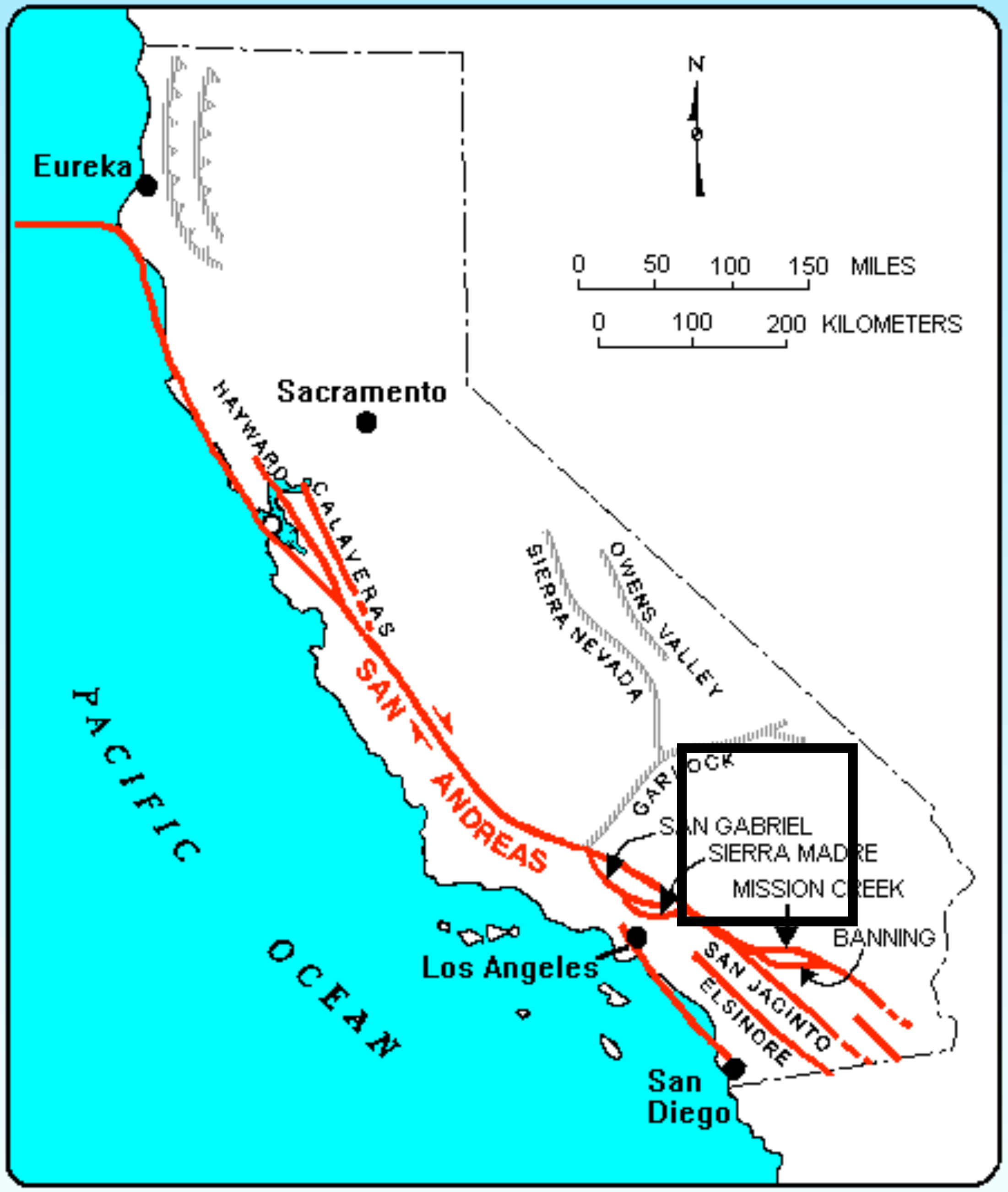
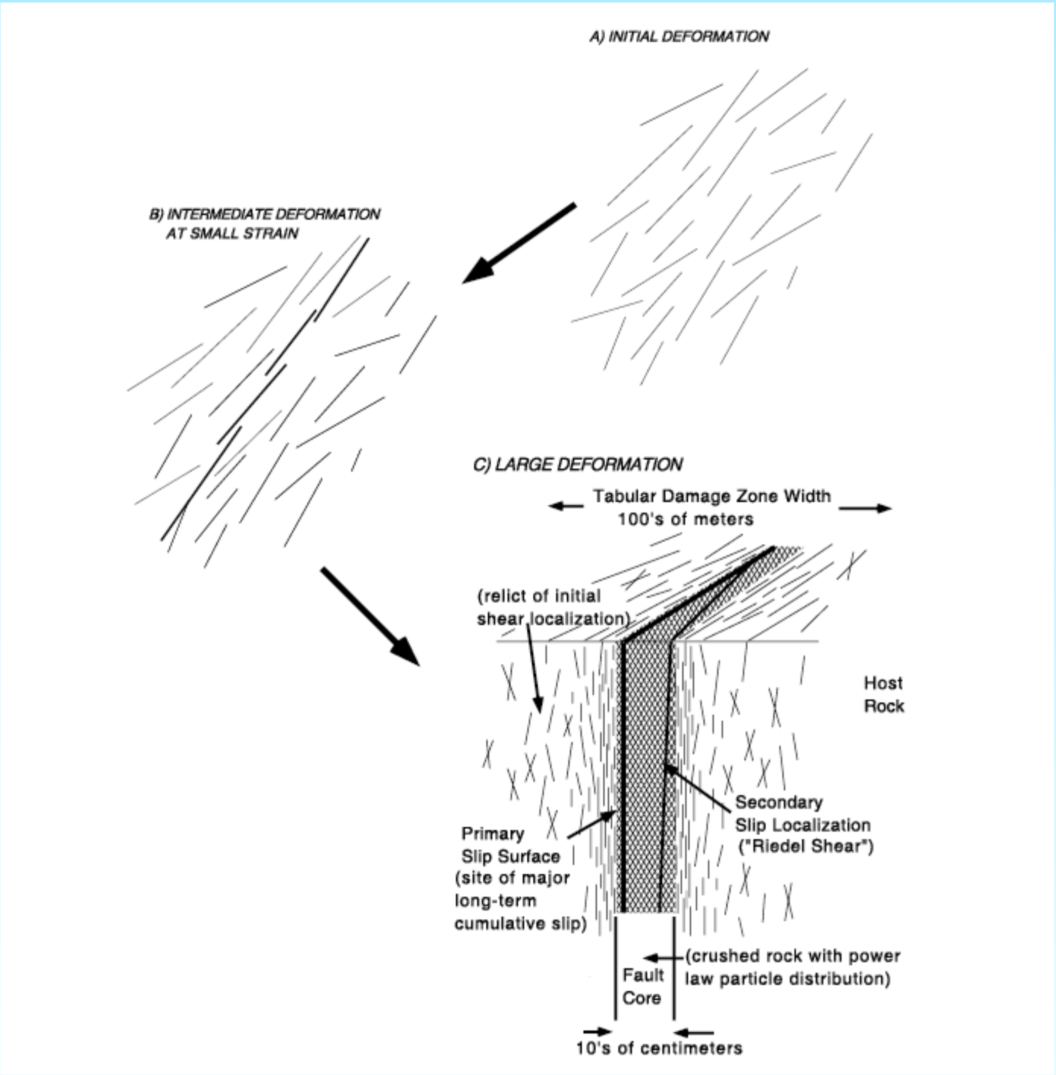
# Modeling coseismic deformation of compliant fault zones to estimate stress in the upper crust

Elizabeth Hearn, UBC

where?




what?




Ben Zion et al. 2003

# Idea: compliant zones as stress barometers?

There are permanently compliant zones around active faults in the Mojave and elsewhere (e.g., Fialko et al., 2002; Li et al., 1999).

These zones soften slightly (damage increases) in response to local earthquakes (Vidale and Li, 2003).

↓

In an earthquake, these zones should strain in response to **both** the total stress (due to coseismic CZ weakening) **and** coseismic stress change (due to permanent CZ weakness).

Hearn, E and Y. Fialko, J. Geophys. Res. 2009

# Today's talk

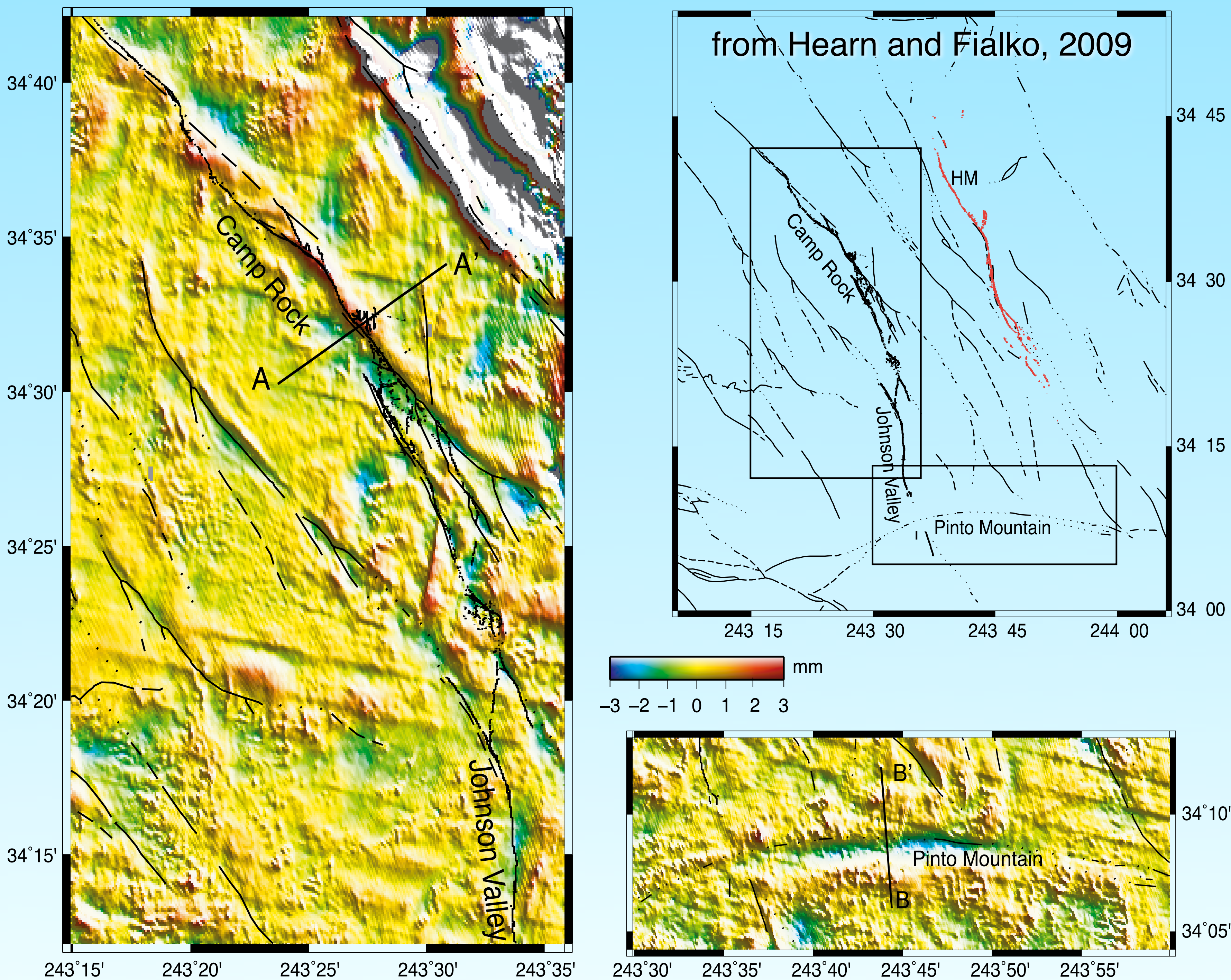
1. Compliant zones around faults,
coseismic changes to their elastic properties

2. How we would *expect* compliant zones to deform in response to a nearby earthquake

3. Modeling approach

4. How compliant zones *actually* deform and what this says about the state of stress in the upper crust

# Pockets of damaged material in the uppermost crust around active faults



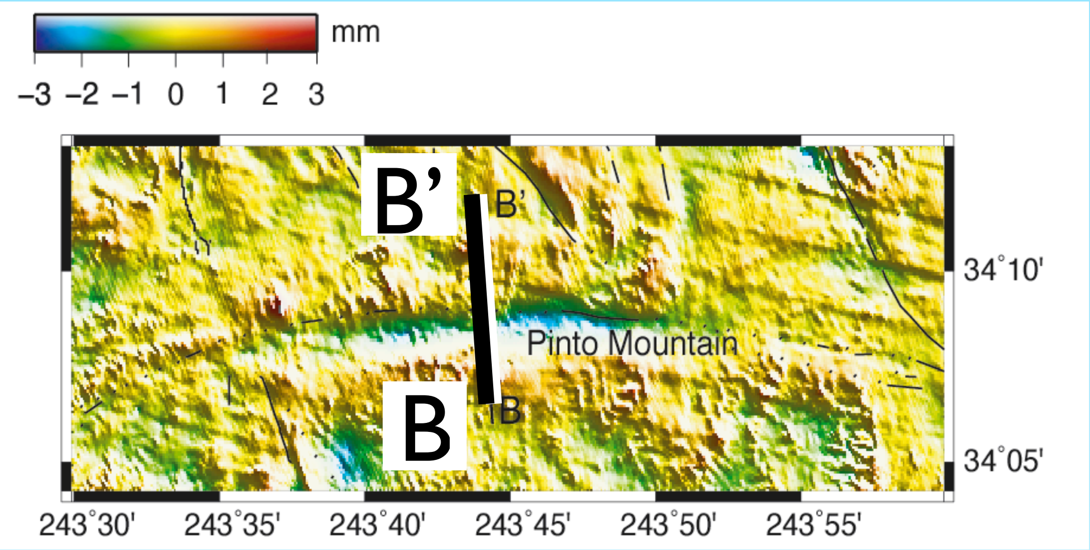

Concentrated strain shows up as wrinkles on filtered inSAR images of coseismic deformation.

