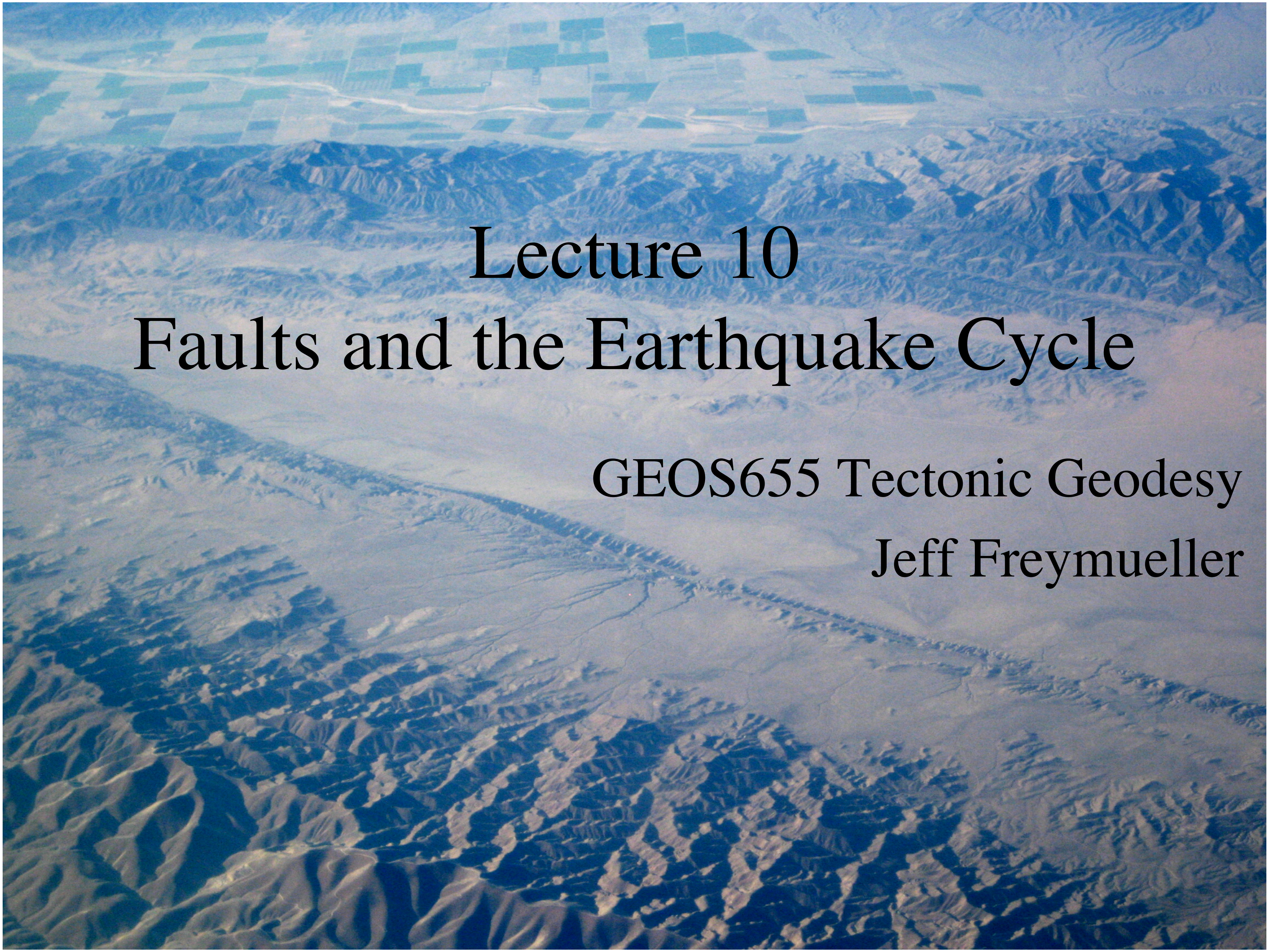
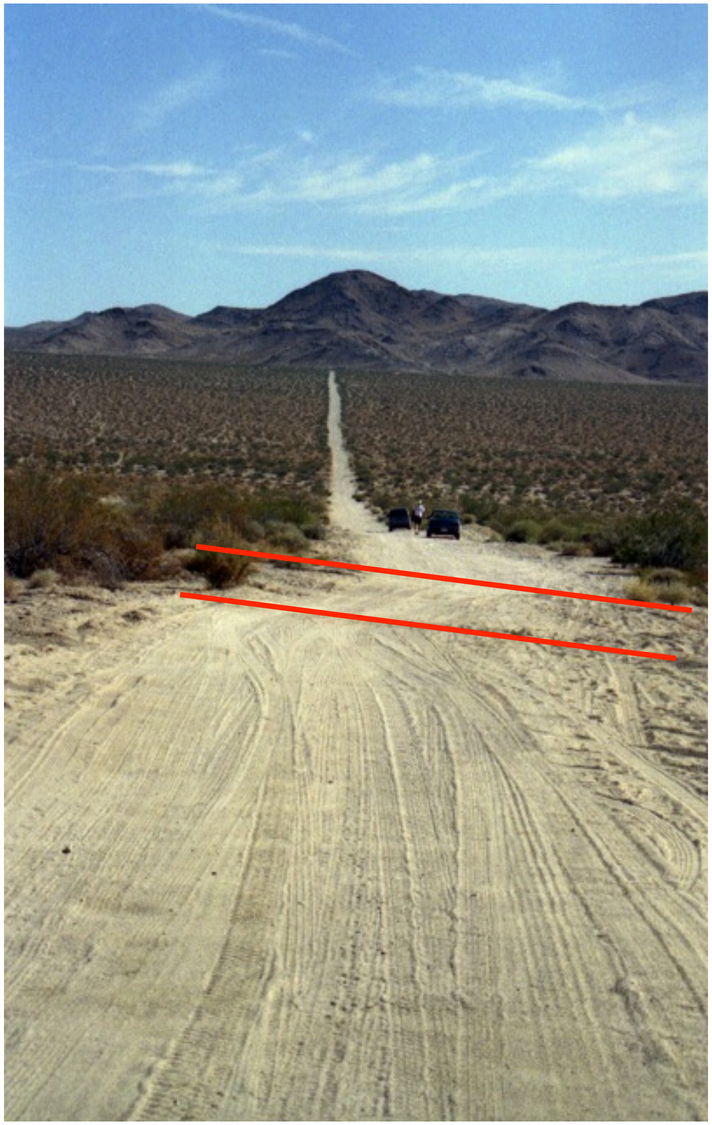


