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H4.SMR/1642-10

"IAG-IASPEI Joint Capacity Building Workshop on Deformation Measurements and Understanding Natural Hazards in Developing Countries"

17 - 23 January 2005

The Earthquake Cycle, Geodesy and Earthquake Hazards: General Models and Case Studies from Subduction and Transform Boundaries

J. Freymueller

Geophysical Institute
University of Alaska,
Fairbanks

The Earthquake Cycle, Geodesy and Earthquake Hazards:

General Models and Case Studies from Subduction and Transform Boundaries

Jeff Freymueller
Geophysical Institute
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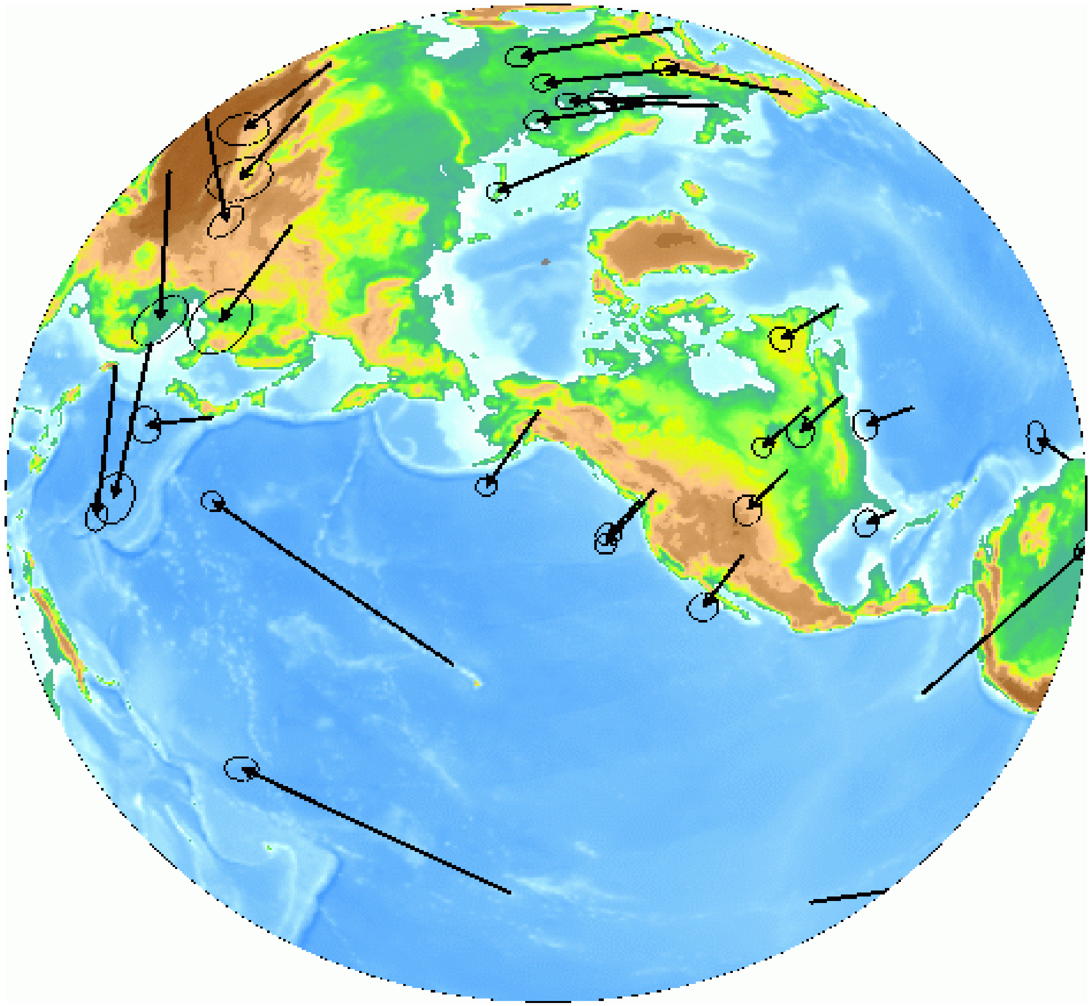
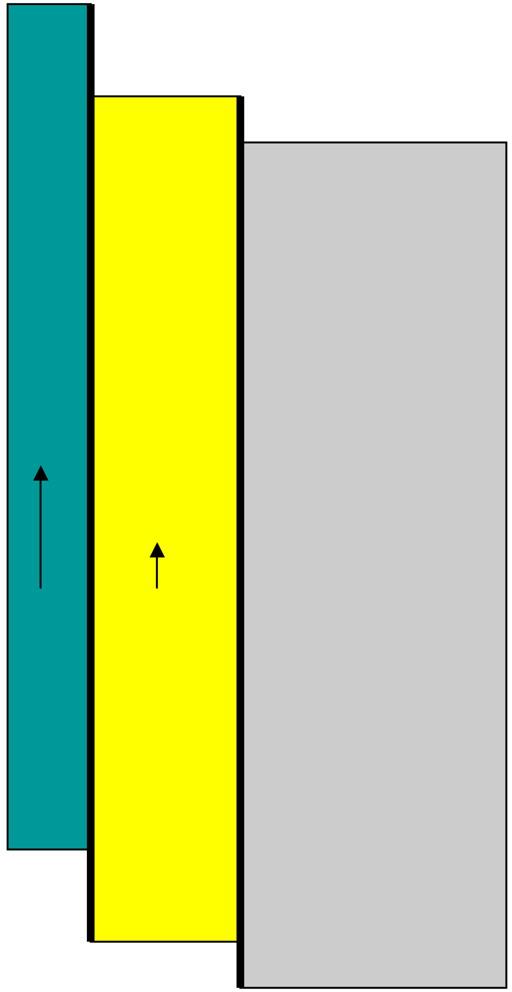
Block-like Motion





Outline

- Physics of Faults: Stick-Slip vs. Stable Sliding
- A Simple "Earthquake Cycle" Model
- Geodetic Implications
- Examples
- Learning from Large Earthquakes
- Postseismic Deformation Effects

Physics of Faults: Stick-slip vs. Stable Sliding

- An earthquake is caused by sudden slip on a fault
  - Mw 4-5: a few centimeters average slip
  - Mw 7: a few meters average slip
  - Mw 9: 10-20 average slip

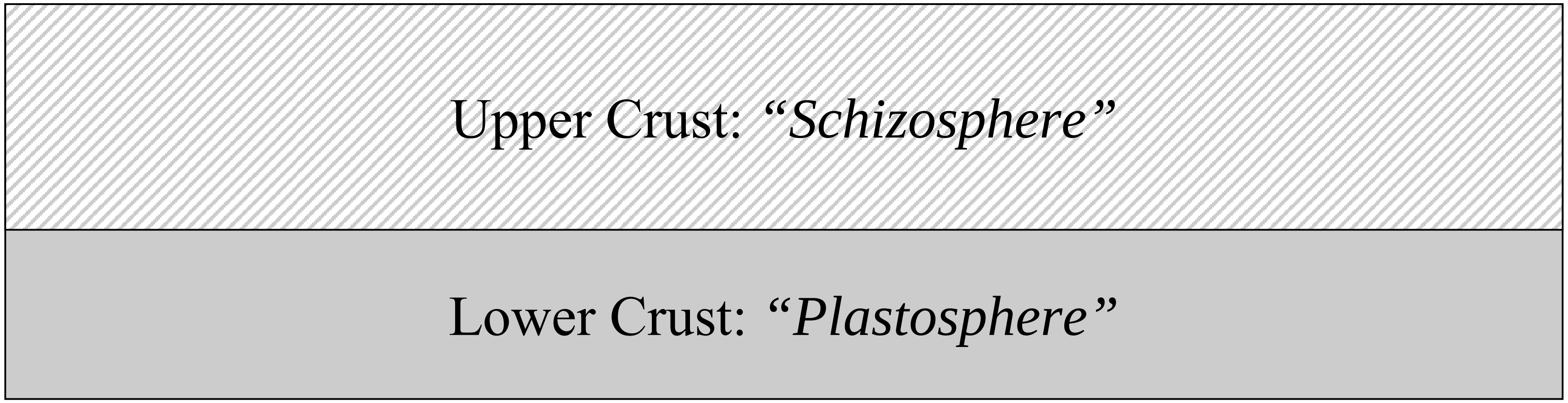
  NB. Typical fault slip rates are mm to cm per year
- Why do faults move many years or centuries' worth of slip in a matter of seconds during an earthquake?

Physics of Faults: Terminology

Can divide fault zone based on how rocks deform (terminology of Scholz)

- *Schizosphere* deforms by brittle failure of rock
- *Plastosphere* deforms by flow: plastic, ductile

- Seismic slip involves brittle failure, occurs in schizosphere



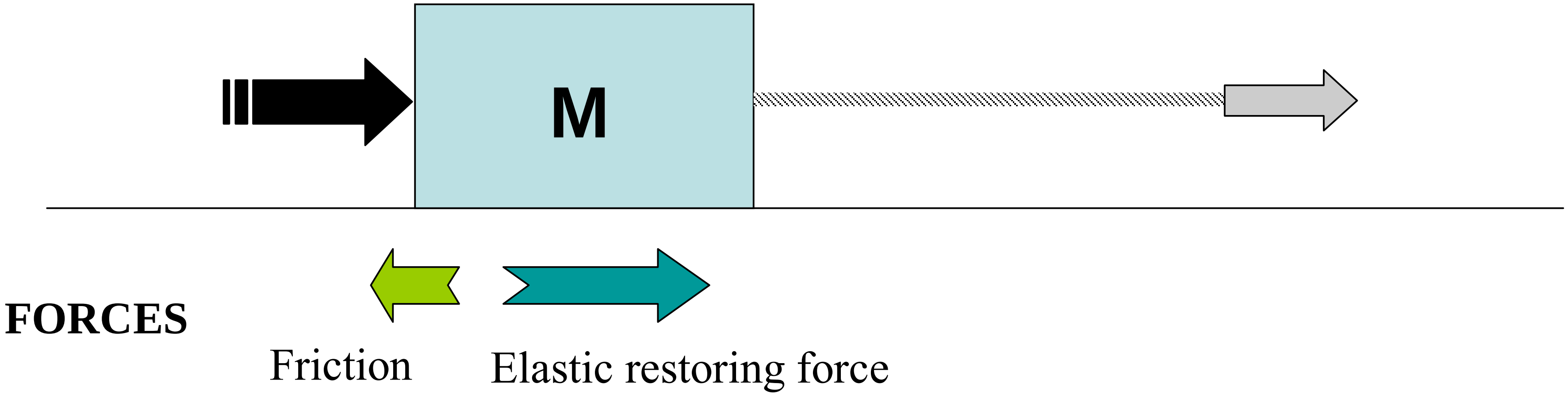
Is This Reasonable?

- Temperature increases with depth
  - Expect non-brittle failure at depth
- Most continental earthquakes are shallow
  - Strike-slip earthquakes in upper 10-15 km
  - Crustal dip-slip earthquakes similar
  - Subduction zone thrust earthquakes deeper
- Does not explain intermediate and deep Wadati-Benioff zone seismicity
- *But*, fault slip not only controlled by depth

Two Types of Slip

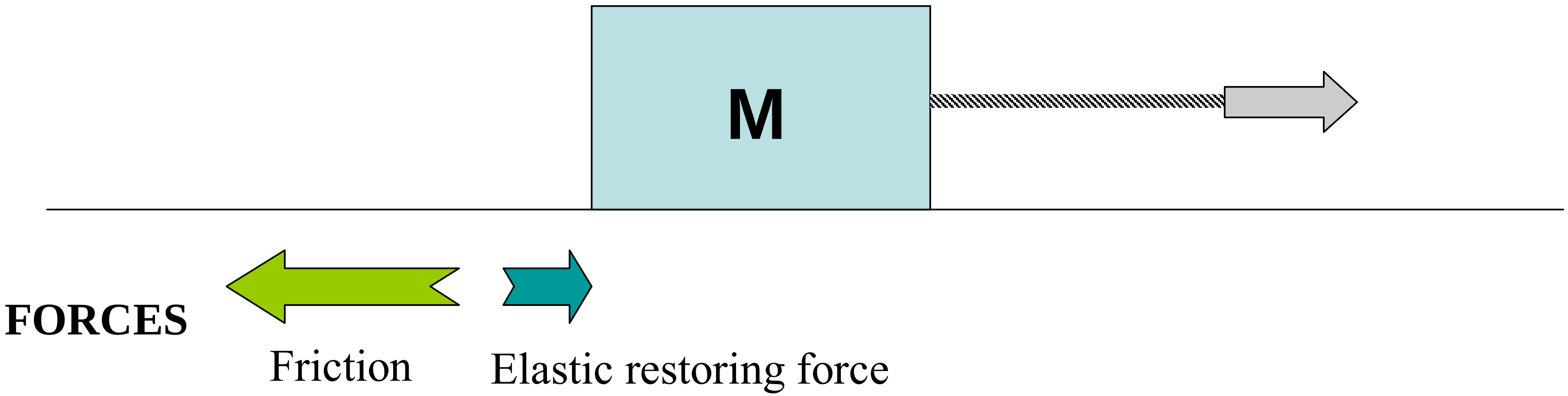
- Stick-slip (seismic)
  - Two sides of interface stuck together: **friction**
  - Slip occurs when friction is overcome
  - Slip controlled by dynamic friction, healing
- Stable Sliding (aseismic)
  - Two sides slide continually past each other
  - Slip occurs all the time
  - Slip controlled by plastic, ductile, or viscous yielding
- Transient slip also occurs

A Simple Analogue: Spring Slider



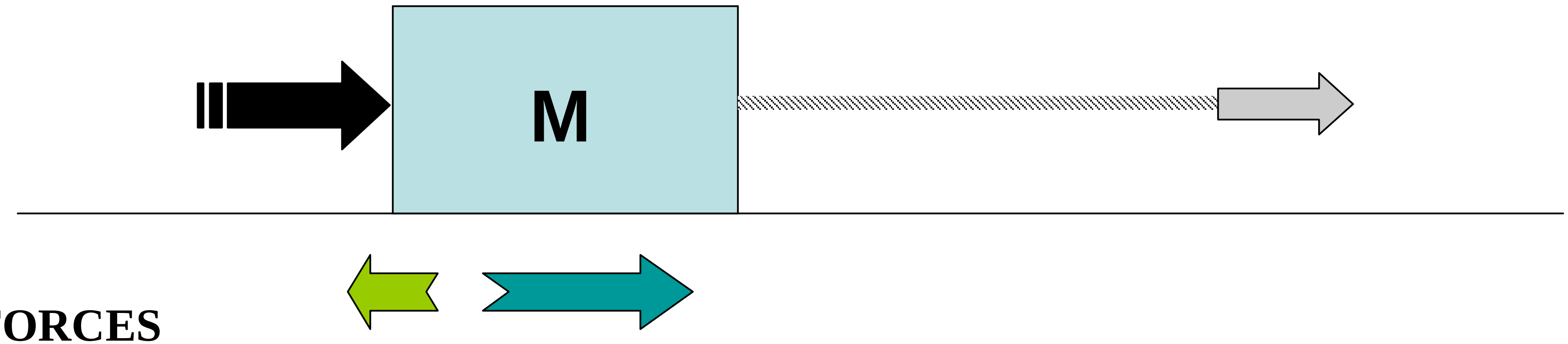
- Block is held in place by force of friction
- Moving load point increases elastic force
- Slips when elastic force exceeds friction

A Simple Analogue: Spring Slider



- Block is held in place by force of friction
- Moving load point increases elastic force
- Slips when elastic force exceeds friction

Frictional Instability



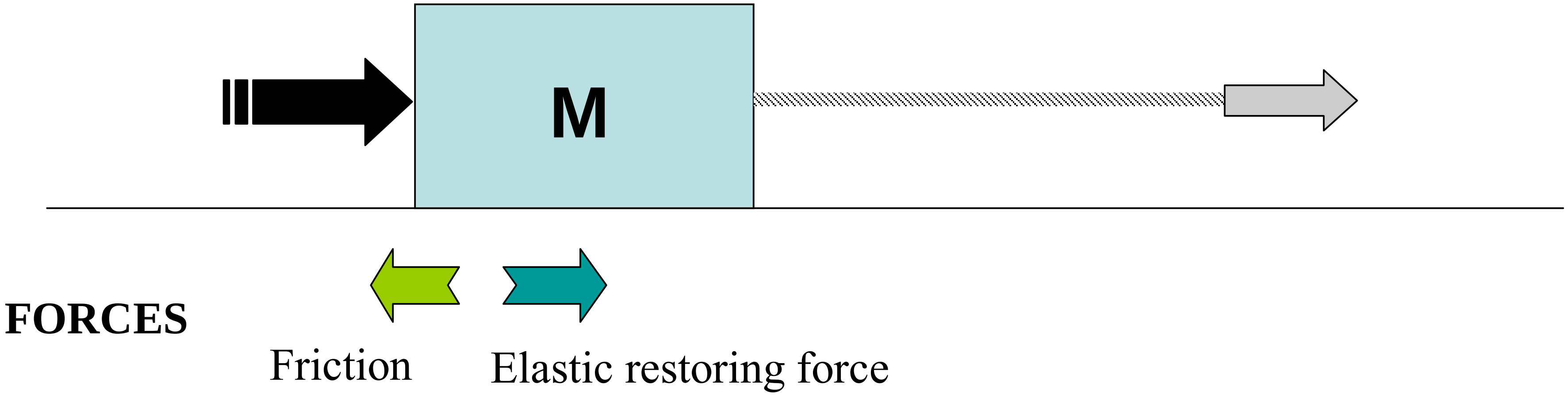
FORCES

Friction

Elastic restoring force

- Velocity-weakening (dynamic < static friction)
  - Fe > Ff; block accelerates
  - Velocity increases, Ff decreases; block accelerates more
  - Fe decreases with slip, in few seconds Fe < Ff; block decelerates
  - Velocity decreases, Ff goes up; block decelerates and stops

Alternative: Stable Sliding

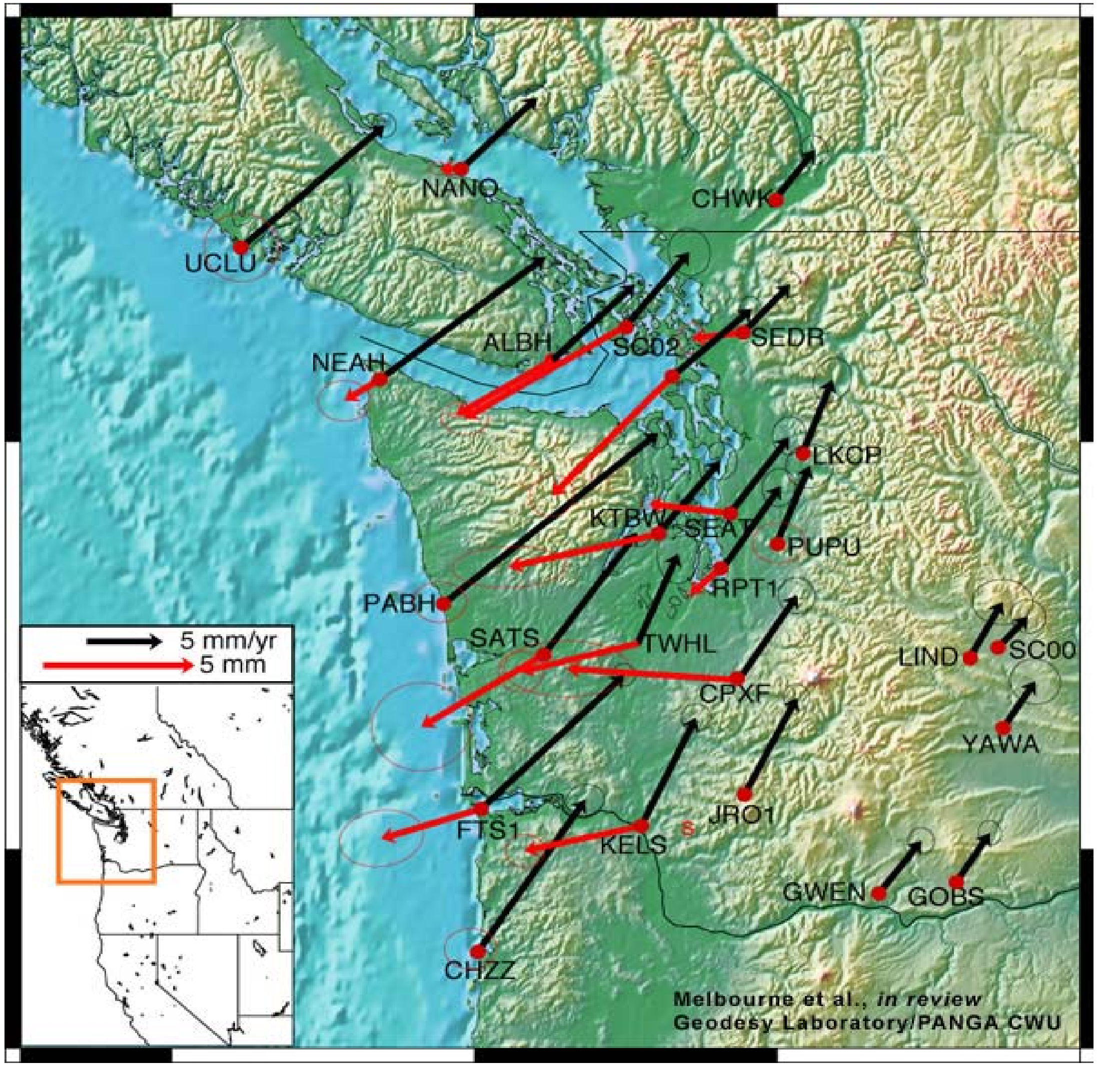


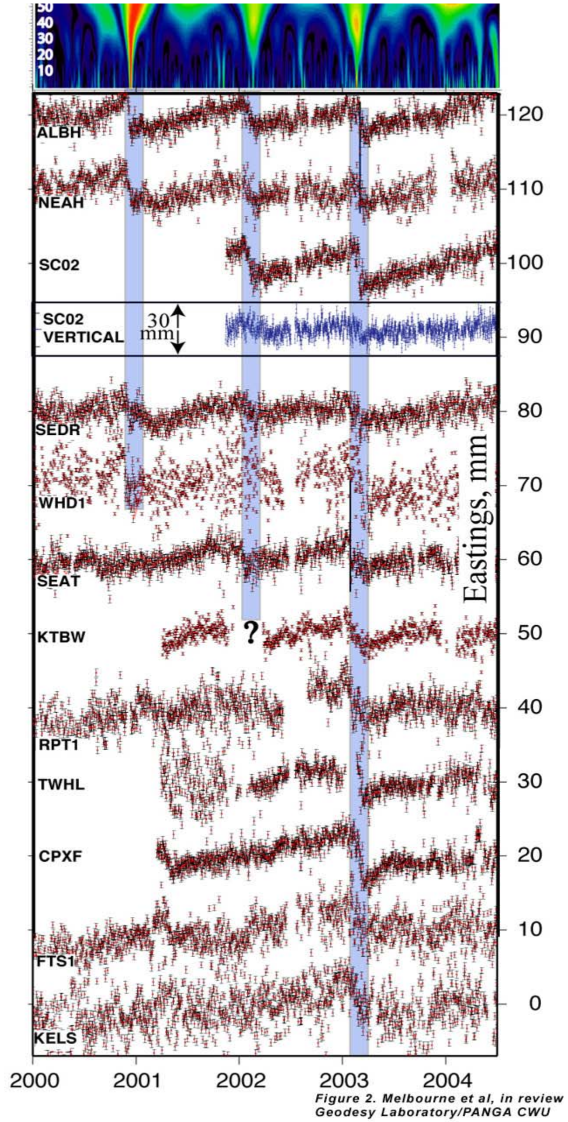
- Velocity-strengthening (dynamic > static friction)
  - Fe > Ff; block accelerates
  - Velocity increases, Ff increases; acceleration stops
  - But velocity remains the same
  - Velocity reaches equilibrium with shear stress

Rate and State Friction Law

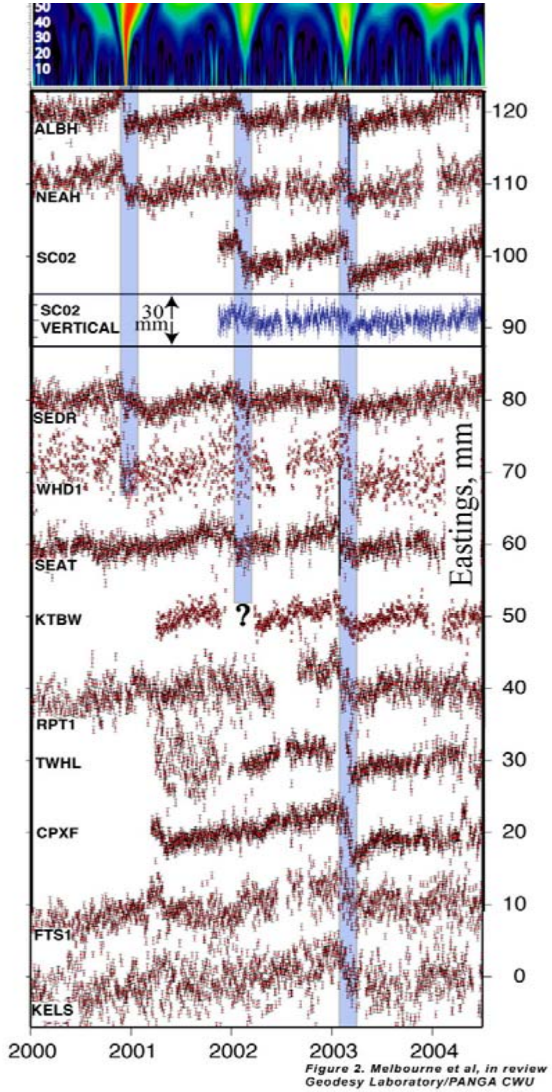
- These two kinds of frictional behavior both described by a **rate and state-dependent friction** law (Ruina, 1983)
  - Empirical relation based on laboratory data
  - Describes the evolution of friction with slip velocity and time
  - Describes fault weakening and healing
- It works!

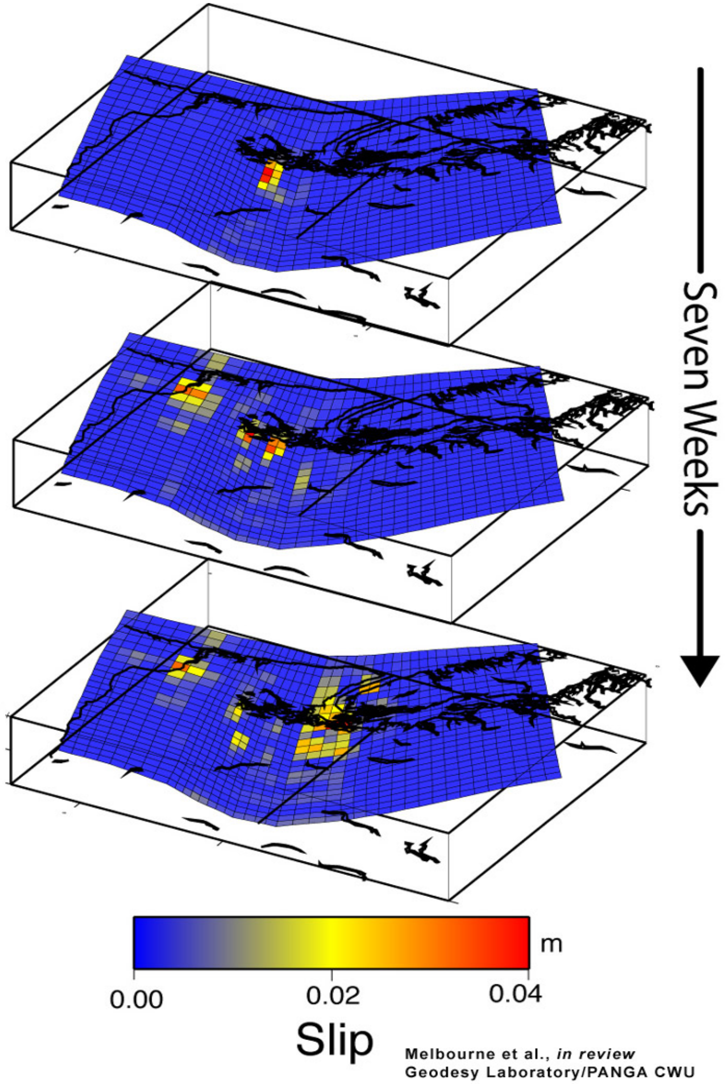
Slow Slip Events





Displacement and Slip Model



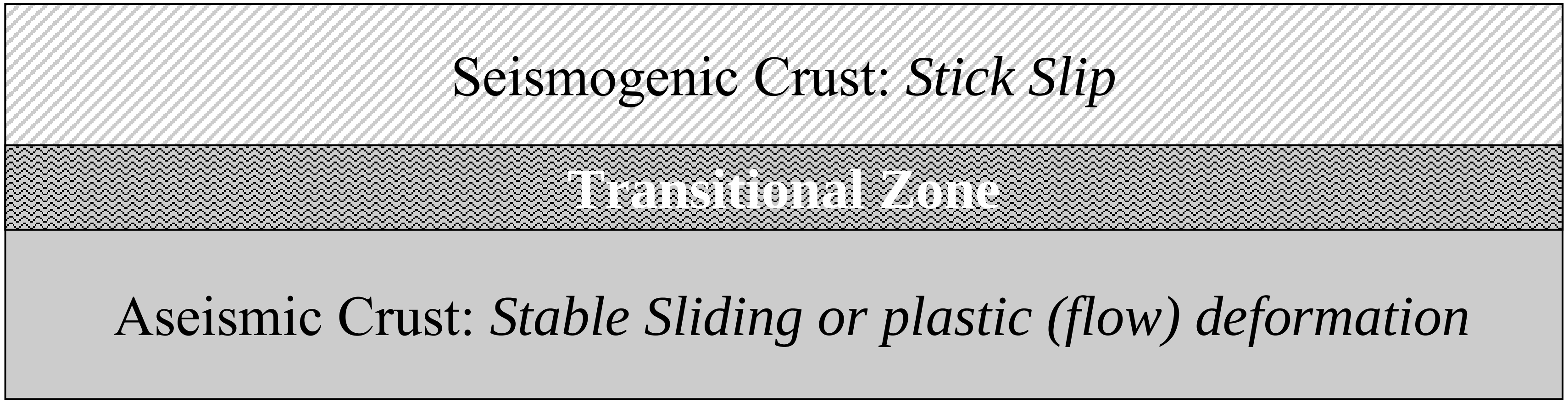


A More Realistic Picture

Can divide fault zone based on how fault slips

- *Seismogenic Crust* exhibits stick slip
- *Transitional Zone* may exhibit complex behavior
- *Aseismic Crust* exhibits stable sliding

• Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone

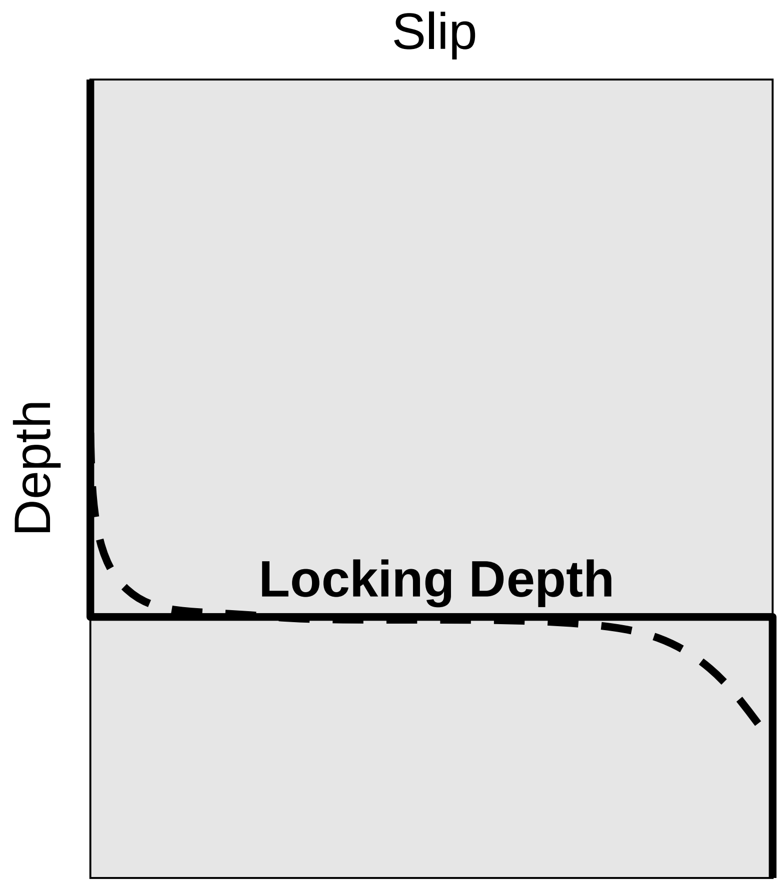


A Simple “Earthquake Cycle” Model

- Based on the spring-slider analogue model
- Between earthquakes:
  - Shallow fault is locked
  - Deeper fault is creeping at long-term slip rate
  - Stress builds up: elastic strain energy stored in crust
- During earthquake, shallowfault slips
  - Stress on fault reduced
- Cycle repeats forever

Geodetic Implications

- Between earthquakes
  - Fault does not slip from surface to **locking depth**
  - Fault slips continuously beneath locking depth
  - May be finite transition zone between locked and slipping parts
- During earthquake
  - Shallow fault slips



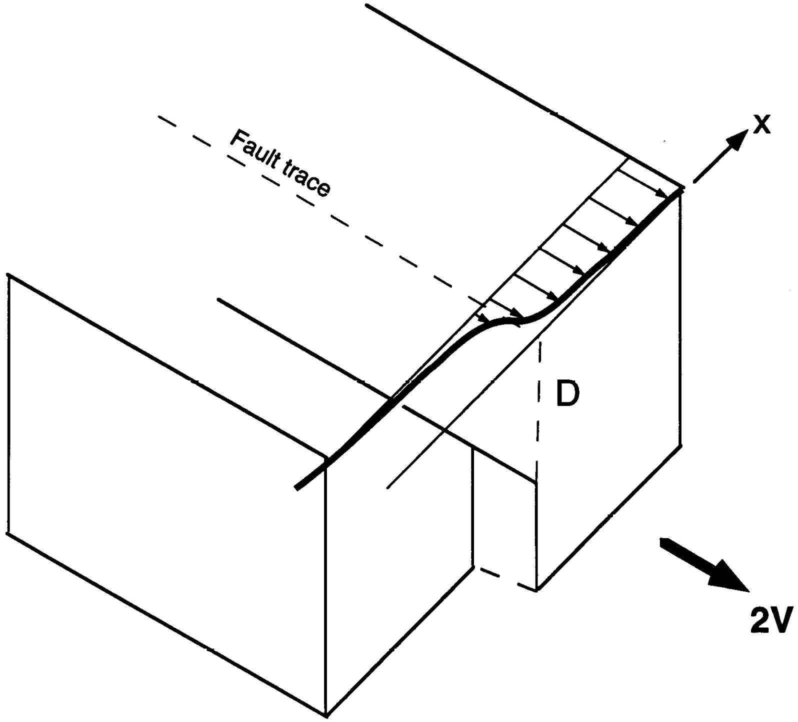
Shallow Locked Fault Causes Deformation

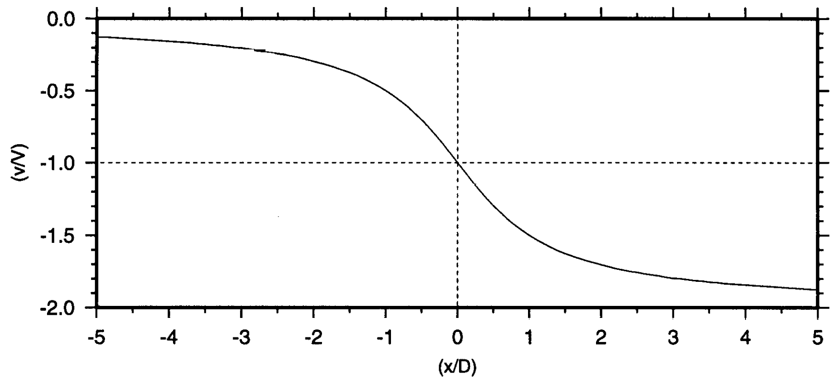
- Earth deforms as elastic body over short timescales
- Locked shallow fault + slipping deep fault produces elastic strain in vicinity of fault
  - Most important close to fault
  - Far from fault, motion is same as rigid blocks
- Post-seismic deformation to be discussed later

