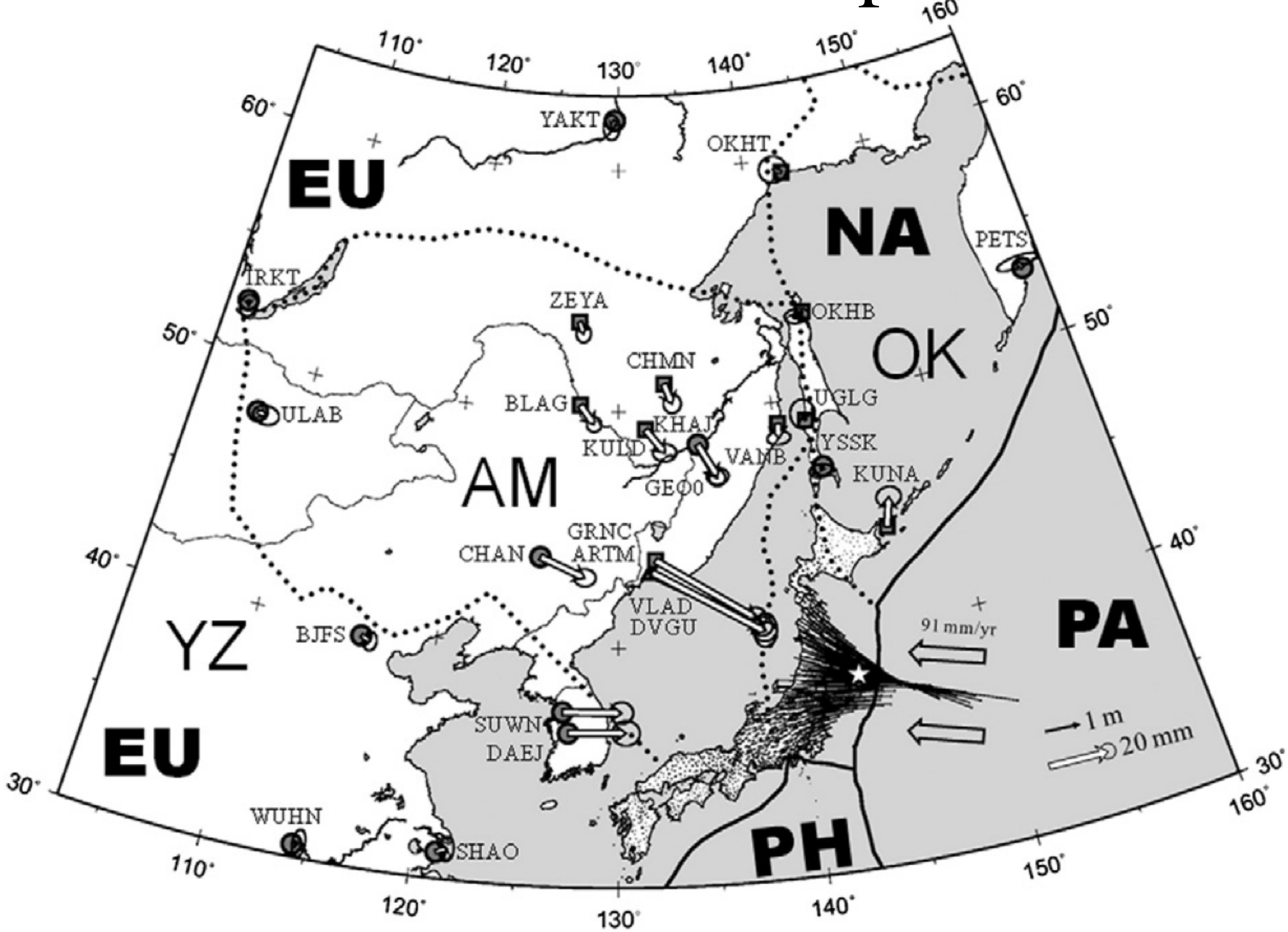
Heki, 2004 (EPSL)

Predicted Far-Field Displacements

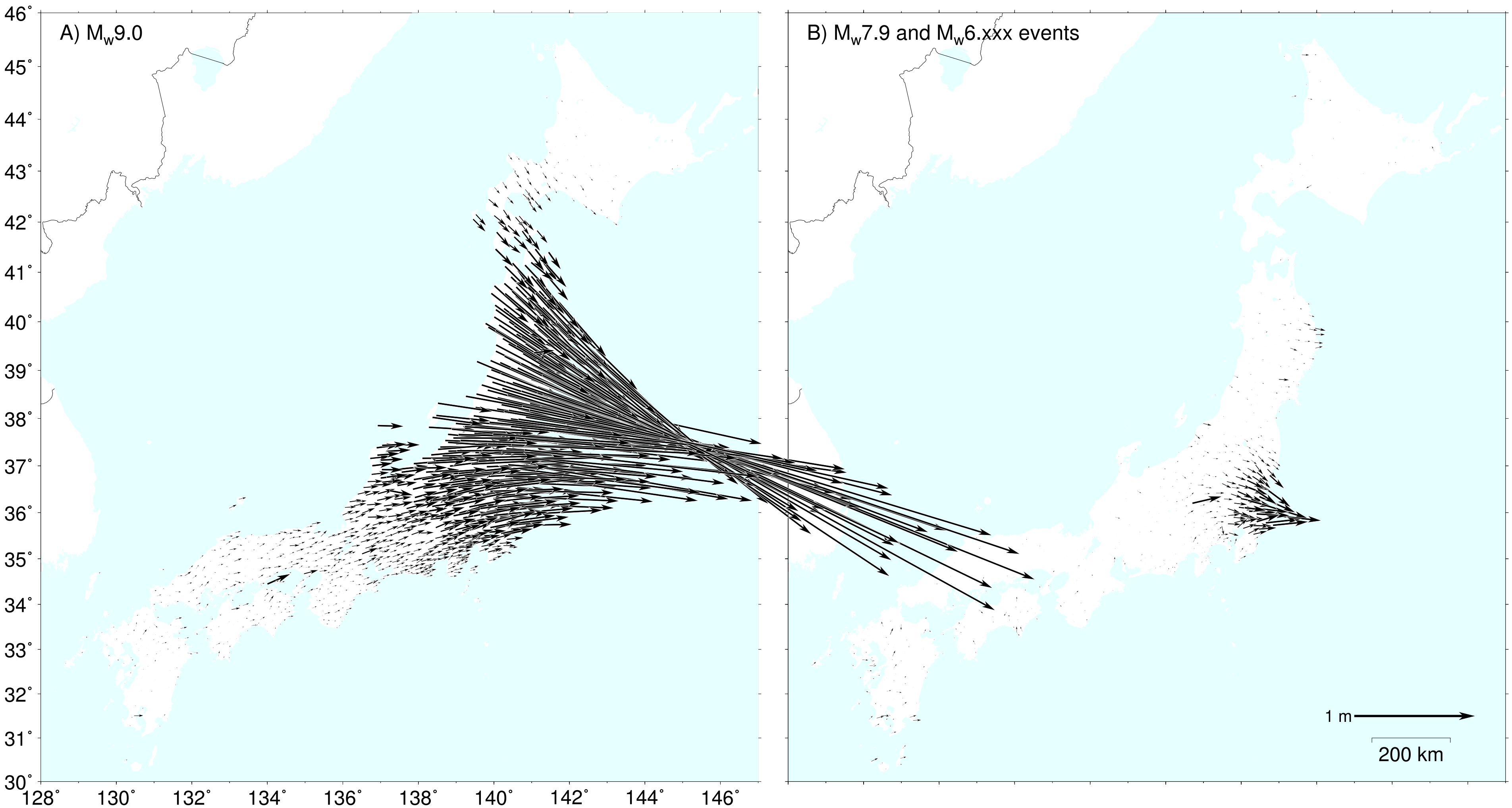


- Based on Gavin Hayes' preliminary finite fault model (USGS NEIC), computed to advise IGS analysis centers of expected far field displacements
- 3-5 cm in Korea
- 1-2 cm in eastern China
- Centimeters or more everywhere in Japan.

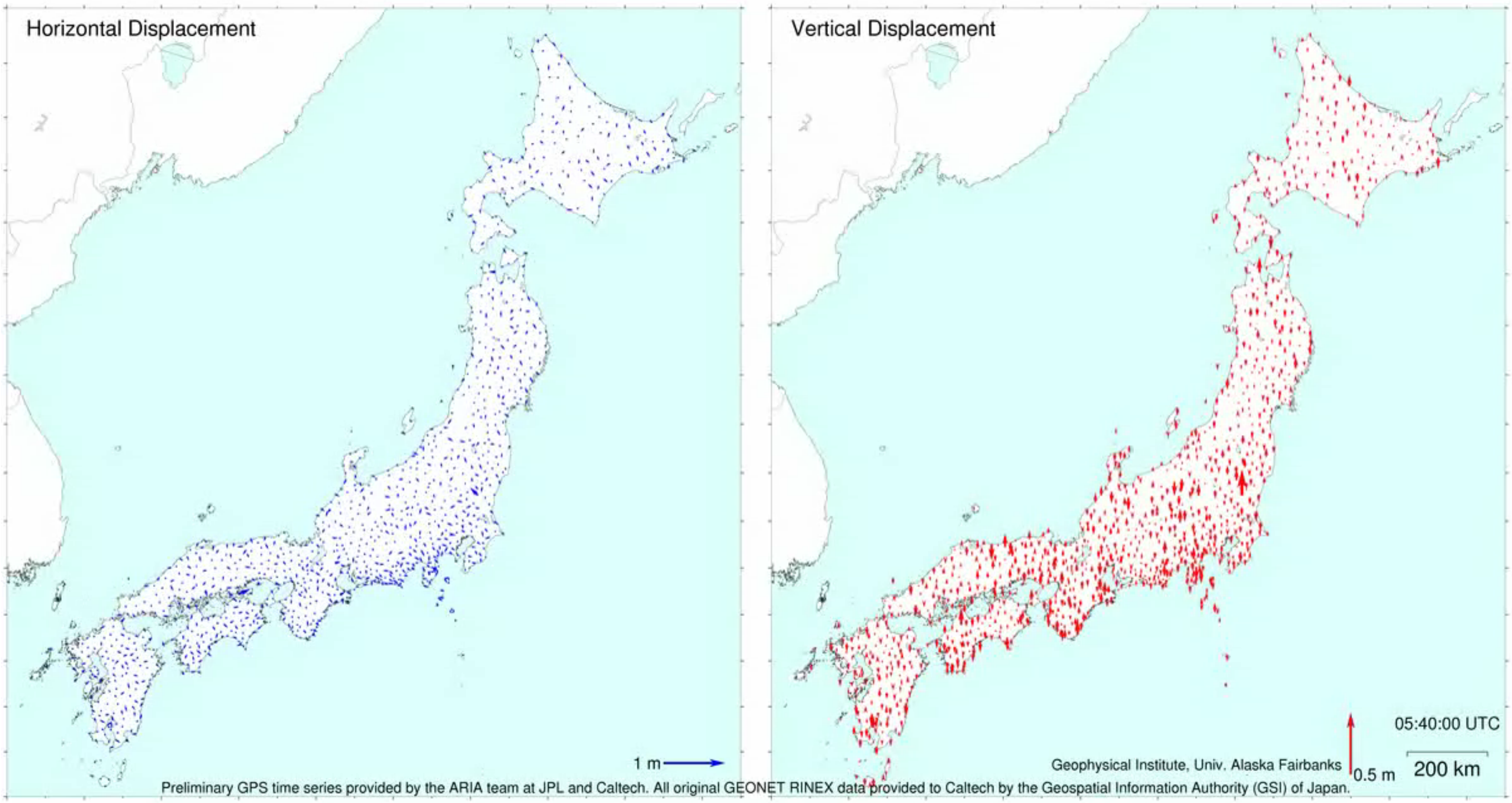
Measured Far-Field Displacements



Tohoku-oki Earthquake (2011)