Lecture 10
Faults and the Earthquake Cycle

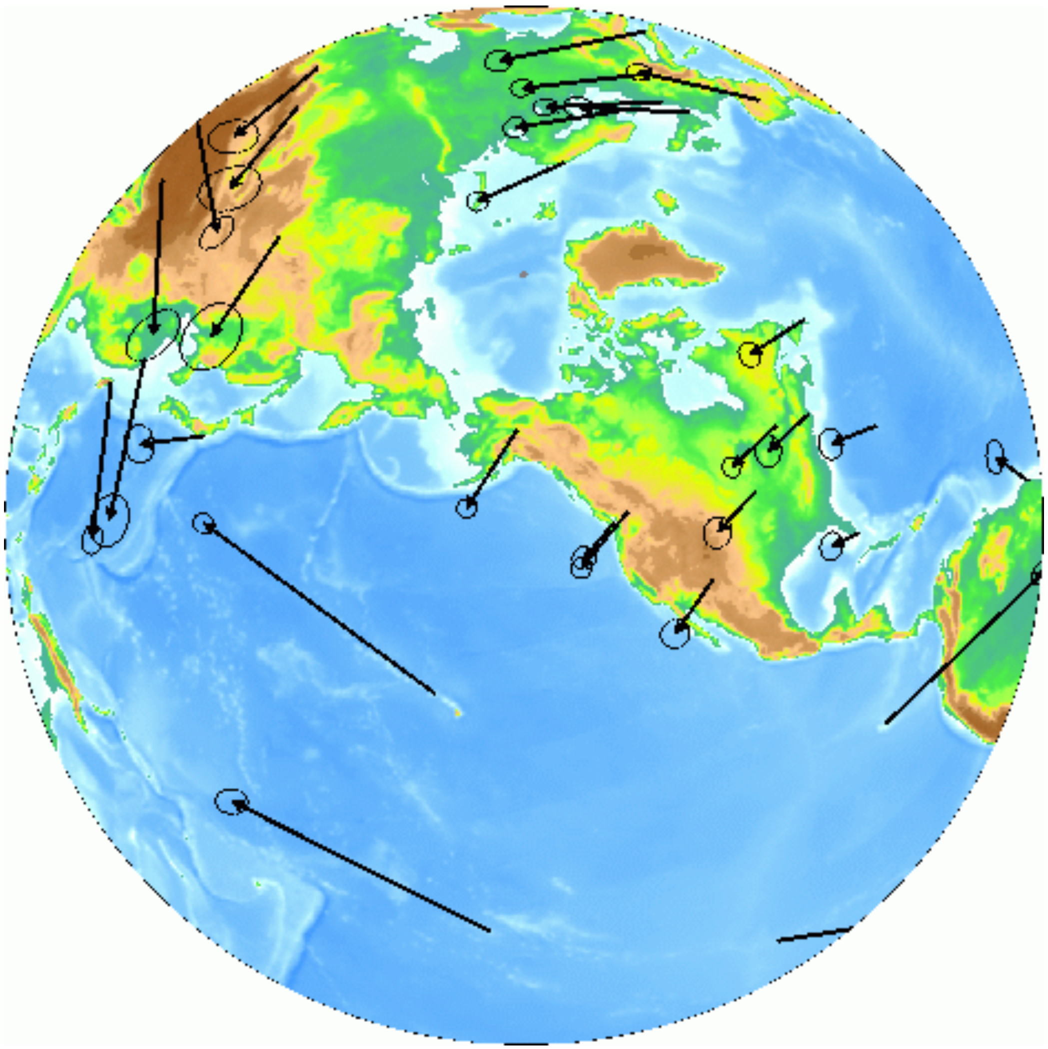
GEOS655 Tectonic Geodesy

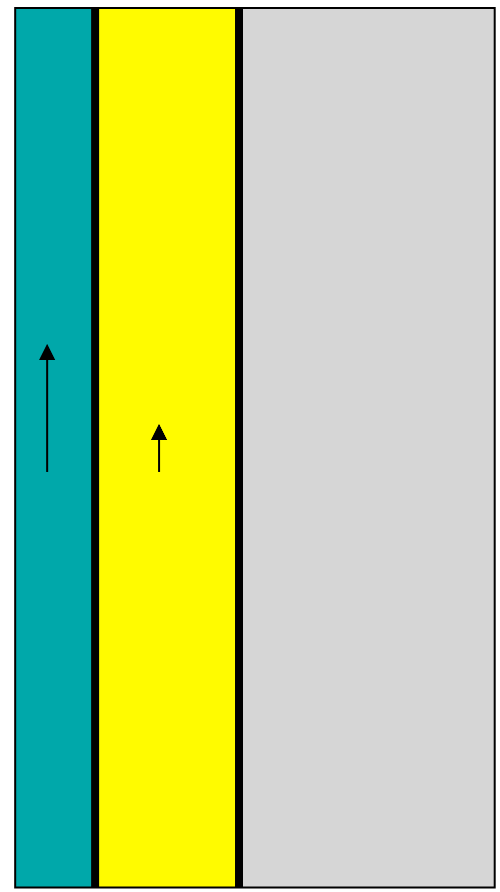
Jeff Freymueller

Faults at the Surface

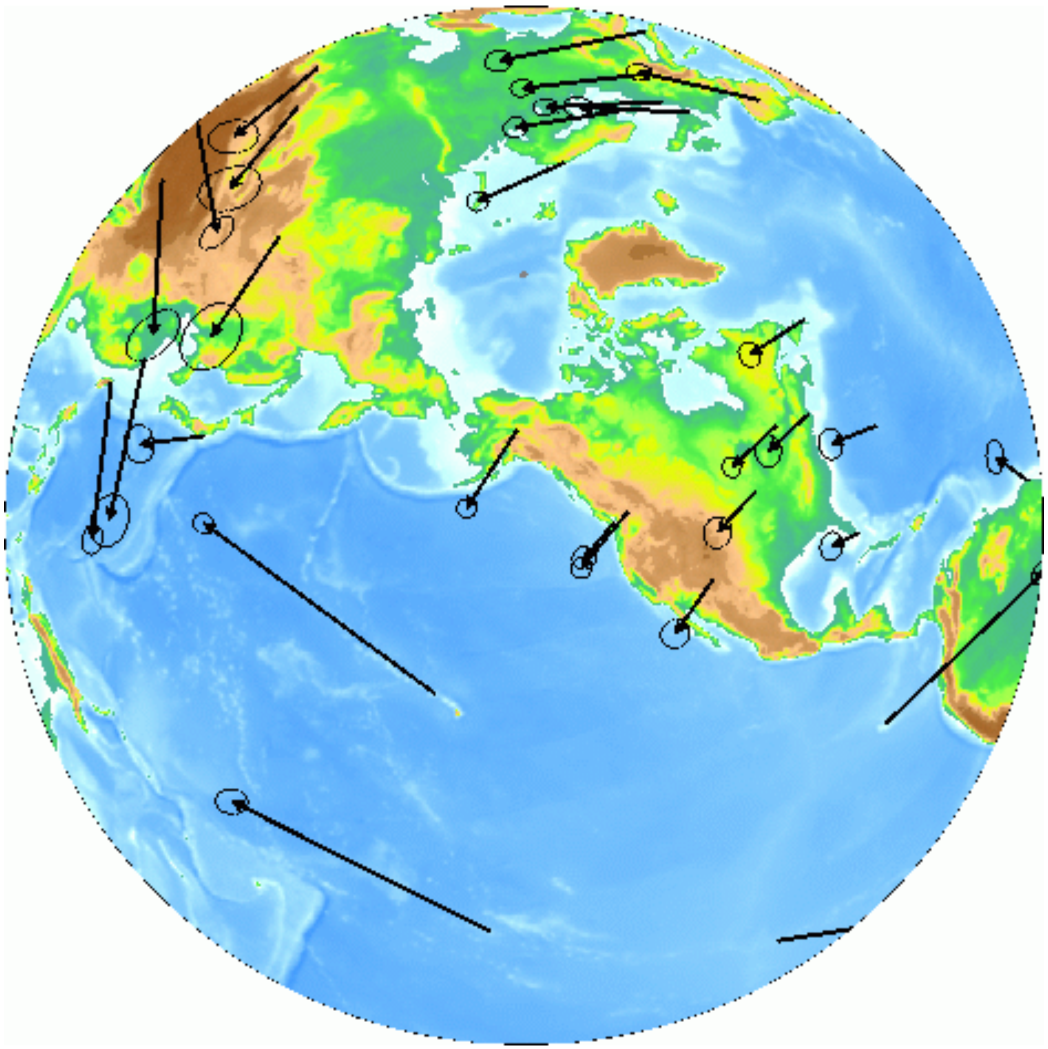


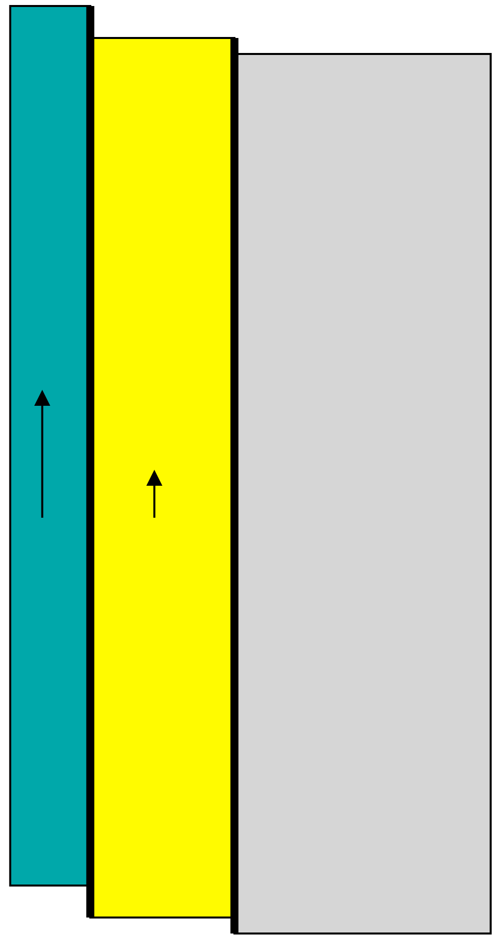
Block-like Motion



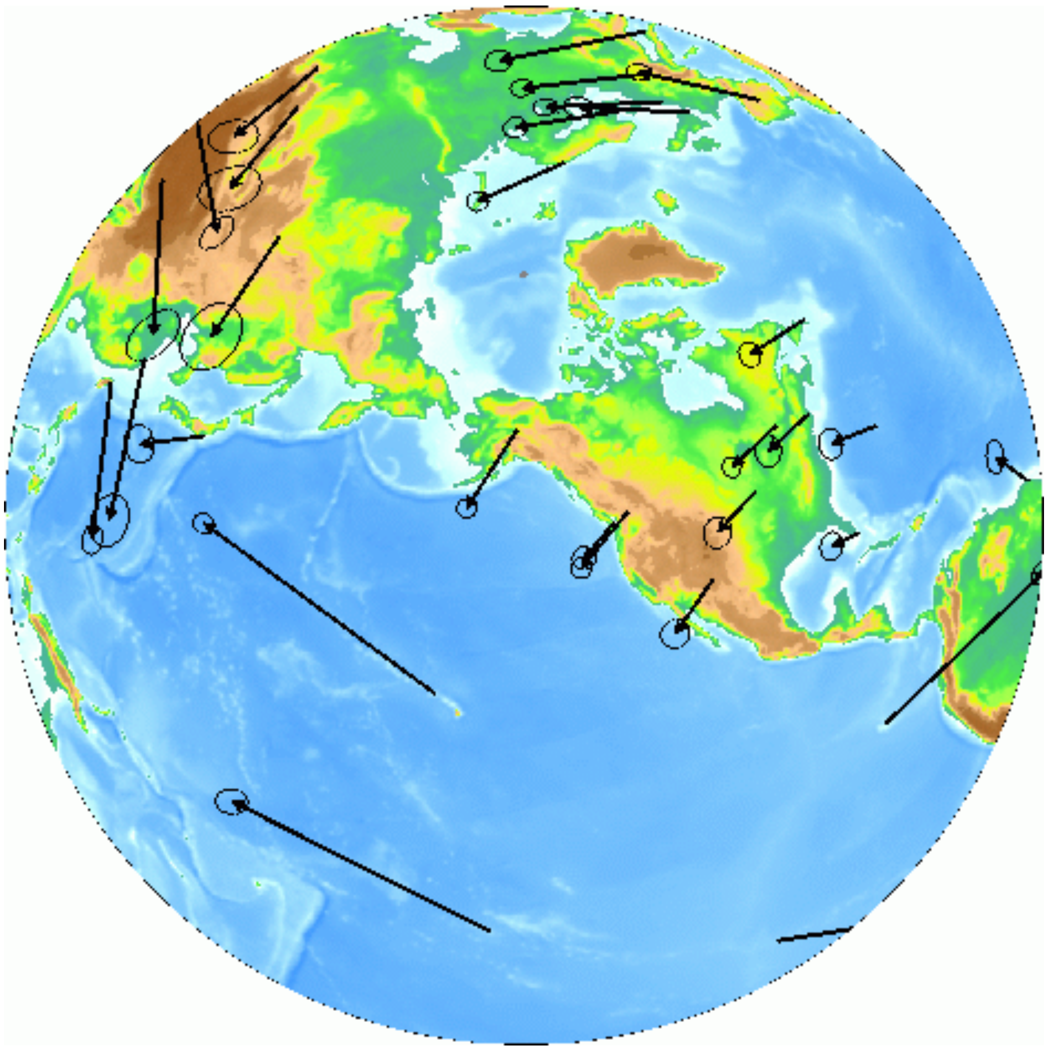


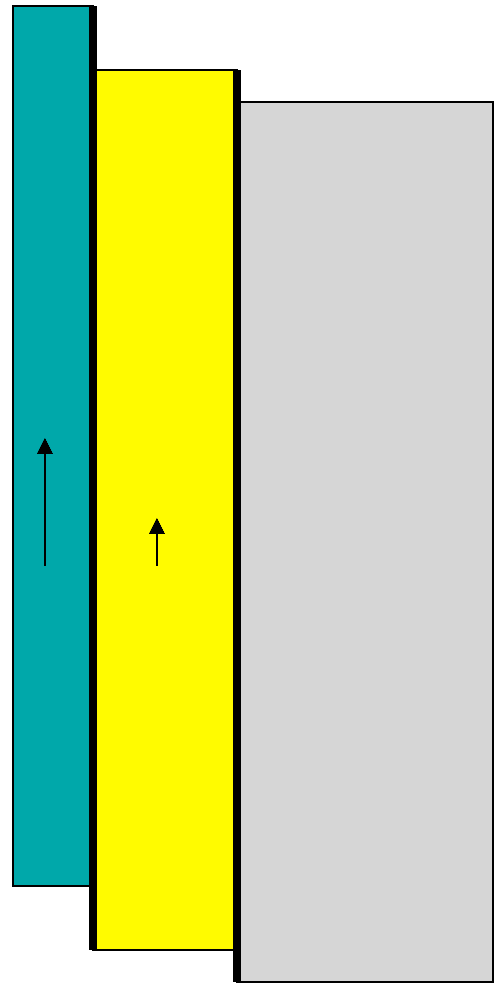
Block-like Motion



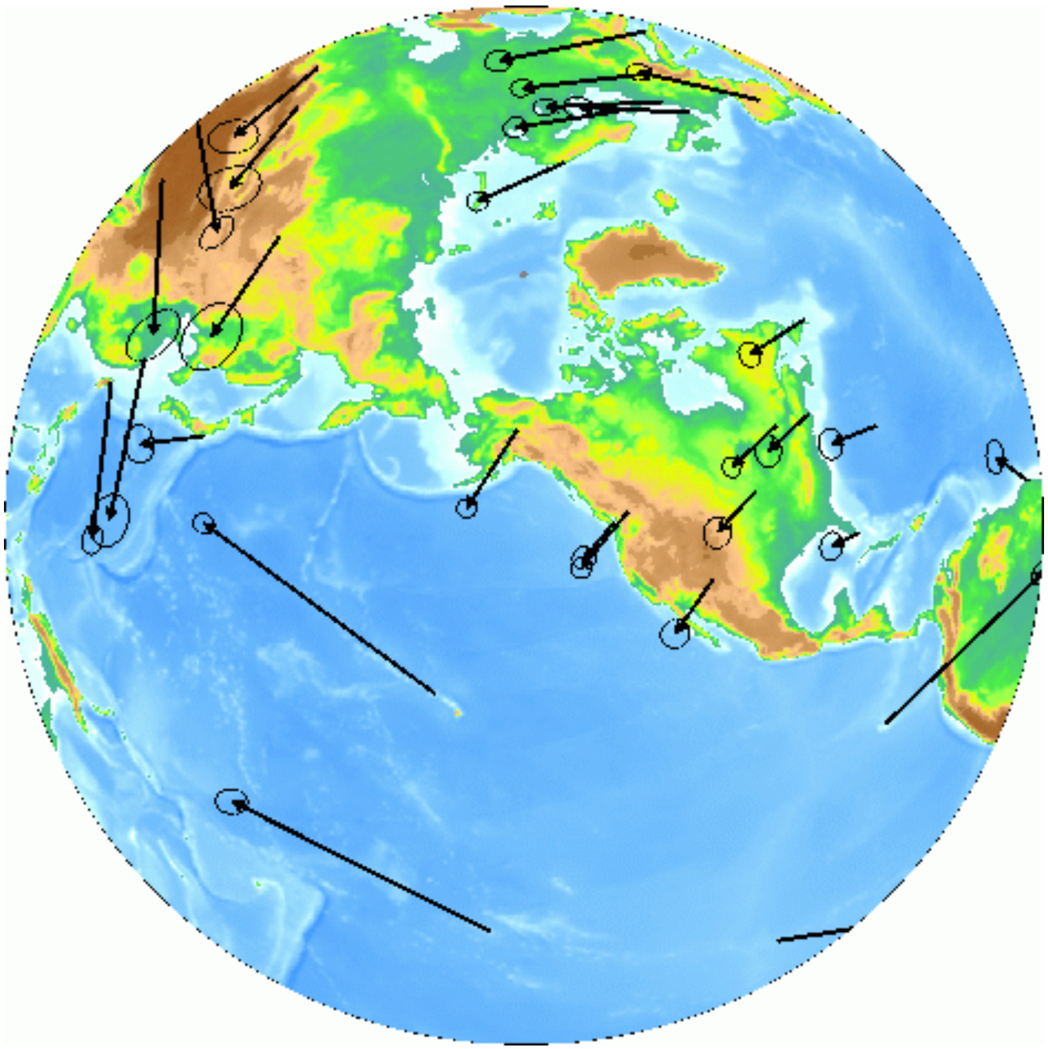


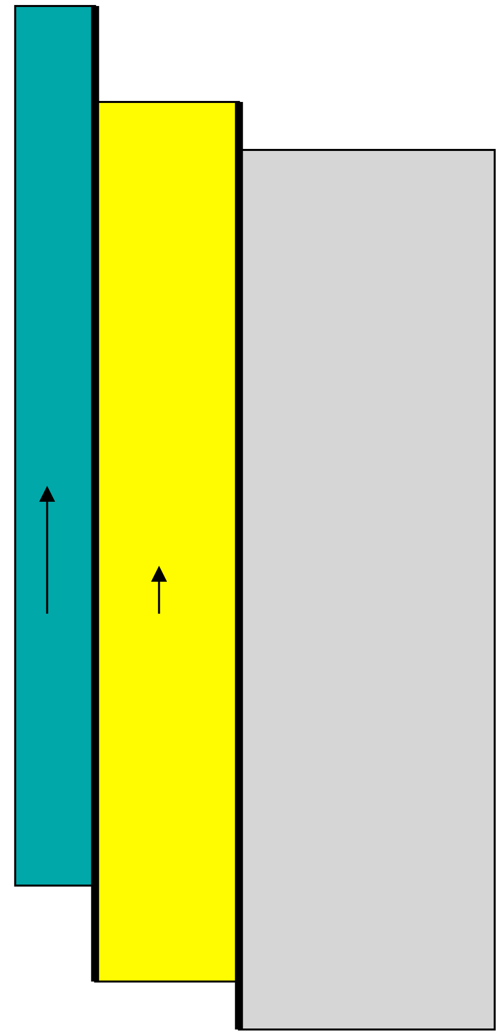
Block-like Motion





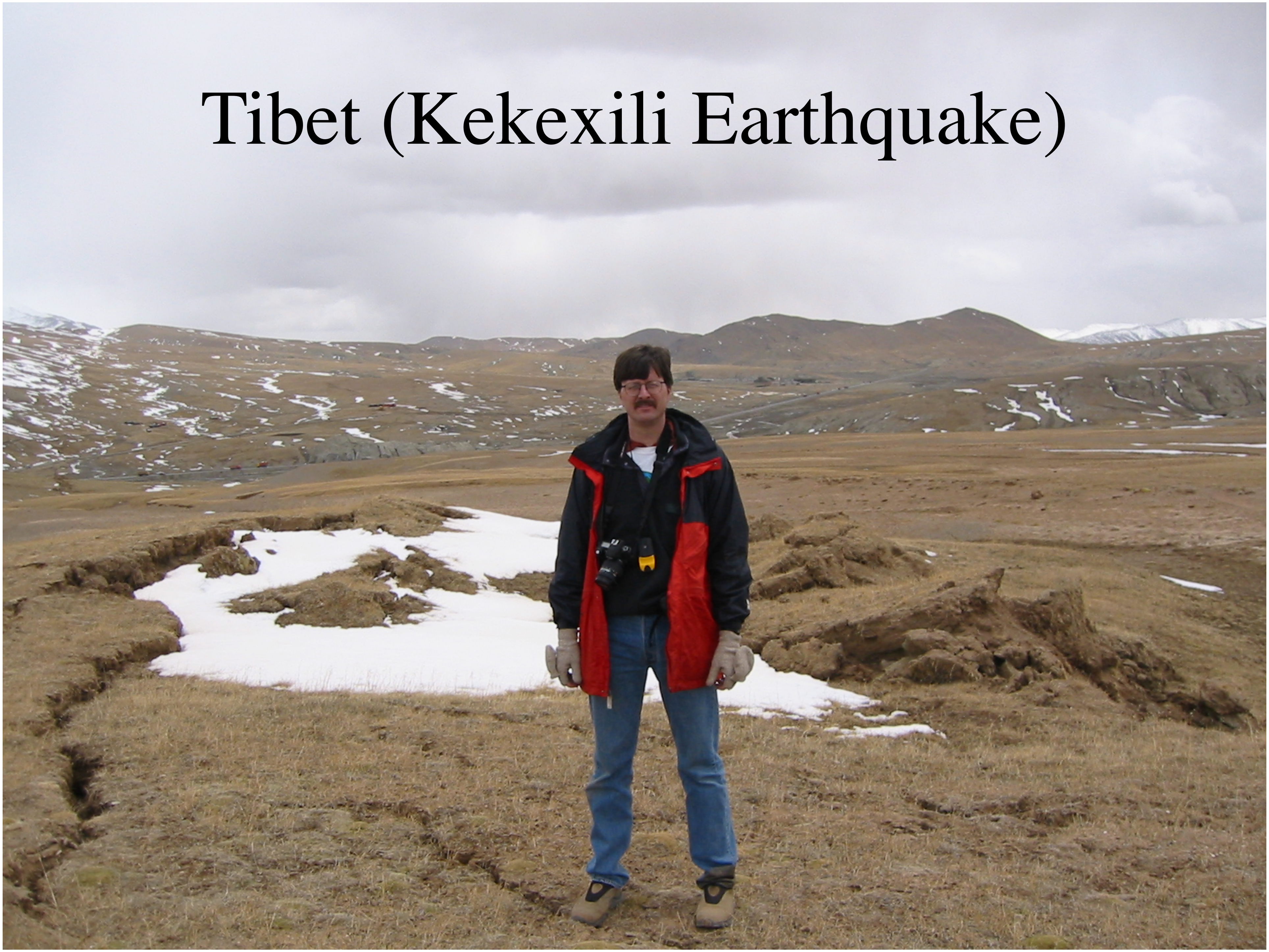
Block-like Motion



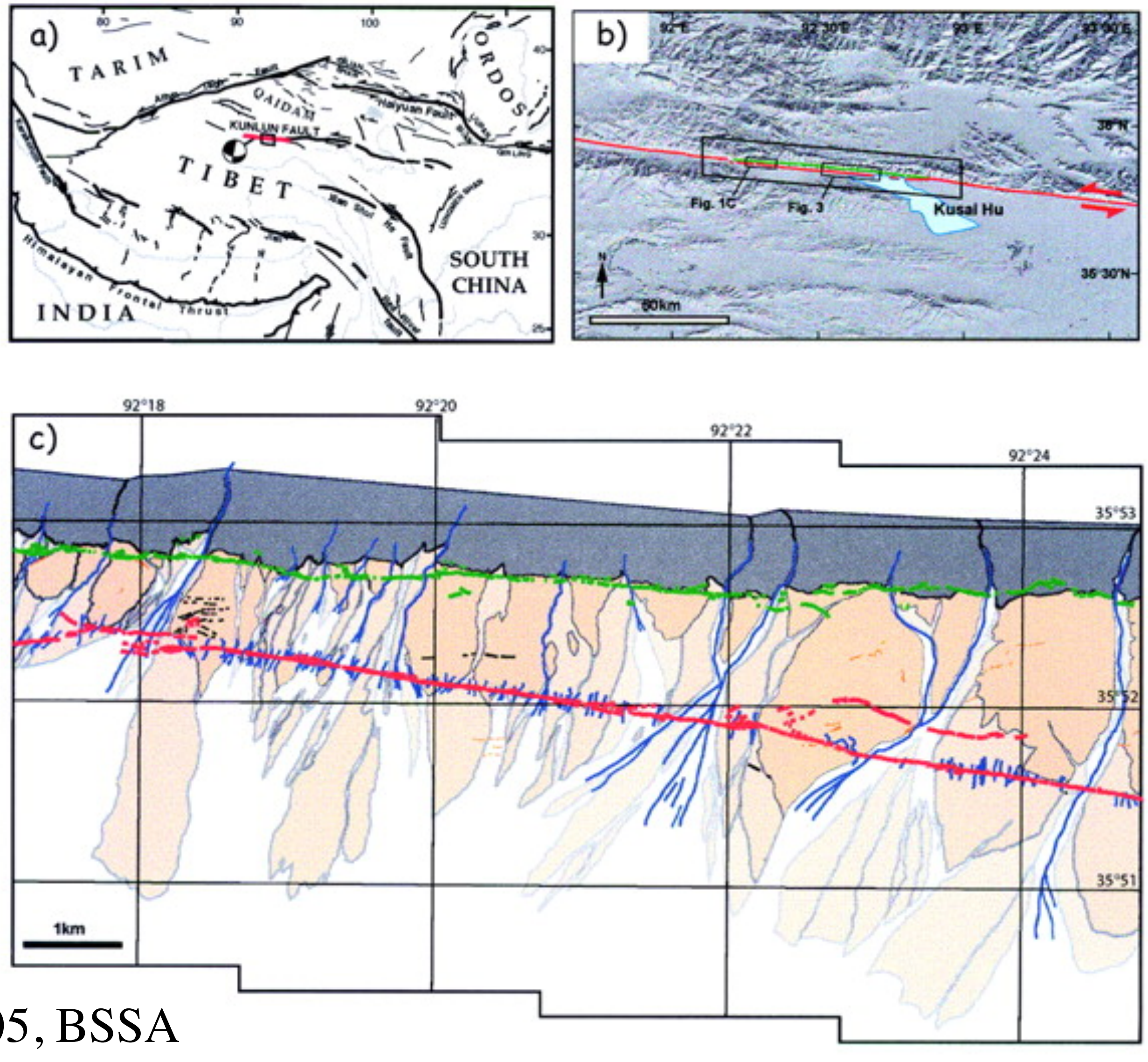


What is a Fault?

- A surface within the earth on which **slip** occurs.
- Usually considered to be planar.
- Not all cracks or breaks in rocks are faults.
- Fault offsets can be as small as millimeters or as large as hundreds of kilometers.
- Fault system: A set of related faults that play the same role.


Tibet (Kekexili Earthquake)

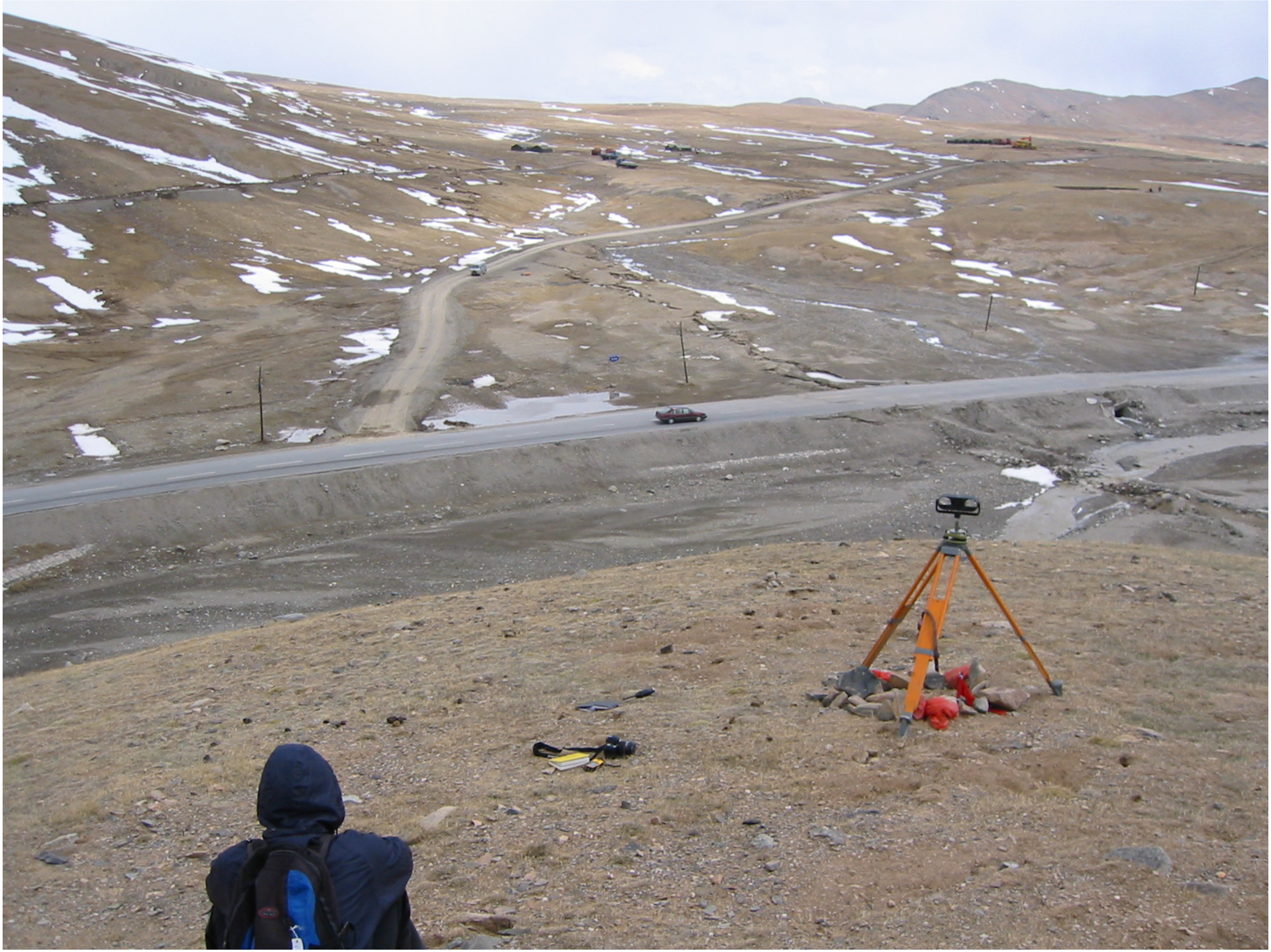
Setting and Rupture



King et al., 2005, BSSA

Surface Rupture

- Ruptured Kusai Lake segment of Kunlun fault and Kunlun Pass fault
- Approximately 2.5 meters displacement at crossing of Qinghai-Tibet Highway, ~6 meters displacement farther west on parts of the Kusai Lake segment



Denali Fault 2002

2002 Denali Fault Earthquakes

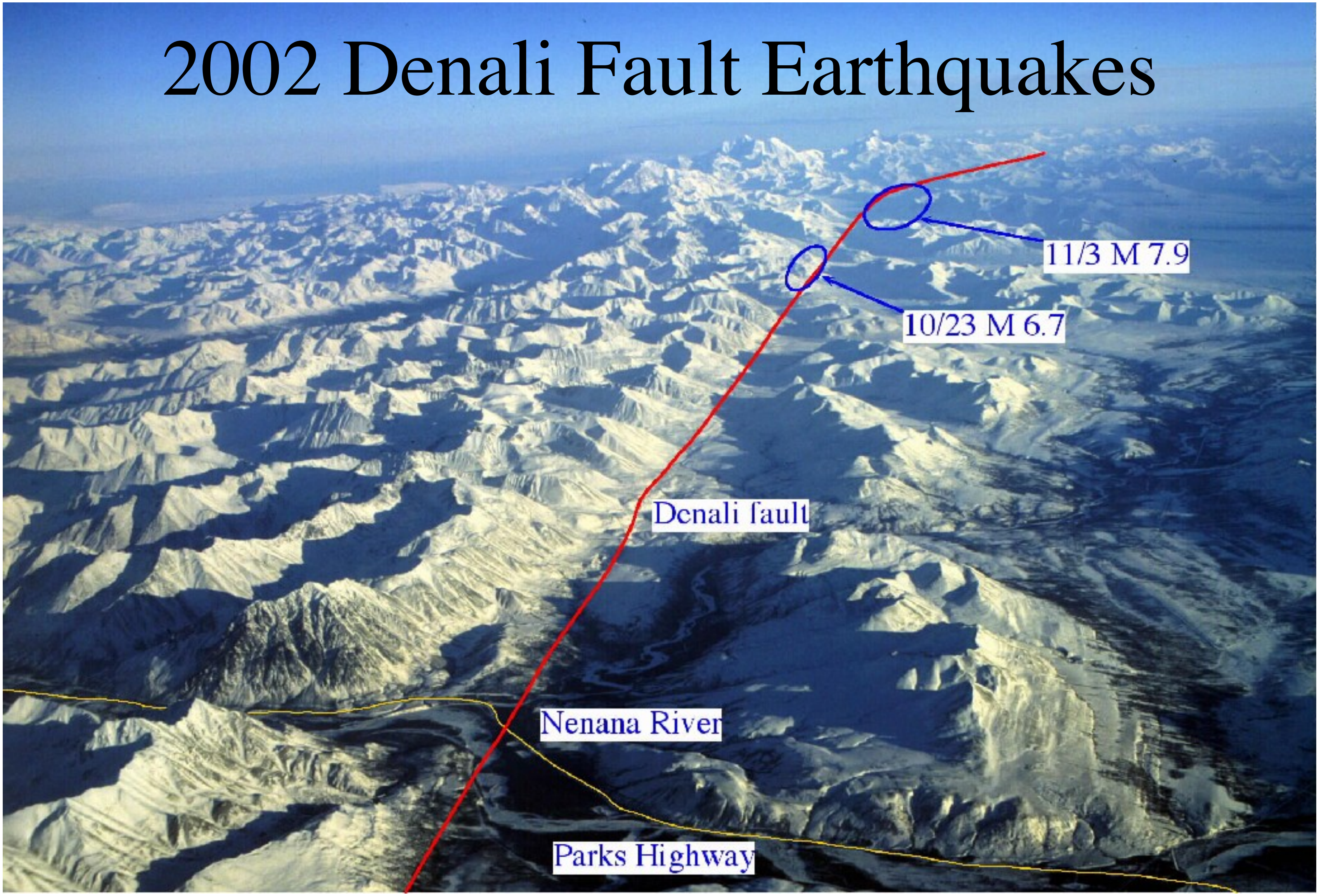


Photo Wes Wallace, UAF


Two minor fault strands

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

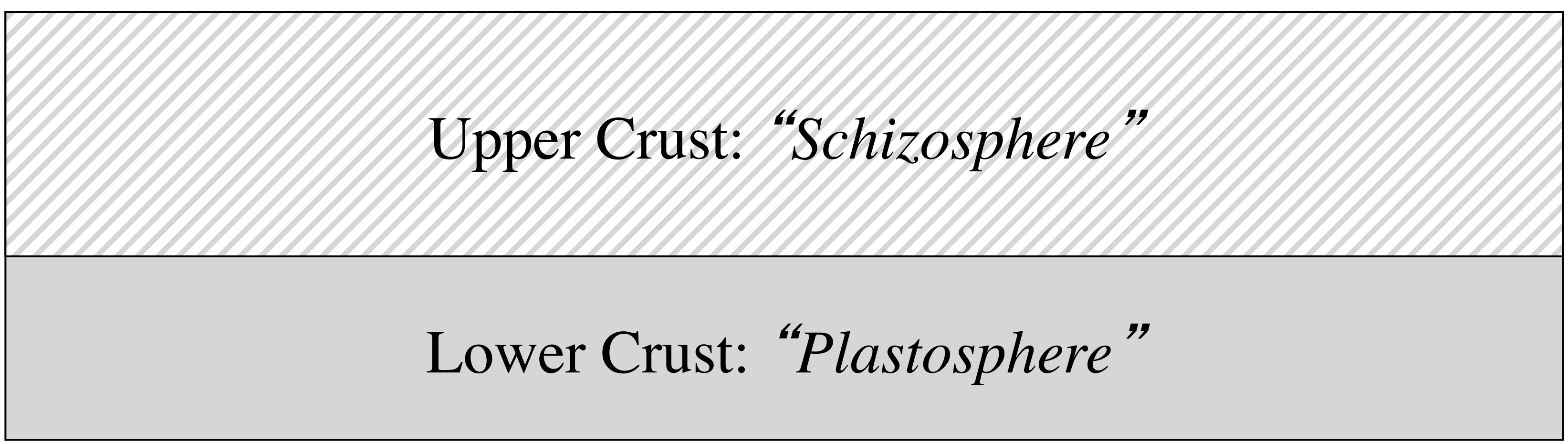
  Typical fault slip rates are mm to cm per year
- Why do faults move many years or centuries' worth of slip in a matter of seconds during an earthquake?

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



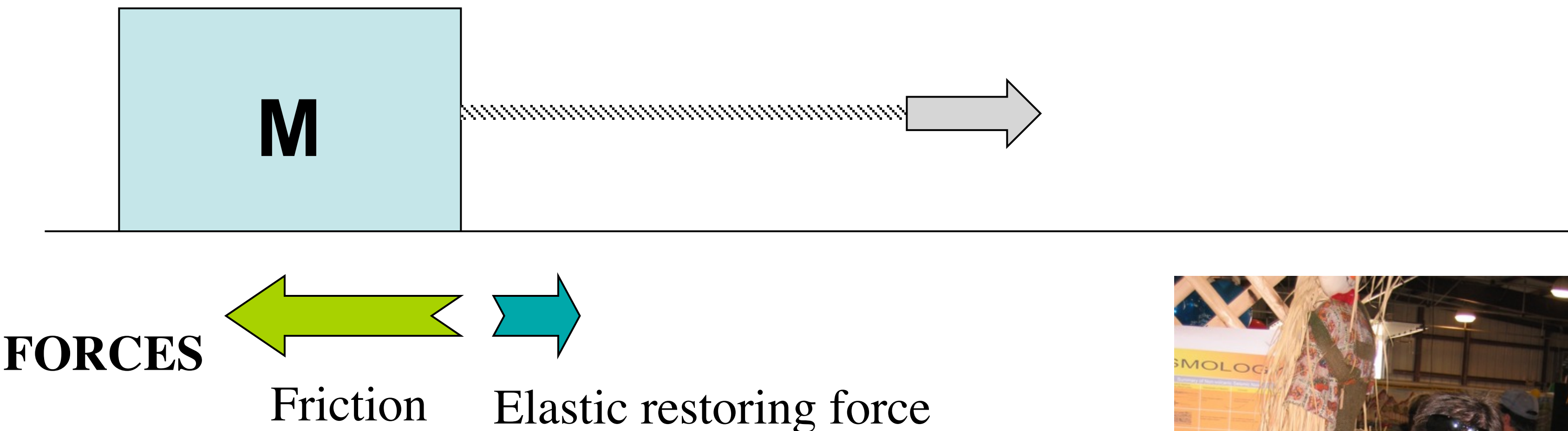
Is This Reasonable?

- 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

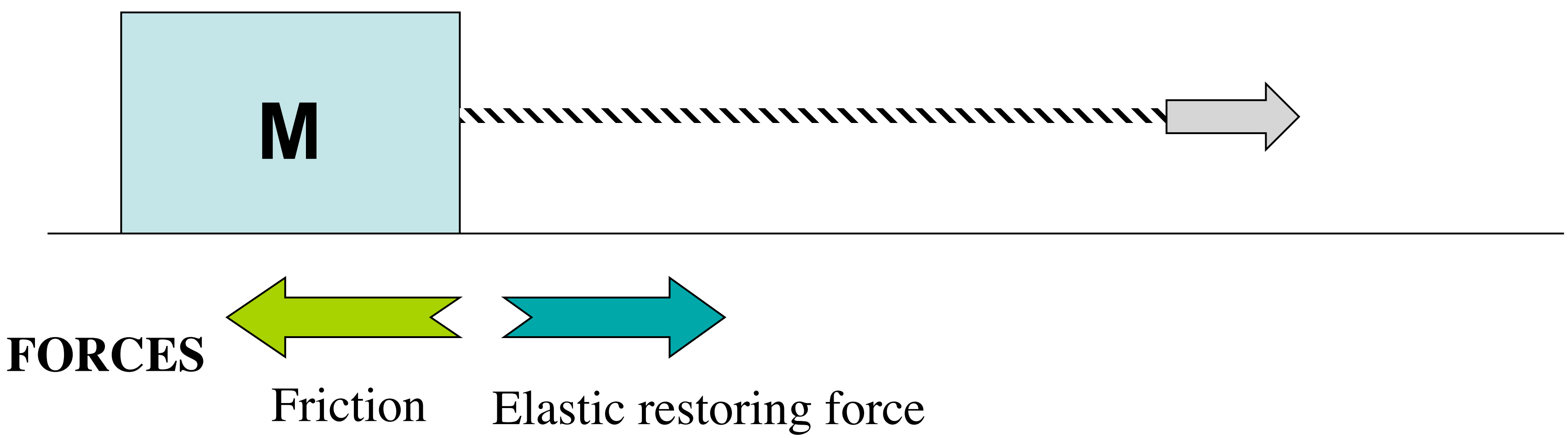
- Stick-slip (seismic)
  - Two sides of interface stuck together: **friction**
  - Slip occurs when friction is overcome
  - Slip controlled by dynamic friction, healing
- Stable Sliding (aseismic)
  - Two sides slide continually past each other
  - Slip occurs all the time
  - Slip controlled by plastic,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

A Simple Analogue: Spring Slider



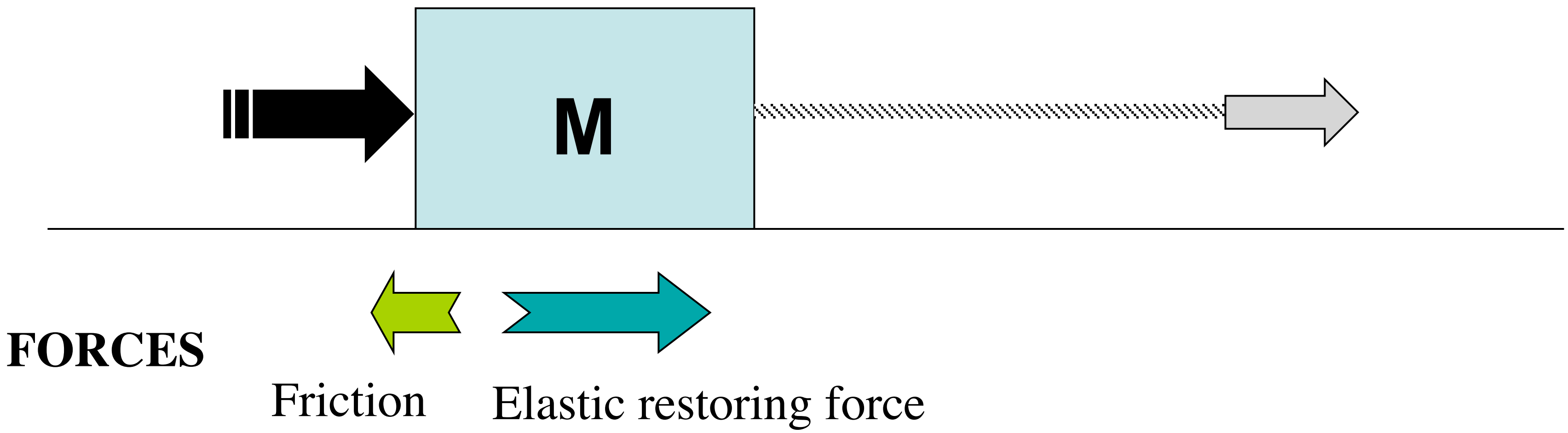
- Block is held in place by force of friction

A Simple Analogue: Spring Slider



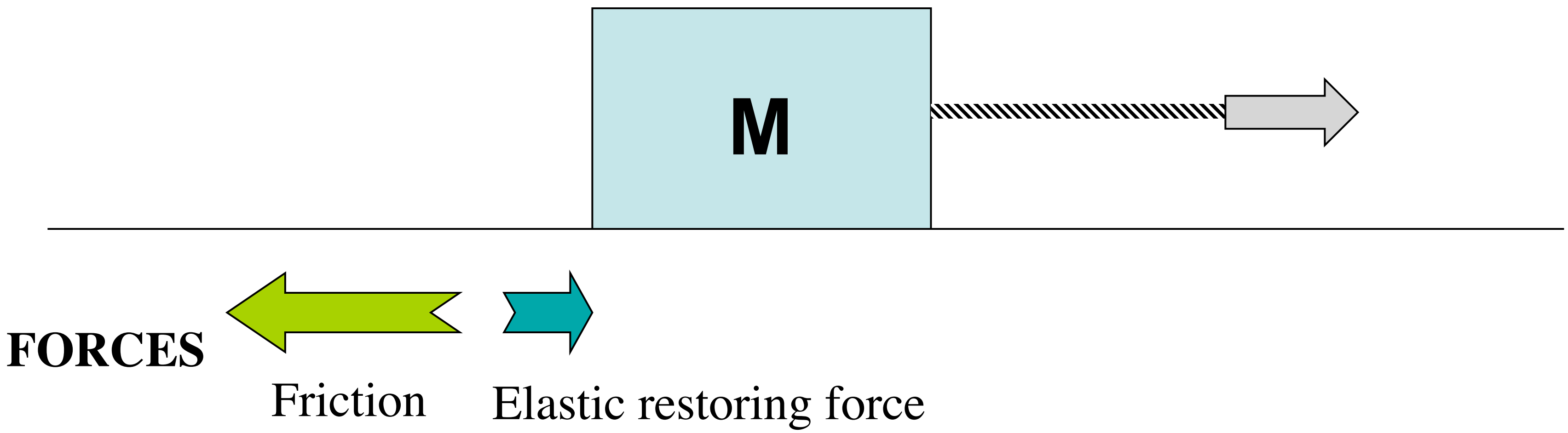
- Block is held in place by force of friction
- Moving load point increases elastic force