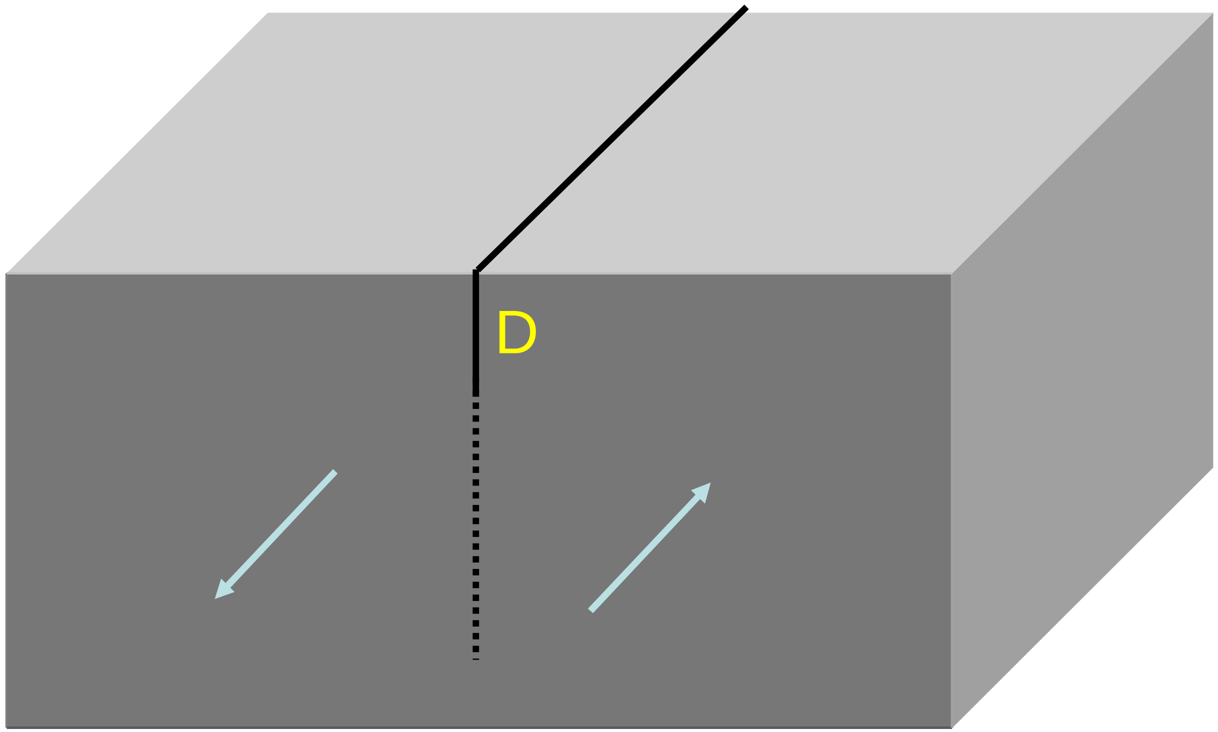
Elastic Fault Deformation

Example: 2D strike slip fault

- (Infinitely long fault)
- Velocity profile follows arctangent(x/D)
- Half of deformation seen on each side of fault
- Most elastic deformation within 2-3 locking depths of fault



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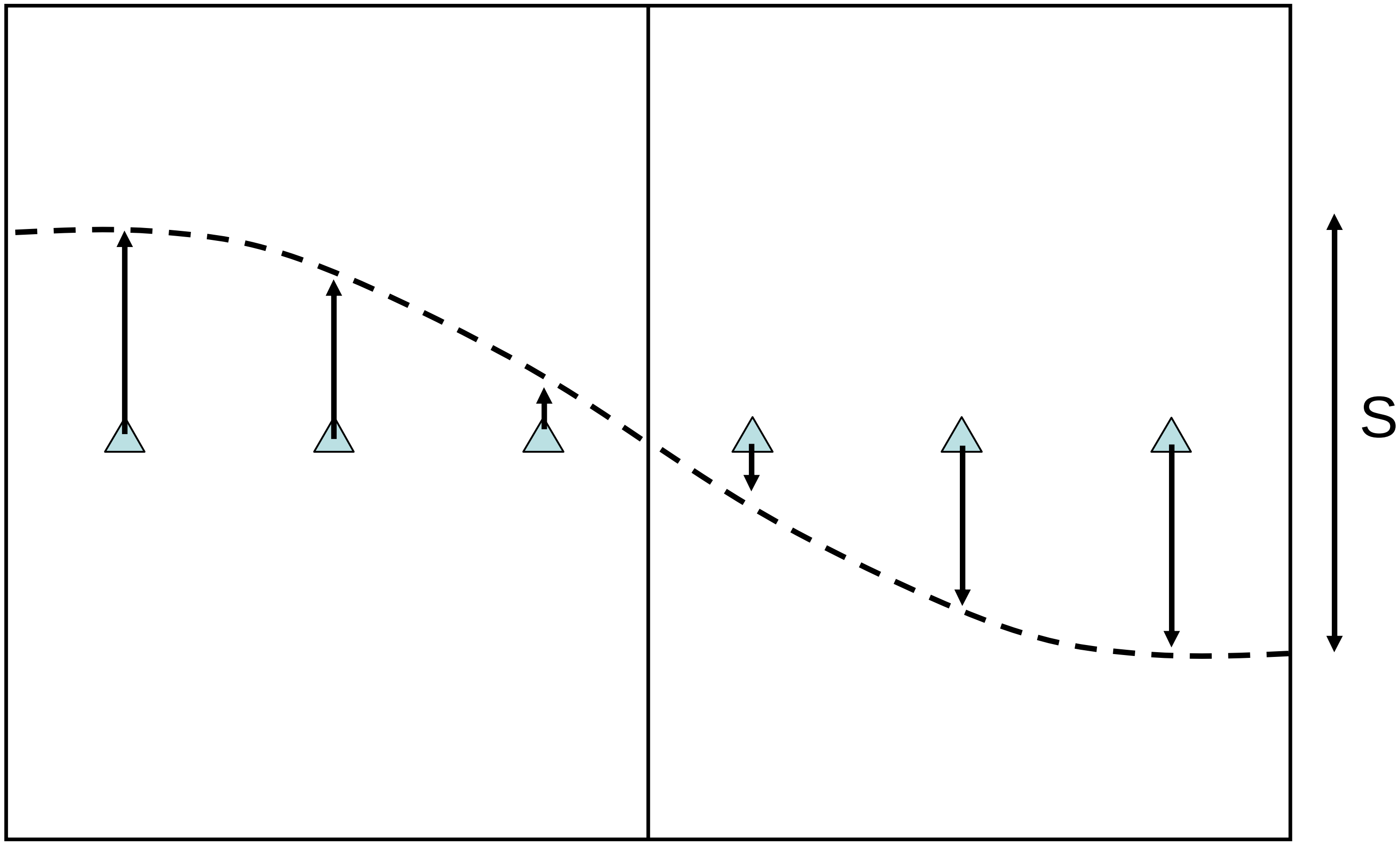
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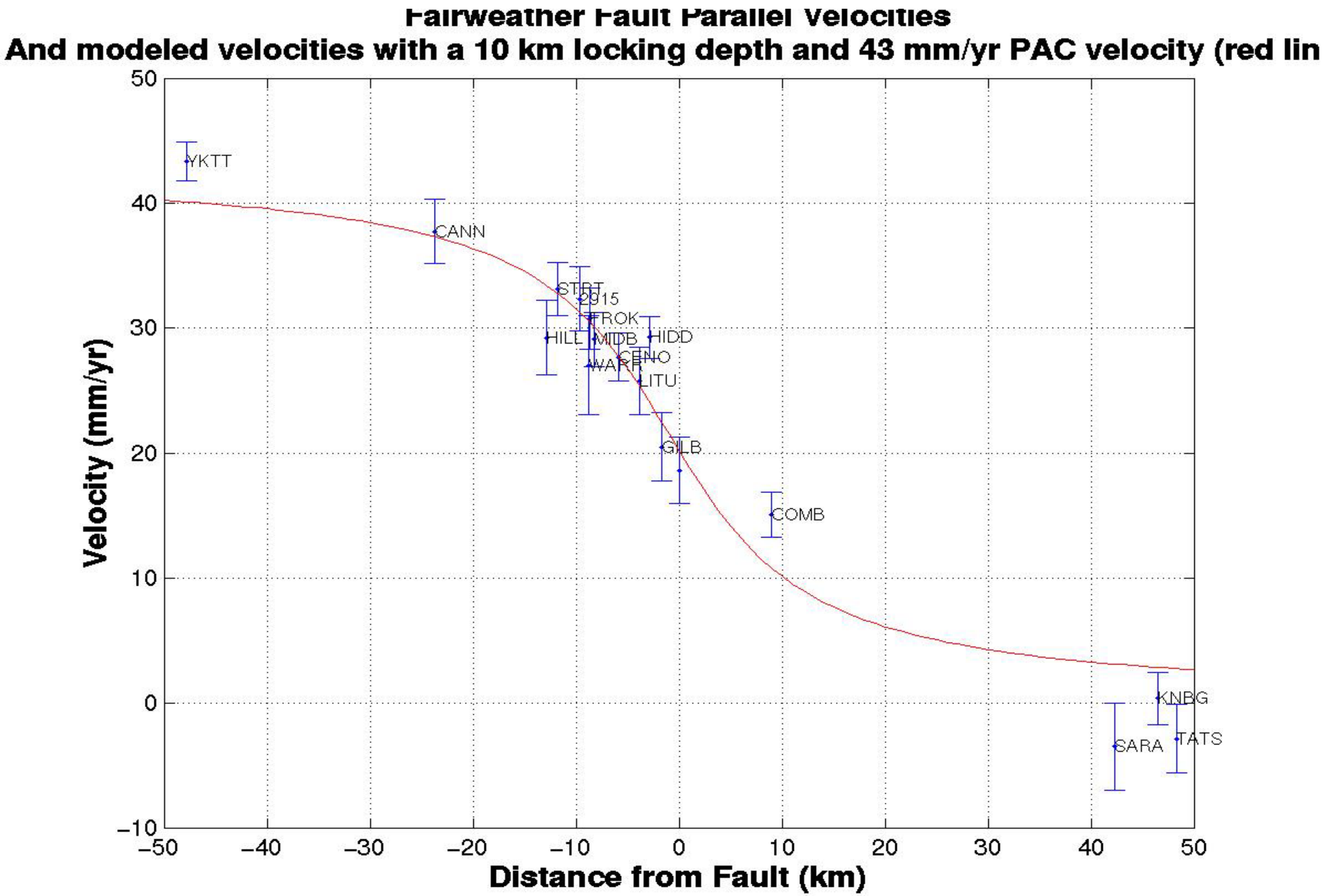
An Example

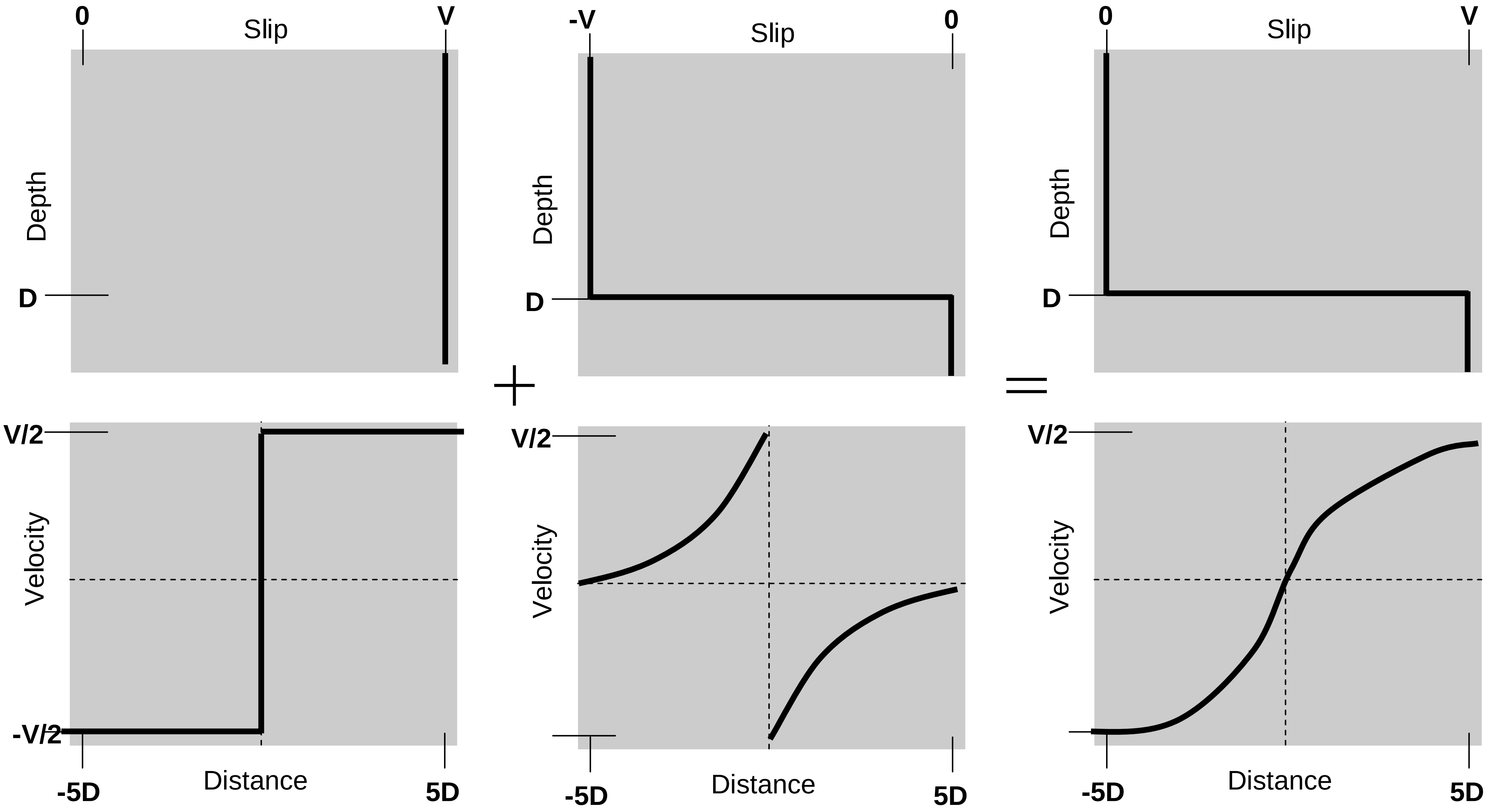


Fairweather Fault Parallel Velocities
And modeled velocities with a 10 km locking depth and 43 mm/yr PAC velocity (red lin
Velocity (mm/yr)
Distance from Fault (km)
YKTT
CANN
STRT
2915
FROK
HILL
MIDB
HIDD
CENO
WARR
LITU
GILB
COMB
KNBG
TATS
SARA
50
40
30
20
10
0
−10
−50
−40
−30
−20
−10
0
10
20
30
40
50

Modeling Elastic Deformation

- We can model effect of locked faults using **elastic dislocation** theory with an elastic **half-space**
  - There are simple analytical expressions for 2D
  - There are standard computer codes for 3D
  - The same codes work for earthquake (coseismic) deformation
- A simple approach is to represent motions by a combination of rigid block motion and "backslip" to cancel the motion on the shallow fault (Savage and Burford, 1973)
- Backslip represents the ***slip deficit*** of the shallow fault

Superposition



2D Strike Slip Fault

$$V(x) = \frac{S}{\pi}\operatorname{atan}\left[\frac{(x - x_f)}{D}\right]$$

Savage and Burford (1973)

$V(x)$ = fault-parallel velocity at position x

S = long-term slip rate

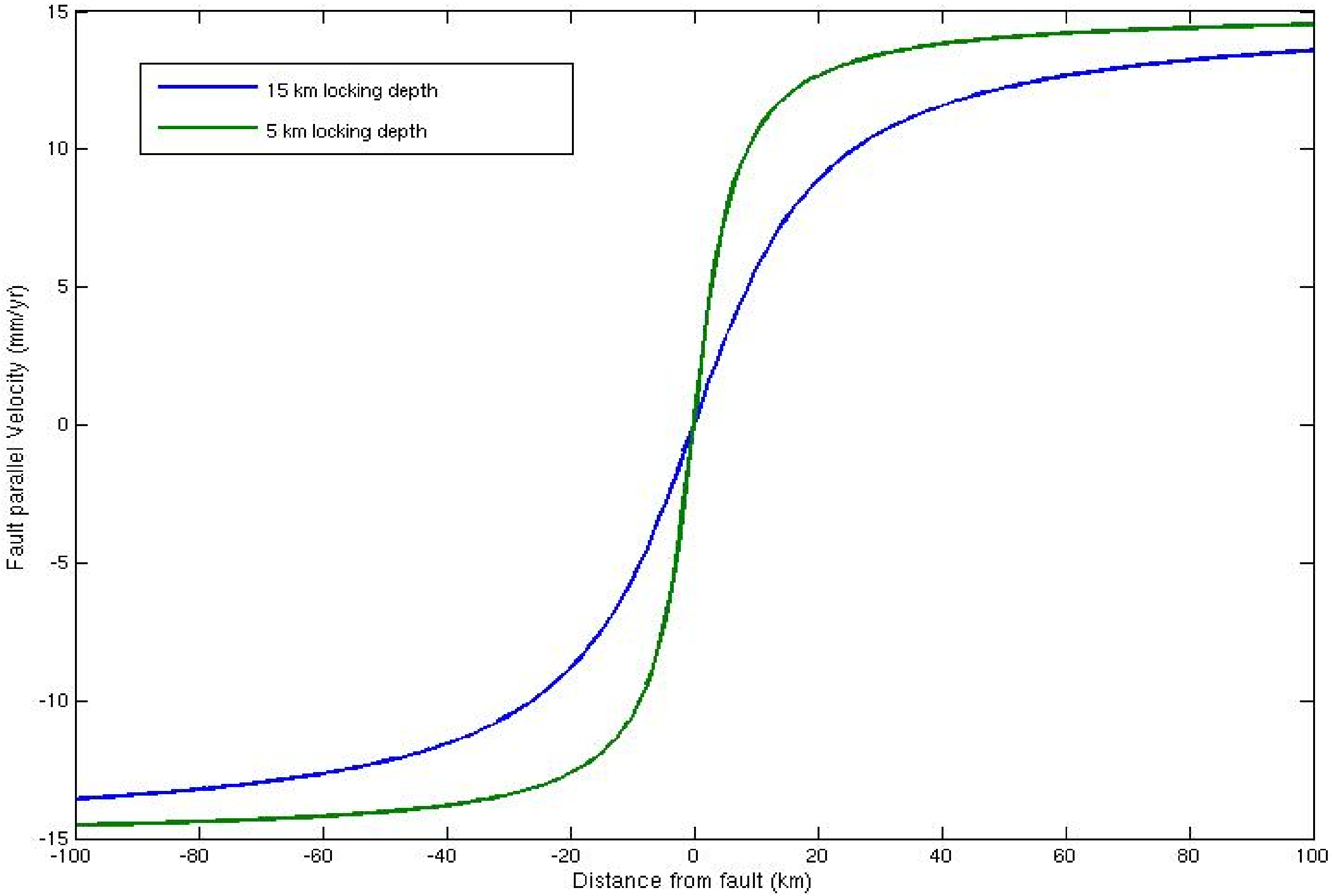
D = locking depth

x = perpendicular distance of site from fault

x_f = position of fault

In this formulation, a site on the fault has zero velocity

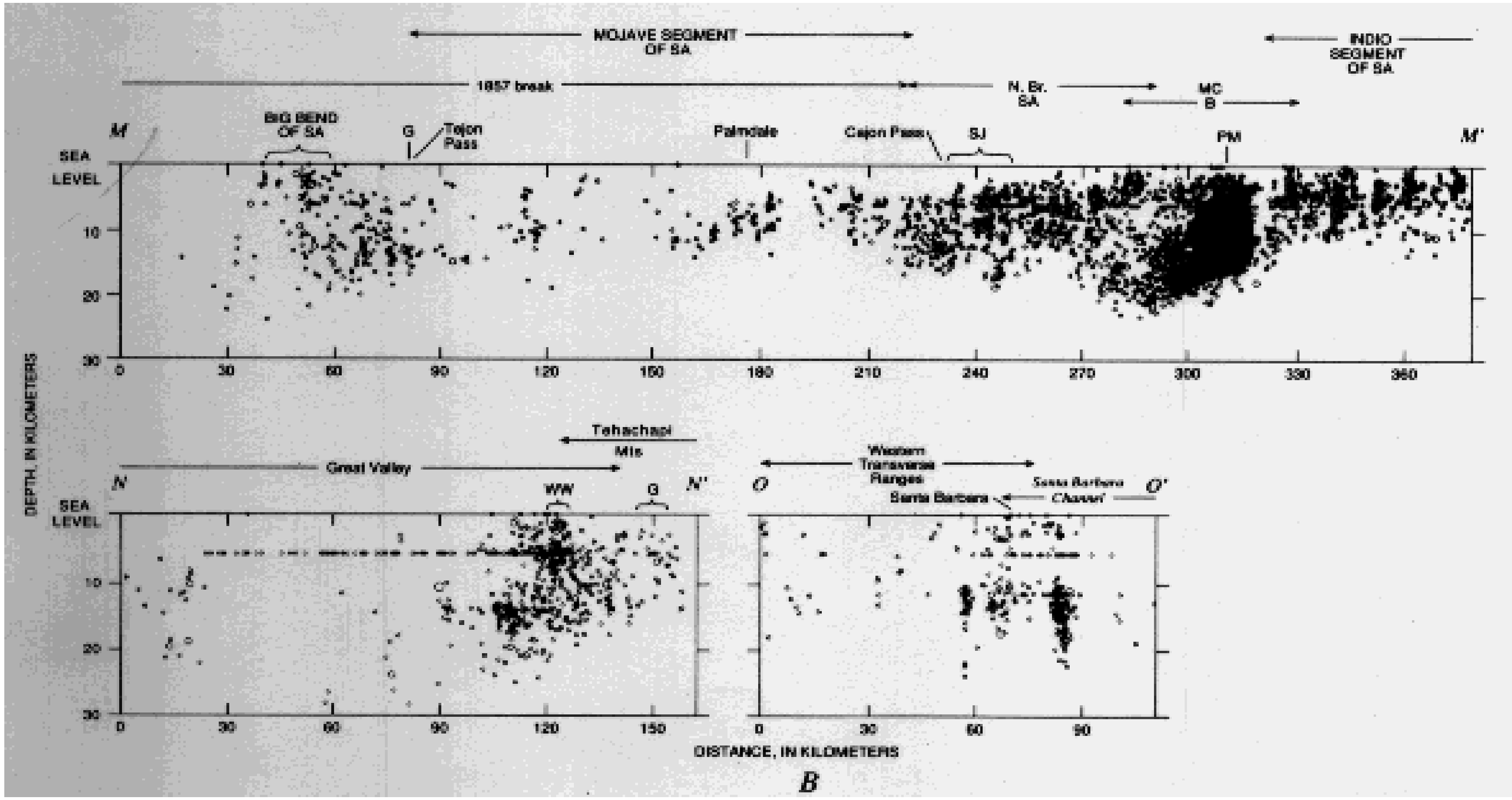
Changing the Locking Depth



How to Constrain Locking Depth?

- Good correlation between maximum depth of microseismicity and maximum depth of slip in large earthquakes
- First-order approximation: maximum depth of microseismicity = locking depth
  - Usually 12-18 km for strike-slip faults
  - Usually 25-50 km for subduction thrust
- Remember uncertainty in source depth!
- Or estimate it with slip rate from geodetic data

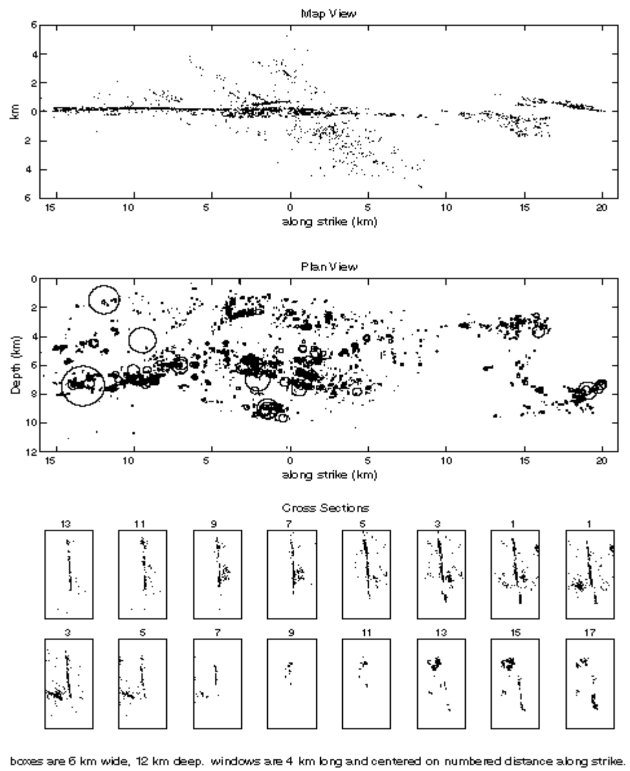
Maximum Depth of Seismicity

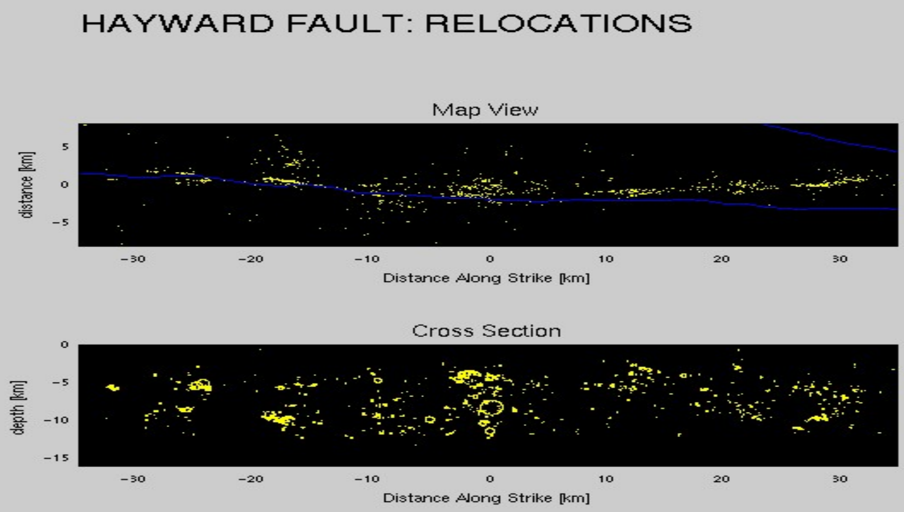


Hill et al., 1991

Detailed Depth Sections

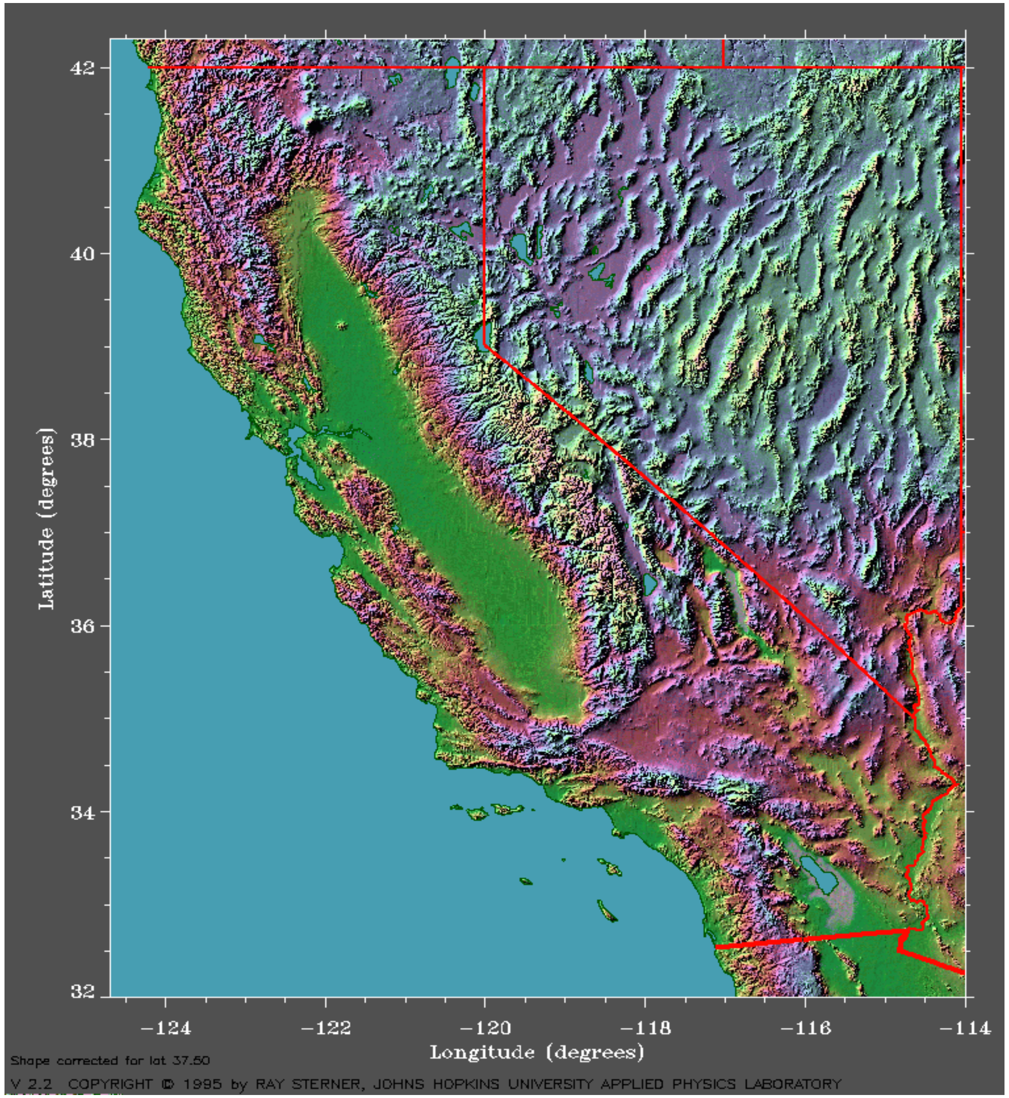
Calaveras fault





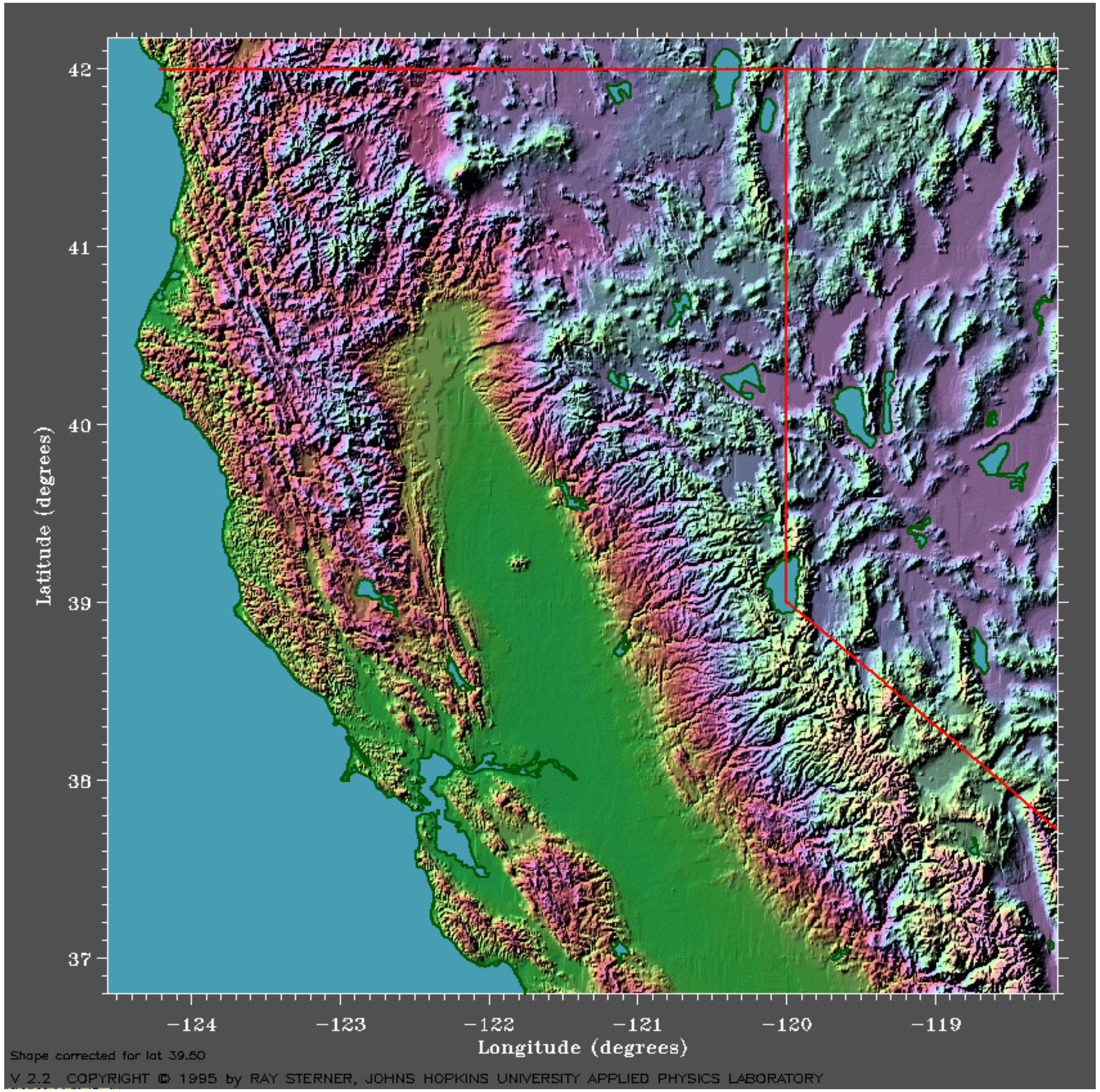
Waldhauser et al., 1999

Examples from California

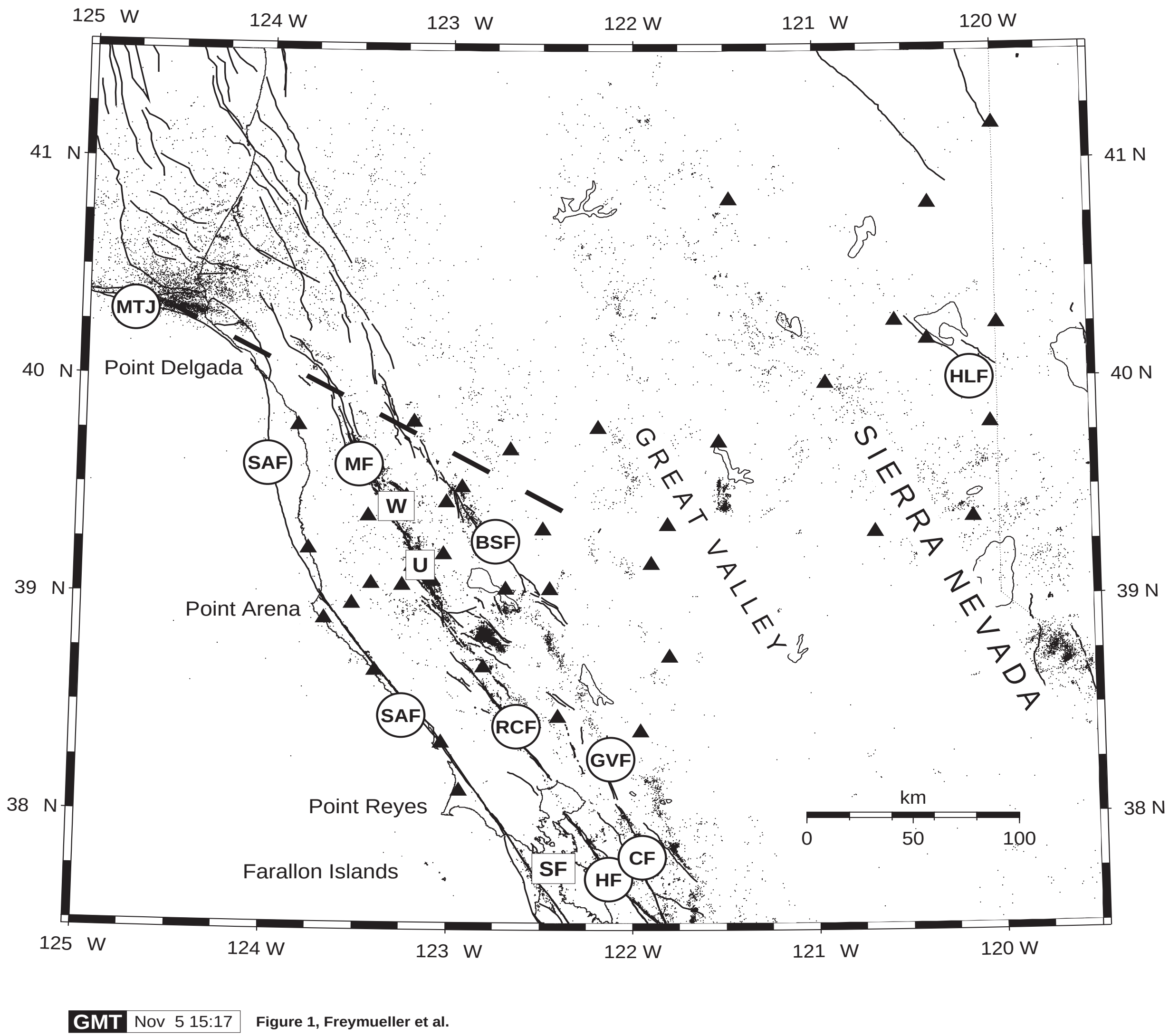


- Sierra Nevada-Great Valley (SNGV) block is stable
- Pure strike-slip west of SNGV
- Extension east of SNGV
- Also strike slip on eastern edge of SNGV

