Earthquakes and Stress in the Earth's Crust:

Studying crustal stress can help constrain the physics of faulting.

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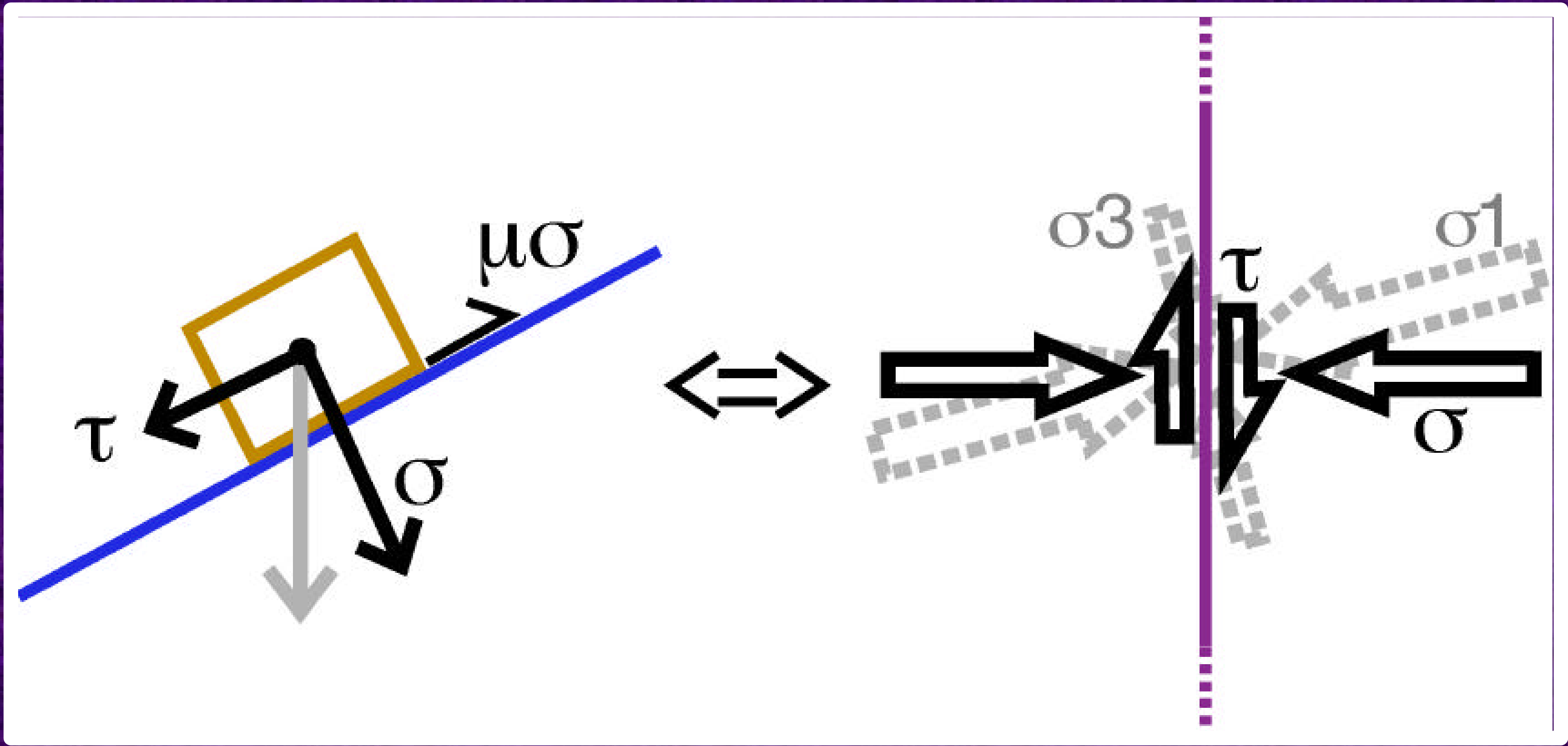
Fault Strength