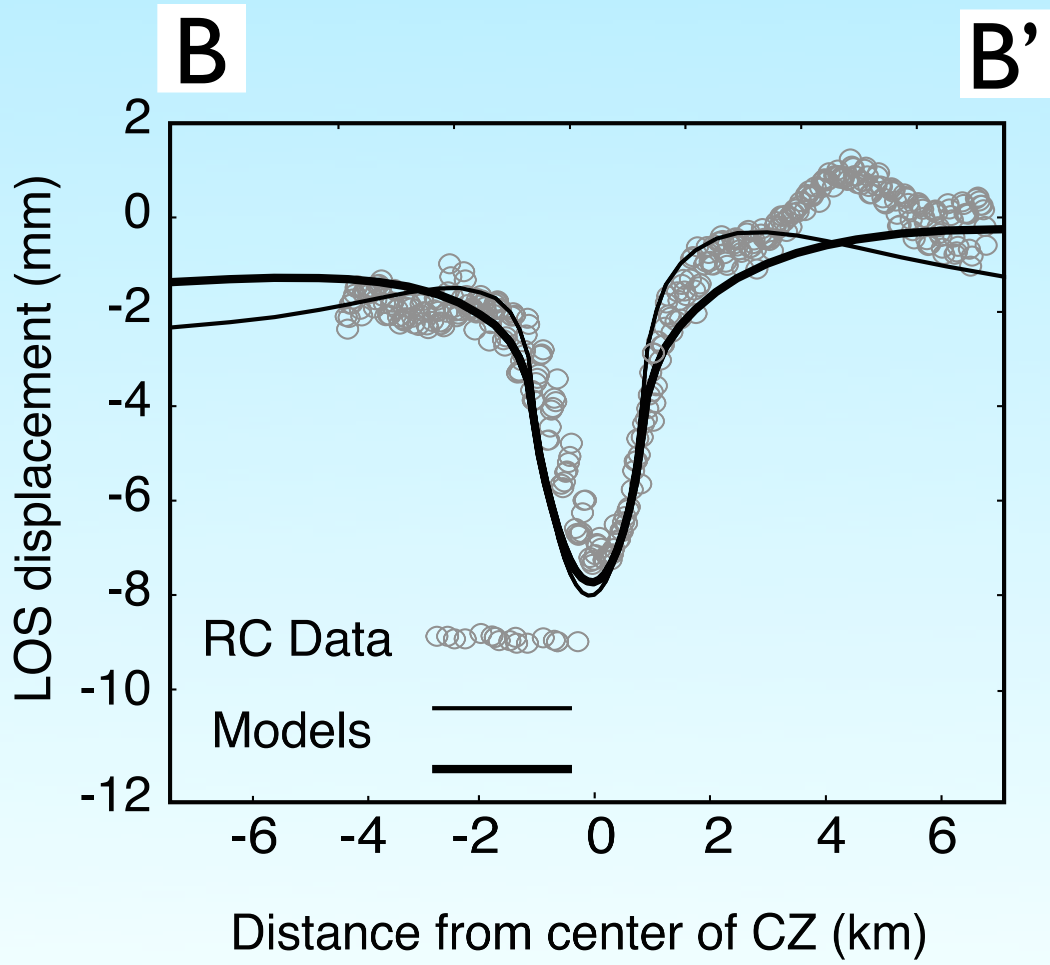
Colors are line-of-sight (LOS) displacements, toward the satellite.

+ is upward and east-southeast.

- is down, west-northwest

# Damaged material in the uppermost crust around active faults: past models

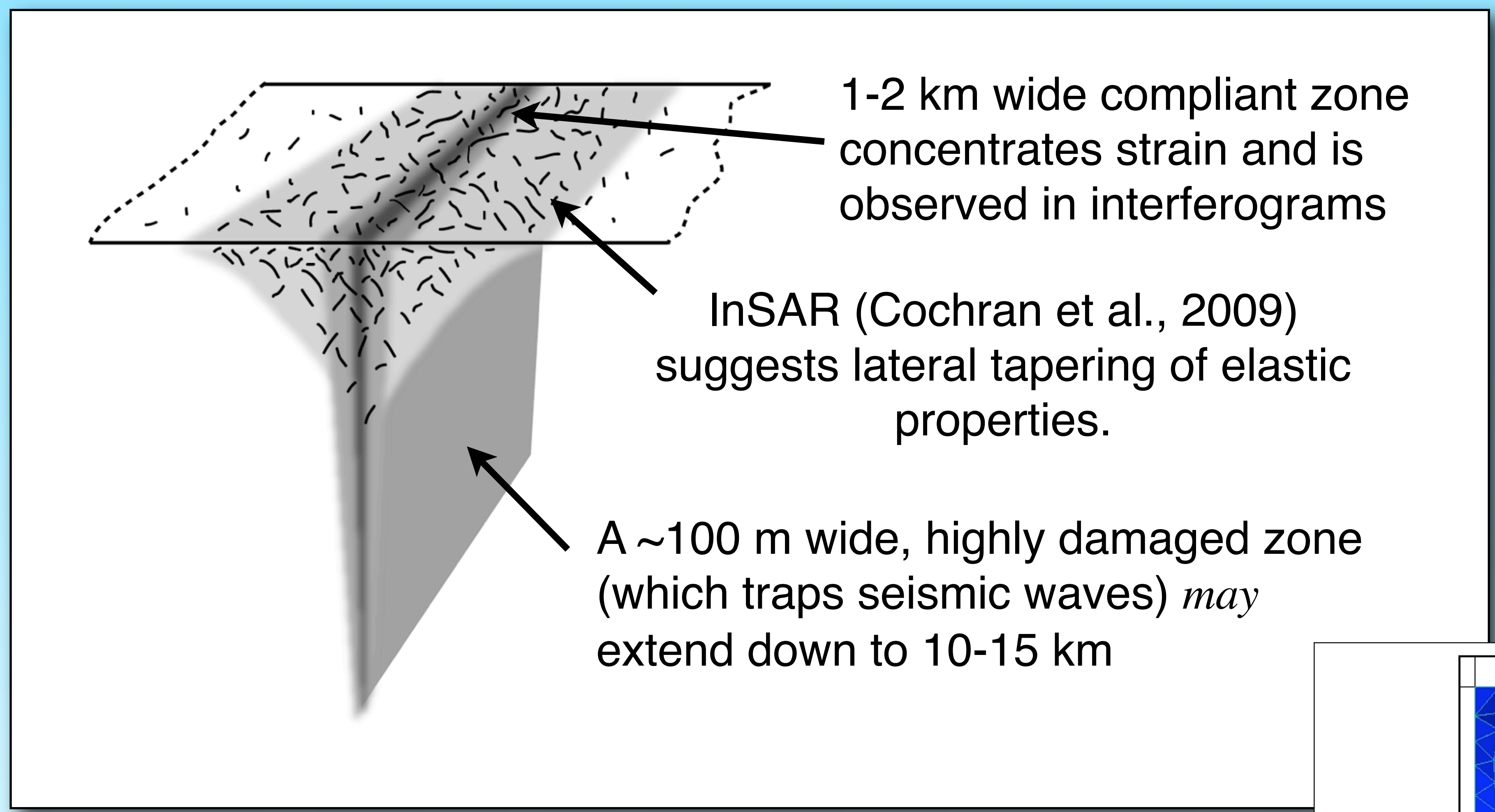


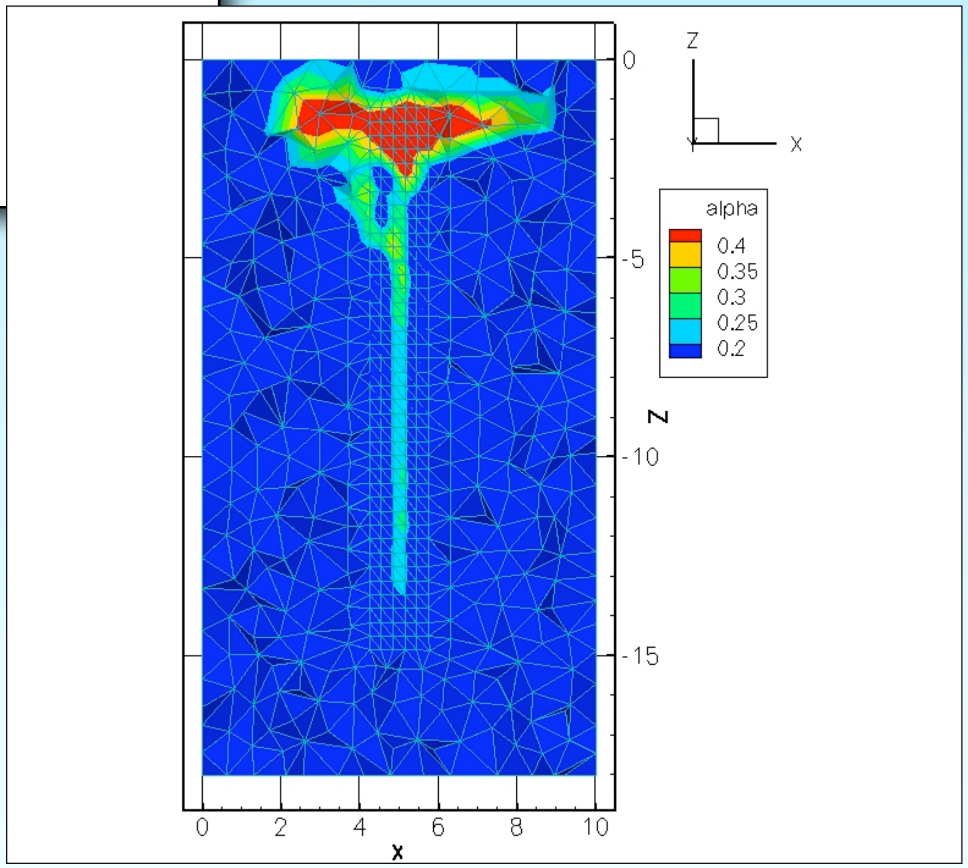

Models suggest ~1-2 km wide zones, 3-15 km deep, with G about 50% of host rock value (varies).

Seismic studies show these low-strength zones, but ~100 m wide.

# Likely features of highly damaged (compliant) zones around faults




geodetic and seismic data and static deformation models (e.g. Cochran et al., 2009, Fialko et al., 2002, Vidale and Li, 2001, 2003, and others)



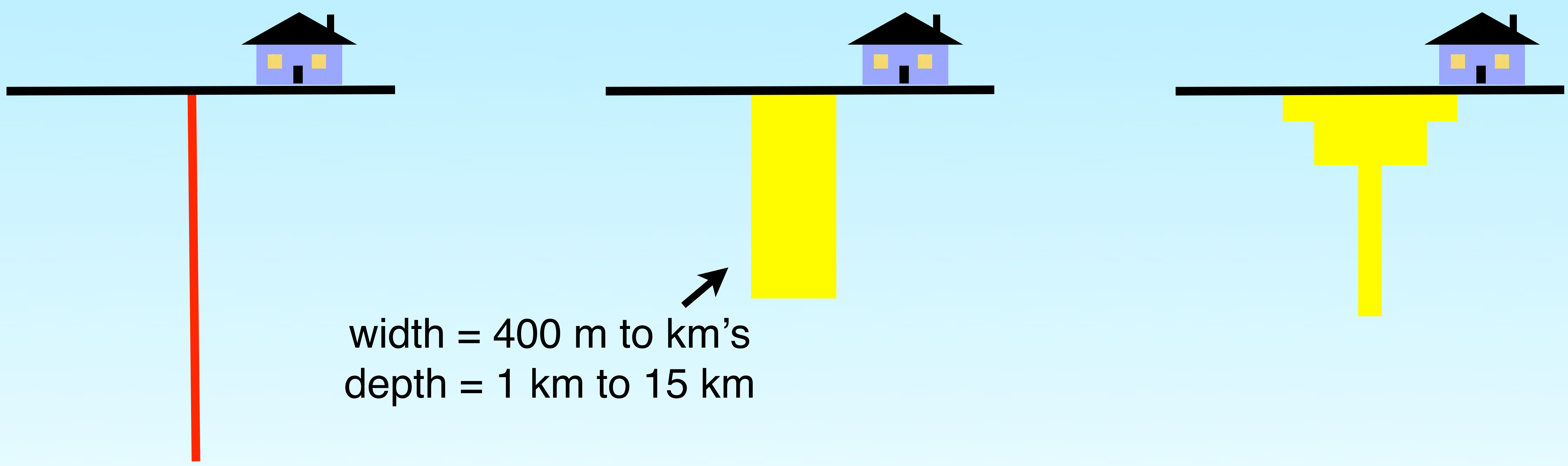

damage rheology models of fault formation and models of dynamic rupture propagation with plastic strain (Finzi et al., 2009; Ma et al., 2008)

# Our models: softened continuum surrounding faults (still oversimplified)

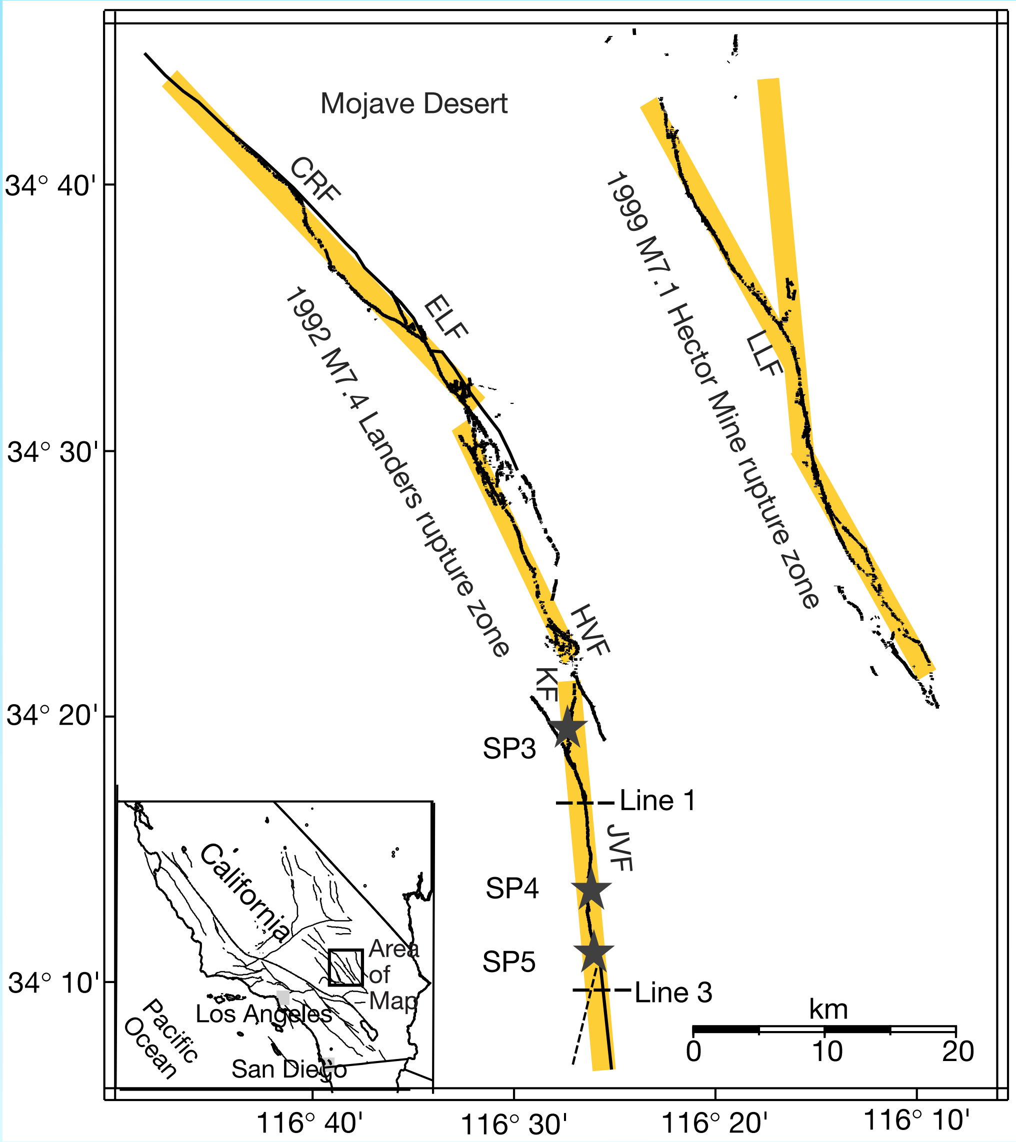
Typical FE deformation model

This study and Fialko group CZ models

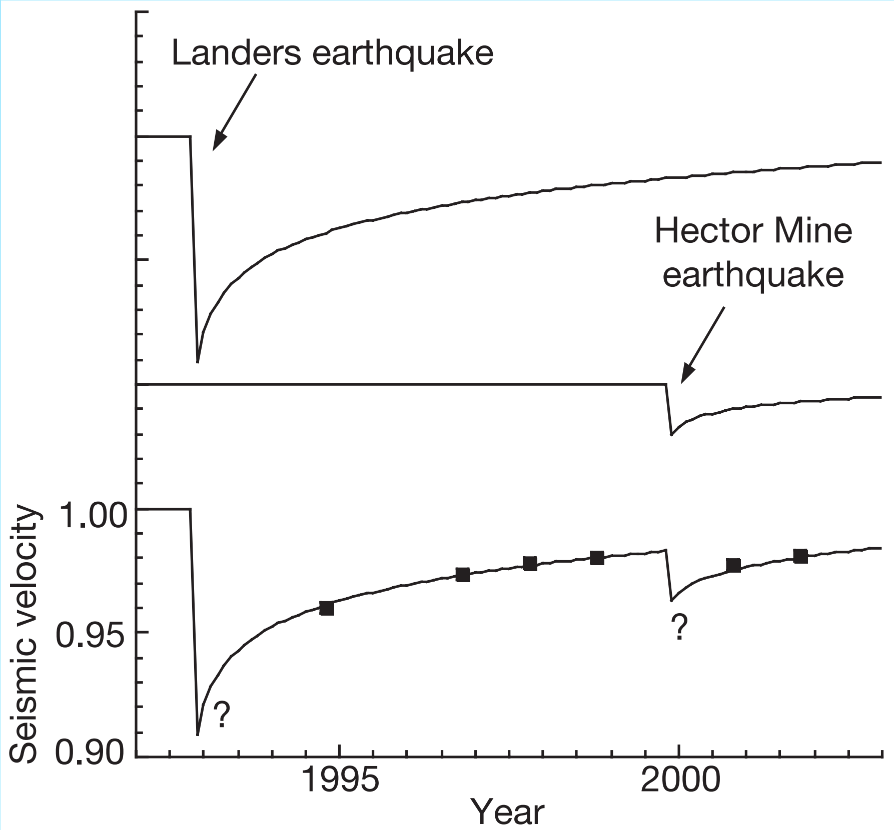
Our tapered CZ models



# $V_p$ and $V_s$ decrease slightly in response to shaking during local earthquakes




Vidale and Li (2003)