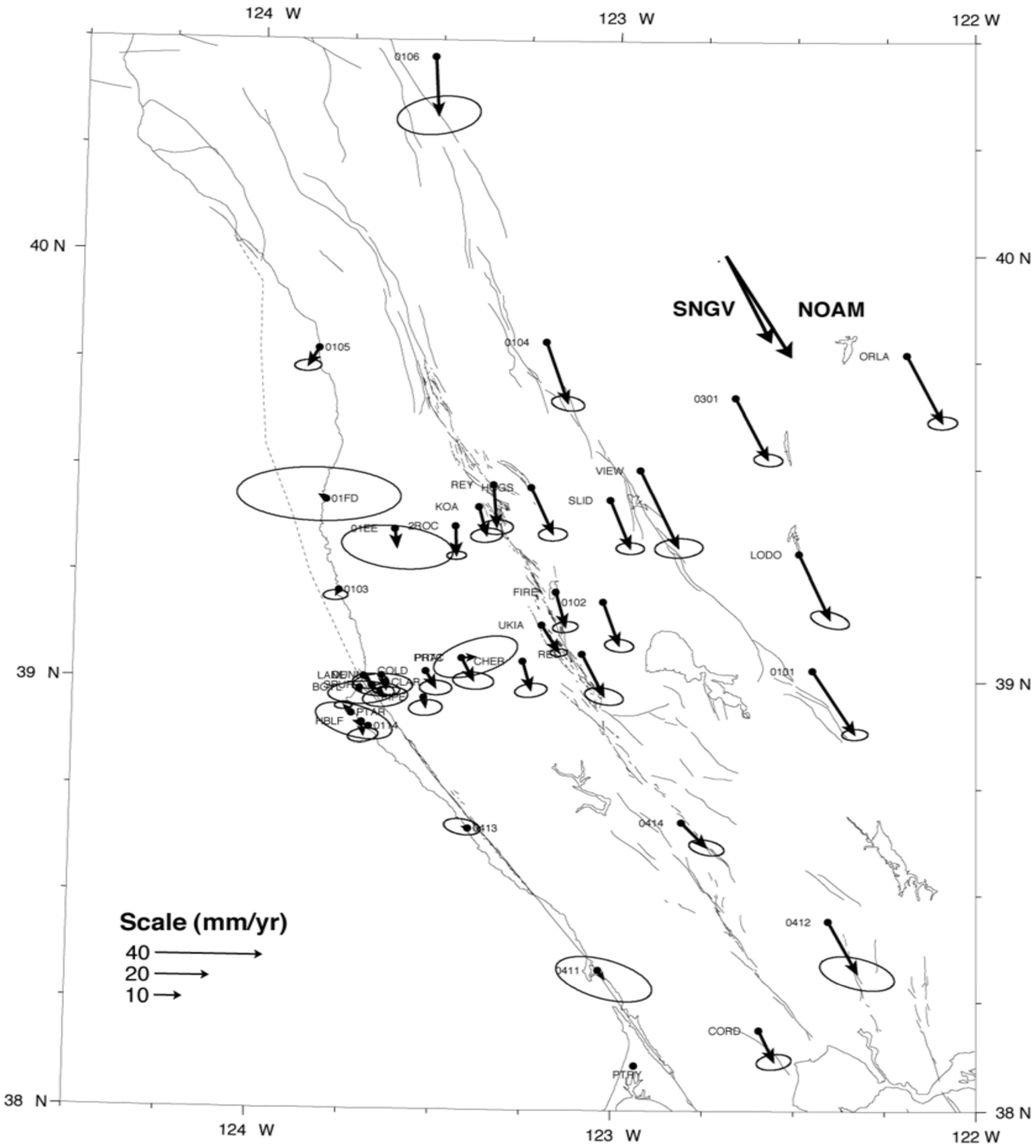
Northern California



Major Faults



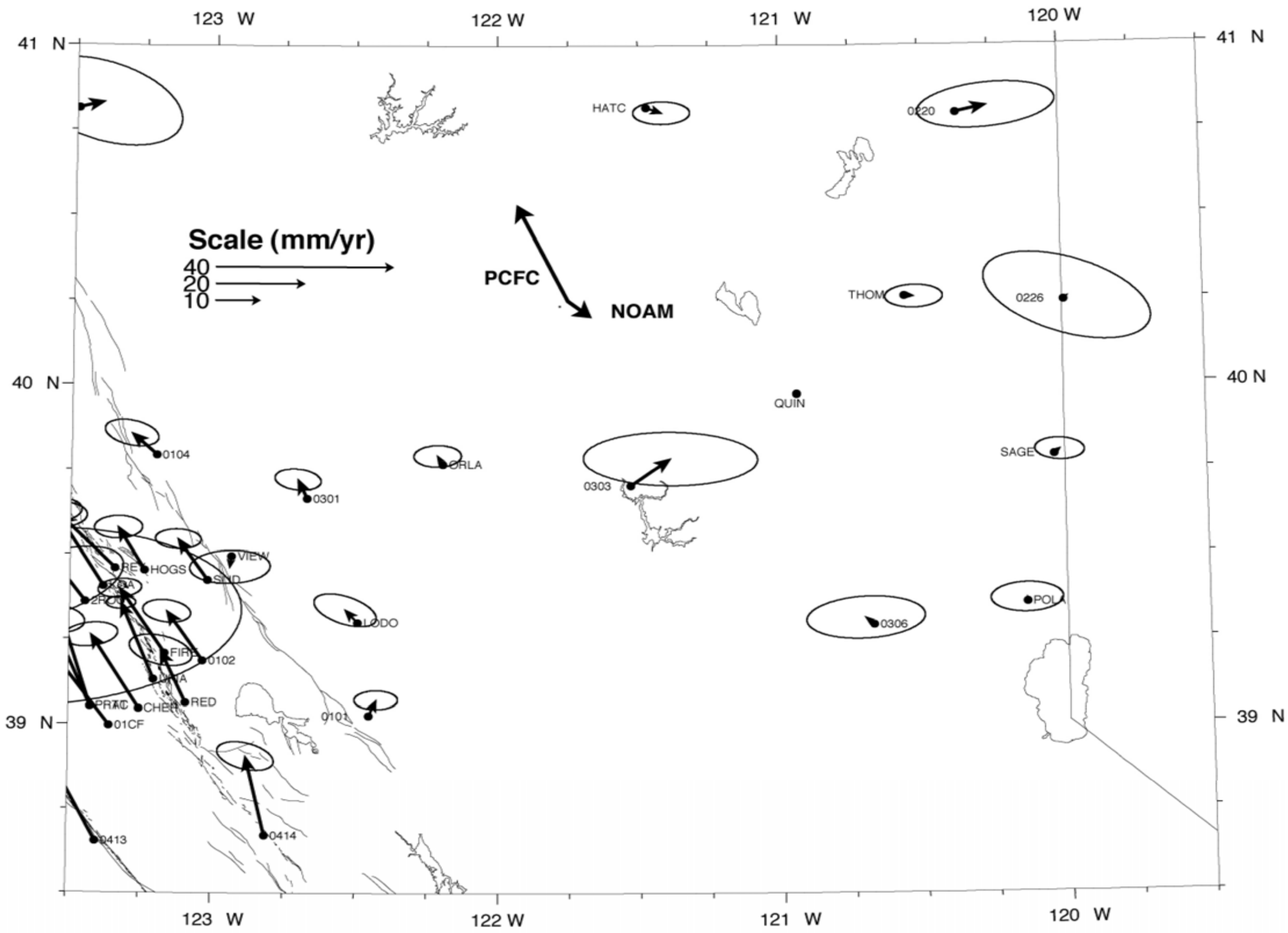
Freymueller et al., 1999

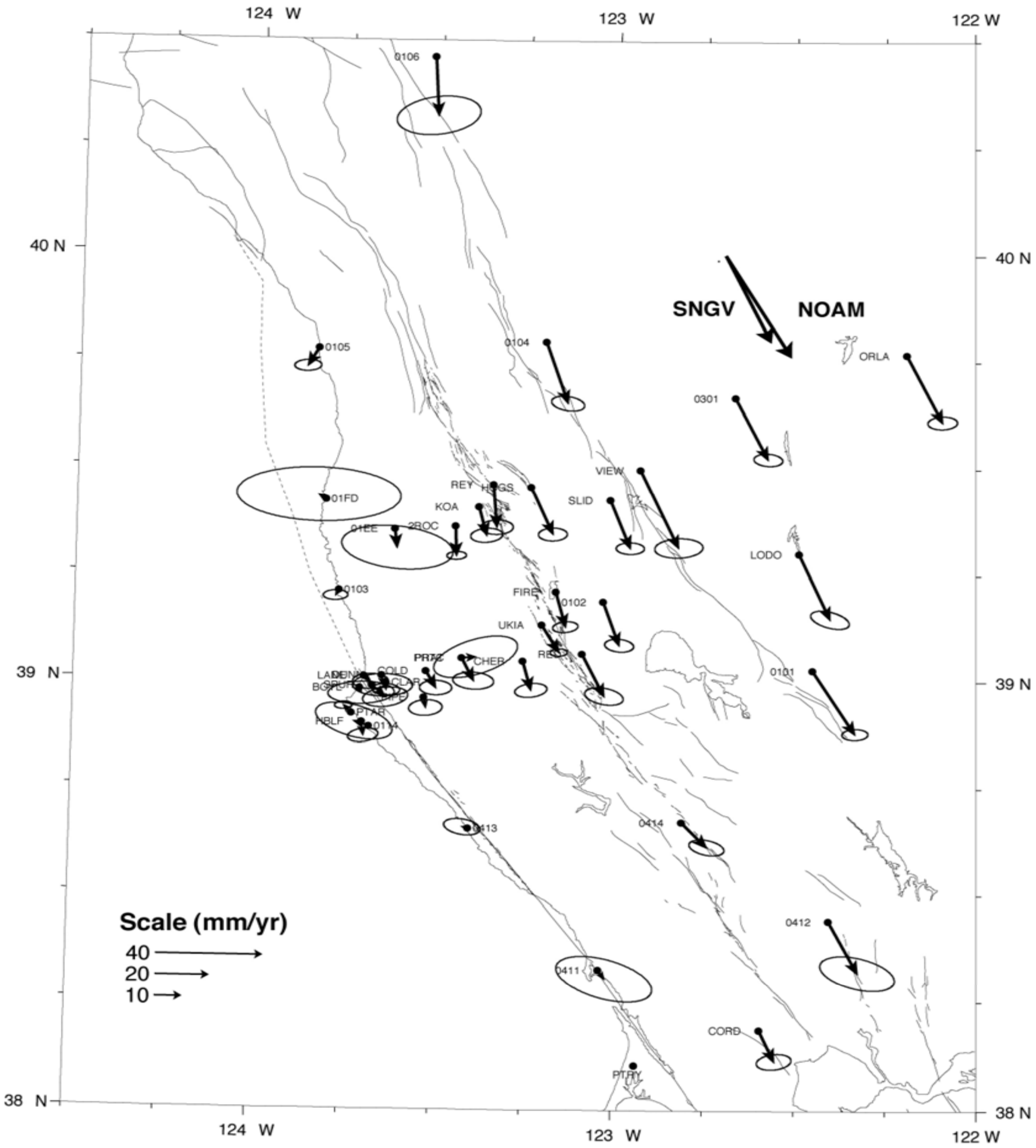


Velocities

- Relative to PCFC
  - Defined by VLBI and PTRY site
- Motions are parallel to SNGV-PCFC relative motion
- 40 mm/yr total across Coast Ranges

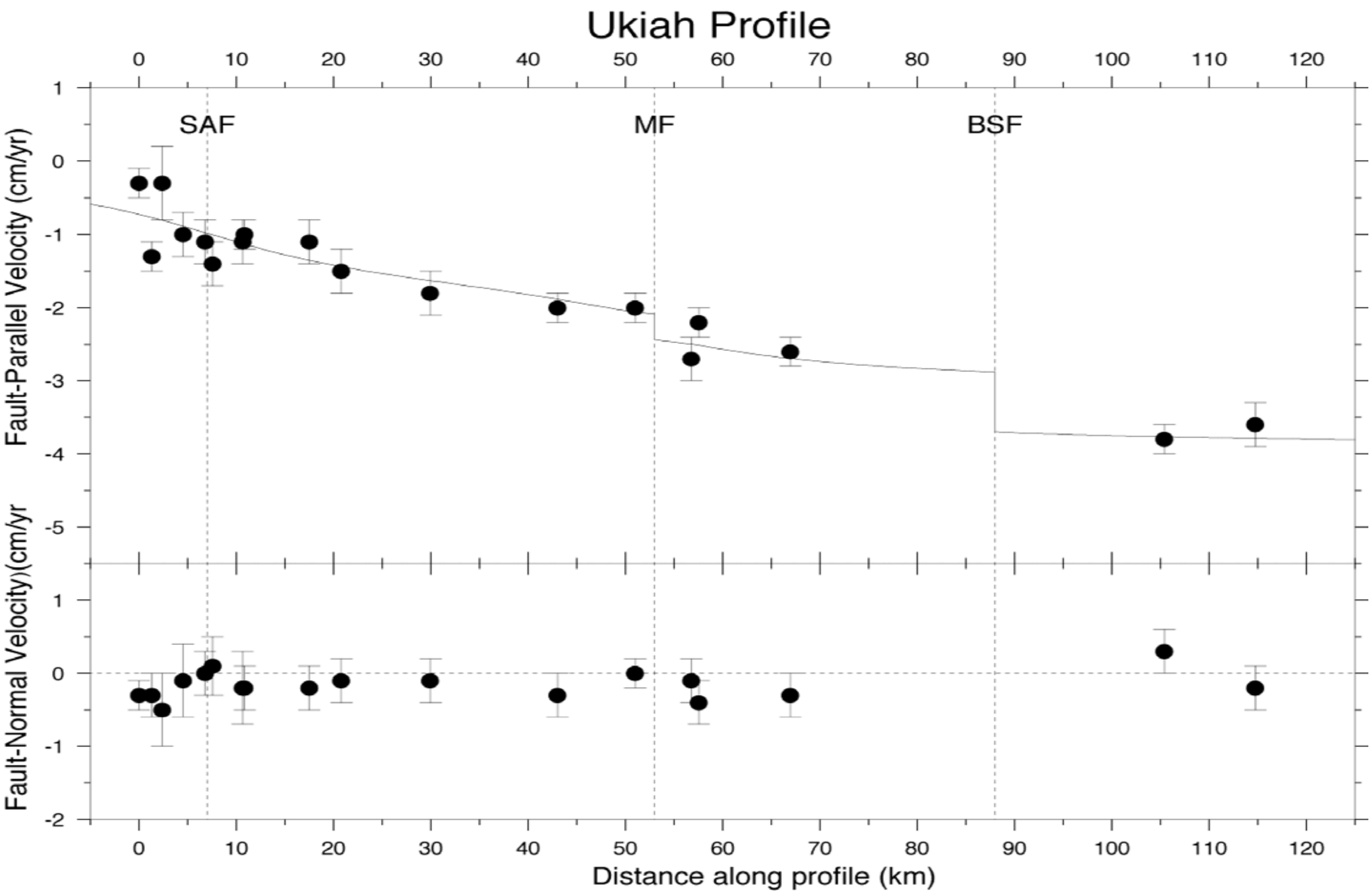
Relative to QUIN on SNGV



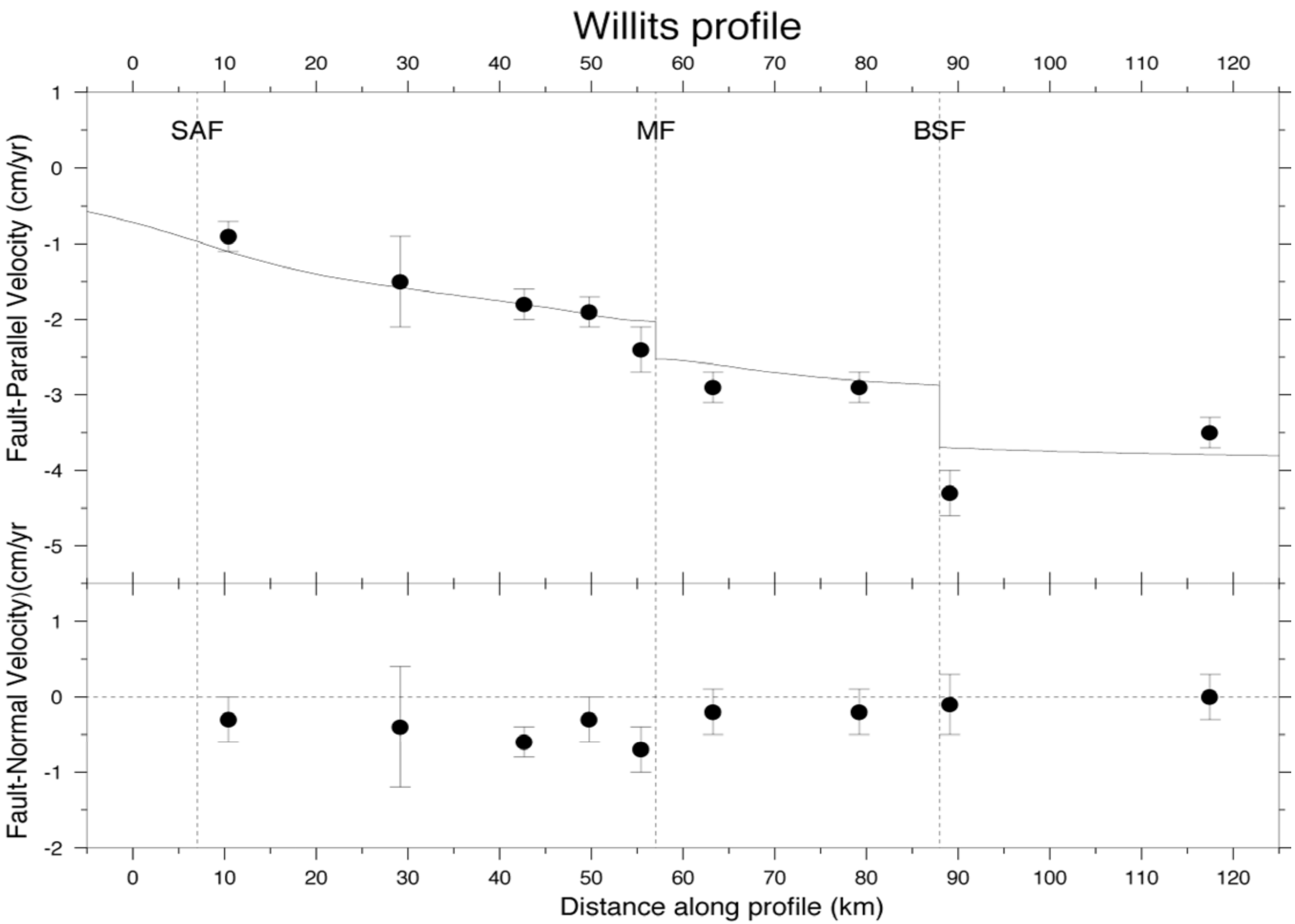


Models

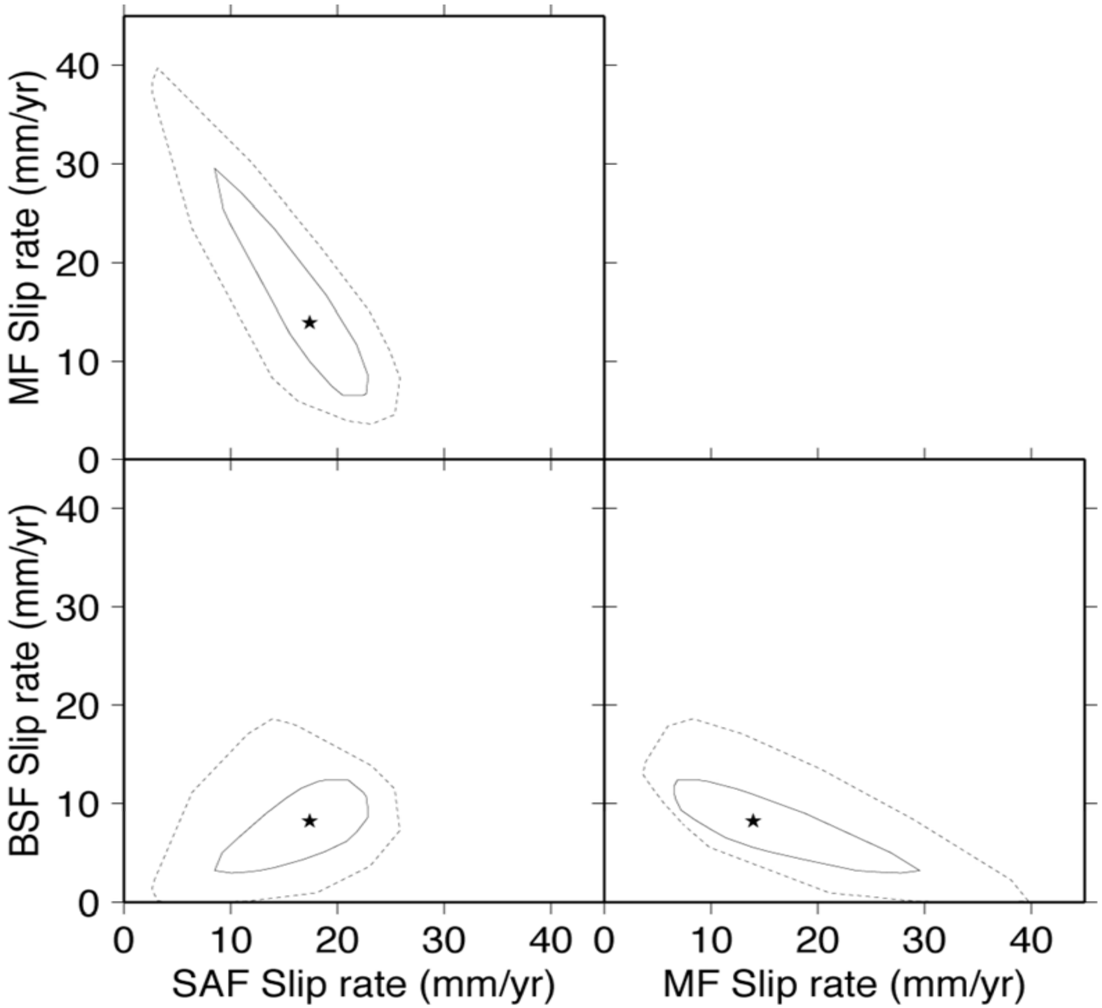
- 3 parallel strike-slip faults 30-40 km apart
- Have some constraints on slip rate from geology
- Locking depth not well known
- Some shallow creep documented



Ukiah Profile
SAF
MF
BSF
Fault-Parallel Velocity (cm/yr)
Fault-Normal Velocity)(cm/yr
Distance along profile (km)
0
10
20
30
40
50
60
70
80
90
100
110
120
1
0
-1
-2
-3
-4
-5
1
0
-1
-2

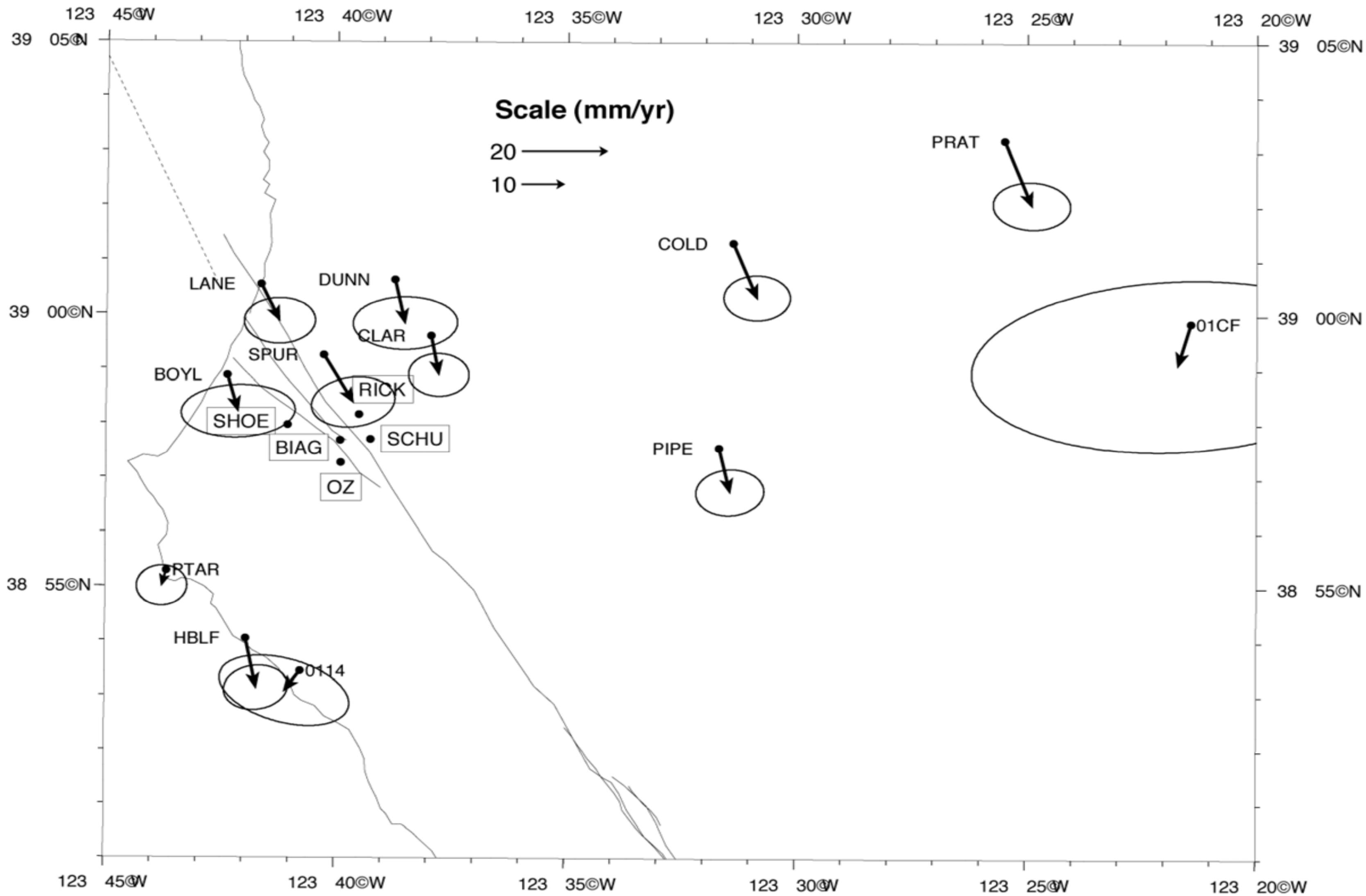

Willits profile
SAF
MF
BSF
Fault-Parallel Velocity (cm/yr)
Fault-Normal Velocity)(cm/yr
Distance along profile (km)

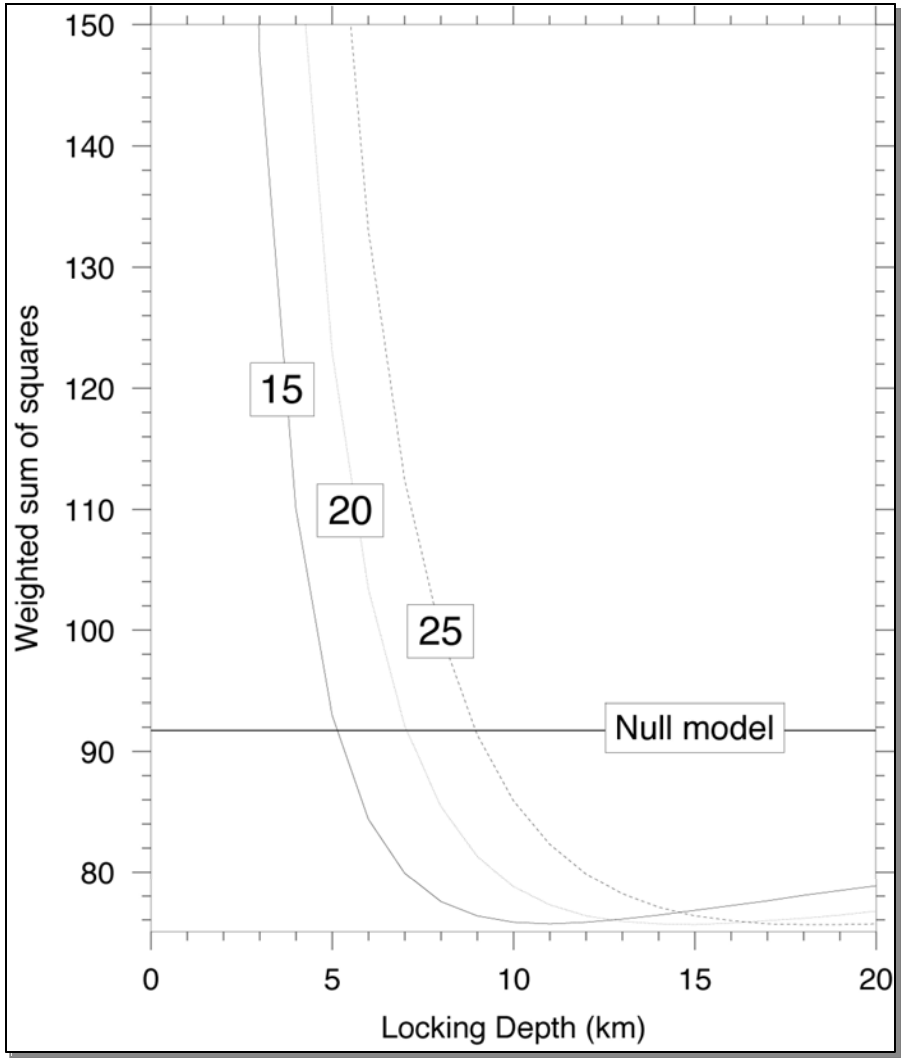
Slip Rate Tradeoffs



- Total slip rate 40 mm/yr
  - SAF 17.4 (+2.5,-3.1)
  - MF 13.9 (+4.1,-2.8)
  - BSF 8.2 (+2.1,-1.9)
  - BSF creeping
- Significant tradeoffs between individual fault slip rates

SAF Locking Depth at Pt. Arena

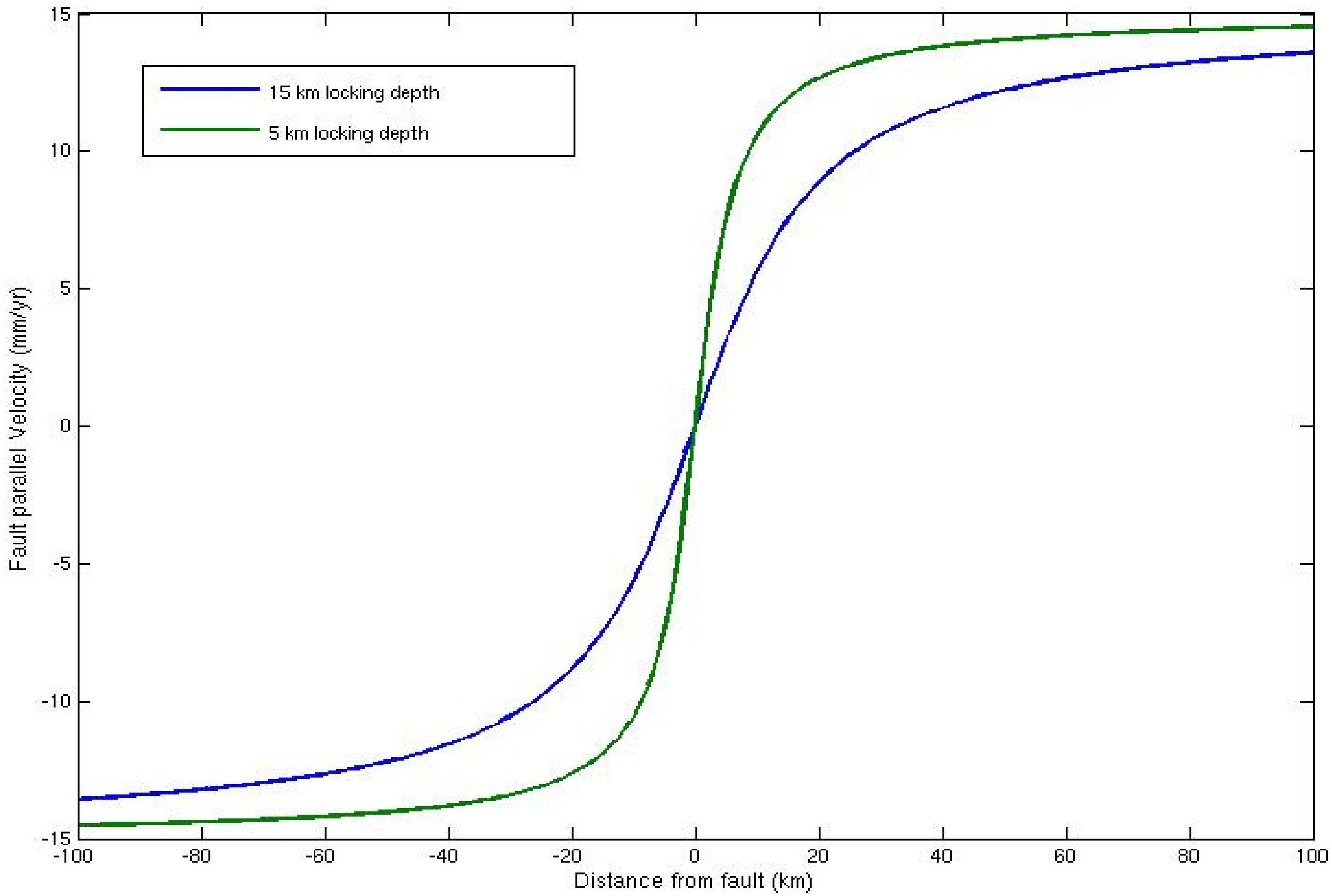



150
140
130
120
110
100
90
80
Weighted sum of squares
15
20
25
Null model
0
5
10
15
20
Locking Depth (km)

Comments on Models

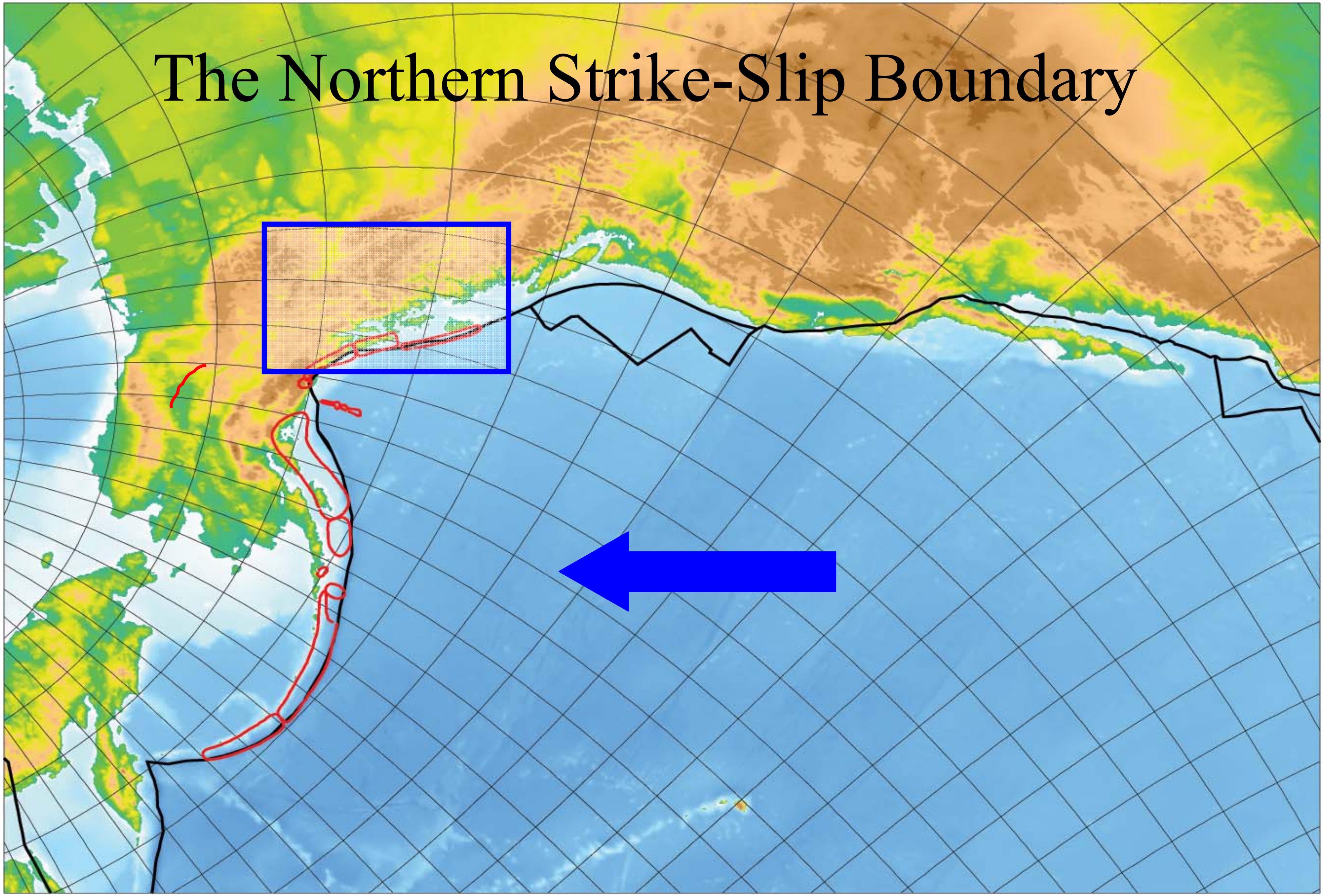
- For multiple parallel faults, the total slip rate of all faults is well determined, but the individual slip rates are not.
- If locking depths are well known, this resolution problem is eased.
- Data can be explained reasonably well by putting more slip on central fault with very deep locking depth