A Simple Analogue: Spring Slider



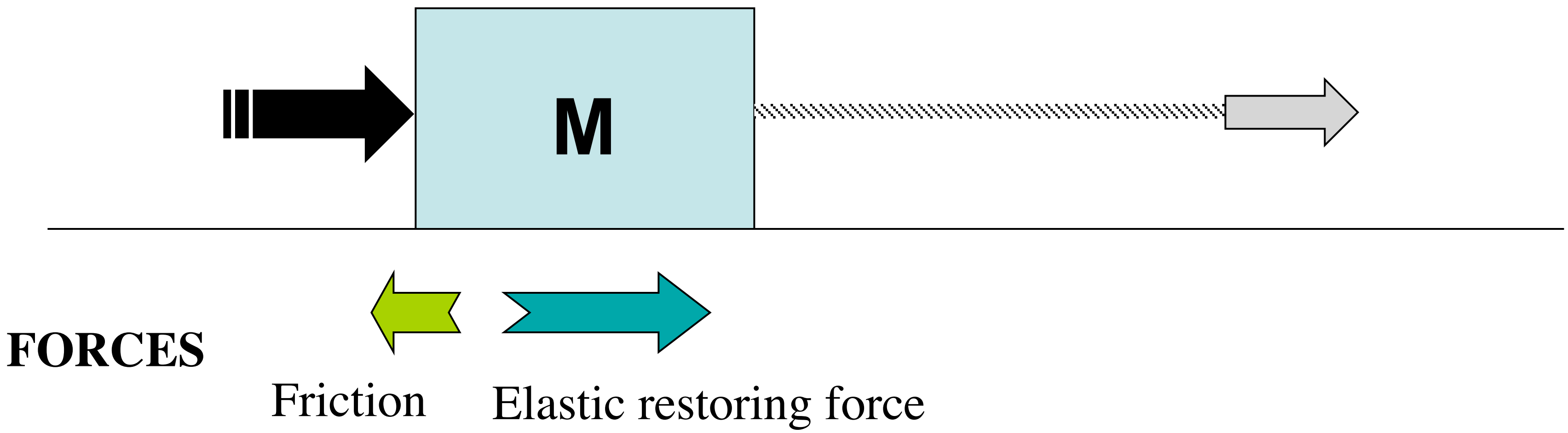
- Block is held in place by force of friction
- Moving load point increases elastic force
- Slips when elastic force exceeds friction

A Simple Analogue: Spring Slider



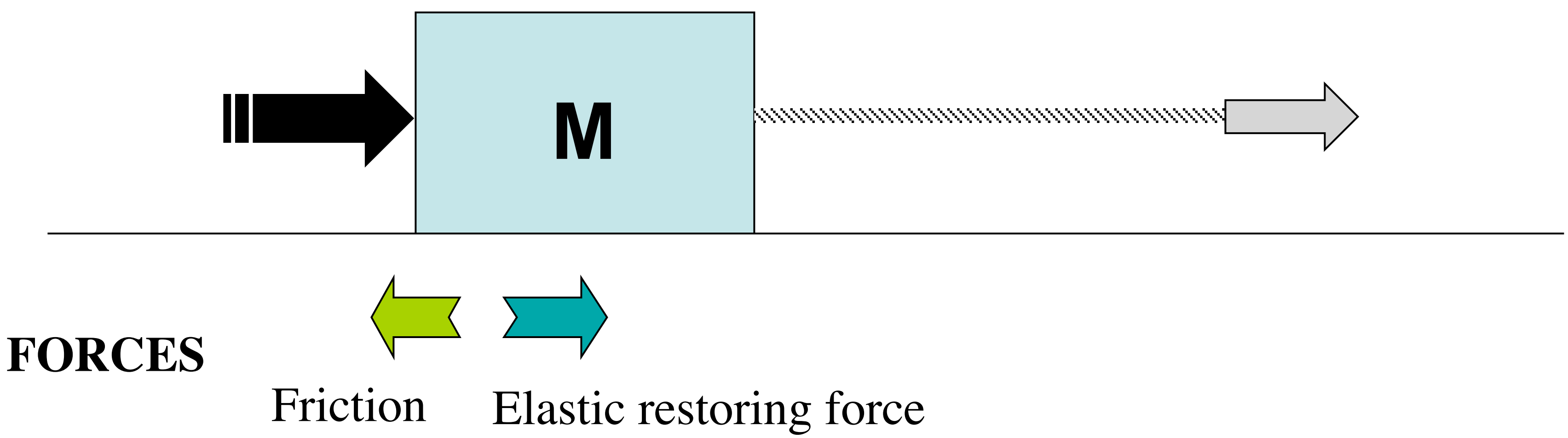
- Block is held in place by force of friction
- Moving load point increases elastic force
- Slips when elastic force exceeds friction

Frictional Instability



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

Alternative: Stable Sliding



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

Rate and State Friction Law

- Freshman physics: static friction and dynamic friction
  - How does static friction transition to dynamic?
- 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
- Based on curve fitting rather than fundamental physics, but it works!

Rate and State Friction Law

- The rate and state friction law describes the coefficient of friction in terms of the rate of sliding and a state variable. The state variable evolves with time according to a state evolution law.

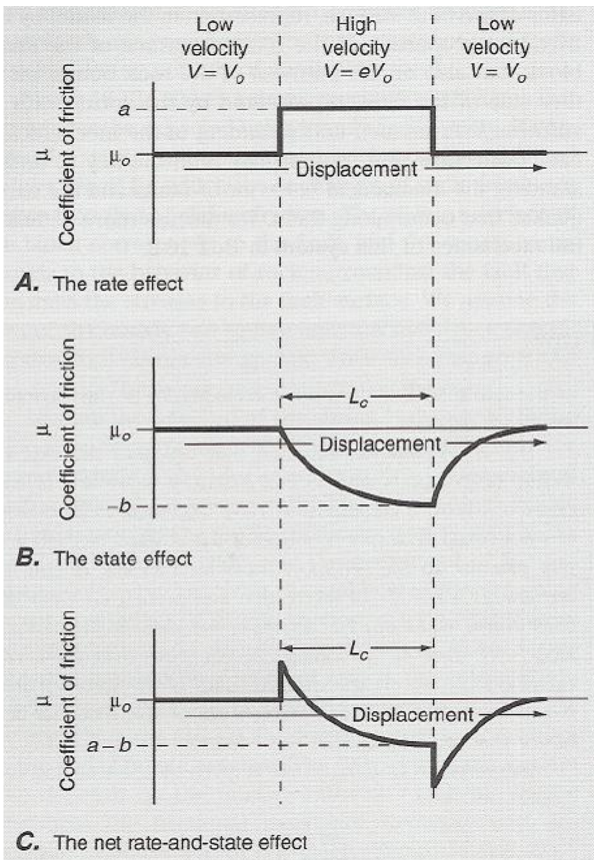
$$\mu(V,\theta) = \mu_0 + a\ln\left(\frac{V}{V_0}\right) + b\ln\left(\frac{V_0\theta}{D_c}\right)$$

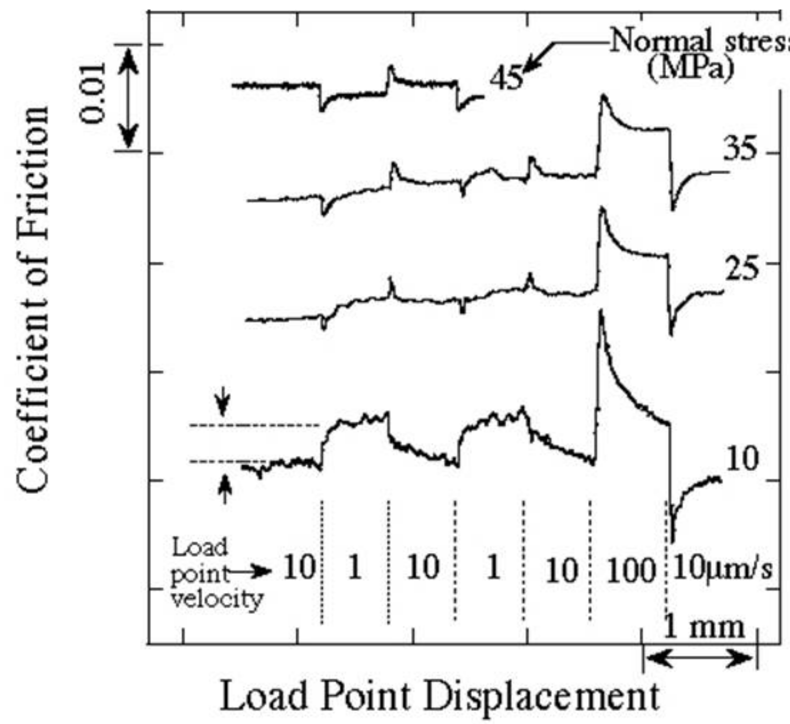
$$\frac{d\theta}{dt} = 1 - \left(\frac{V\theta}{D_c}\right)$$

- At steady state ($\theta_{ss} = D_c/V_{ss}$),

$$\mu_{ss} = \mu_0 + (a-b)\ln\left(\frac{V}{V_0}\right)$$

Examples from the Lab





Stability of Slip

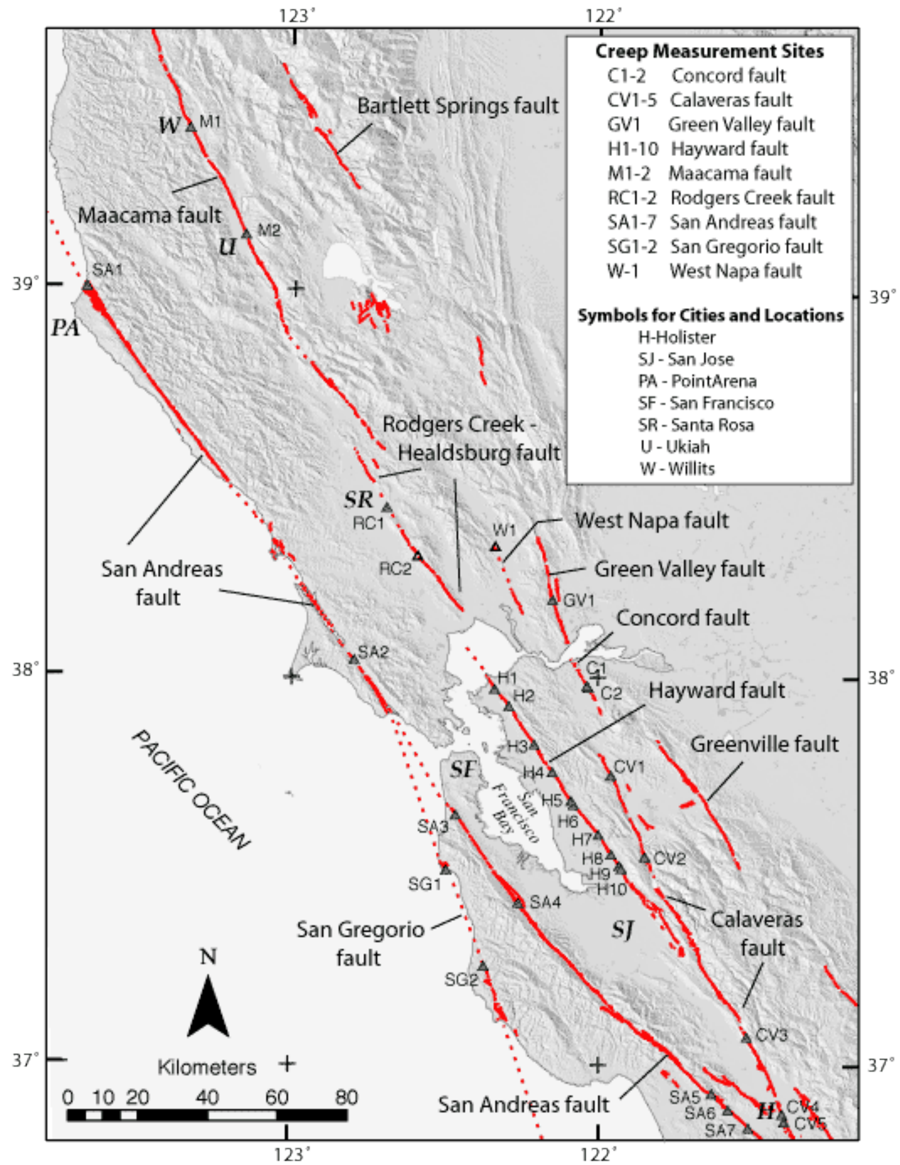
$$\mu_{ss} = \mu_0 + (a - b)\ln\left(\frac{V}{V_0}\right)$$

- The rate and state law predicts that slip can either be stable or unstable
  - Velocity strengthening = stable (a–b ≥ 0)
    - Friction ***increases*** as slip velocity increases, retards slip acceleration
  - Velocity weakening = unstable (a–b < 0, high normal stress)
    - Friction ***decreases*** as slip velocity increases, causing runaway acceleration of slip ➔ an earthquake
    - The runaway stops quickly because the stored elastic strain energy is depleted
  - Conditionally stable (a–b < 0, high normal stress)
    - System slips stably because elastic stresses decrease faster than coefficient of friction

Creeping Faults (Willits, CA)

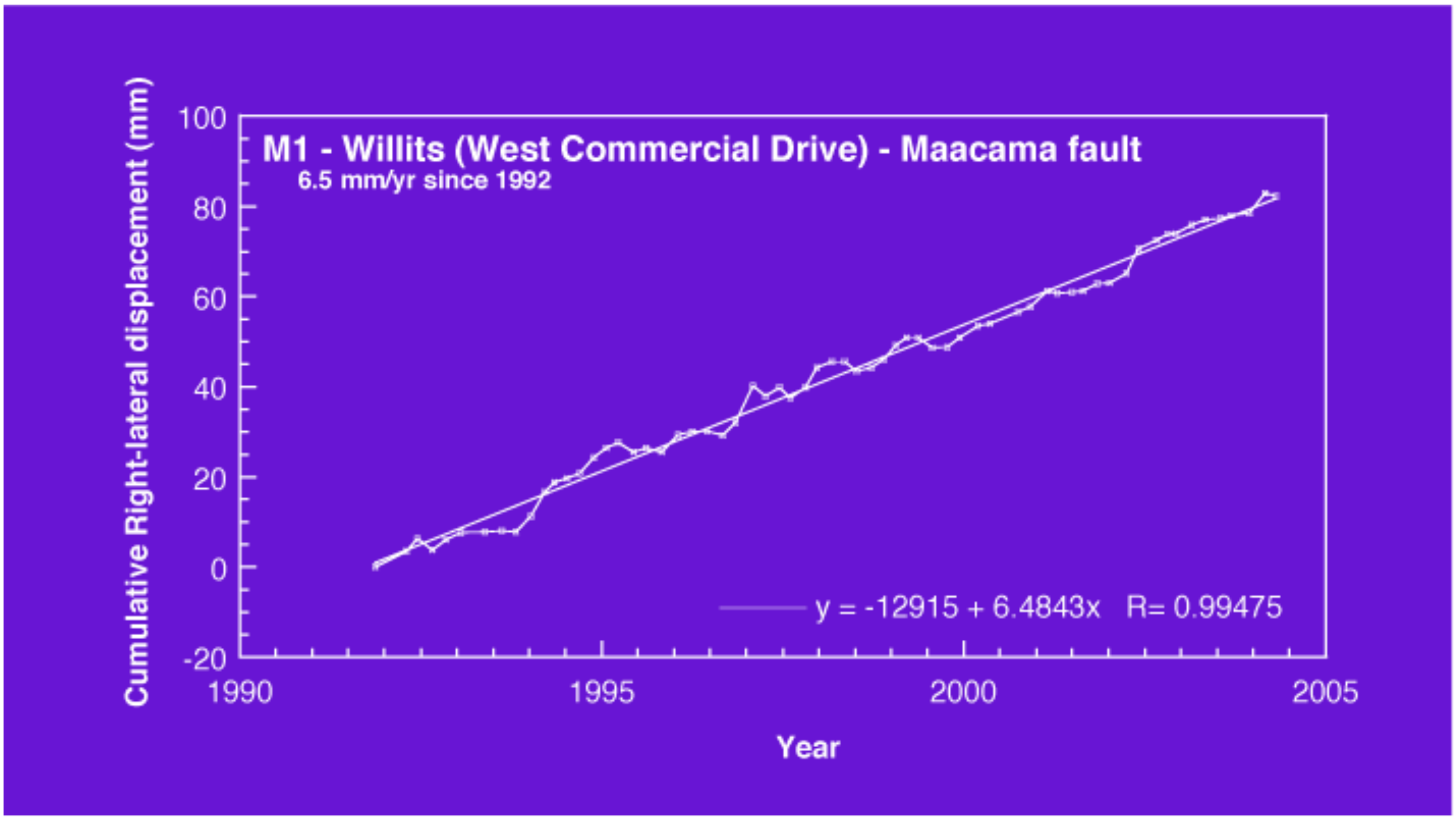
Can you spot the fault?

Creep Monitoring

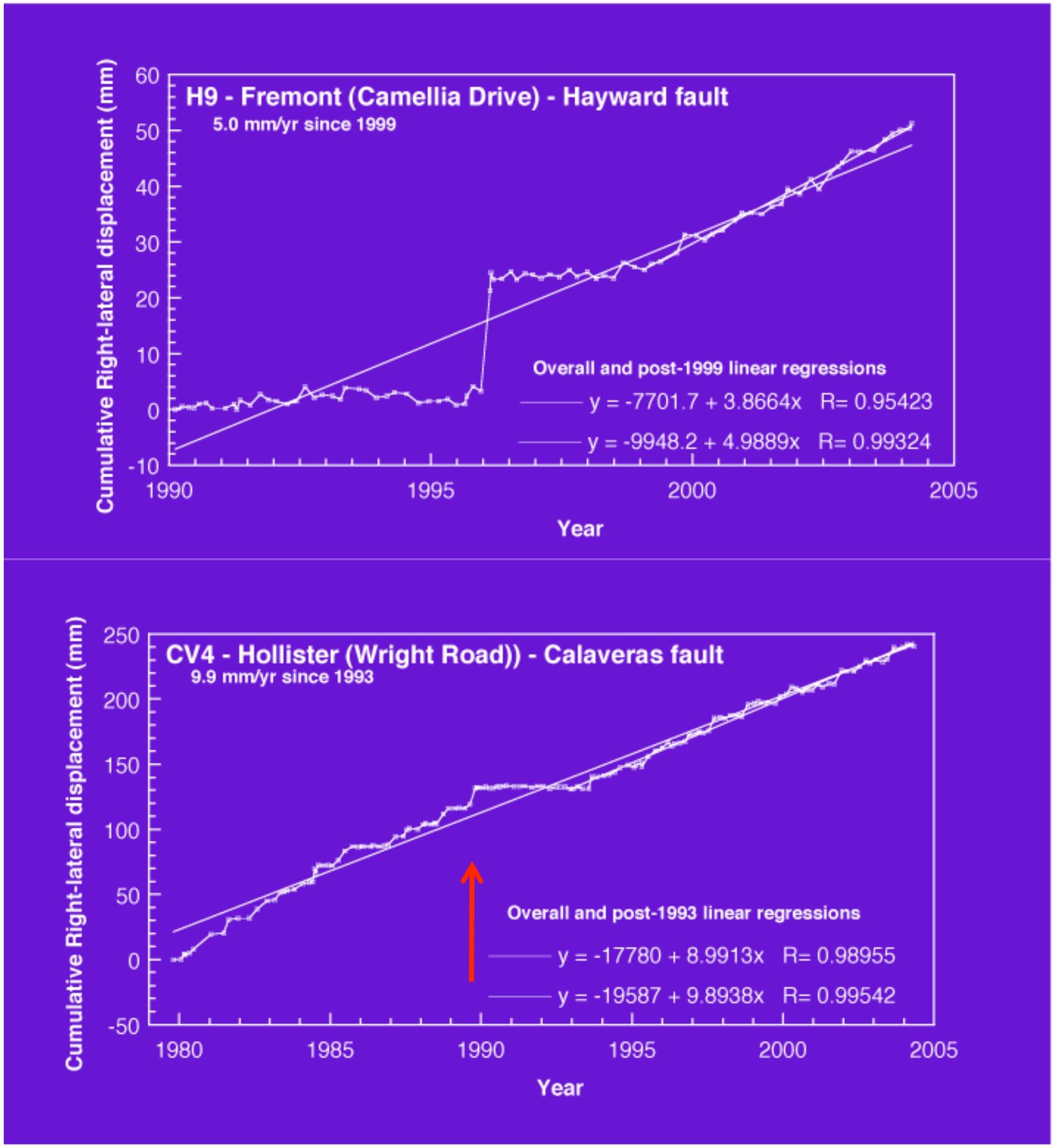


- San Francisco State U. has been running a fault creep monitoring program for almost 30 years:
- http://funnel.sfsu.edu/creep/CreepMap.html

Here is the Willits Creep Rate



Time-dependent Creep



1996
Creep event

1998.5
Creep resumes

1989
Loma Prieta

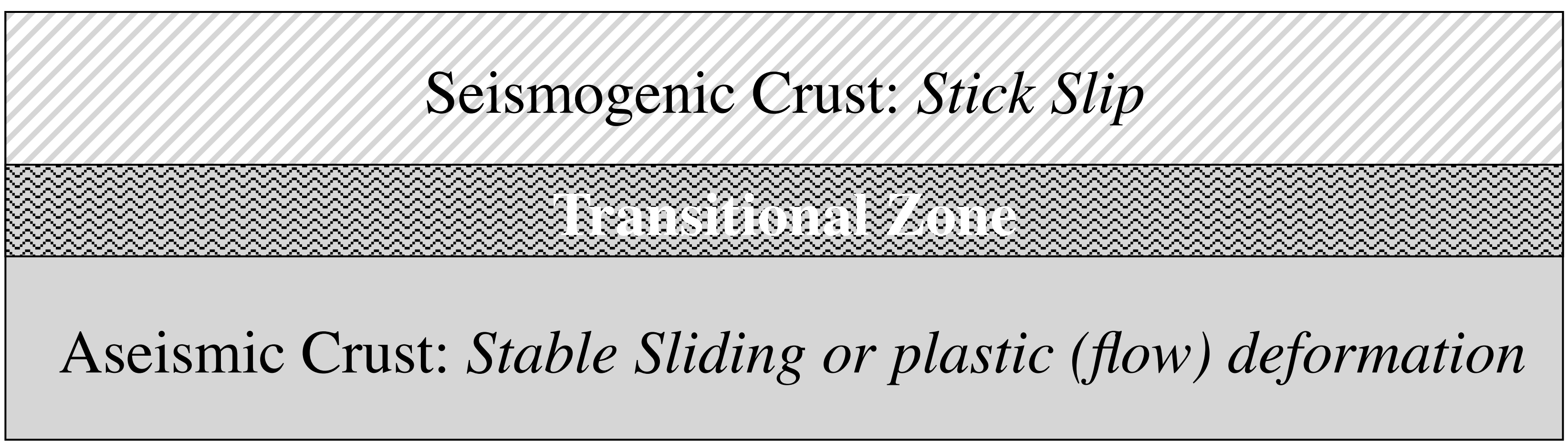
1993
Creep resumes

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

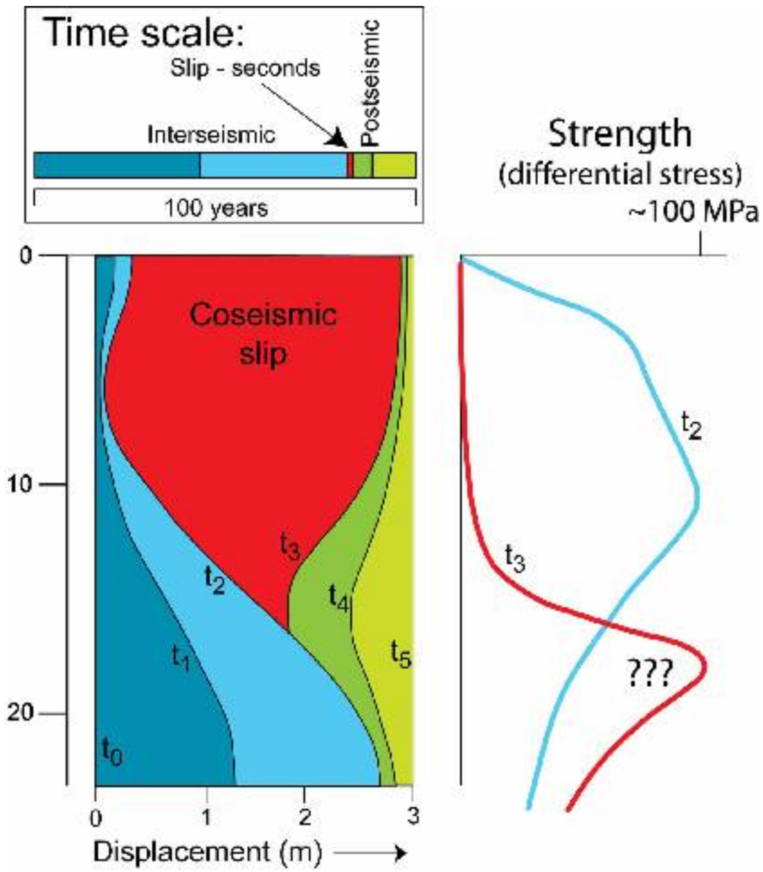
- Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone



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

The Slip History on a Fault



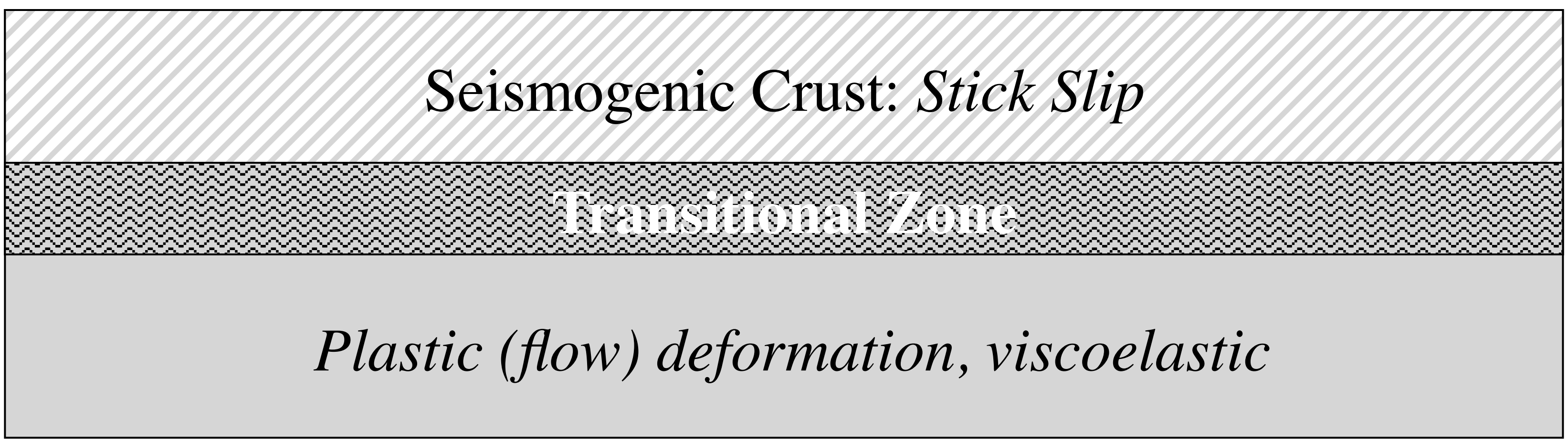
Looks like the figure at left

- Most of the slip in the upper part occurs as coseismic slip in an earthquake.
- Slip rate varies with depth and time in the cycle.
- Strength/stress history also time and depth variable.
- In this figure, the "locking depth" is time dependent.