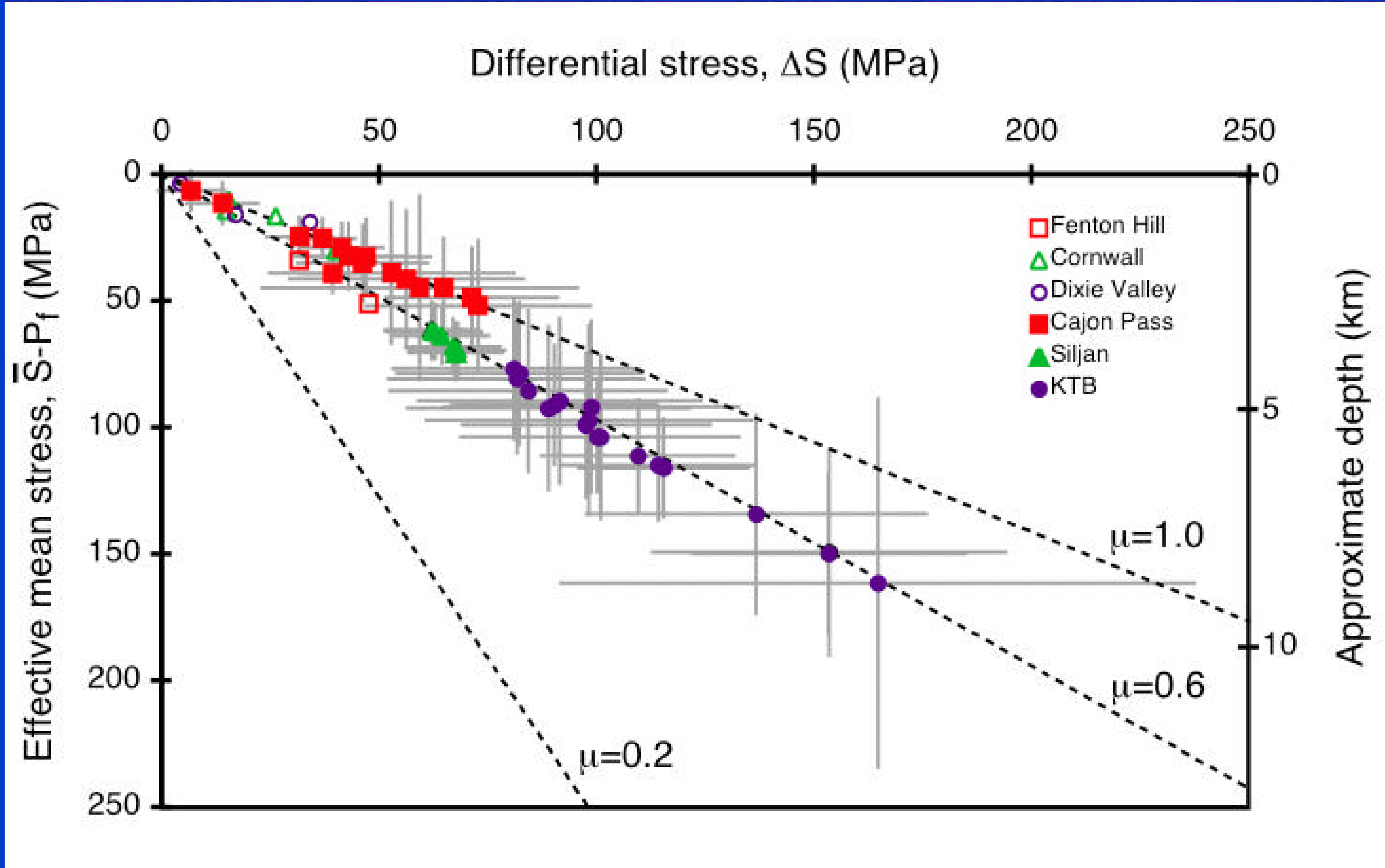


failure if $\tau > \mu(\sigma - p)$

Rocks in the Lab: μ=0.6-0.85

τ = shear stress
σ = normal stress
p = pore pressure
μ = coefficient of friction

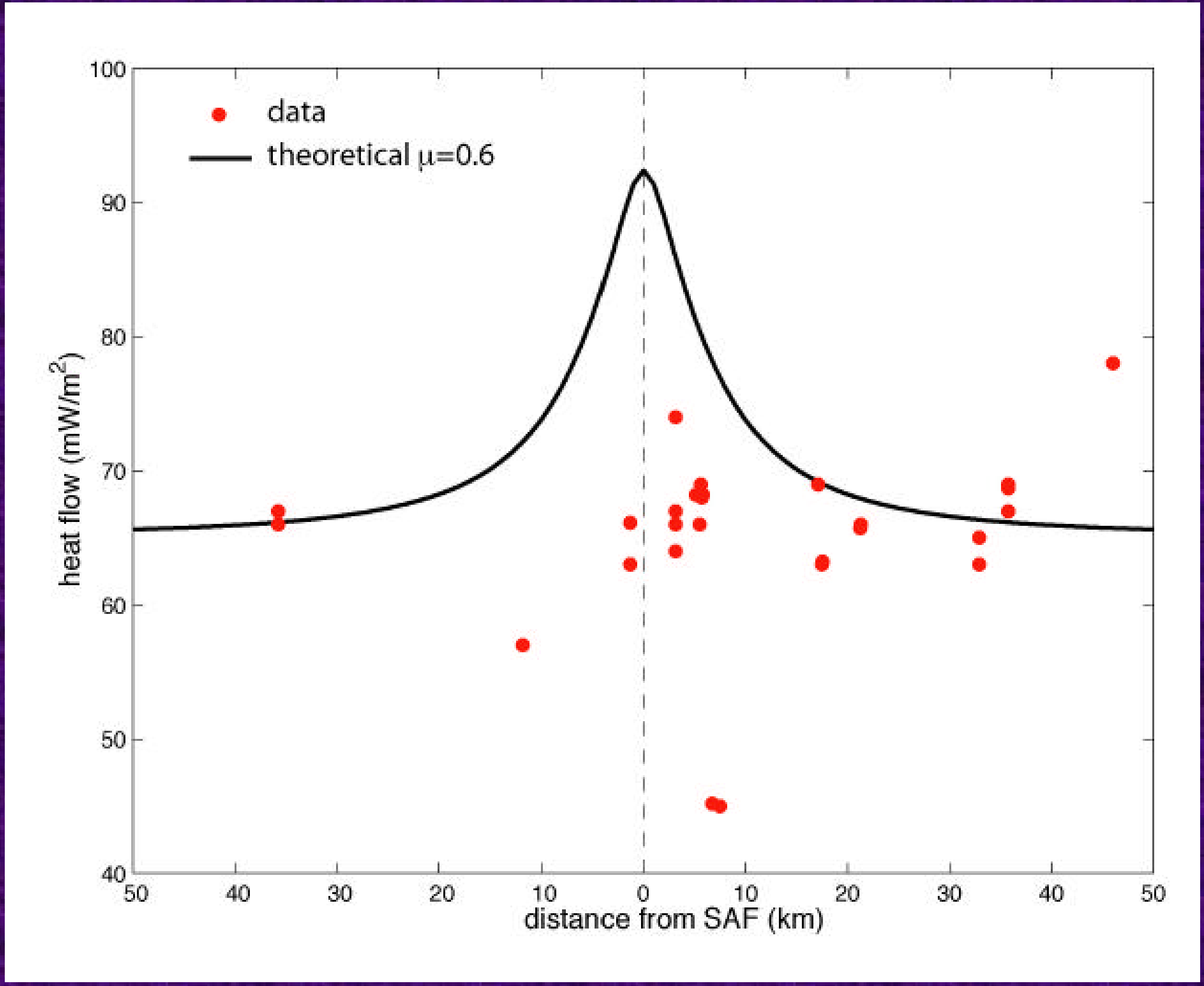
Observations in deep boreholes imply μ=0.6, and deviatoric stress on order of 100 MPa



Townend and Zoback, Geology, 2000.

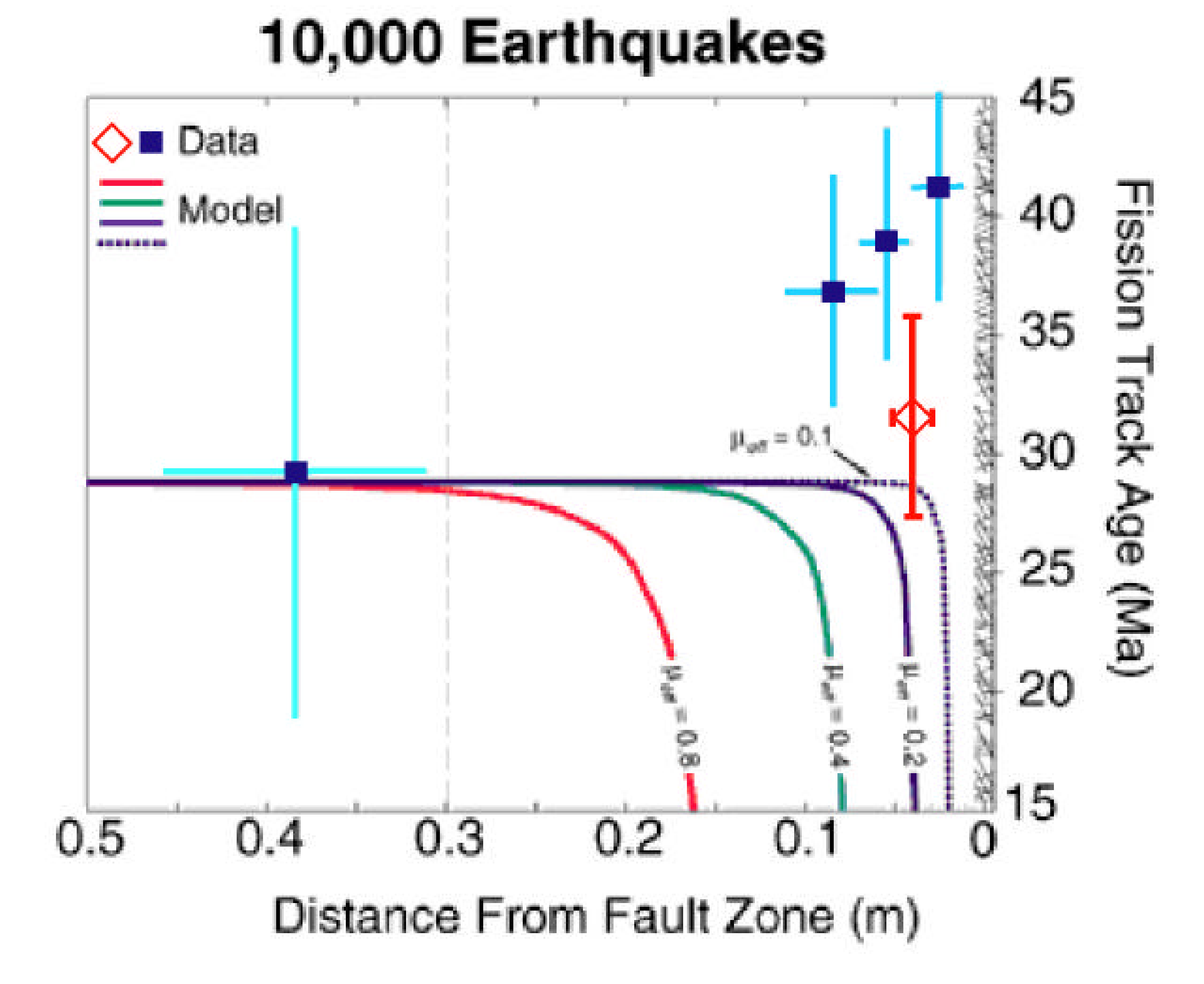
The San Andreas Fault, California

Photo: R. Wallace



Lack of a heat flow anomaly near the San Andreas Fault implies:

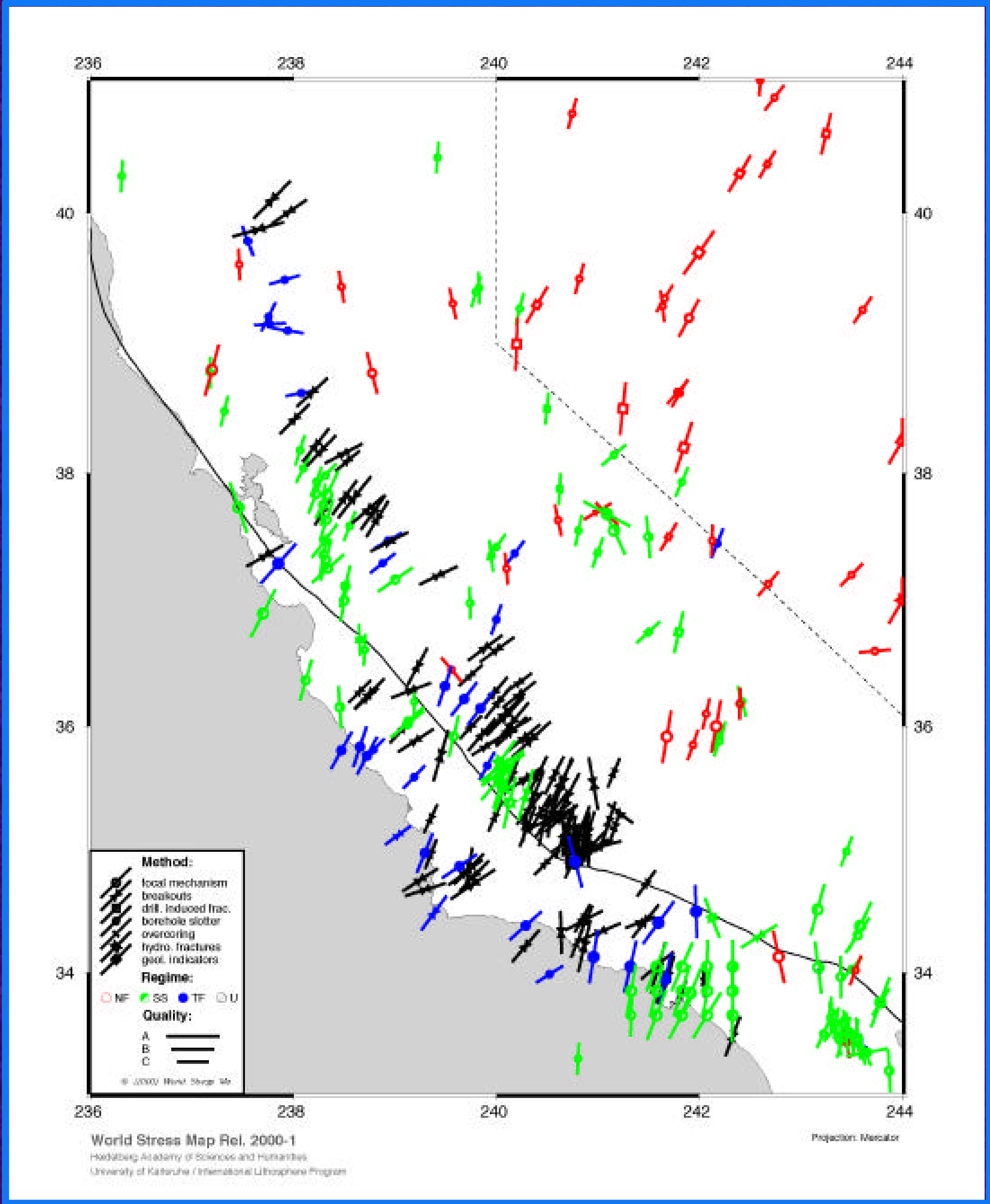
- shear stress < 20 MPa
- $\mu<0.1$



Fission track ages near the fault have not been reset by heating, which implies μ<0.2

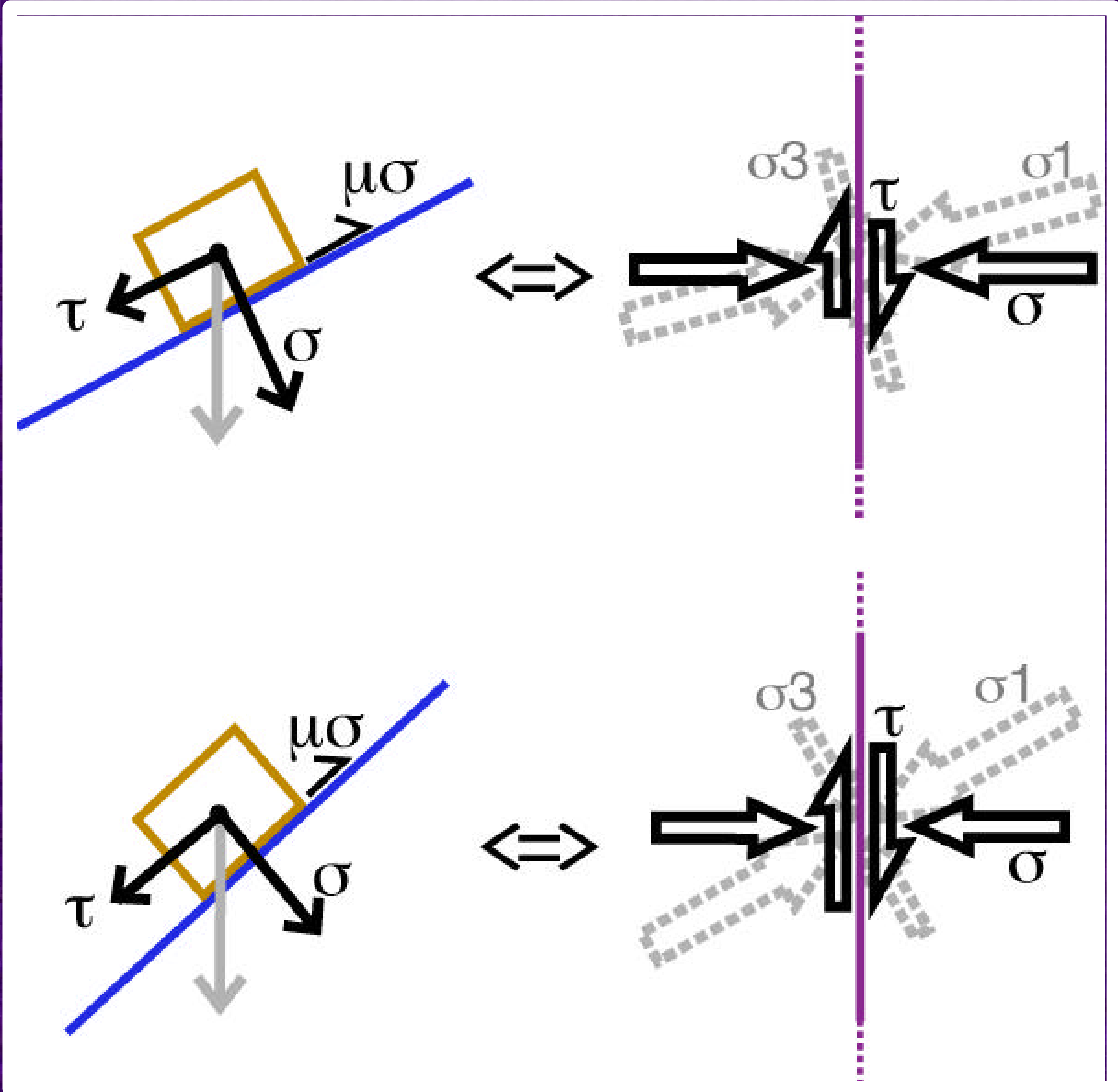
D'Alessio et al, AGU 2001.

Crustal Stress Orientations in California



The San Andreas Fault is at “high angle” to the stress field - implying that the fault is not well oriented for failure.