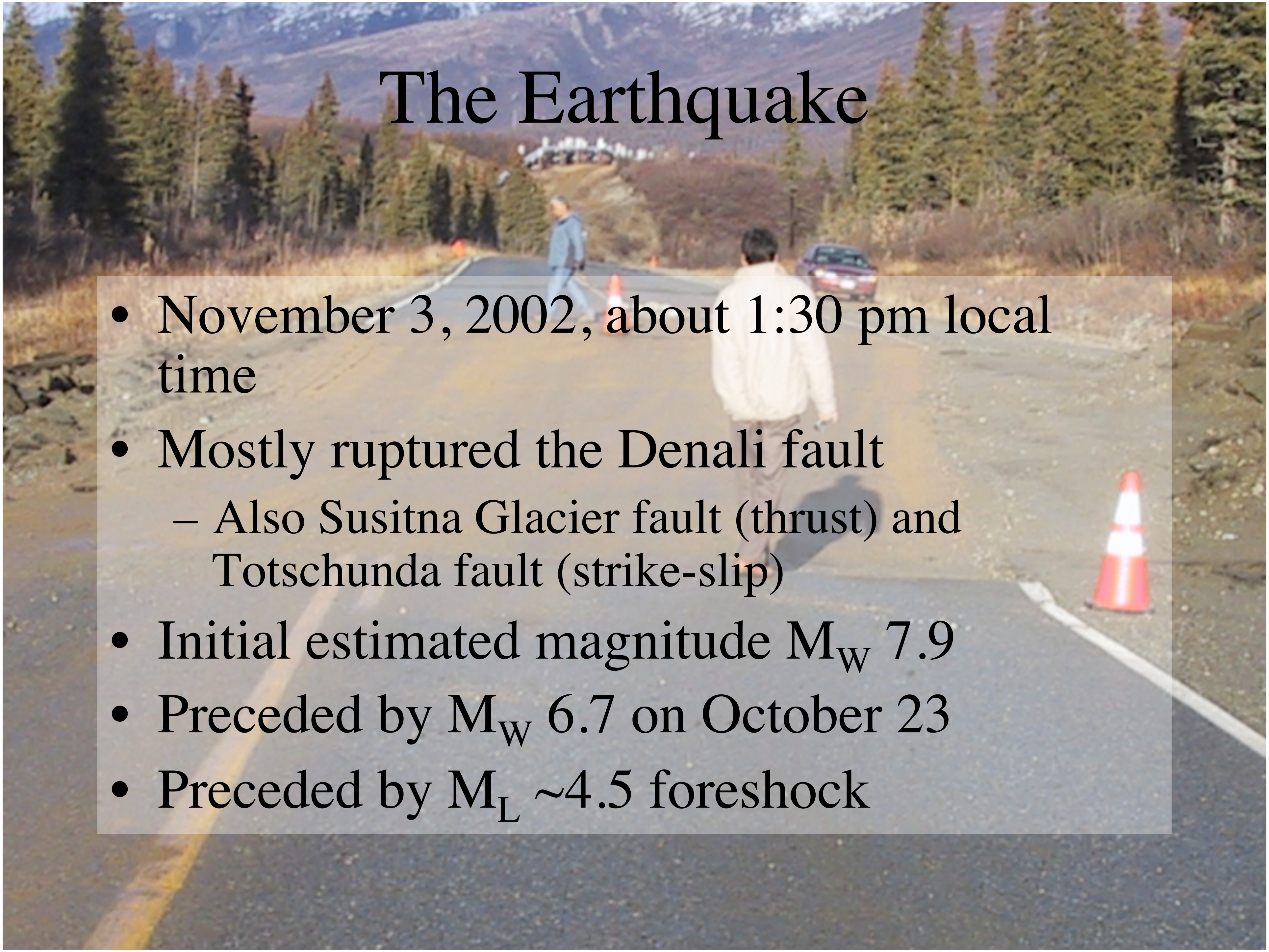


Movie of an Earthquake



Grapenthin and Freymueller (submitted)

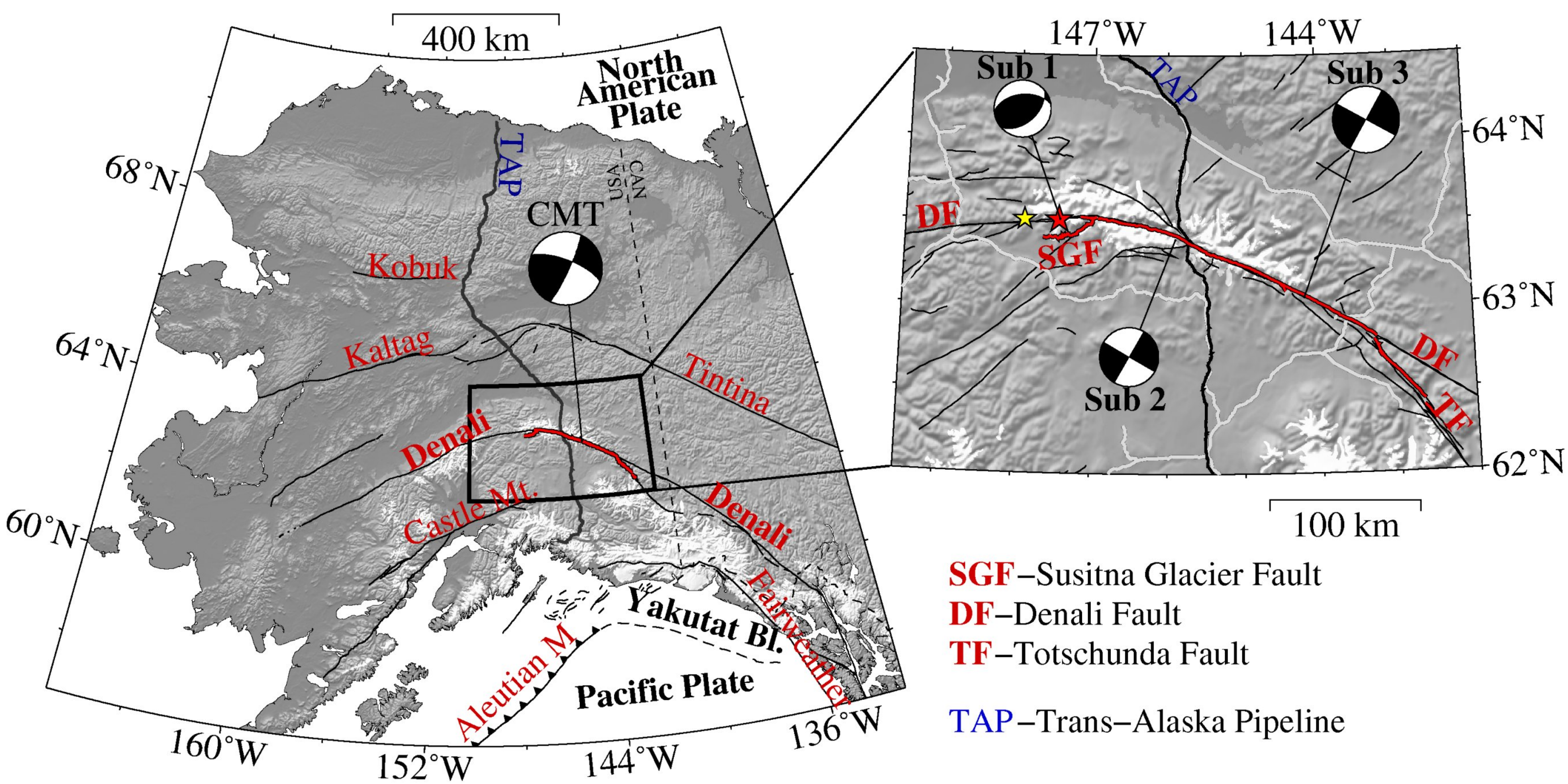

The 2002 Denali Earthquake



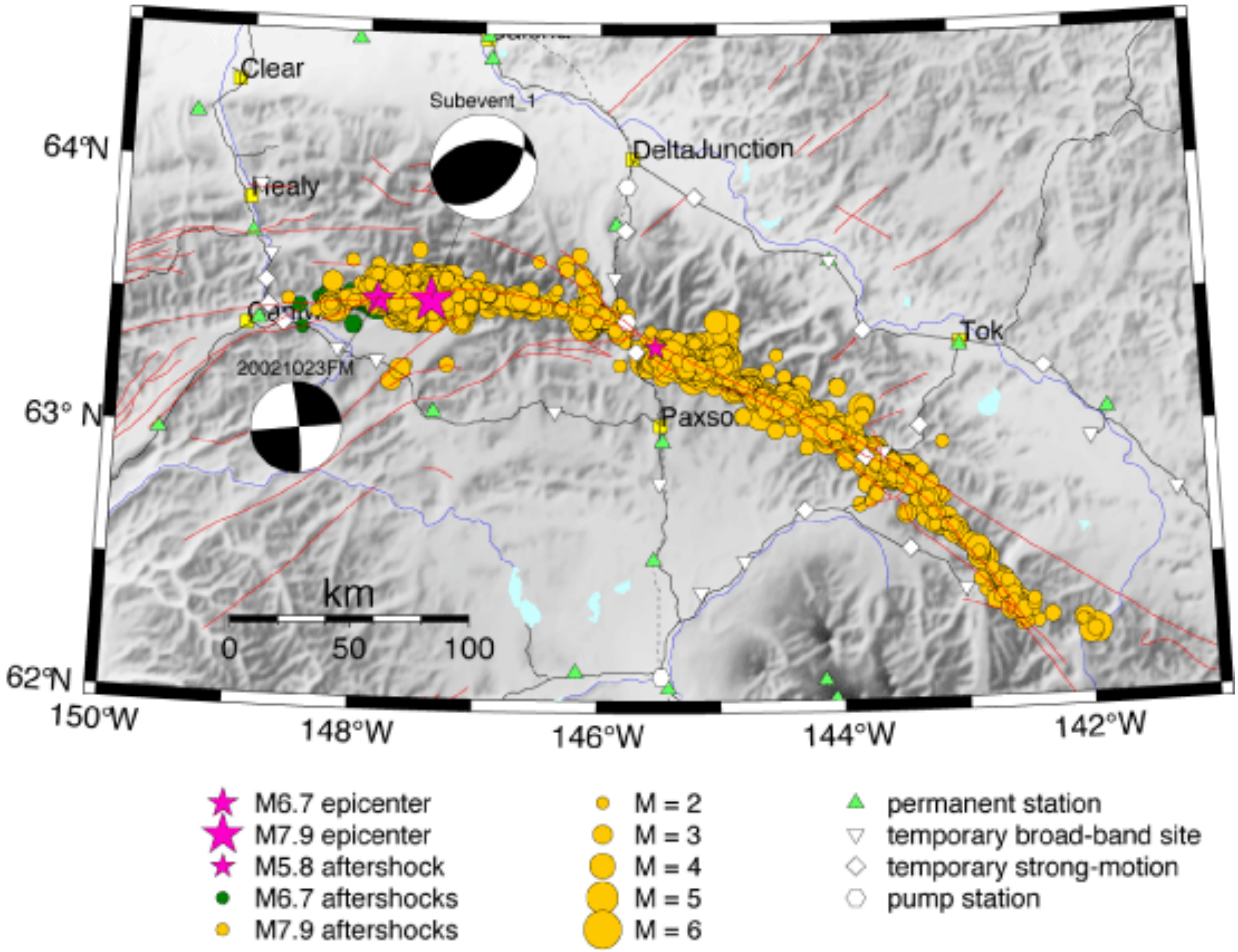
The Earthquake

- November 3, 2002, about 1:30 pm local time
- Mostly ruptured the Denali fault
  - Also Susitna Glacier fault (thrust) and Totschunda fault (strike-slip)
- Initial estimated magnitude M_W 7.9
- Preceded by M_W 6.7 on October 23
- Preceded by M_L ~4.5 foreshock