A More Realistic Picture

Can divide fault zone based on how fault slips

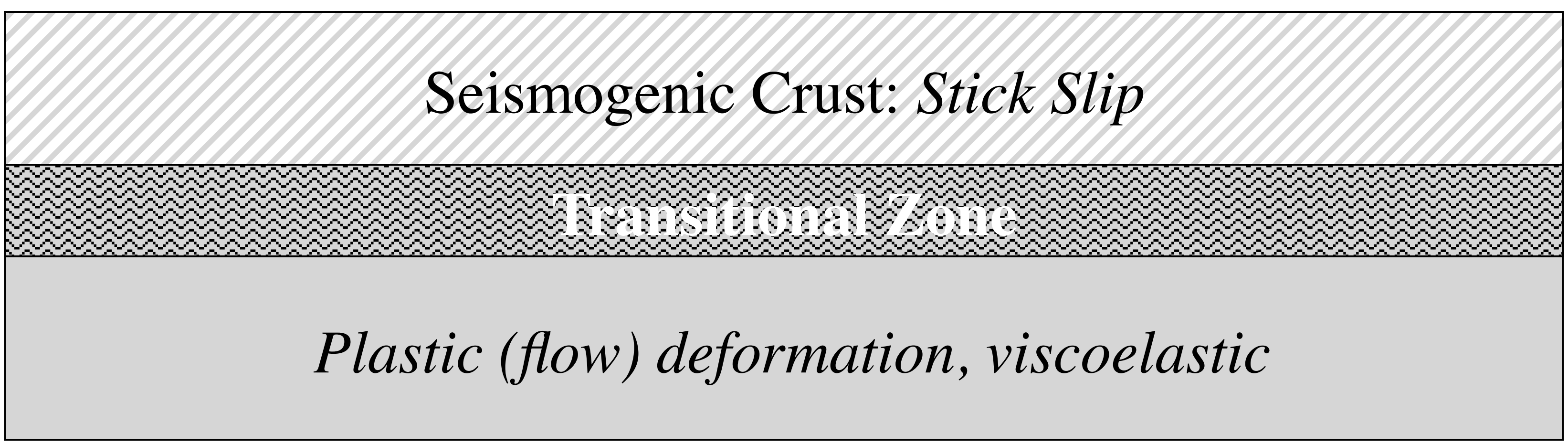
- Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone
- Mantle is certainly viscoelastic, fault-mantle connection less clear
- Subject to intensive ongoing research



A More Realistic Picture

Shallow Seismogenic Zone slips mainly in earthquakes

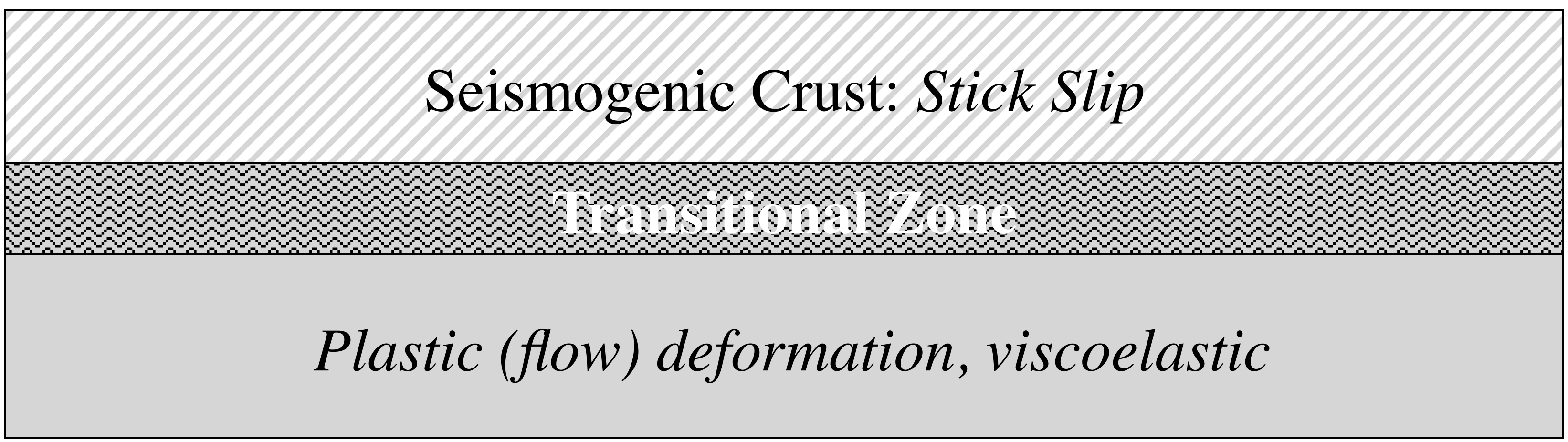
- Shallow fault creep is unusual, but clearly observed.
- Most faults appear to be locked at shallow depth.



A More Realistic Picture

Transitional Zone is particularly dynamic

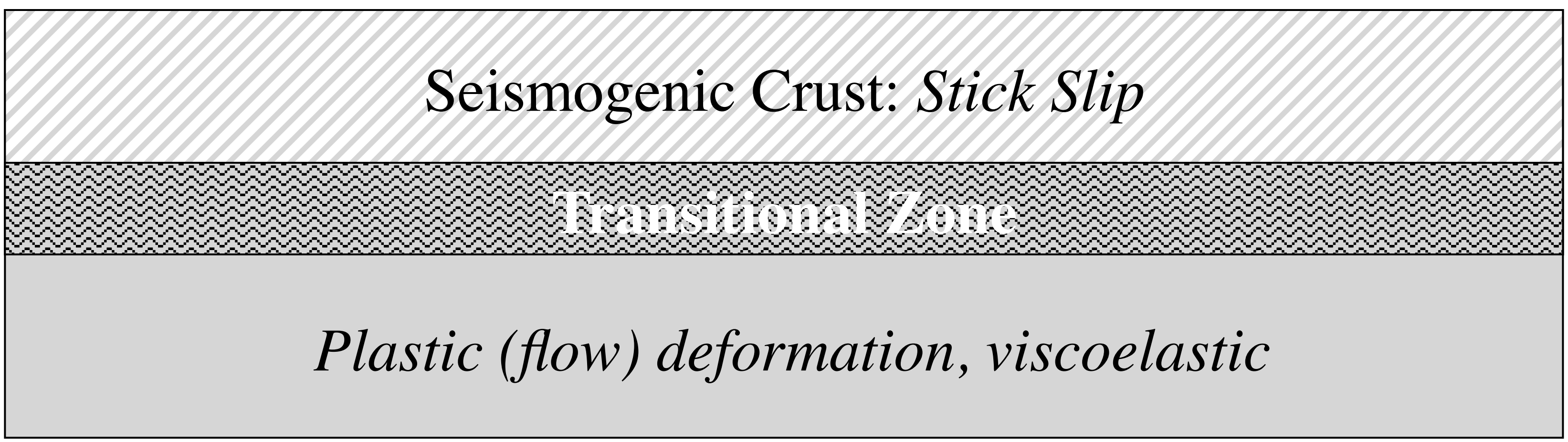
- Experiences substantial postseismic afterslip (more tomorrow)
- Is known to experience transient creep in some circumstances.
- Subject to intensive ongoing research



A More Realistic Picture

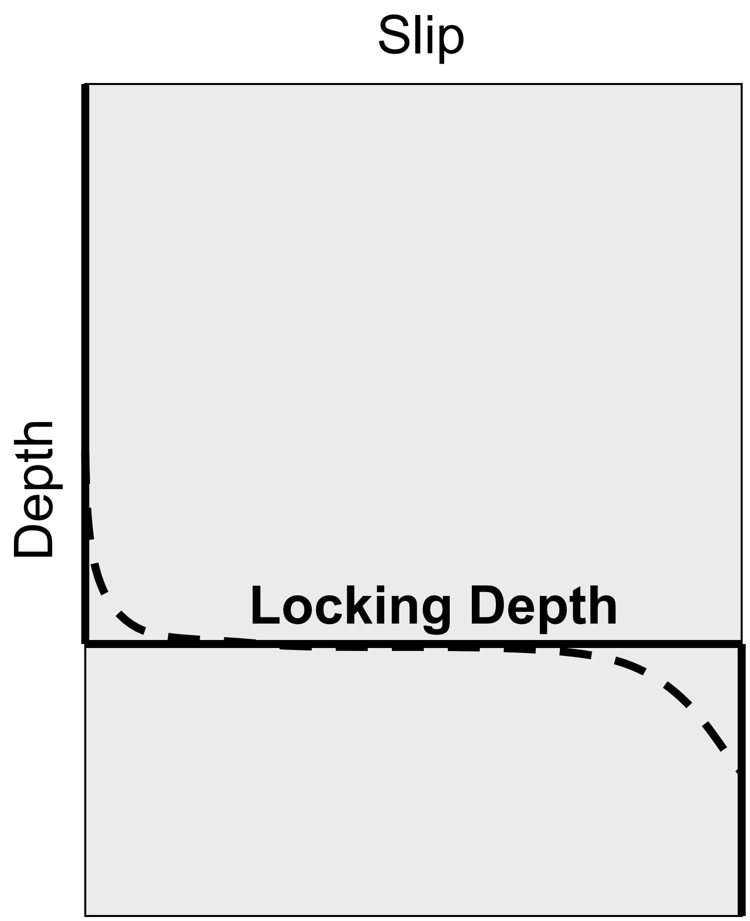
Deep Shear Zones may respond postseismically

- Postseismic models disagree about depth extent of aferslip
- Deep crustal shear zones may slip/shear at a relatively uniform rate
- Asthenospheric mantle displays viscoelastic behavior.



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

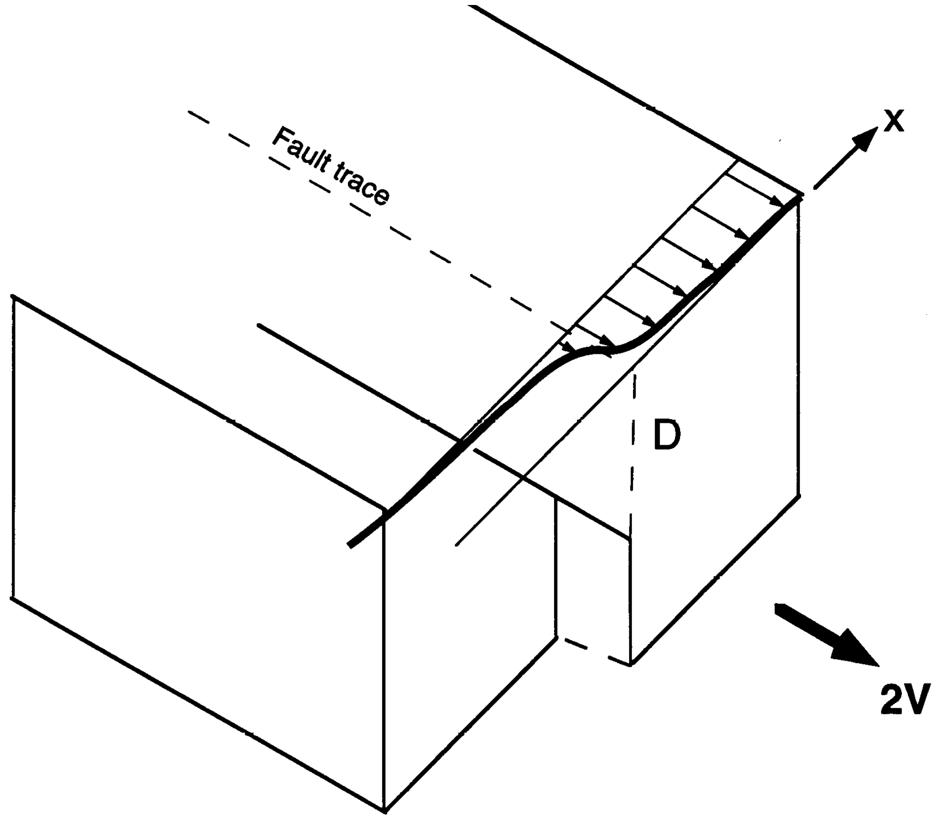
Example: 2D strike slip fault

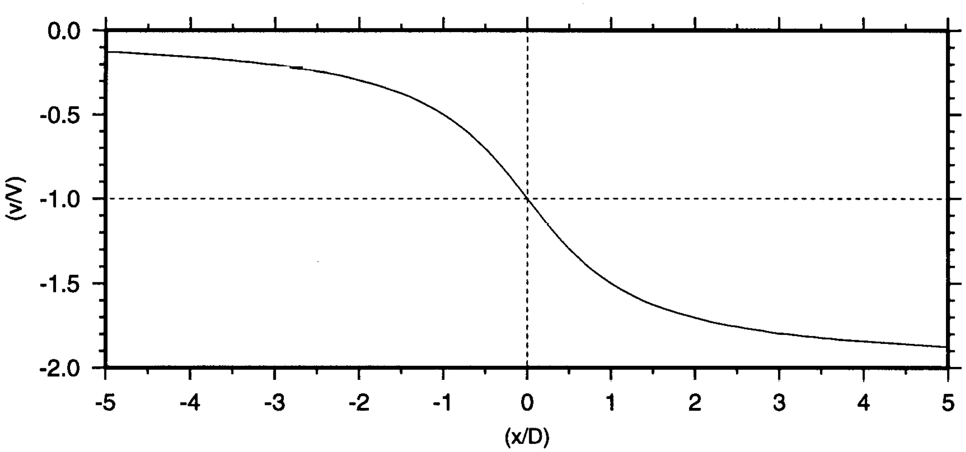
• (Infinitely long fault)

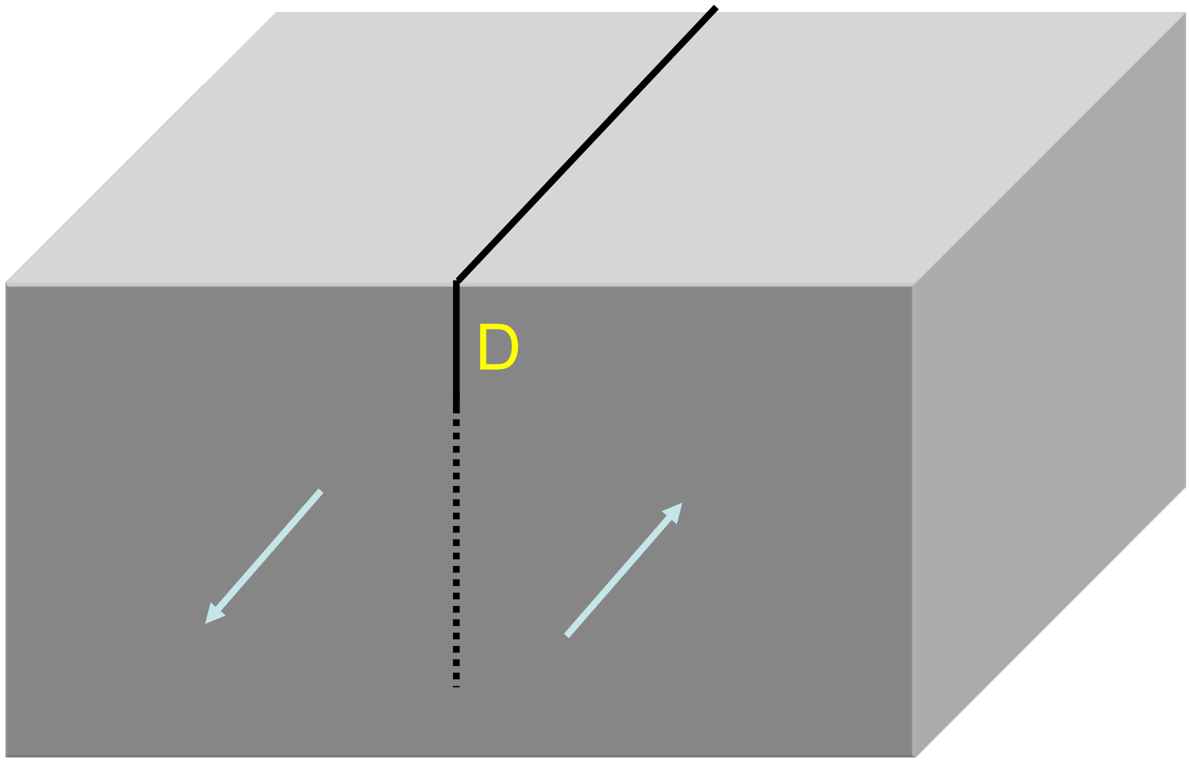
• Velocity profile follows arctangent(x/D)

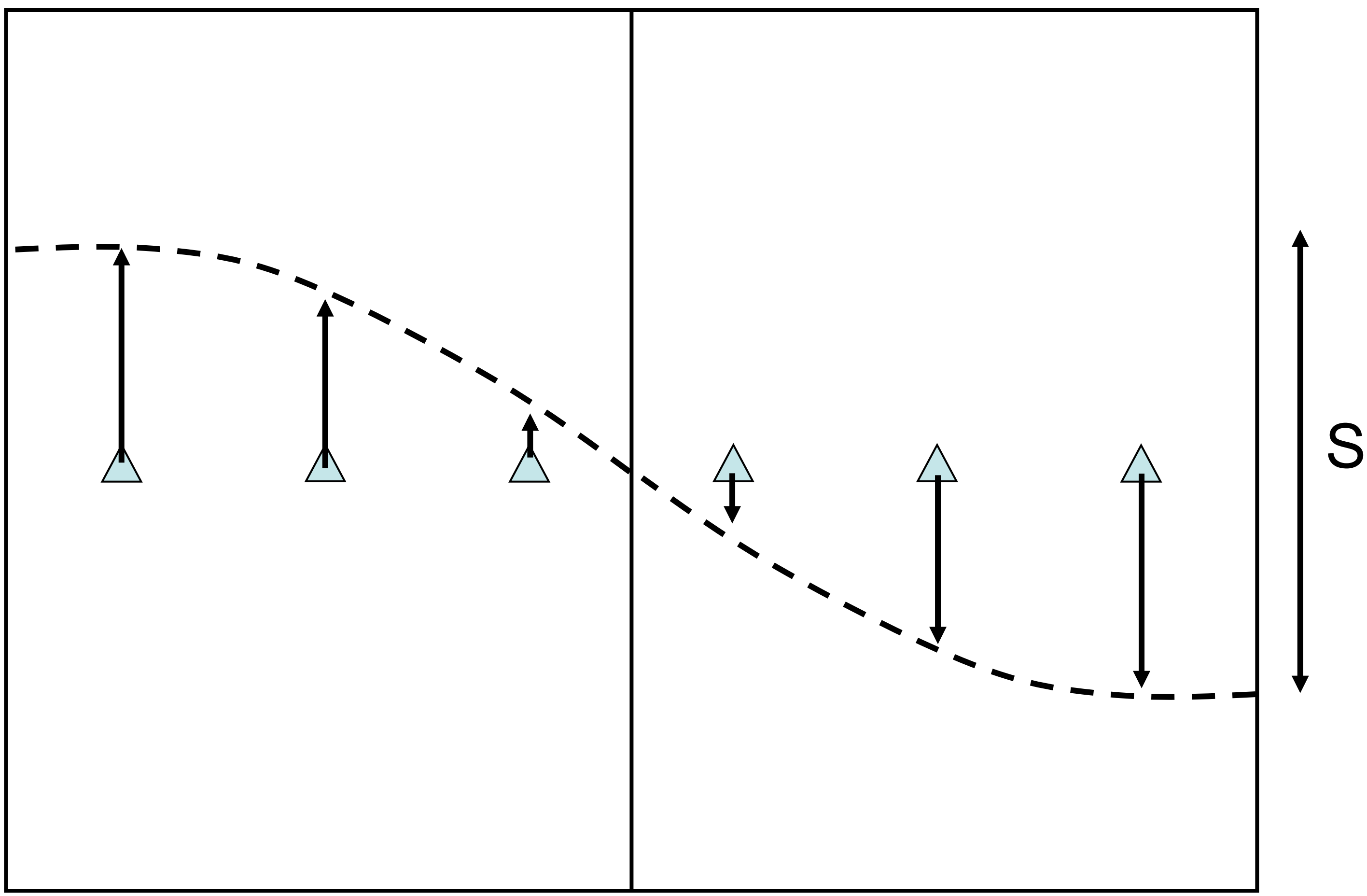
• Half of deformation seen on each side of fault

•Most elastic deformation within 2-3 locking depths of fault

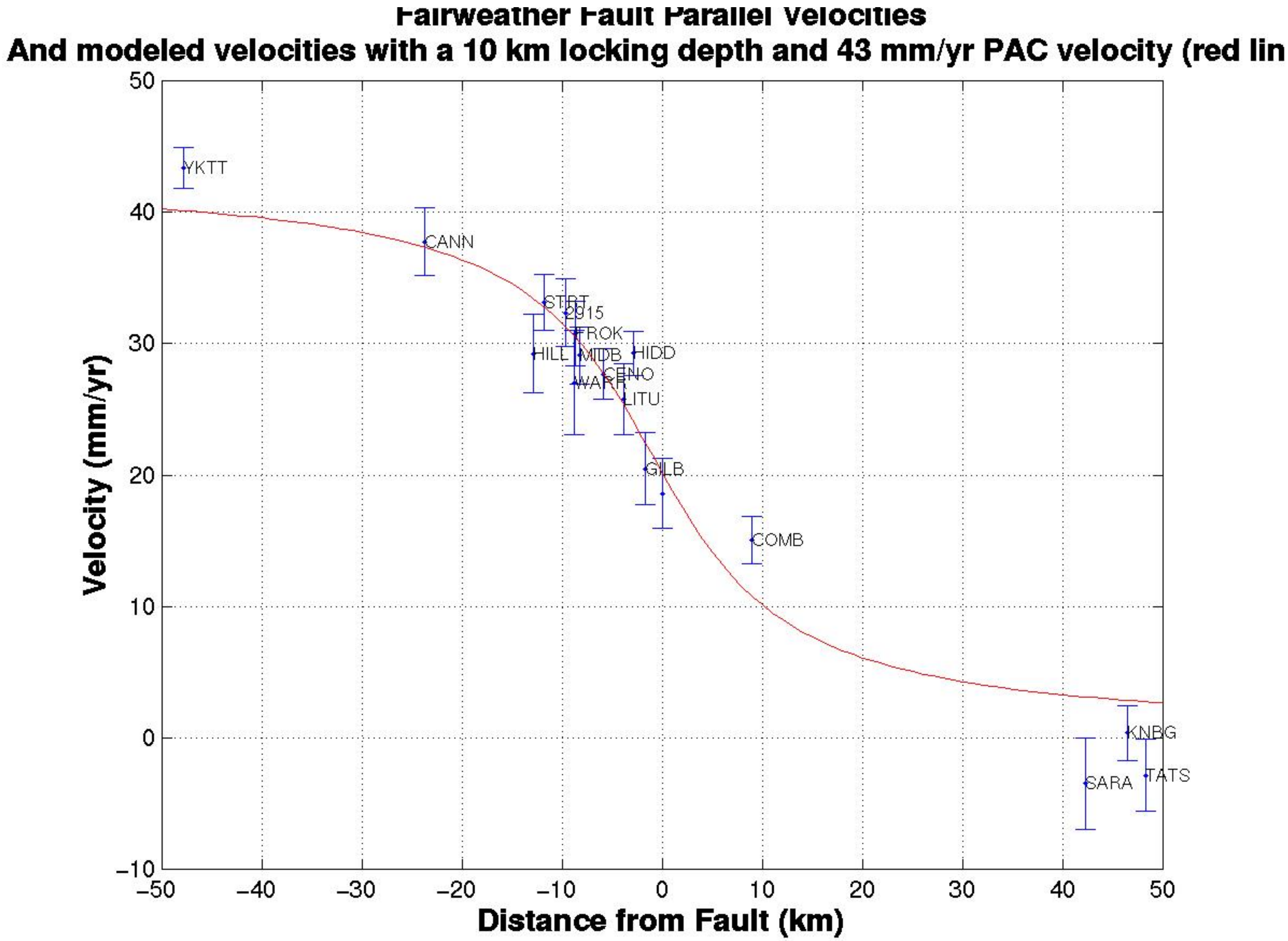





D


S

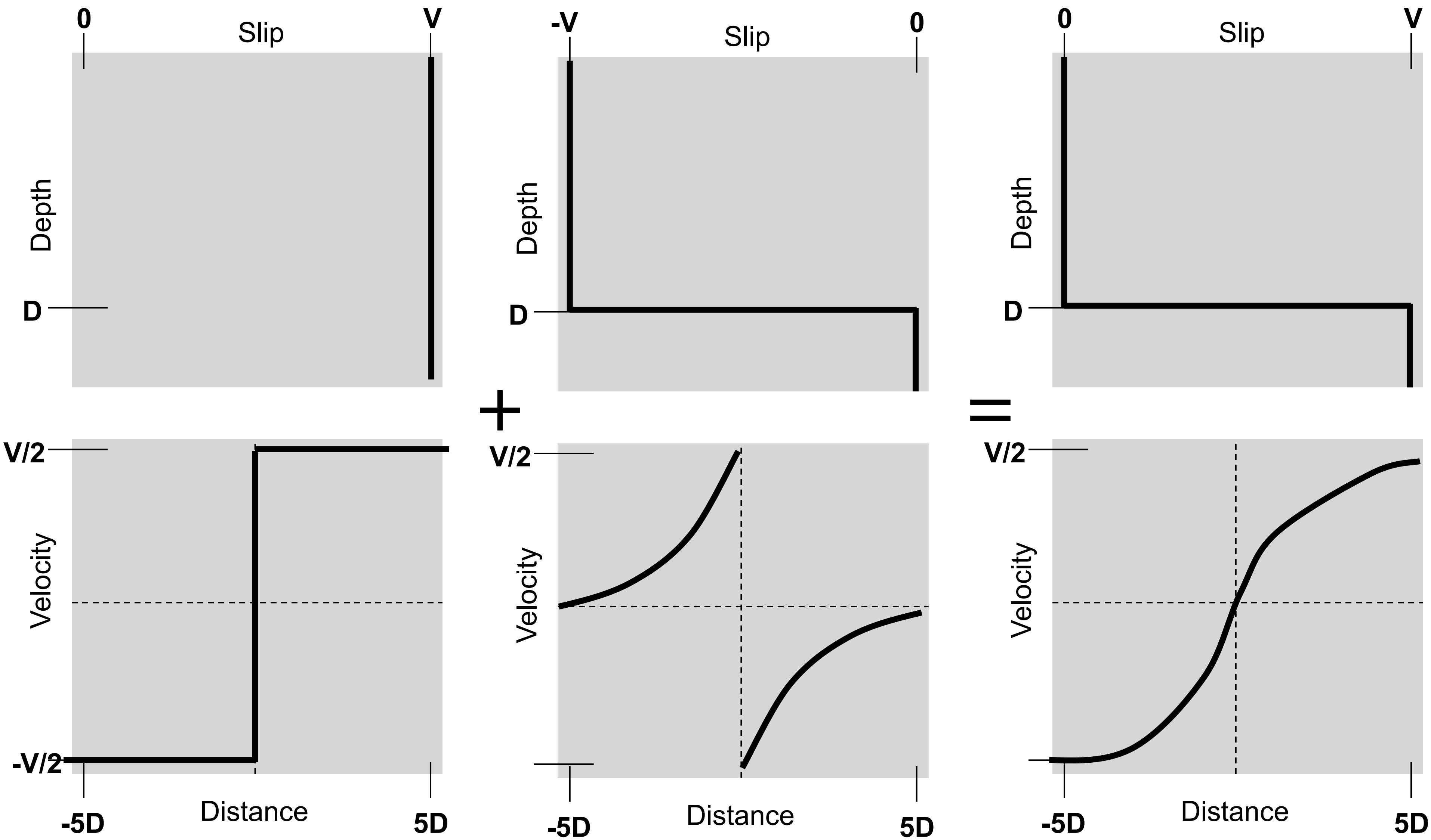
An Example


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)
50
40
30
20
10
0
−10
−50
−40
−30
−20
−10
0
10
20
30
40
50
YKTT
CANN
STRT
2915
FROK
HILL
MIDB
HIDD
CENO
WARR
LITU
GILB
COMB
KNBG
TATS
SARA