World Stress Map Project



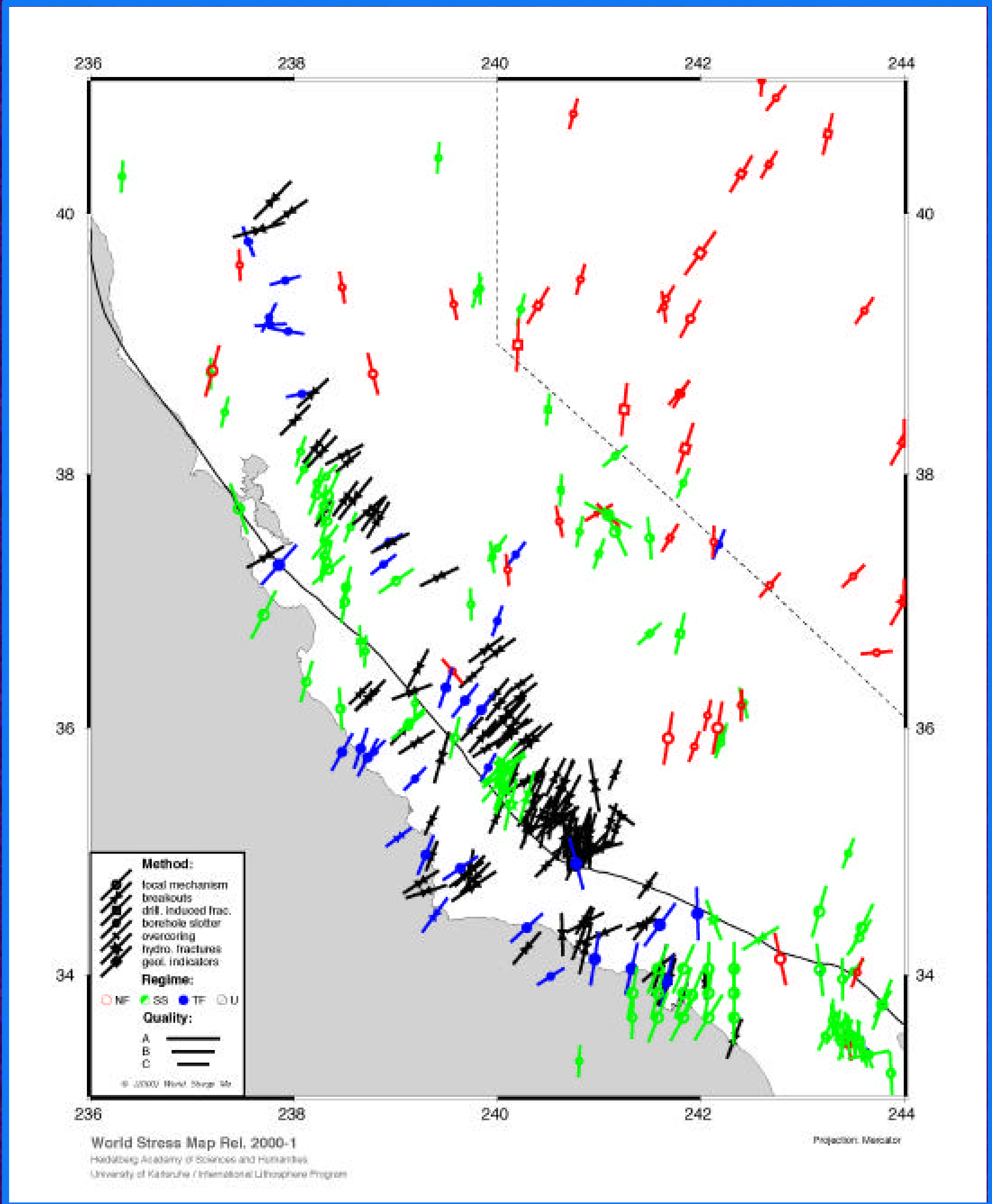
“high-angle”
- high normal stress
- low shear stress
- unfavorable for slip

“low-angle”
- low normal stress
- high shear stress
- favorable for slip

Conventional Model of the San Andreas Fault

- The surrounding crust is strong and at high stress (deviatoric stress ~100 MPa.)
- Most faults are strong (μ=0.6)
- The San Andreas is anomalously weak (strength on the order of 10 MPa.)
- The San Andreas is at high angle to the stress field, minimizing the resolved shear stress.

Crustal Stress Orientations in California



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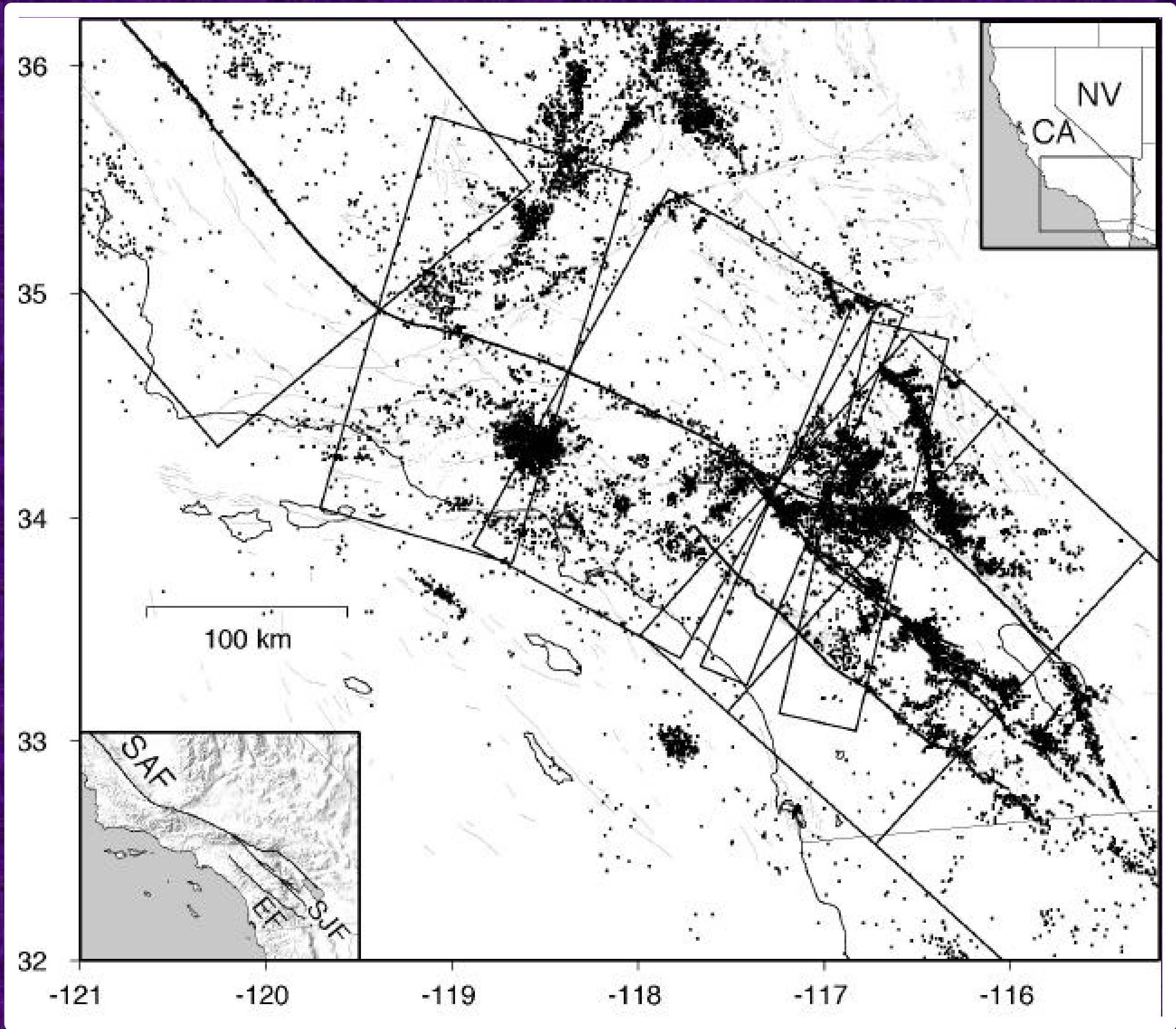
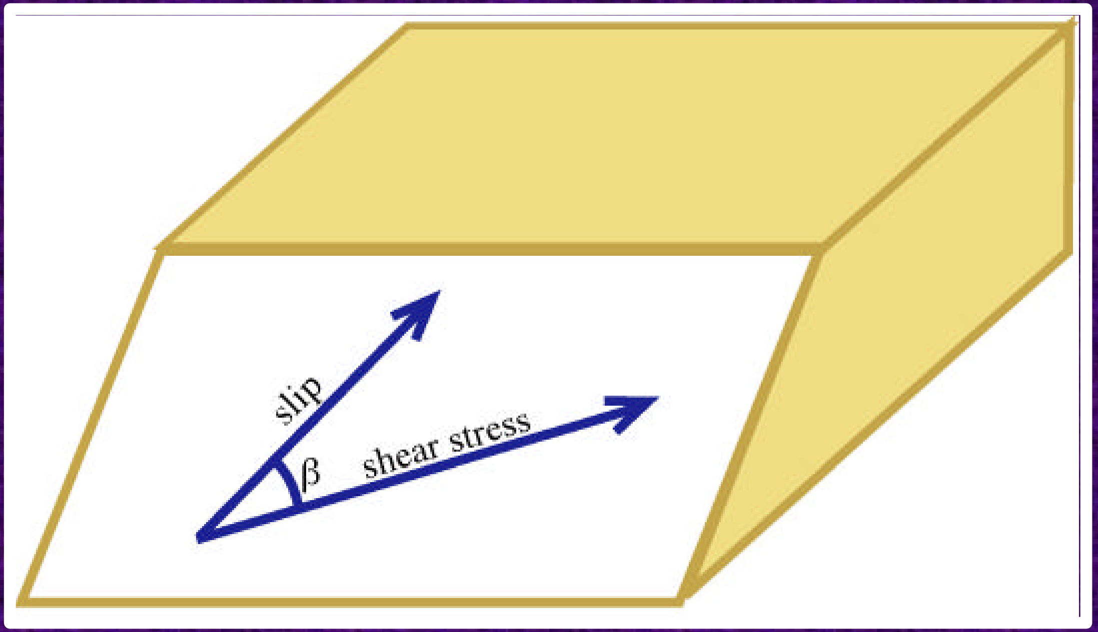