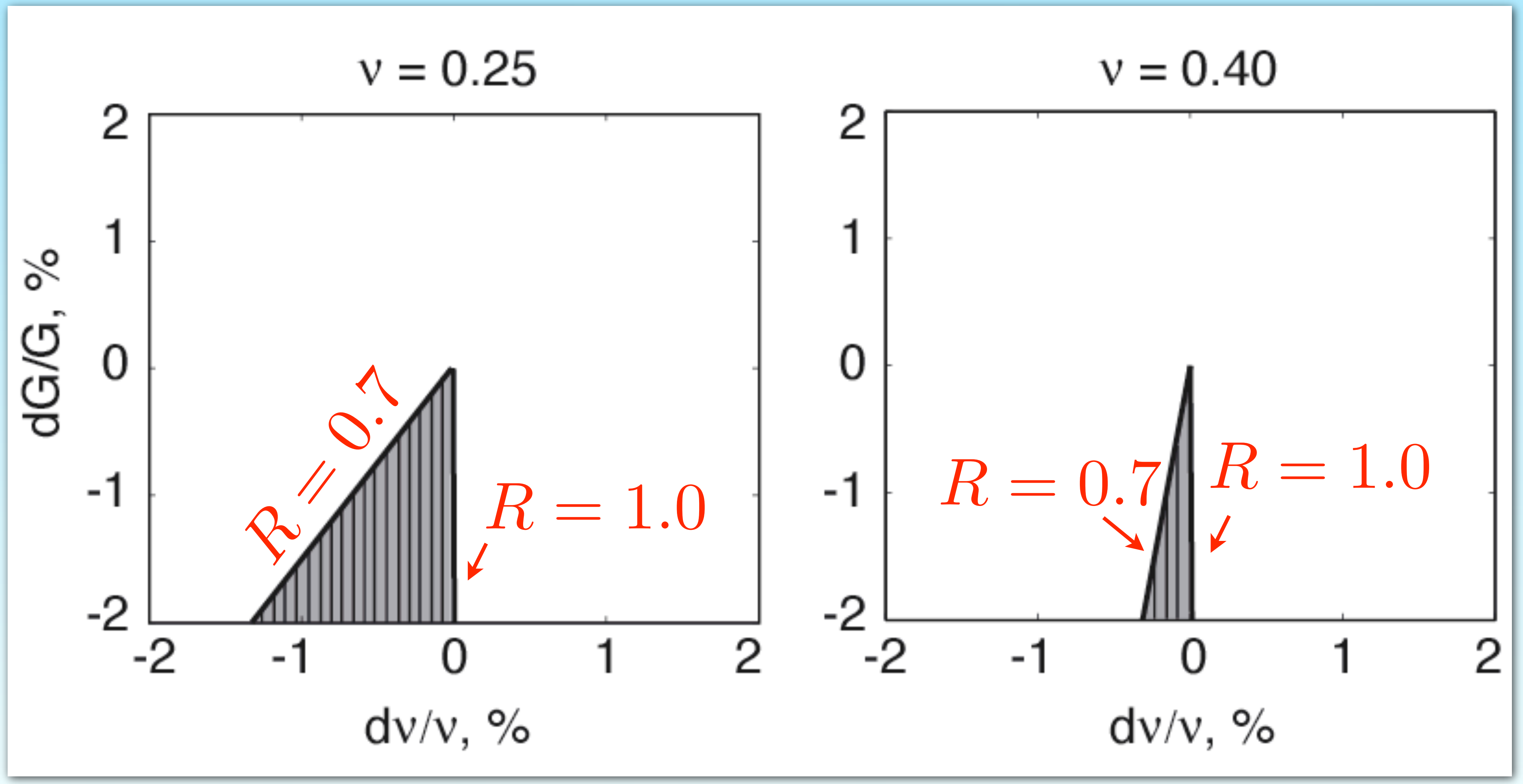

Vidale and Li (2003)

$V_s$ decreased by about 1-2%

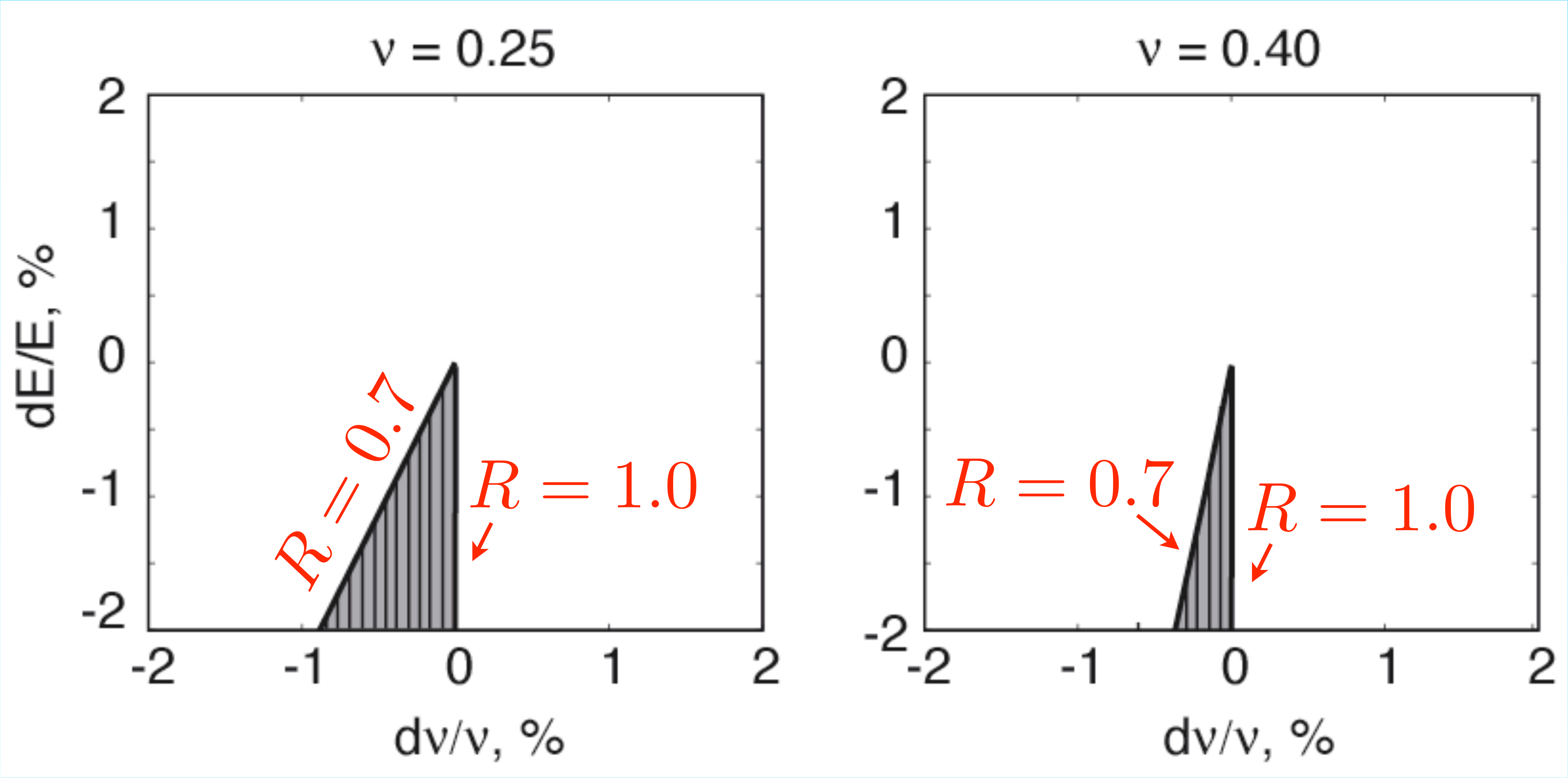
$V_p$ decreased by a similar percentage (maybe a bit more)

# Coseismic changes to G and $\nu$, based on decreases in $V_p$ and $V_s$

$$\frac{dV_p}{V_p} \approx -0.01 \ to \ -0.02 \qquad R = \frac{dV_s/V_s}{dV_p/V_p} \approx 0.7 \ to \ 1$$



# Coseismic changes to E and $\nu$, based on changes to $V_p$ and $V_s$




$$K = \frac{E}{3(1-2\nu)}$$

Note that bulk modulus K *must* decrease

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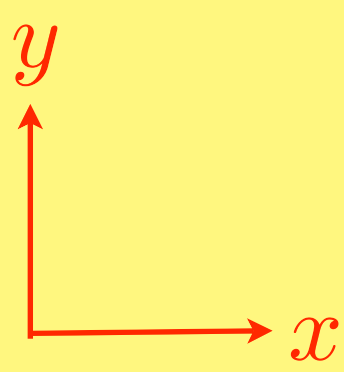
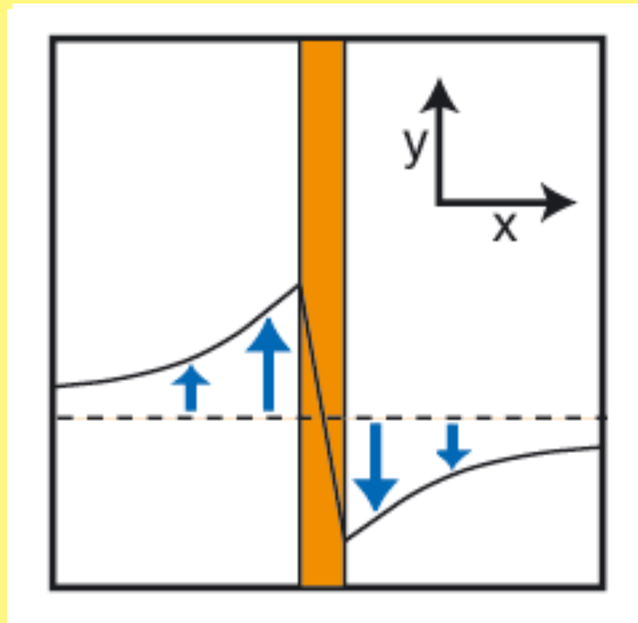
# Expected strain: simple shear




$$\epsilon_{xy} = \frac{\tau_{xy}}{2G_{cz}}$$

$$d\epsilon_{xy} = \frac{\partial \epsilon_{xy}}{\partial \tau_{xy}} \partial \tau_{xy} + \frac{\partial \epsilon_{xy}}{\partial G_{cz}} \partial G_{cz}$$

- *$d\epsilon_{xy}$ due to change in $\tau_{xy}$ is* $\dfrac{d\tau_{xy}}{2G_{cz}}$

- *$d\epsilon_{xy}$ due to change in $G_{cz}$ is* $-\dfrac{\tau_{xy}}{2G_{cz}}\left(\dfrac{dG_{cz}}{G_{cz}}\right)$

# Strain in response to softening

- amplitude of this component depends on *stress,* elastic properties, and % softening of the CZ

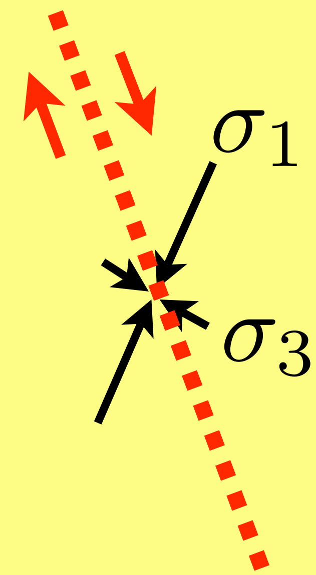
- sense of strain depends on the orientation of the fault zone relative to the stress field

$\sigma_1$ is oriented N 20° E

$\sigma_3$ is oriented N 70° W

$\sigma_2$ is vertical

$\sigma_2 = \rho g h$

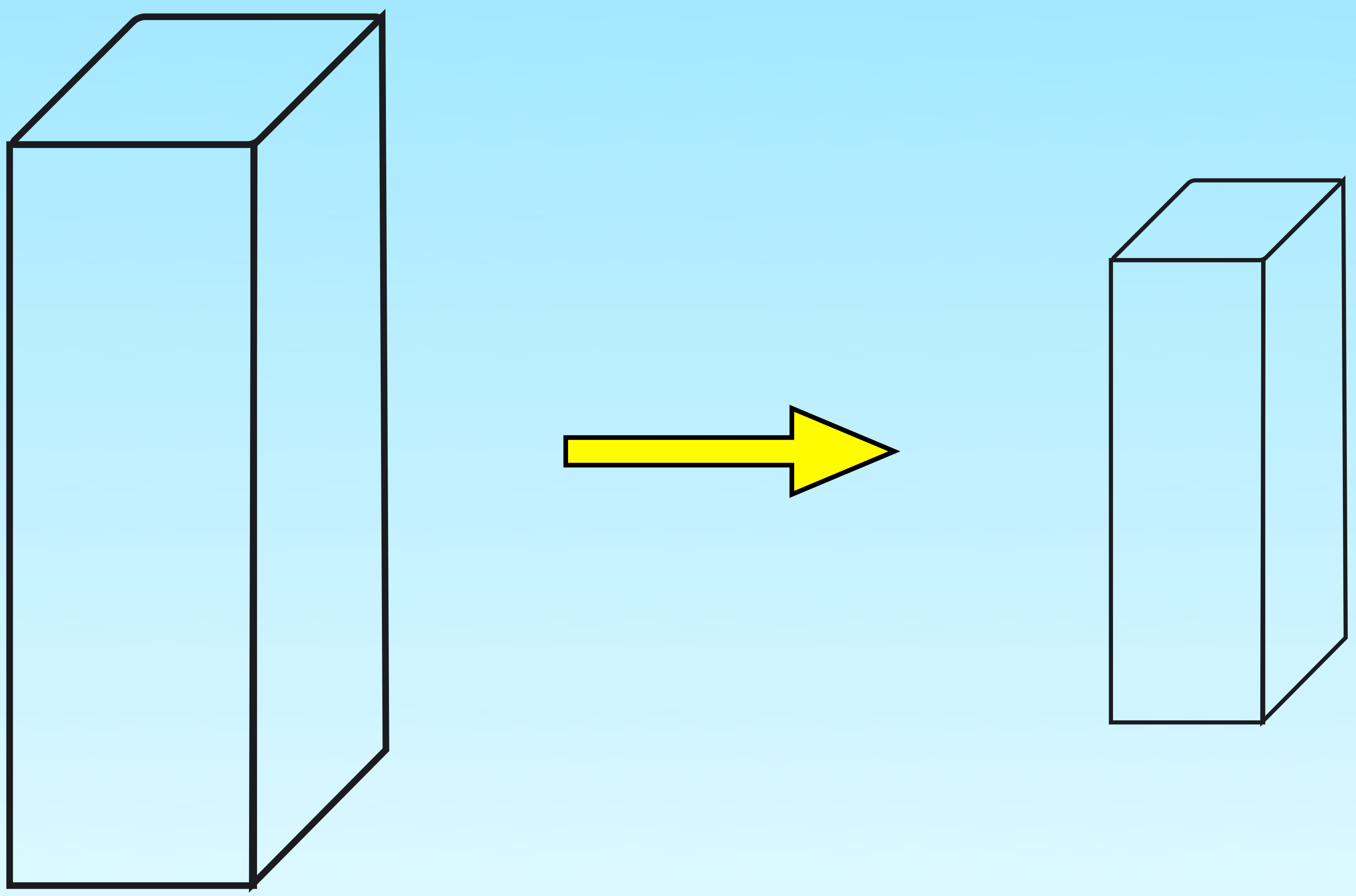



$\sigma_1$ and $\sigma_3$ amplitudes:

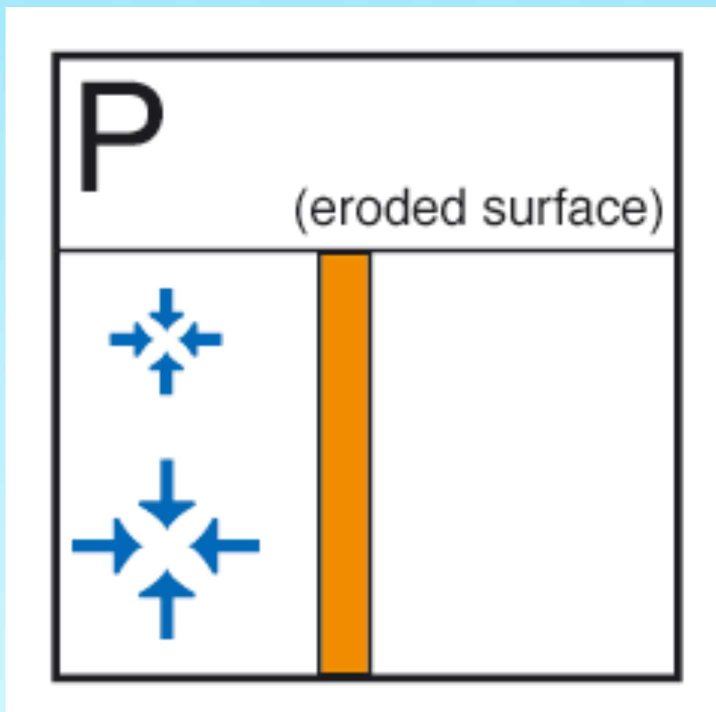
- $\mu$
- transtension vs. transpression vs. pure shear

- for NW-oriented Mojave faults, deviatoric stress should cause right-lateral strain (some contraction)

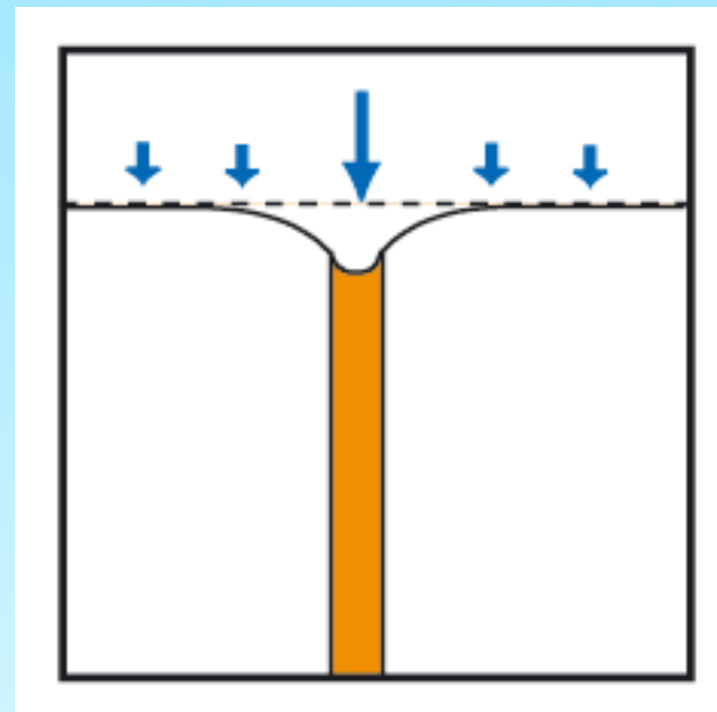
# What happens when bulk modulus K decreases (with no change to lithostatic stress)?



# CZ deformation due to weakening: Lithostatic stress should always cause subsidence




Before earthquake.



Response to coseismic weakening of CZ (unless it's incompressible).

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# Modeling Steps

Model deformation with compliant zones with Young's modulus = $E_0$, under regional stress

Model deformation with slightly softer compliant zones under regional stress (e.g. with E' = $0.99E_0$)

Difference the two results to get CZ deformation in response to softening, caused by regional stress

$\partial E$
(softening)
contribution

\+ Model deformation of model with compliant zones, in response to Hector Mine or Landers earthquake stress change

$\partial \sigma$
contribution

= *Scale and sum* to see what contribution from the total stress and coseismic weakening of compliant zones is permissible

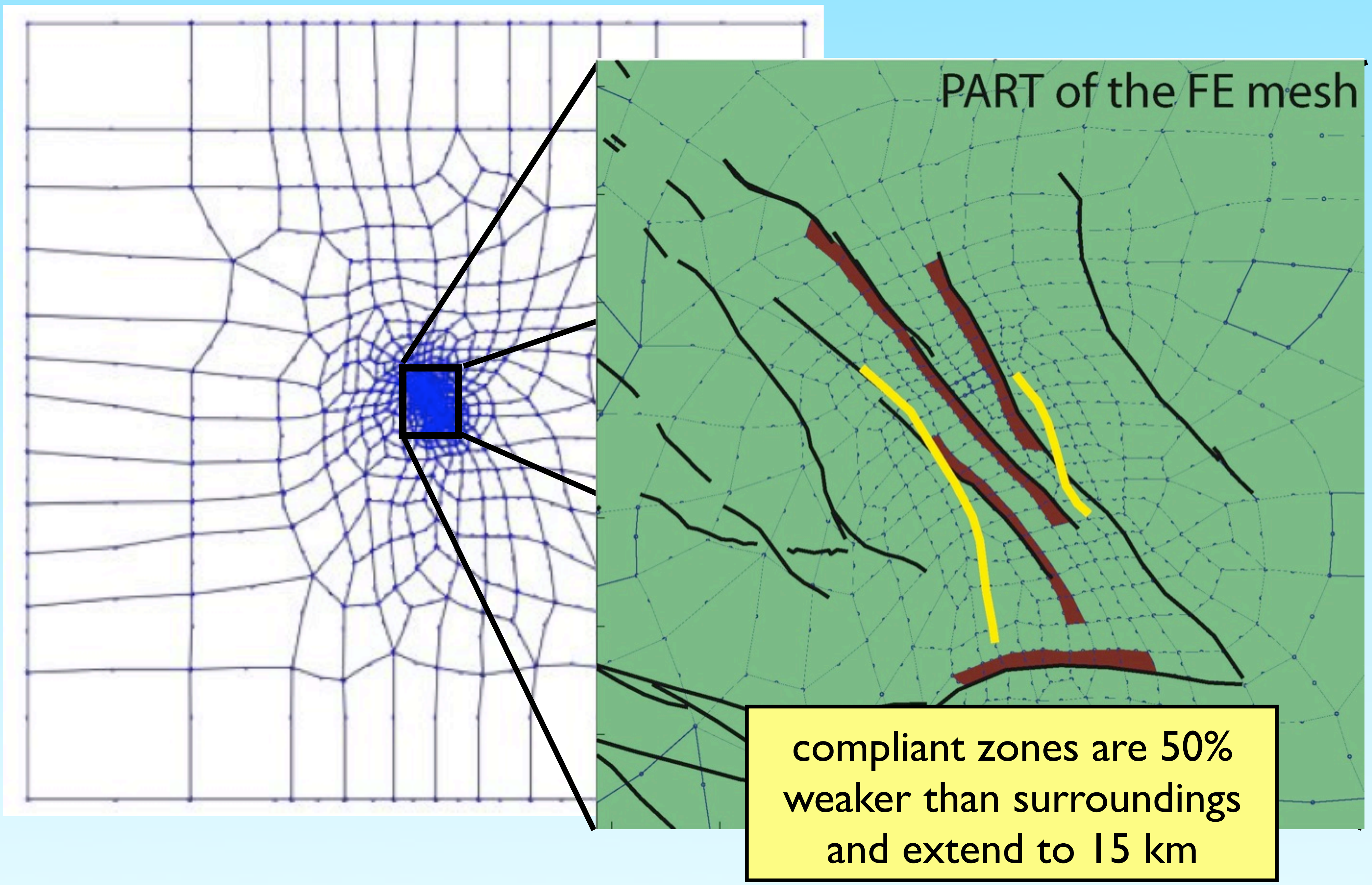
total deformation from both contributions

Compute *coseismic stresses* with ensemble mesh and use a finer mesh to model CZ deformation.

Are coseismic stresses at the profiles sensitive to presence of the other CZ's?

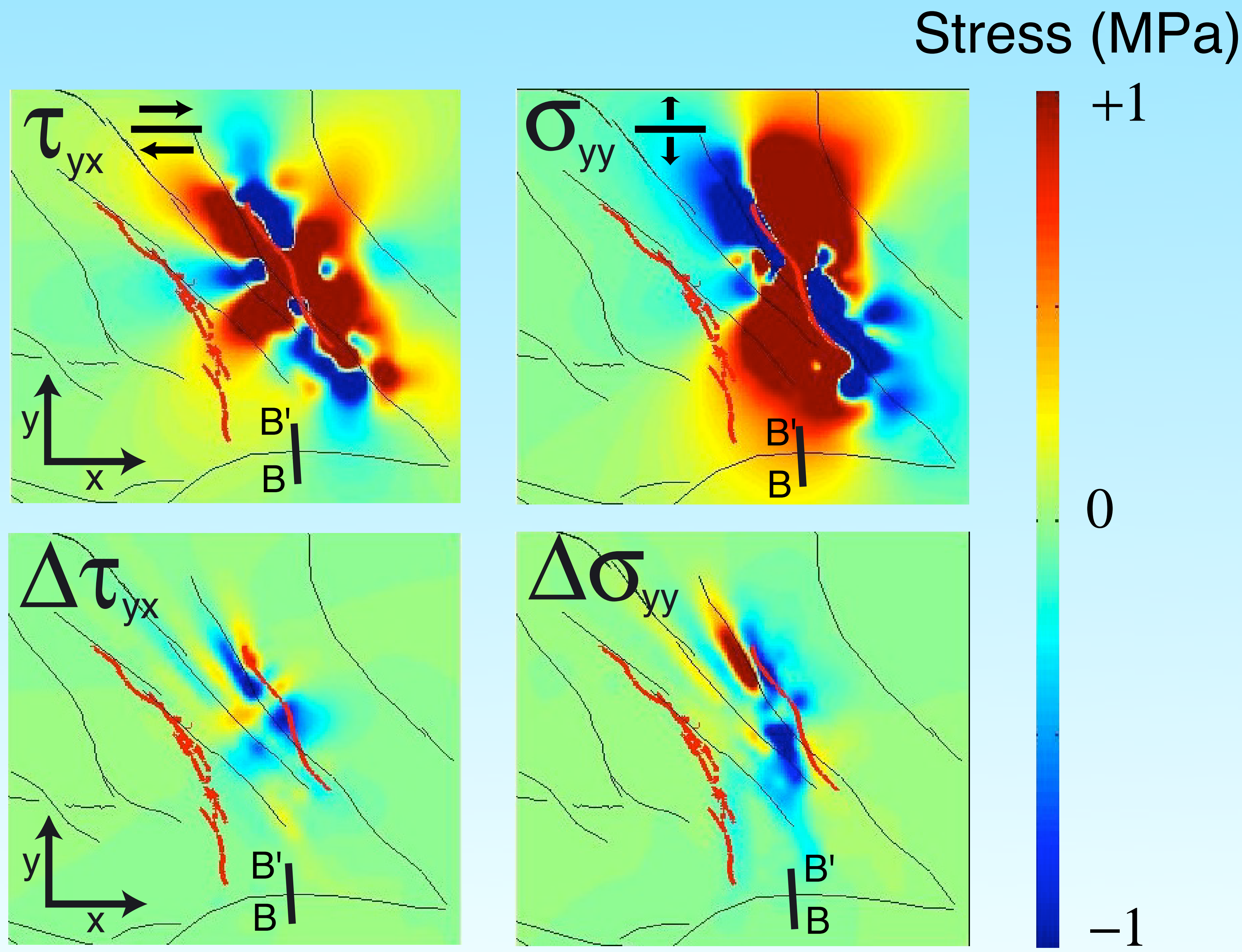
Model deformation of model with compliant zones, in response to Hector Mine or Landers earthquake stress change

$\partial\sigma$
contribution

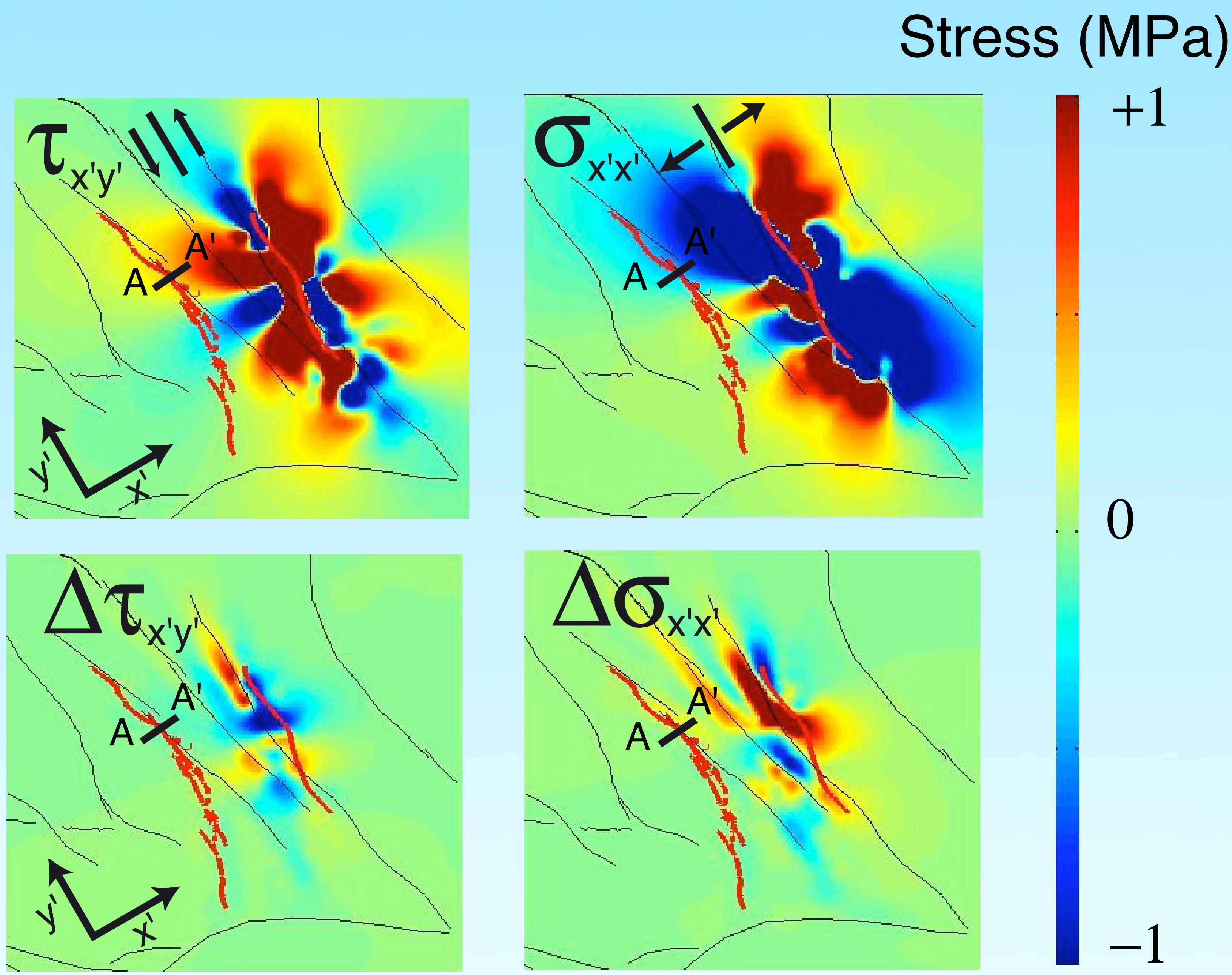



Layered elastic model (modified from Jones and Helmberger 1998)
Impose earthquake slip (inverted from GPS).