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

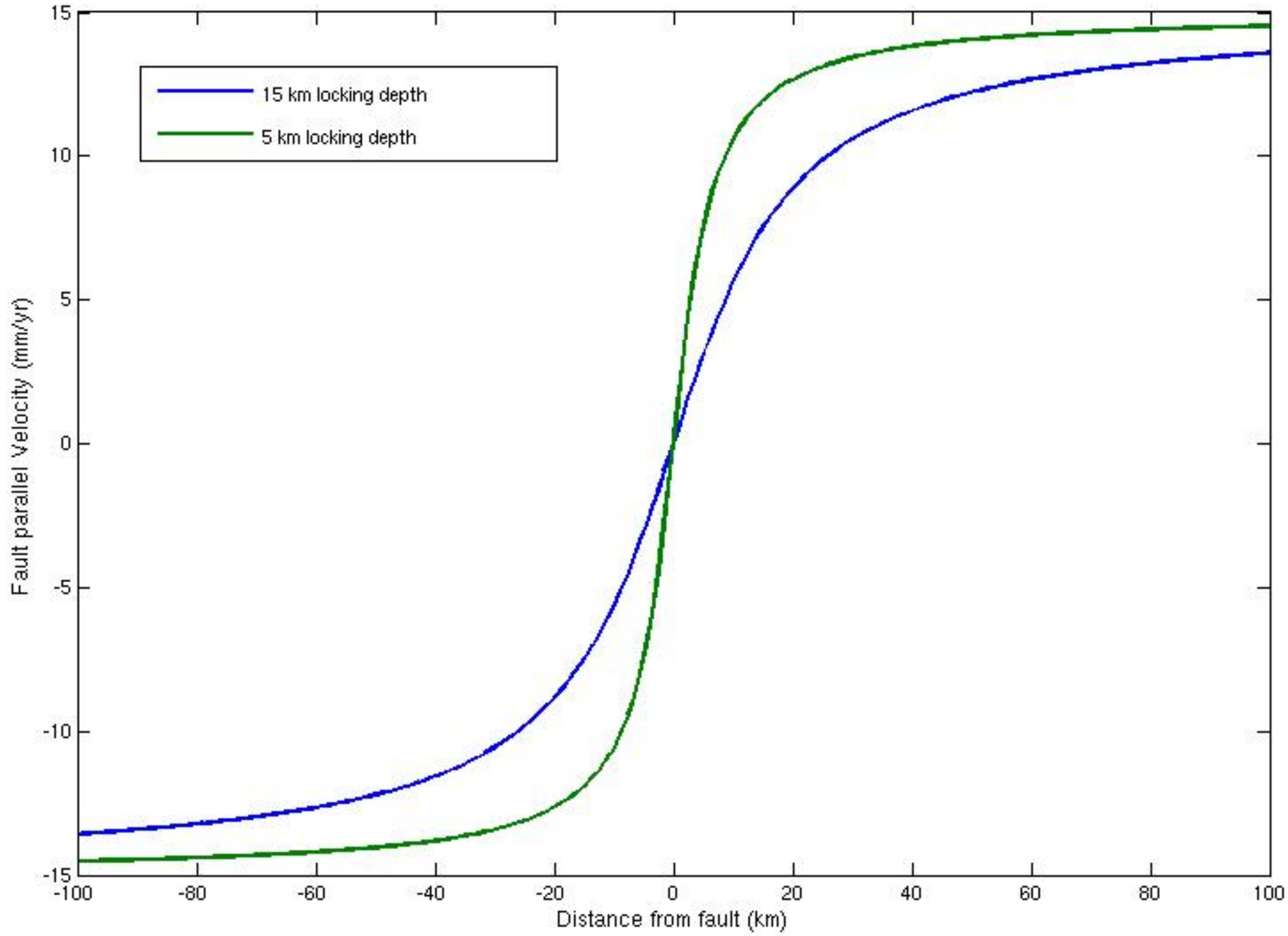
D = locking depth

x = perpendicular distance of site from fault

x_f = position of fault

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

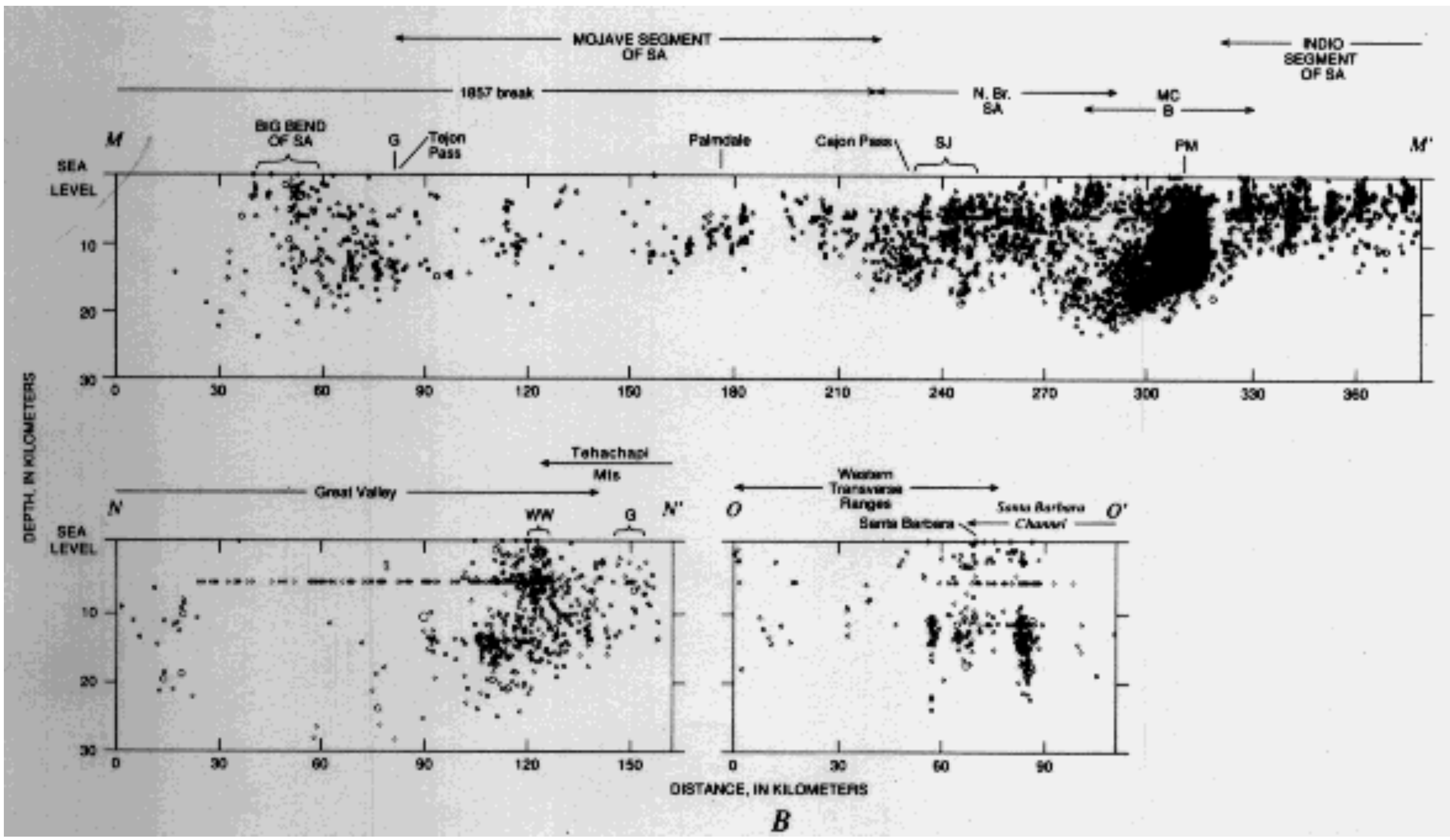
Changing the Locking Depth



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

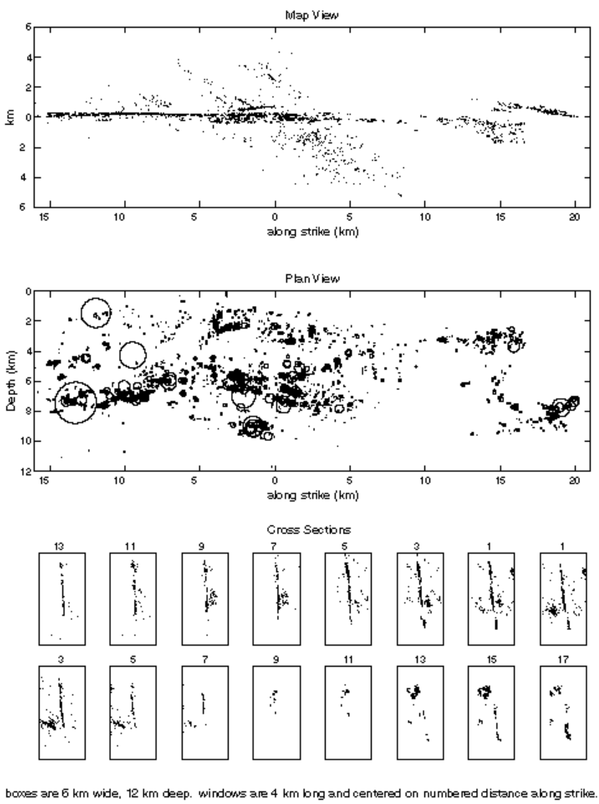
Maximum Depth of Seismicity

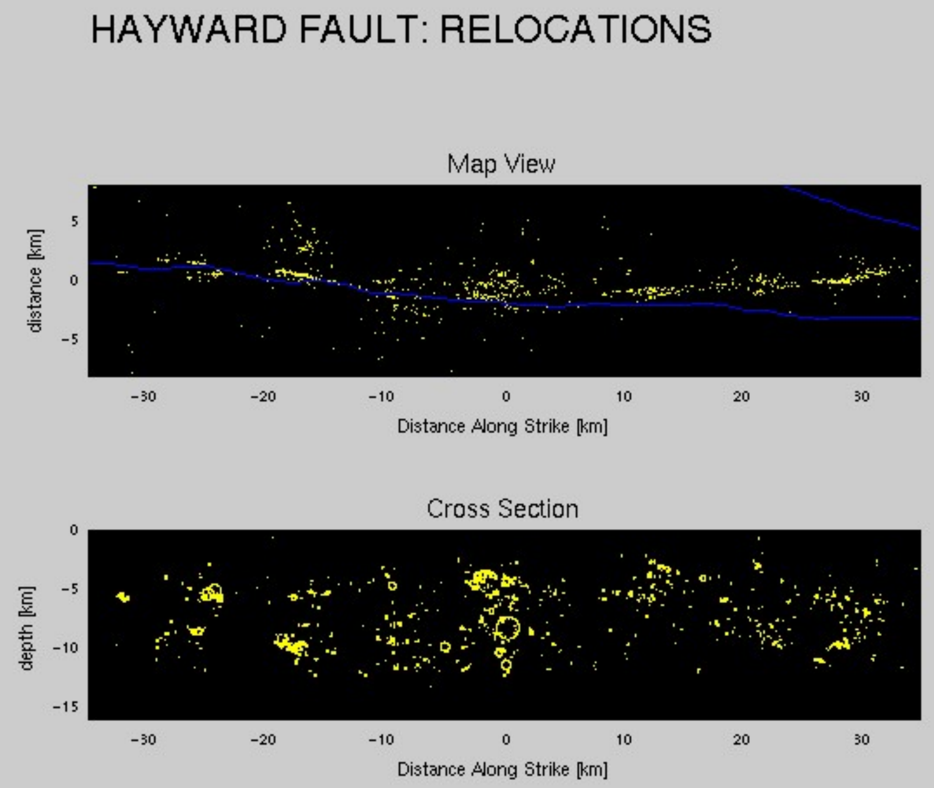


Hill et al., 1991

Detailed Depth Sections

Calaveras fault

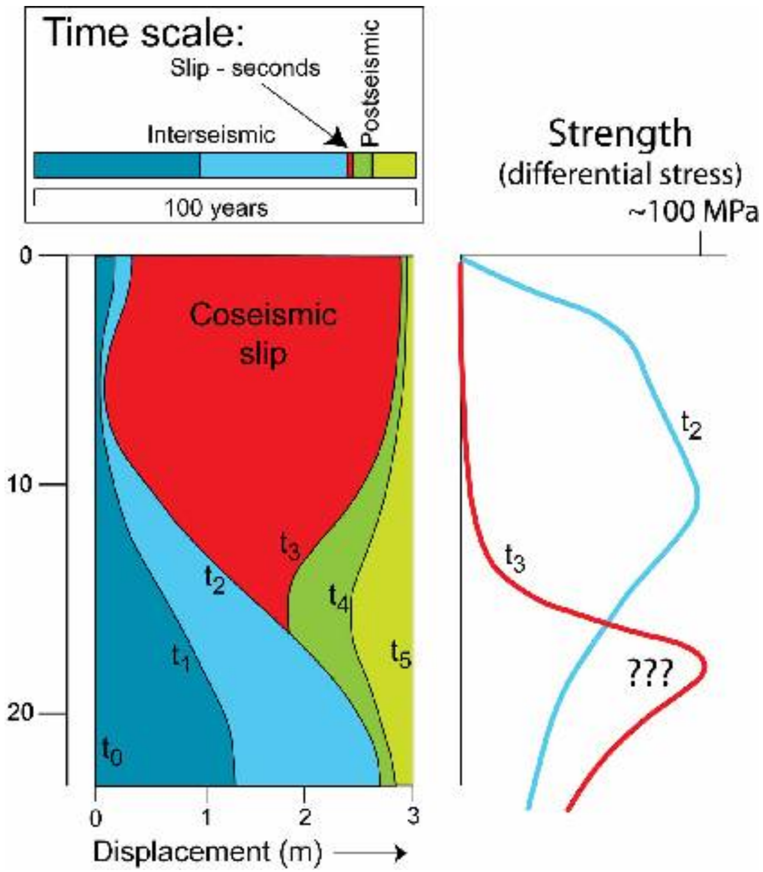




Waldhauser et al., 1999

Creeping Faults (Willits, CA)

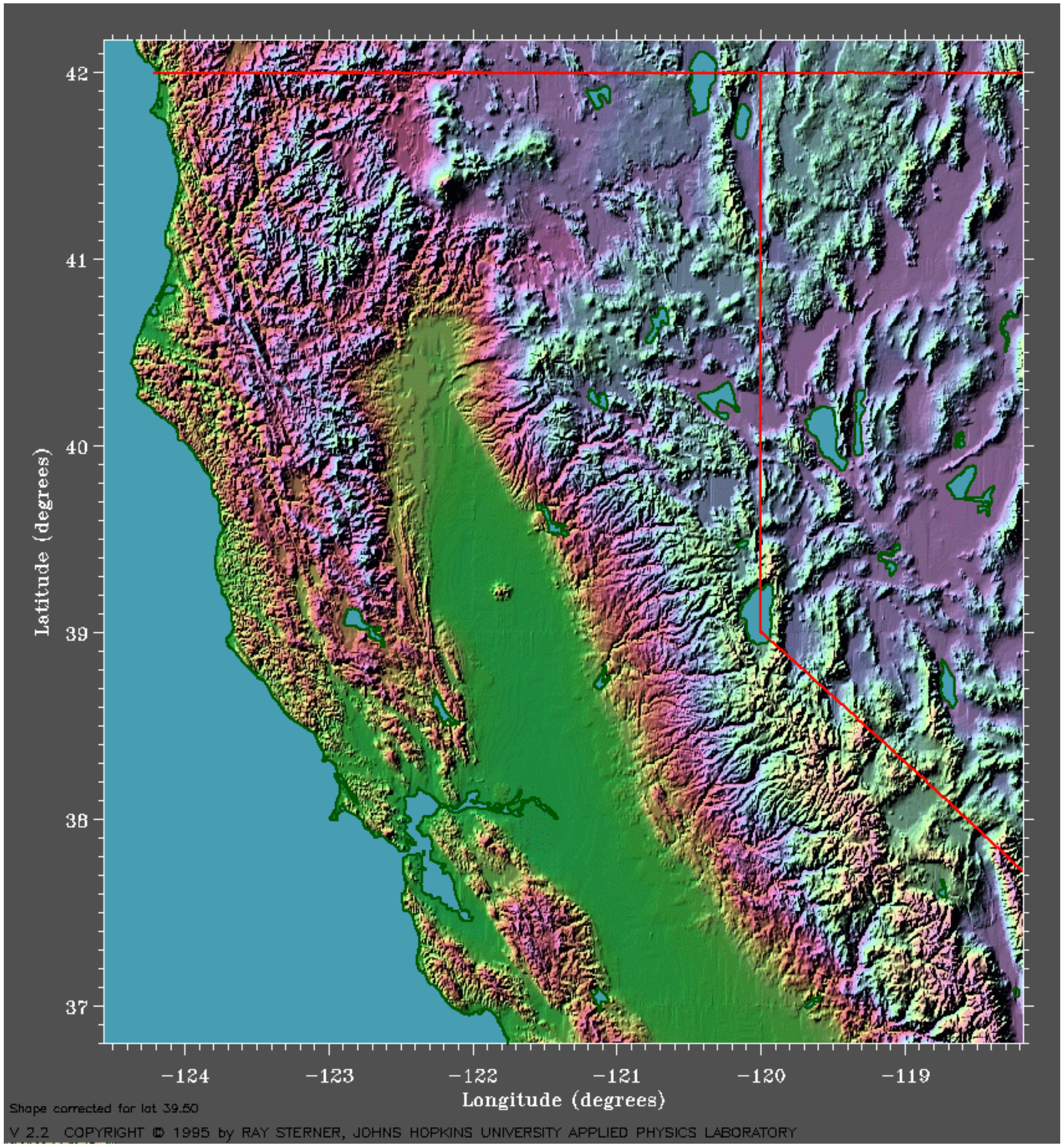
The Slip History on a Fault



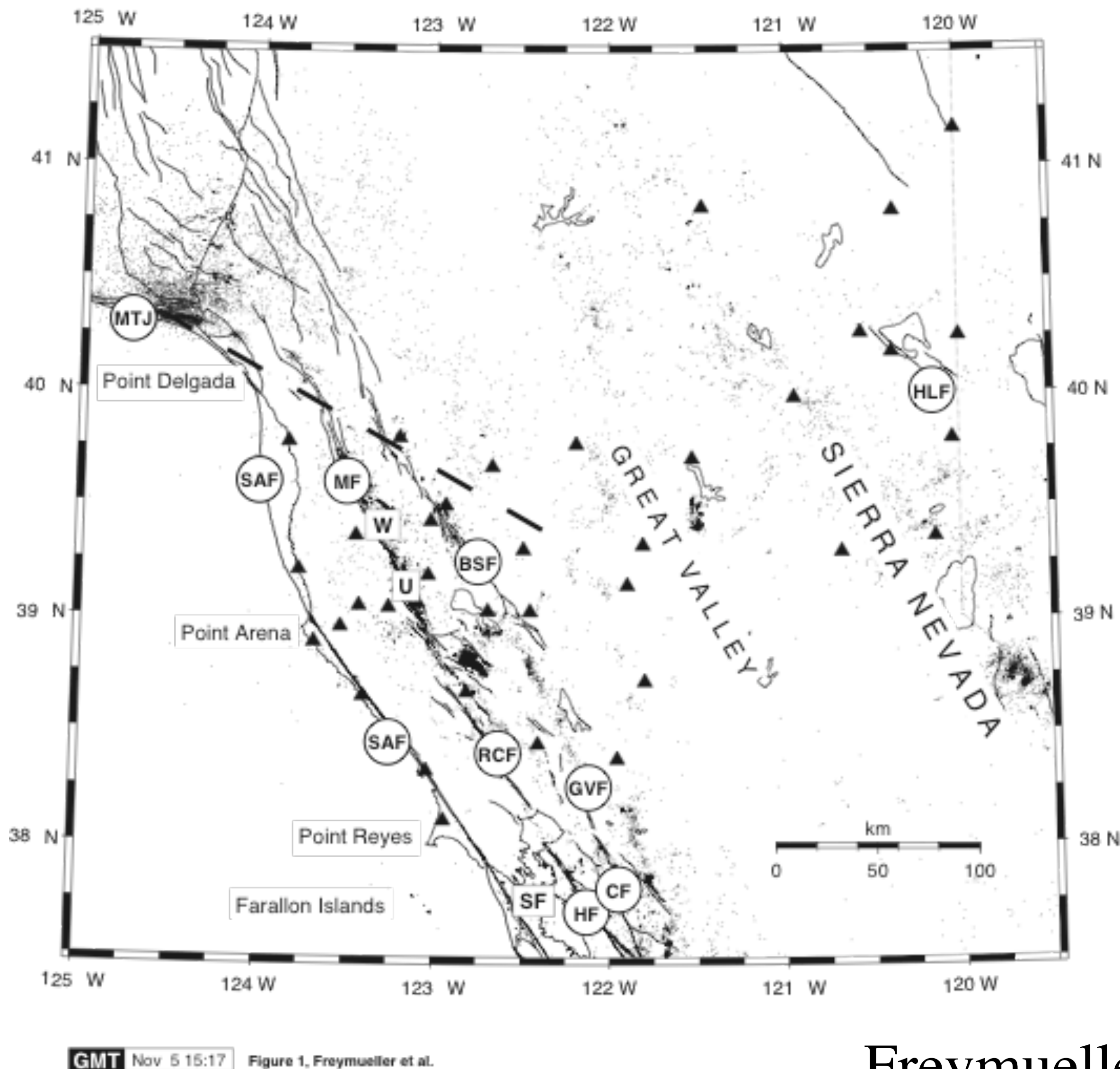
Looks like the figure at left

- Most of the slip in the upper part occurs as coseismic slip in an earthquake.
- Slip rate varies with depth and time in the cycle.
- Strength/stress history also time and depth variable.
- In this figure, the "locking depth" is time dependent.