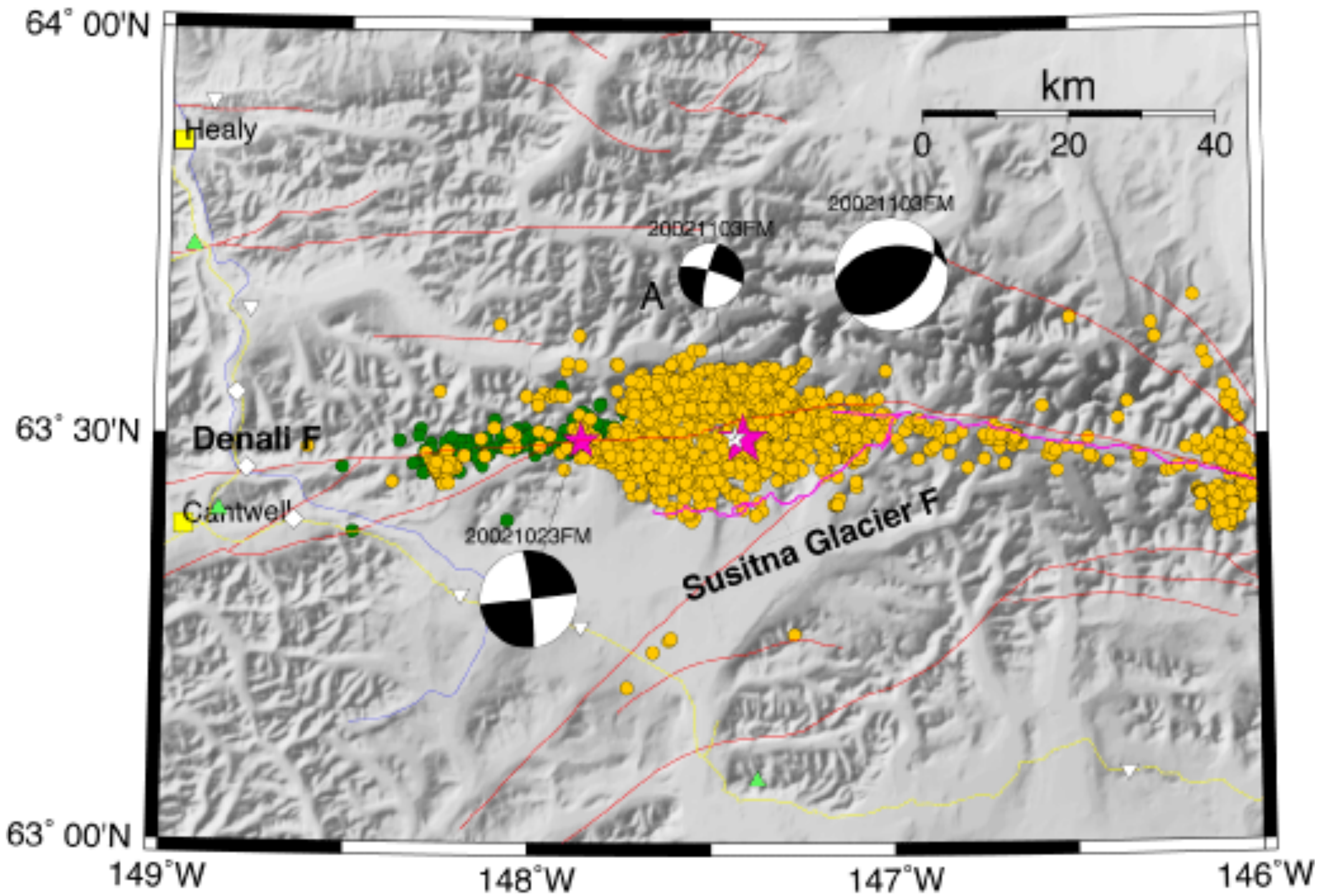
Tectonic setting



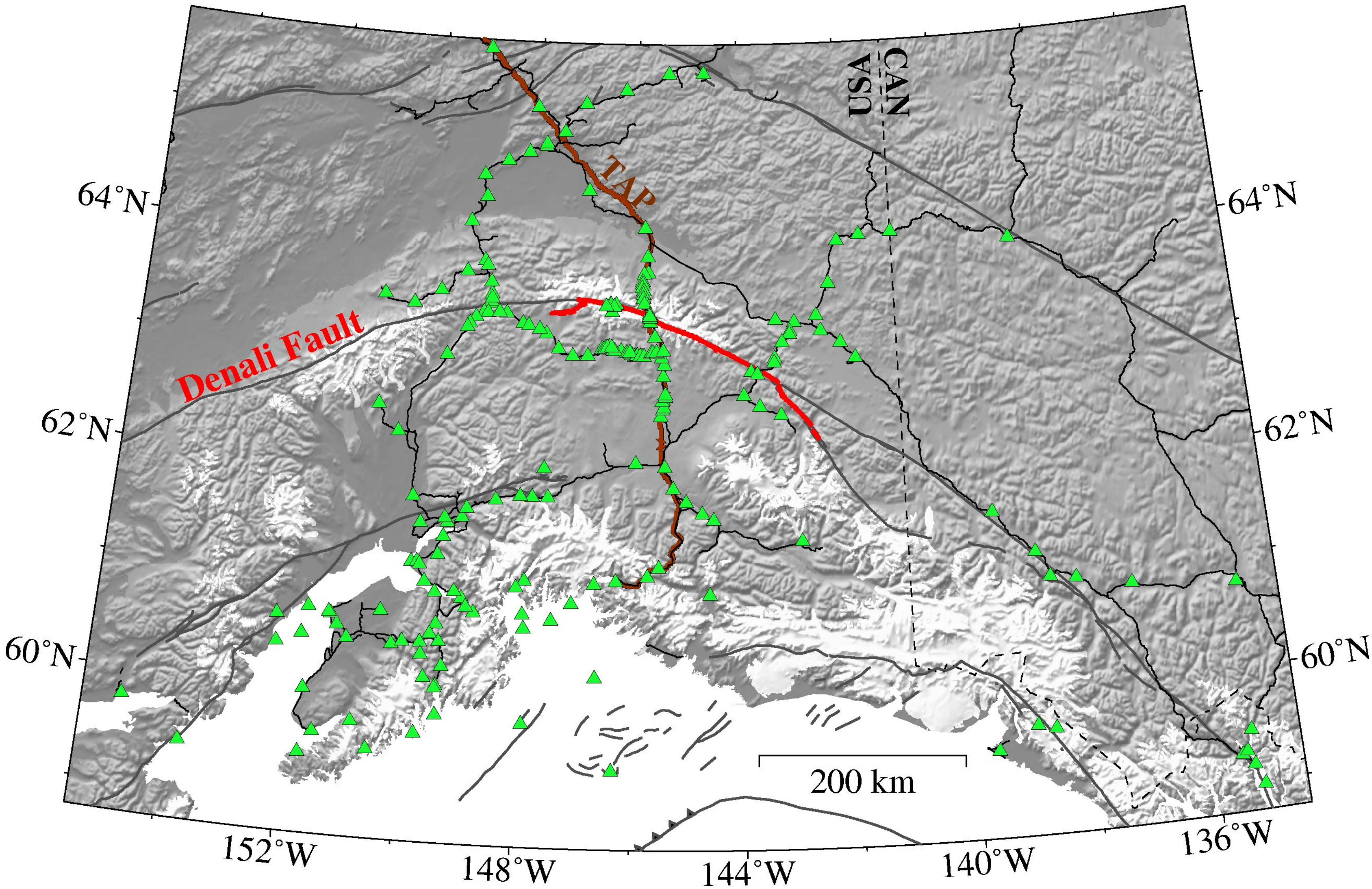
Mainshock and Aftershocks



Epicentral Region



Coseismic GPS Sites

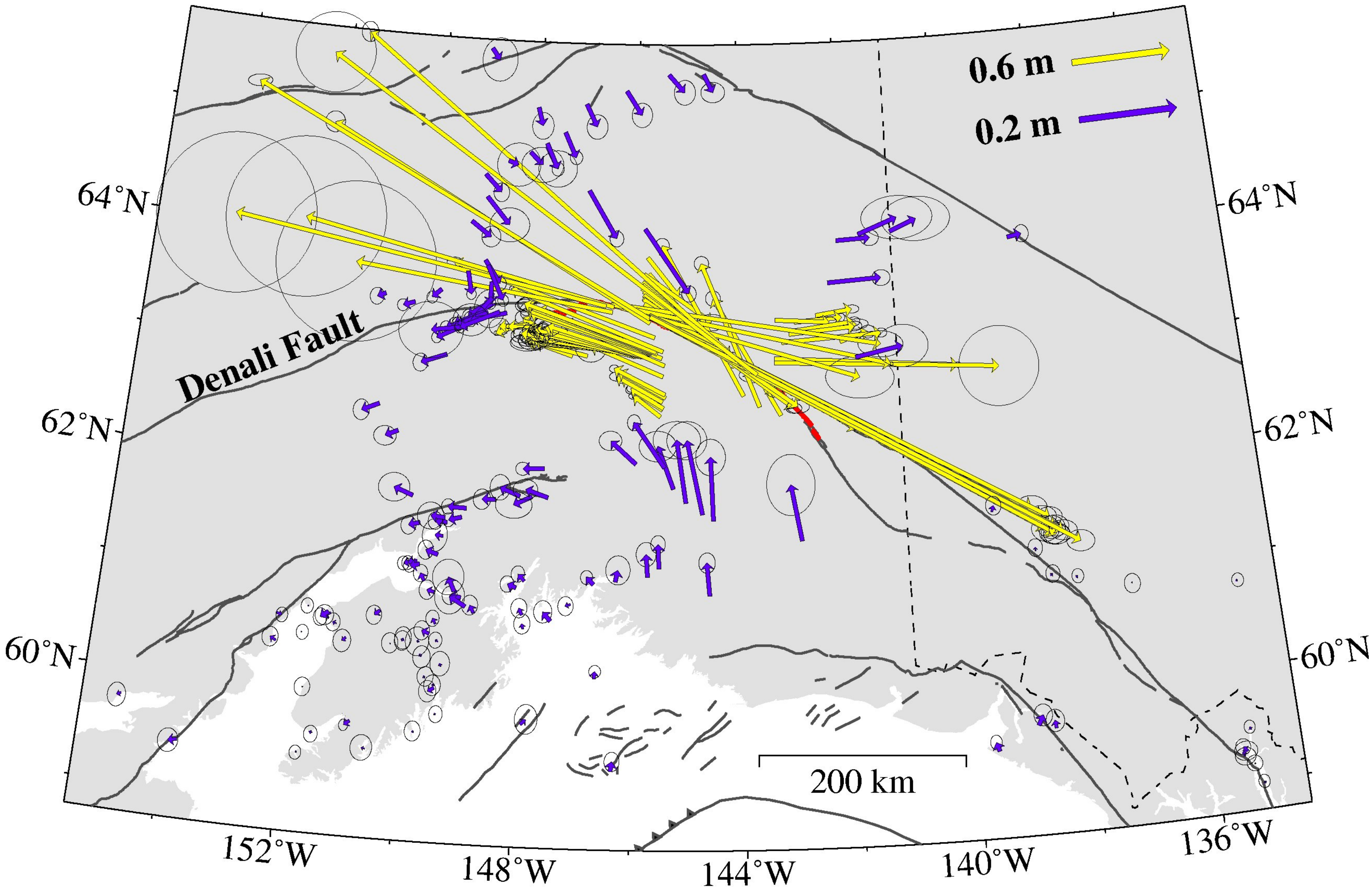


Coseismic Displacements at 232 GPS Sites

Estimation of Displacements

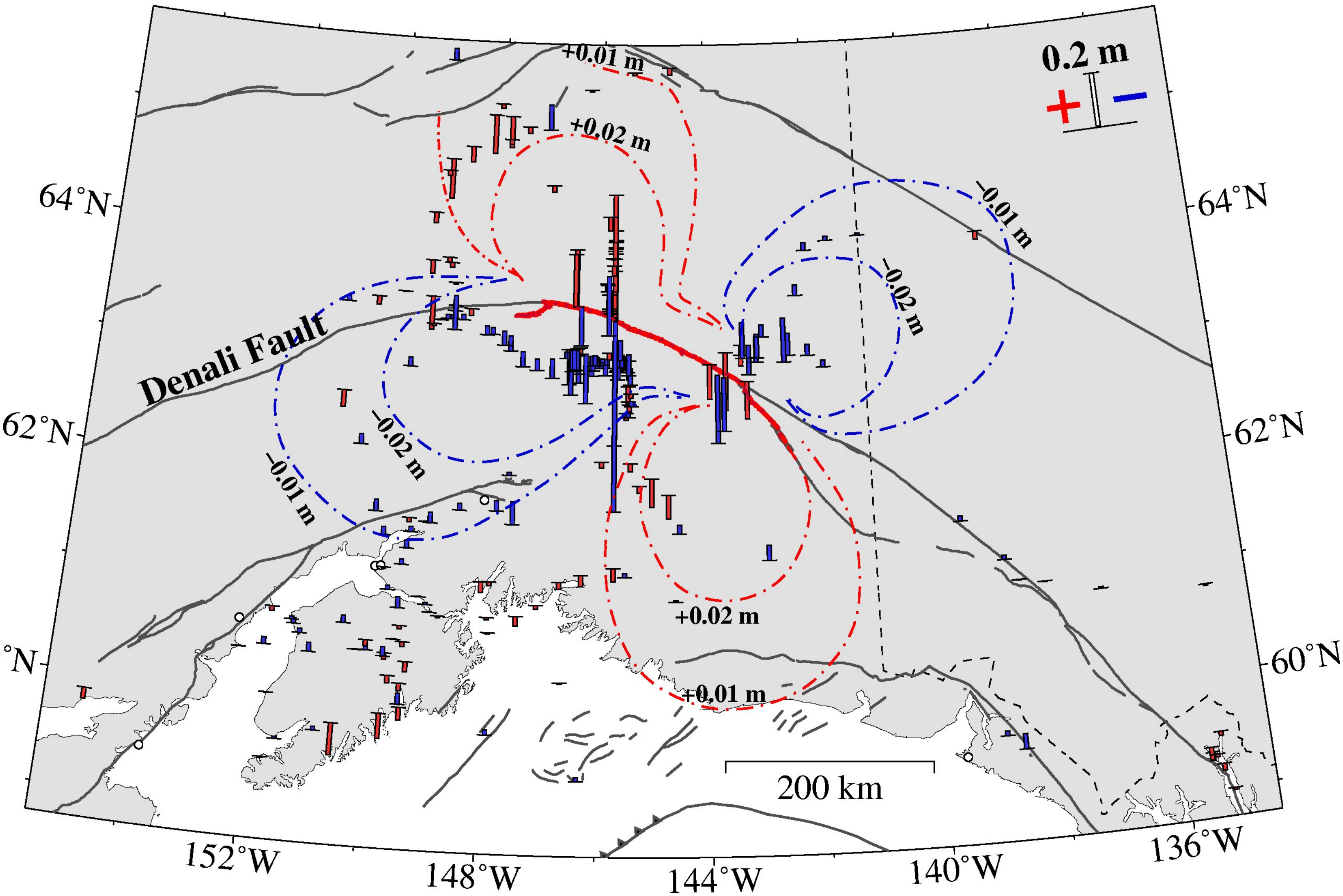
- Continuous GPS
  - Average of 4 days before and after earthquake
- Campaign GPS with well-determined velocities
  - Linear fit to pre-earthquake data plus displacement
  - For sites with imprecise velocity, we used a model or interpolation of surrounding sites
- Campaign GPS with no post-earthquake measurements until summer 2003
  - Postseismic correction applied based on interpolation of postseismic displacements of surrounding sites.

