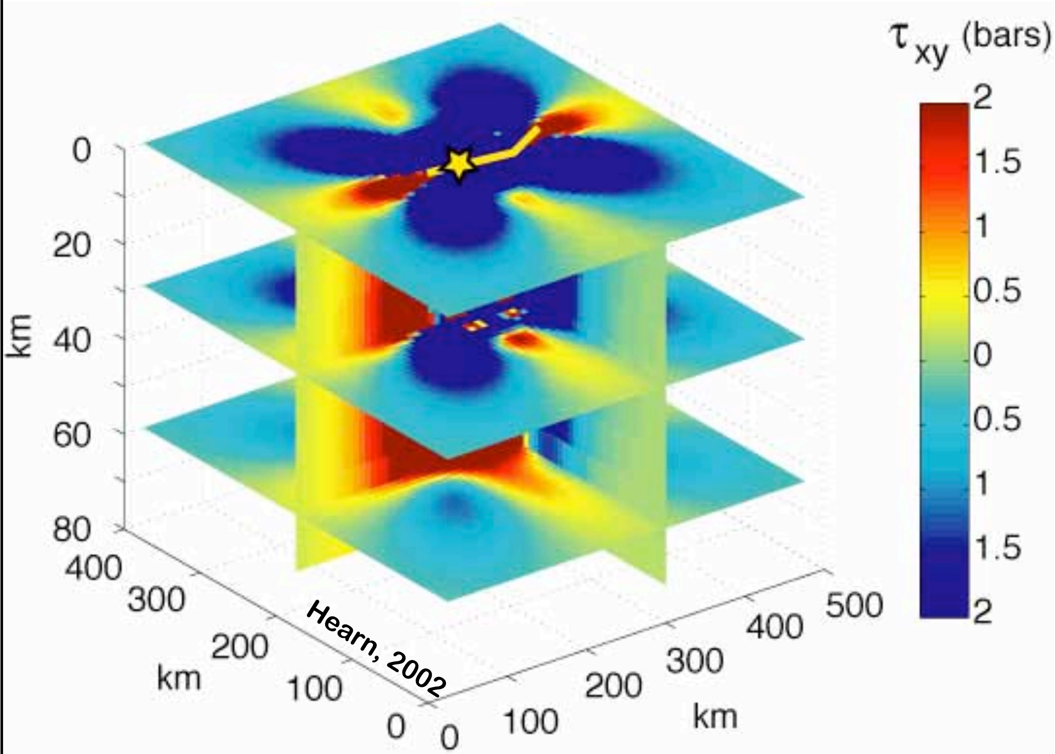
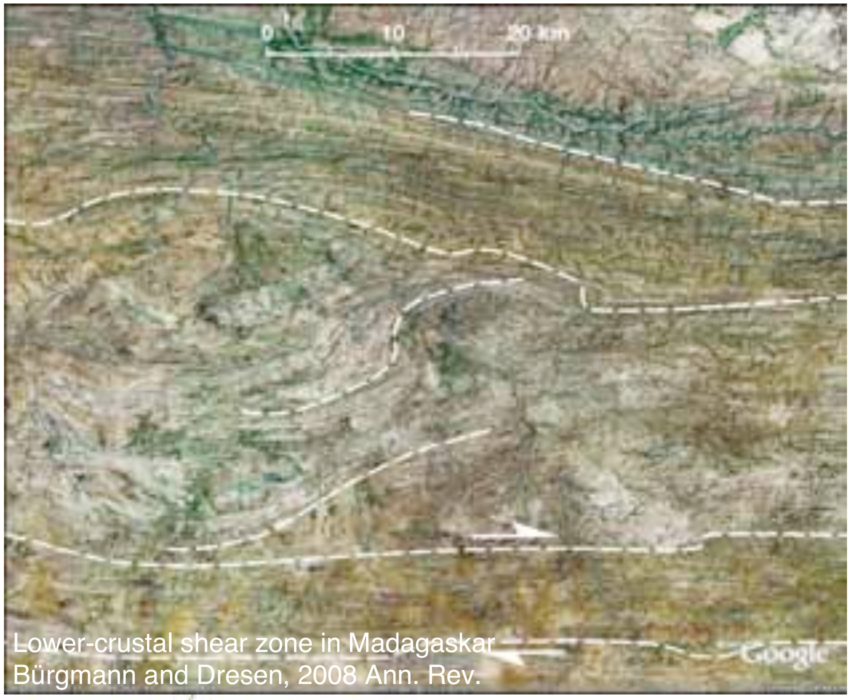
What gives in the lower crust? Evidence from post-loading deformation and exhumed fault zones

Roland Bürgmann, UC Berkeley

With D.C. Chandrasekhar, Georg Dresen, Andy Freed, Jeff Freymueller, Tom Herring, Kaj Johnson and Isabelle Ryder



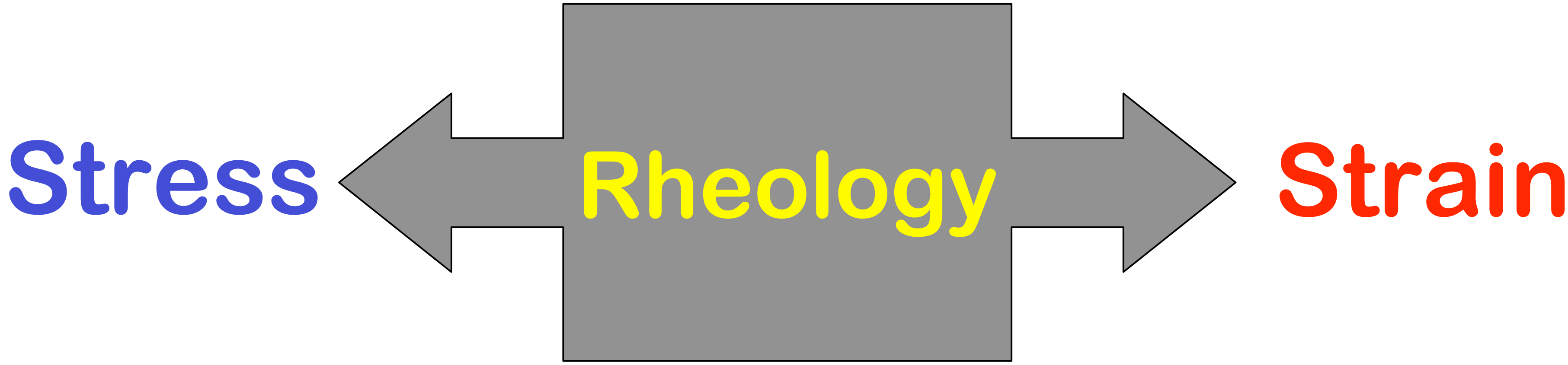


Lower-crustal shear zone in Madagaskar
Bürgmann and Dresen, 2008 Ann. Rev.