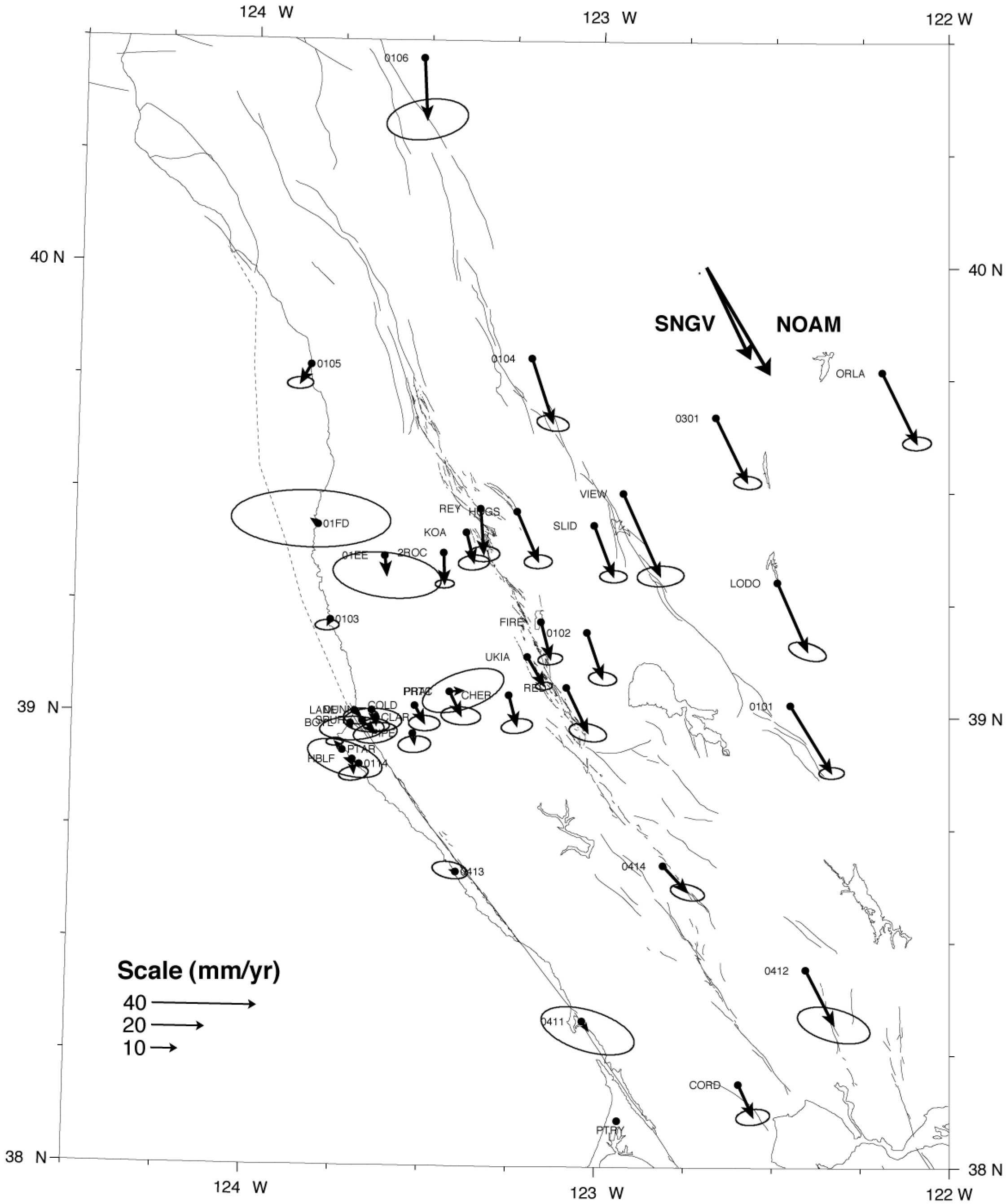
Northern California



Major Faults



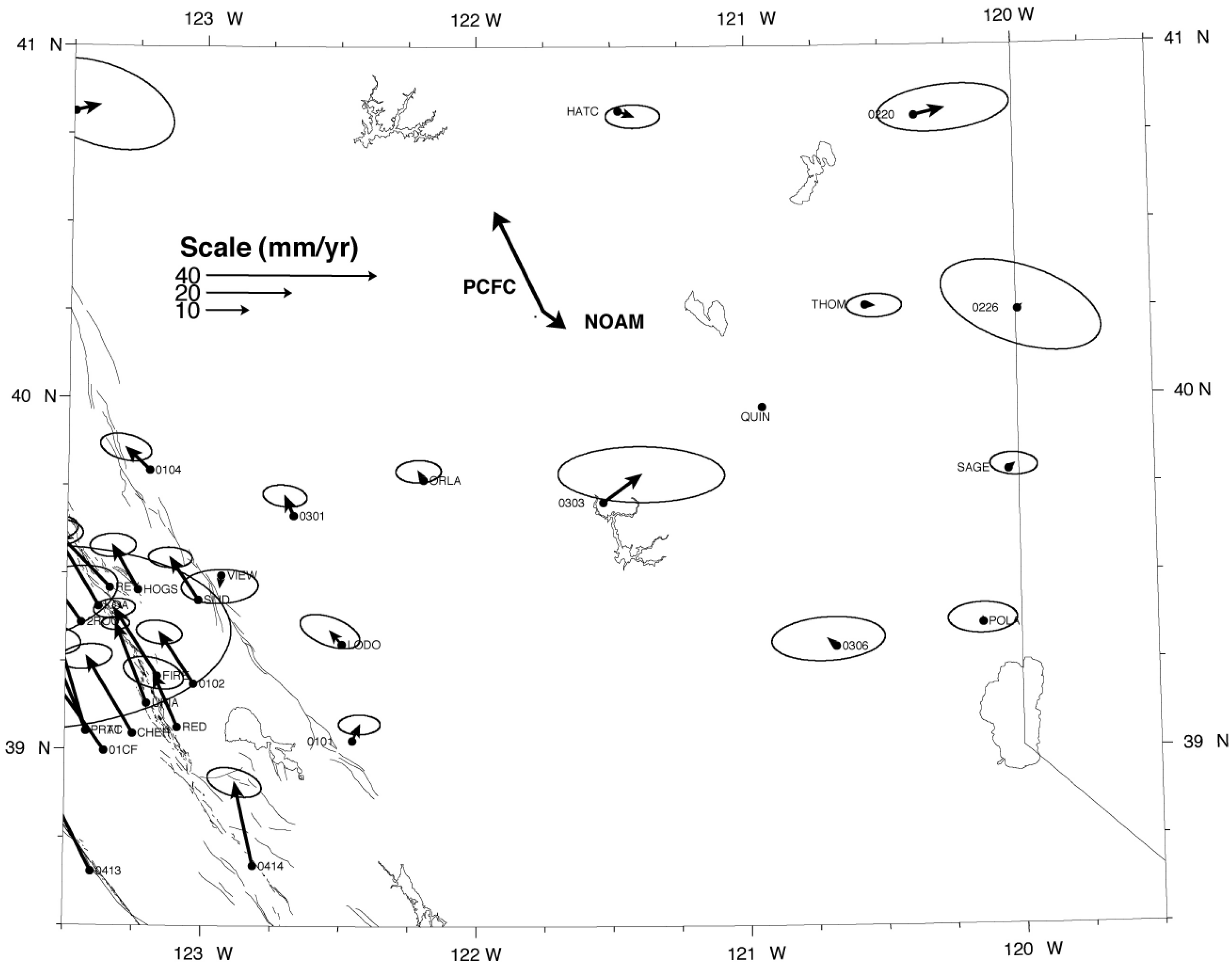
Freymueller et al., 1999

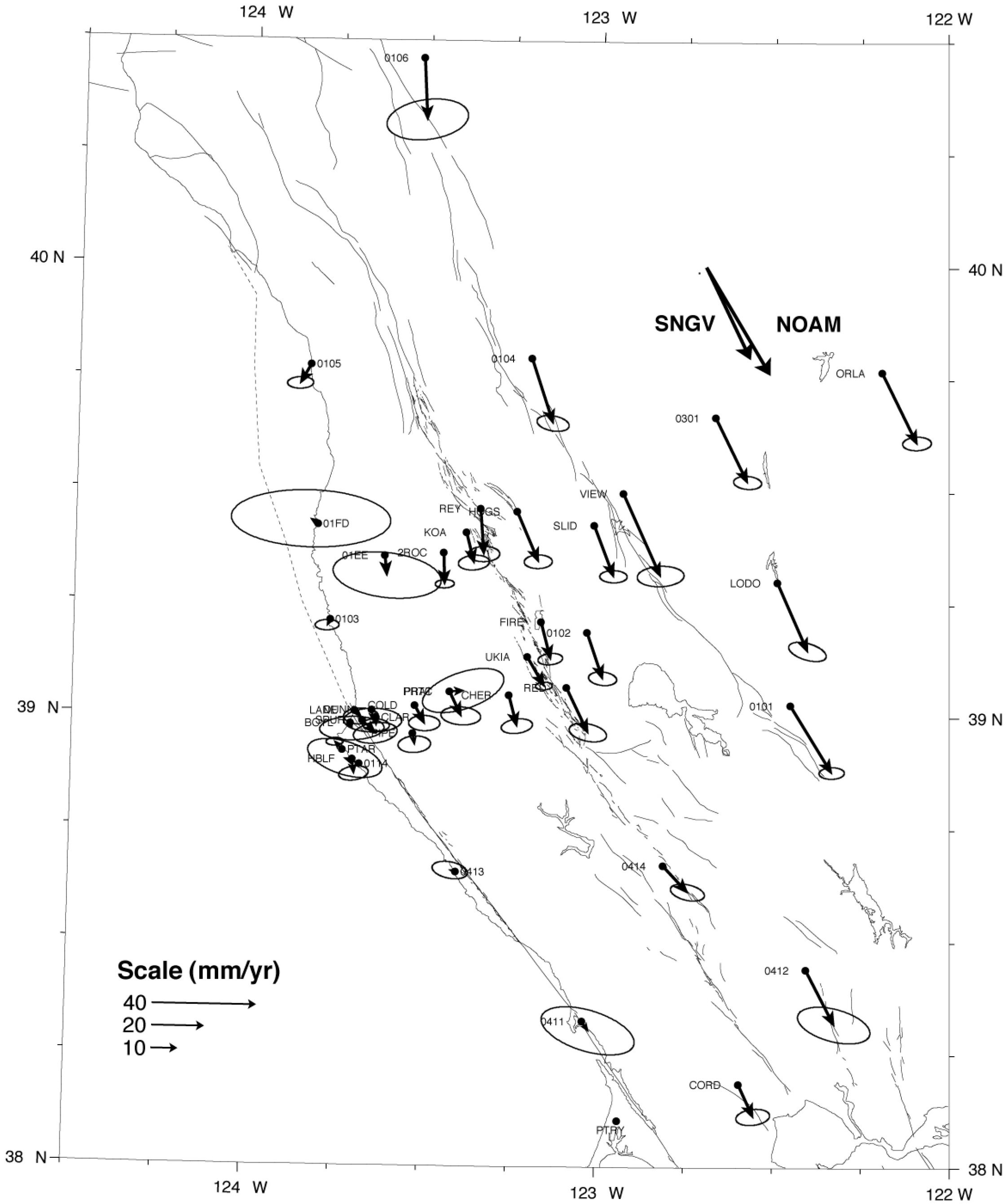


Velocities

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

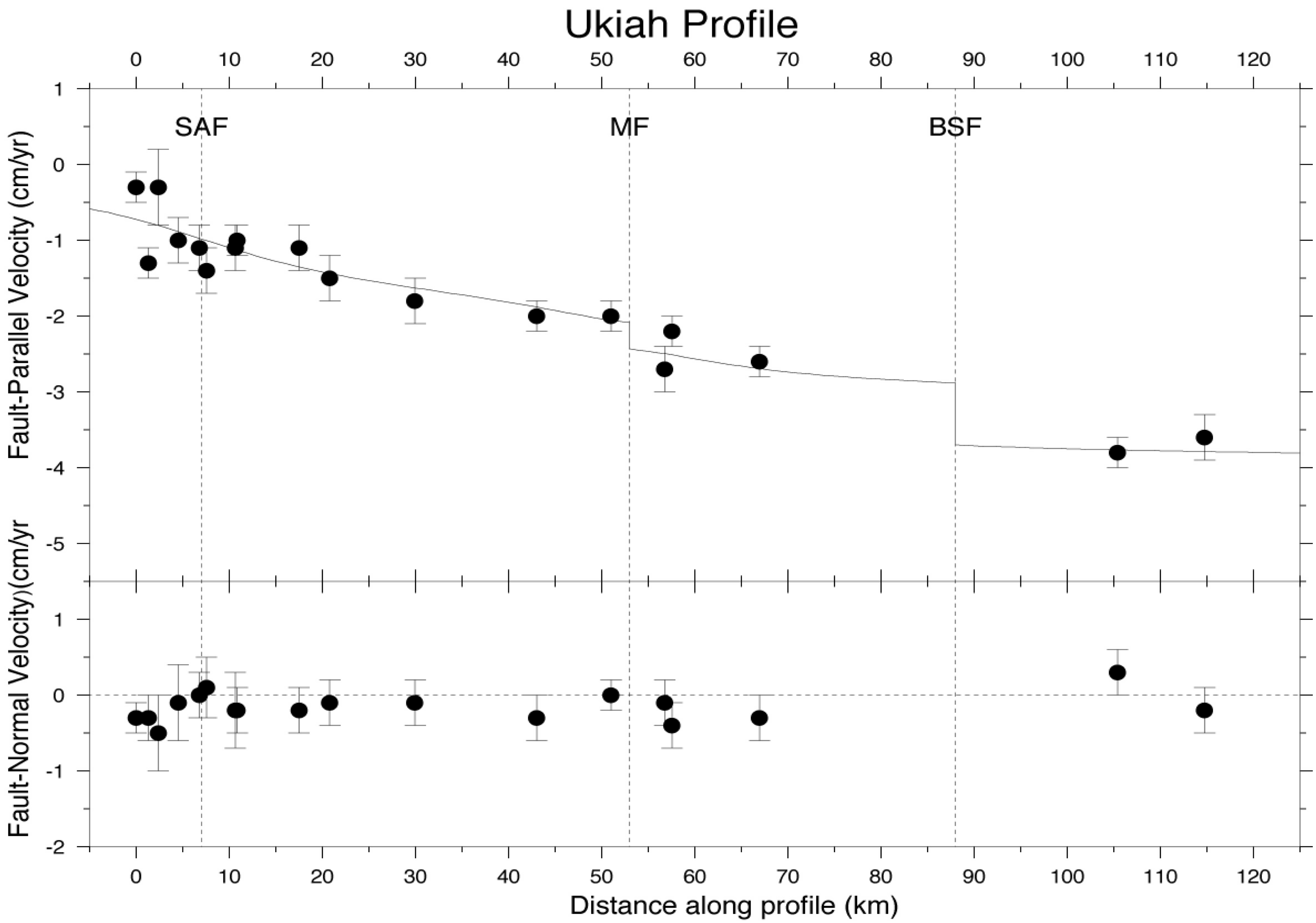
Relative to QUIN on SNGV



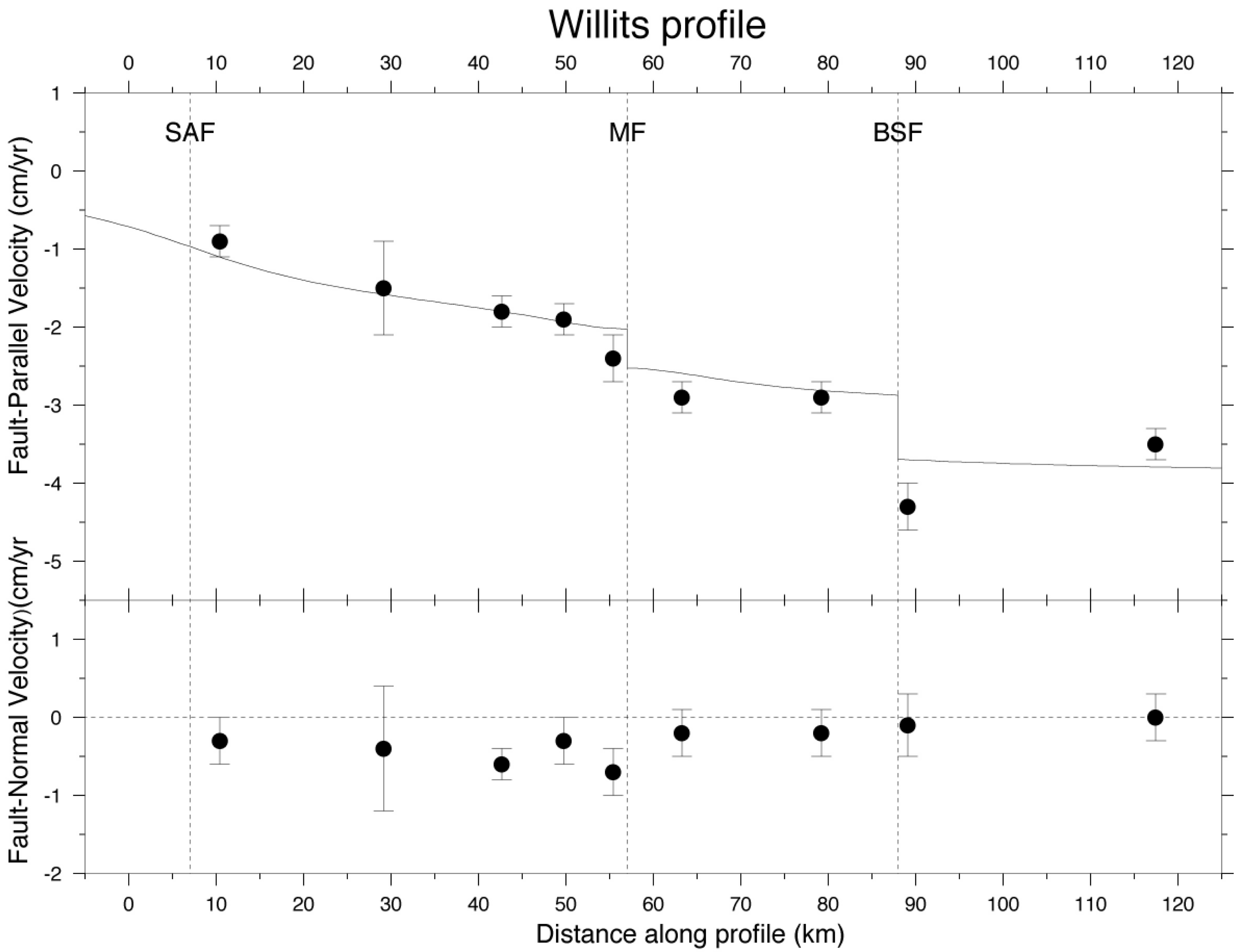


Models

- 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

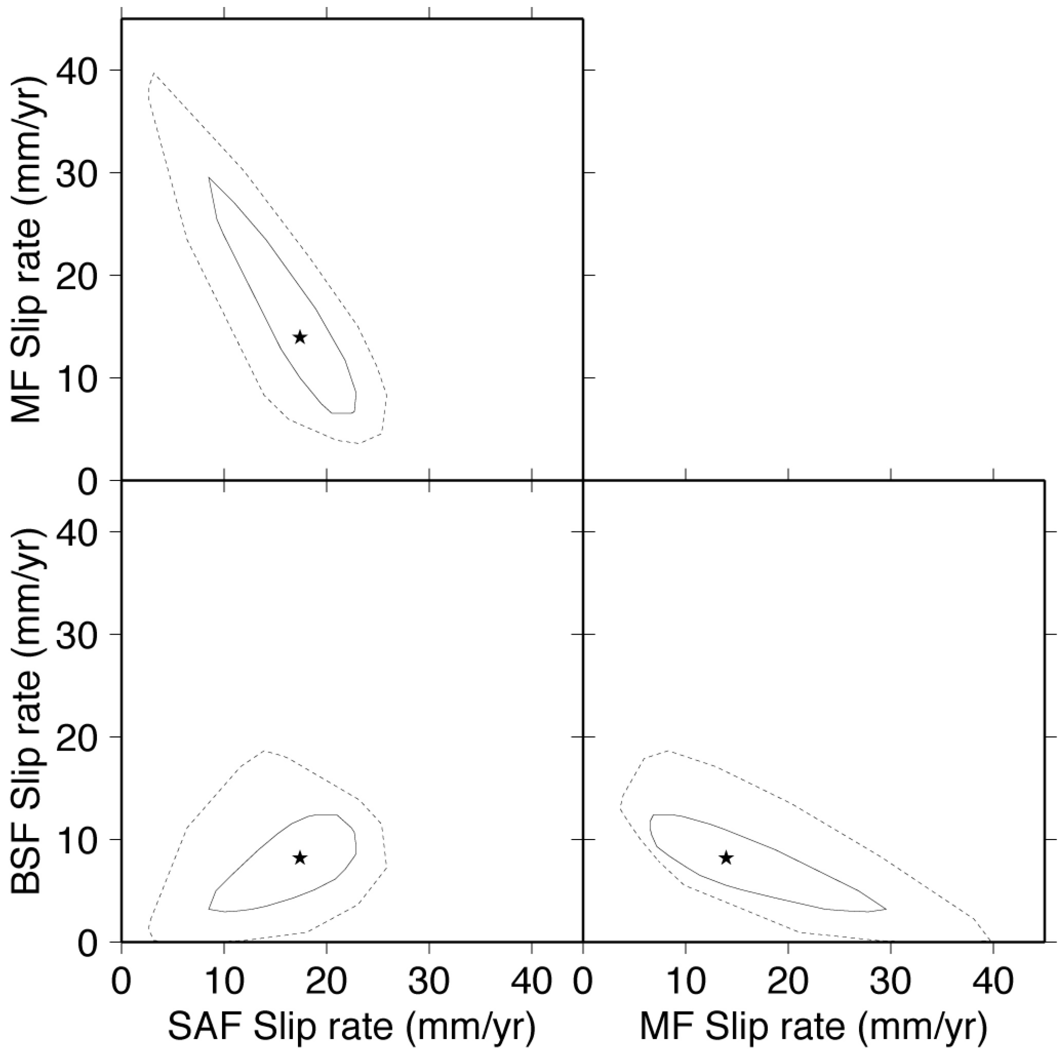


Ukiah Profile
SAF
MF
BSF
Fault-Parallel Velocity (cm/yr)
Fault-Normal Velocity)(cm/yr
Distance along profile (km)
0
10
20
30
40
50
60
70
80
90
100
110
120
1
0
-1
-2
-3
-4
-5
1
0
-1
-2



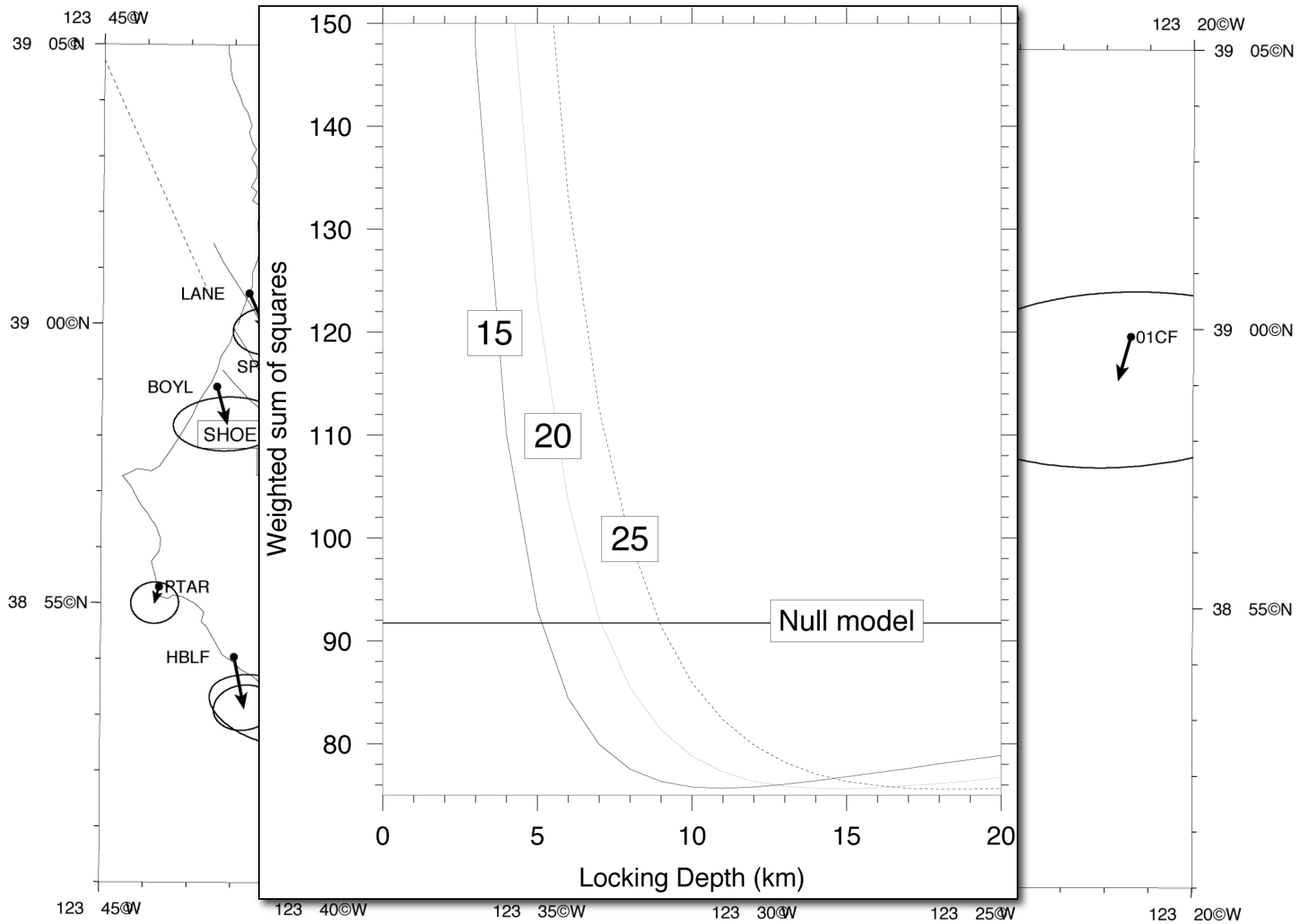
Willits profile
SAF
MF
BSF
Fault-Parallel Velocity (cm/yr)
Fault-Normal Velocity)(cm/yr
Distance along profile (km)

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

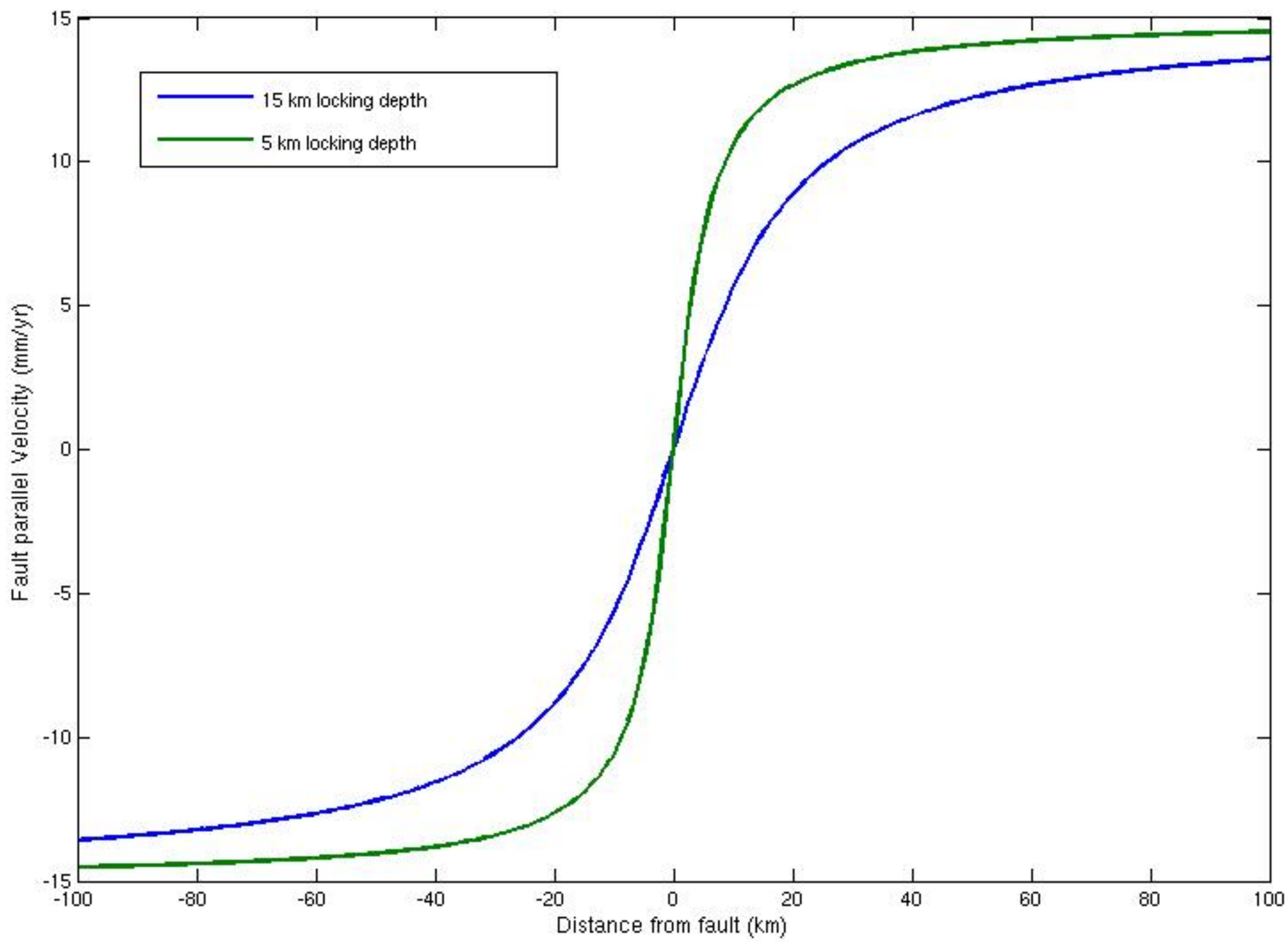
SAF Locking Depth at Pt. Arena



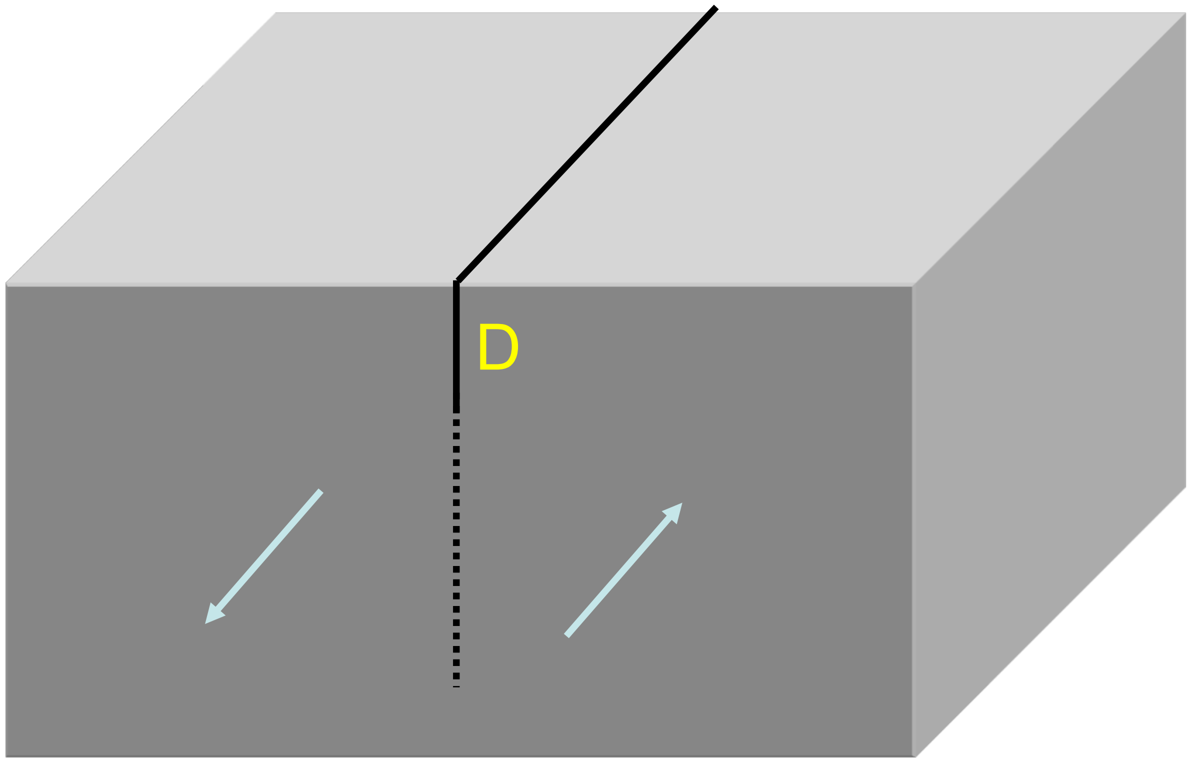
Comments on Models

- 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



Viscoelastic Coupling Model

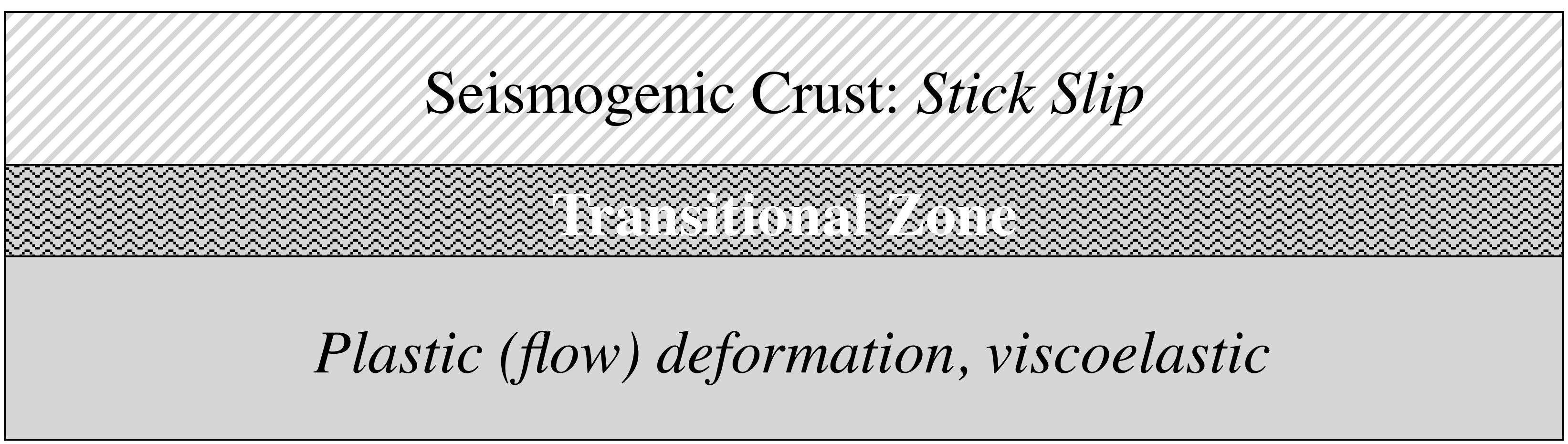


Common: Elastic half-space
Viscoelastic coupling model: Elastic layer over viscoelastic half-space (Savage and Prescott, 1978)