Coseismic Displacements - Horizontal



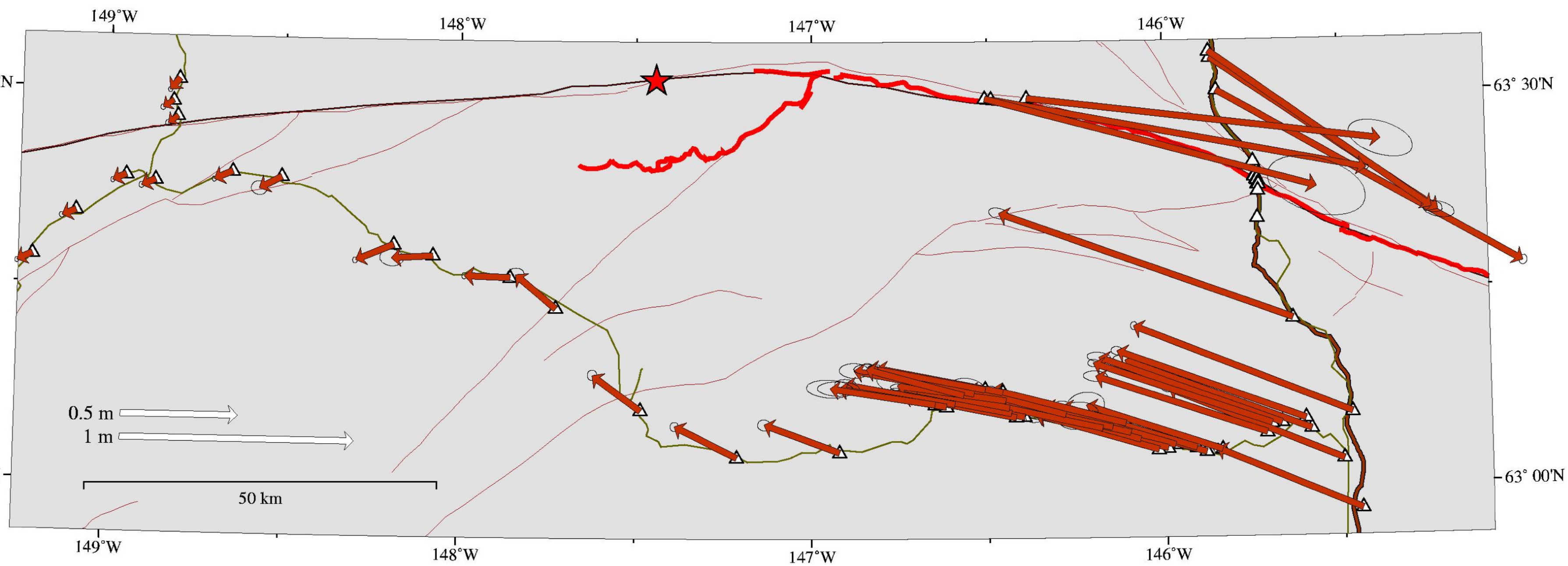
Two scales (3:1)

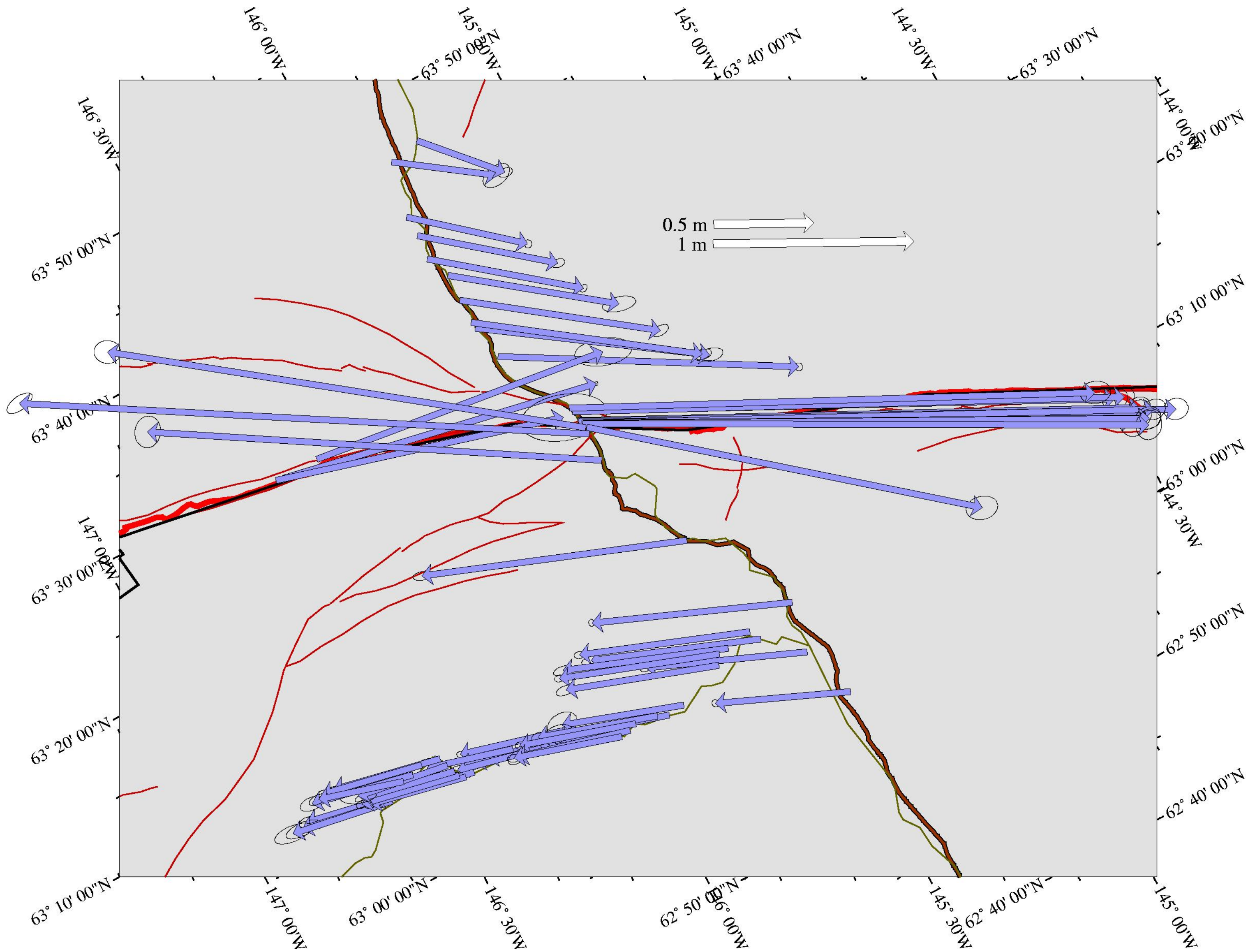
Coseismic Displacements - Vertical



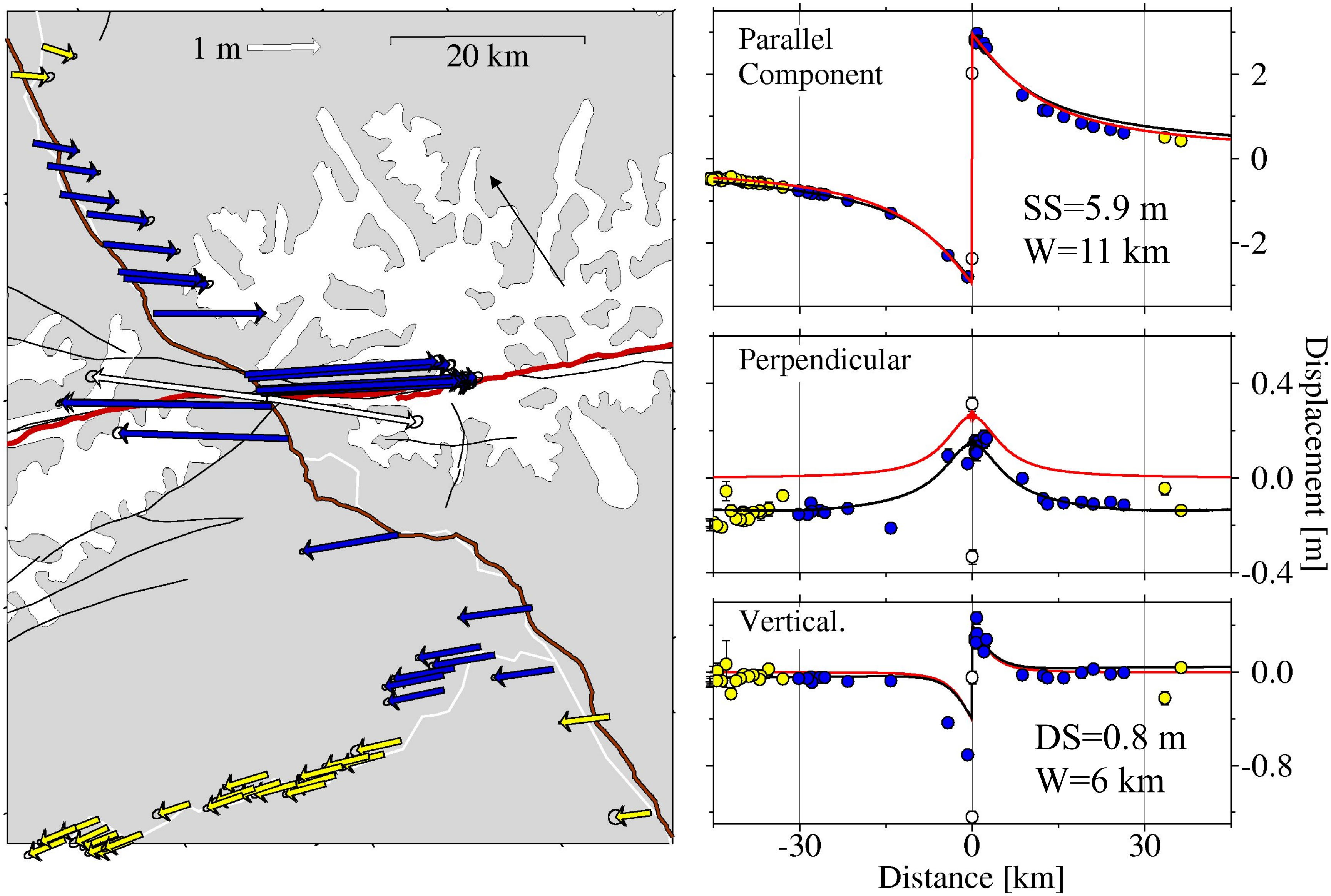
Modeled Vertical Displacement Field (from GPS data)

Western Part of Rupture

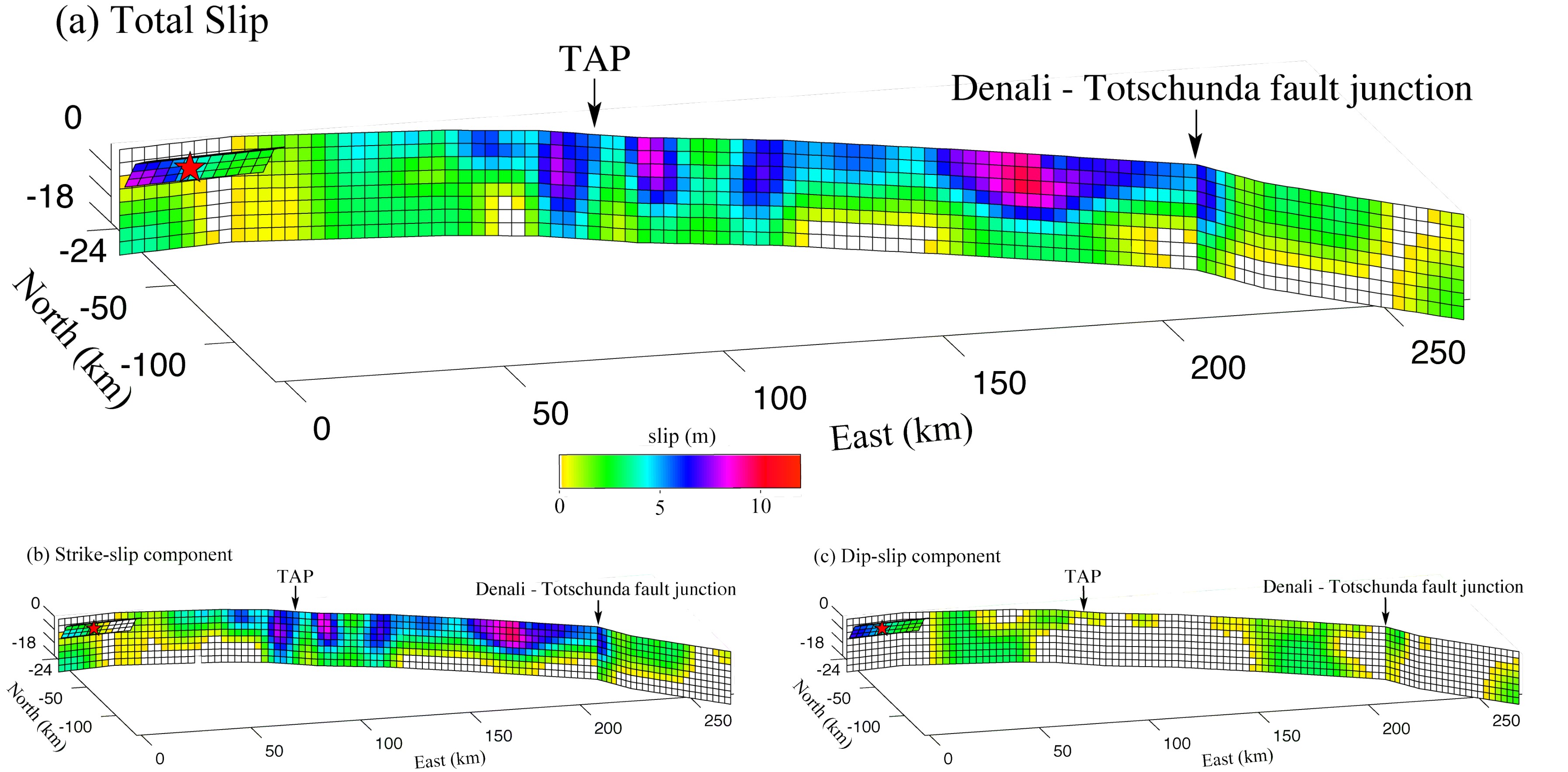



0.5 m
1 m
146° 00'W
145° 30'W
145° 00'W
144° 30'W
146° 30'W
147° 00'W
146° 00'W
145° 30'W
145° 00'W
63° 50' 00"N
63° 40' 00"N
63° 30' 00"N
63° 20' 00"N
63° 10' 00"N
63° 00' 00"N
62° 50' 00"N
62° 40' 00"N
144° 00'W
144° 30'W