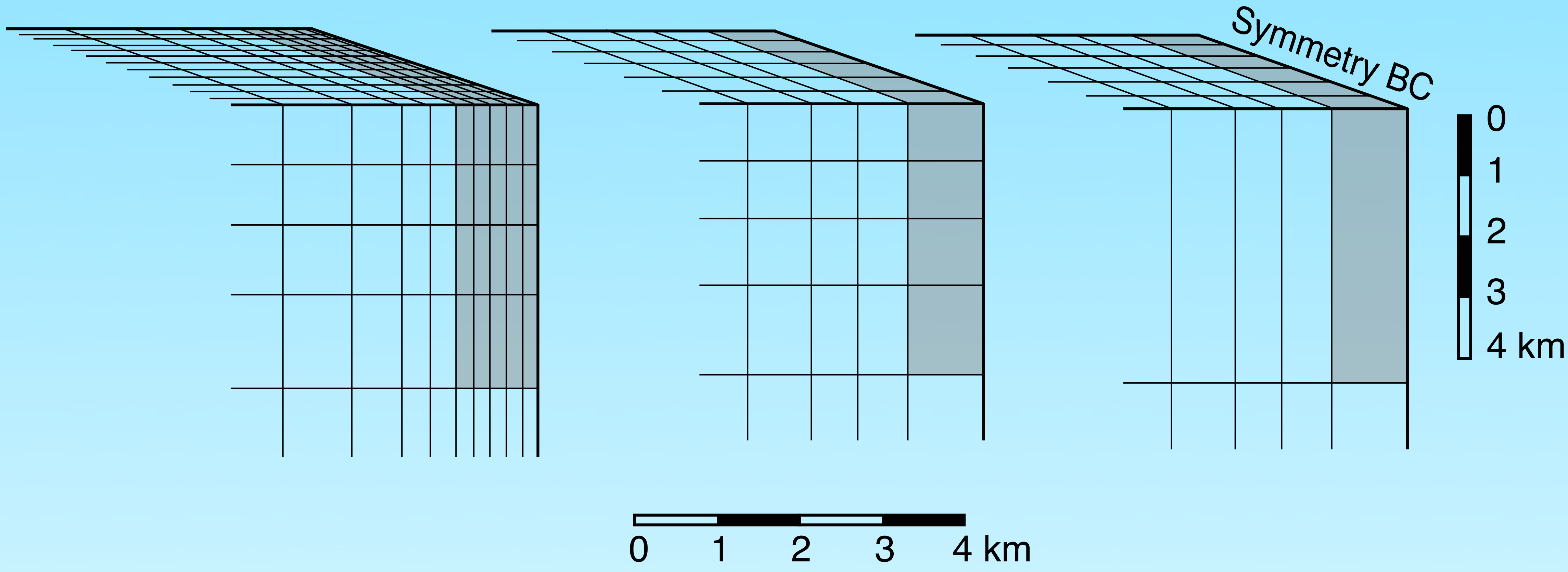
# Effect of compliant zones on Hector Mine earthquake coseismic stress change Pinto Mountain Fault



# Effect of compliant zones on Hector Mine earthquake coseismic stress change Camp Rock Fault



# Finer meshes



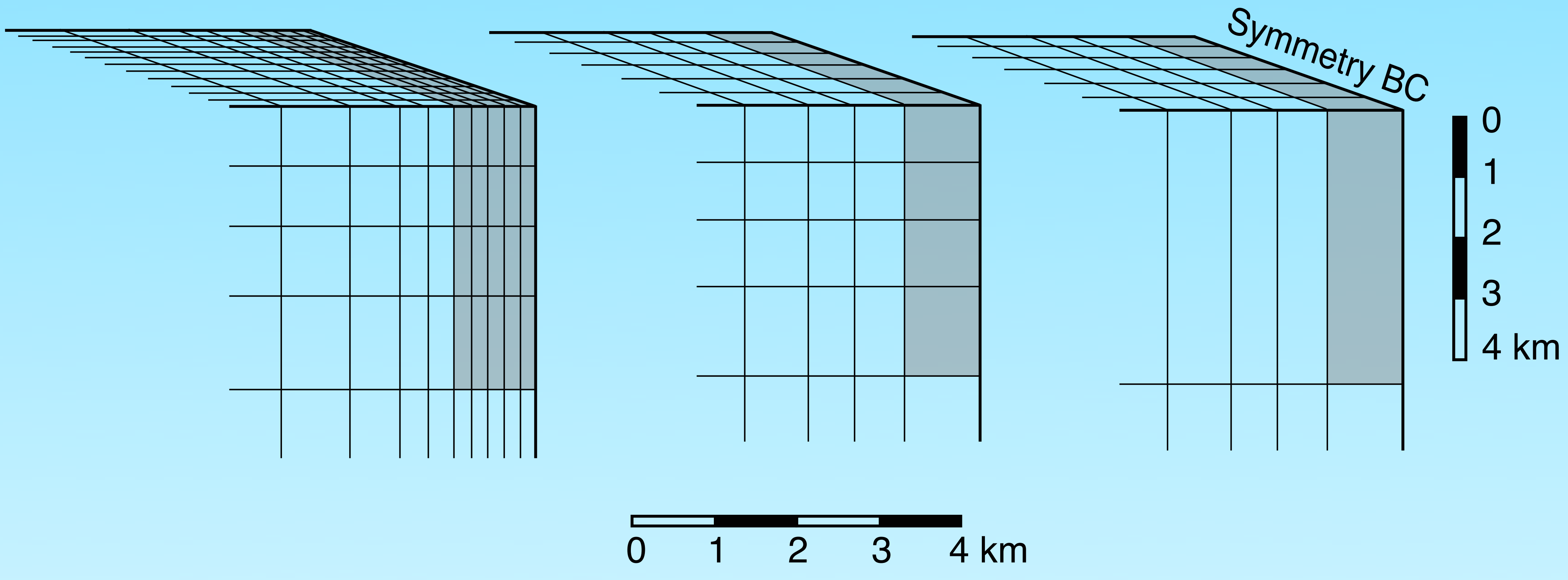

Coseismic stress from the big model (do not vary).

Various estimates of tectonic stresses.

Stress applied via:

- displacing boundaries (shear and normal stress)
- displacing boundaries + gravitation (lithostatic stress)

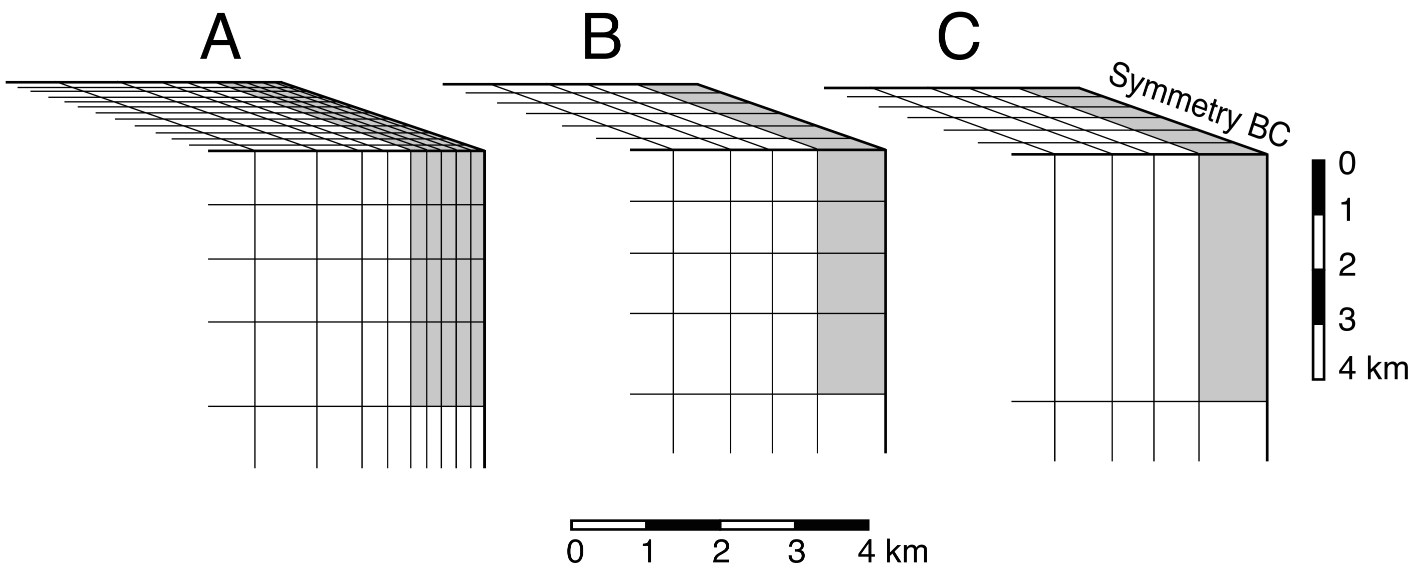
# Finer meshes

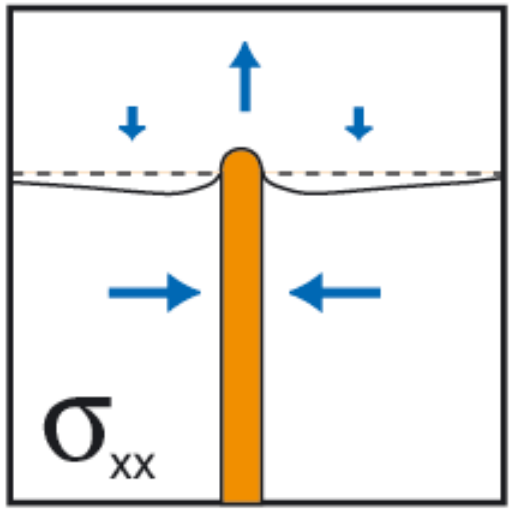



Vary:

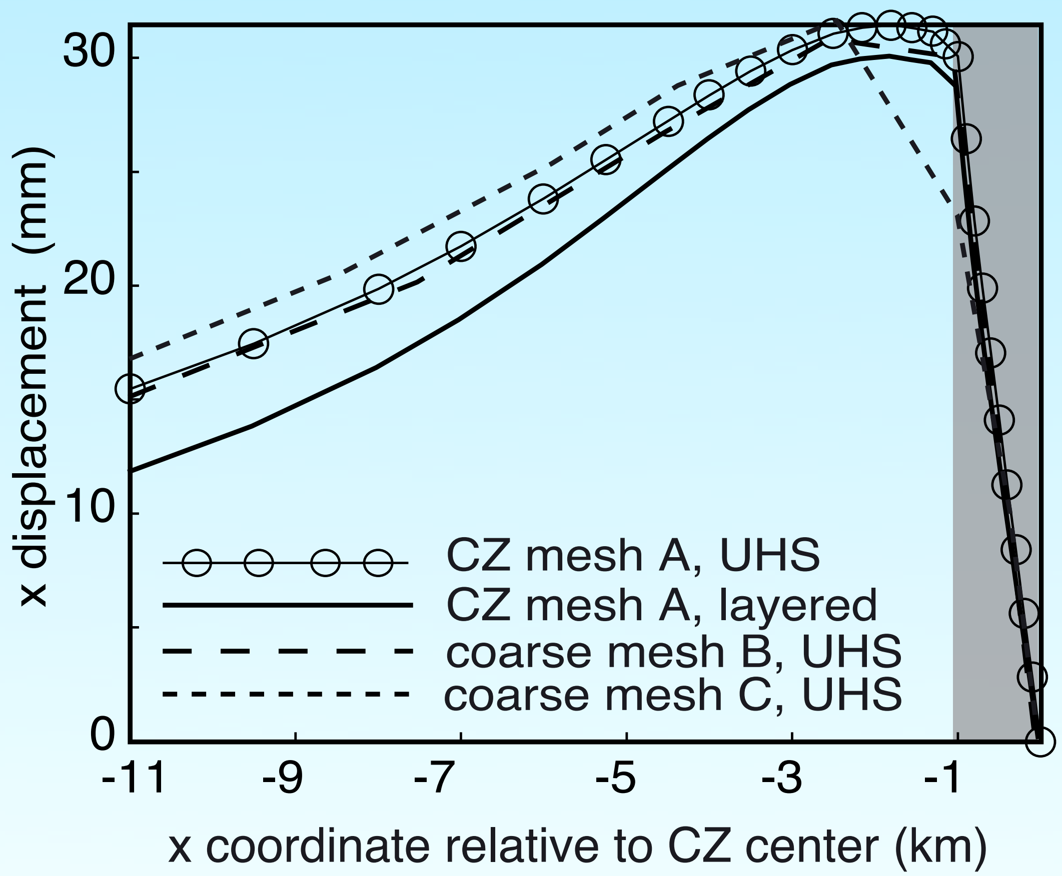
- CZ dimensions
- Background stress
  - deviatoric (resolved shear and normal)
  - lithostatic
- CZ elastic properties and % softening