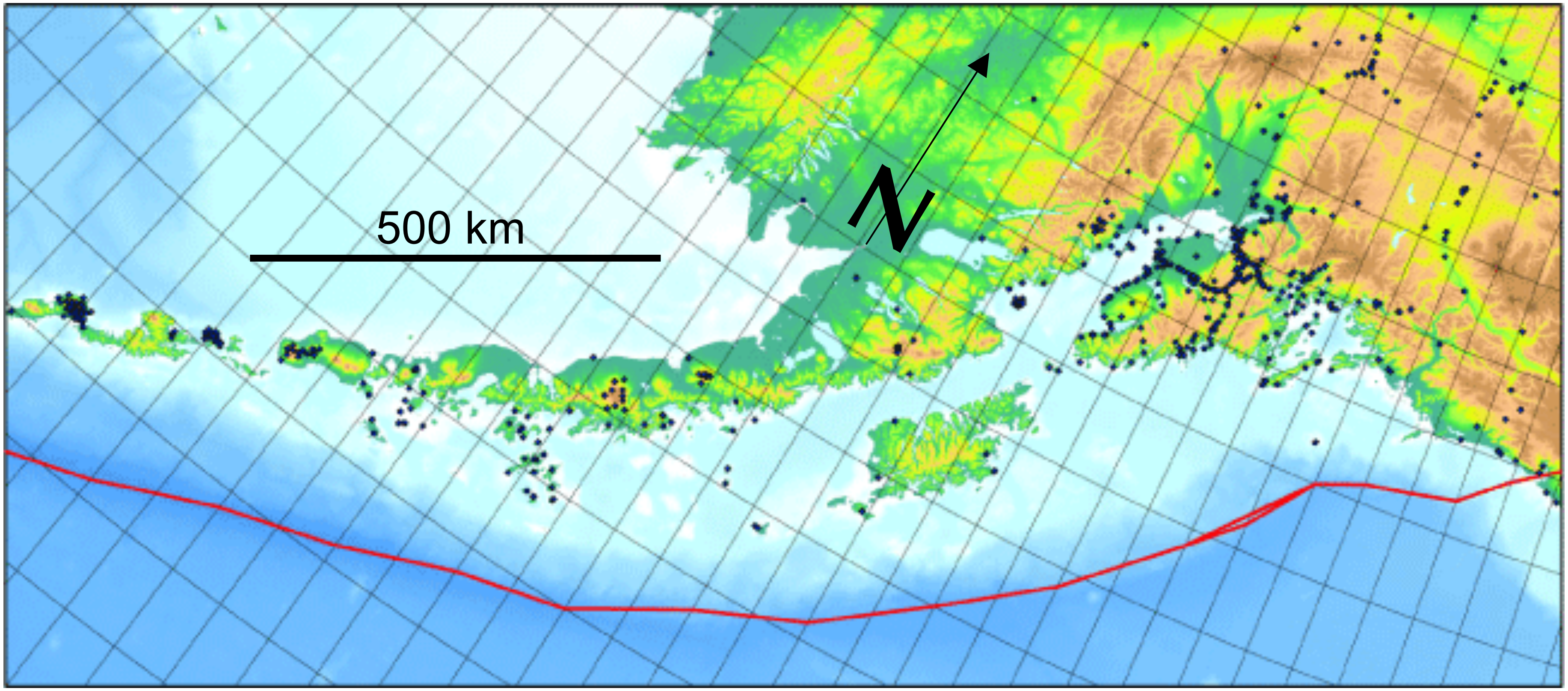
A More Realistic Picture

Can divide fault zone based on how fault slips

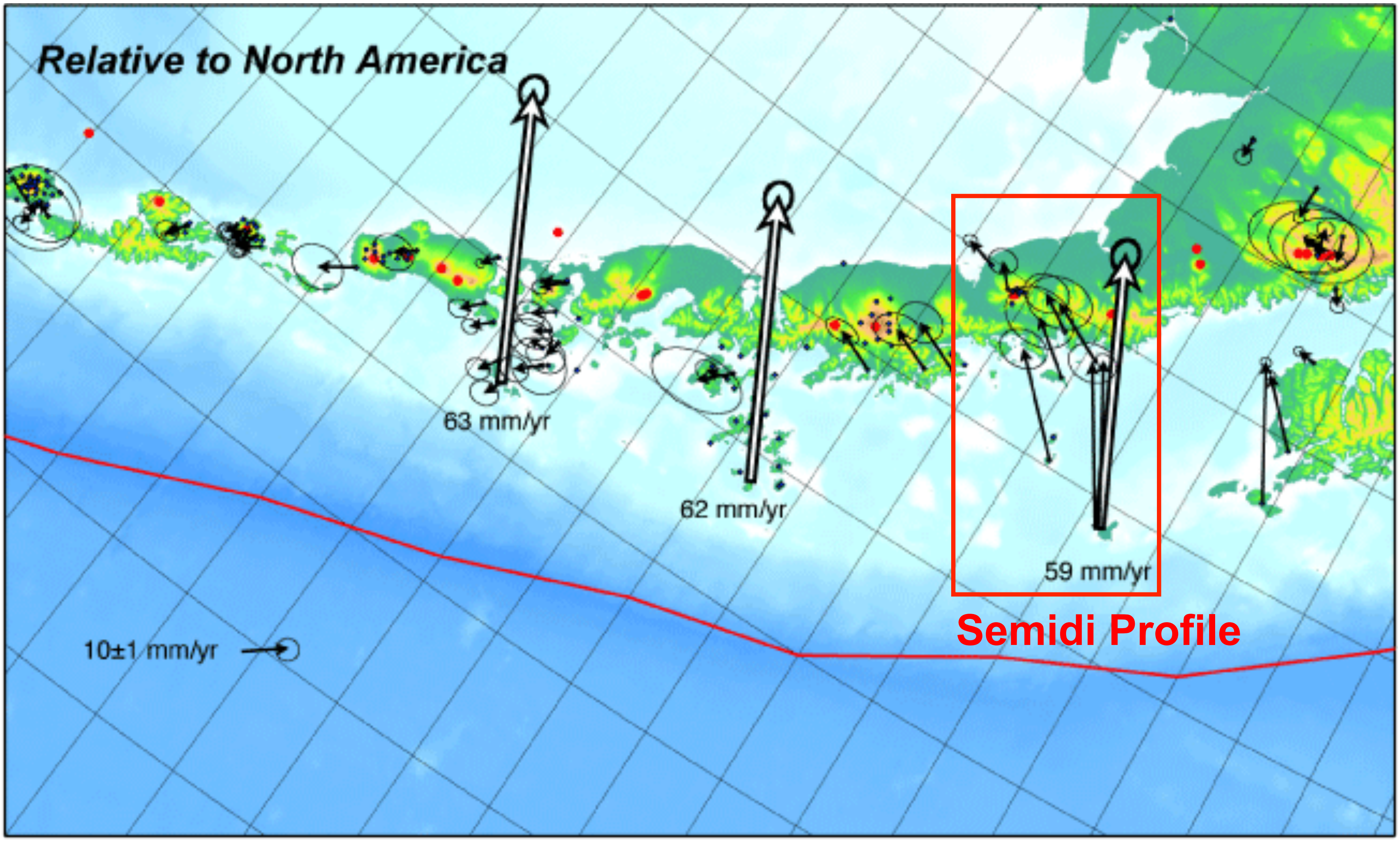
- Crustal earthquakes involve slip of seismogenic crust and possibly transitional zone
- Mantle is certainly viscoelastic, fault-mantle connection less clear
- Subject to intensive ongoing research



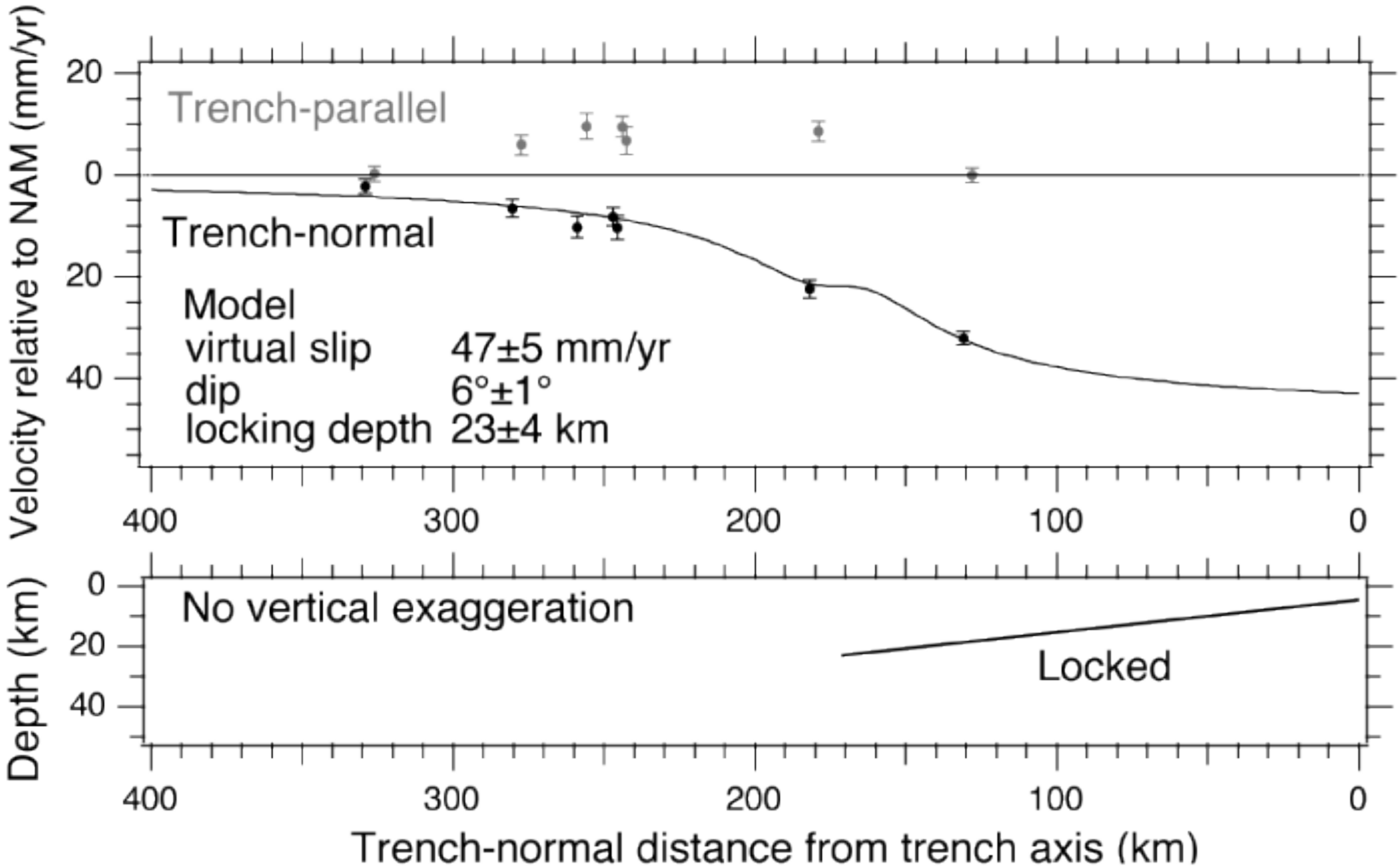
Alaska Subduction Zone



Alaska Peninsula Velocities



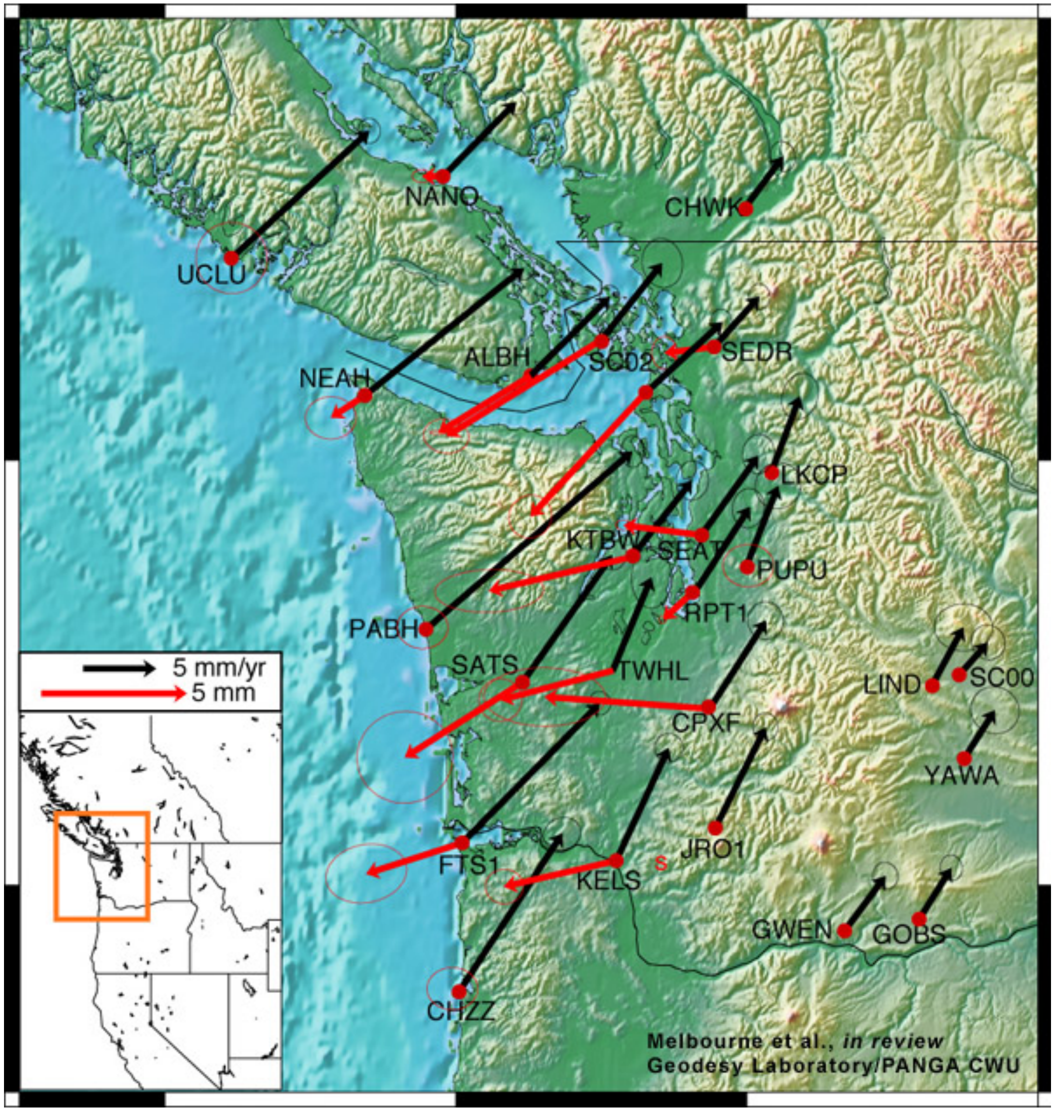
Semidi Profile Model



What Geodesy Constrains

- Horizontal position of downdip end of seismogenic zone
  - Ambiguity between instantaneous and linear transition from locked to creeping
- Dip and depth, but subject to tradeoffs
- "Moment Deficit" – product of fault area and slip deficit
- Limits to resolution
  - Near trench: virtually no resolution
  - Offshore: features of a few 10s of km size

Slow Slip Events



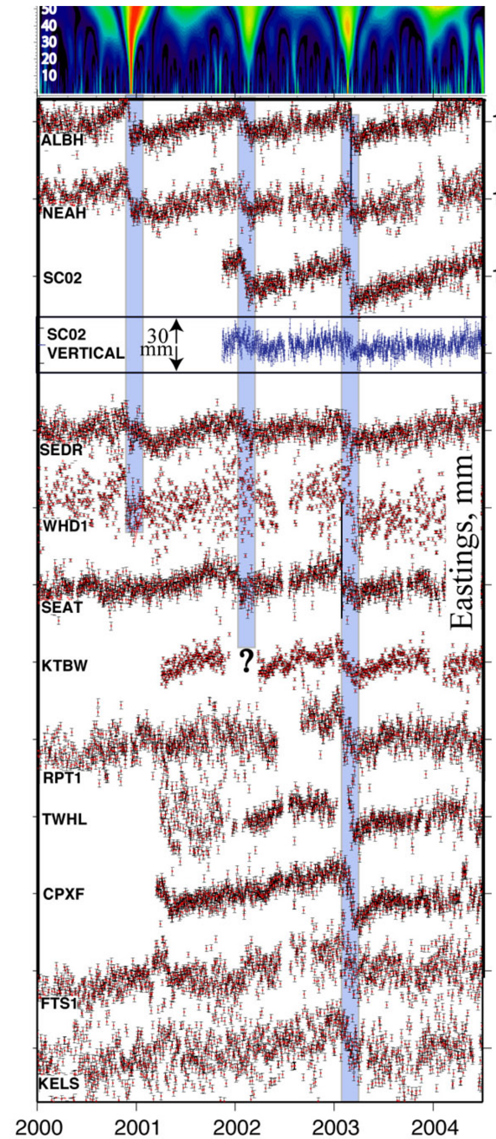
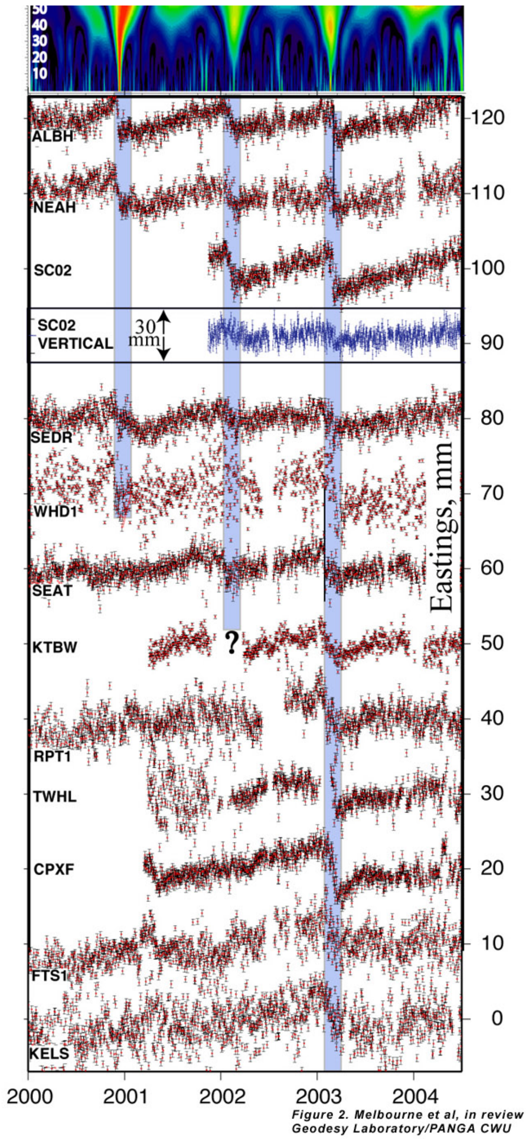
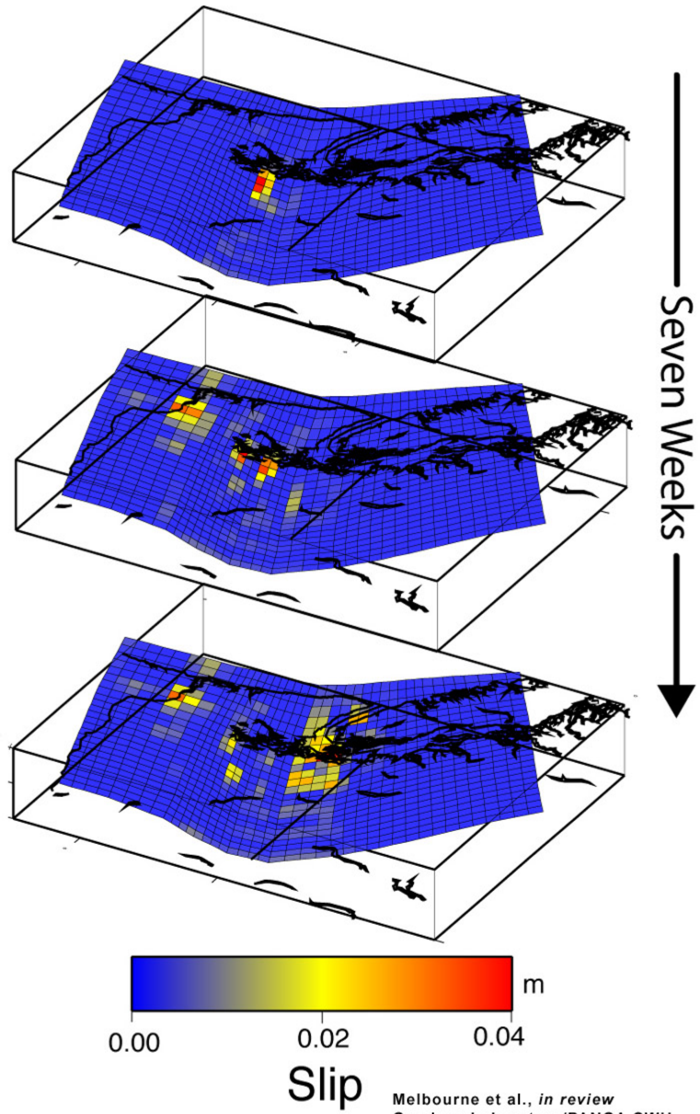


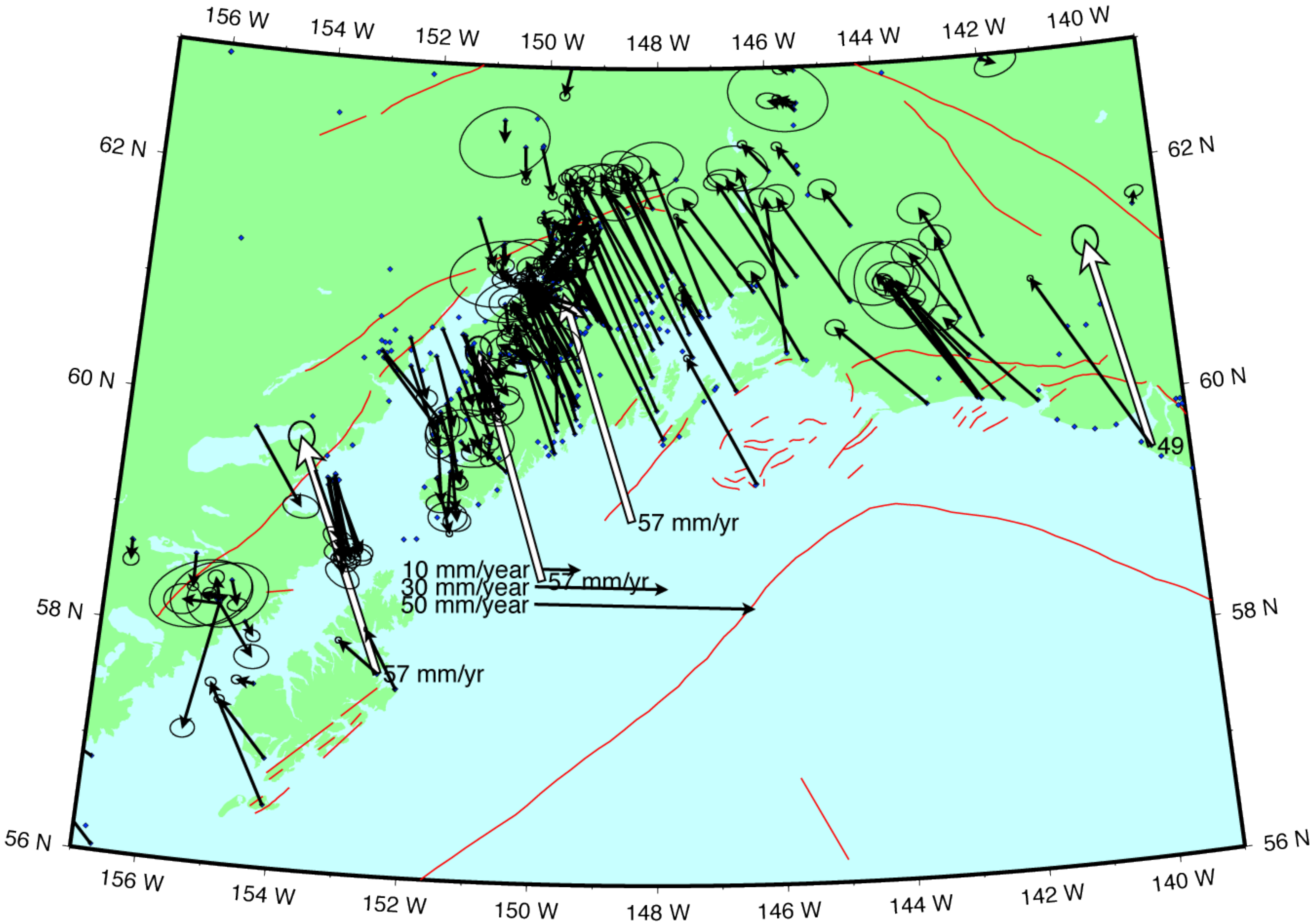
Figure 2. Melbourne et al, in review
Geodesy Laboratory/PANGA CWU