ACTIVE TECTONICS

CIG June 24, 2008

Goal: Illuminate Deformation Processes and Rheology at Depth

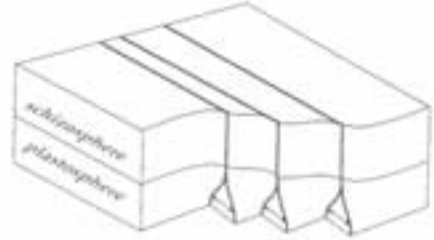


Understanding of the rheology of Earth's lower crust and upper mantle and of deep fault zones is fundamental to studies of

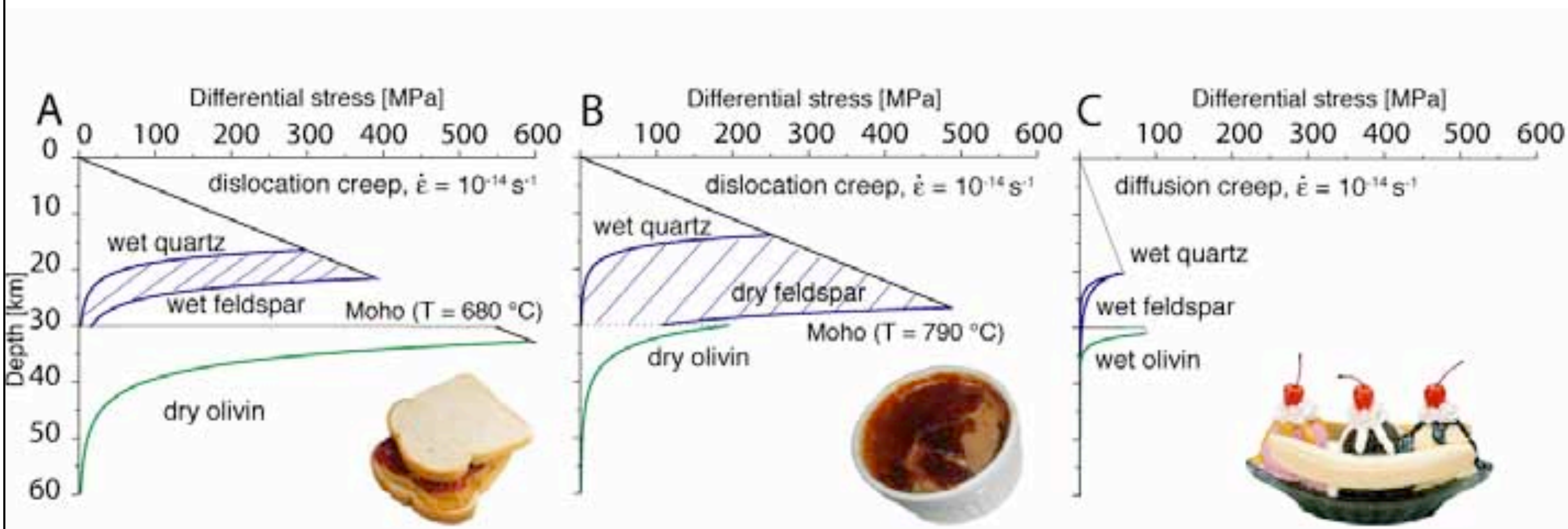
- plate & continental tectonics
- earthquake cycle mechanics
- fault interaction & earthquake hazard

What gives in the lower crust?

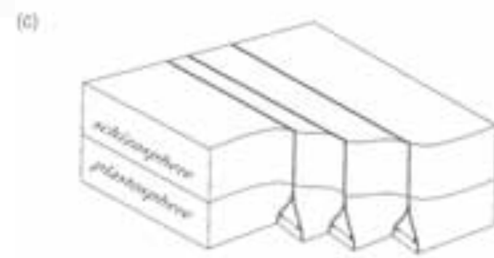
(c)



What gives in the lower crust?



Bürgmann & Dresen, 2008 Ann. Rev.



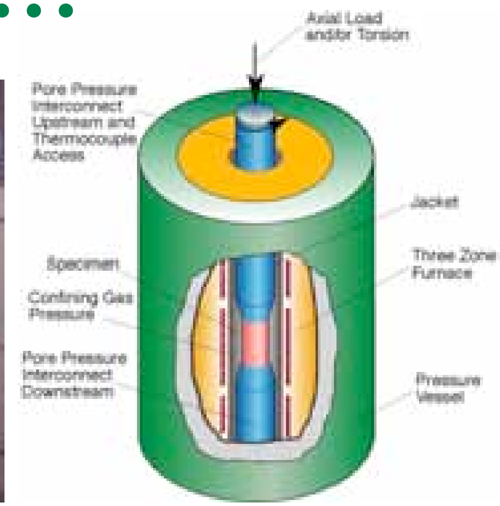
It depends on…

- **(1) Tectonic setting**
- **(2) Lithology, grain size, temperature, and fluids**
- **(3) Strain weakening and localization processes**

From the Laboratory …

- **Advantages:** **Conditions and materials are well known and the experiment can be directly observed**
- **Disadvantages:** **Rock and fault mechanics experiments are run at scales and conditions far from natural environment**