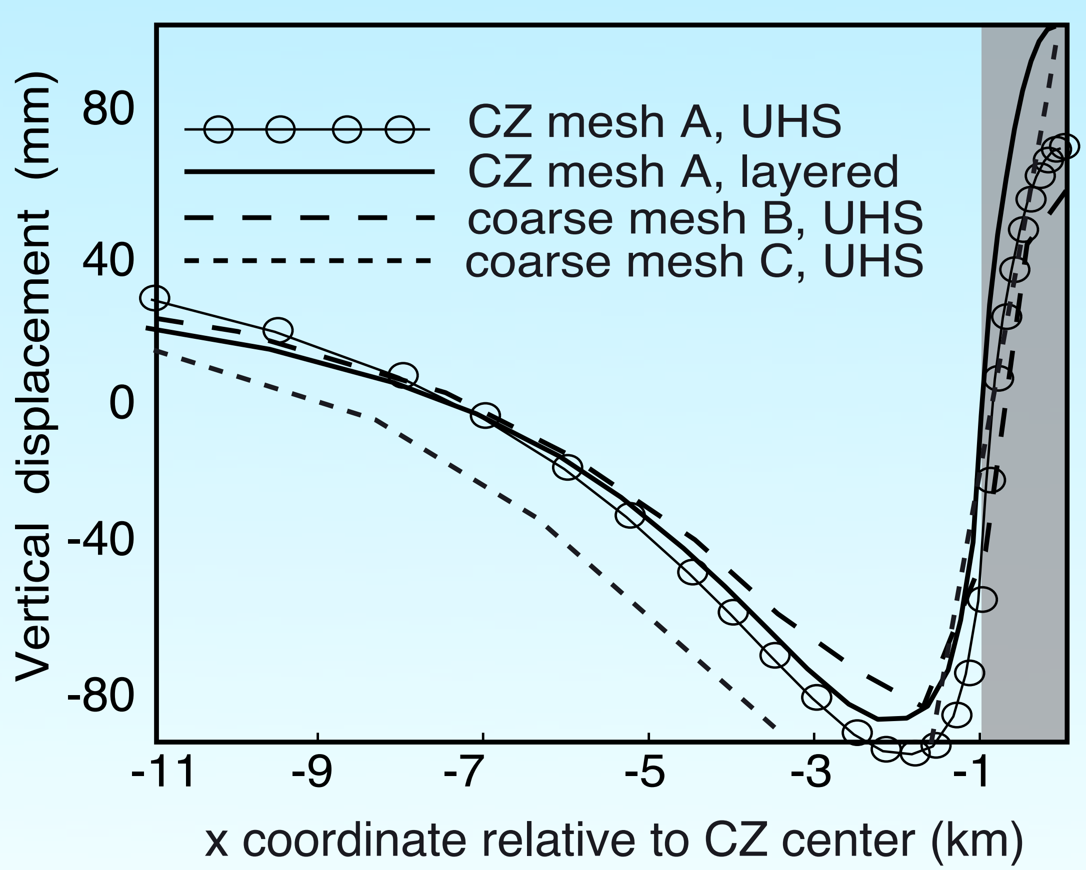
# Sensitivity of modeled strain to element size




$\sigma_{xx}$ = 200 MPa
1% reduction in E



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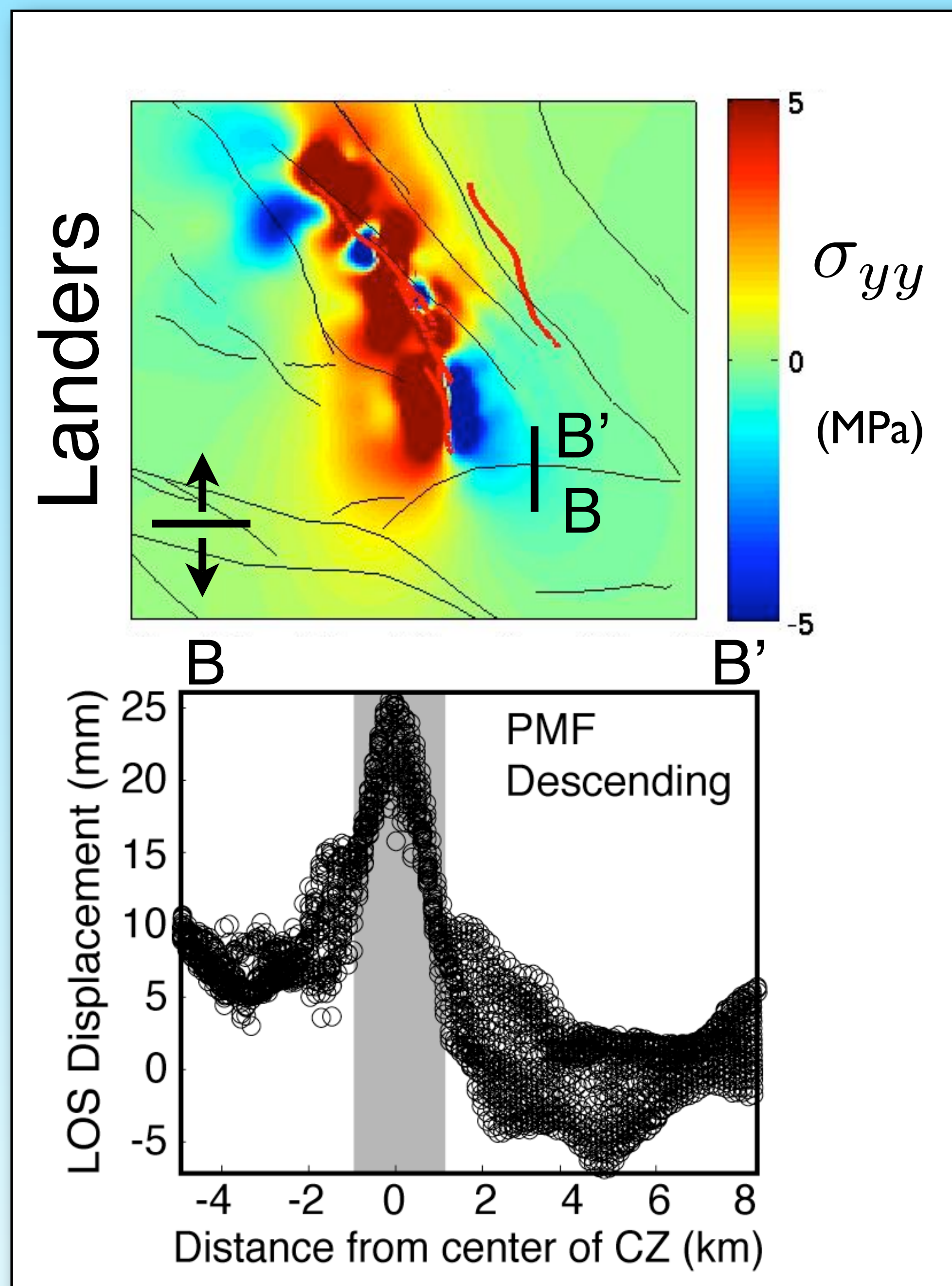
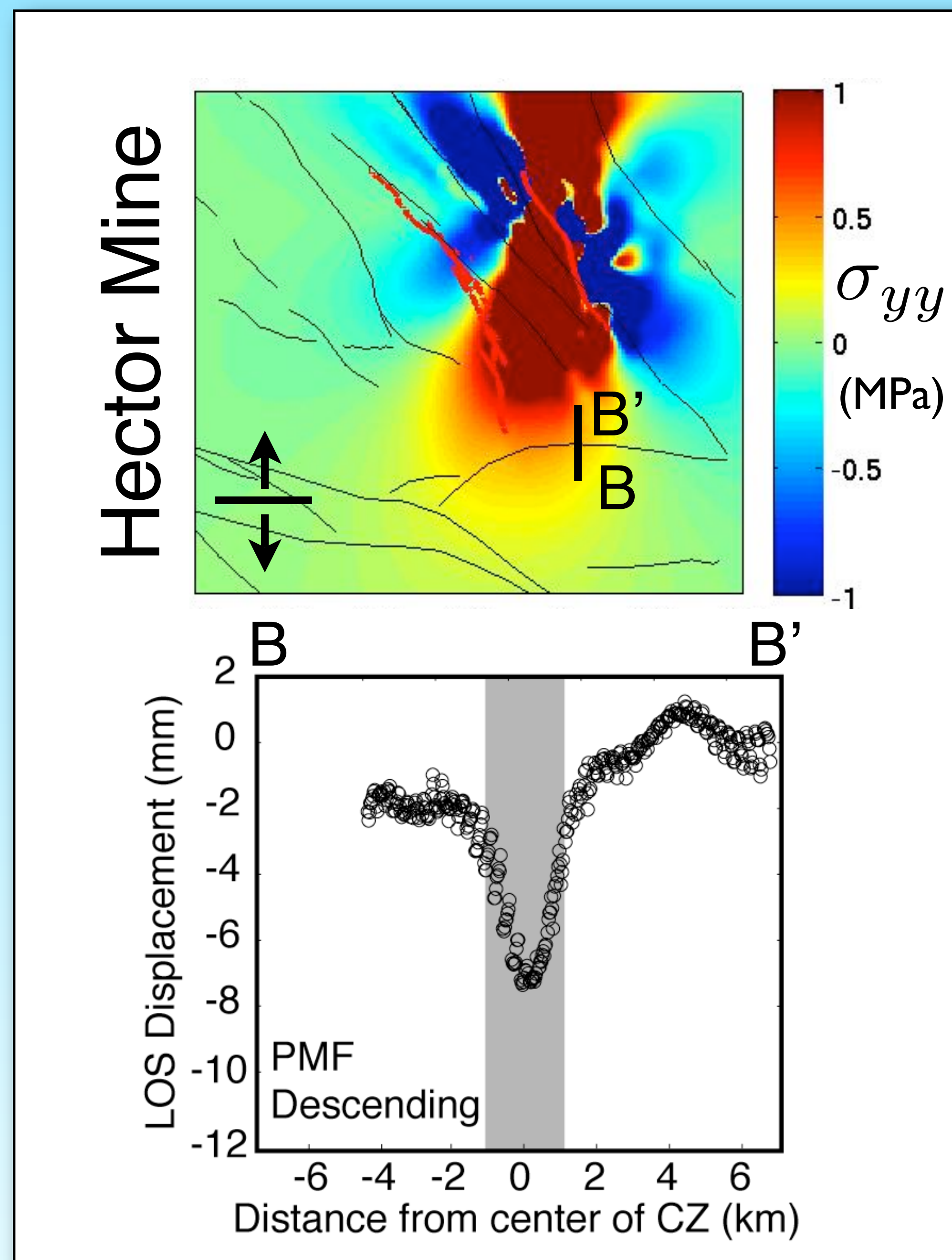
# Pinto Mountain Fault LOS displacement profiles