Richardson Hwy Profile (and the TAPS corridor)

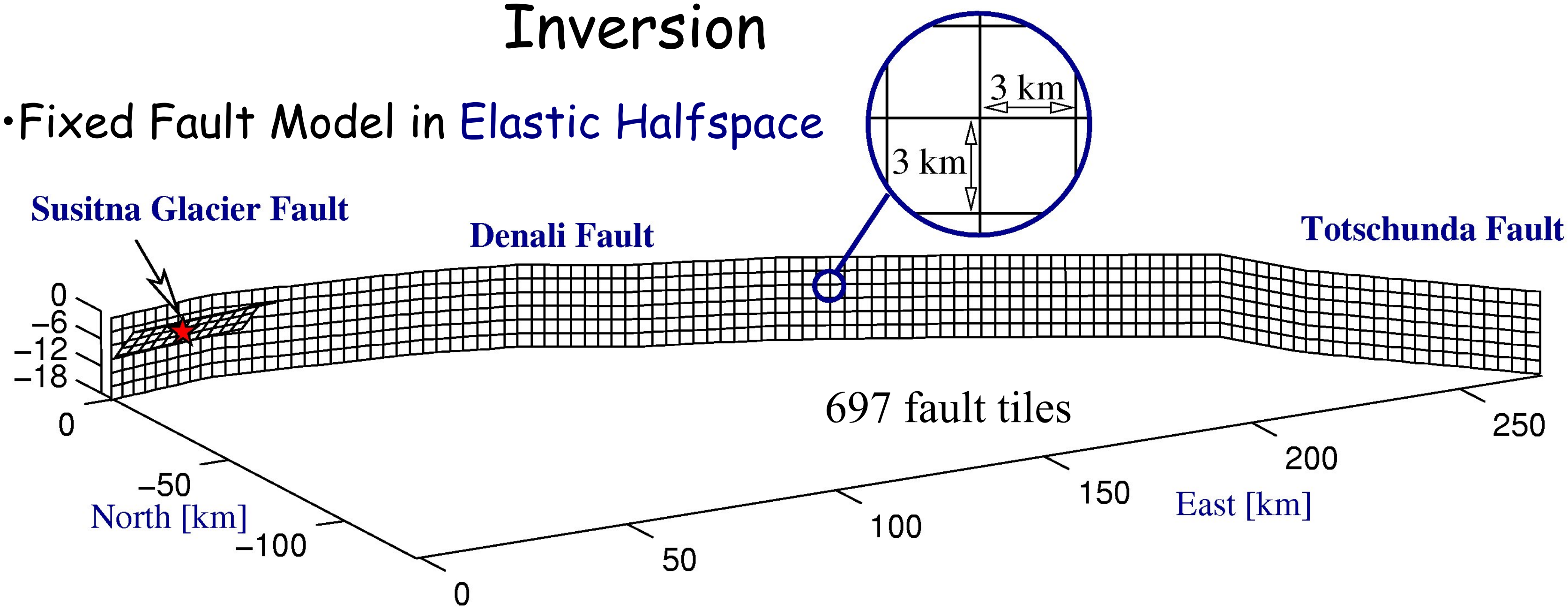


Coseismic Slip Model



Inversion

•Fixed Fault Model in Elastic Halfspace



•Fault model intersects with surface rupture at the surface

•Assume vertical dip on Denali and Totschunda faults

•Extend fault model to 18 km depth

•Use data from 224 GPS sites

•Use Surface Offset Data from Haeussler et al. [2004]

•Bounded Variable Least-Squares inversion

  •Right-Lateral Strike-Slip

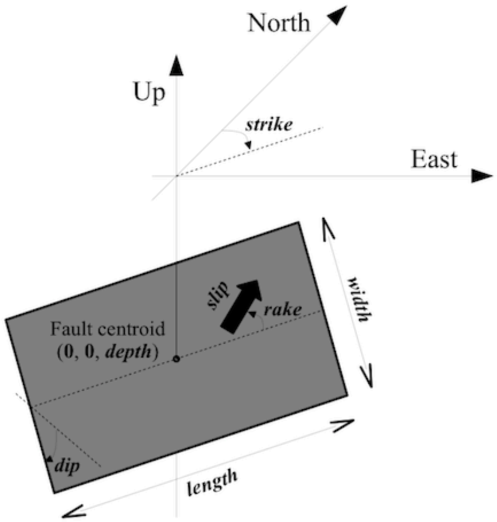
  •North-Side up Dip-Slip

•Apply smoothing

Computing the Model Matrix

- To do the inversion, we need a linear model in the form d = Gm.
- Compute the model matrix G numerically
  - For each fault patch, compute displacements of all sites for unit slip on fault.
  - These displacements form the columns of G
- If there are a small number of fault patches, the system of equations may be invertible
  - If not, we need to add smoothing

3D Dislocation Theory



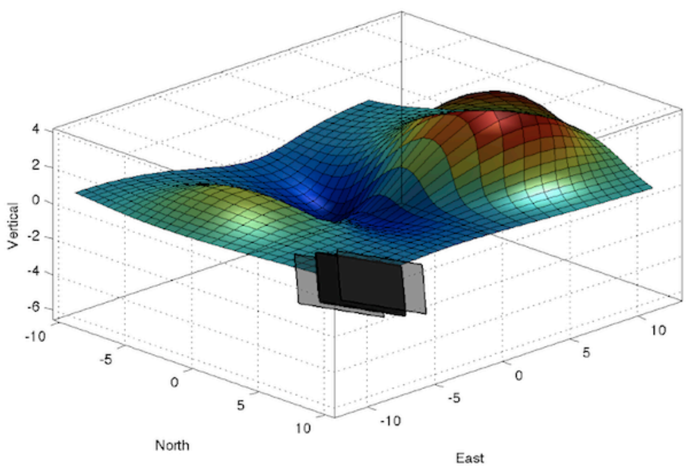
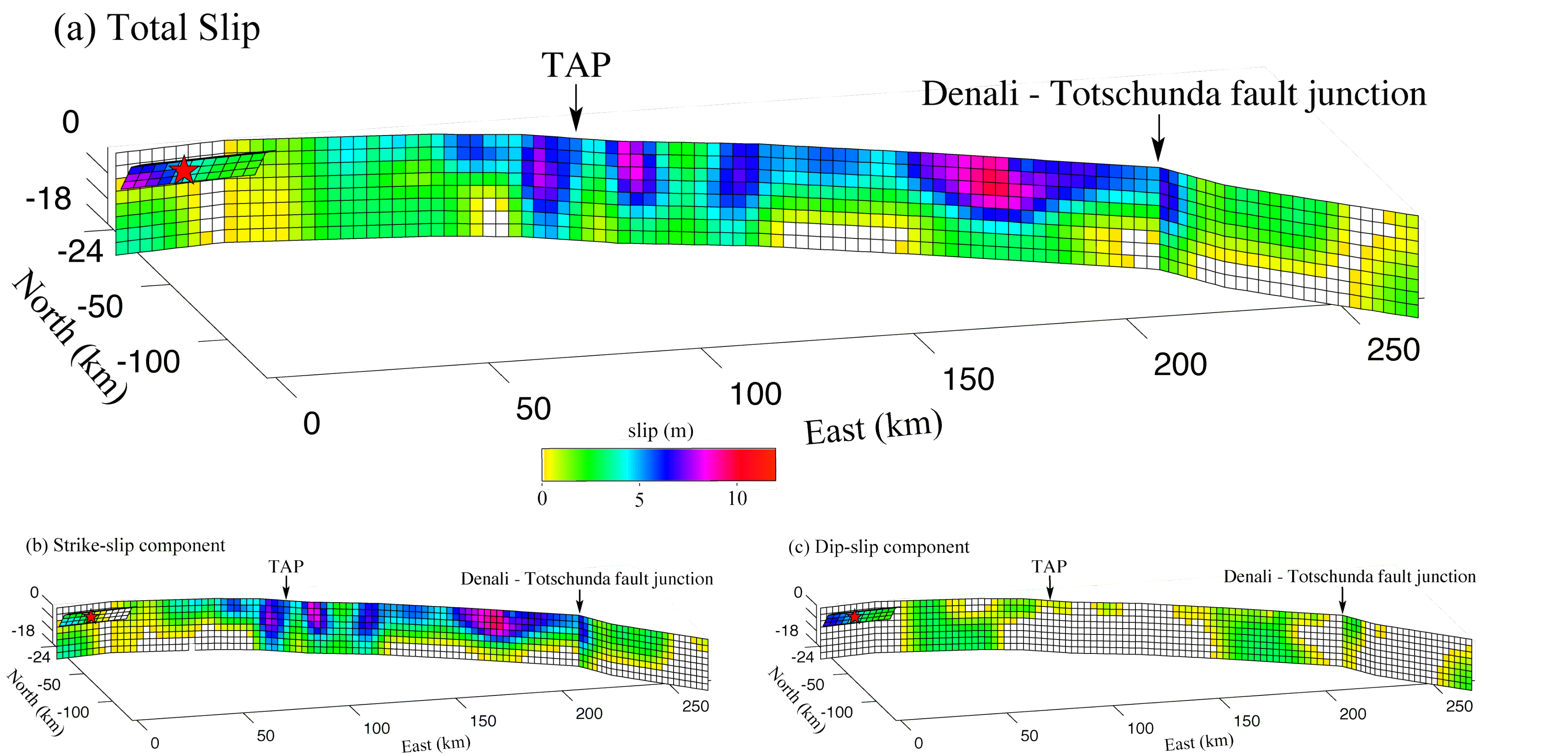


image F. Beauducel

- Compute displacements using 3D elastic dislocation theory
- Code developed by Y. Okada (1985, 1992)
- http://www.mathworks.com/matlabcentral/fileexchange/25982-okada-surface-deformation-due-to-a-finite-rectangular-source

Coseismic Slip Model



Smoothing

- Fault slip can vary on short length scales, but we can't model physics of slip so we only know how it varies from observations.
- To allow for variations in slip, need to estimate distributed slip model
  - But this means more parameters than data, underdetermined or mixed-determined problem
  - Need to do something about this

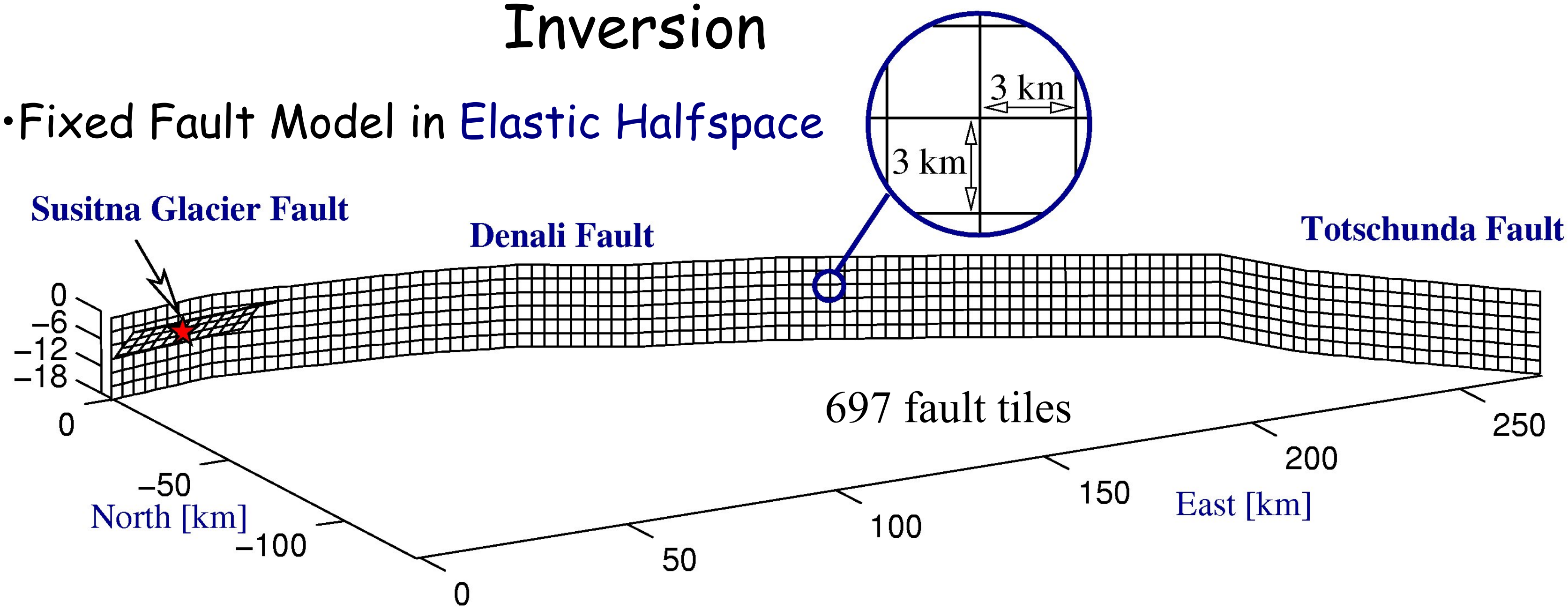
How To Smooth

- Add additional equations to minimize weighted sum of misfit to data and roughness
  - $r^T W r + b^2 (Lu)^T (Lu)$
- Adjust relative weight of these two factors
- Must decide how to choose this weight

- Instead of estimating slip **u**, estimate **Lu**, which is a measure of roughness of slip distribution (and inverse of **L** exists).
- Use SVD to determine solution for **Lu** for *p* eigenvalues.
- Need to decide how to choose *p*.