Texas A&M rock mechanics lab

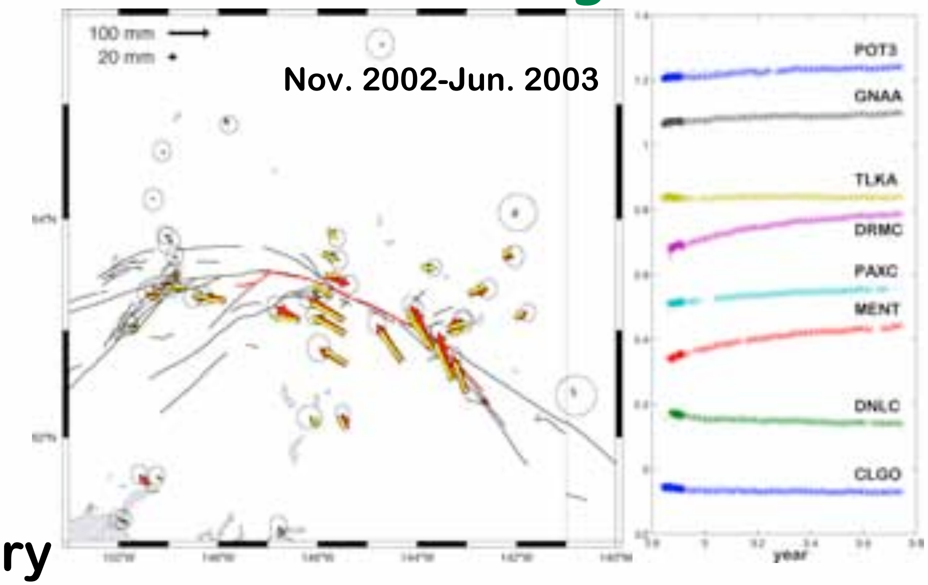


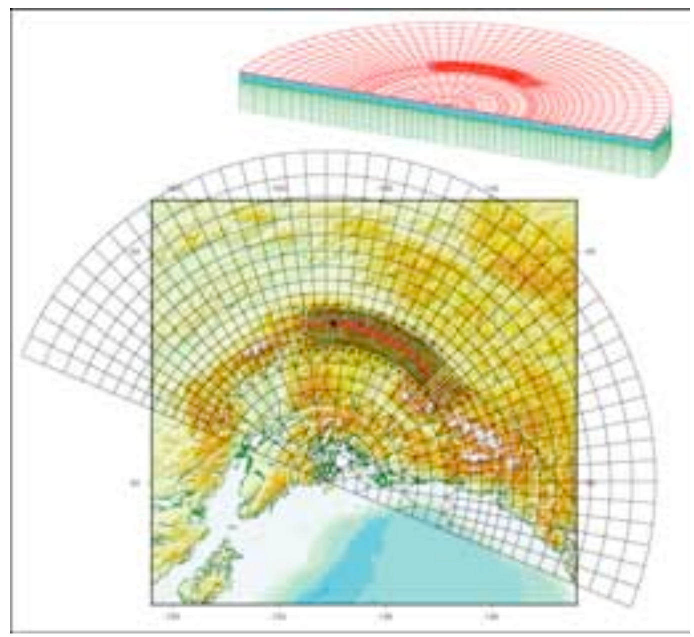
GFZ Gas deformation apparatus

Chris Marone's rock mechanics lab

… to the Natural Laboratory

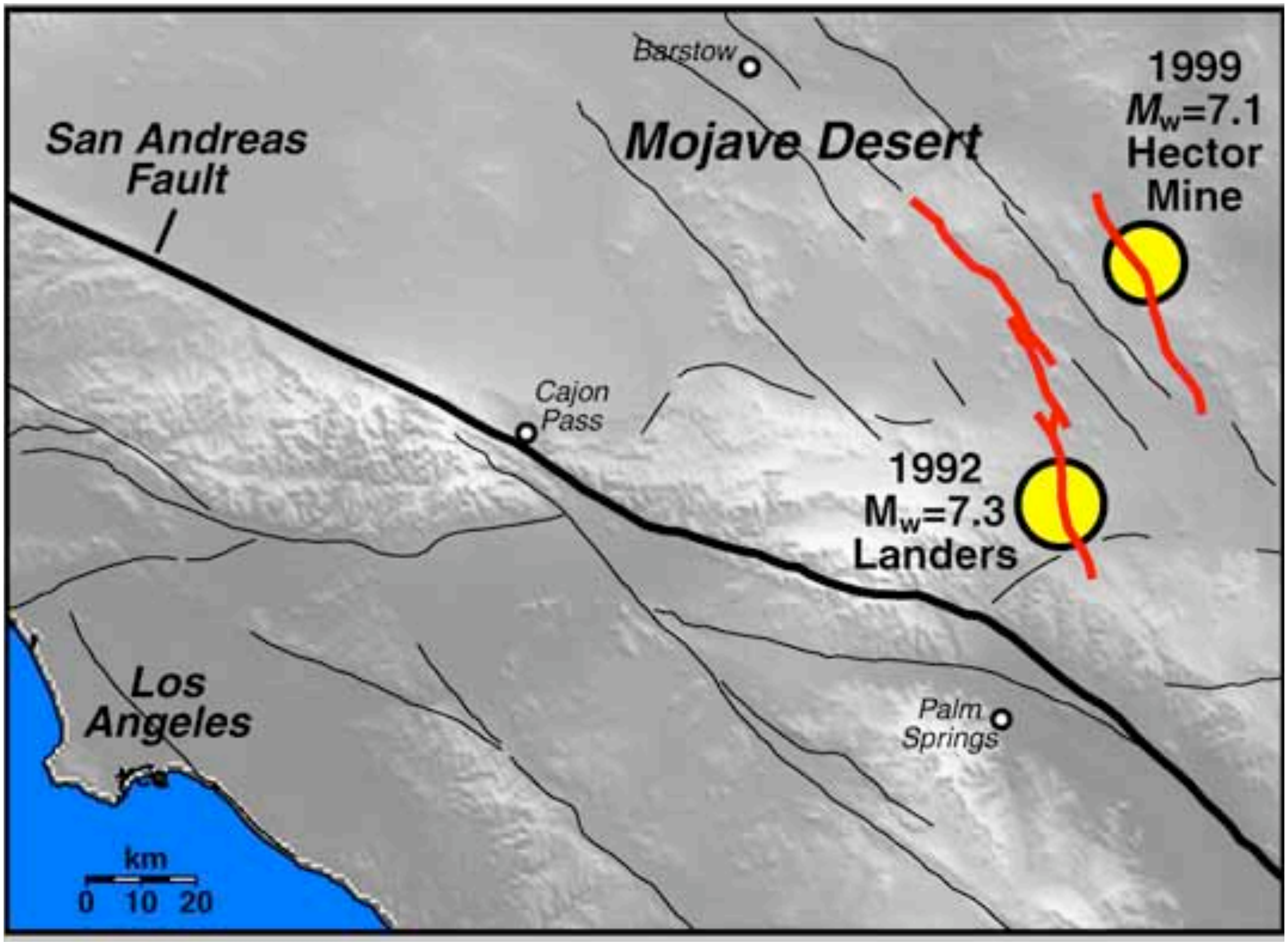
- A large earthquake (or other loading event) initiates a lithosphere-scale rock mechanics experiment that allows us to probe the rheology at depth
  - Establish geometry and boundary and initial conditions (coseismic slip) of experiment
  - Take postseismic deformation measurements (GPS, InSAR, …)
  - Use models to resolve deformation processes and determine relevant rock or fault constitutive properties
- Examples: Mojave Desert, Denali, Tibet, and NW India