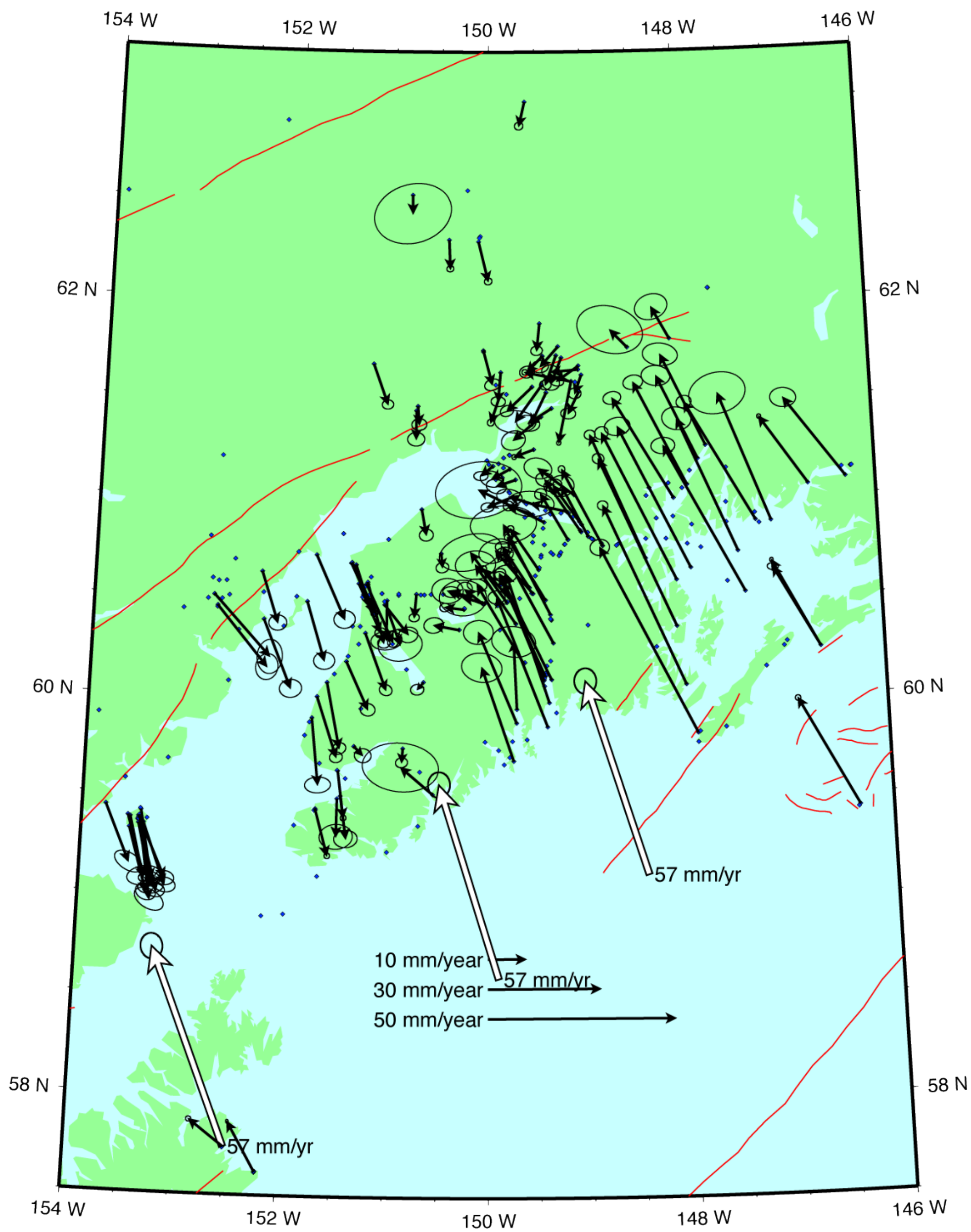
Displacement and Slip Model





Present Horizontal Velocities

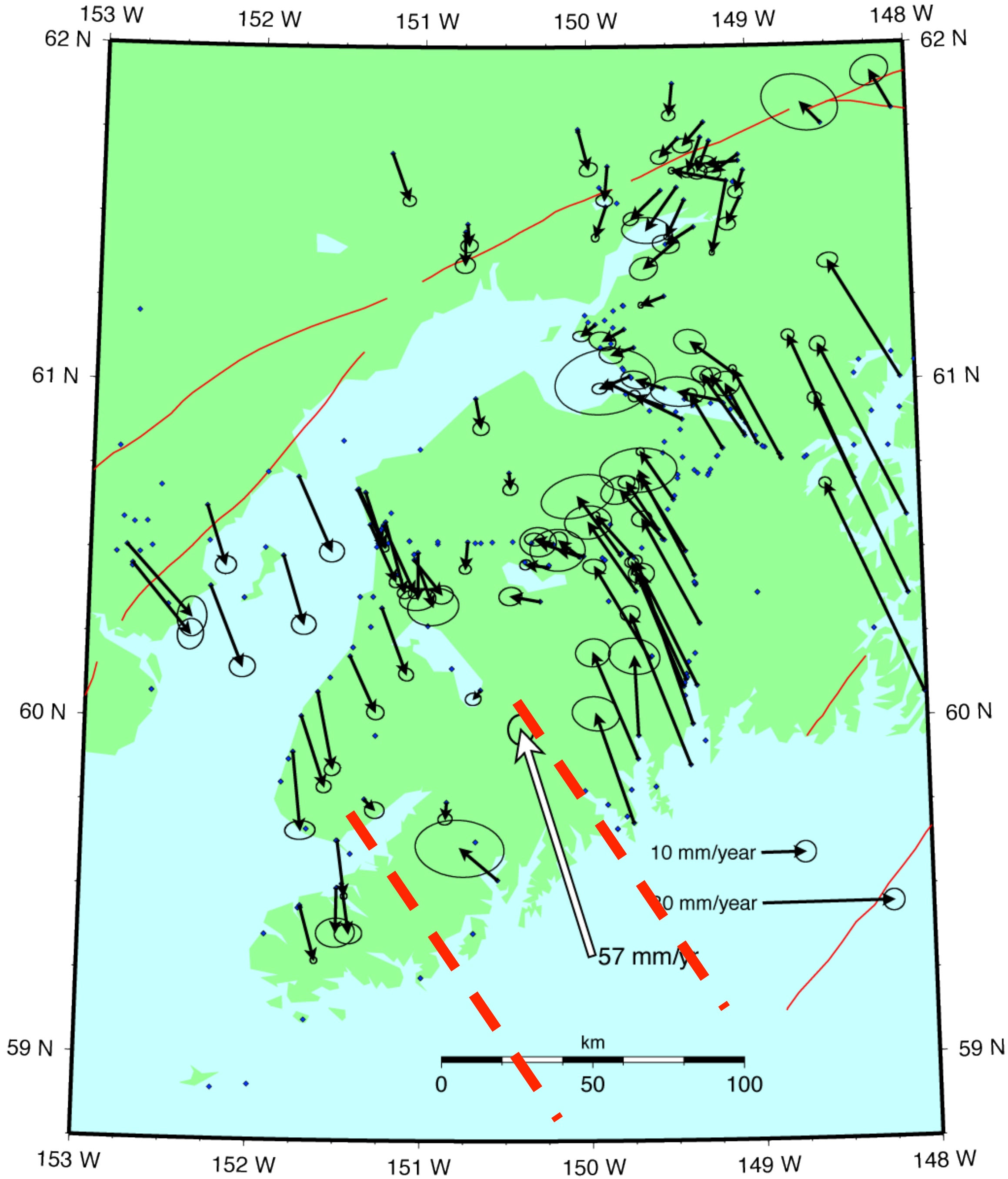




Kenai

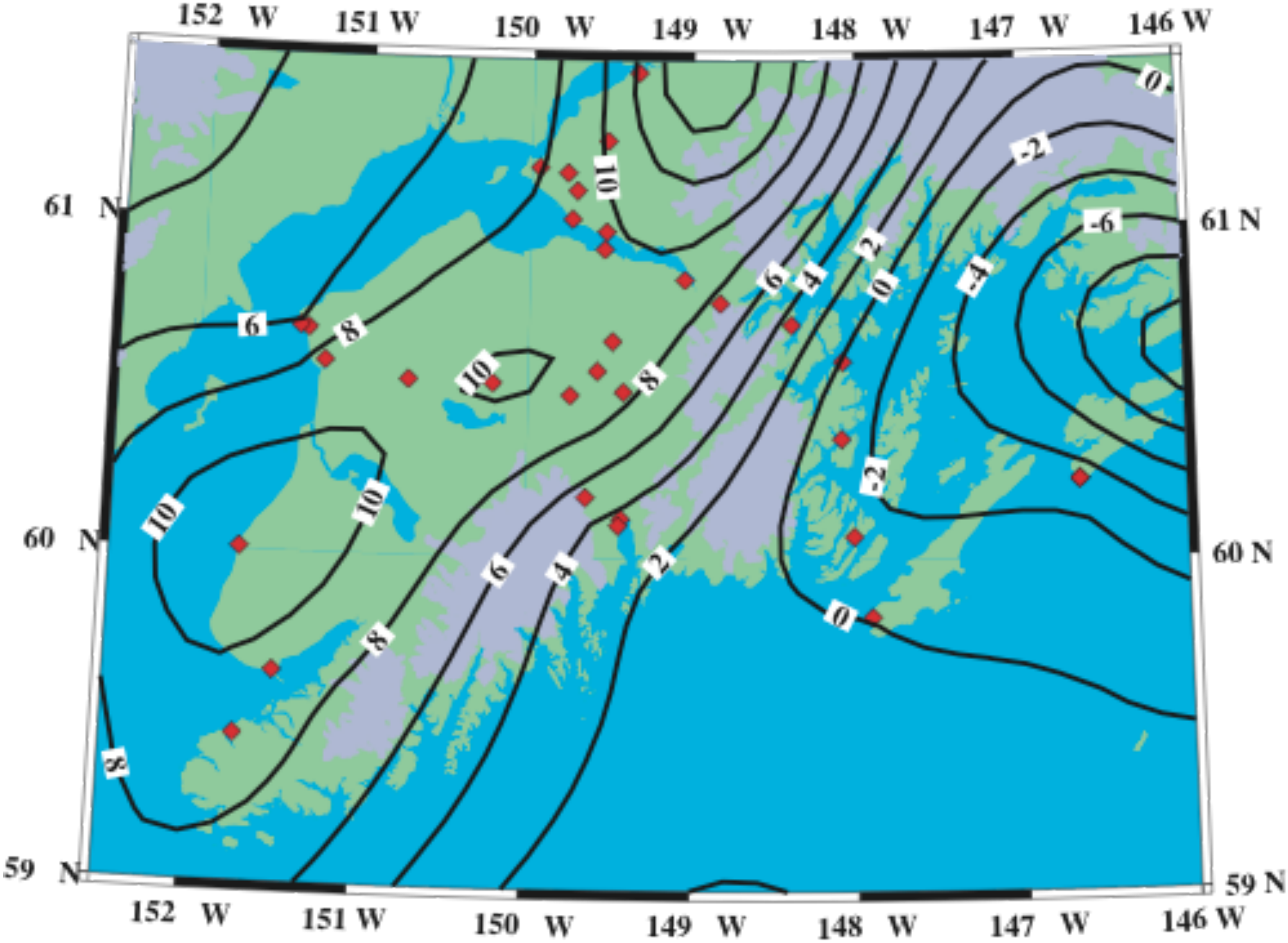
- Combination of
  - locked subduction zone (NNW)
  - postseismic deformation (SSE)
- Up to 55 mm/yr relative to NOAM
- Up to ~75 mm/yr relative motions
- Along-strike changes in seismogenic zone

Kenai Detail

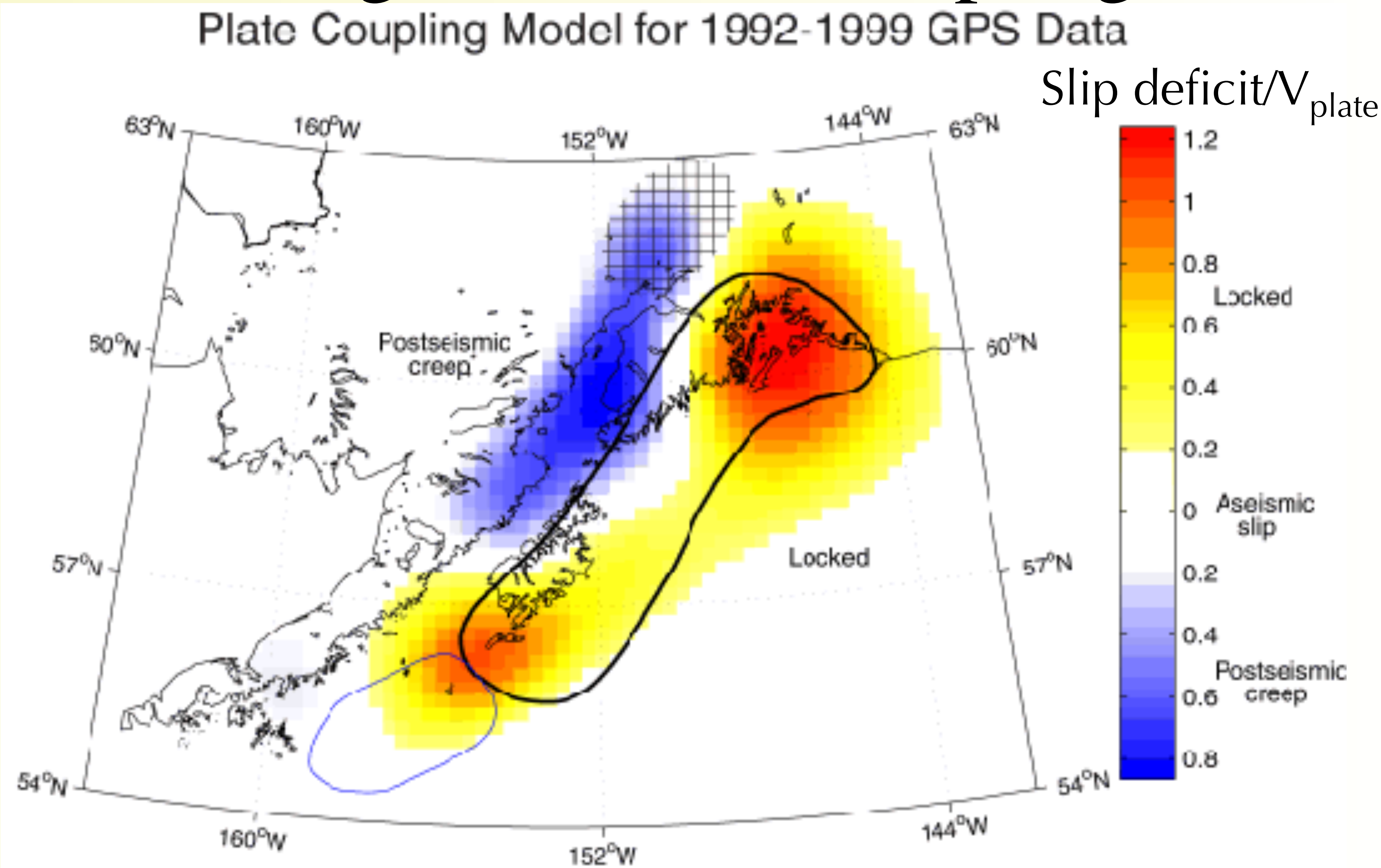


- Obvious transition between western and eastern Peninsula
- Look at sites same distance from trench
- Edge of plate coupling toward western edge of Peninsula
  - Edge of PWS asperity

GPS Uplift Rates

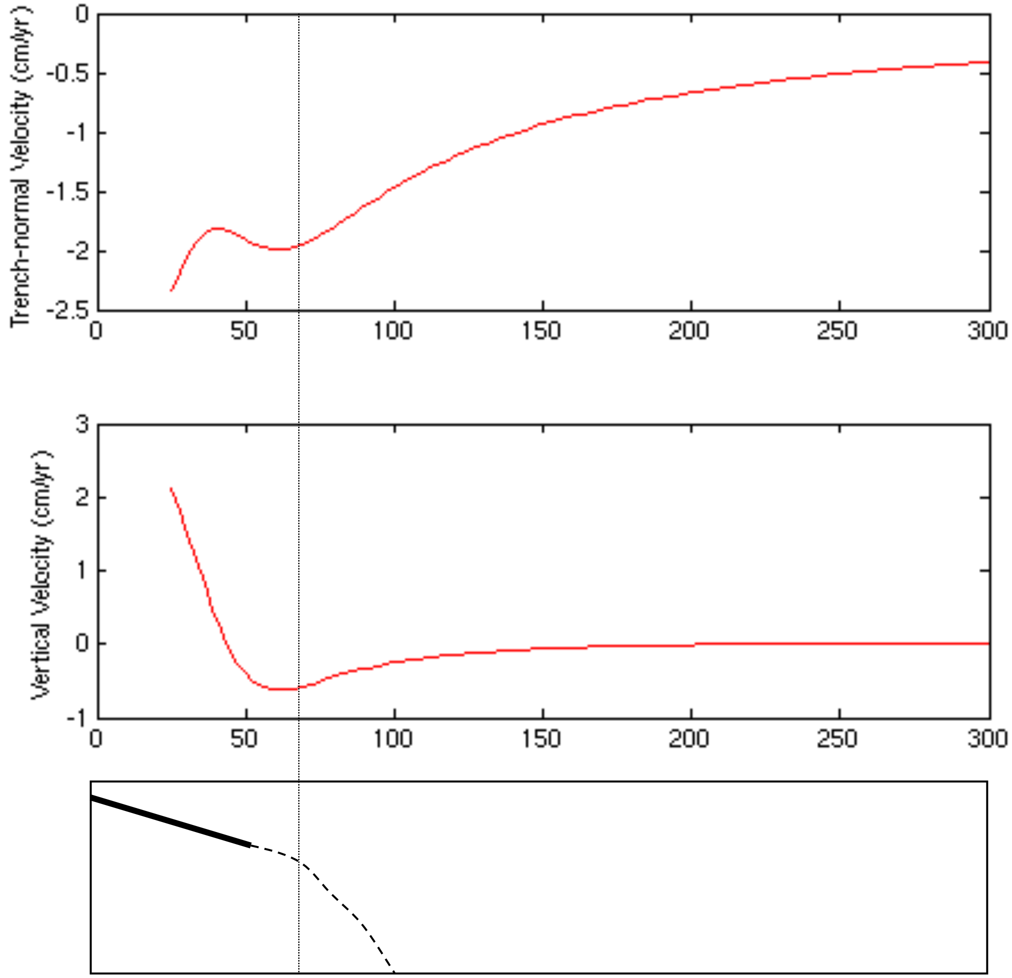


Regional Plate Coupling



Zweck et al. (2002)

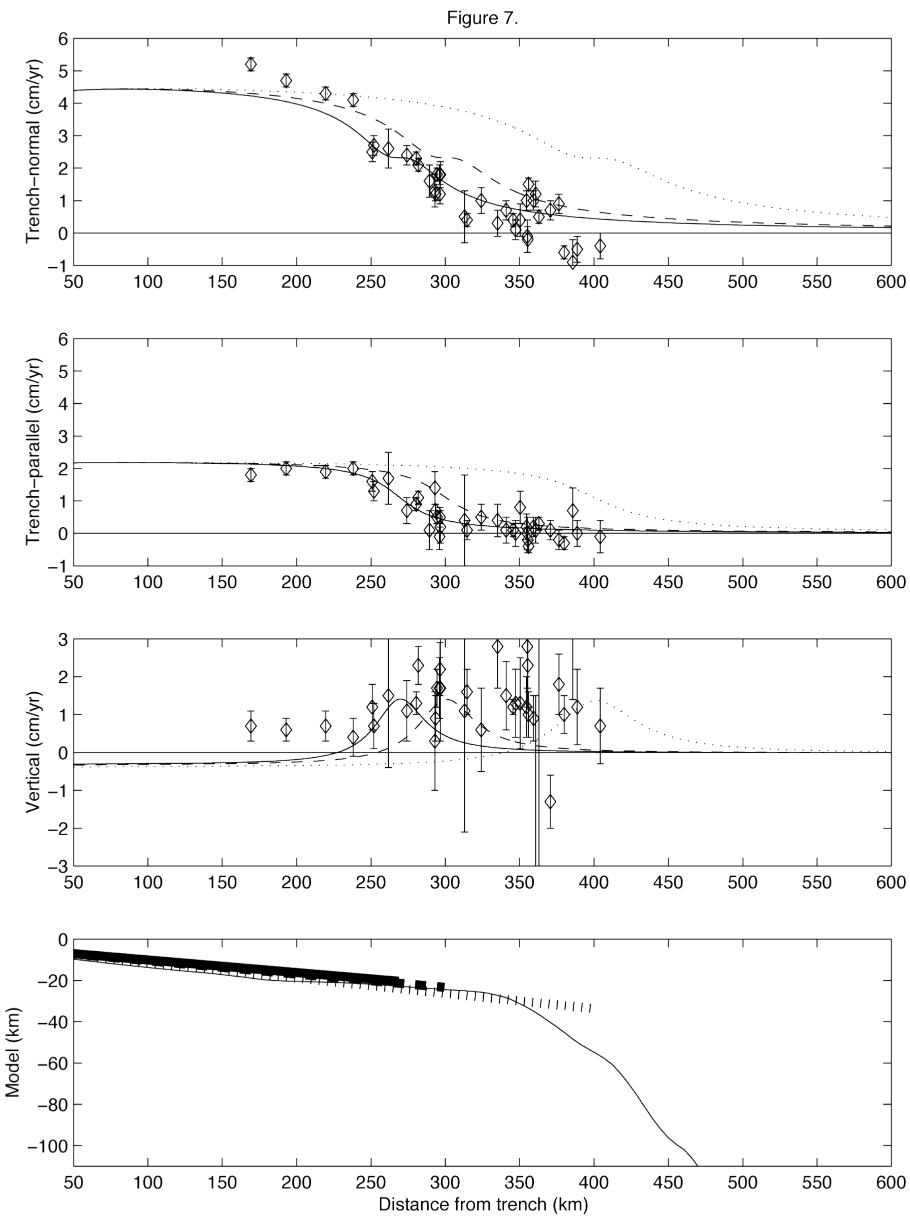
A Model for Kamchatka

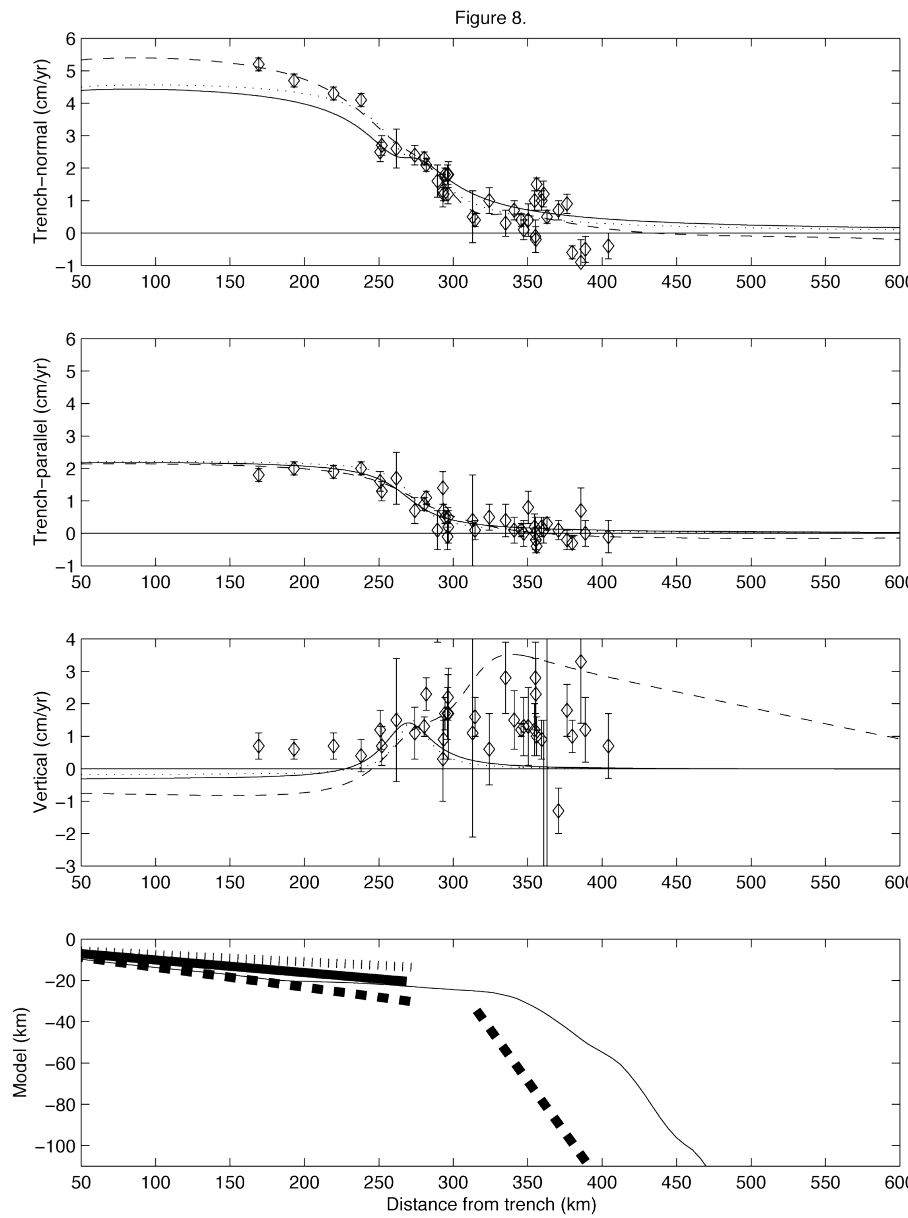


10 cm/yr

Convergence

35 degree dip





From Freymueller *et al.* (2000), JGR