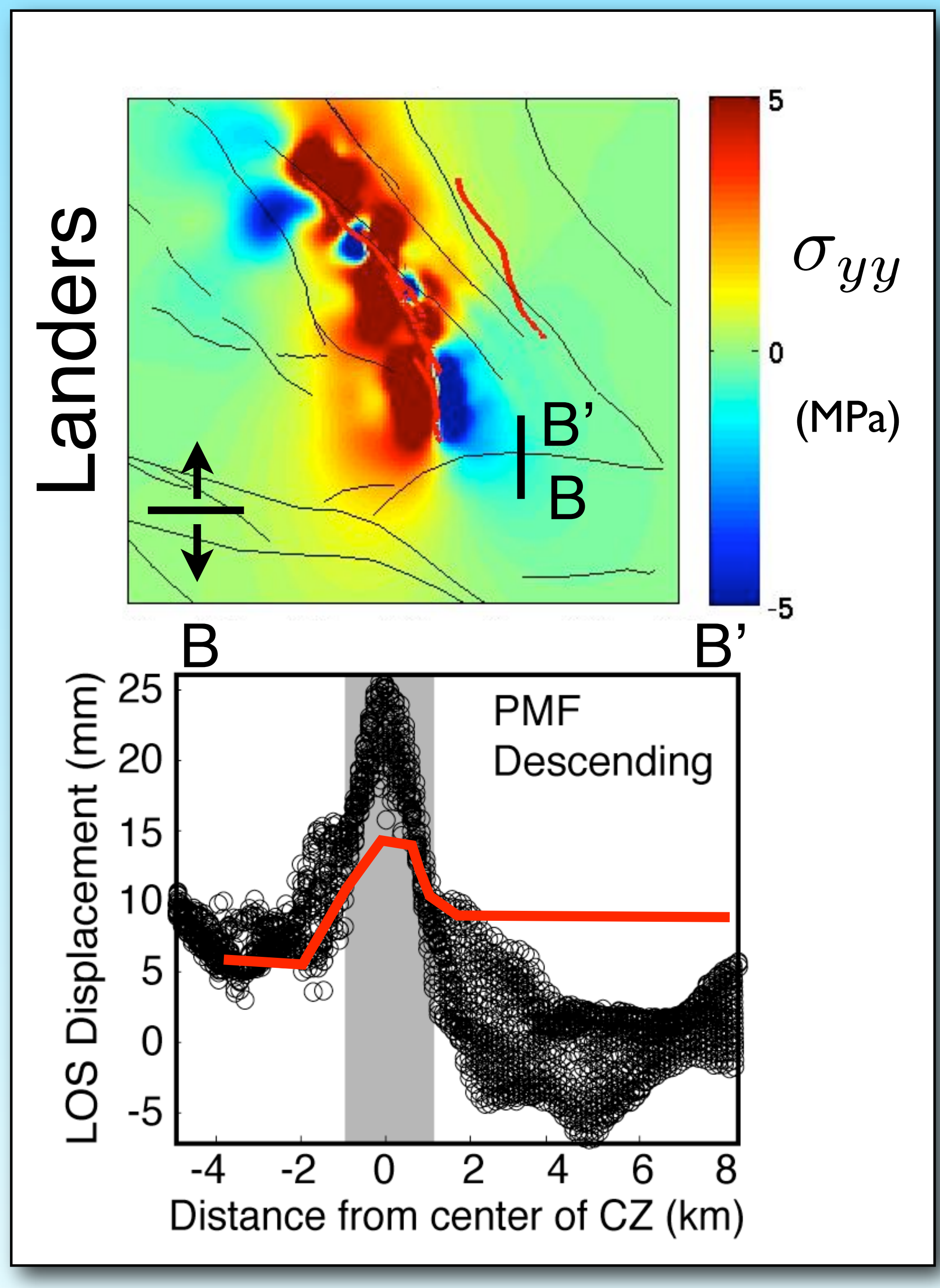


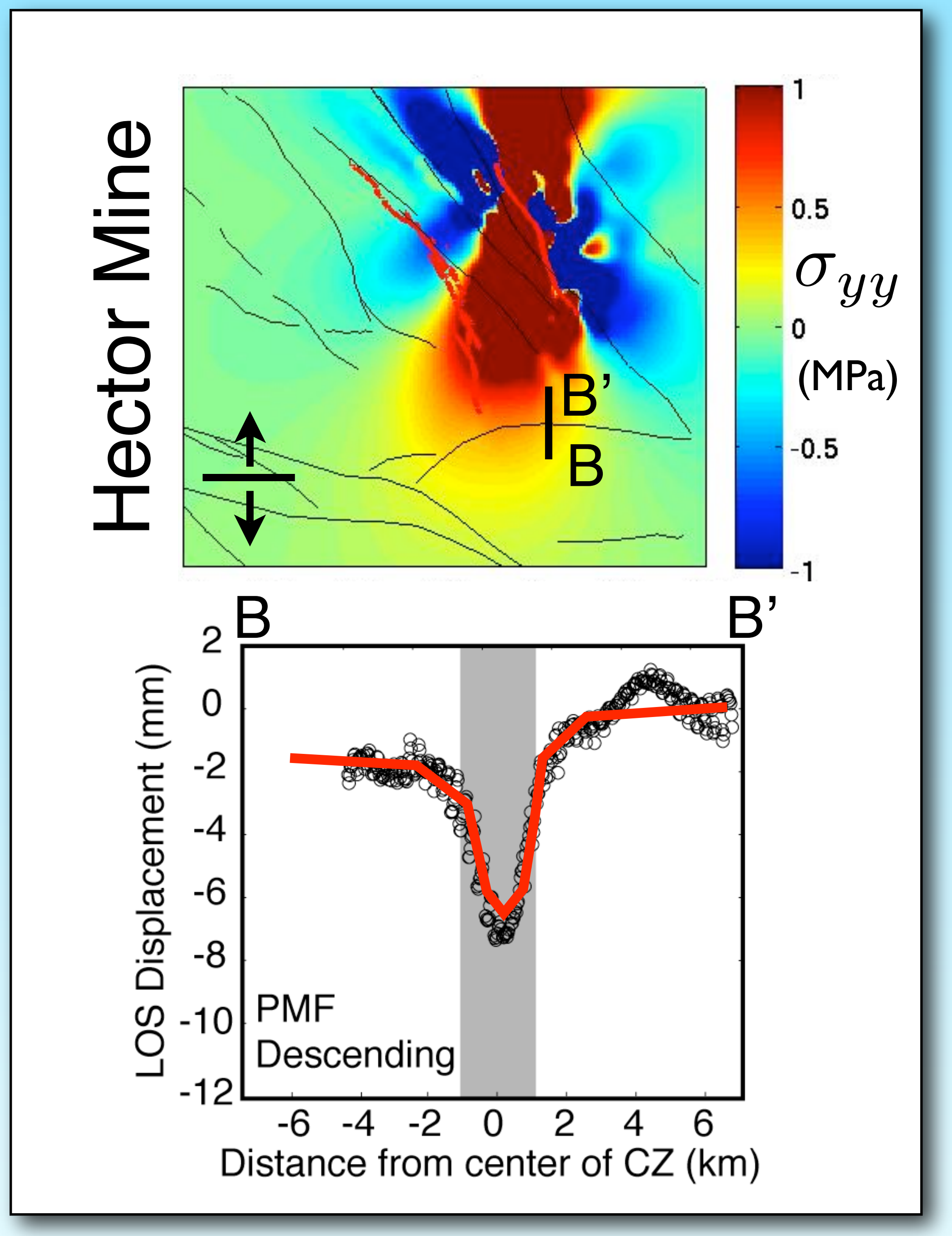




UP and a bit of LEFT-LATERAL

DOWN

# Pinto Mountain Fault LOS displacement profiles



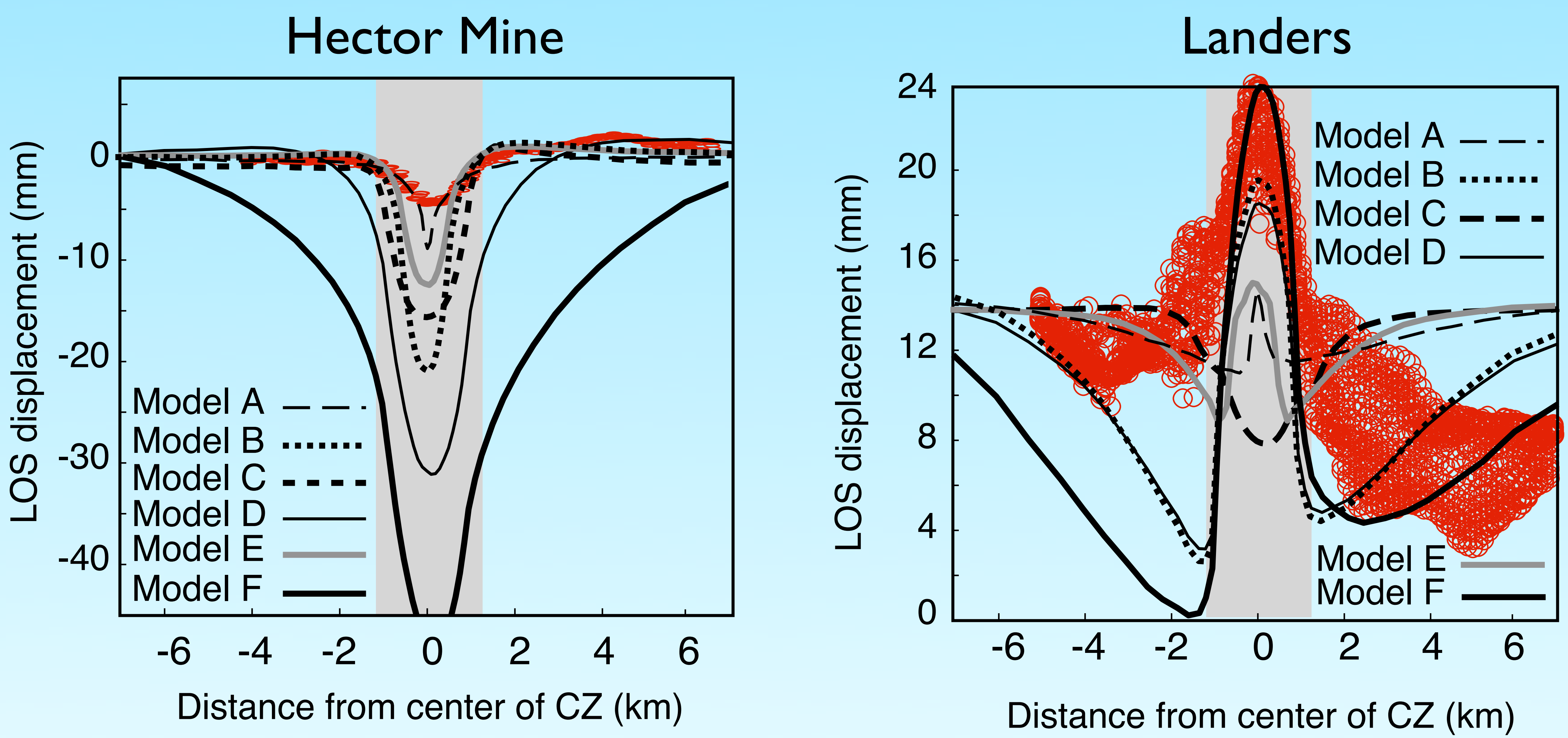




shear sense is backward for Landers

insufficient uplift ($E_{cz} = .5E_{host}$)

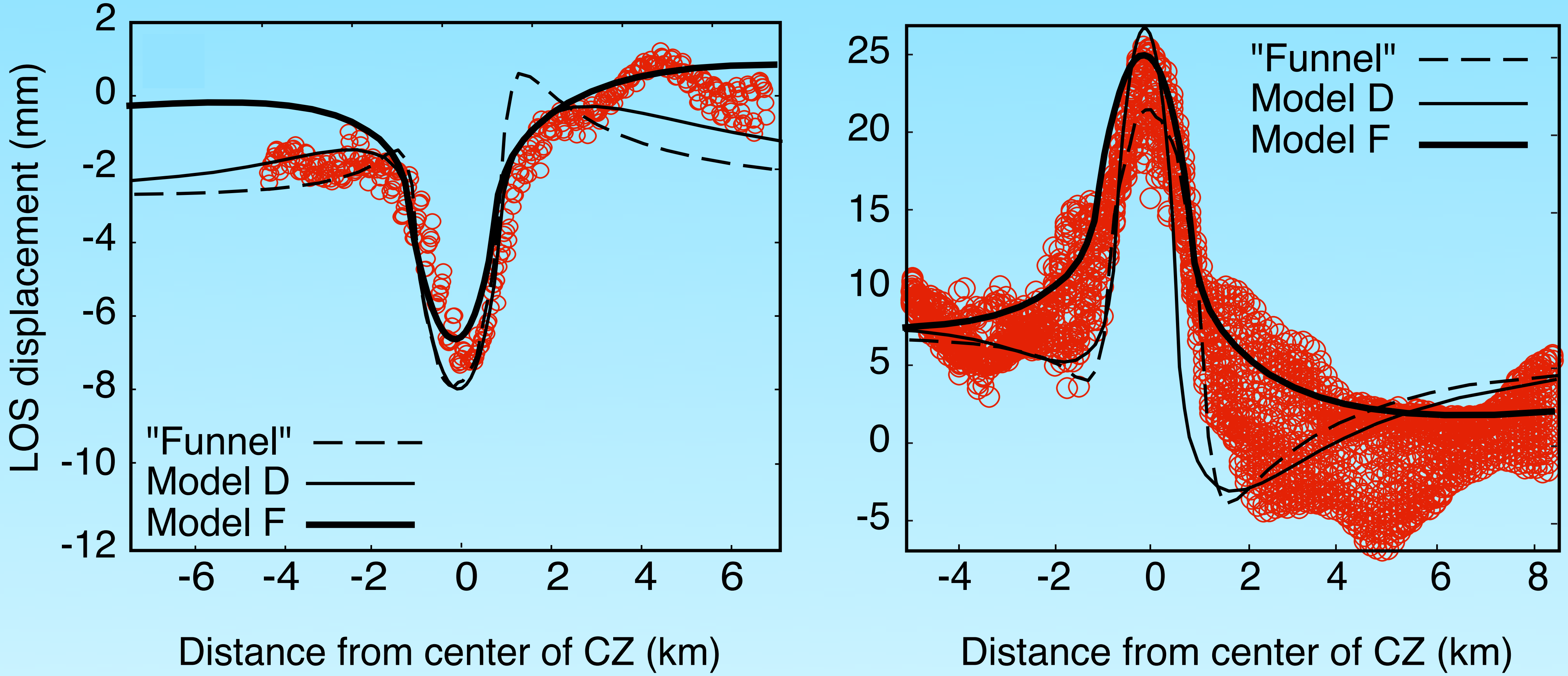
# Adding the softening contribution

- assume a 1% decrease in E
- vary CZ width (400m to 2 km) and depth (1 to 15 km)




Yikes.

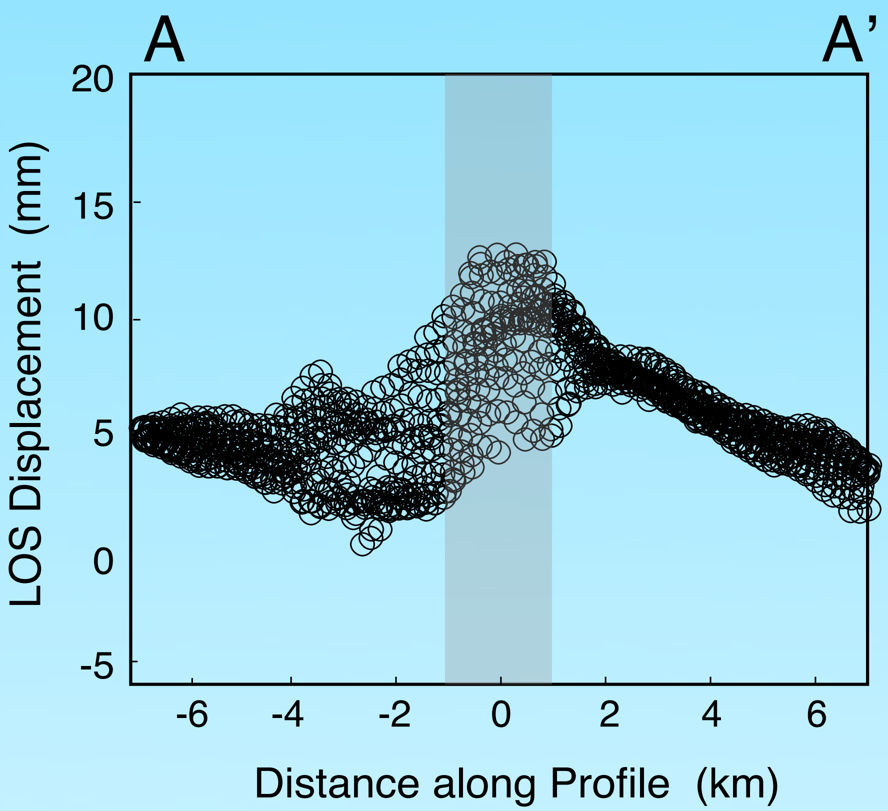
# What works?



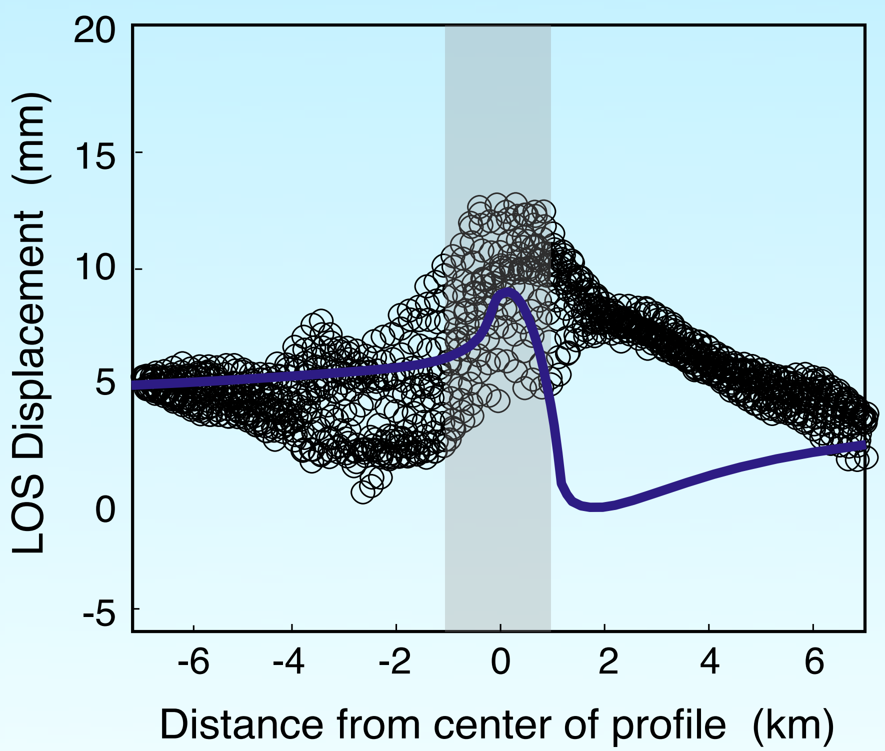

If we restrict softening to a few % and CZ is half as rigid as the host rock:

- 2 km wide near the surface
- may taper at depth
- incompressible or anisotropic? (to prevent subsidence)
- background stress: pure shear, high friction