Freed et al., 2006, JGR

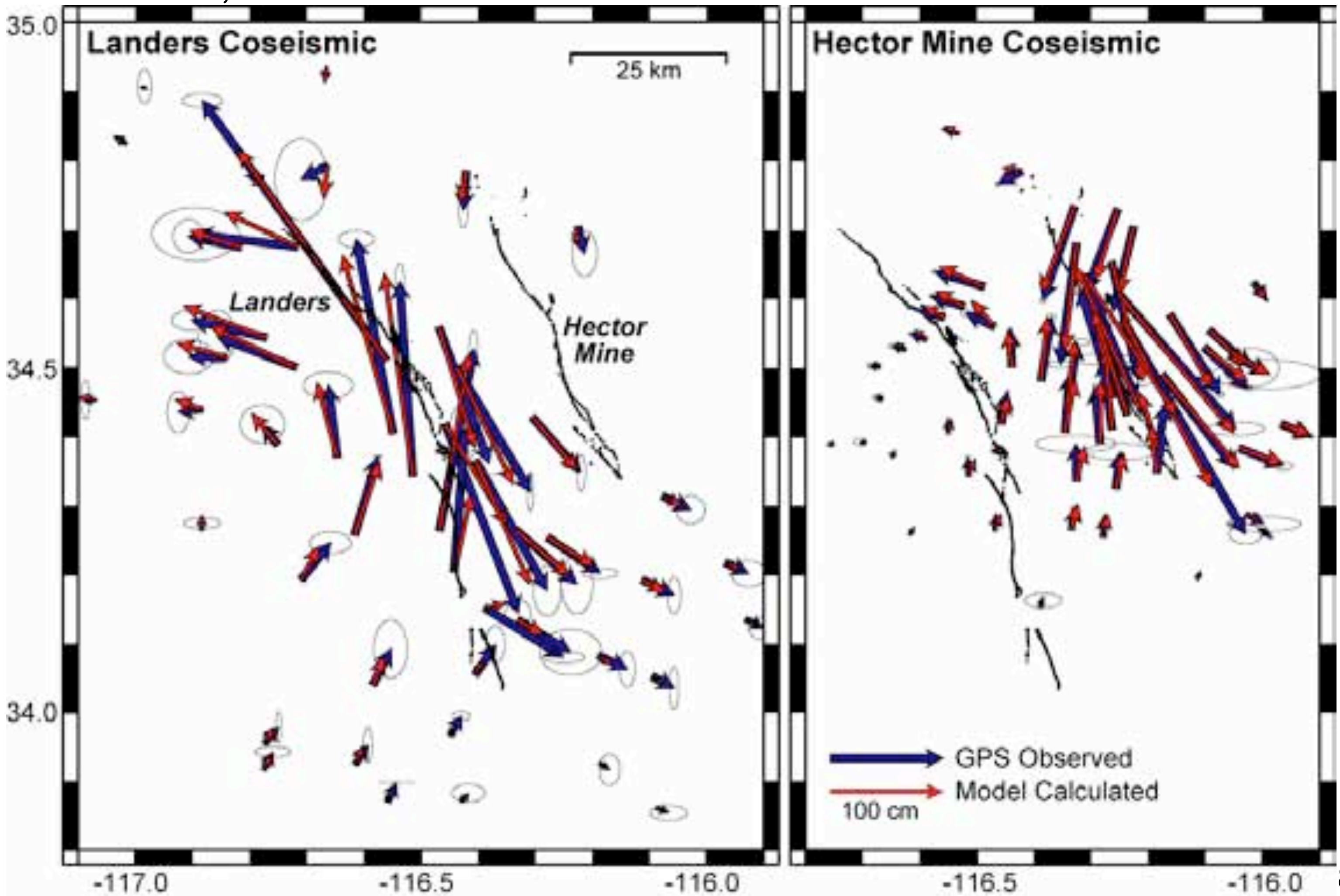
Mojave Desert Earthquakes



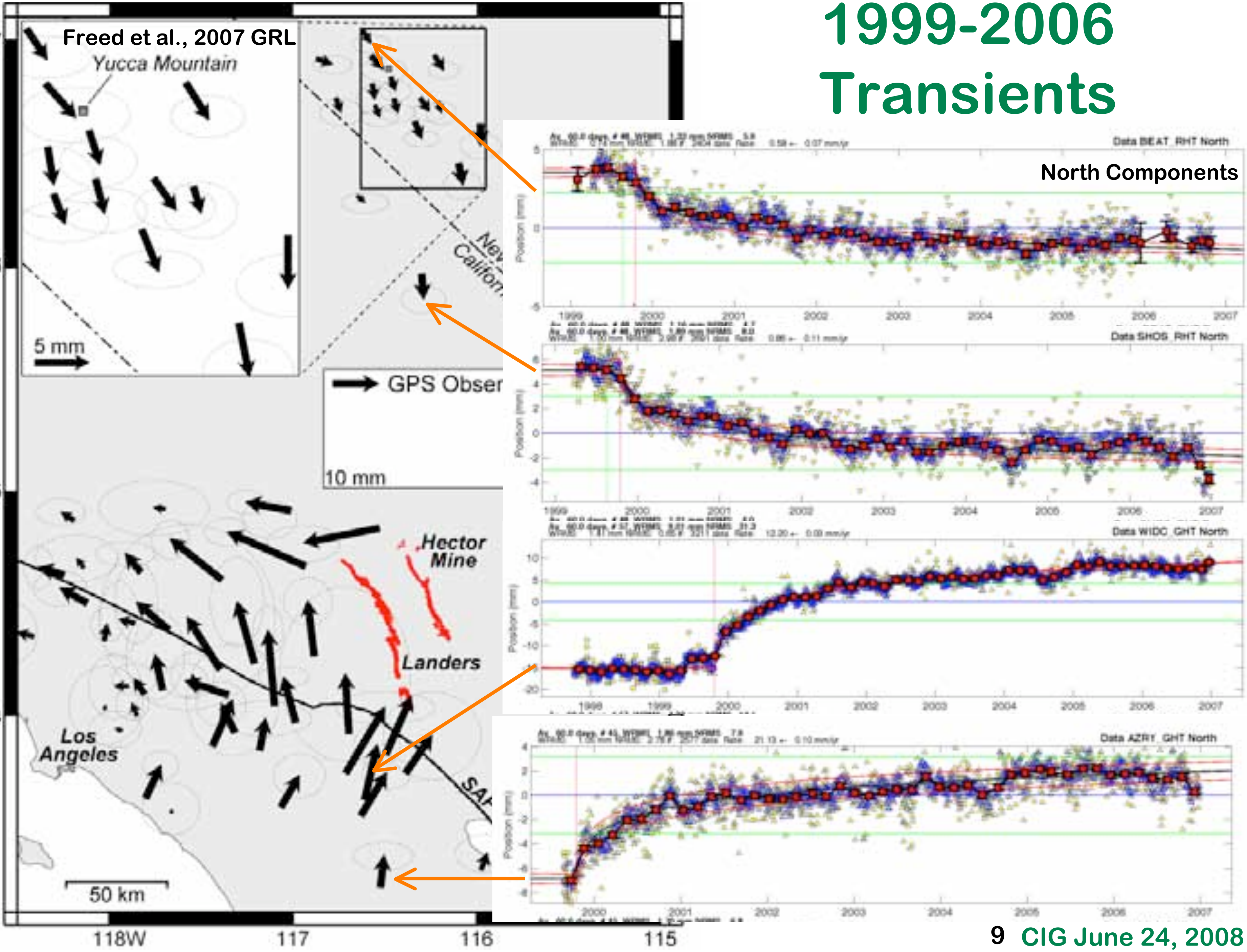
Coseismic Source

- We adopt coseismic slip models and layered elastic structure of Simons et al. 2002 and Fialko, 2004
- All models are driven by stress changes from both earthquakes