Slip Rate/Locking Depth Tradeoff

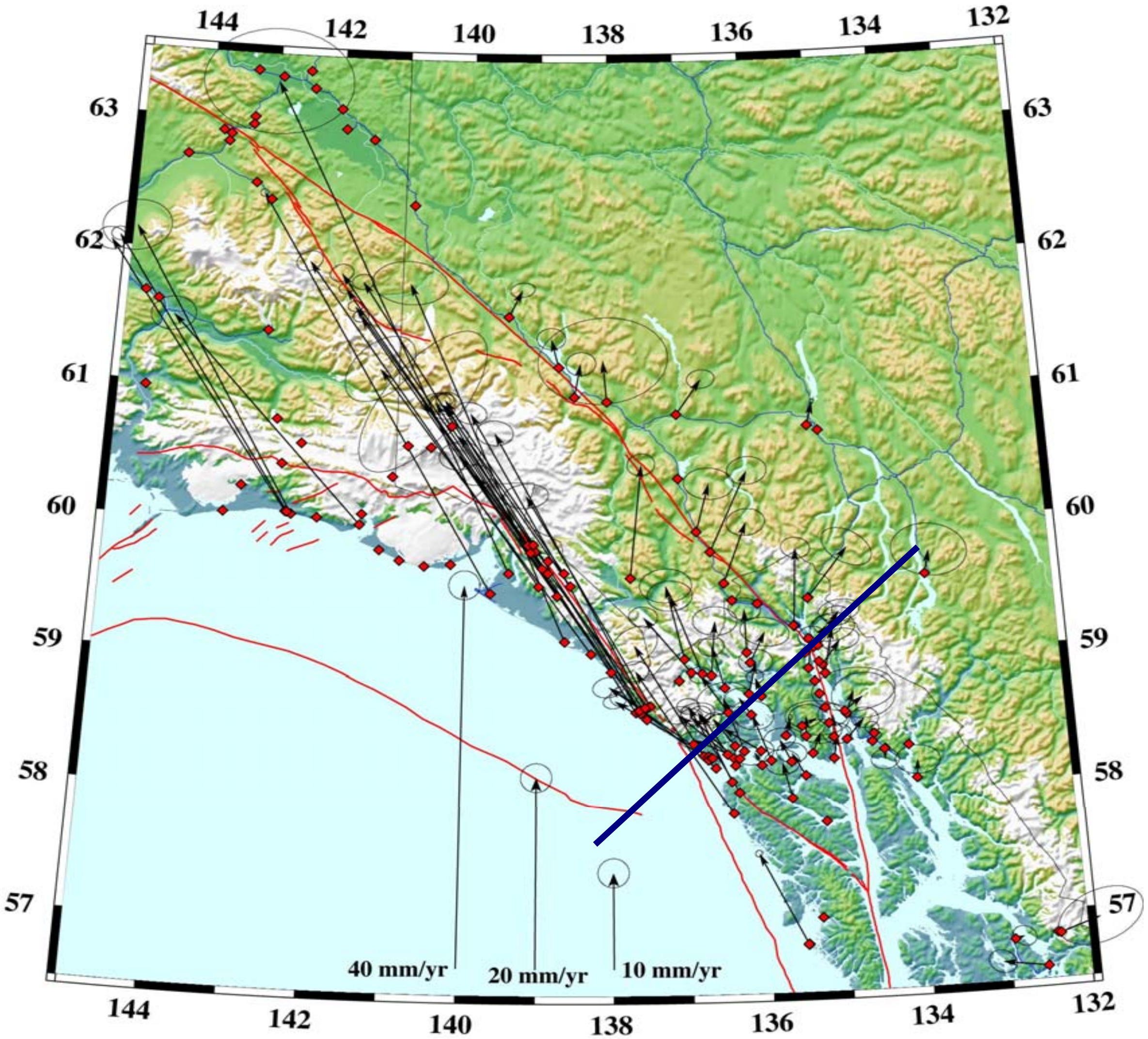



Southeast Alaska

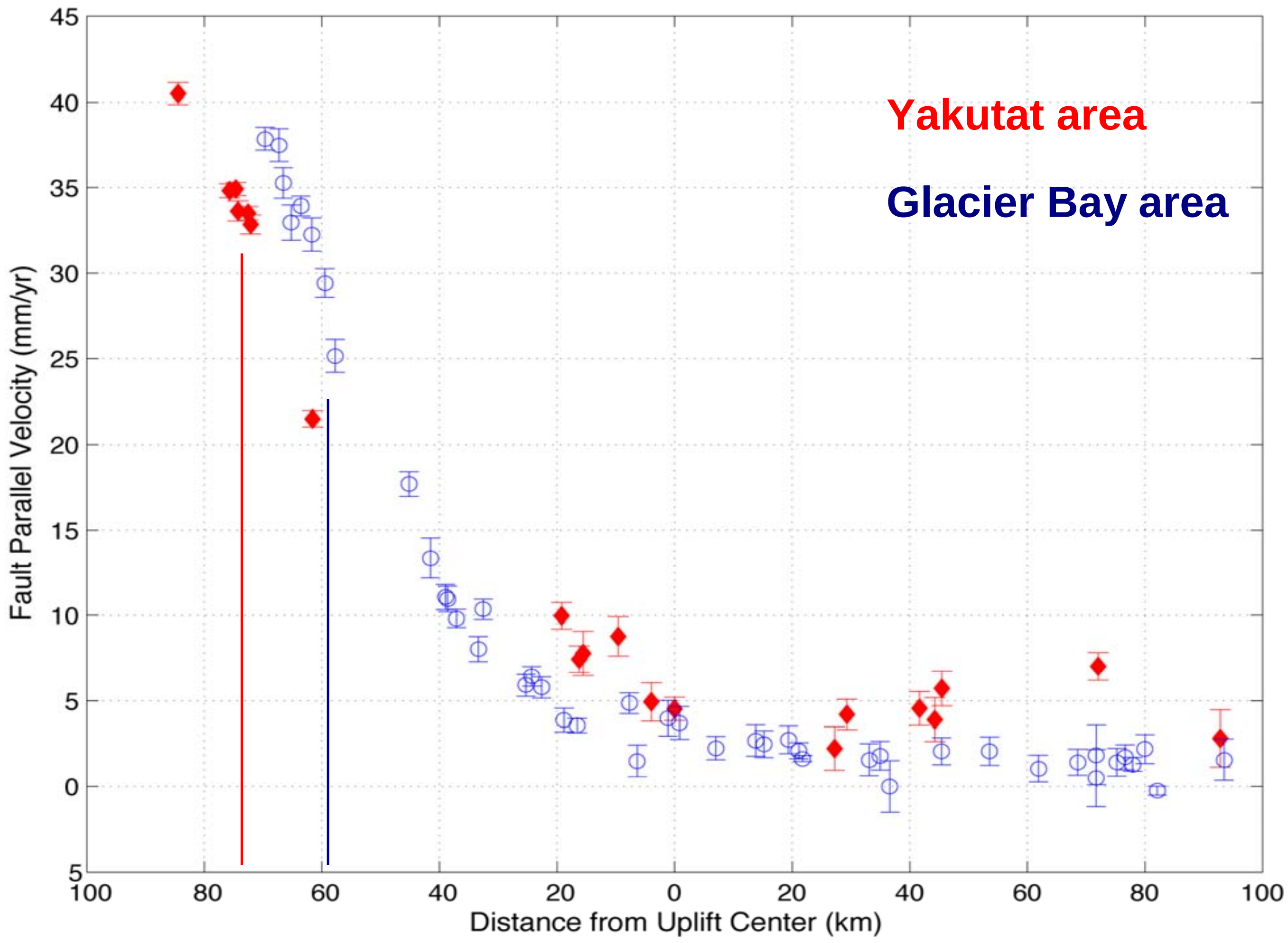
The Northern Strike-Slip Boundary



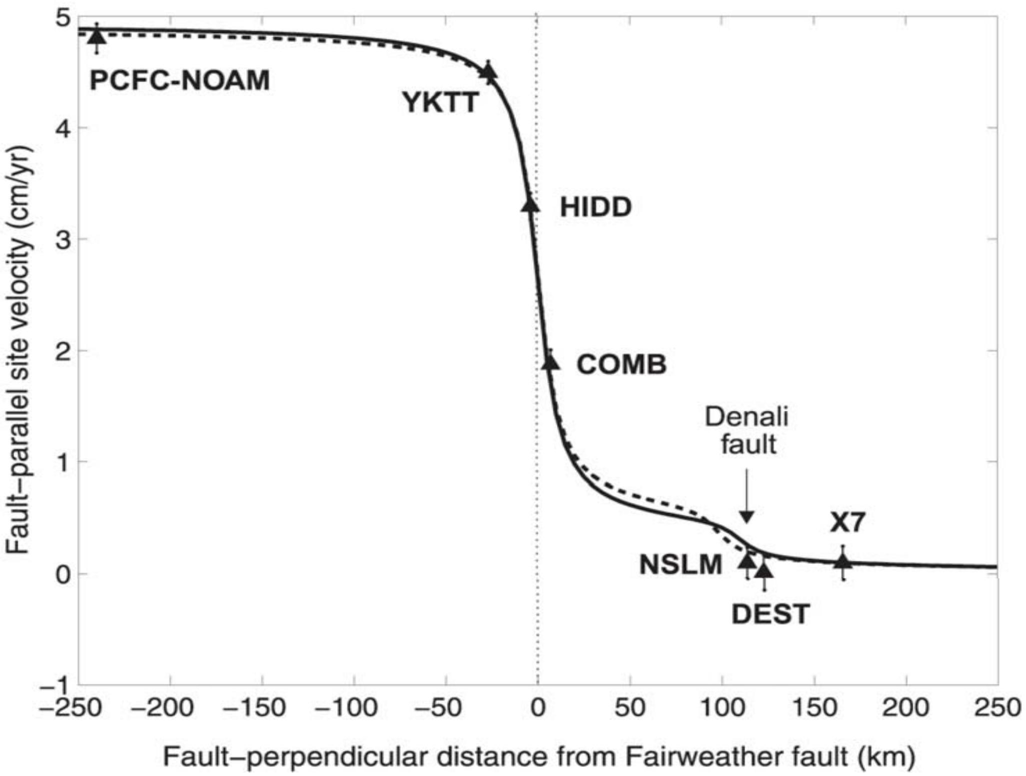
GPS Velocity Field



Fault-Parallel Velocities

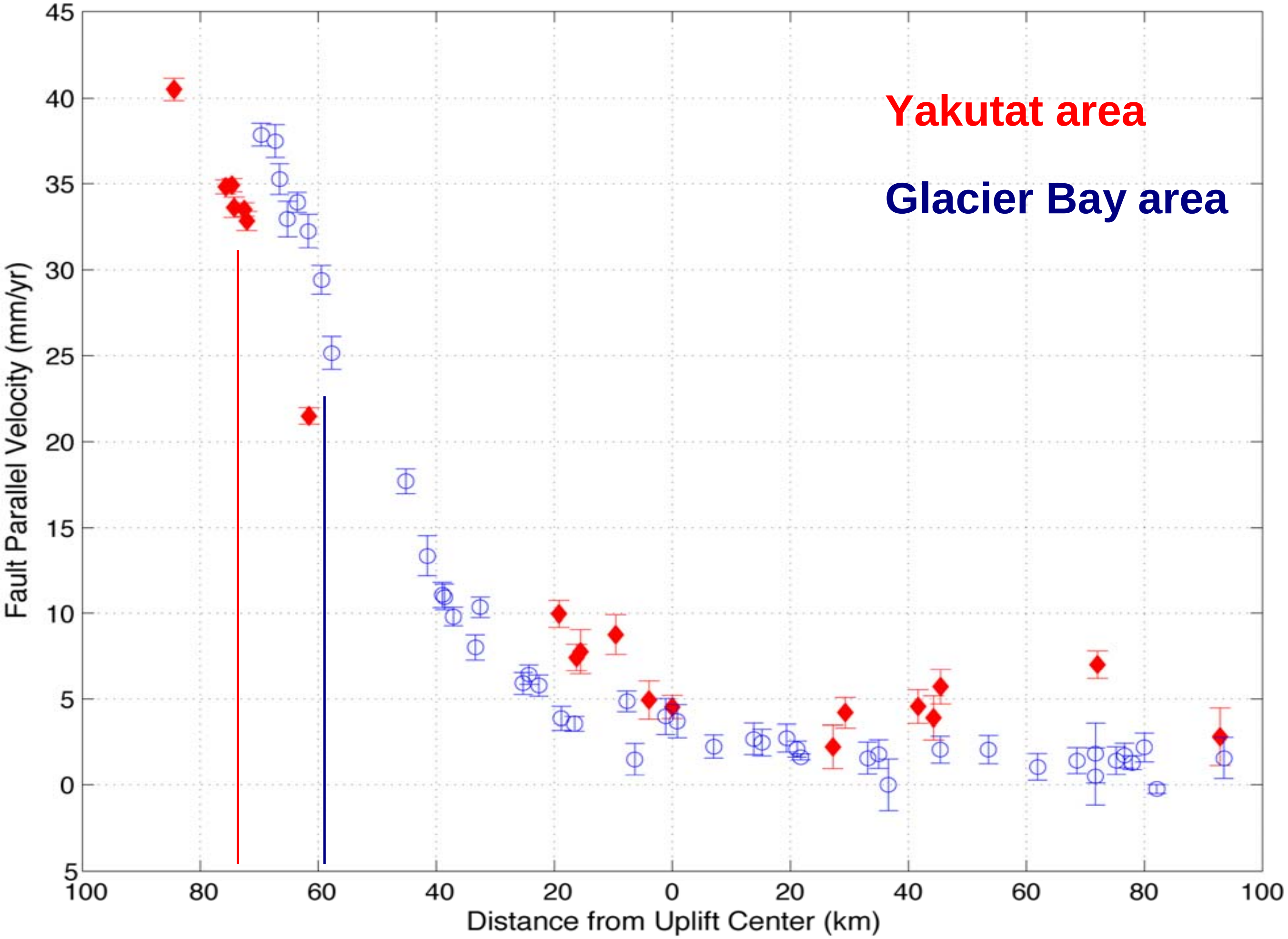


(Earlier) Model For Yakutat Region



- Fletcher and Freymueller (2003)
- Fairweather Fault
  - 46±2 mm/yr
  - 9.0 ± 0.8 km locking
- Denali fault
  - 3.7 ± 1.4 mm/yr
  - Dashed line is for fault location displaced 5 km west

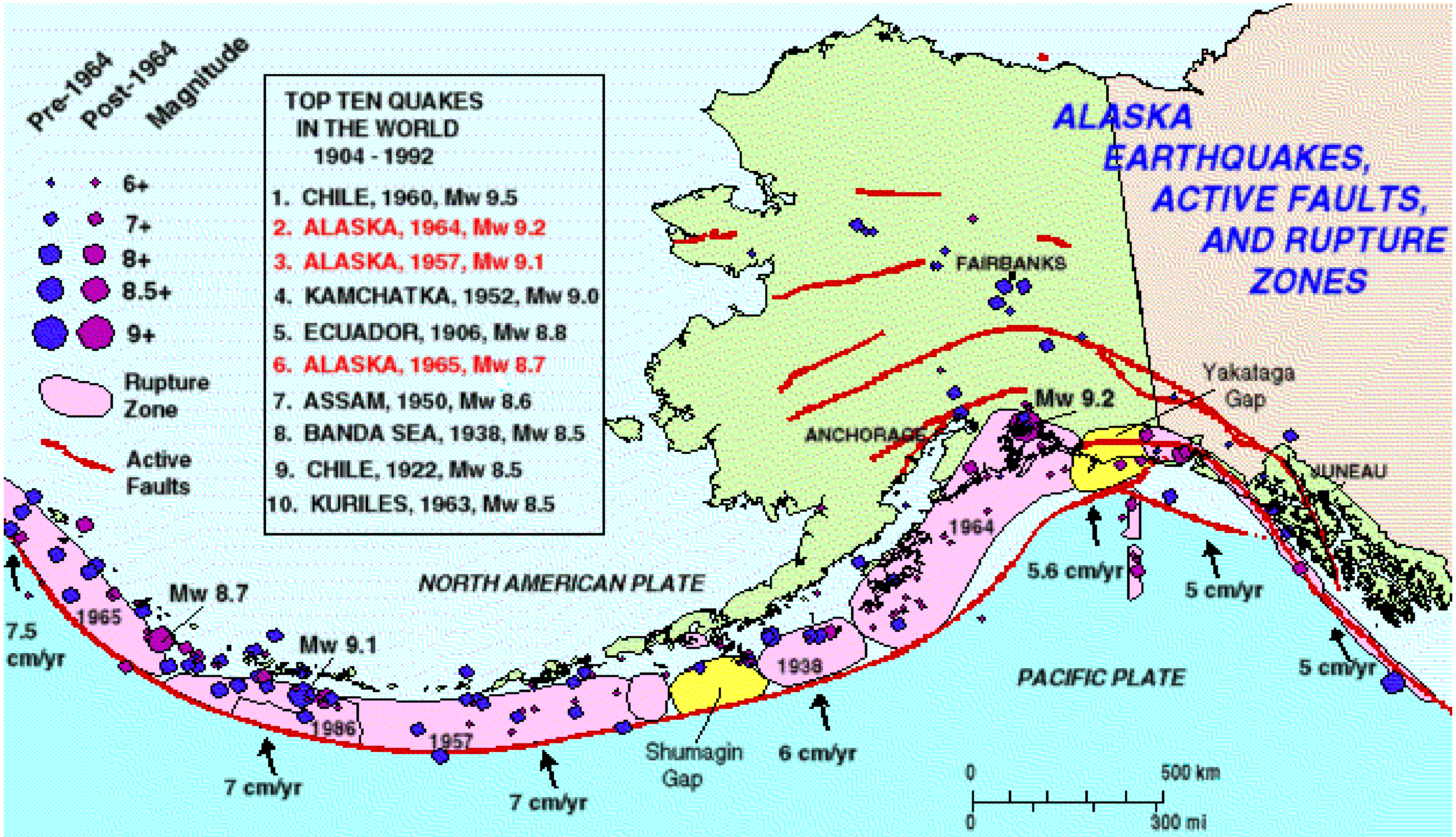
Same Model Fits New Data



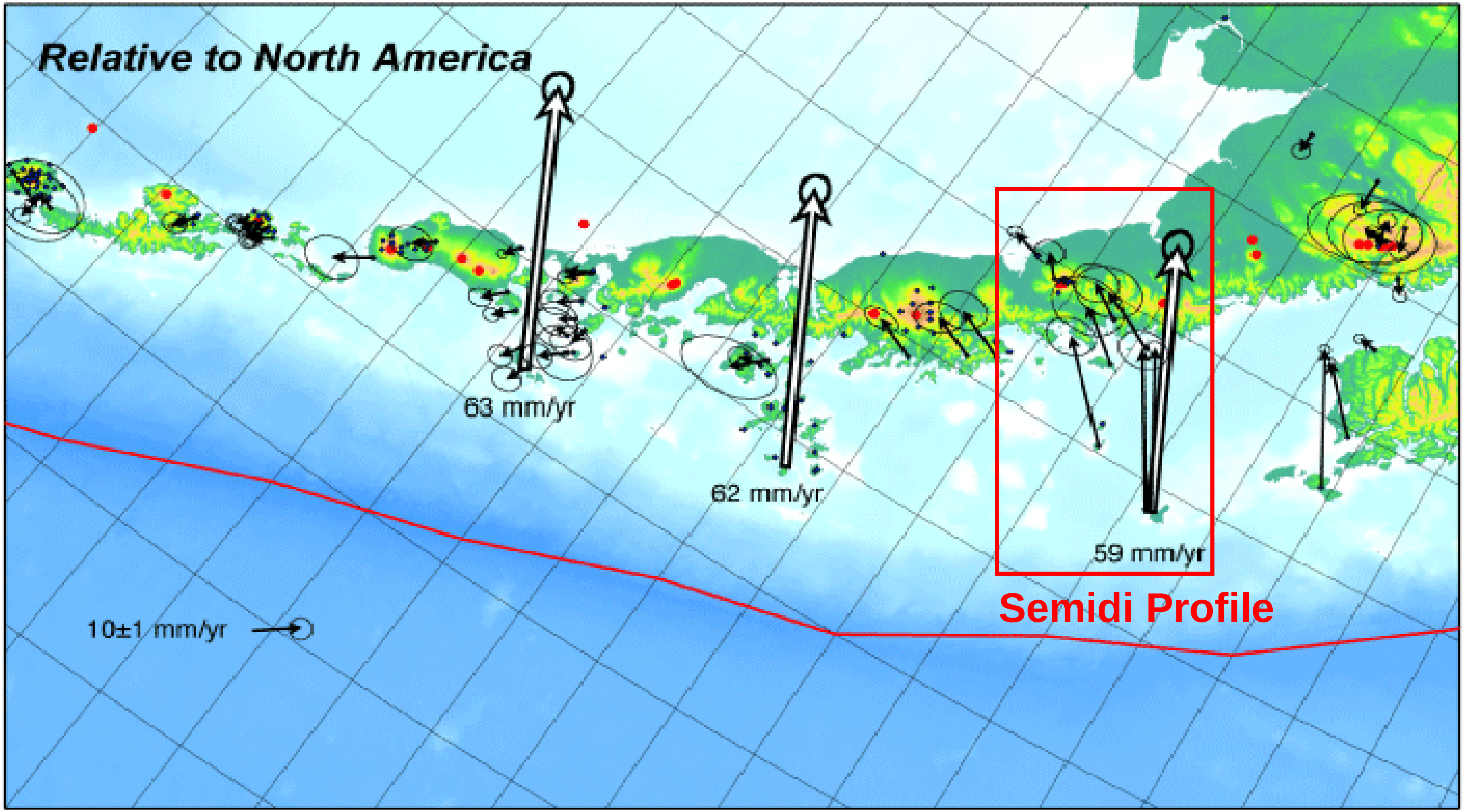
Comments on Simple Model

- Simple elastic model works well in many cases
- To estimate both slip rate and locking depth, you need an isolated fault and a good distribution of sites within 10-20 km of fault
- Additional information from geology/paleoseismology (slip rate) and seismicity (locking depth) are usually needed to supplement geodetic data

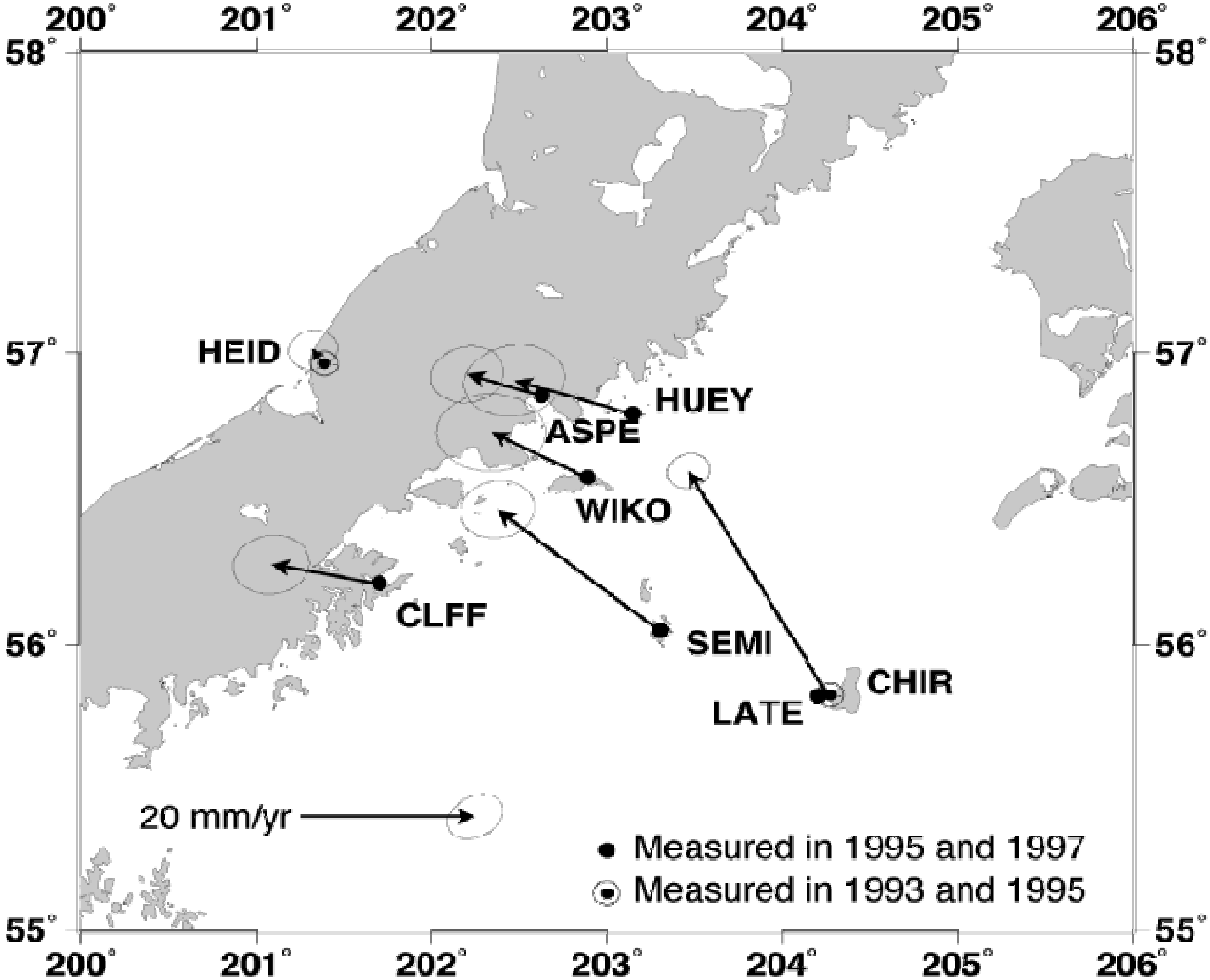
Major Faults and Earthquakes



Alaska Peninsula Velocities

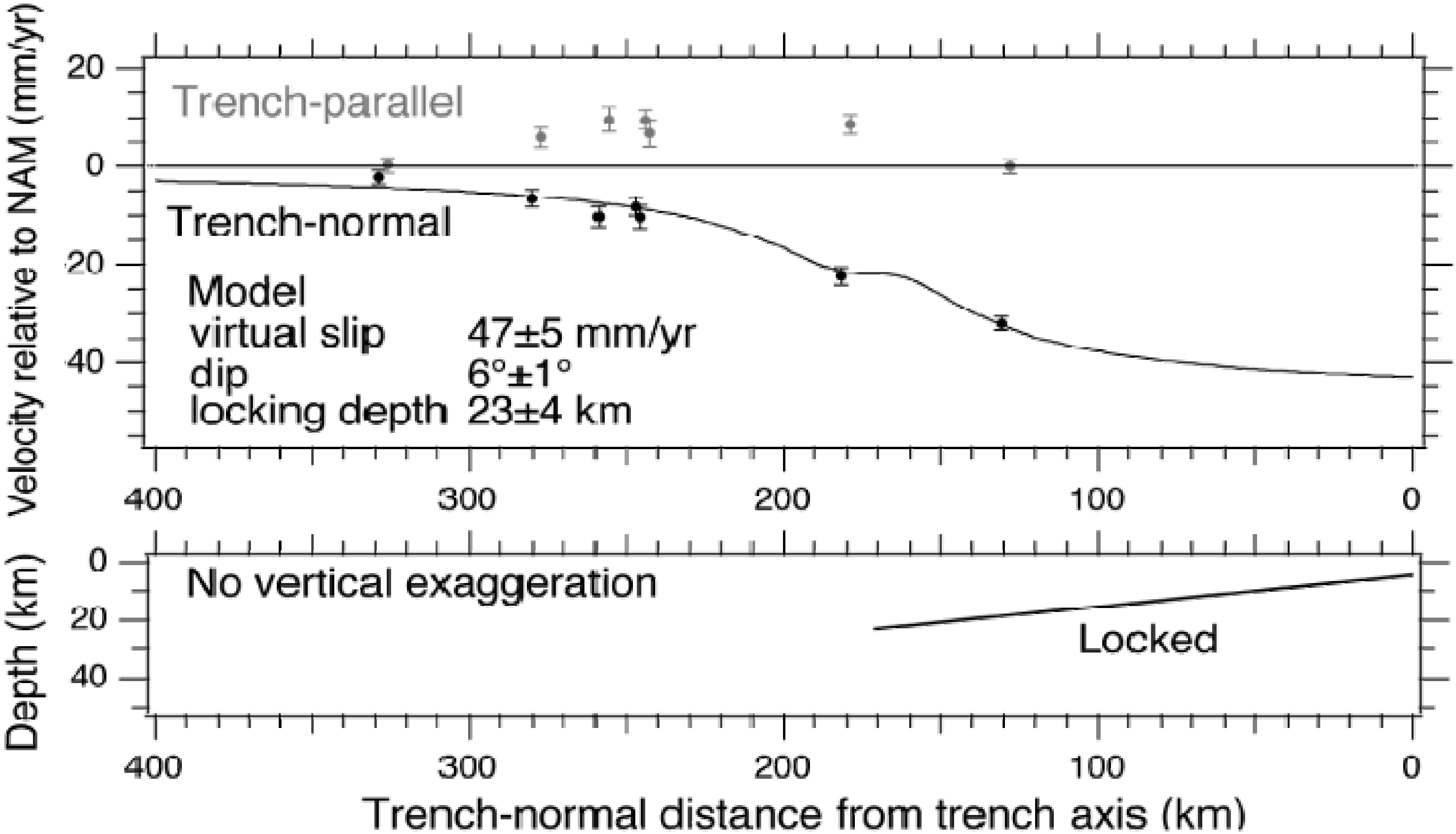


Semidi Profile



Fletcher et al., 2001

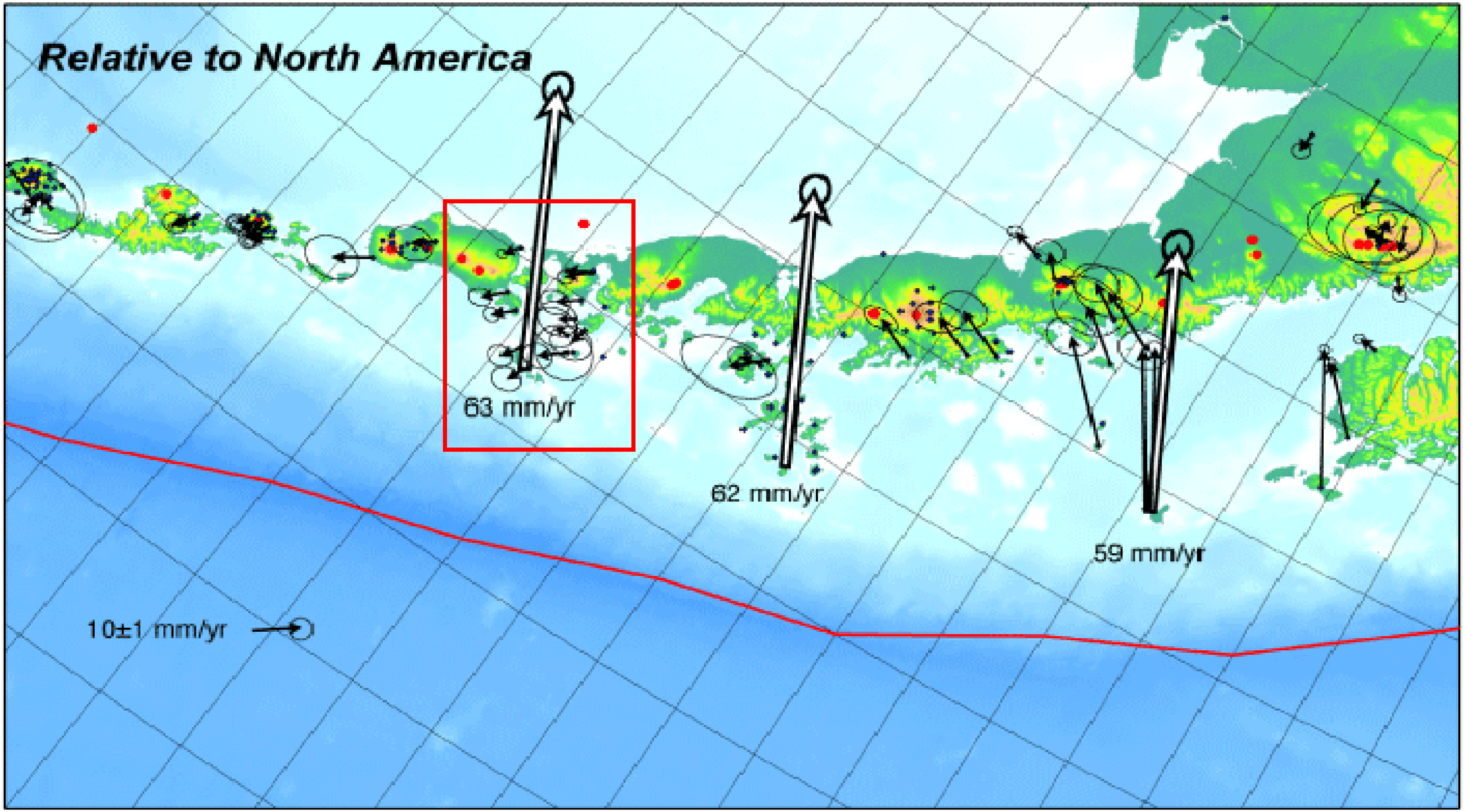
Semidi Profile Model



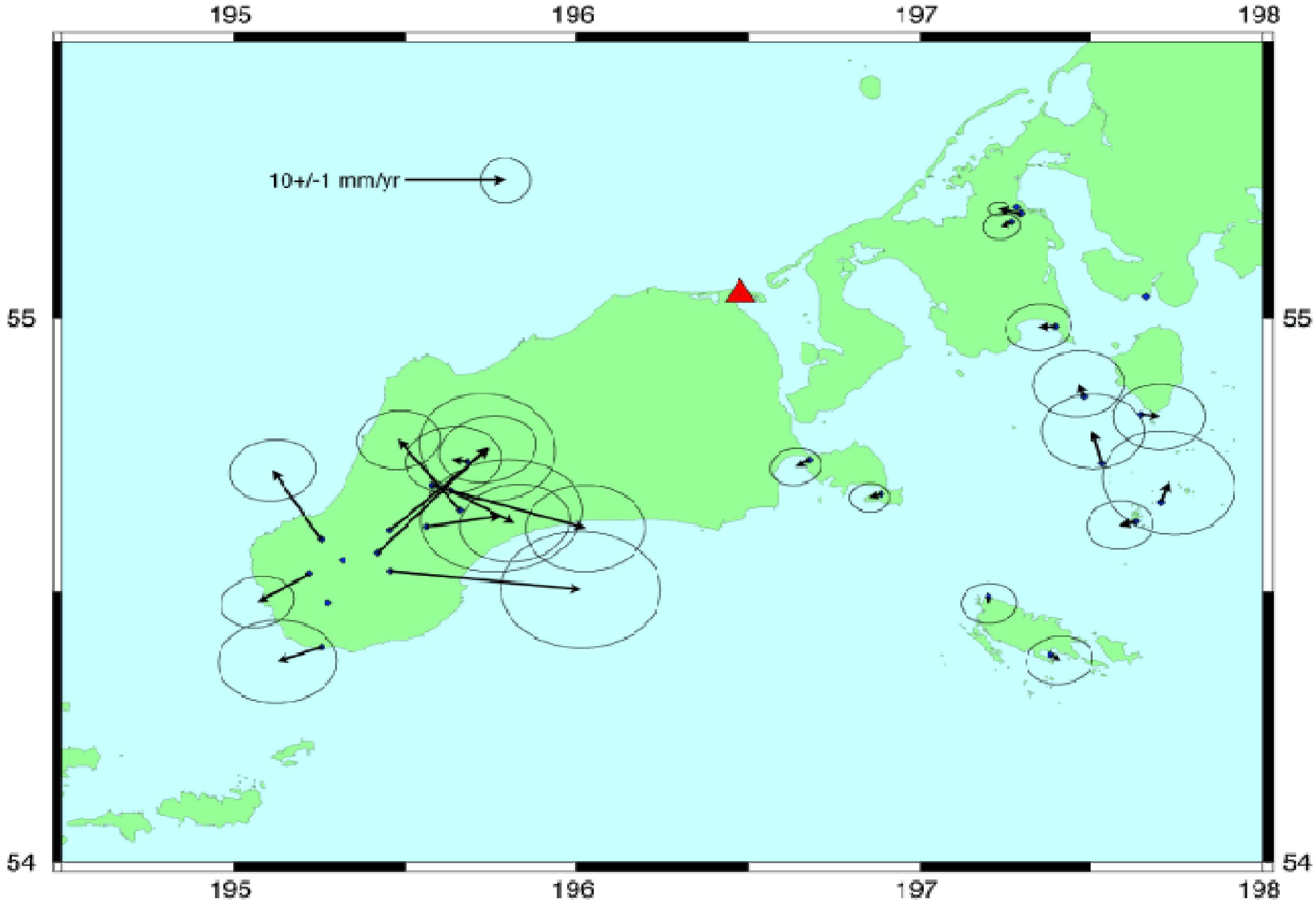
Semidi Profile Results

- Locked zone is ~180 km wide
- Estimated slip deficit is ~80% of plate motion rate
- **–> Wide, strongly-coupled seismogenic zone**
- Residual trench-parallel component of several mm/yr