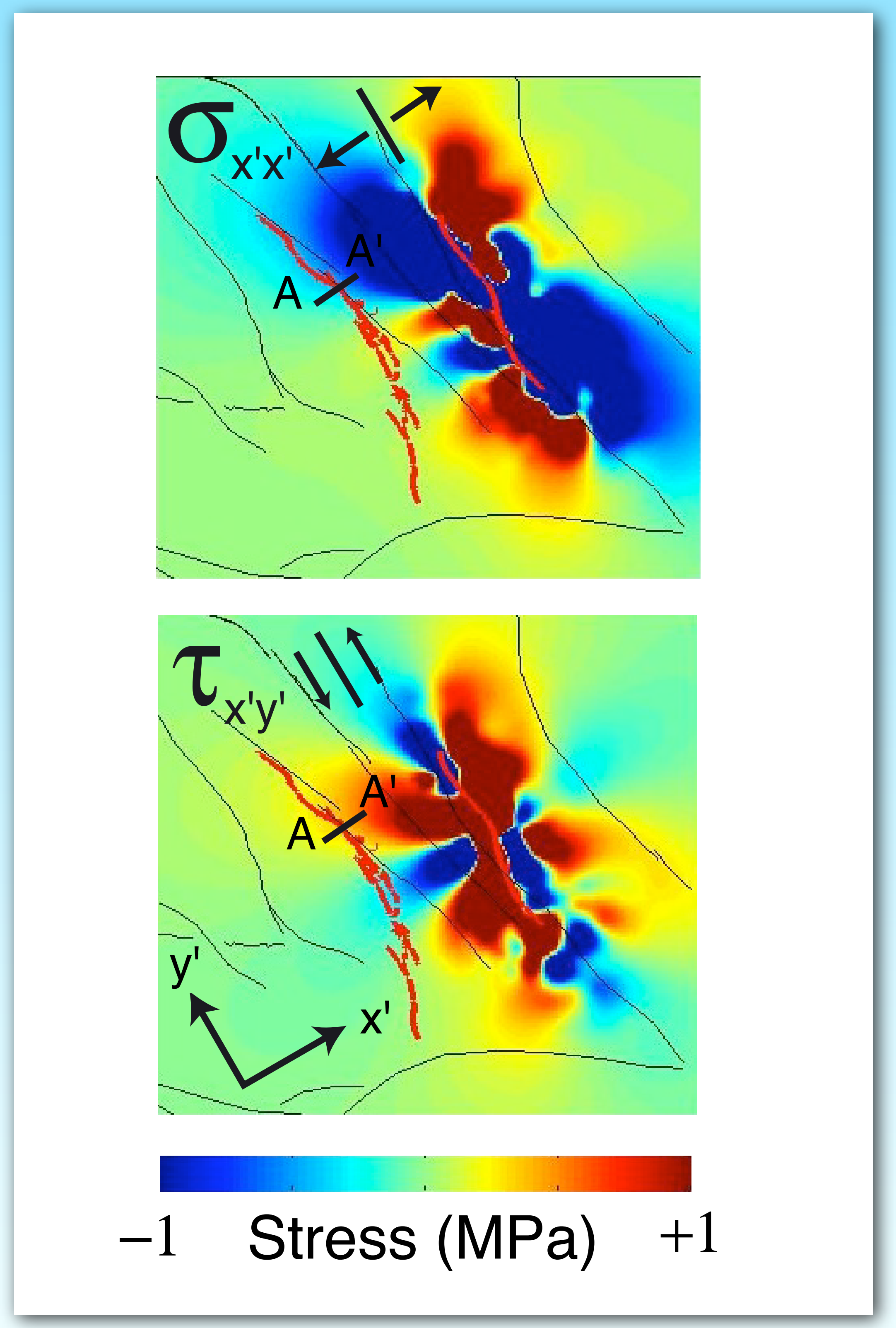
# Camp Rock Fault LOS displacement profile




LOS displacements:
UP and a bit of
RIGHT-LATERAL




deformation from
coseismic stress:
($E_{cz}$ = .5$E_{host}$)
UP and a bit of
LEFT-LATERAL



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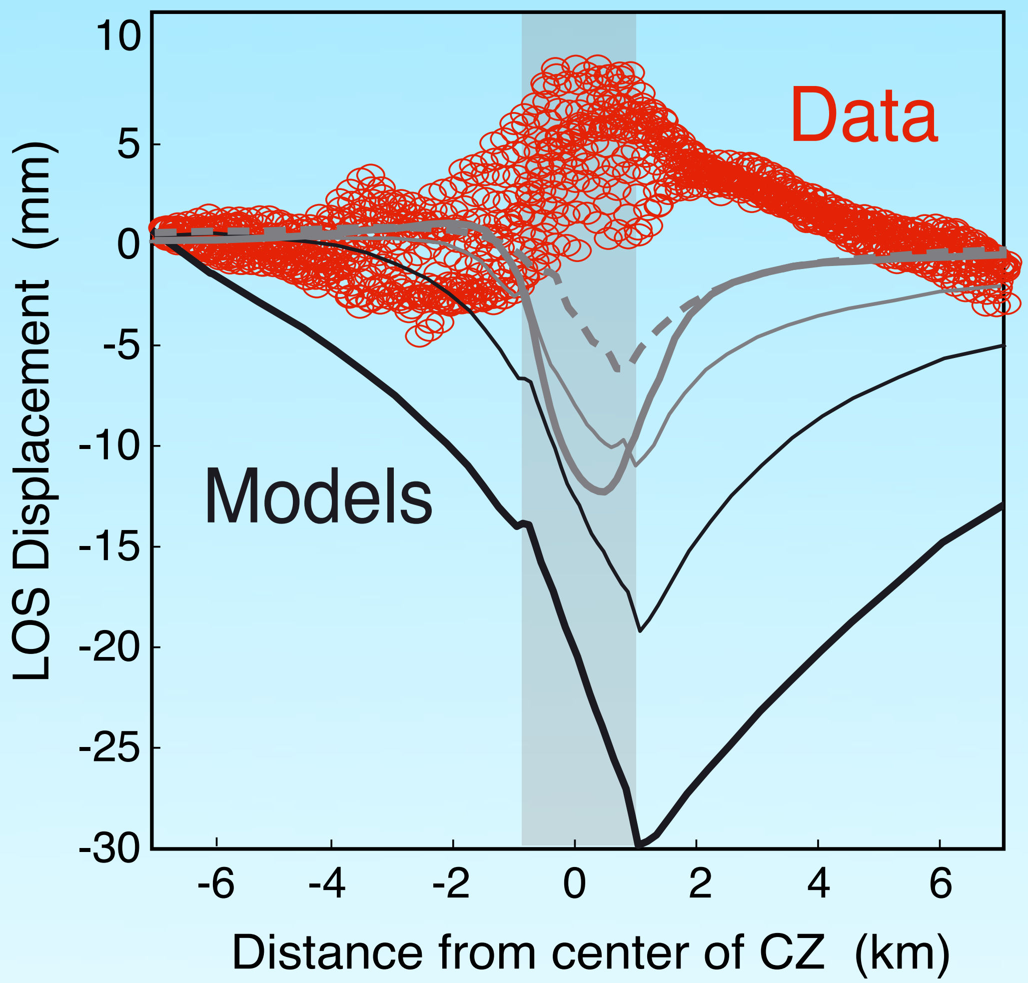
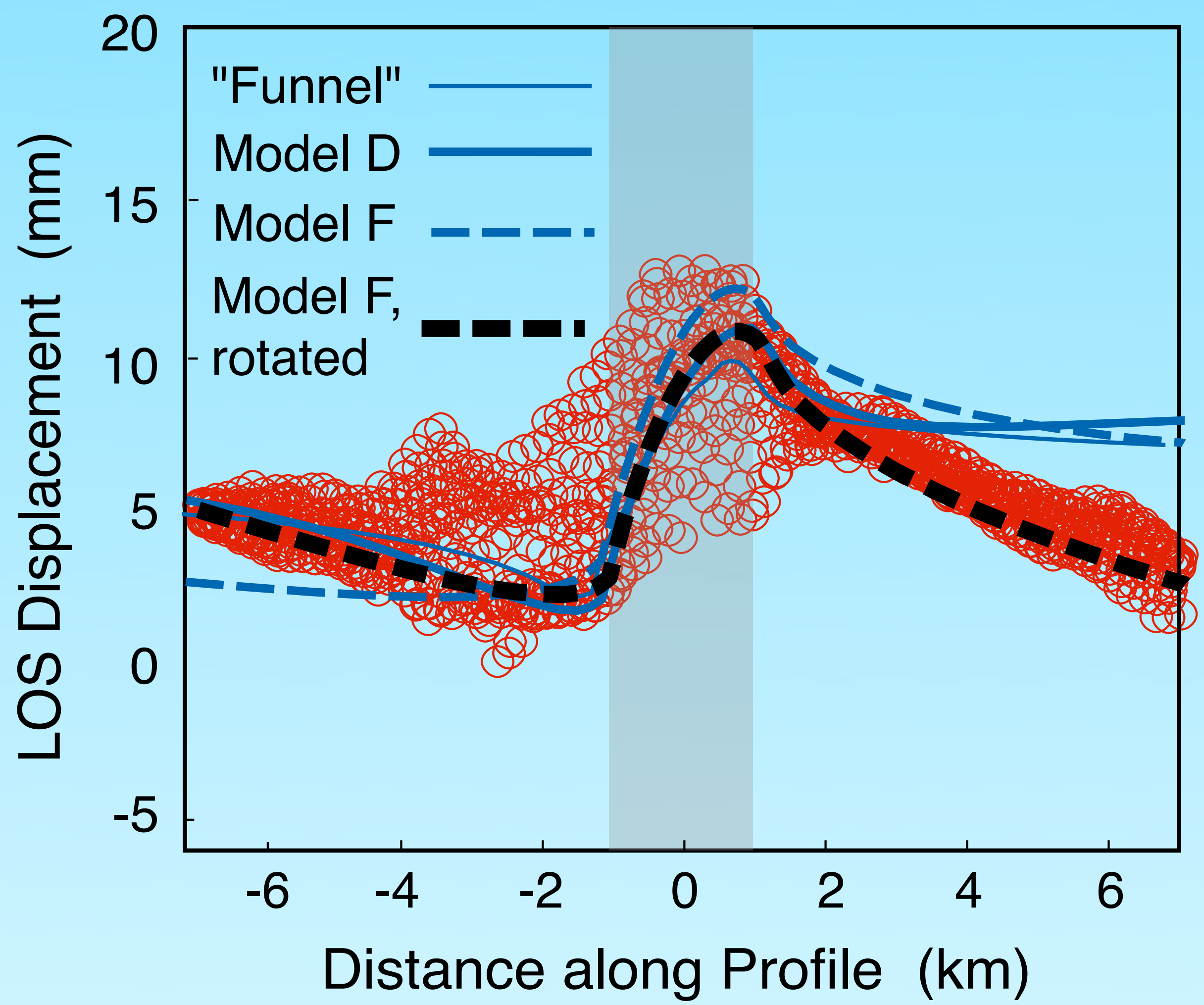



Yikes again.

# What works for the Camp Rock Fault CZ?



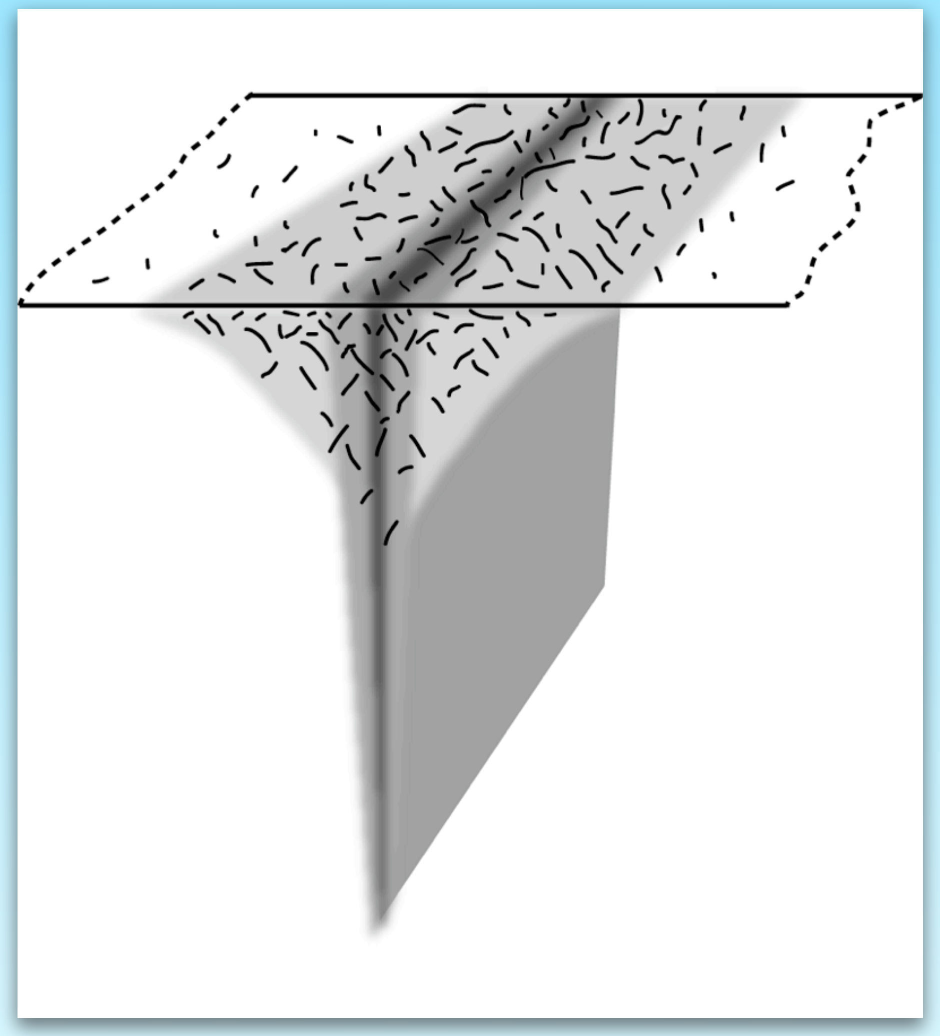

Must soften 4-9 % and CZ is >80% as rigid as the host rock

- 2 km wide near the surface
- may taper at depth
- incompressible or anisotropic? (to prevent subsidence)
- background stress: pure shear, high friction

# Best PMF and CRF models

## Similarities:

- 2 km wide near the surface
- may taper at depth
- incompressible or anisotropic? (or shallow?) to prevent subsidence
- background stress: pure shear, high friction coefficient



## Differences:

- Different strength contrast with host rock
- Different % softening in response to earthquake

# Main conclusion

Given

• compliant zone geometry and strength contrast

(*targeted* seismic, geodetic, and modeling studies)

• *%* change in elastic properties

(trapped wave and other seismic studies)

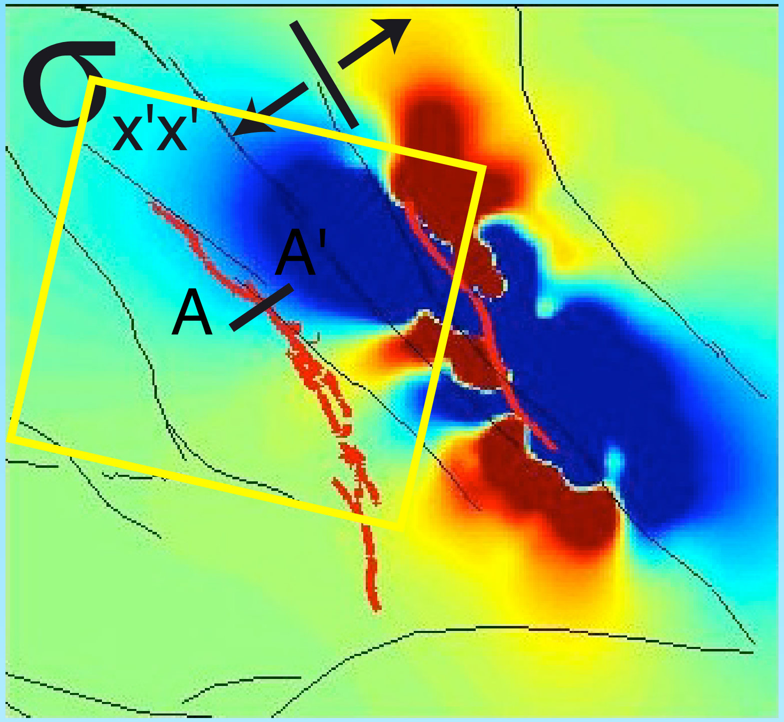
• coseismic stress perturbation

(dense GPS and seismic networks, elastic model)

we should be able to place constraints on background stress on the uppermost crust using models of compliant zone strain based on LOS displacements.

# Also

• Compliant zones probably do not influence static stress transfer significantly at distances of exceeding tens of km.




Future directions:

- Model spatial variations in elastic moduli
- Model more extreme tapering with depth (to 100 m)
- *Why no subsidence?*