Freed et al., 2007 GRL



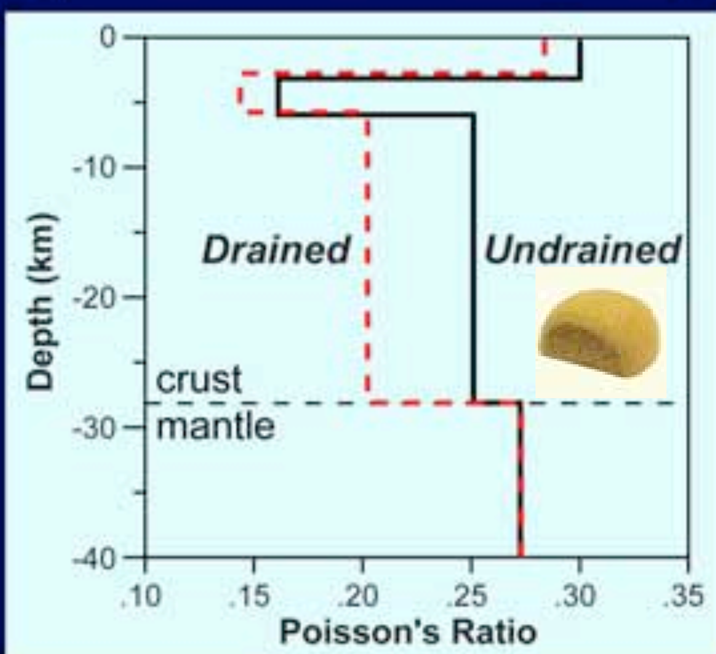
1999-2006 Transients

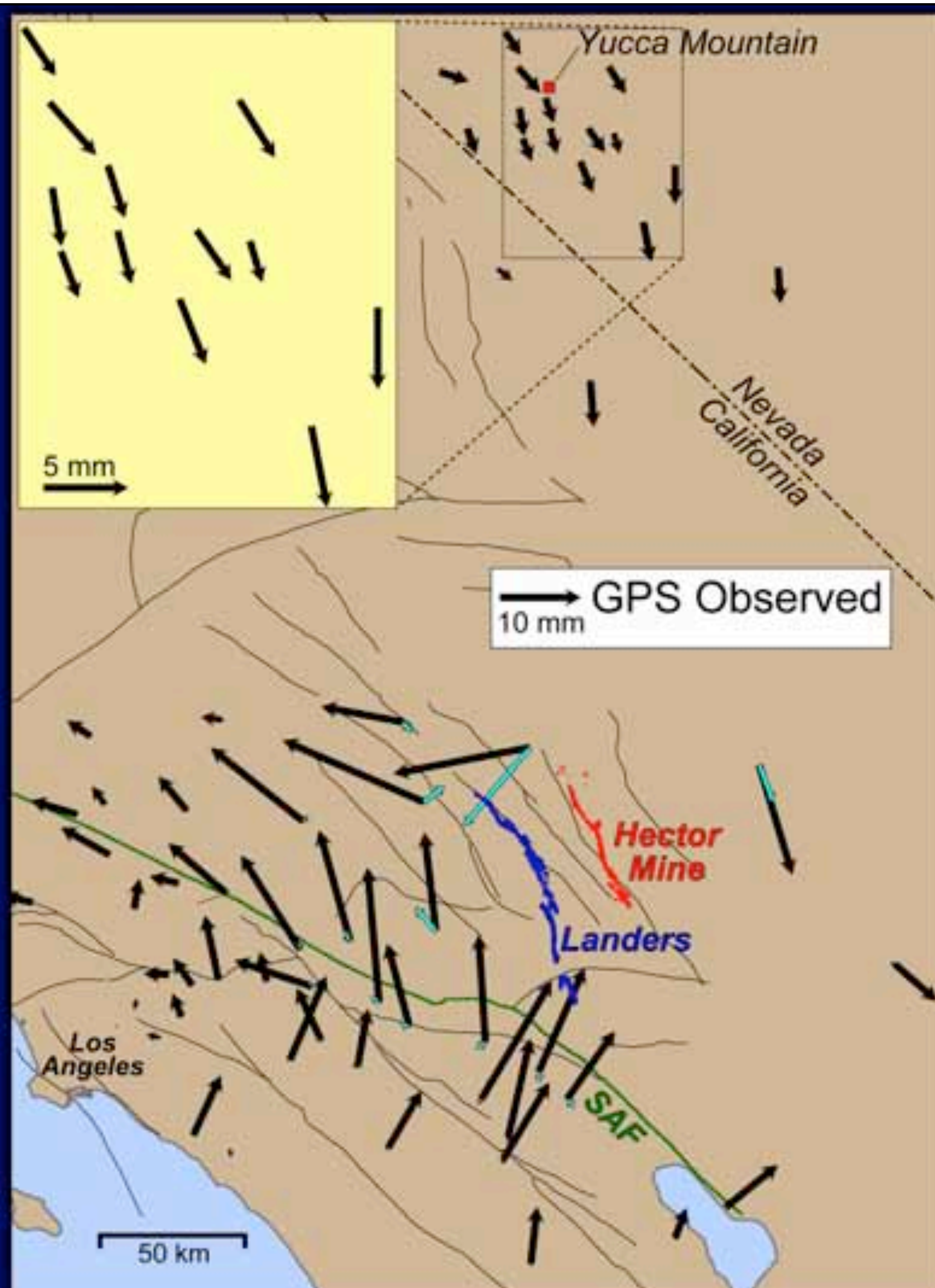


Comparisons Between Observed and Calculated Cumulative Horizontal Surface Displacements

Numerical Models

- Upper Mantle Flow
- Lower Crustal Flow
- Poroelastic Rebound
- Stress Driven Afterslip