Southern California Seismicity 1984-1998

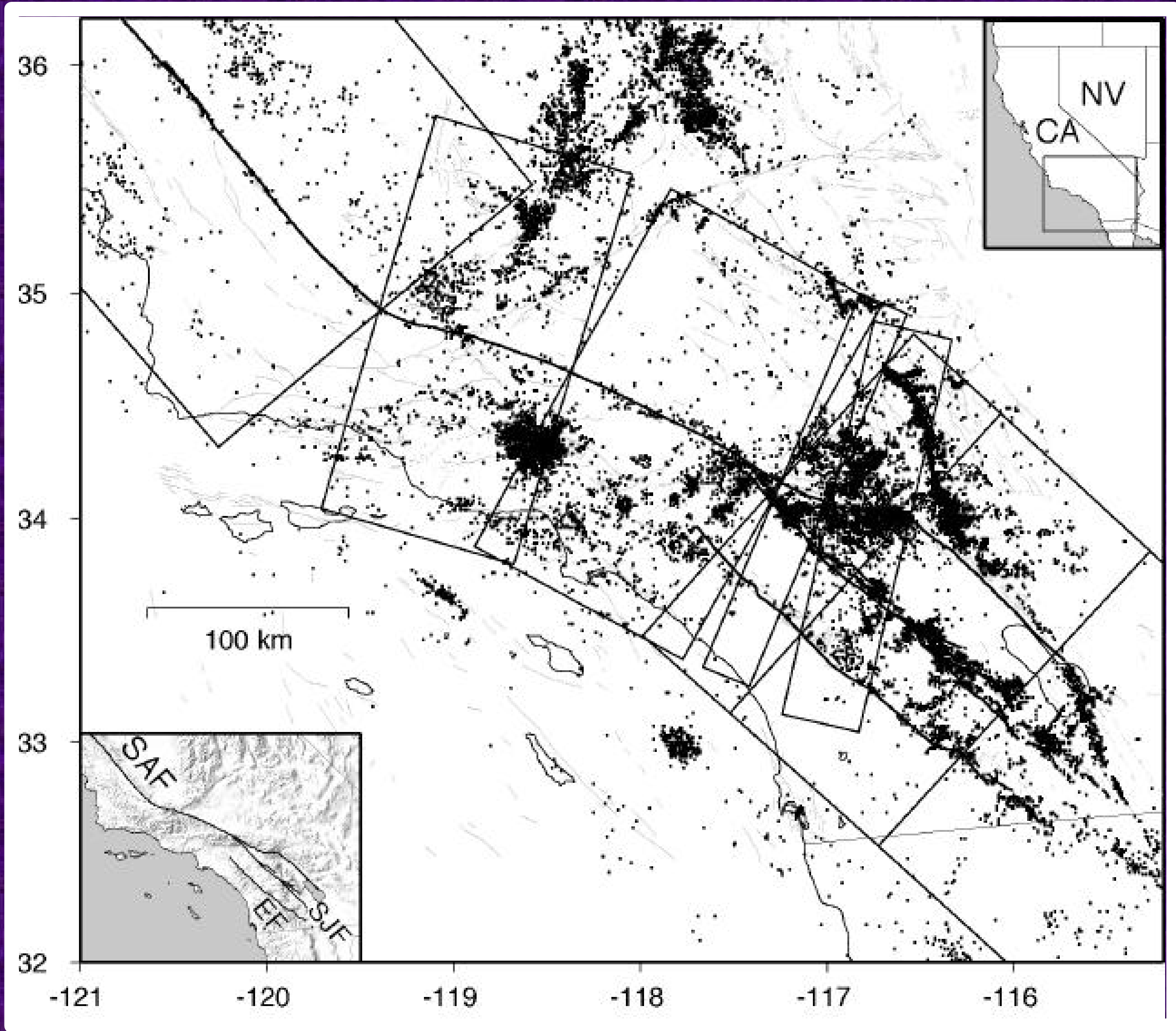
Inverting earthquake slip directions for stress orientation



Assume:
- Slip is in the direction of shear stress on fault plane.
- Stress orientation is constant over space and time of data.

Minimize: misfit angle β

Constrain:
- Orientation of 3 principal stress axes.
- Relative magnitude of principal stresses.
- No absolute stress magnitudes.



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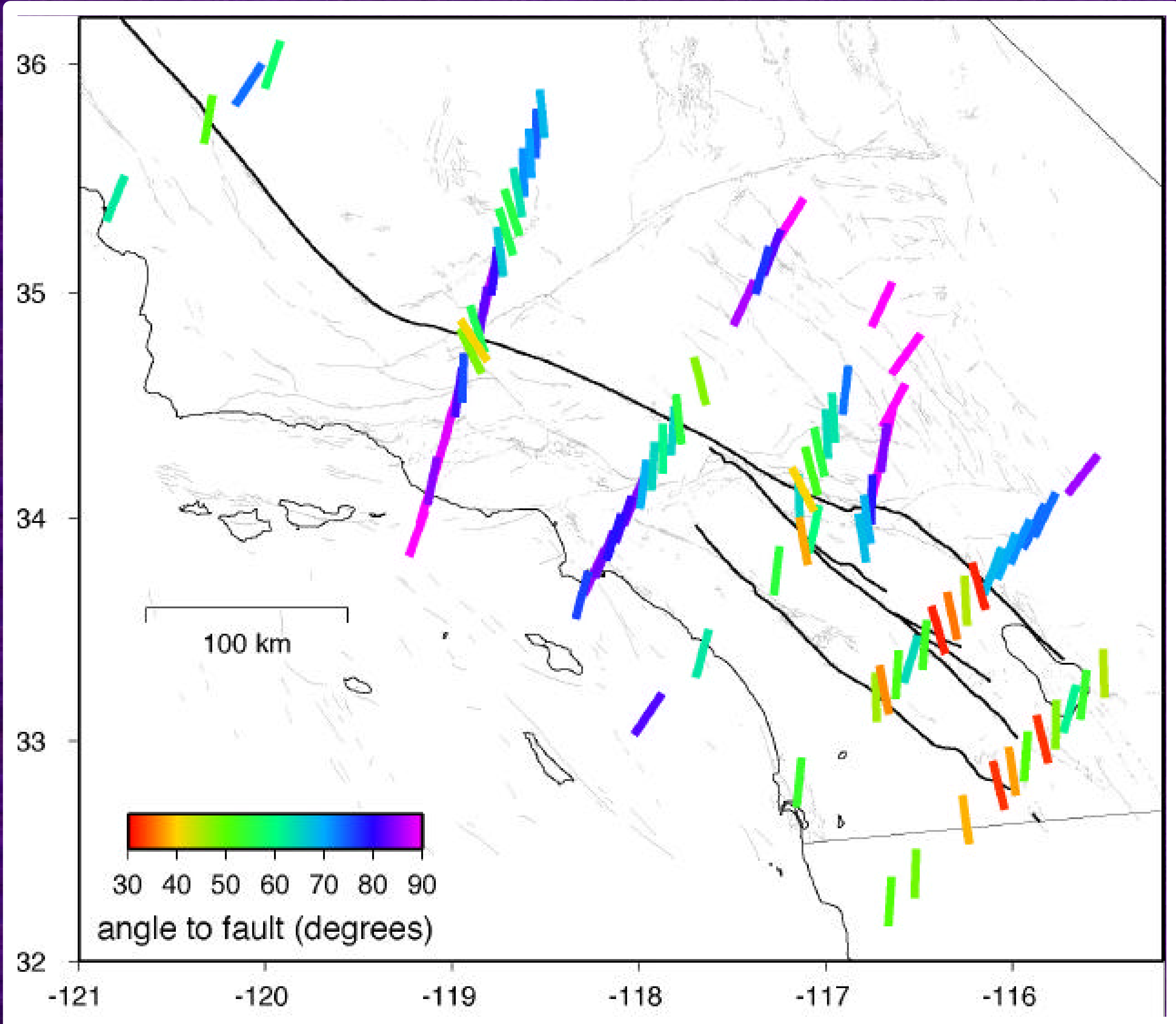
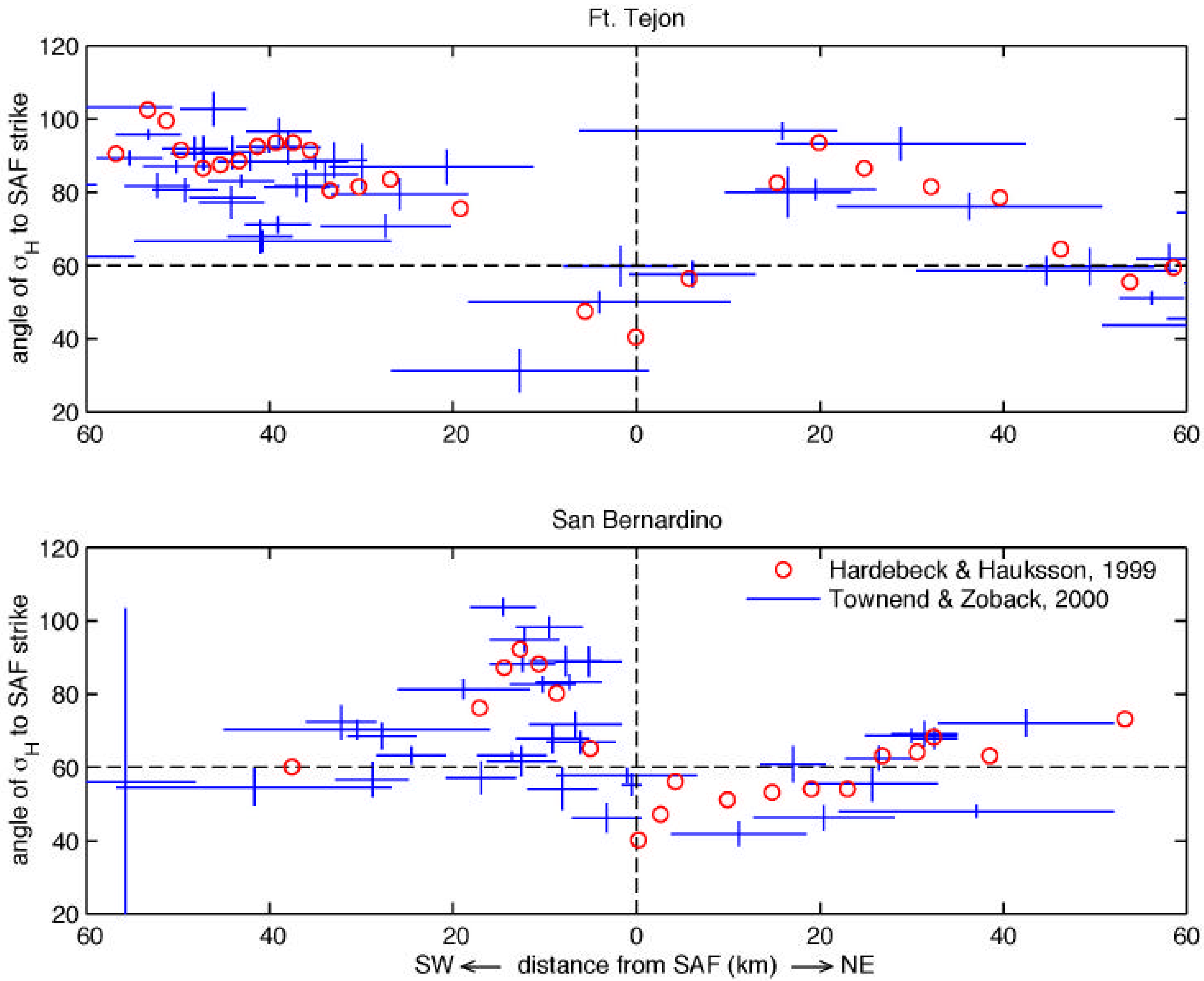