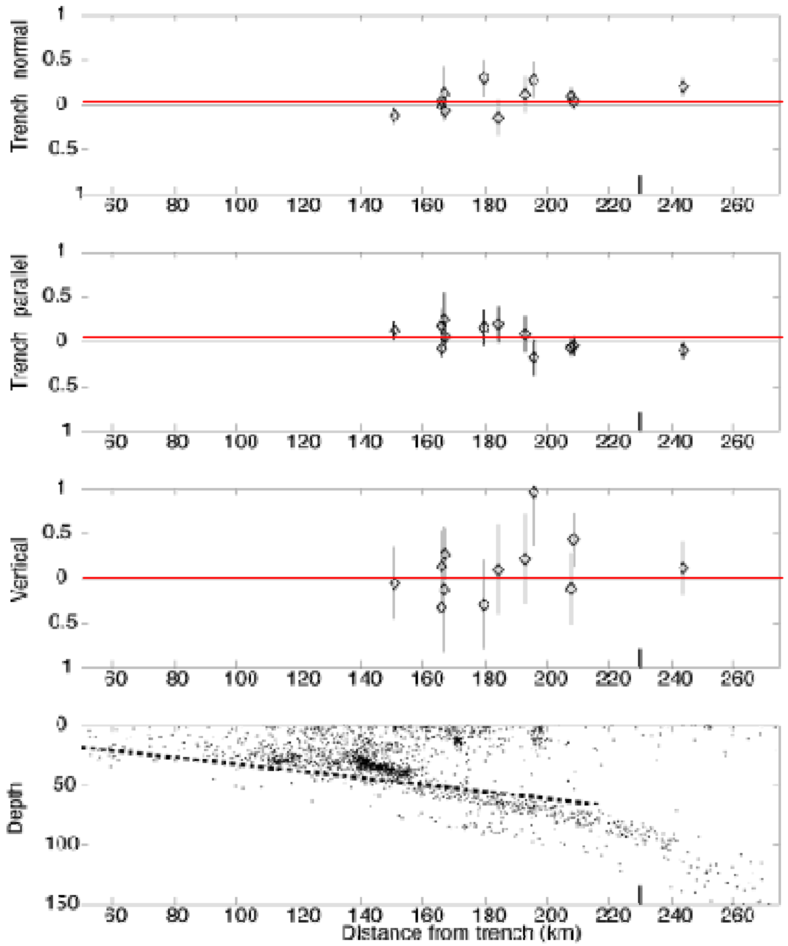
Sanak Profile



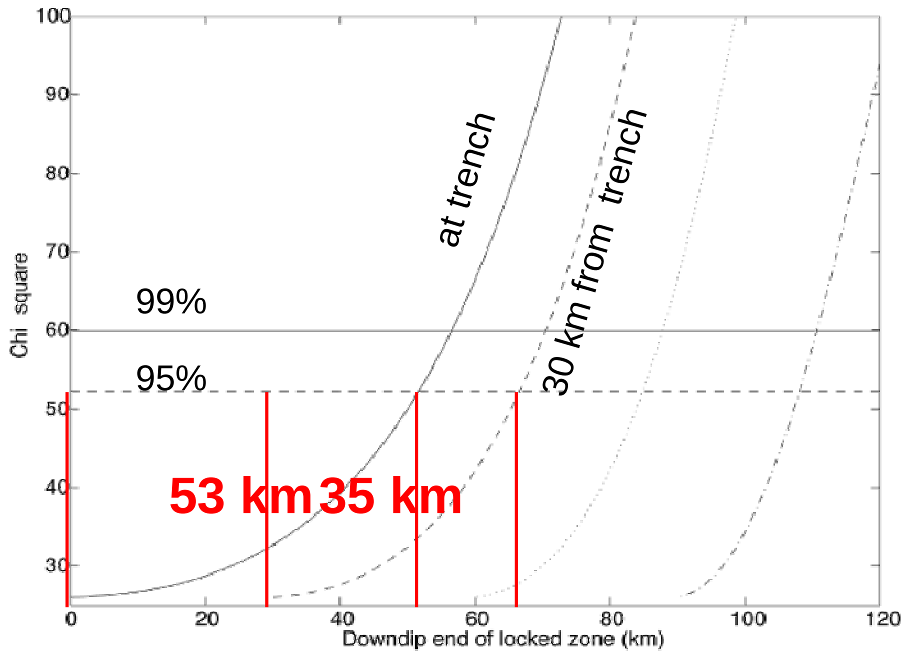
Sanak to Unimak Data



Sanak Profile Model

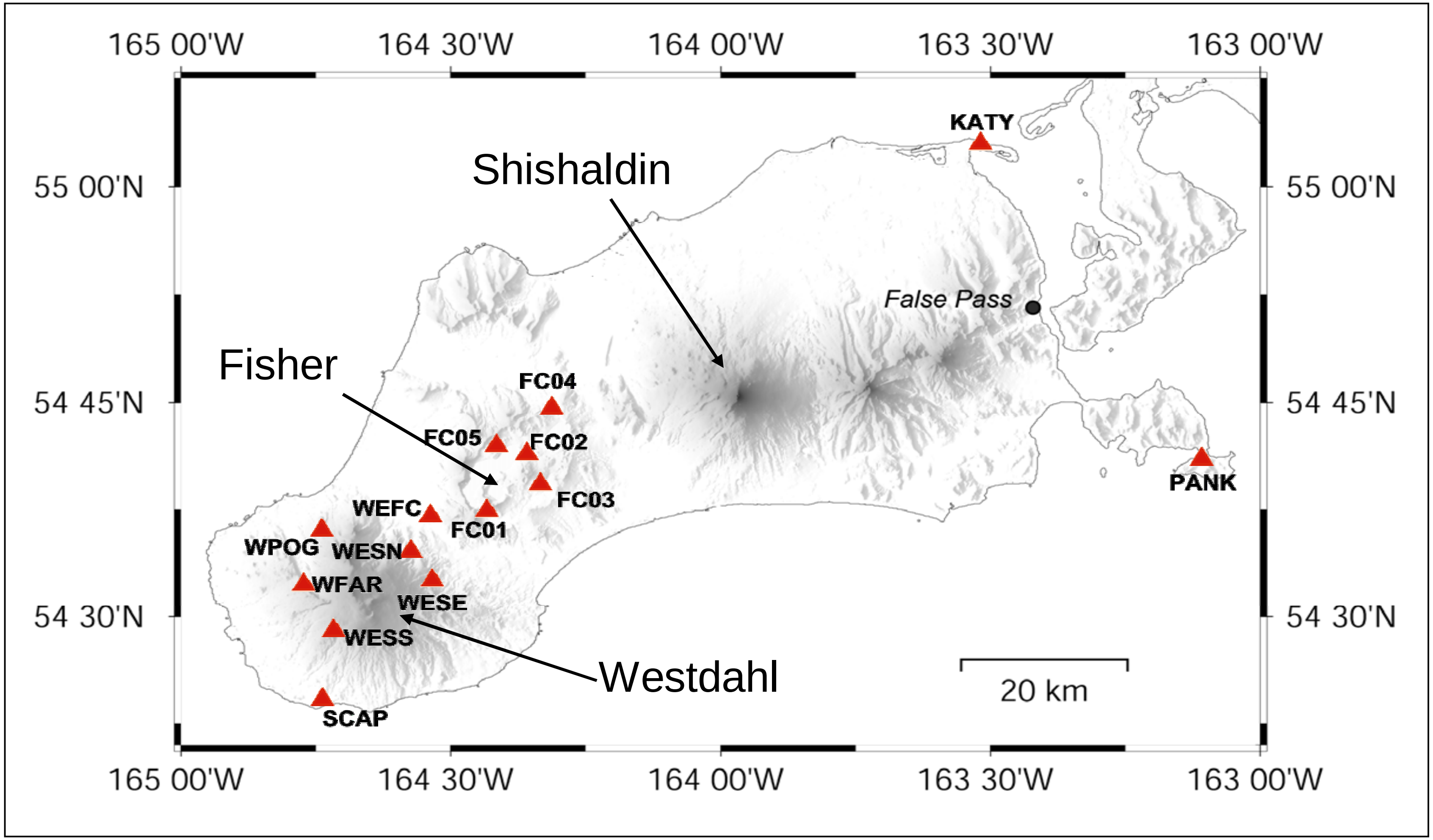


- Best-fit is no locked zone
- How wide can locked zone be without violating data?

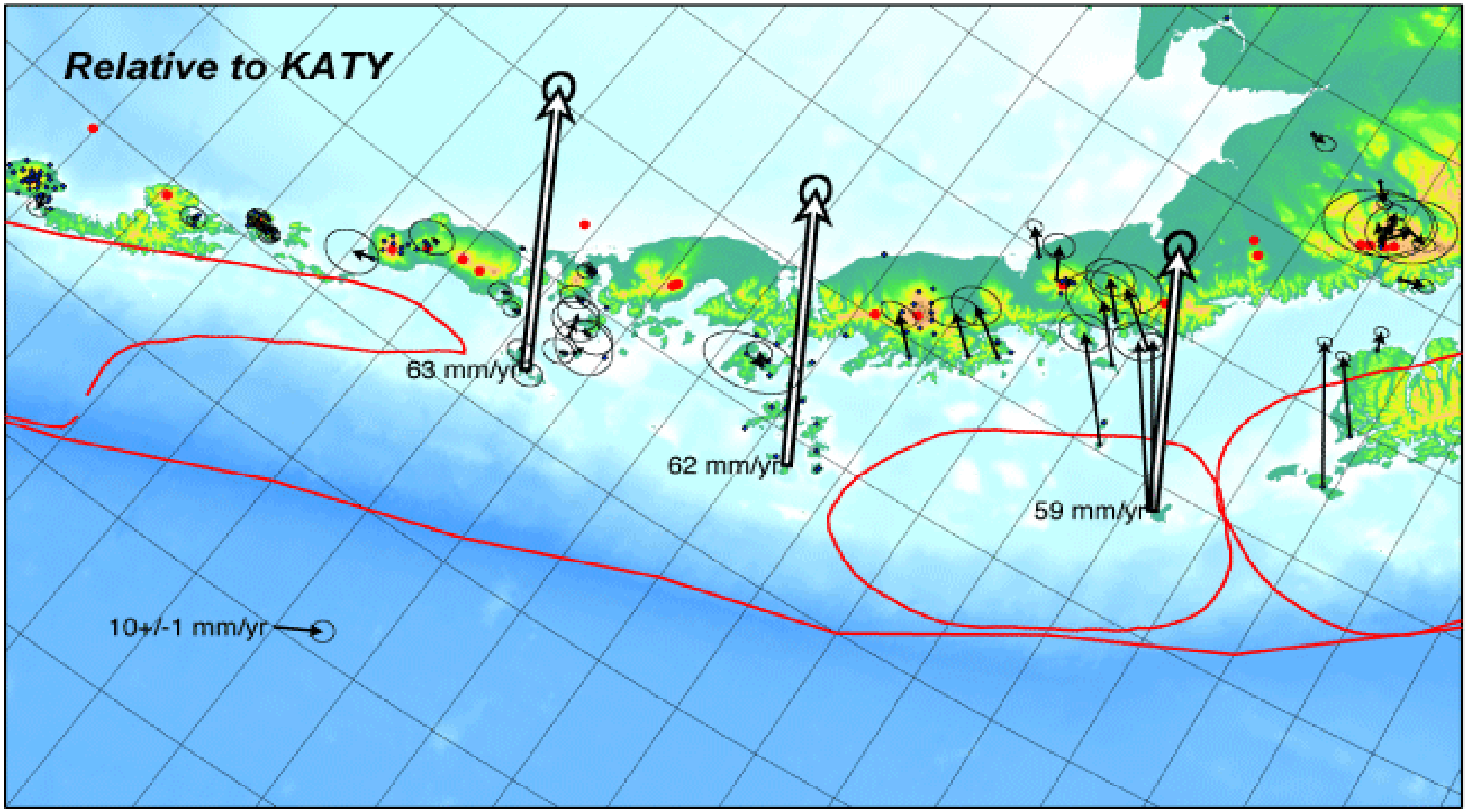


Freymueller and Beavan, 1999

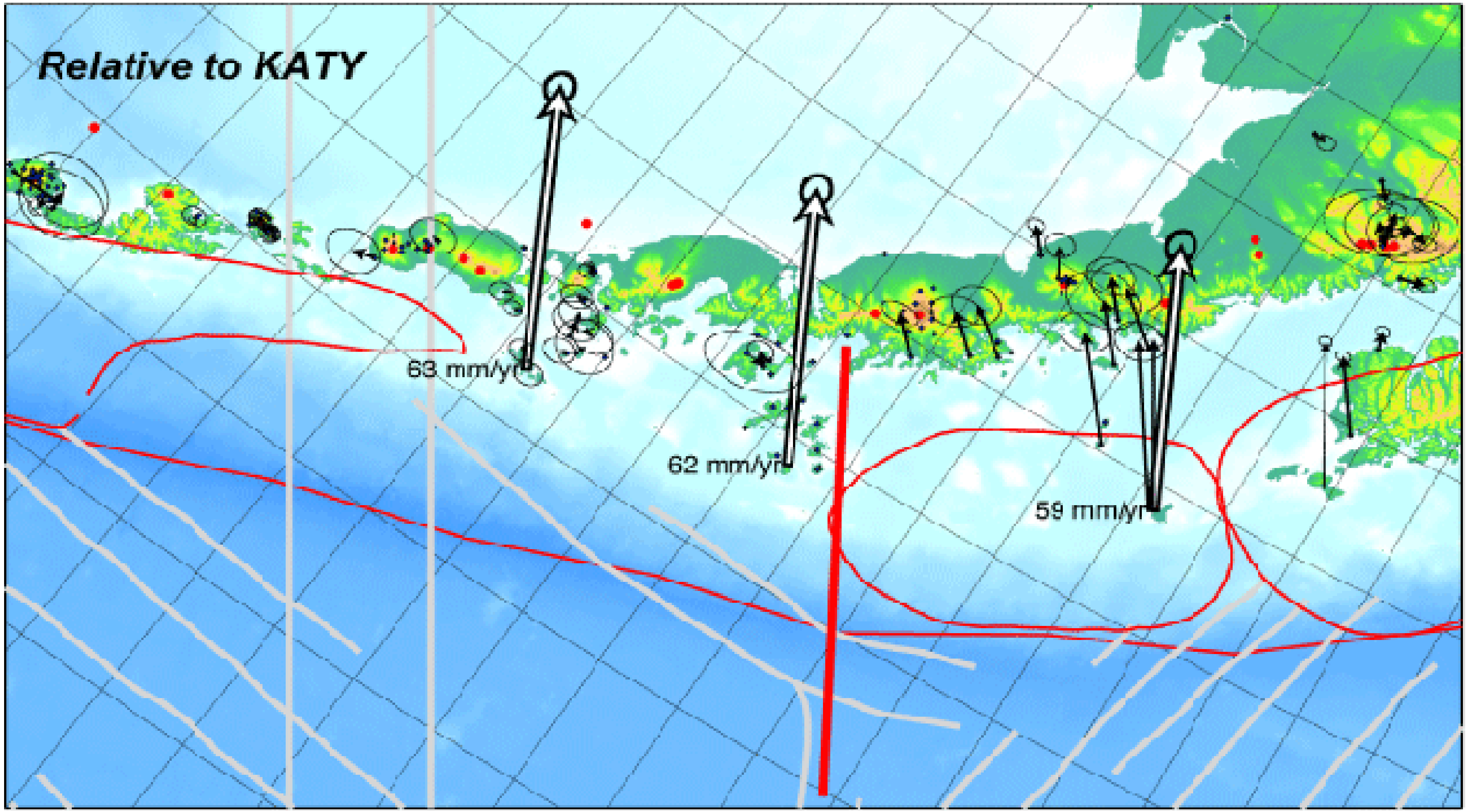
How Far Does Creeping Extend?



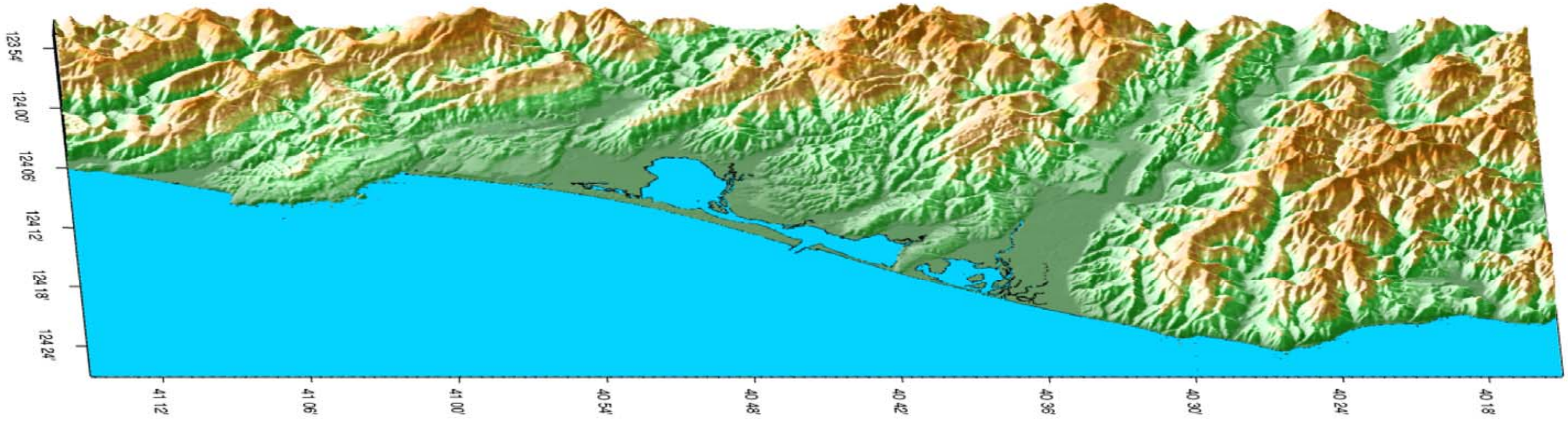
How Sharp is Transition?



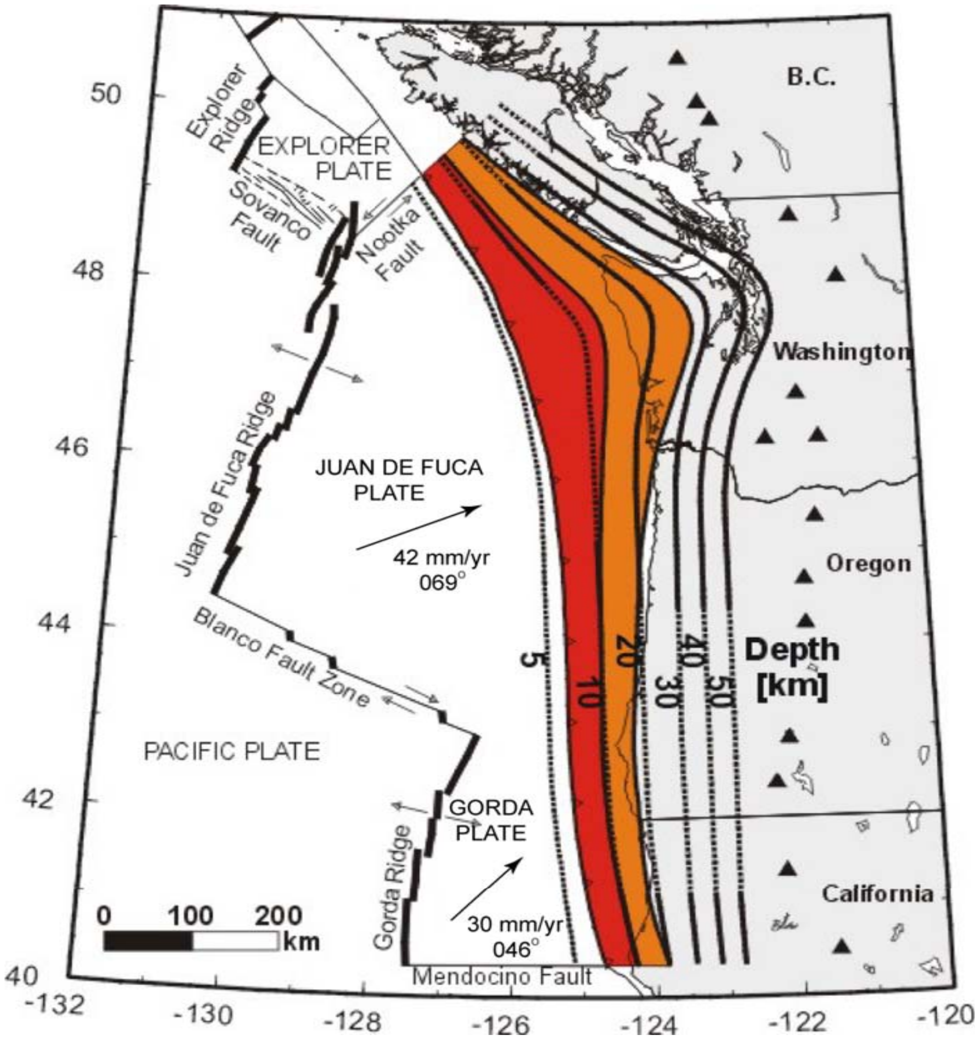
Correlated Features?



Mendocino Triple Junction

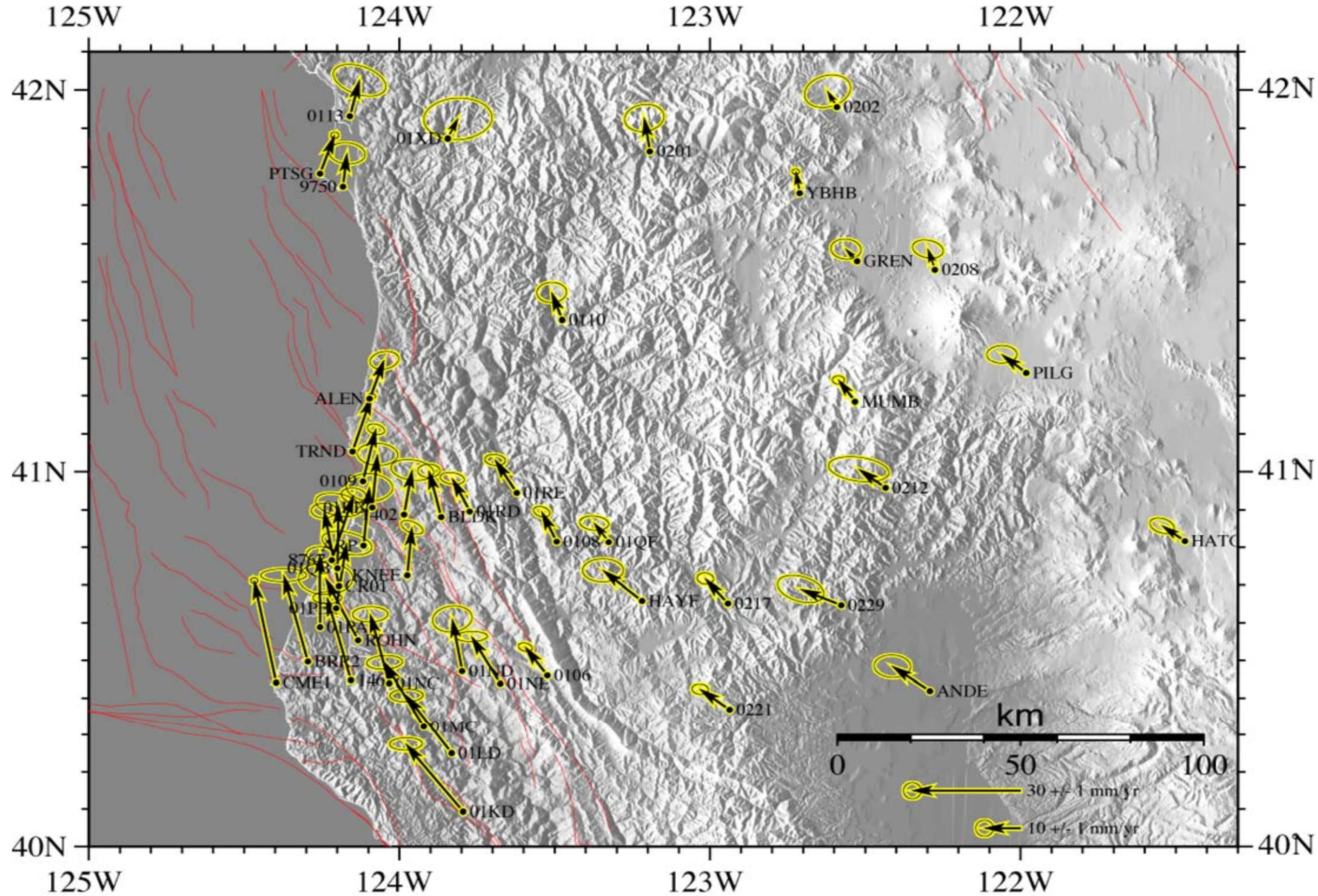


Subduction/Transform Boundary



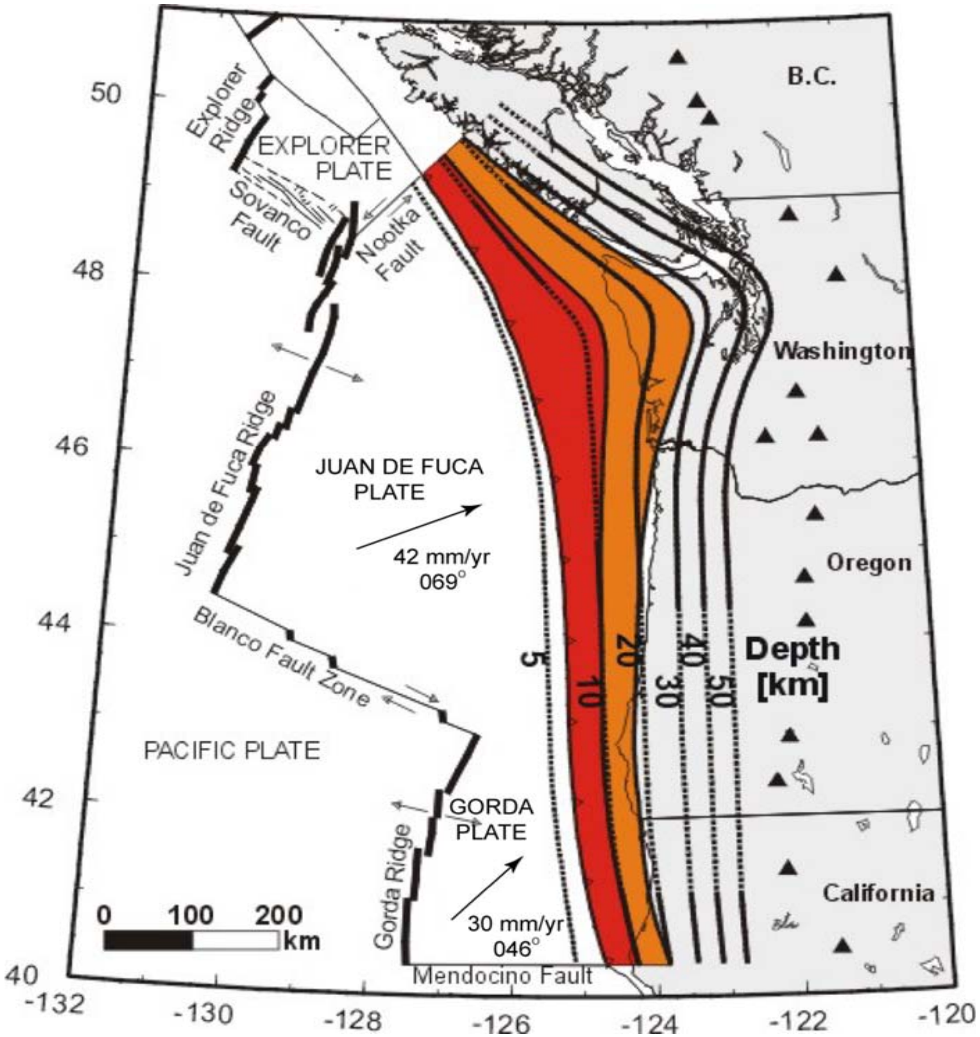
- Pacific-North America-Juan de Fuca triple junction
- Southern end of the Cascadia subduction zone
- Northern end of San Andreas fault system

Velocities Relative to NOAM



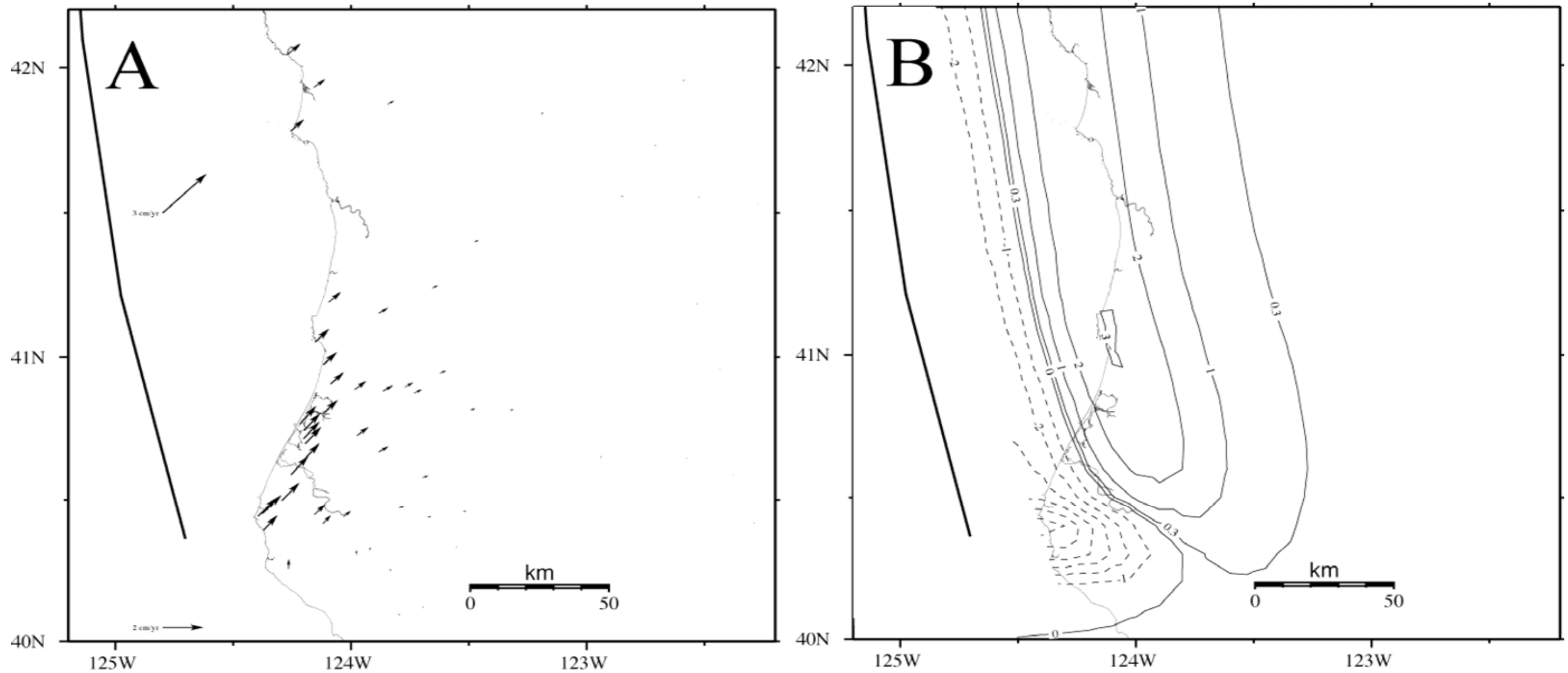
Williams et al., in prep

Removing Effect of Subduction

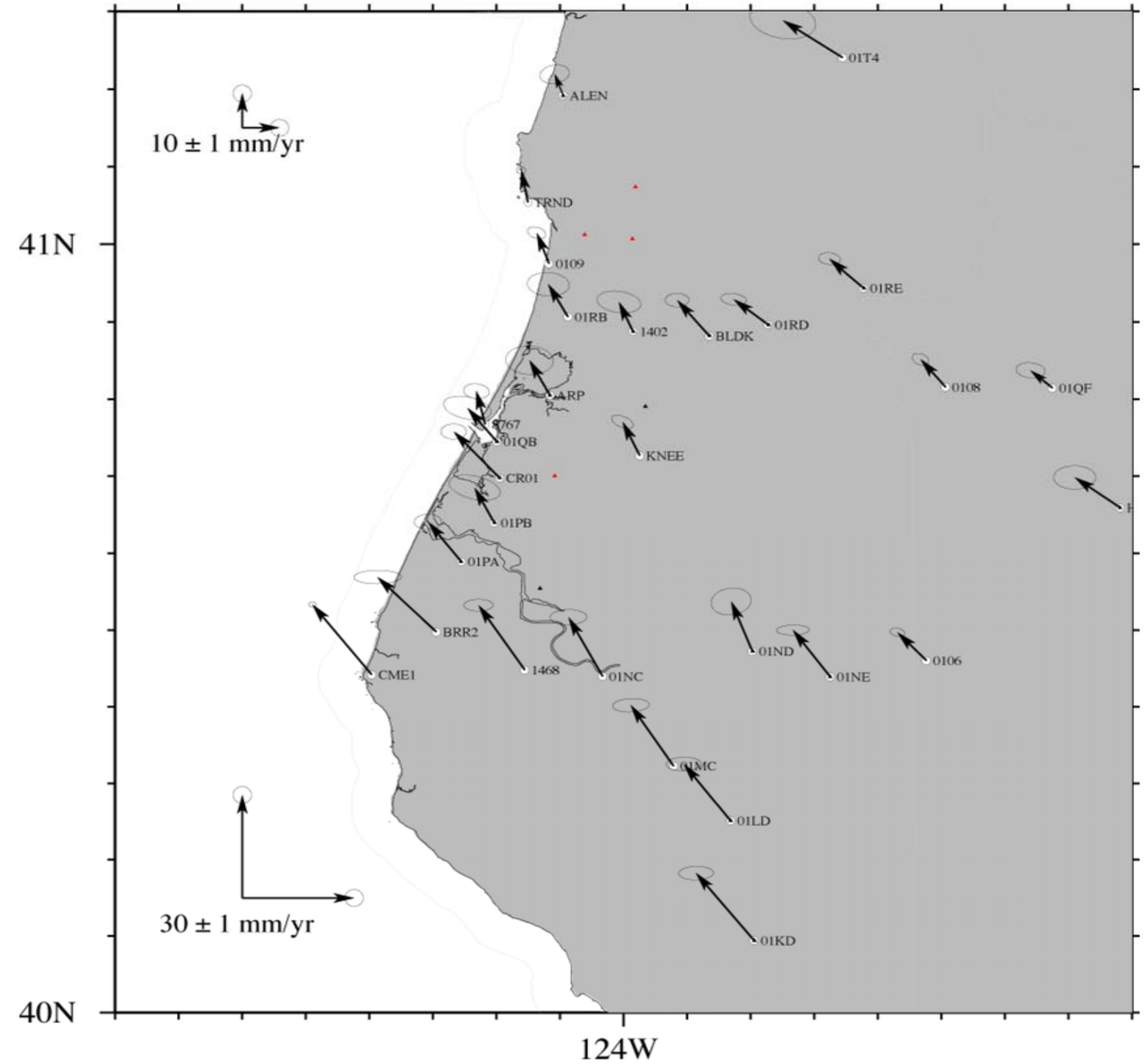


- Want to study upper plate structures
- Calculate elastic strain using model of Flück et al. (1997)
- Gorda Plate assumed to end at Mendocino Fault