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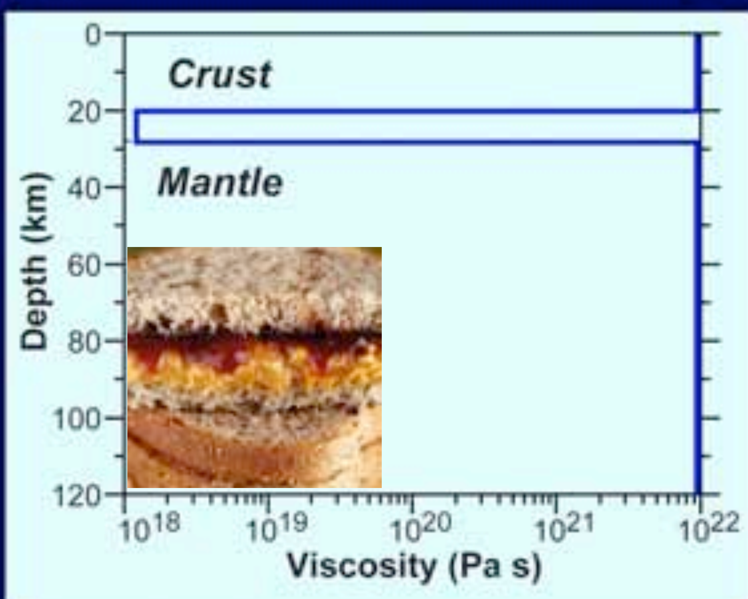

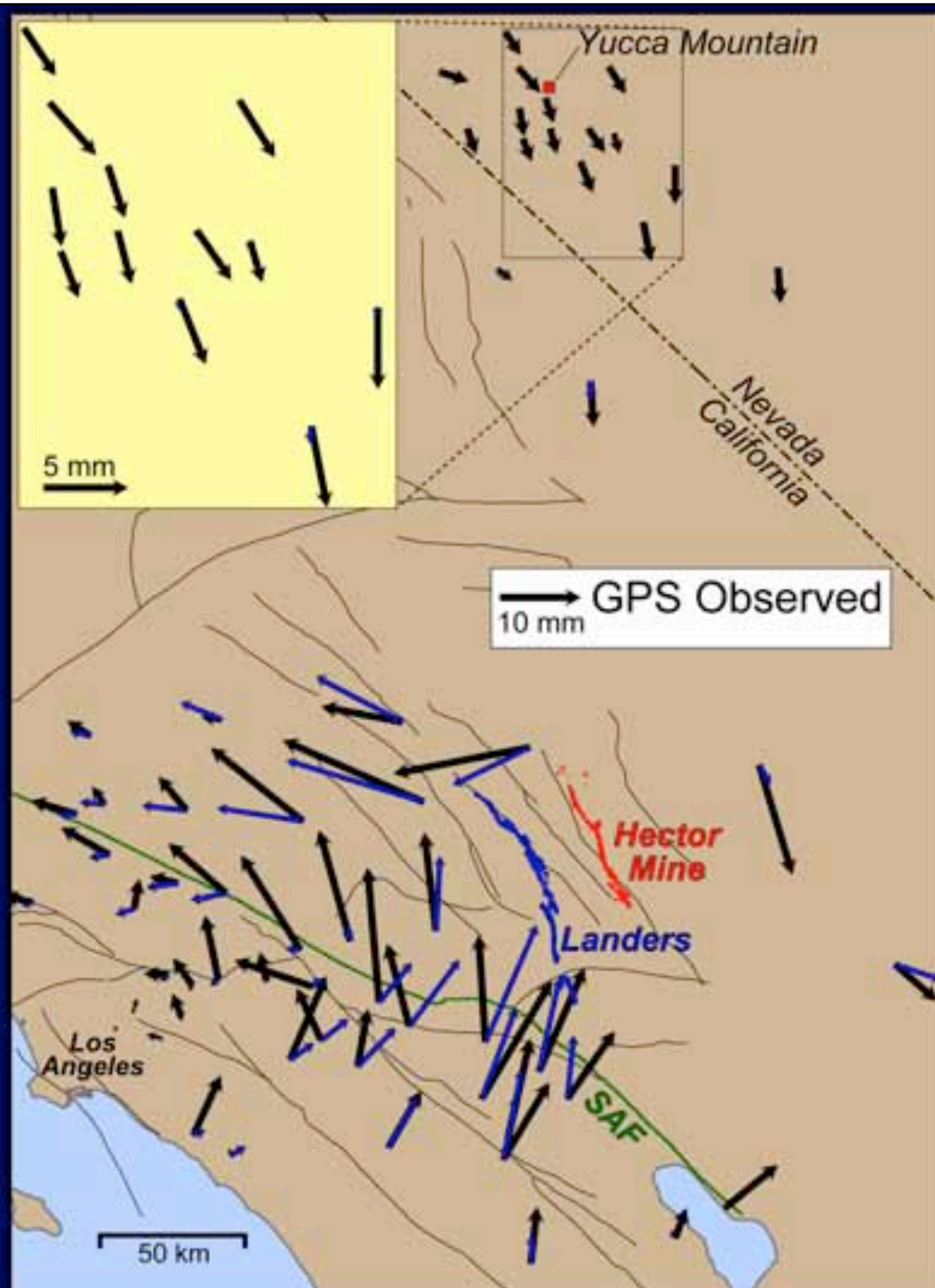

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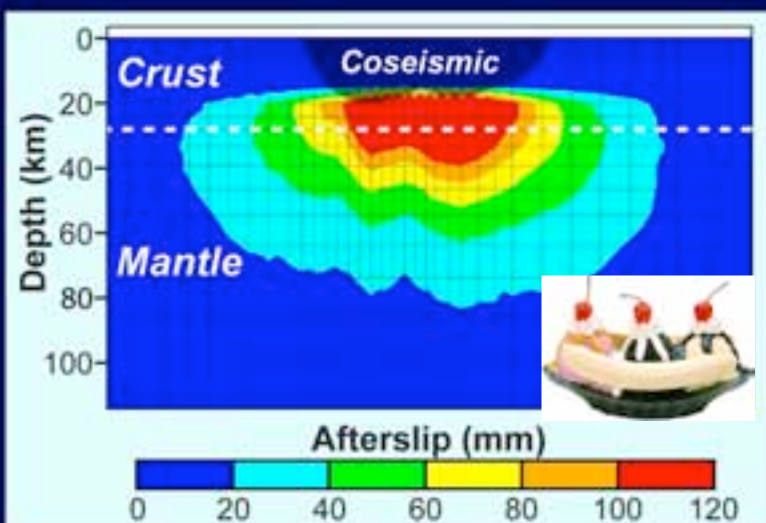