Hardebeck and Hauksson, Science, 1999.

Far-field stress at high angle to SAF.

Near-field stress at low angle to SAF.

Implies that SAF is of similar strength to its immediate surroundings.



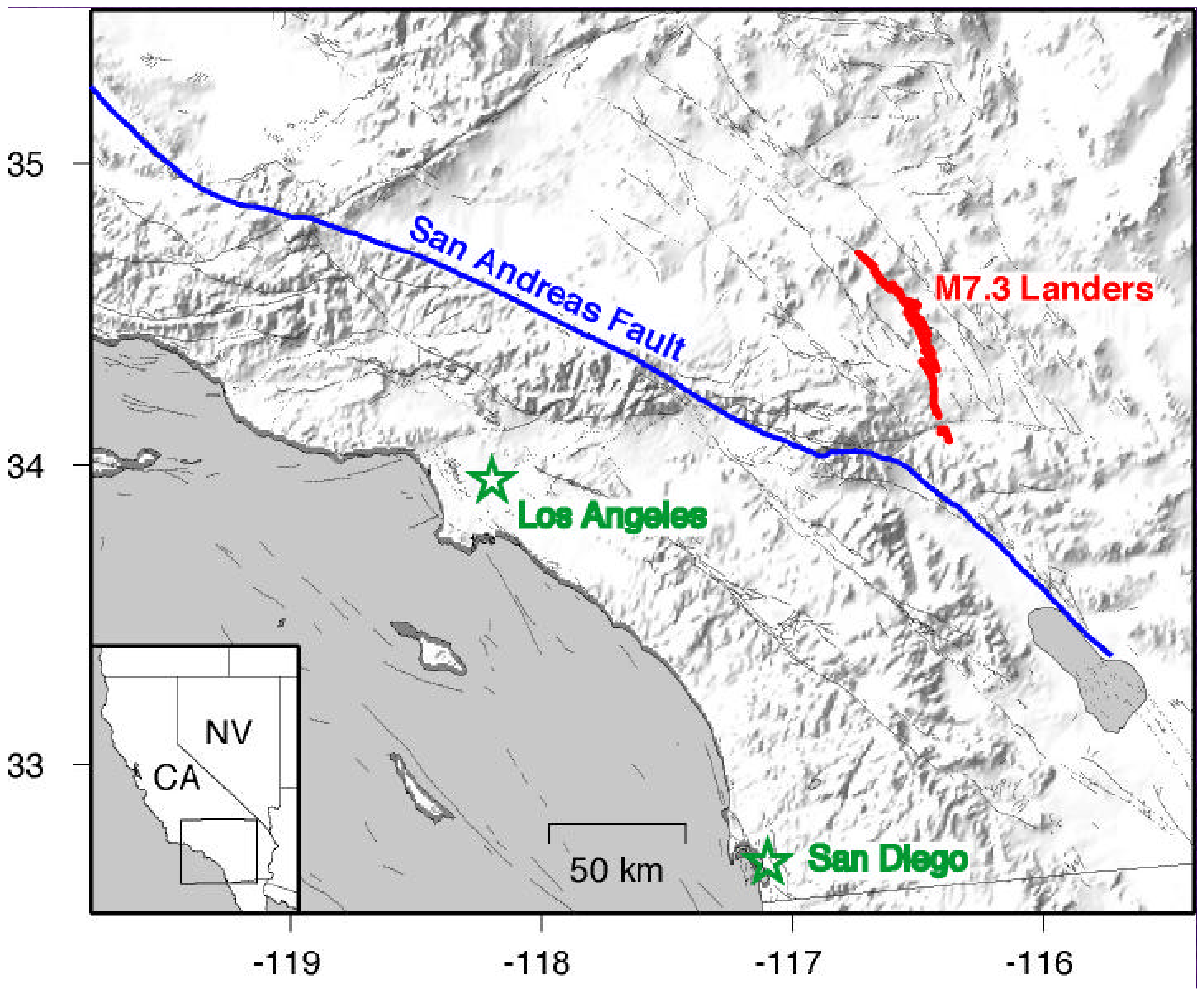
Ft. Tejon
angle of σH to SAF strike
120
100
80
60
40
20
60
40
20
0
20
40
60
San Bernardino
Hardebeck & Hauksson, 1999
Townend & Zoback, 2000
SW ← distance from SAF (km) → NE

Observed stress axis at ~45° to the fault implies:

- The shear stress on the SAF is equivalent to the deviatoric stress.
- The SAF is not relatively weak.