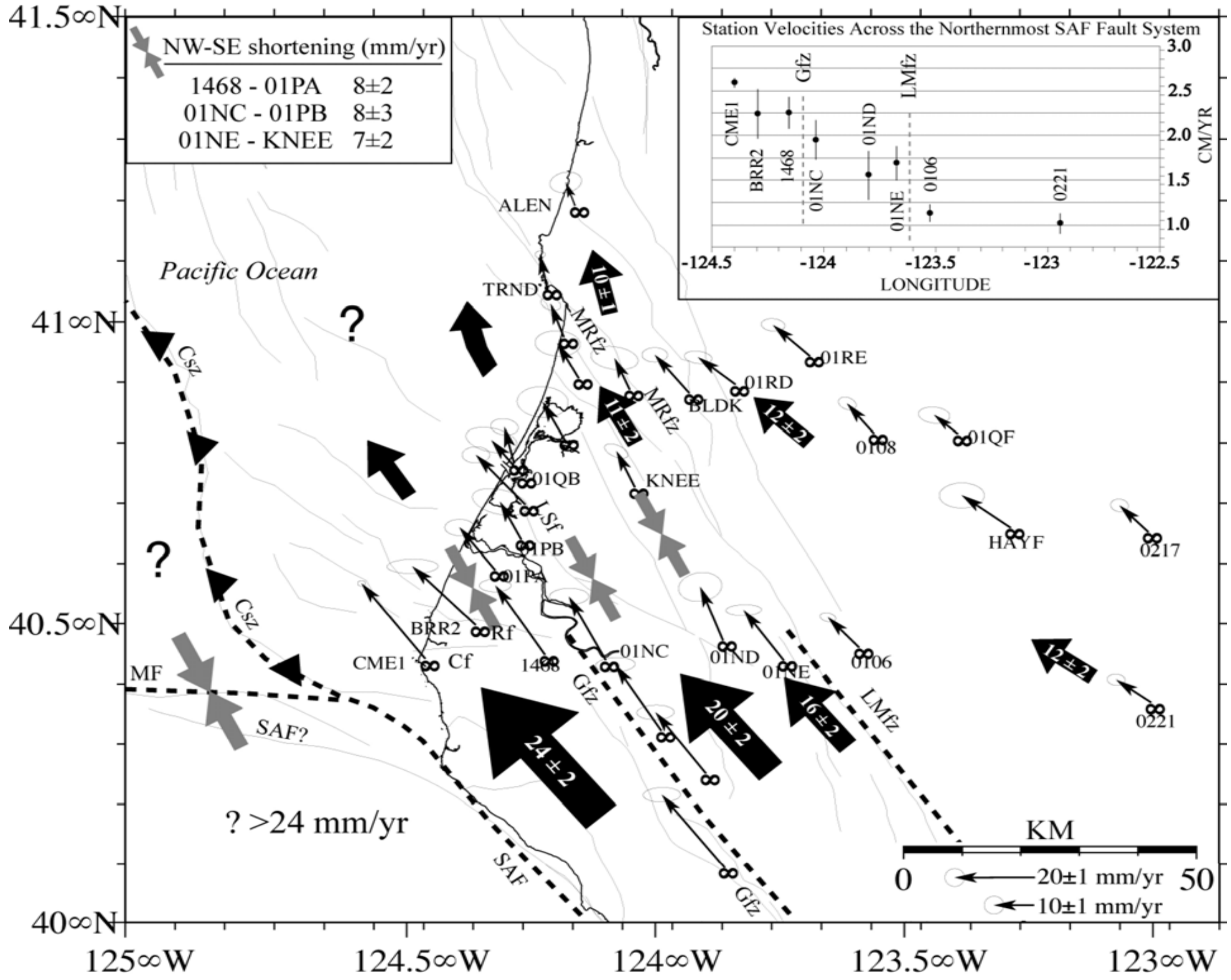
Subduction Correction



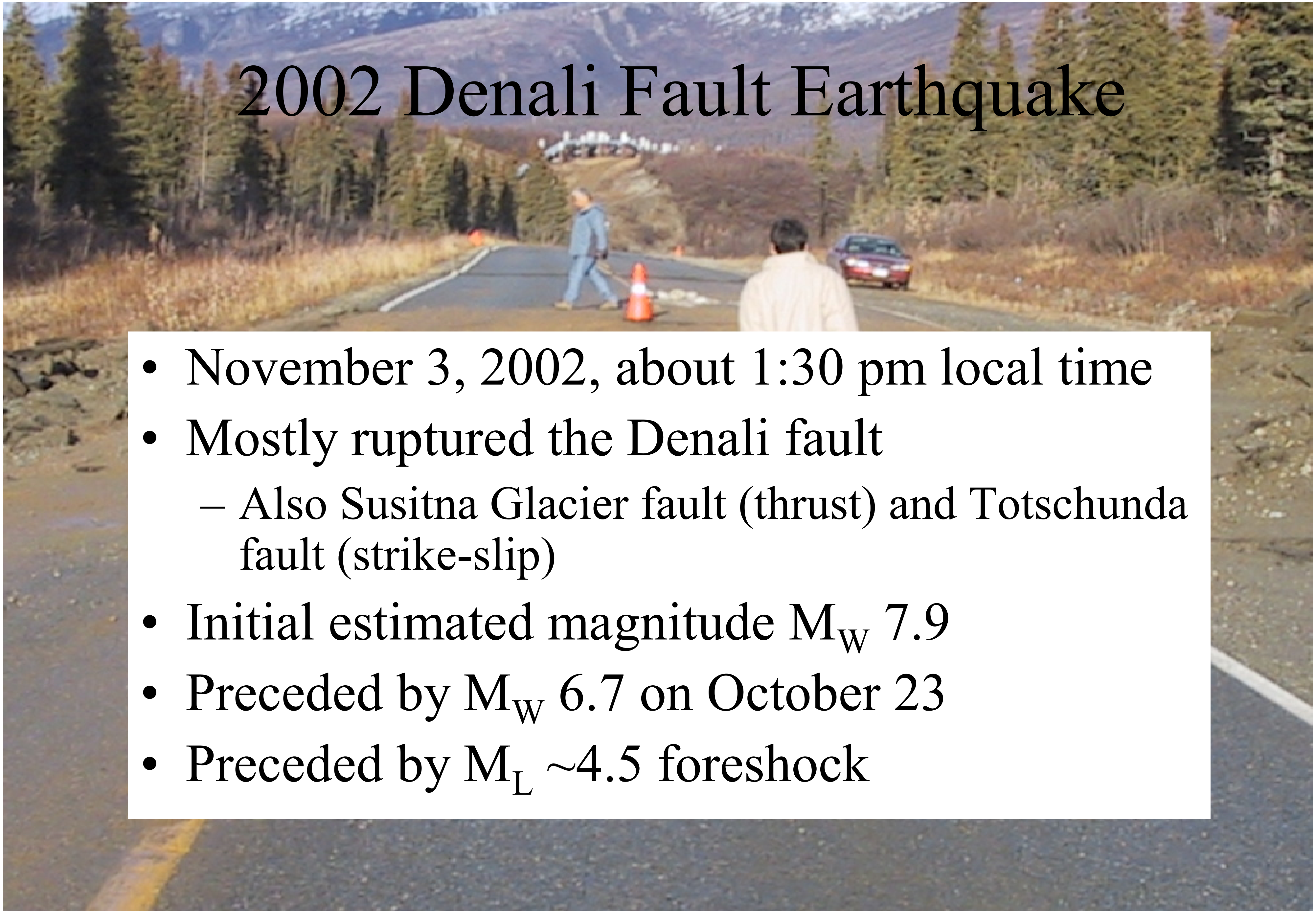
Velocities with Subduction Removed



Interpreted Features



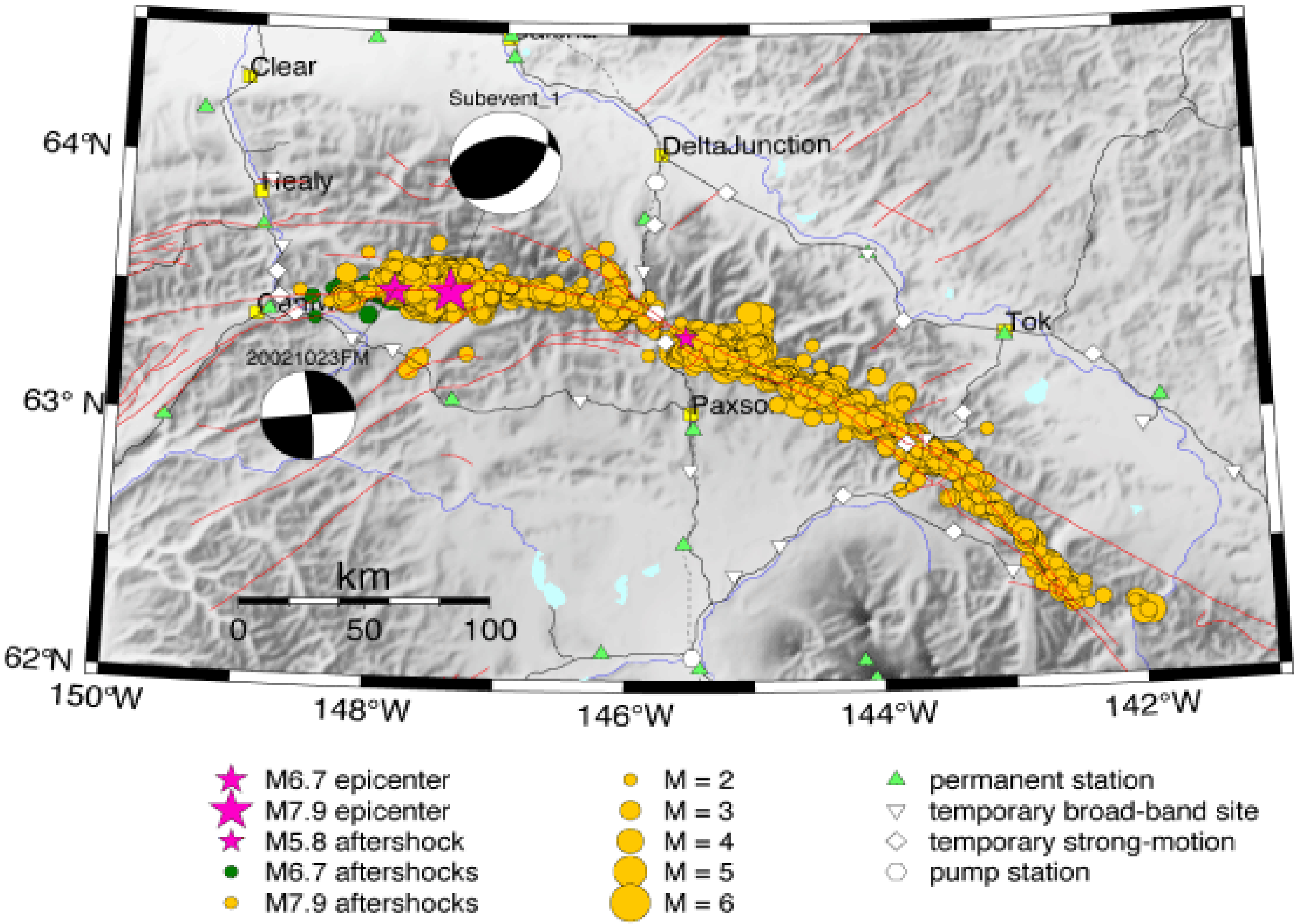

Learning From Large Earthquakes



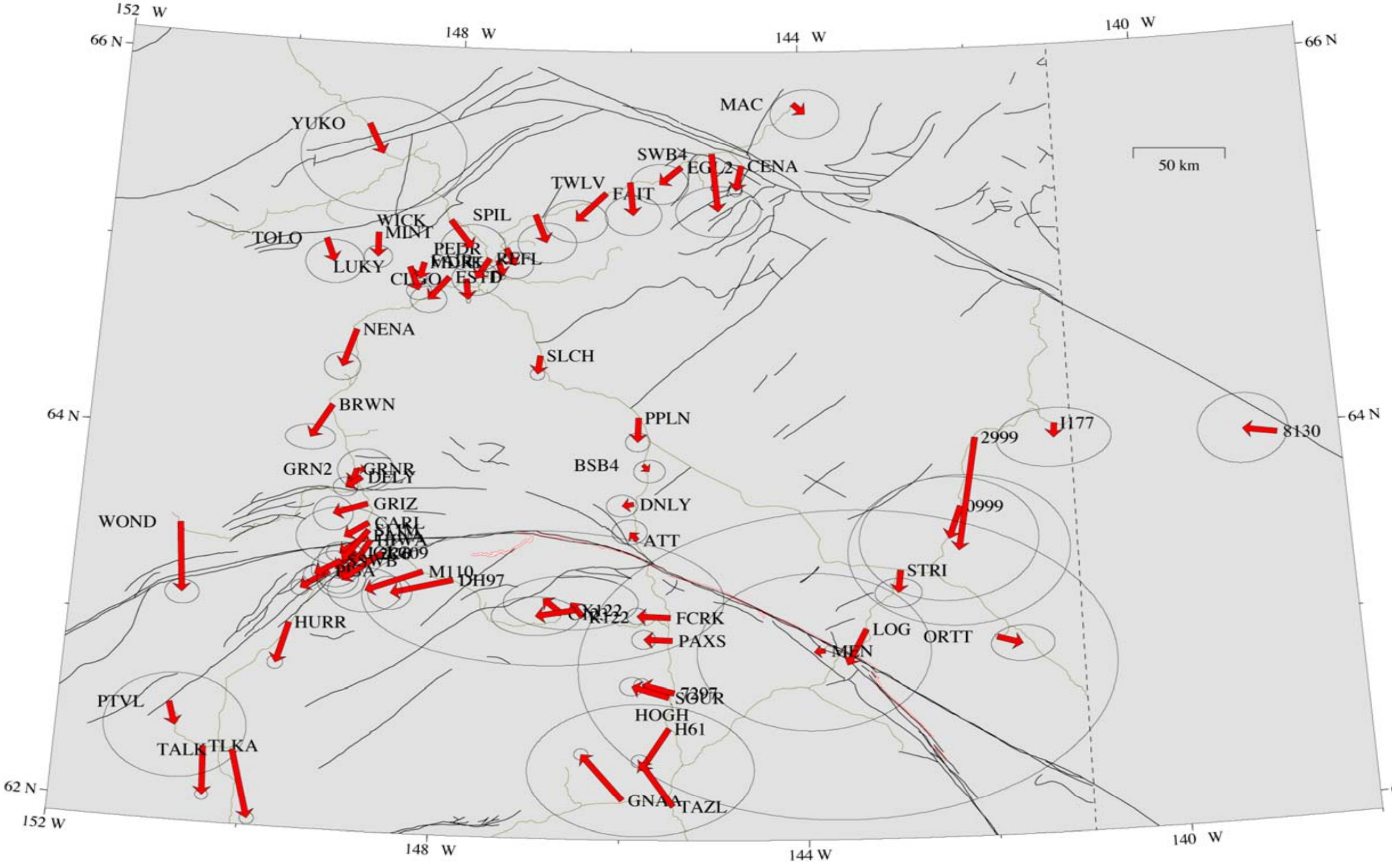
2002 Denali Fault Earthquake

- 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

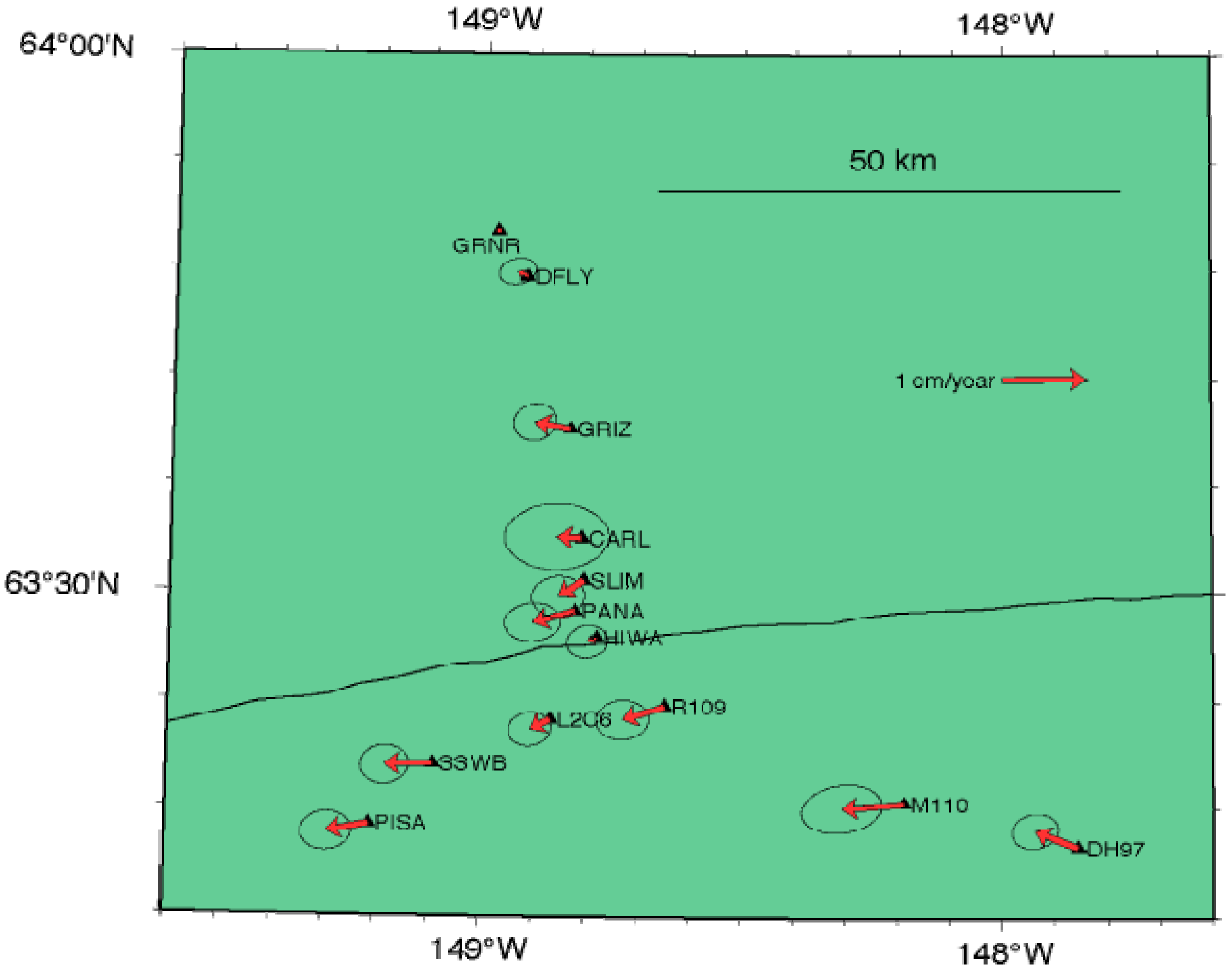
Mainshock and Aftershocks



Most Recent Pre-earthquake Velocity Field



Pre- Earthquake GPS



- 8 mm/yr total
- Possibly ~2-3 mm/yr on northern fault
- ~5-6 mm/yr on McKinley strand

Hilary Fletcher, Ph.D. thesis


Photo by Tony Crone, USGS

Landslide on the Black Rapids Glacier – view up glacier to the west

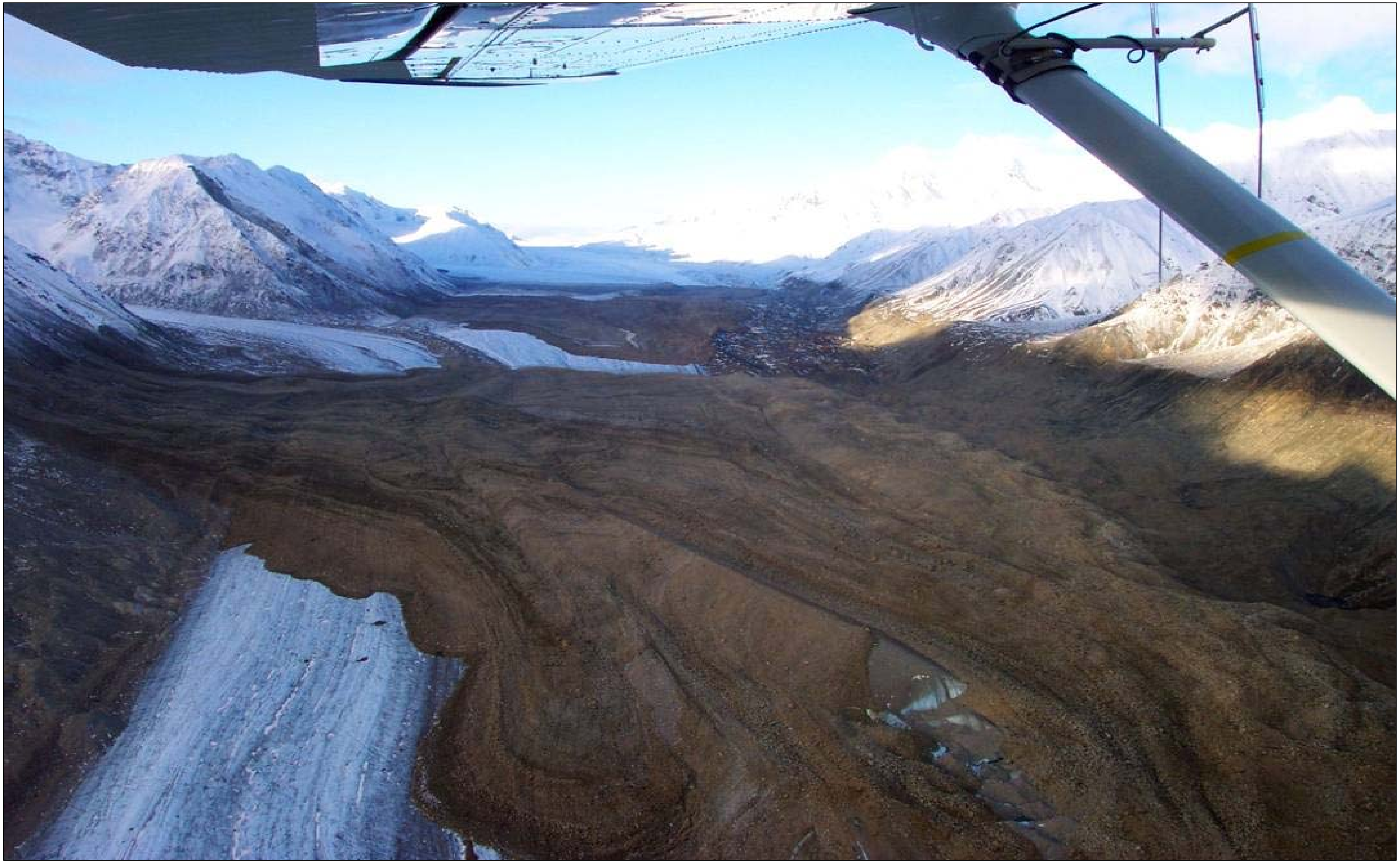
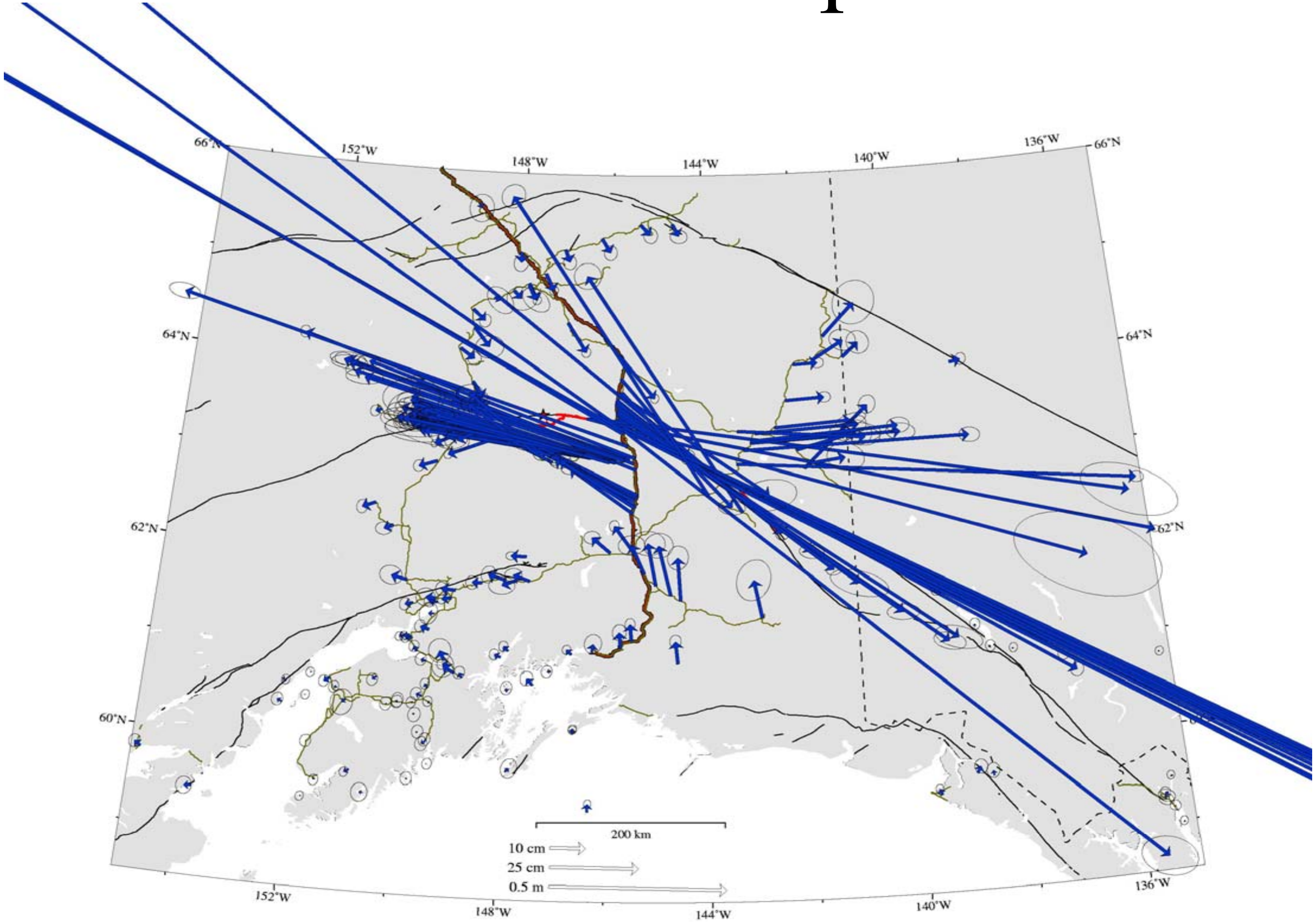


Photo by Dennis Trabant, USGS


6 m right-lateral, 70 cm vertical offset on Gakona Glacier

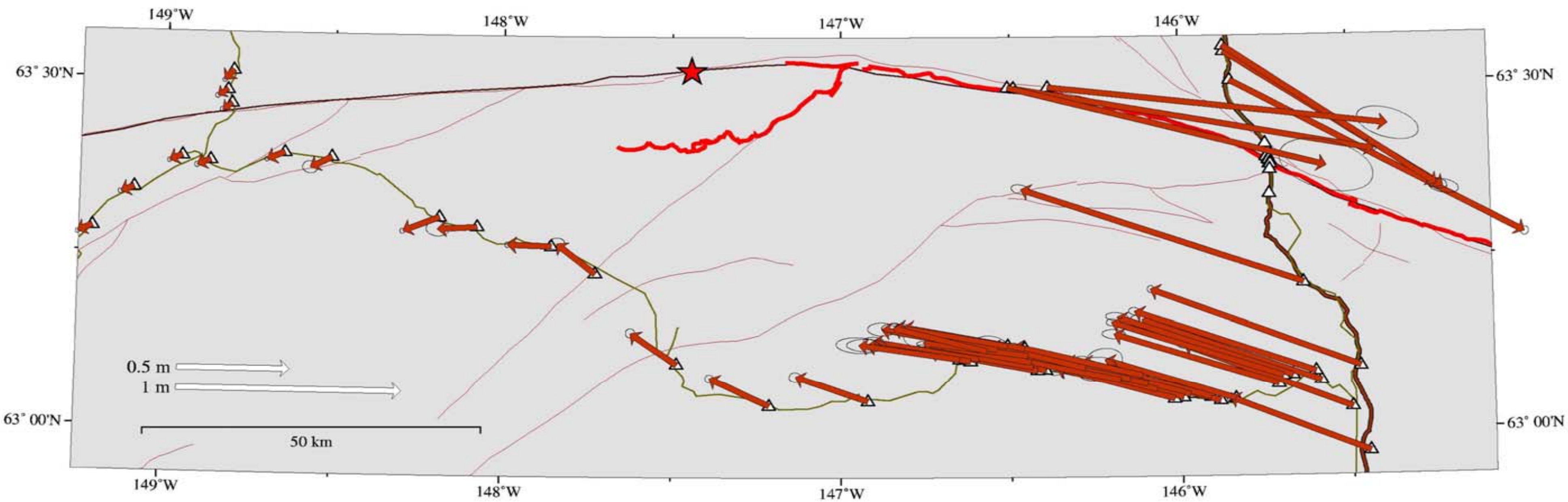

Measuring GPS Displacements

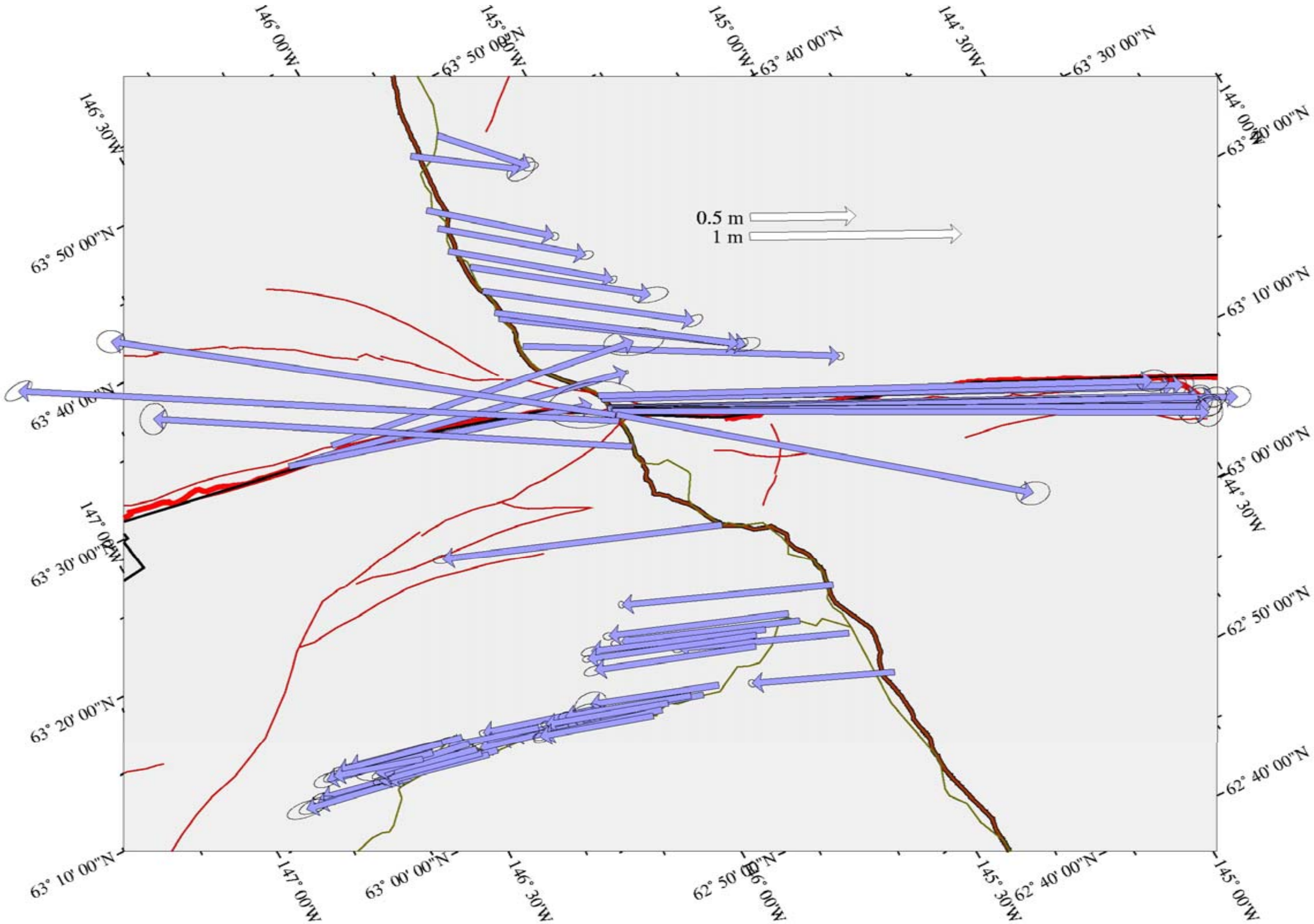
GPS Coseismic Displacements



Hreinsdóttir et al., in prep.

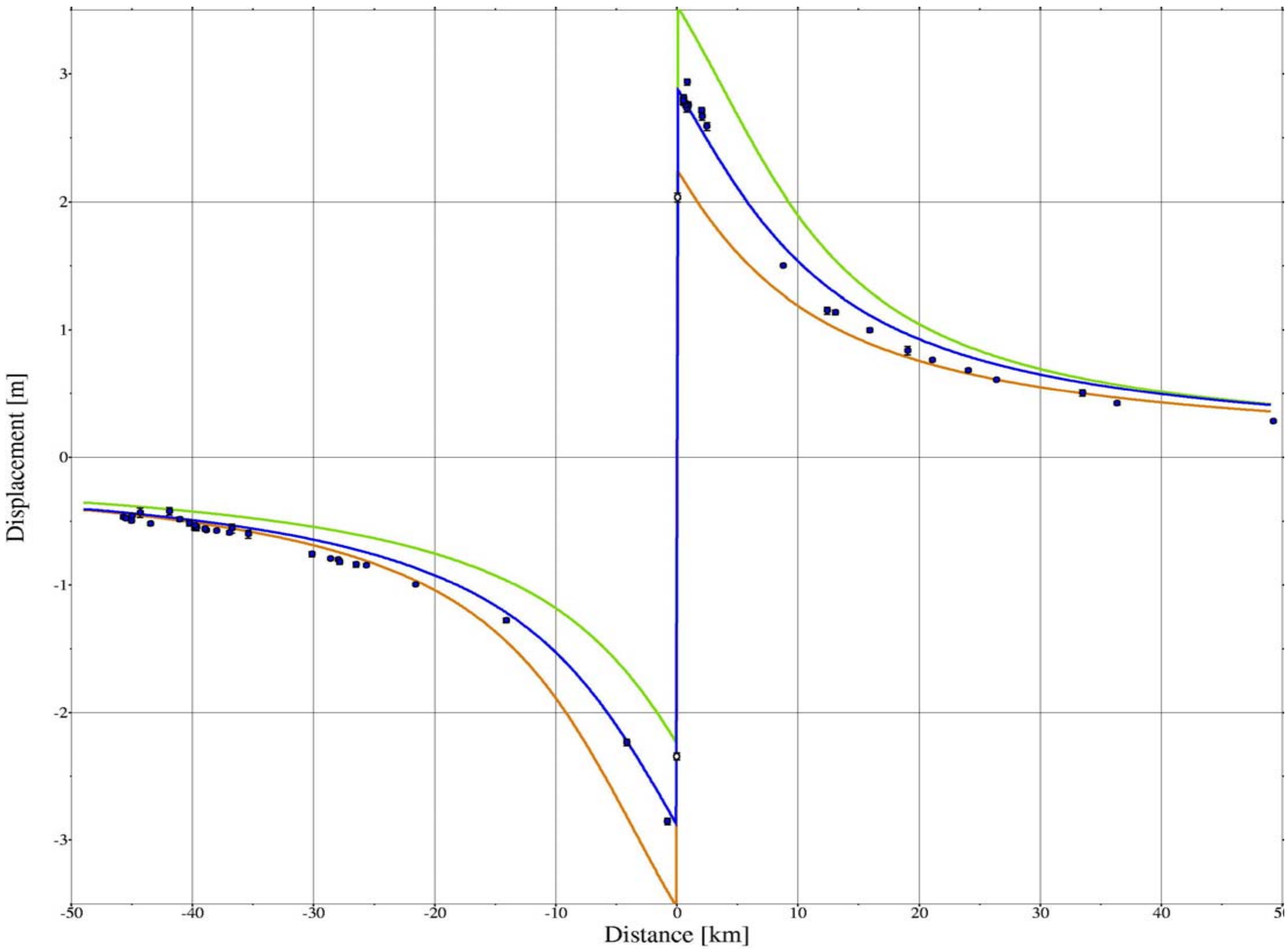
Western Part of Rupture



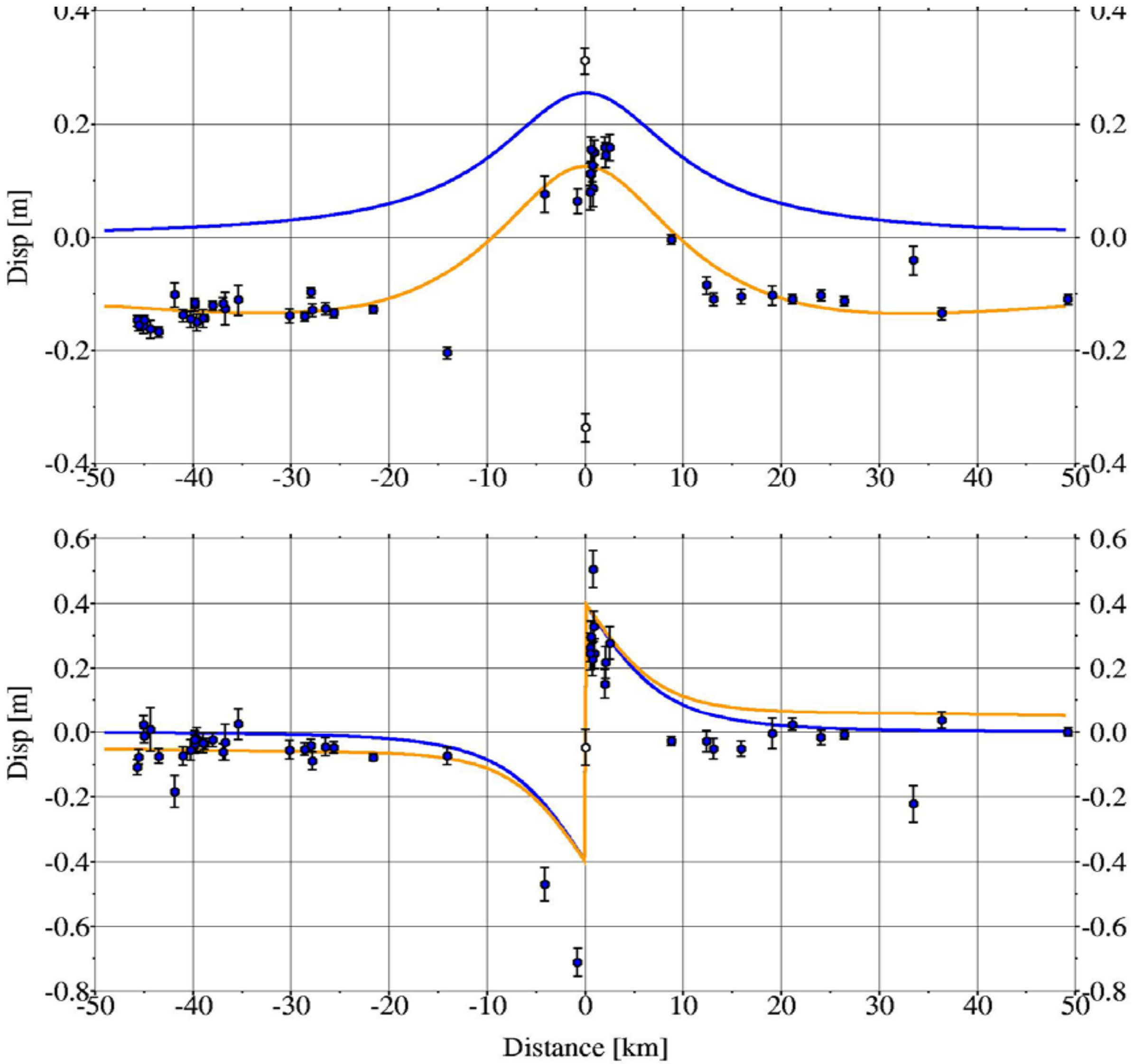


0.5 m
1 m
146° 00'W
63° 50' 00"N
63° 40' 00"N
145° 00'W
144° 30'W
63° 30' 00"N
63° 10' 00"N
63° 00' 00"N
62° 50' 00"N
62° 40' 00"N
63° 20' 00"N
147° 00'W
146° 30'W
145° 30'W