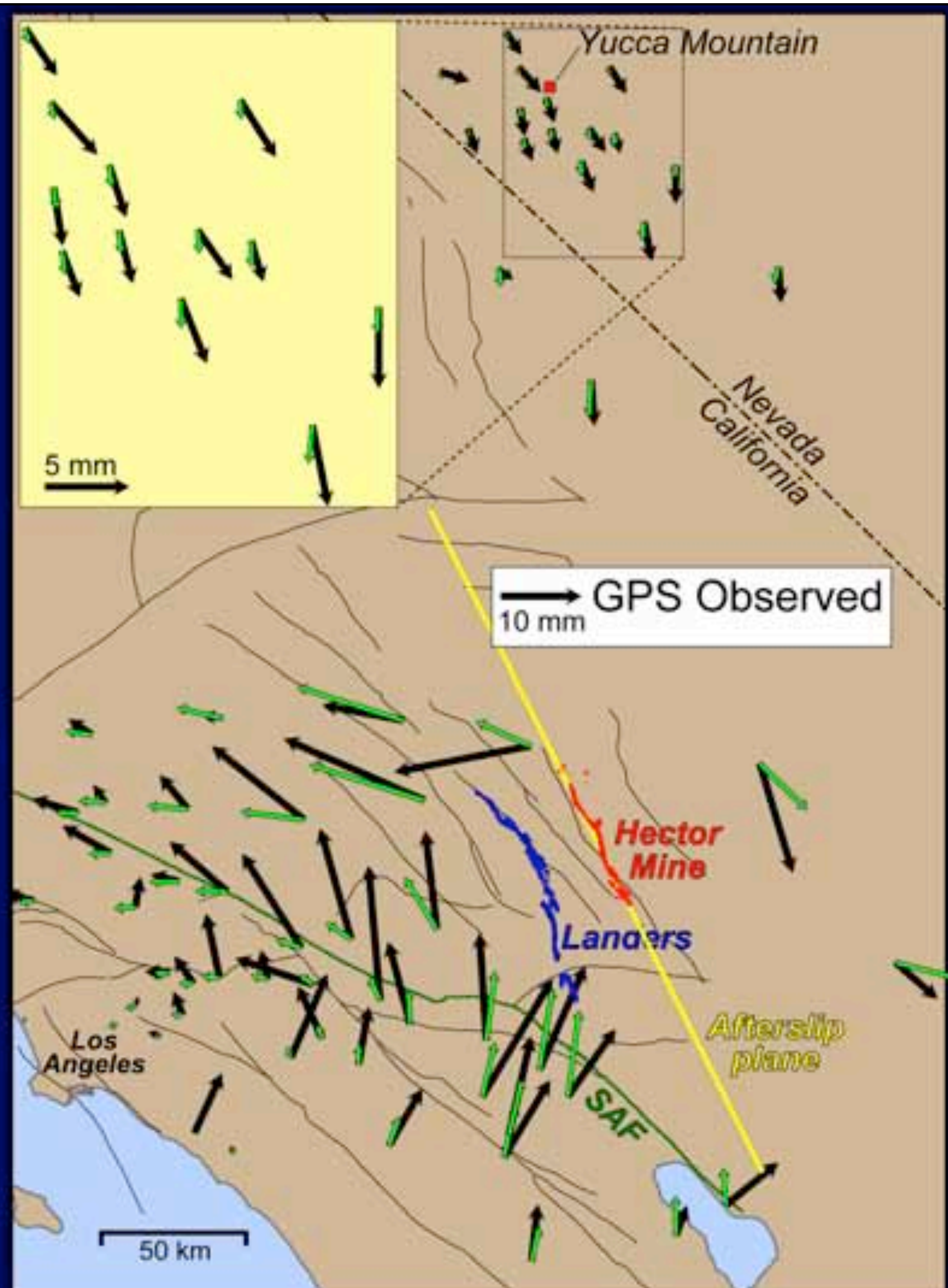

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