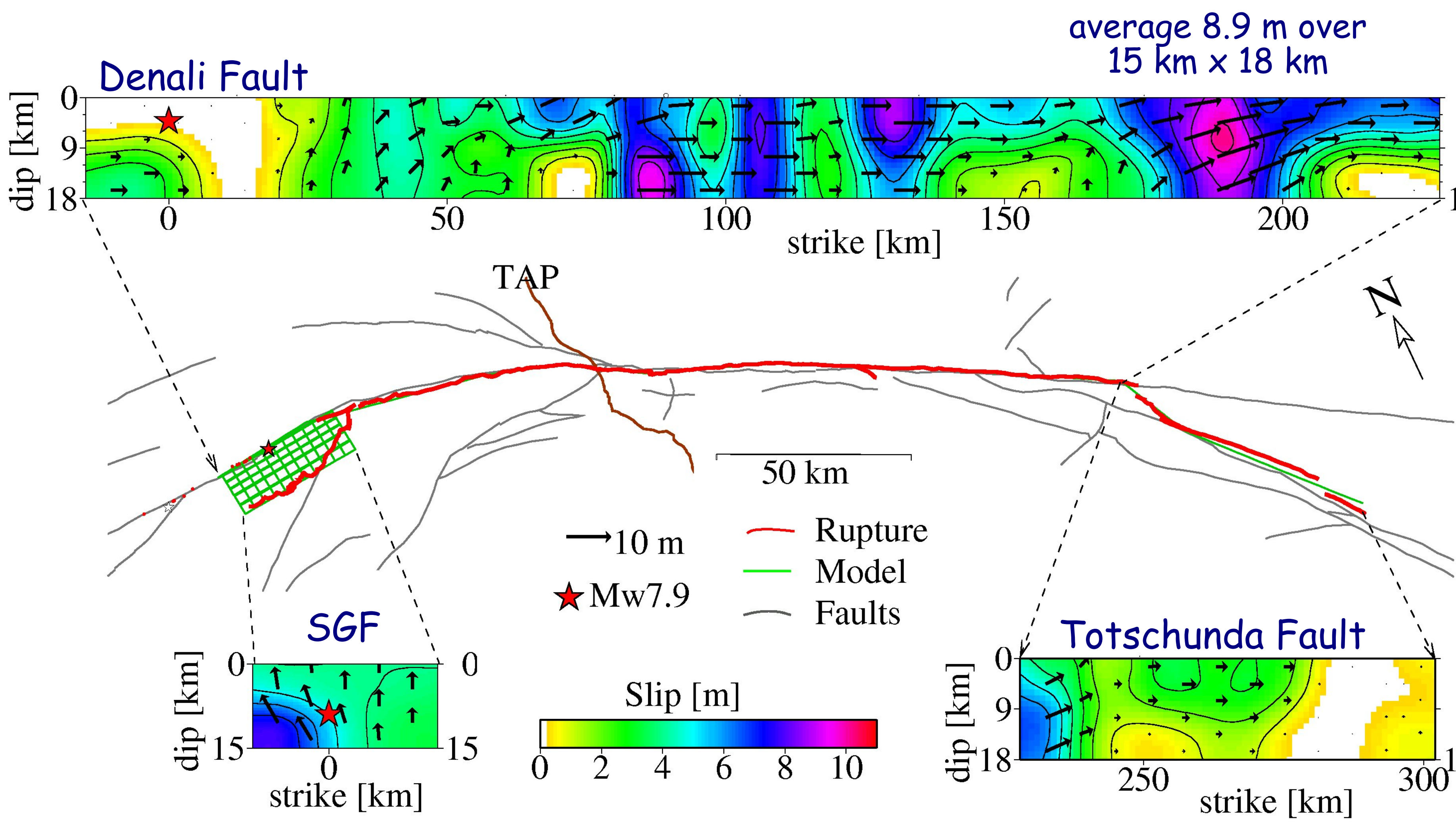
Inversion

- Fixed Fault Model in Elastic Halfspace



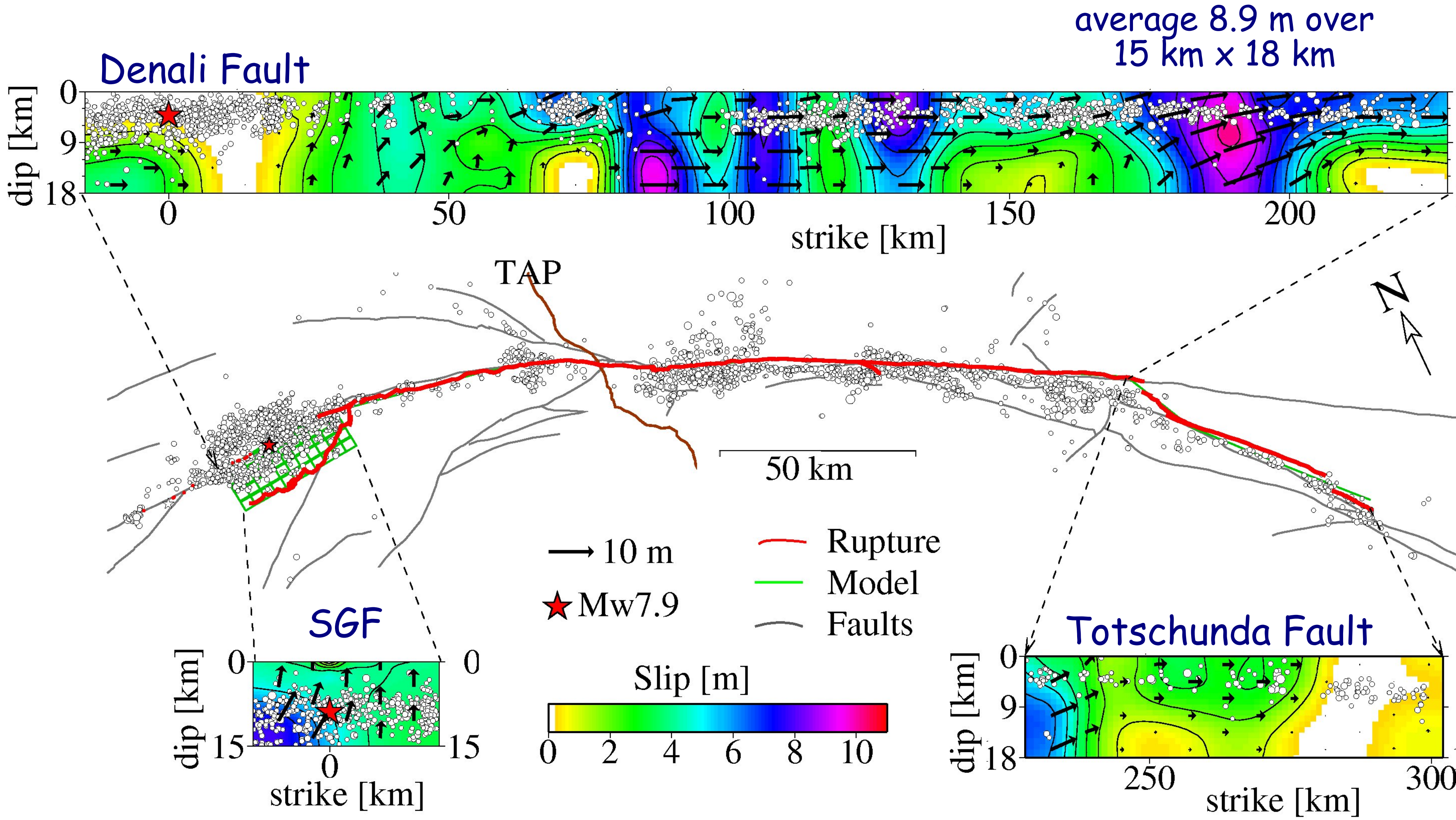
- Fault model intersects with surface rupture at the surface
- Assume vertical dip on Denali and Totschunda faults
- Extend fault model to 18 km depth
- Use data from 224 GPS sites
- Use Surface Offset Data from Haeussler et al. [2004]
- Bounded Variable Least-Squares inversion
    - Right-Lateral Strike-Slip
    - North-Side up Dip-Slip
- Apply smoothing

Coseismic Slip Distribution of the Denali Fault Earthquake



M_0=6.81x10^{20}Nm
M_w7.89

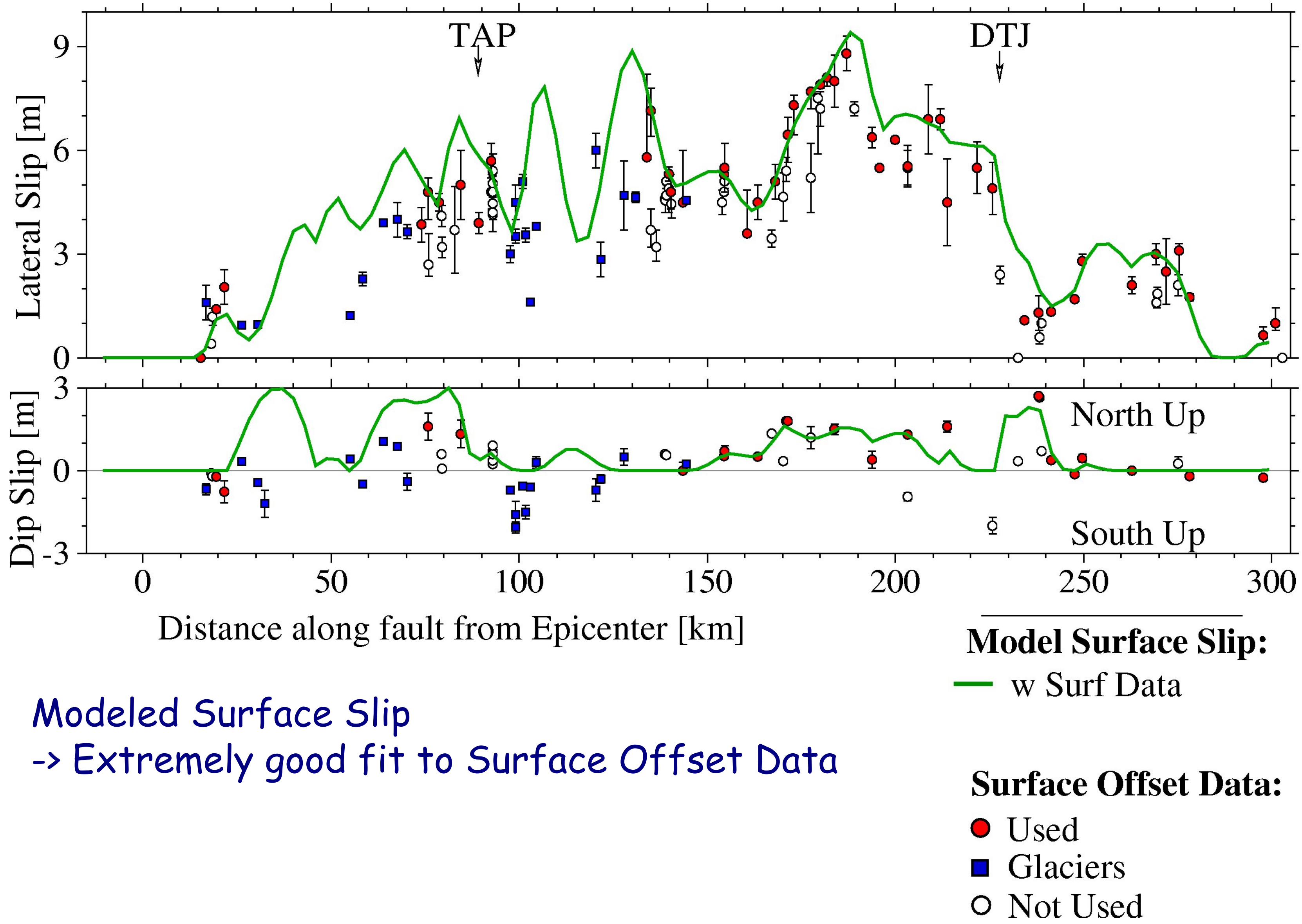
Coseismic Slip Distribution of the Denali Fault Earthquake