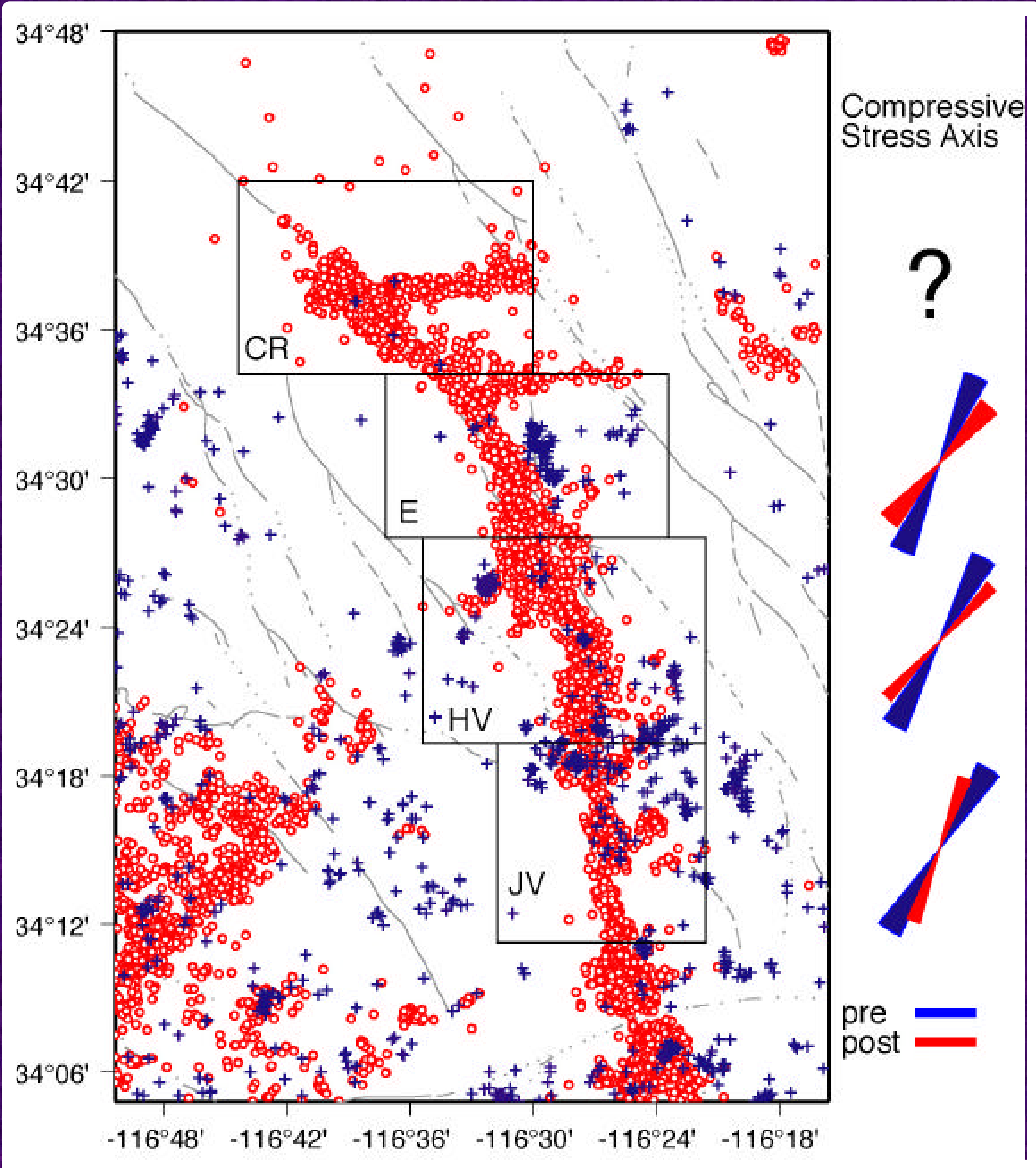
Two possibilities:

- The SAF is strong (Scholz, 2000), μ=0.6, strength = 100 MPa. --- BUT low heat flow implies strength < 20 MPa.
- The deviatoric stress is low, ~10 MPa. --- BUT deviatoric stresses of ~100 MPa are measured in deep boreholes.

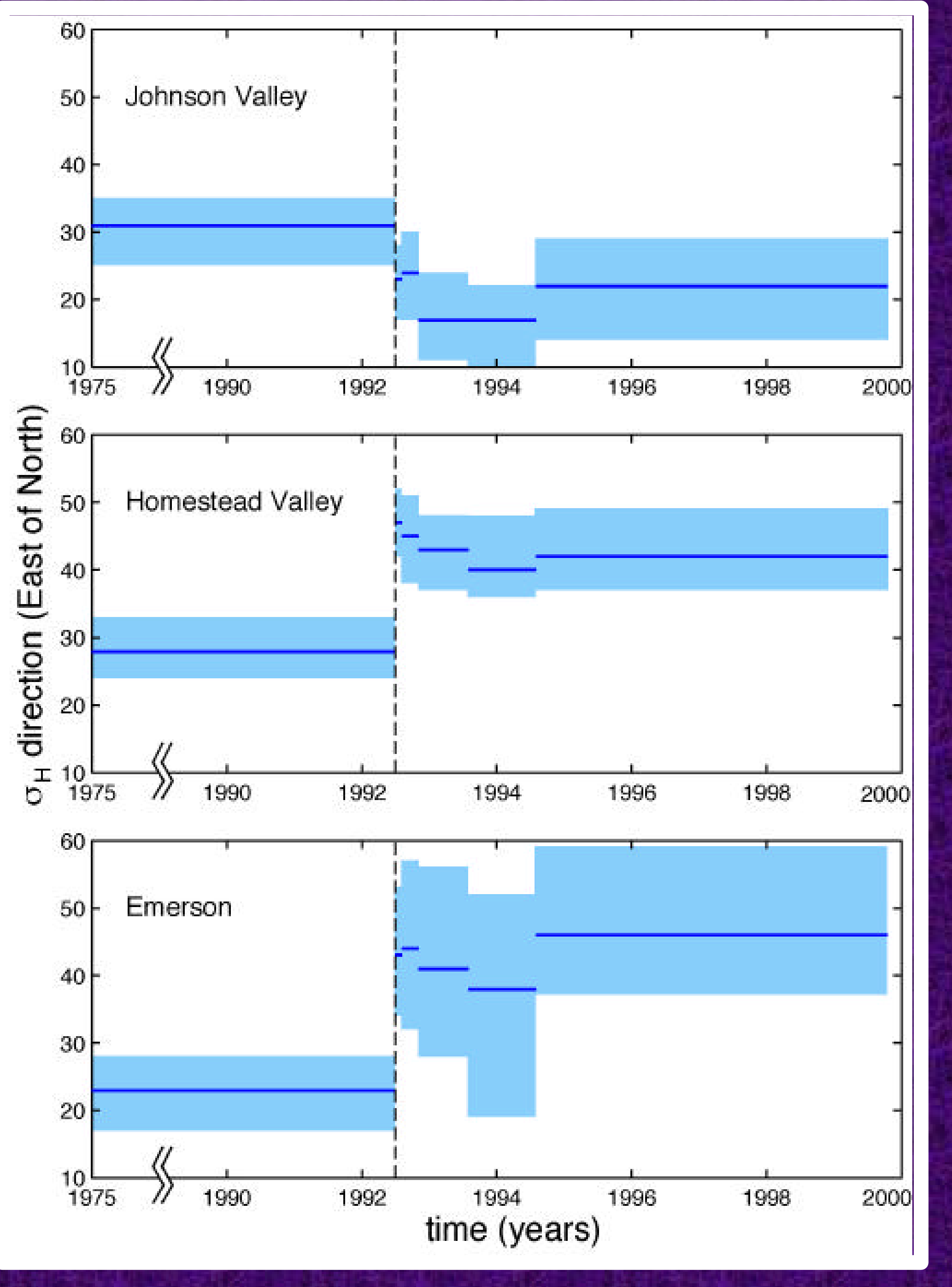


35
34
33
-119
-118
-117
-116
San Andreas Fault
M7.3 Landers
Los Angeles
San Diego
50 km
NV
CA