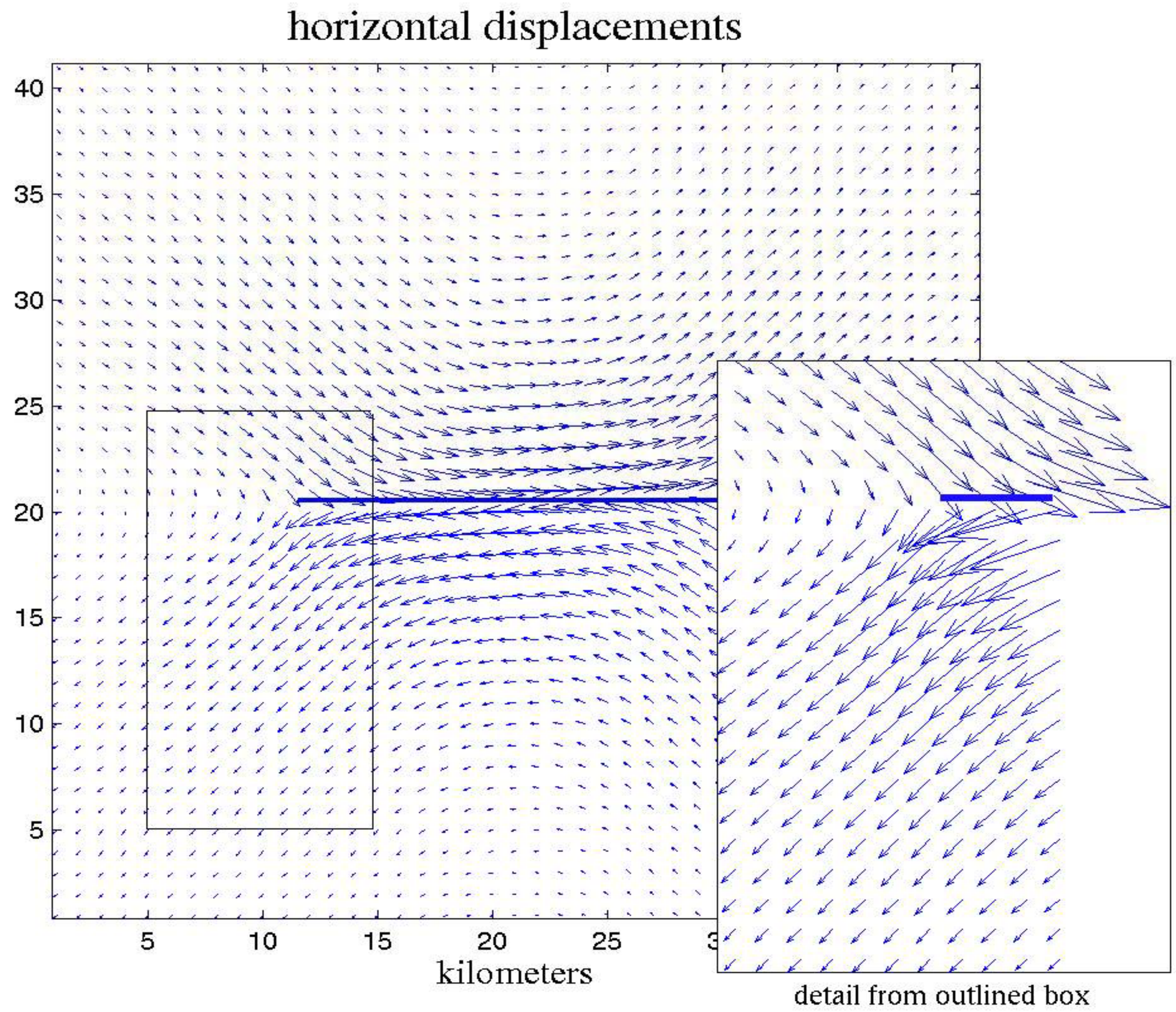
Fault-normal Profile



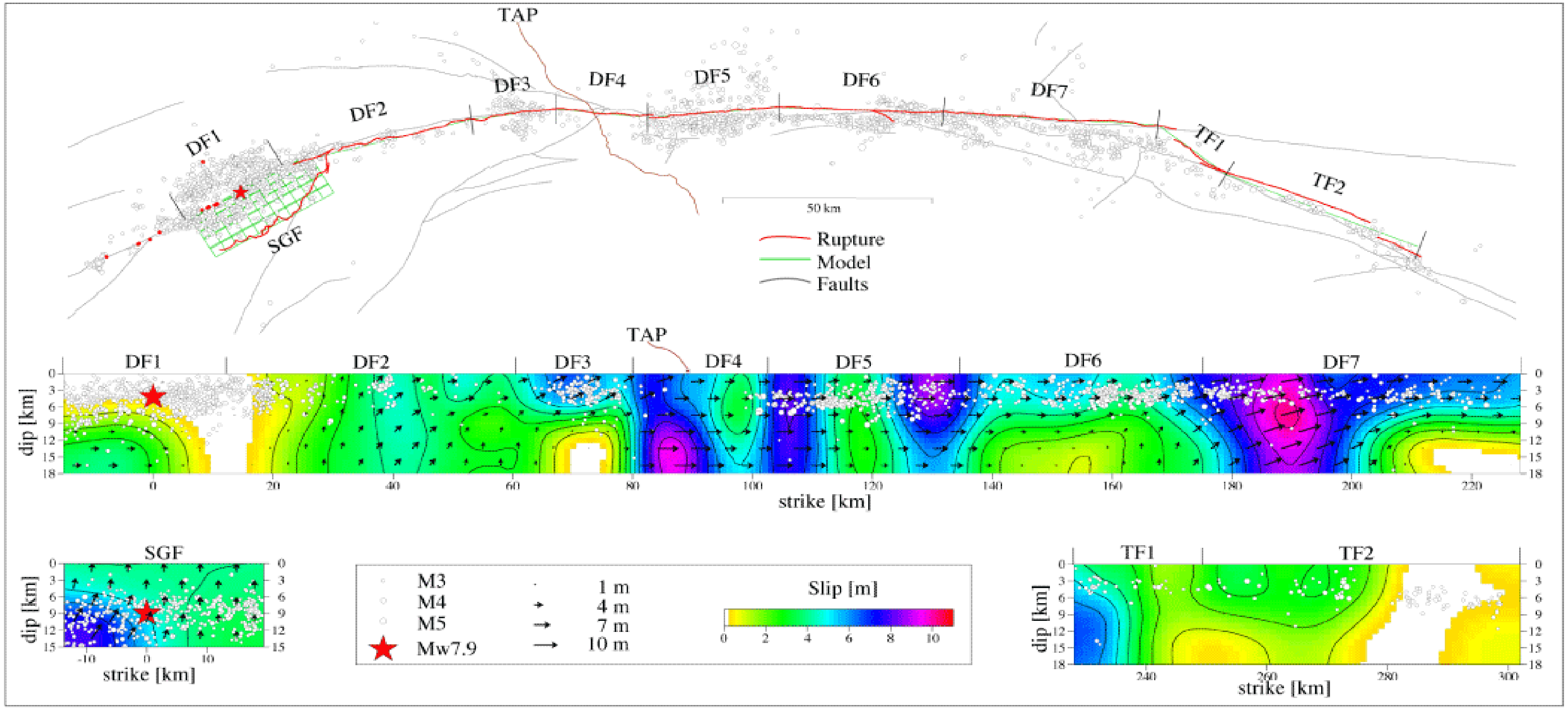
Fault-Normal and Vertical



Why Does Along-Strike Gradient Matter?

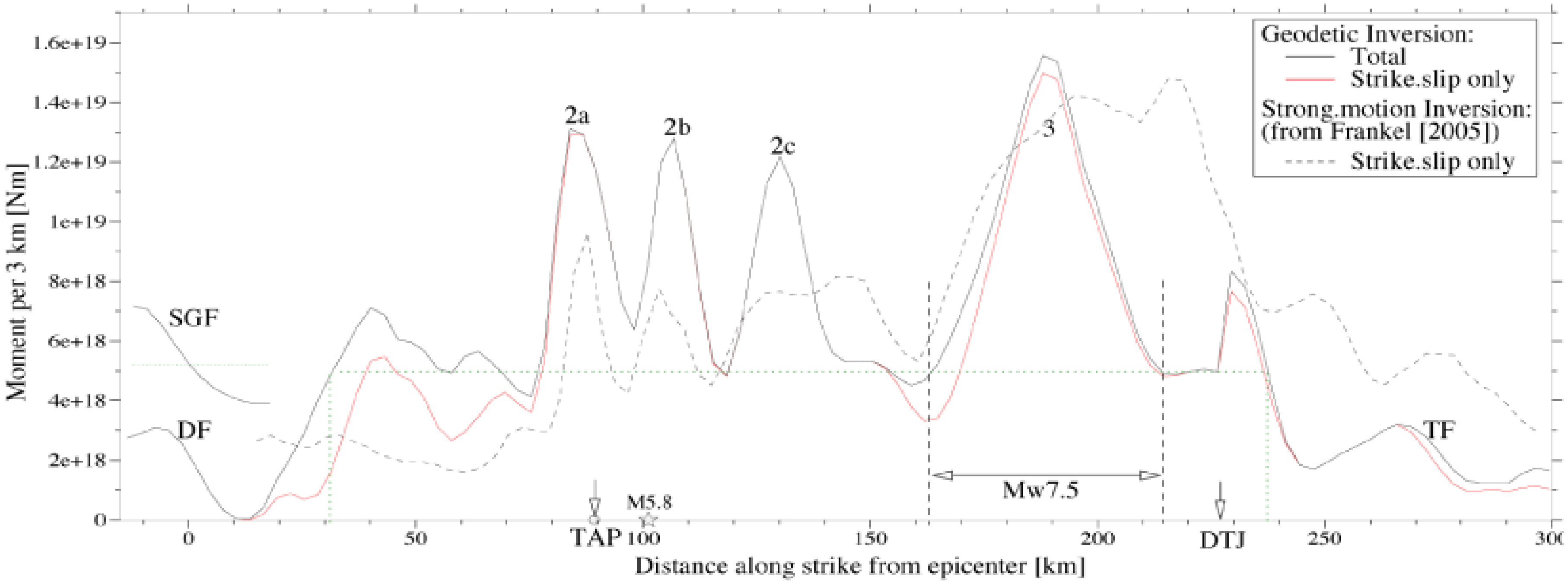


Slip Model



TAP
DF1
DF2
DF3
DF4
DF5
DF6
DF7
TF1
TF2
SGF
50 km
Rupture
Model
Faults
dip [km]
strike [km]
SGF
M3
M4
M5
Mw7.9
1 m
4 m
7 m
10 m
Slip [m]

Total Moment Along Strike



What We Learned From Earthquake

- Depth of slip in earthquake (mostly < 12 km) showed provided locking depth
  - Prior to earthquake, almost no microseismicity
- Earthquake made geometry of fault more clear
- Earthquake confirmed suspicions about the connection between Denali and Totschunda faults

Short-Term vs. Long-Term Rates

Q. Do geodetic measurements over a few years give a good estimate of long-term measurements over thousands of years?

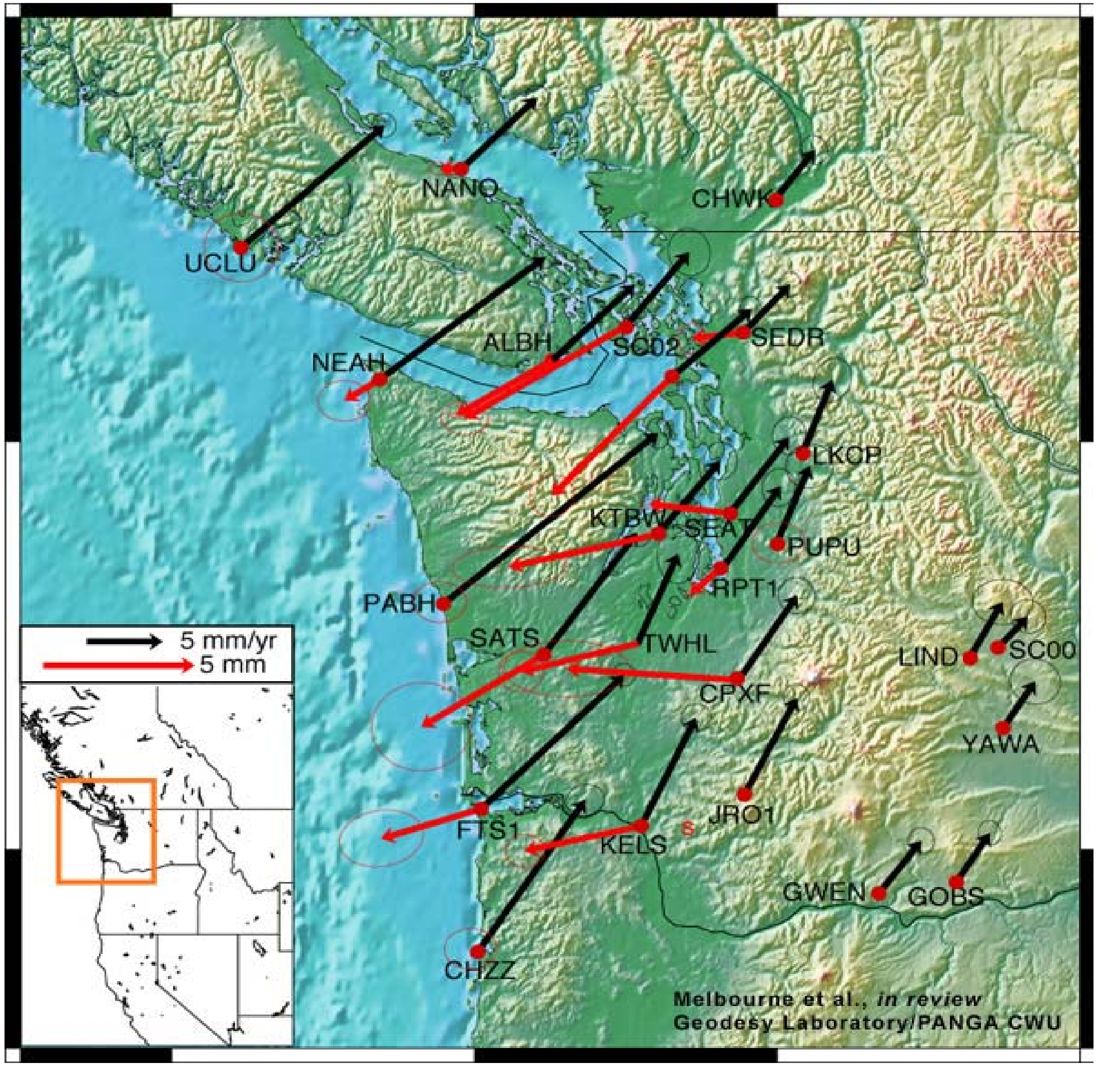
A. Quite often, but not always.

- Creep or slow slip events
- Postseismic Deformation
- Evolution of fault systems over time

Agreement or Disagreement with Geological Slip Rates

- Many examples of agreement
  - GPS agrees at plate tectonic scale
  - San Andreas fault system
  - North Anatolian fault
- Some notable disagreements
  - Central Asia: Altyn Tagh and Karakorum
  - California: Garlock fault, Eastern California Shear Zone
  - Conjugate strike-slip fault systems at the ~50 km scale

Slow Slip Events



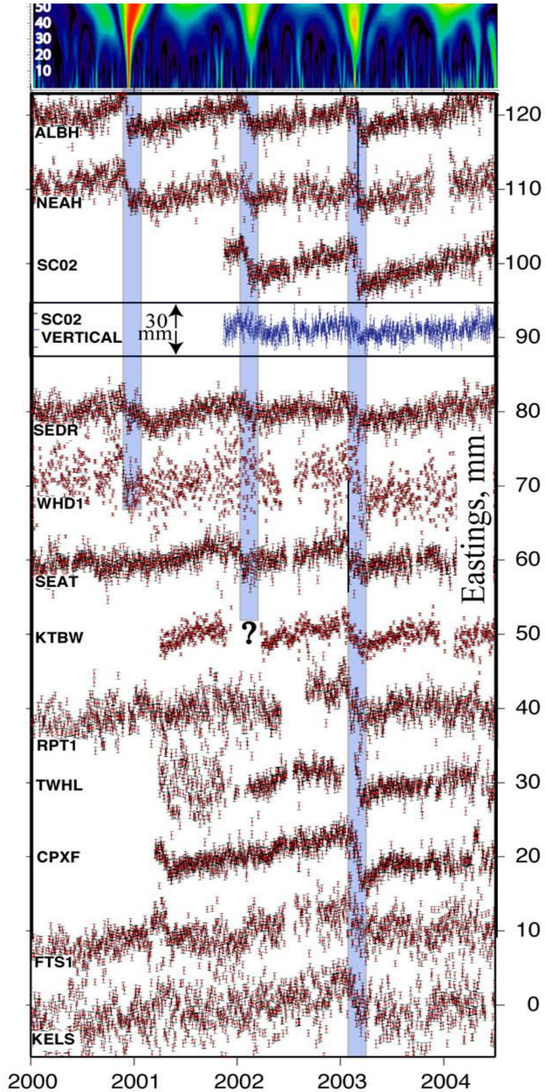
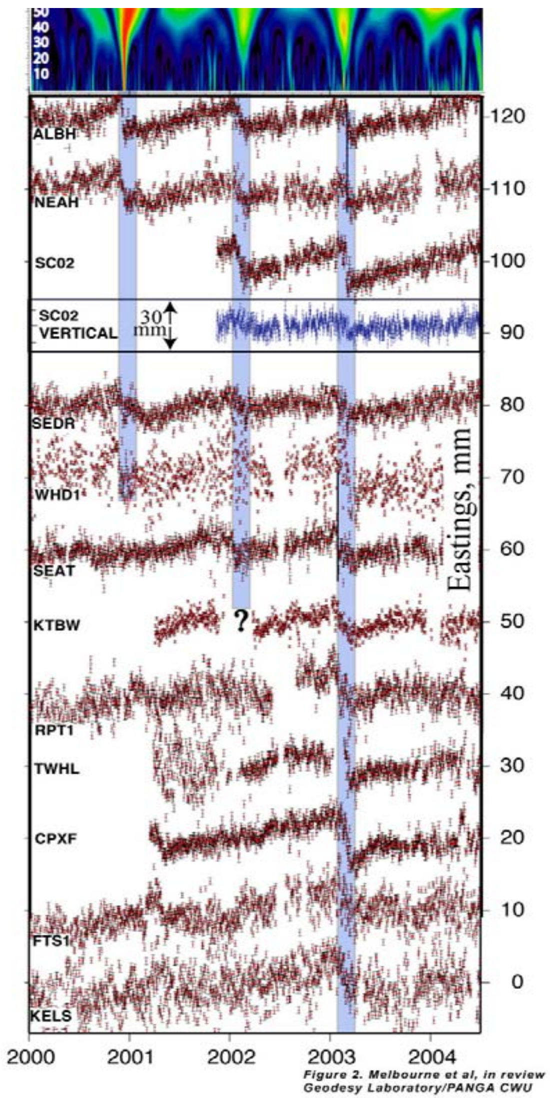
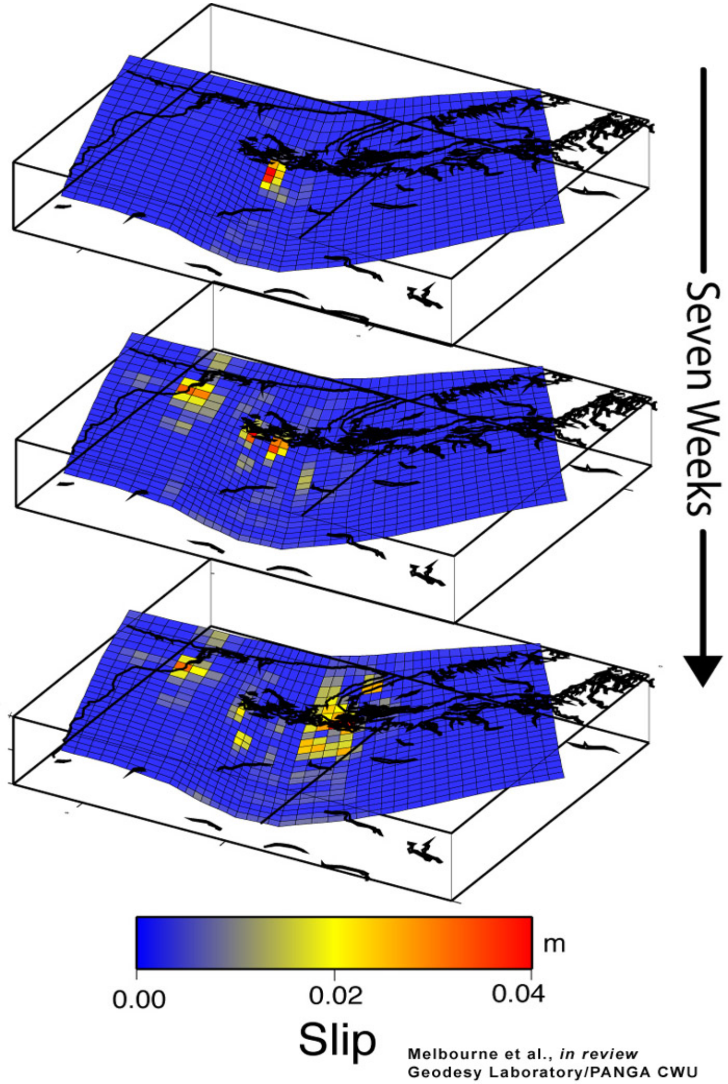


Figure 2. Melbourne et al, in review
Geodesy Laboratory/PANGA CWU

Displacement and Slip Model





Implications of Slow Slip

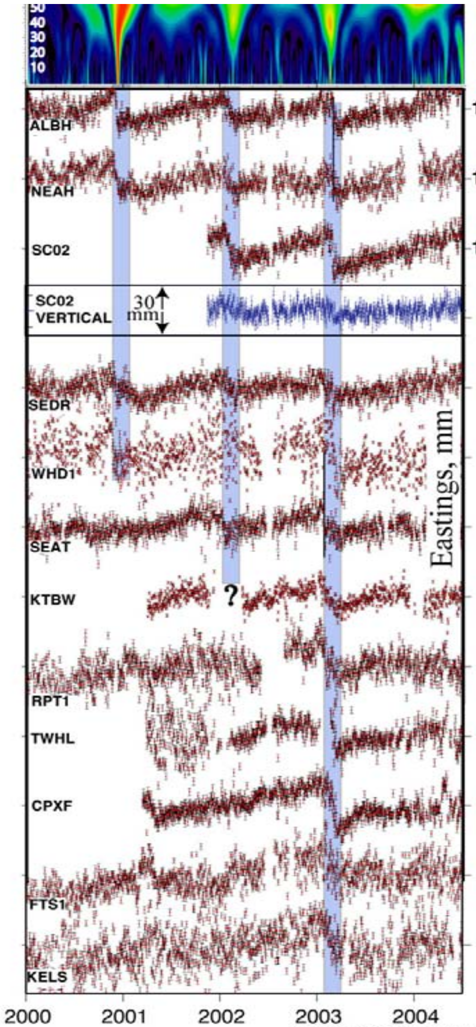


Figure 2. Melbourne et al, in review
Geodesy Laboratory/PANGA CWU

- Short-term average velocity not same as long-term average (months vs. years)
- Locking depth will depend on averaging time for velocities and interval of measurements

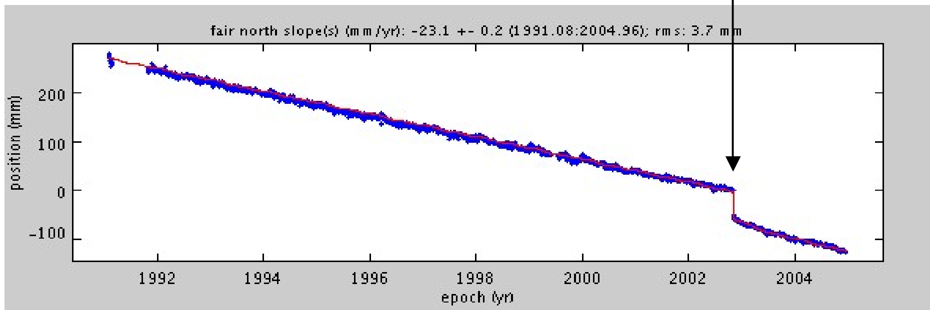
Slow Slip Events Worldwide

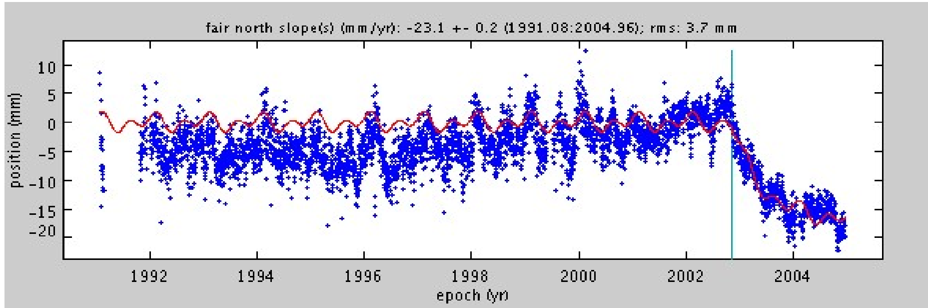
- Very common at subduction zones
  - Cascadia, Japan, Mexico, Alaska
  - Some events very large (Alaska, Mexico, Tokai/Japan)
  - Not always regularly repeating
  - Can be hard to detect (small displacements)
- Similar (non-repeating) creep events seen at a couple of special places on San Andreas
- Other strike slip faults?

Fairbanks After Denali Earthquake

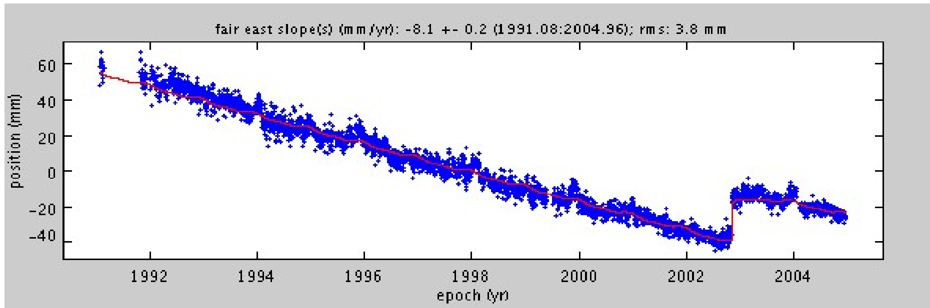
Mw7.9, 11/3/2002

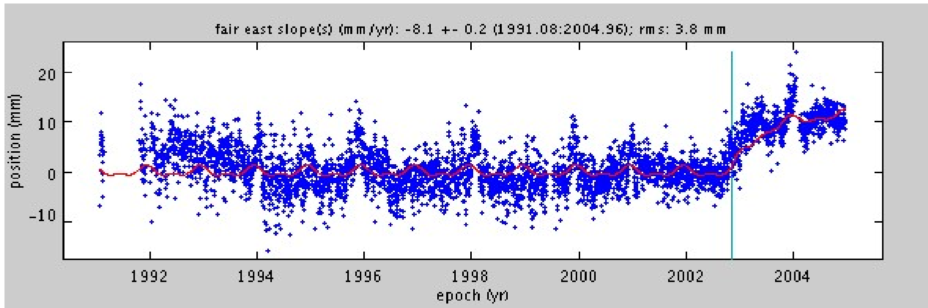
North





East





ITRF Time Series

De-trended, offsets removed

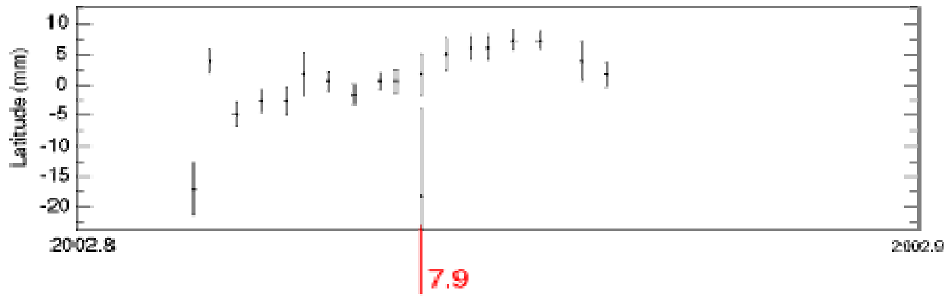
Time series from http://sopac.ucsd.edu

Station : DH97

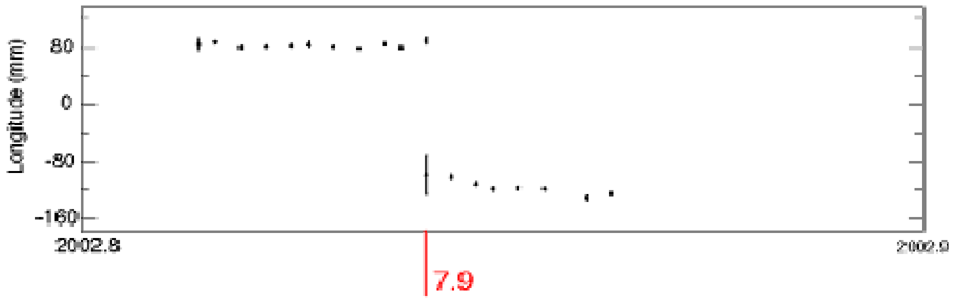
E212.14, N63.27, 940.59 (m)

19 Daily Solutions (2002.8 - 2002.9)

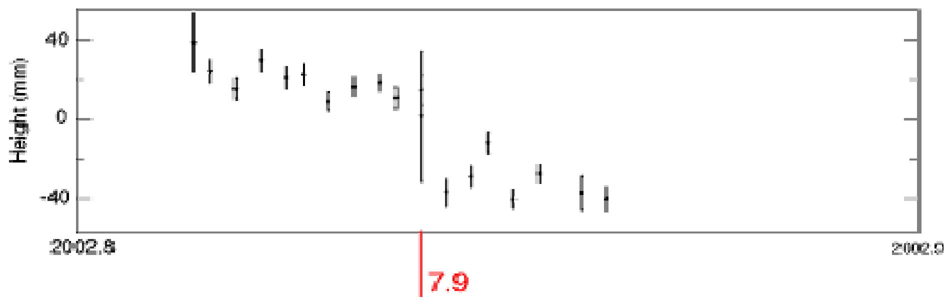
Motion rate 230.6 +- 34.0 (mm/yr) Repeatability 3.2 (mm)



Motion rate -6417.7 +- 42.2 (mm/yr) Repeatability 49.7 (mm)



Motion rate 97.2 +- 0.0 (mm/yr) Repeatability 0.0 (mm)



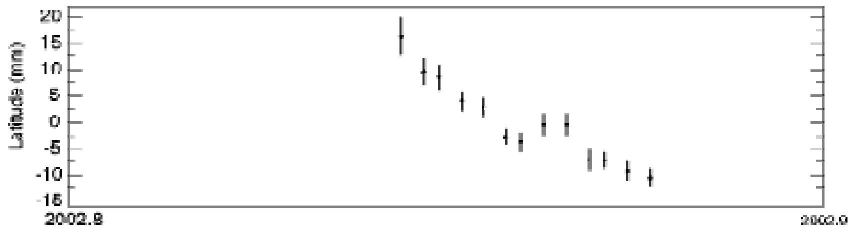
Time Series of Site Position drawn by akda at GI/UAF, Thu Nov 28 09:21:06 AKST 2002

Station : DNLY

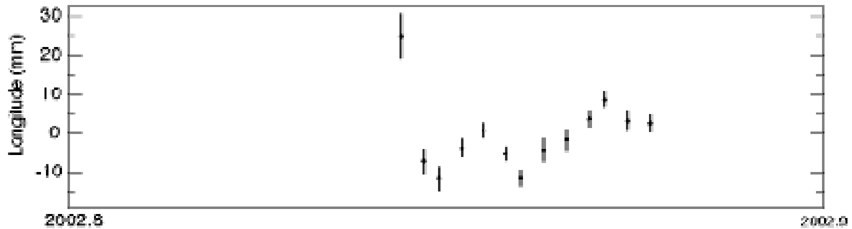
E214.11- N63.70- 554.28 (m)

13 Daily Solutions (2002.8 - 2002.9)

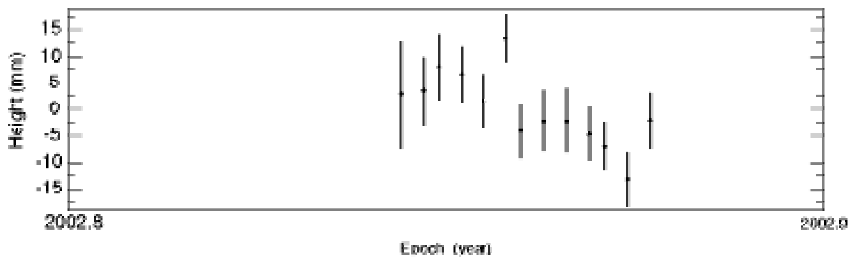
Motion rate 52.5 +- 0.0 (mm/yr) Repeatability 0.0 (mm)



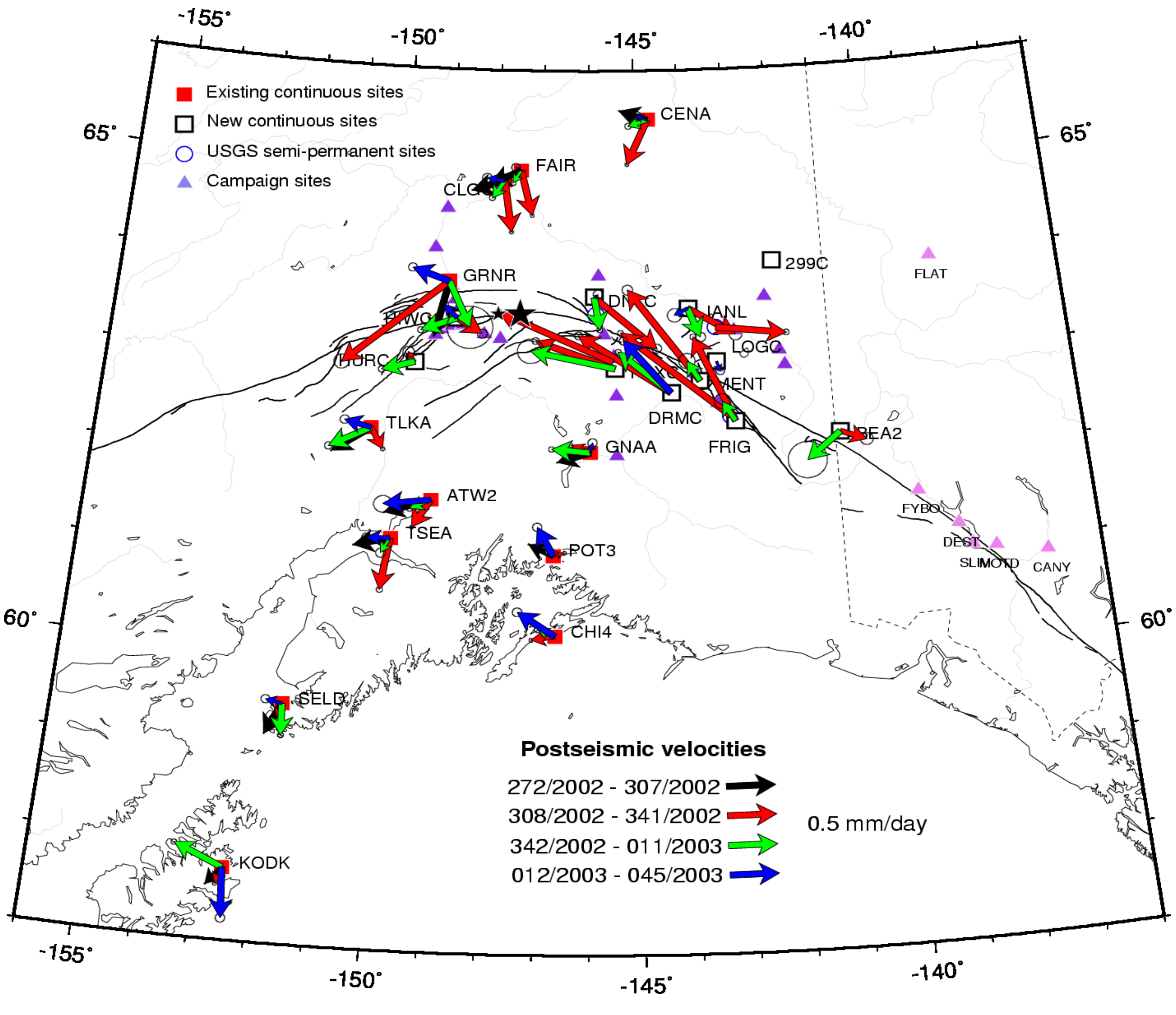
Motion rate 65.8 +- 0.0 (mm/yr) Repeatability 0.0 (mm)