M_0=6.81x10^{20}Nm
M_w7.89

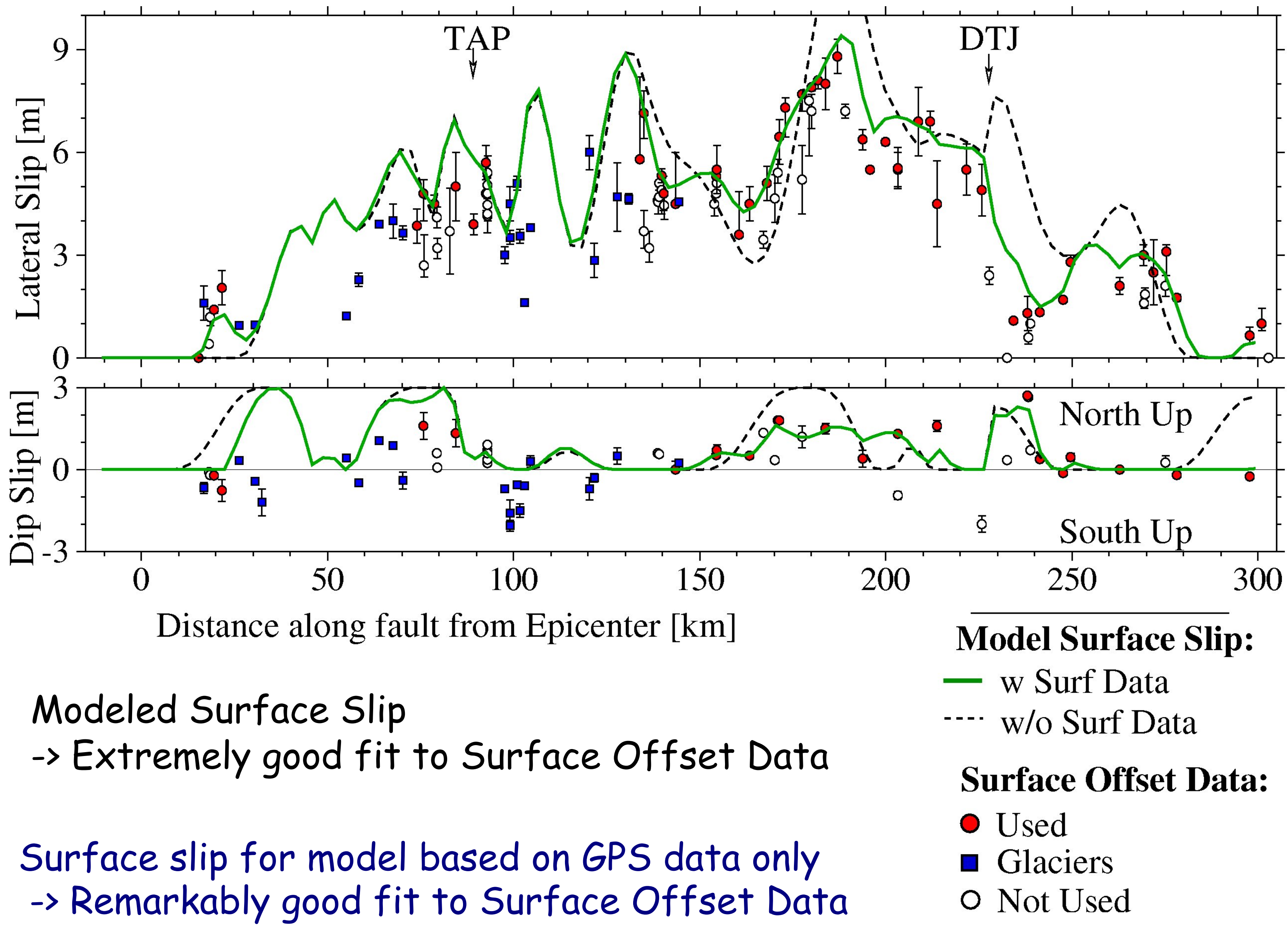
Relocated aftershocks from Ratchkovski et al. [2003]

Comparison With Surface Offset Data



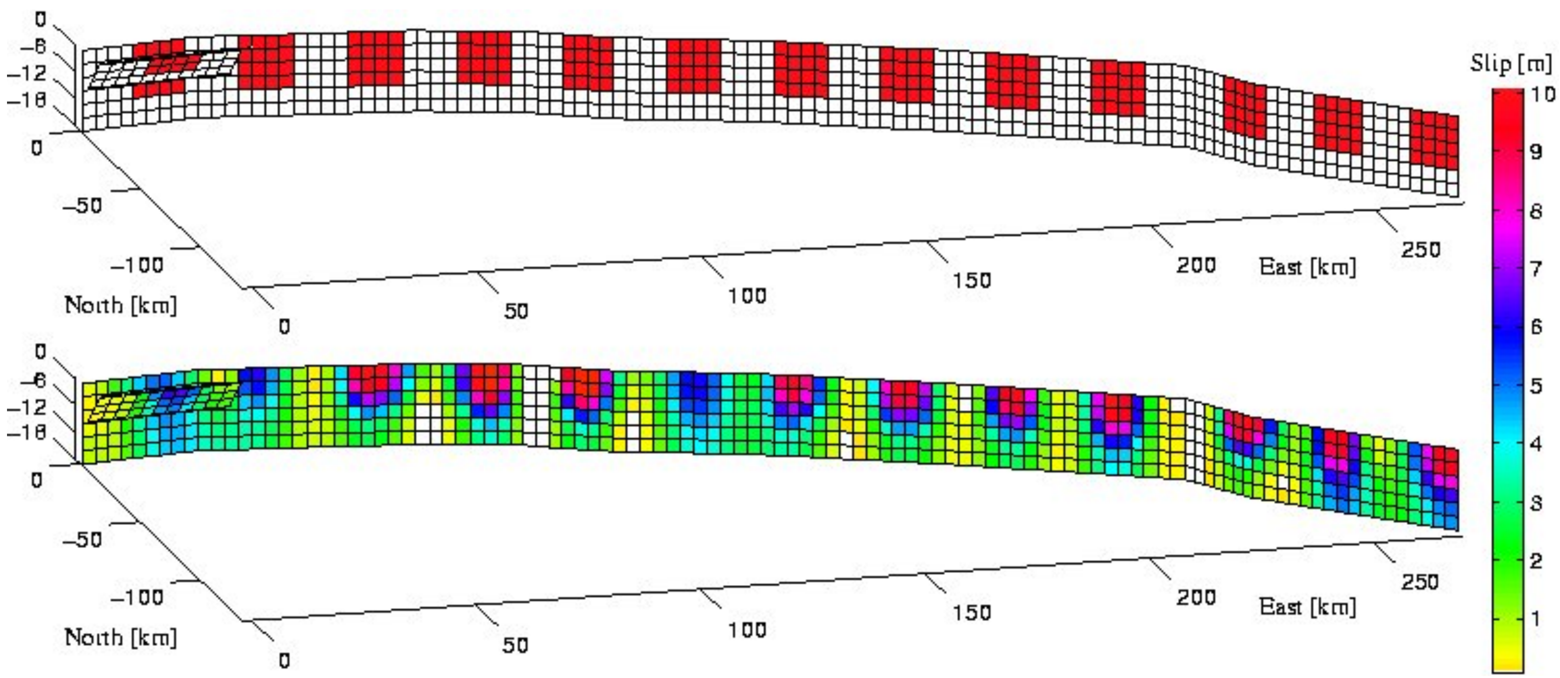
Modeled Surface Slip
-> Extremely good fit to Surface Offset Data

Comparison With Surface Offset Data



Modeled Surface Slip
-> Extremely good fit to Surface Offset Data

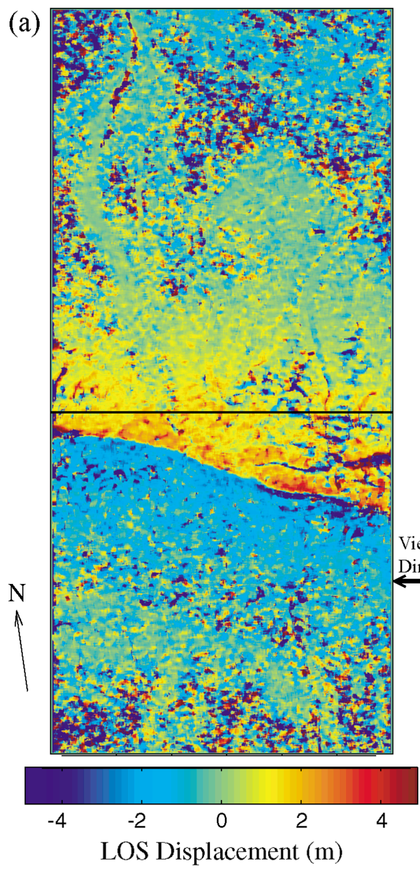
Surface slip for model based on GPS data only
-> Remarkably good fit to Surface Offset Data

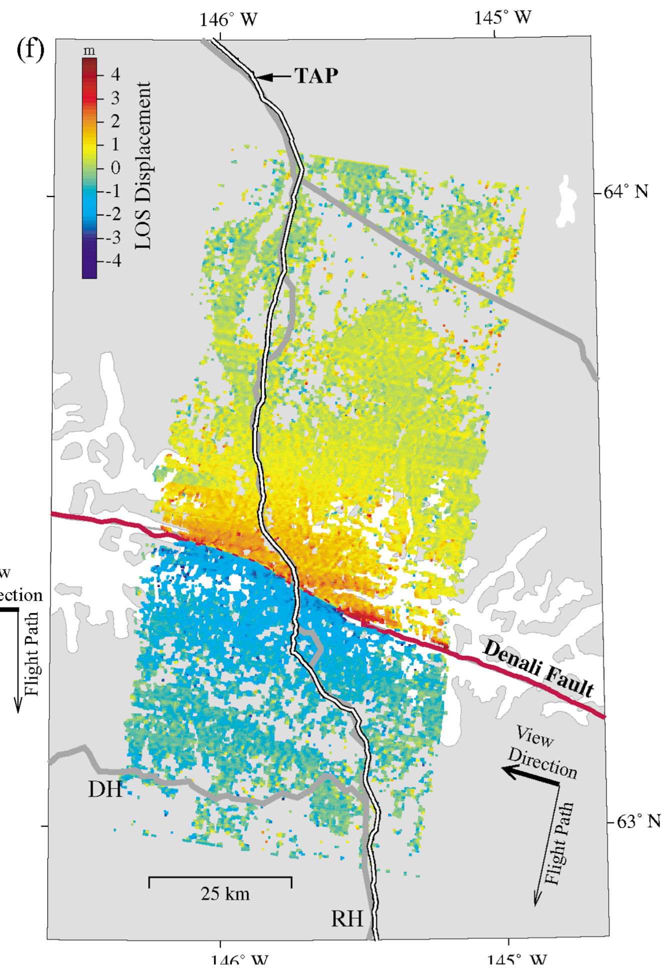


0
−6
−12
−18
0
−50
−100
North [km]
0
50
100
150
200
250
East [km]
Slip [m]
10
9
8
7
6
5
4
3
2
1