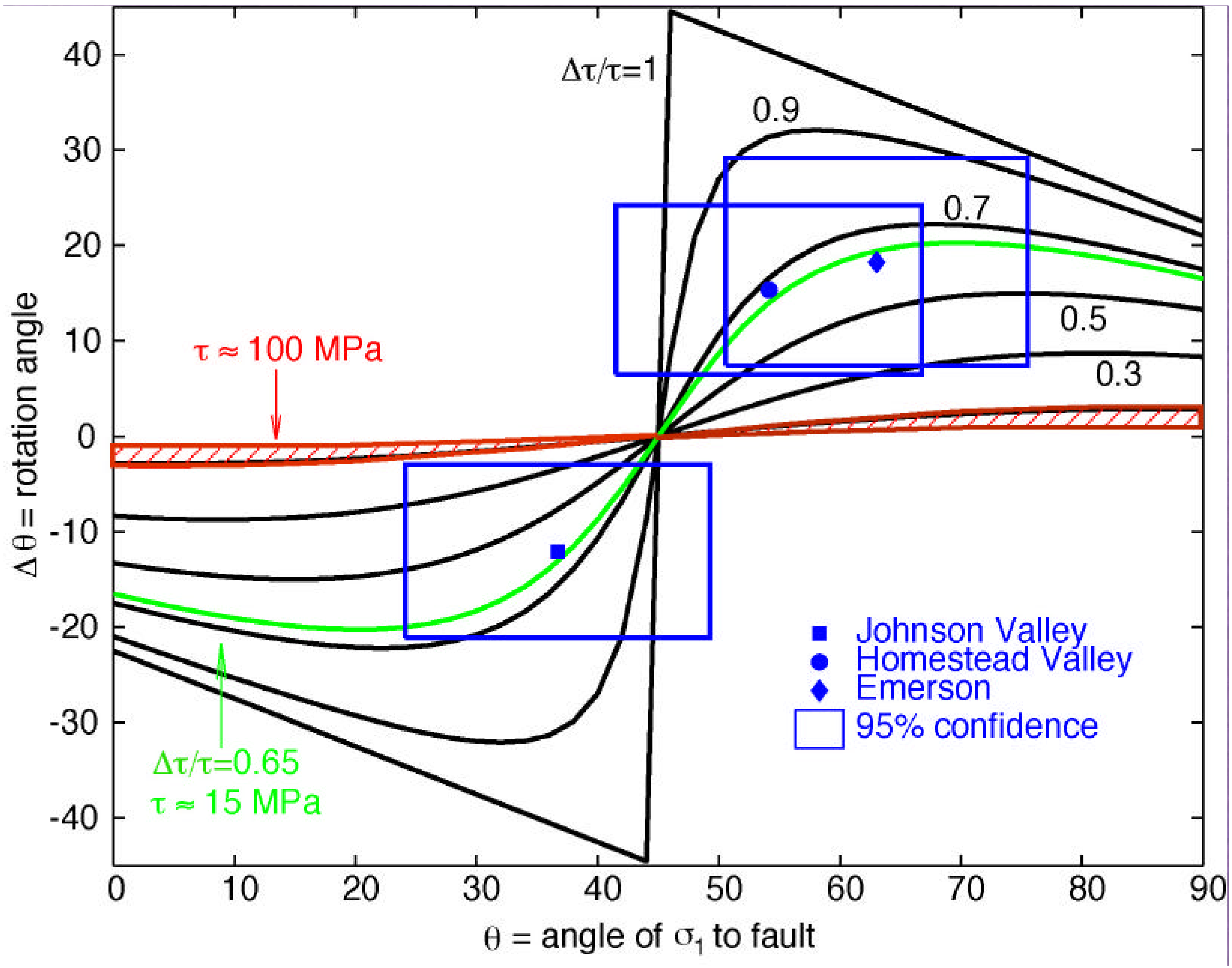
Stress rotation due to the 1992 M7.3 Landers earthquake



Stress rotation due to the 1992 M7.3 Landers earthquake



- An earthquake-induced stress rotation implies low background deviatoric stress, on the order of earthquake stress drop, ~10 MPa.
- If background deviatoric stress was high, ~100 MPa, the relatively small earthquake stress change wouldn’t noticeably change the stress field.
- The stress rotation is dependent on only two things: θ, the orientation of the fault in the stress field; and $\Delta\tau/\tau$, the ratio of the stress change to the background stress.



Δτ/τ=1
0.9
0.7
0.5
0.3
τ ≈ 100 MPa
Δτ/τ=0.65
τ ≈ 15 MPa
Johnson Valley
Homestead Valley
Emerson
95% confidence
Δθ = rotation angle
θ = angle of σ1 to fault
40
30
20
10
0
-10
-20
-30
-40
0
10
20
30
40
50
60
70
80
90

Conventional Model

- The surrounding crust is at high deviatoric stress (order 100 MPa)
- Most faults are strong, ~100 MPa (μ=0.6)
- The San Andreas is anomalously weak, with strength order of 10 MPa.
- The San Andreas is at high angle to the stress field, so the resolved shear stress is order 10 MPa.

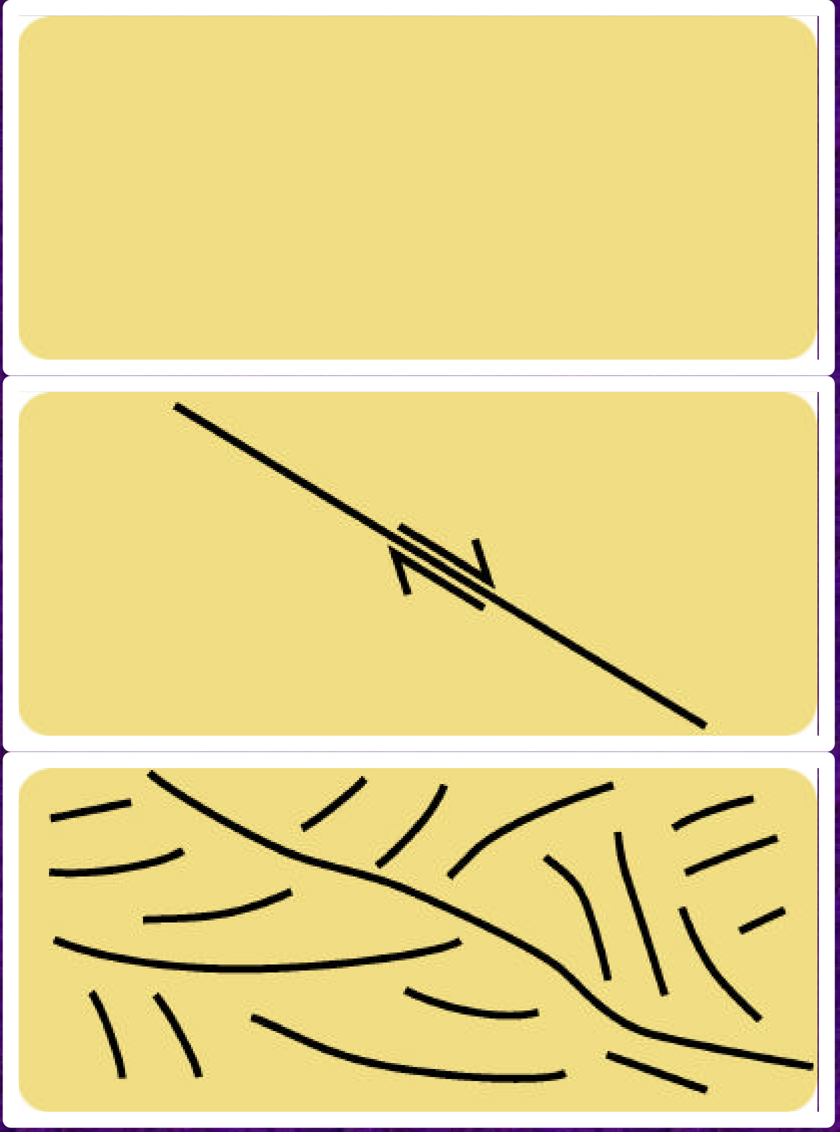
Alternative Model

- The surrounding crust is at low deviatoric stress (order 10 MPa)
- Most faults are weak, strength order 10 MPa.
- The San Andreas also has strength on the order of 10 MPa.
- The San Andreas is at low angle to the stress field, so the resolved stress on the fault is order 10 MPa.

Fault weakening mechanisms

- High-pressure fluids decrease effective normal stress (Hubbert & Rubey, 1959; Rice, 1992; Sibson, 1992)
- Fault zone materials with low μ. Difficult to find a fault zone mineral that is weak and stable at high temperature and pressure.
- Dynamic weakening:
  - highly velocity dependent friction (Heaton,1990)
  - fault-opening waves (Andrews & Ben-Zion,1997)
  - acoustic fluidization (Melosh, 1996)
  - pore pressure increase (Brodsky & Kanamori, 2000)

MODEL: major active faults are weak, relatively intact crust is strong



Intraplate:
- no major active faults
- strong
- high stress

Simple Plate Boundary:
- one major active faults
- strong except for fault
- high stress, oriented so that little stress on fault

Complex Plate Boundary:
- many major active faults
- weak planes in many orientations
- low stress

Summary

<u>Stress and Fault Strength - San Andreas Fault:</u>

Observations:

- The compressional stress axis is ~45° to the SAF within ~10 km of the fault.
- The M7.3 Landers earthquake rotated the local stress orientations by ~20°.

Inferences:

- Deviatoric stress is low, ~10 MPa.
- The shear stress on the SAF is comparable to the deviatoric stress.
- The SAF is weak in an absolute sense, but not in a relative sense.