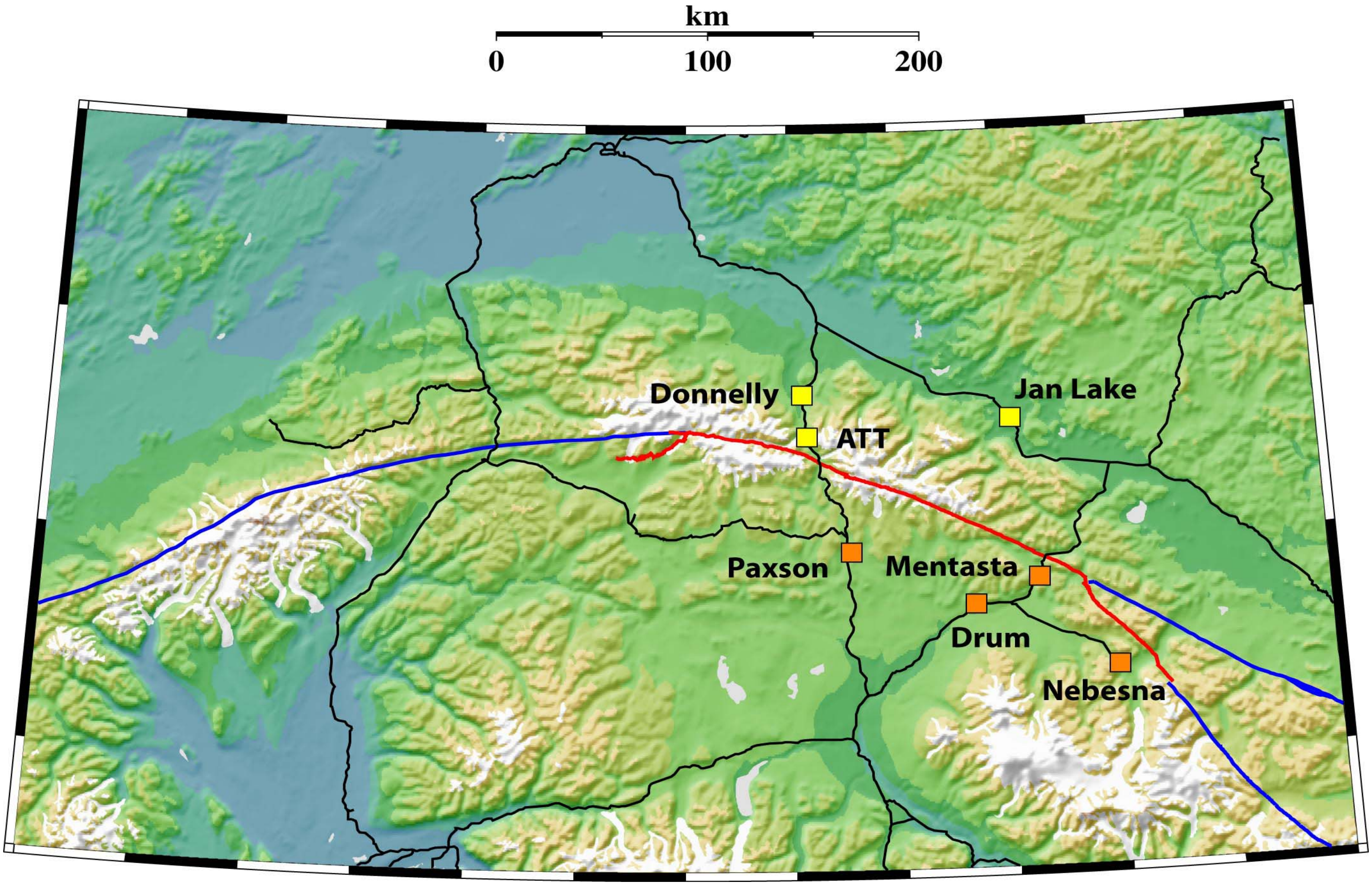


Motion rate 153.4 +- 0.0 (mm/yr) Repeatability 0.0 (mm)

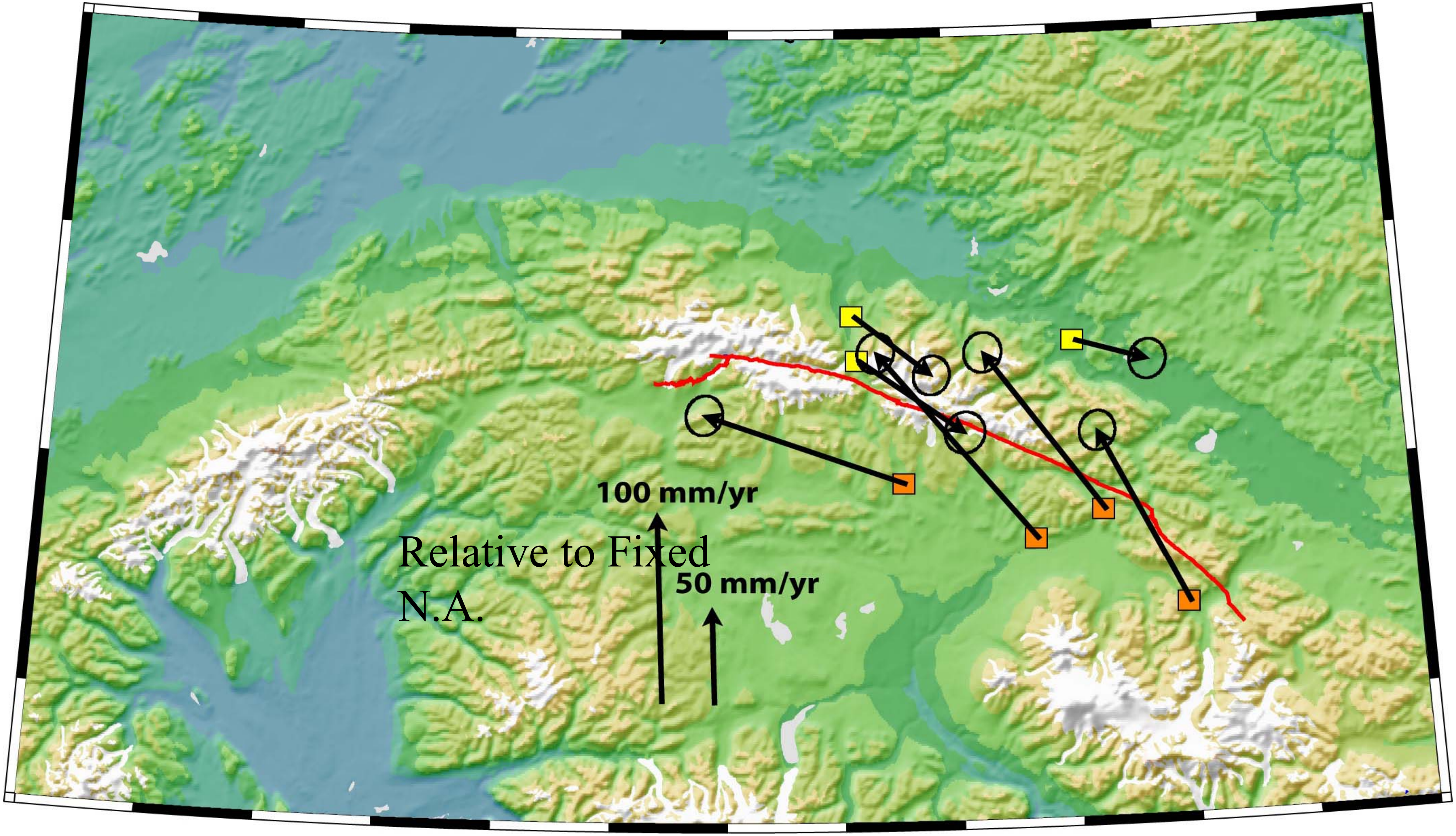


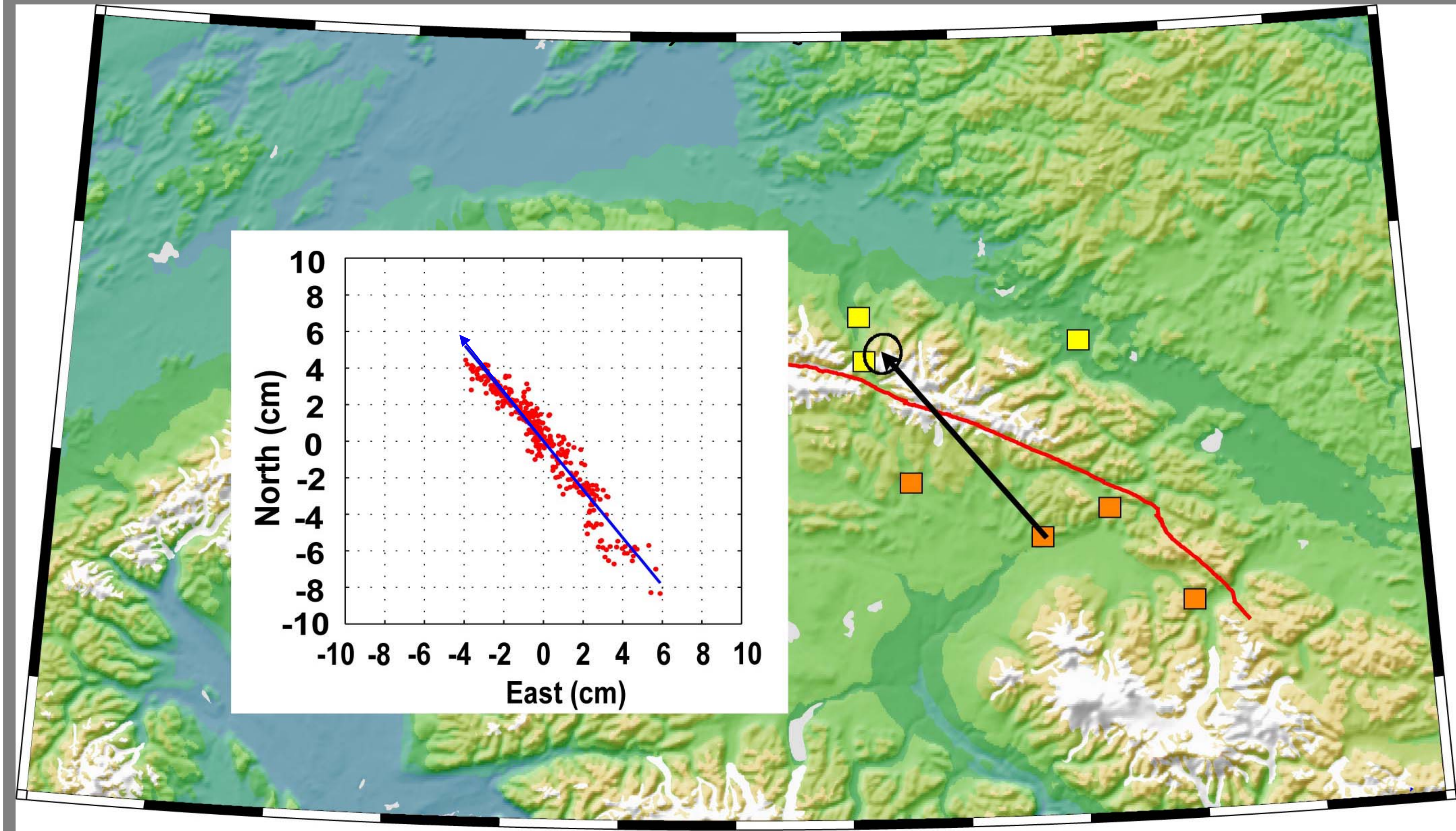
Postseismic Displacements

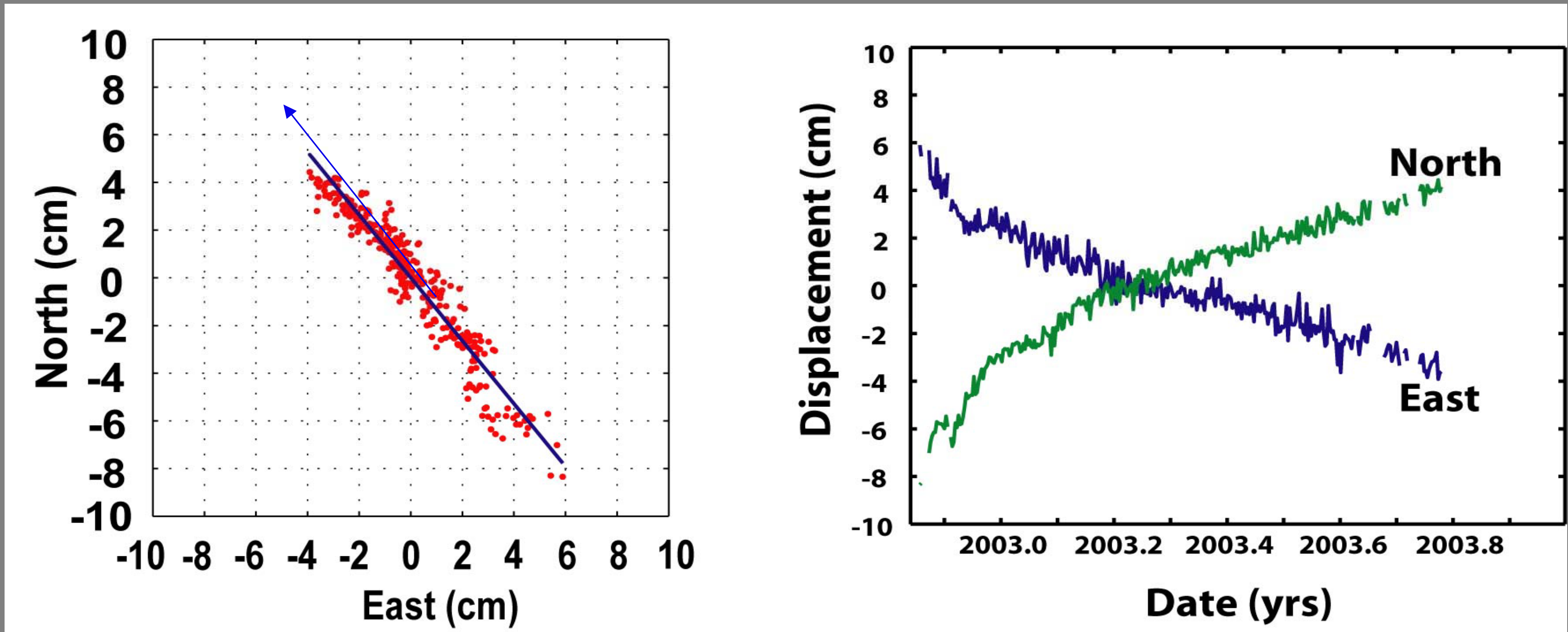



km
0
100
200
Donnelly
Jan Lake
ATT
Paxson
Mentasta
Drum
Nebesna

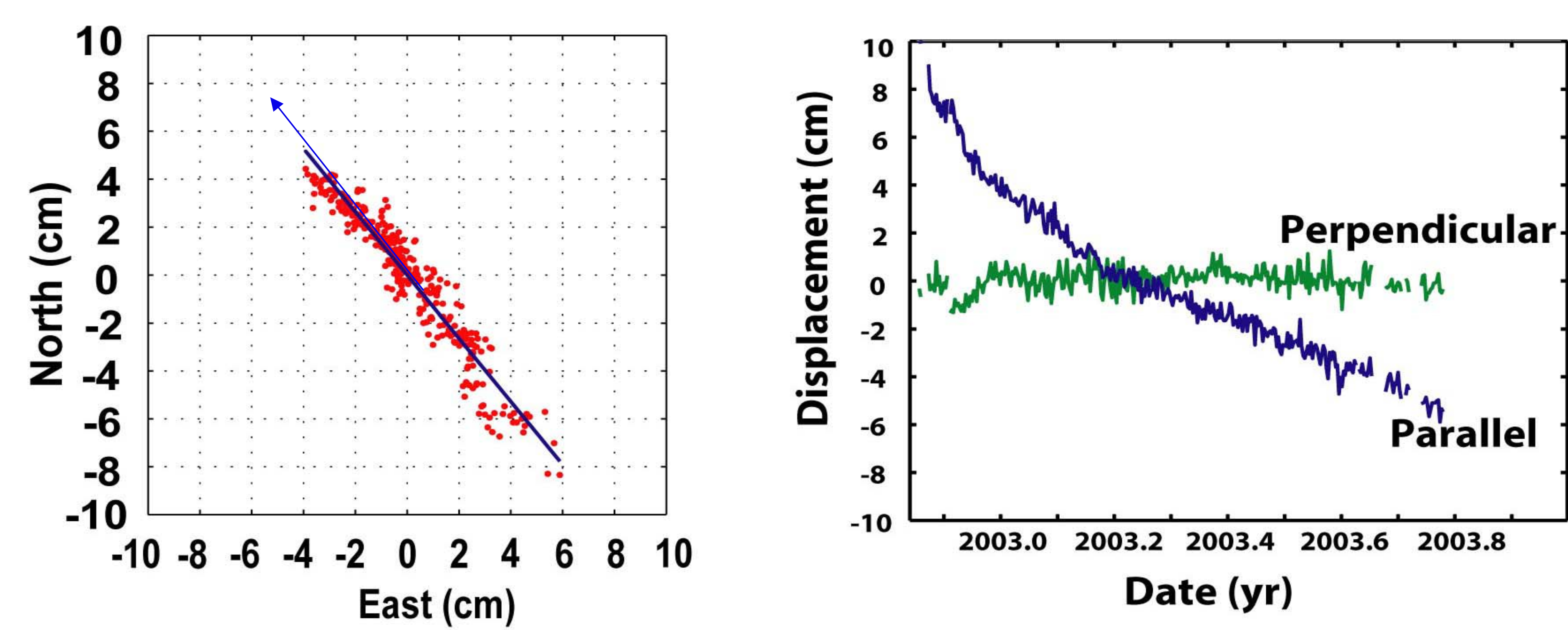
One year of postseismic deformation: Average velocities are 20-25 times faster than before the earthquake



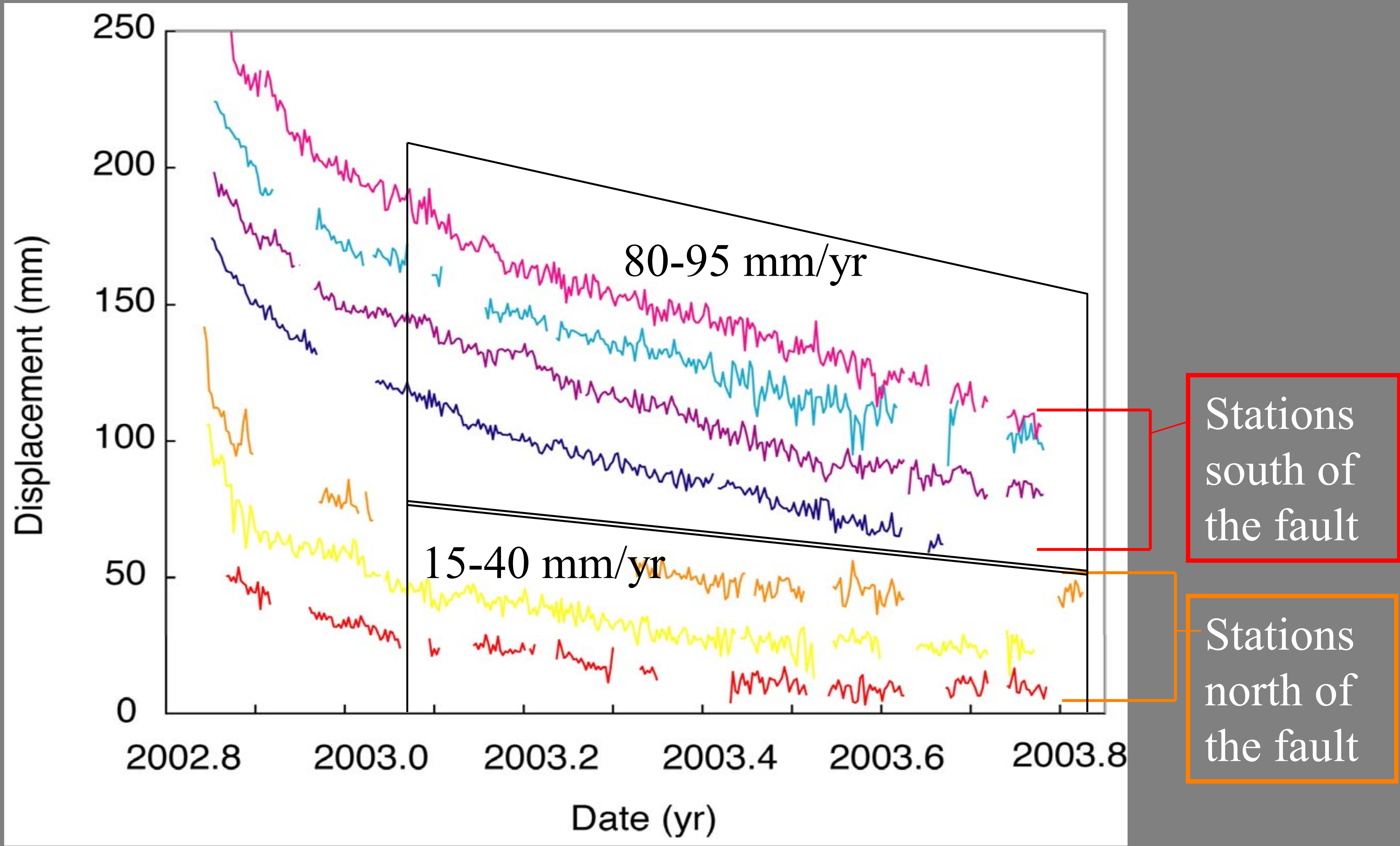

North (cm)
East (cm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10 -8 -6 -4 -2 0 2 4 6 8 10



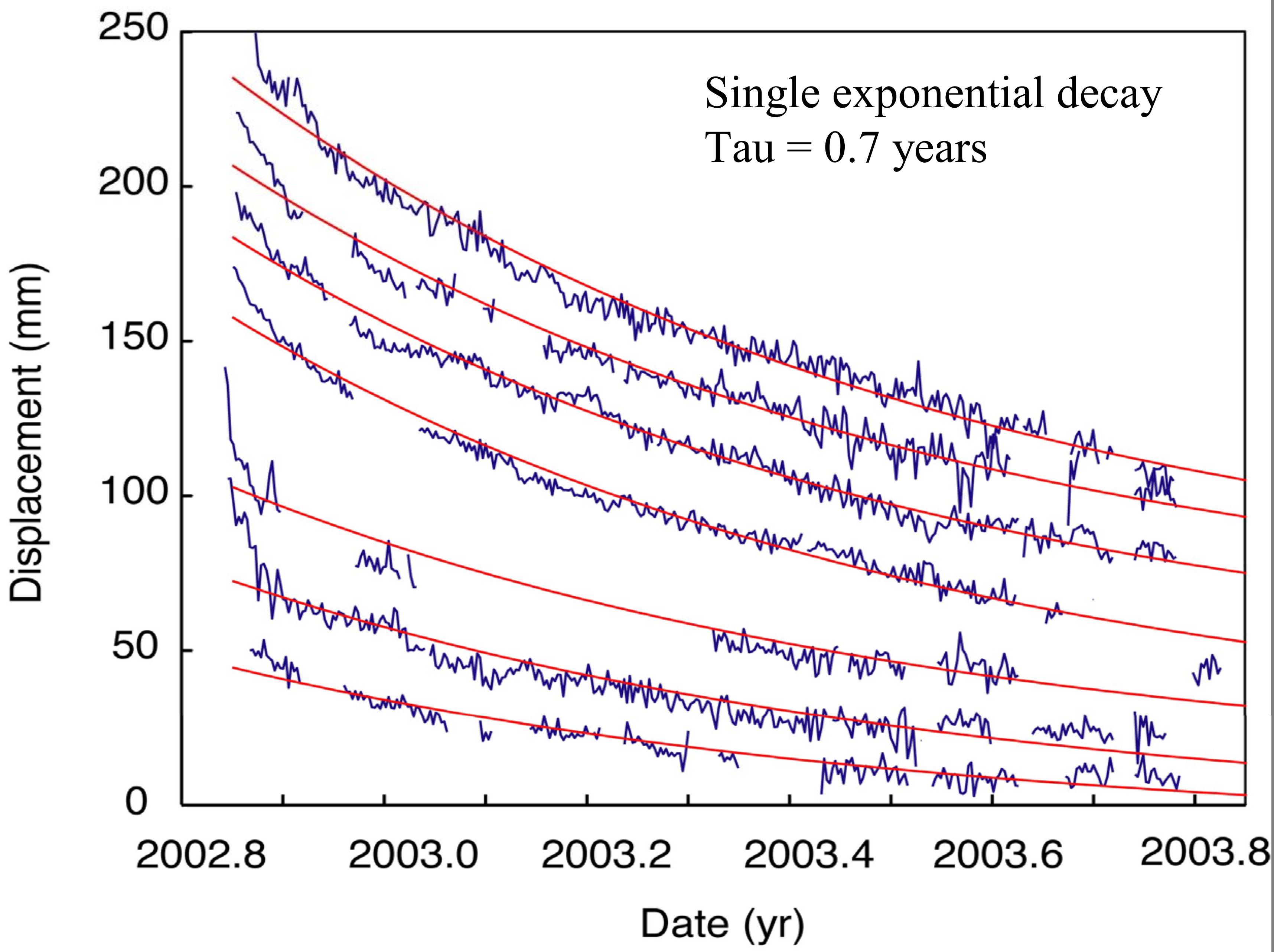
North (cm)
East (cm)
Displacement (cm)
Date (yrs)
North
East



North (cm)
East (cm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10 -8 -6 -4 -2 0 2 4 6 8 10
Displacement (cm)
Date (yr)
2003.0 2003.2 2003.4 2003.6 2003.8
Perpendicular
Parallel



Pre-earthquake velocities were only ~5 mm/yr


Single exponential decay
Tau = 0.7 years
Displacement (mm)
250
200
150
100
50
0
2002.8
2003.0
2003.2
2003.4
2003.6
2003.8
Date (yr)

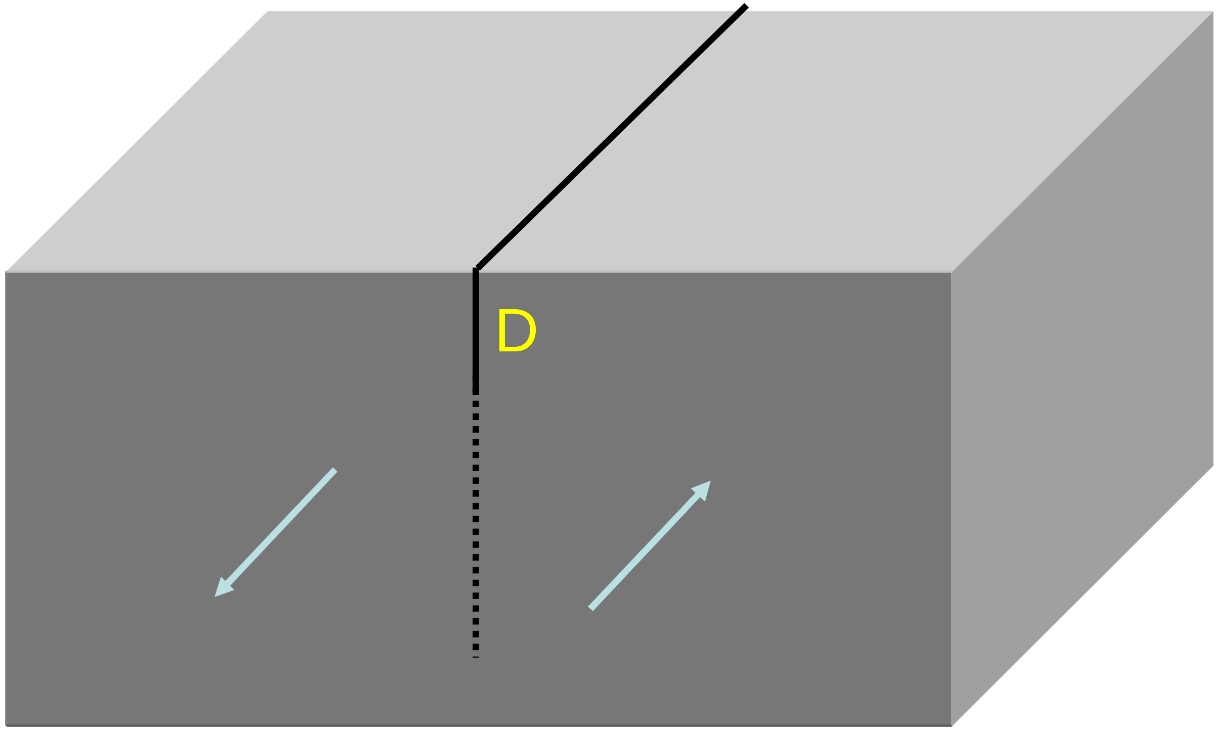
Postseismic Deformation

- Shallow afterslip
  - Commonly up to 10-20% of coseismic
- Deep afterslip
  - Can be significant fraction of coseismic
- Poroelastic relaxation
  - Groundwater migration caused by coseismic stress changes
- Viscoelastic relaxation
  - Flow in lower crust
  - Flow in upper mantle
- All mechanisms will occur, but which is most important?

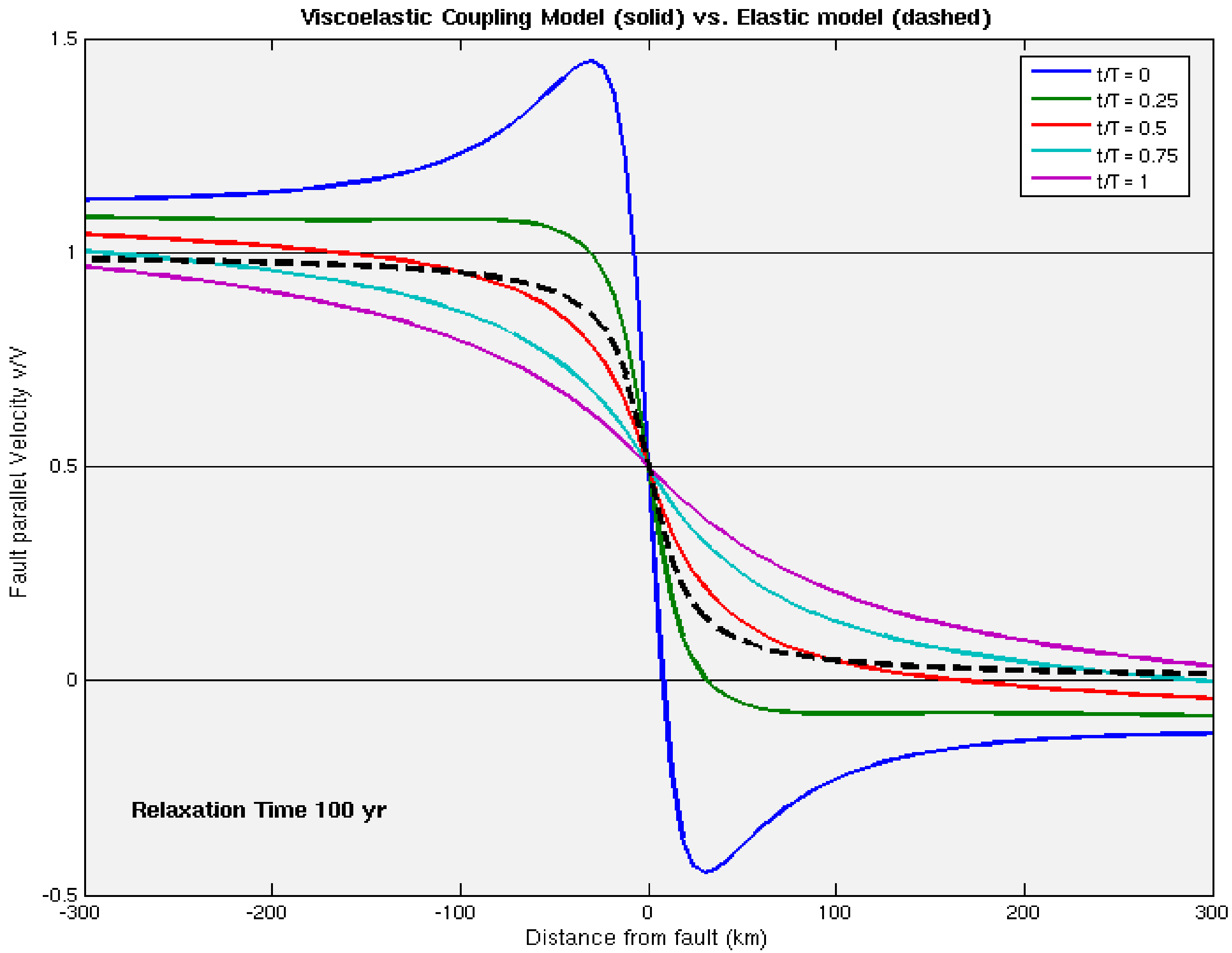
Where, How Much, How Long?

- Shallow afterslip
  - Very close to fault, weeks to months (maybe 1 year)
- Deep afterslip
  - Broader signal, usually decays within a few years
- Poroelastic relaxation
  - Concentrated close to fault, for larger earthquakes mostly several cm or less
- Viscoelastic relaxation
  - Can be very broad, may last for years to decades
- A rule of thumb: Postseismic effects are likely to be significant out to a distance of ~1 fault length away from rupture

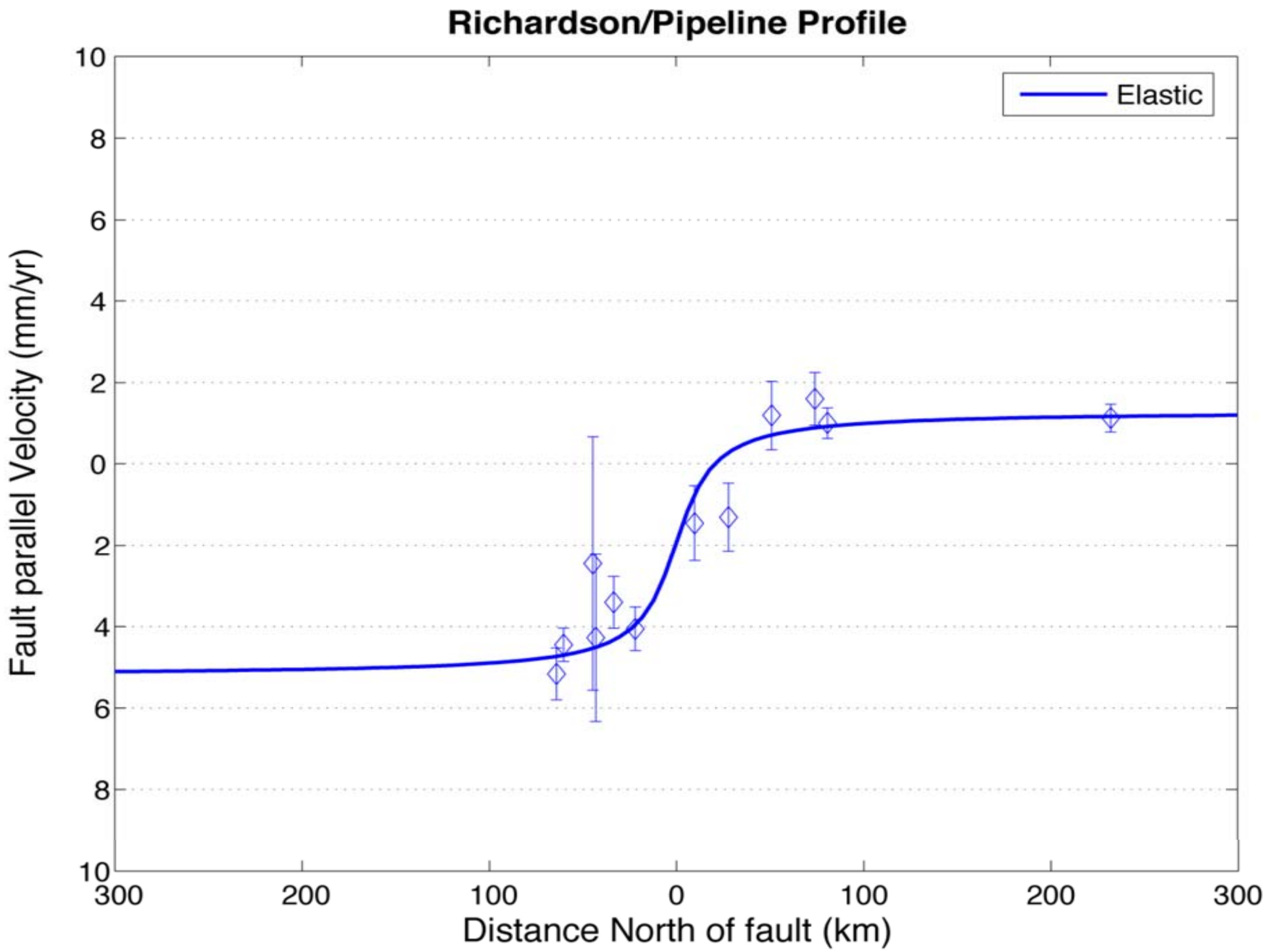
Viscoelastic Coupling Model



Common: Elastic half-space
Viscoelastic coupling model: Elastic layer over viscoelastic half-space
(Savage and Prescott, 1978)


Viscoelastic Coupling Model (solid) vs. Elastic model (dashed)
t/T = 0
t/T = 0.25
t/T = 0.5
t/T = 0.75
t/T = 1
Fault parallel Velocity v/V
Distance from fault (km)
Relaxation Time 100 yr
1.5
1
0.5
0
-0.5
-300
-200
-100
0
100
200
300

Data and Elastic Model



Data and Viscoelastic Model

A More Realistic Picture

Can divide fault zone based on how fault slips

- Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone
- Mantle is certainly viscoelastic, fault-mantle connection less clear
- Subject to intensive ongoing research