SAR Range Offset Data

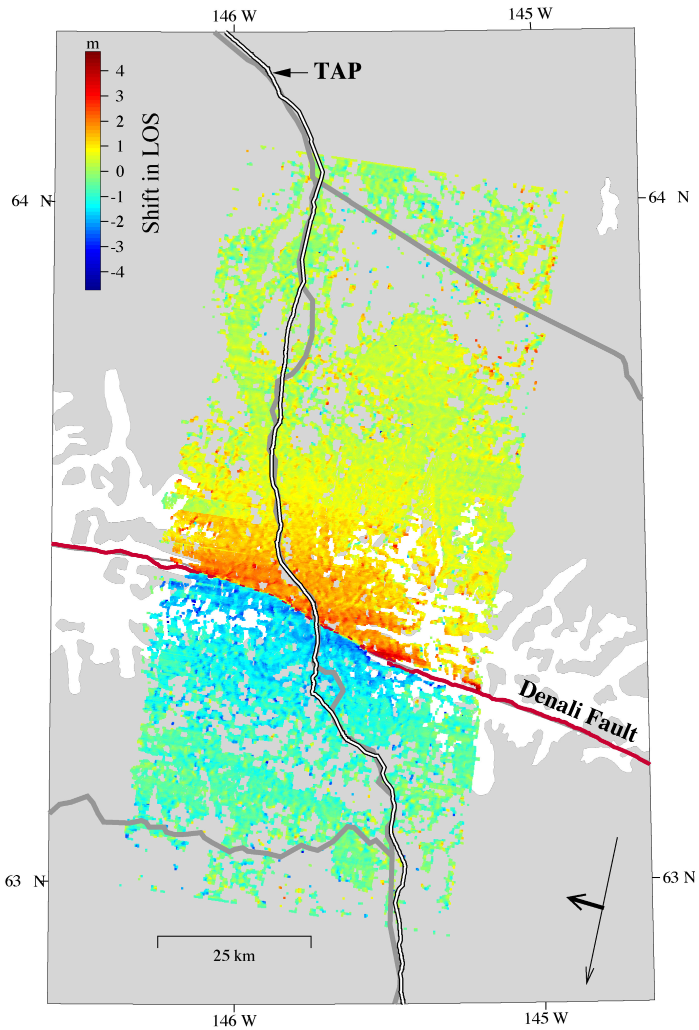
Unfiltered





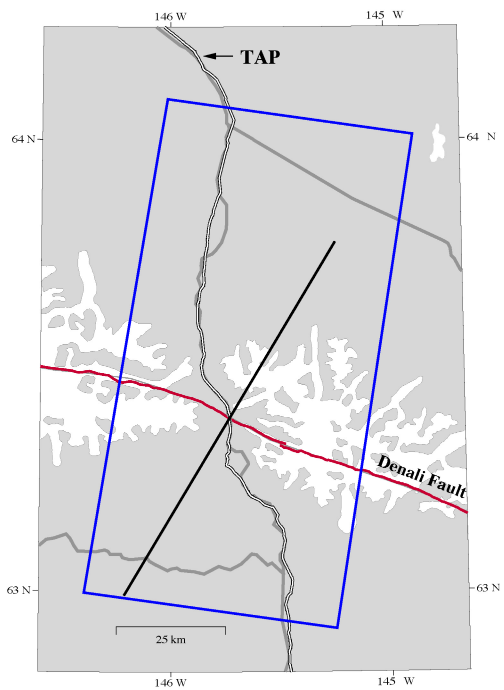
Filtered, bad data masked out

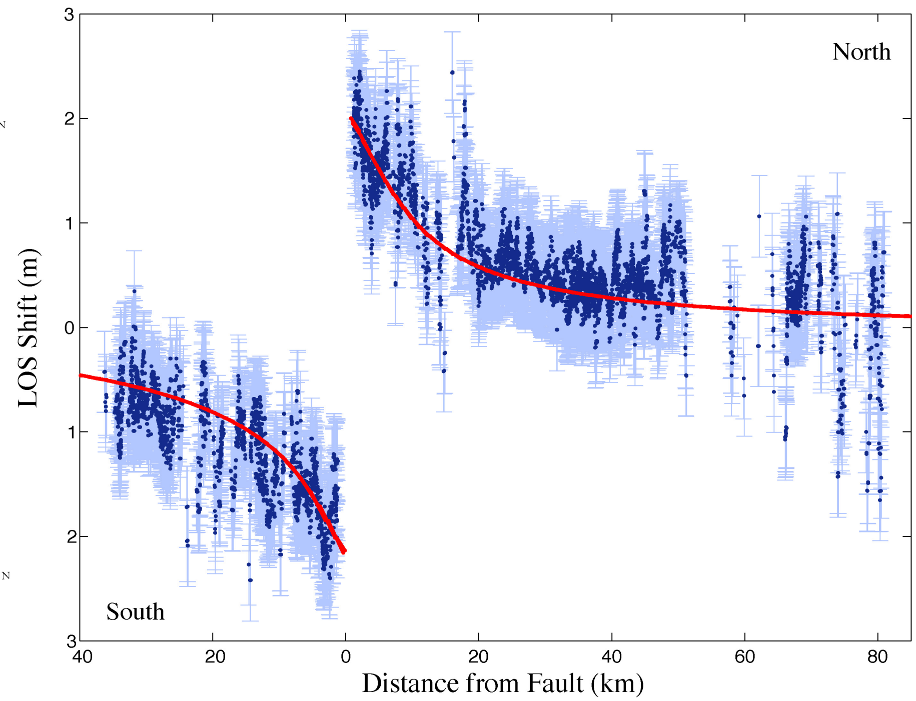
Filtered Speckle Tracking Offset Map



- Sharp demarcation between the sense of motion on the north and south sides of the fault
- Positive shifts north of the fault indicate motion to the east - southeast (towards the satellite)
- Negative shifts south of the fault indicate motion to the west-northwest (away from the satellite)
- Maximum offsets on both sides of the fault occur east of the pipeline - ~3 m in LOS in the north and ~2 m in LOS in the south
- Maximum offsets roughly translate into 4 m of lateral displacement north of the fault and 3 m of lateral displacement south of the fault
- Offset uncertainty is ~ 0.4 m

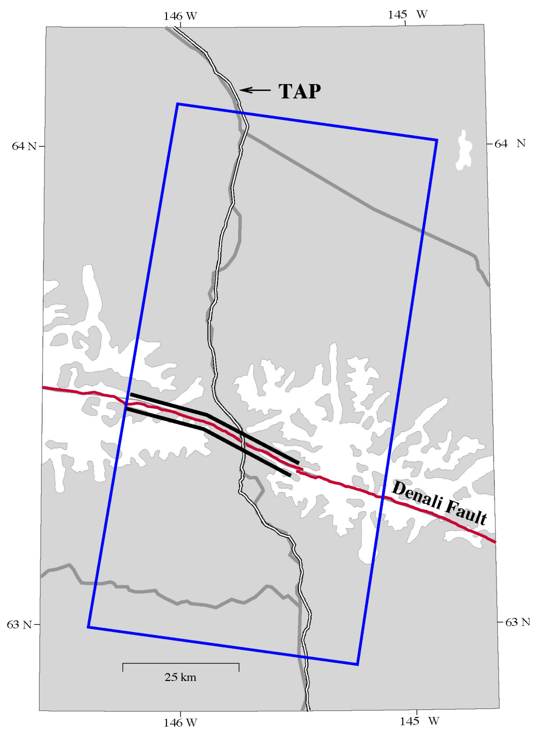
Richardson Highway Profile

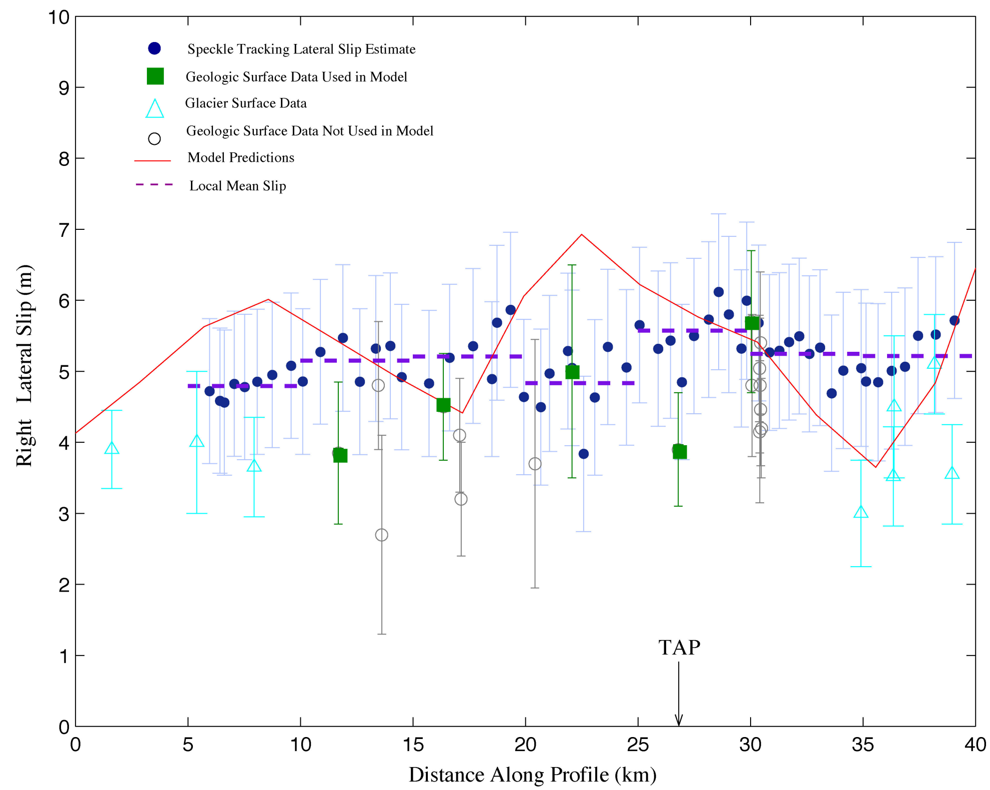




- Decaying curves typical of right-lateral strike-slip motion
- Displacement in LOS across the fault is ~ 4 m, which roughly translates to 6 m of right-lateral slip
- Speckle tracking data agrees well with predictions from GPS model, particularly near the fault where model resolution is highest

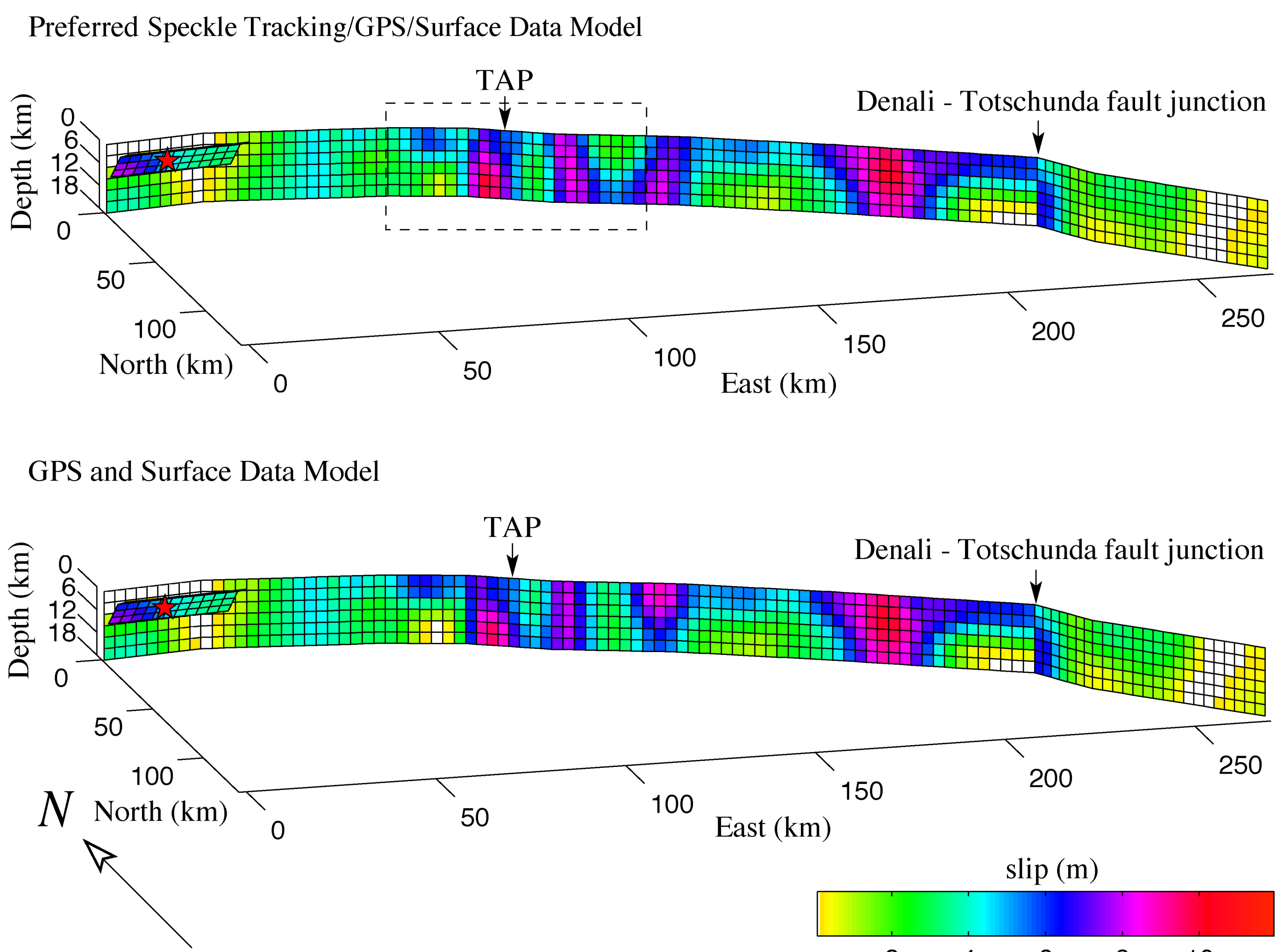
Lateral Slip Estimate



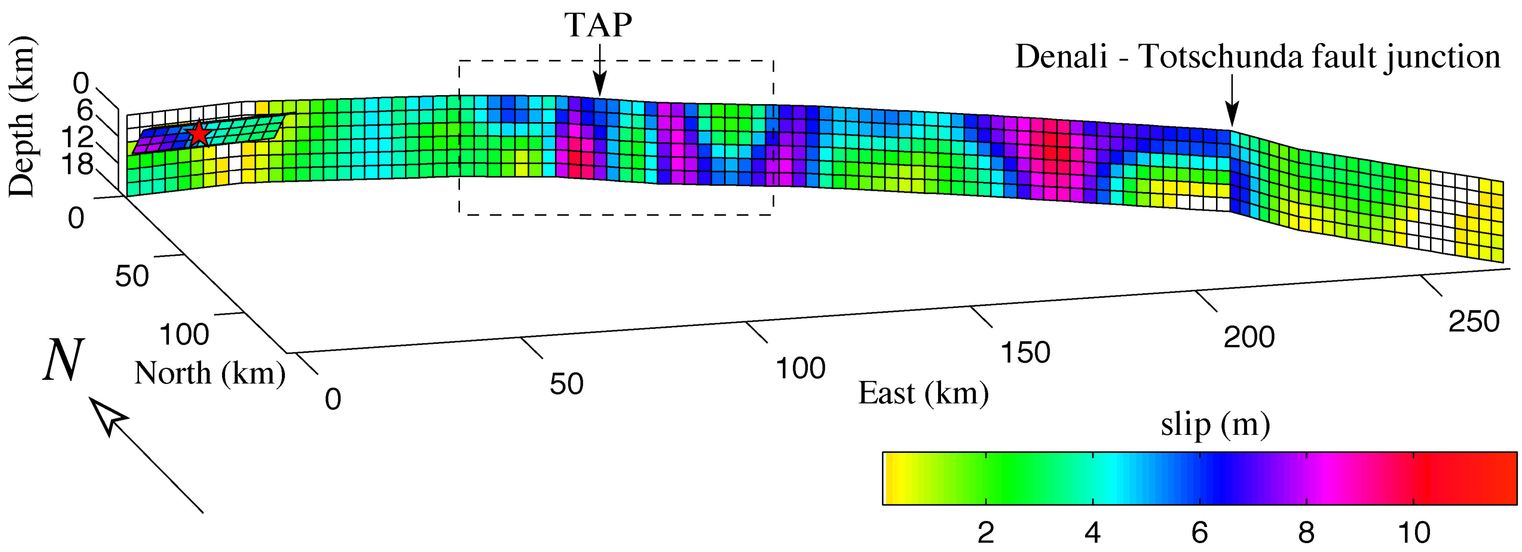


- Converted along-strike profiles of the speckle tracking data into full lateral slip estimates in geographic coordinates
- Largest geologic offset measurements within 1 sigma of mean slip estimate
- Other geologic offset measurements an average of 1.44 sigma below mean slip estimate

Model Comparison



Combined Slip Distribution Model



- Total moment of $6.85*10^{20}$ N•m, corresponds to an $M_w 7.89$ earthquake
- Average of 4.5 m of dip-slip on the Susitna Glacier fault
- On Denali fault, no surface slip around epicenter
- Three patches of high slip (8.5 m - 10 m) between 60 and 140 km
- Largest slip patch ~ 40 km west of DTJ with slip reaching 10 m at surface
- On Totschunda fault, relatively low slip concentrated at shallow depths

Surface Slip Comparison