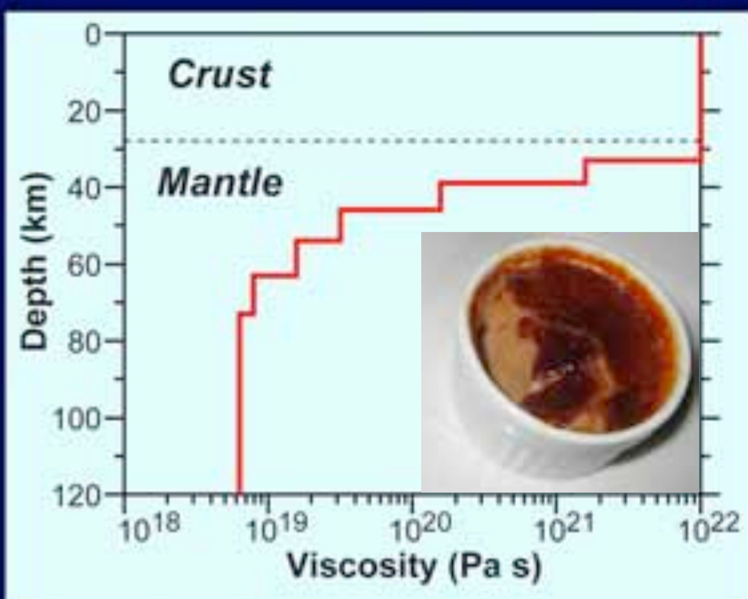
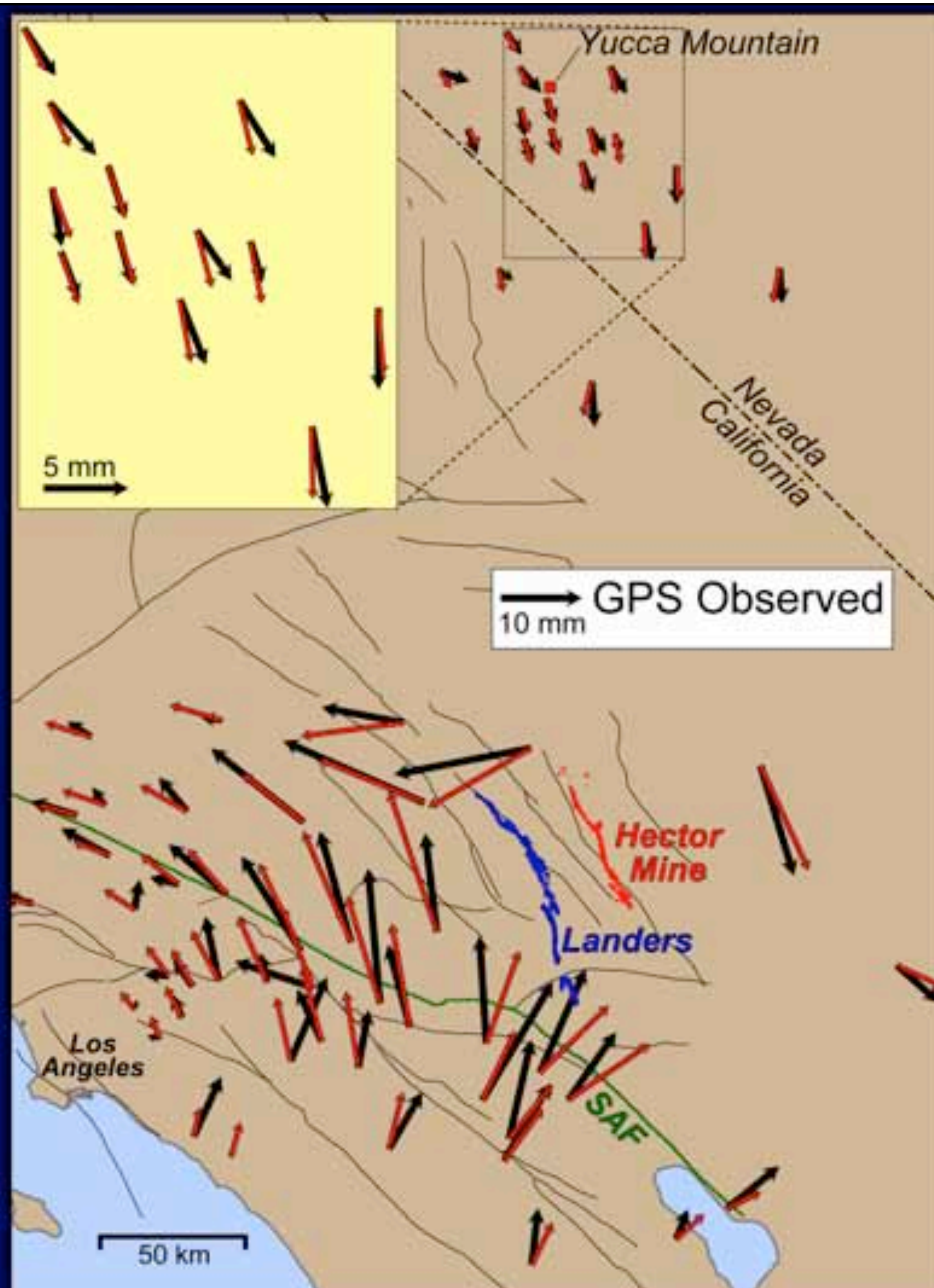
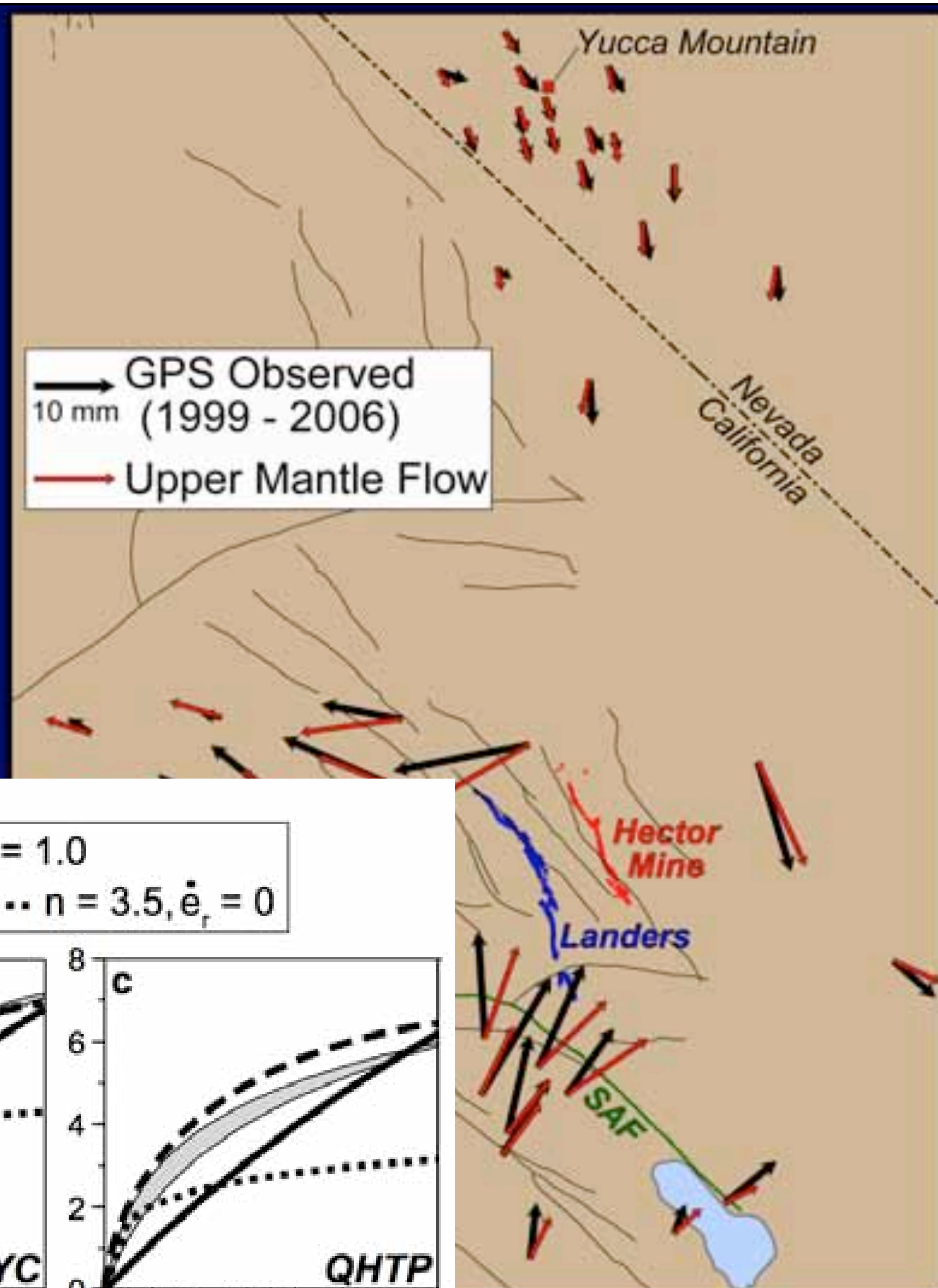
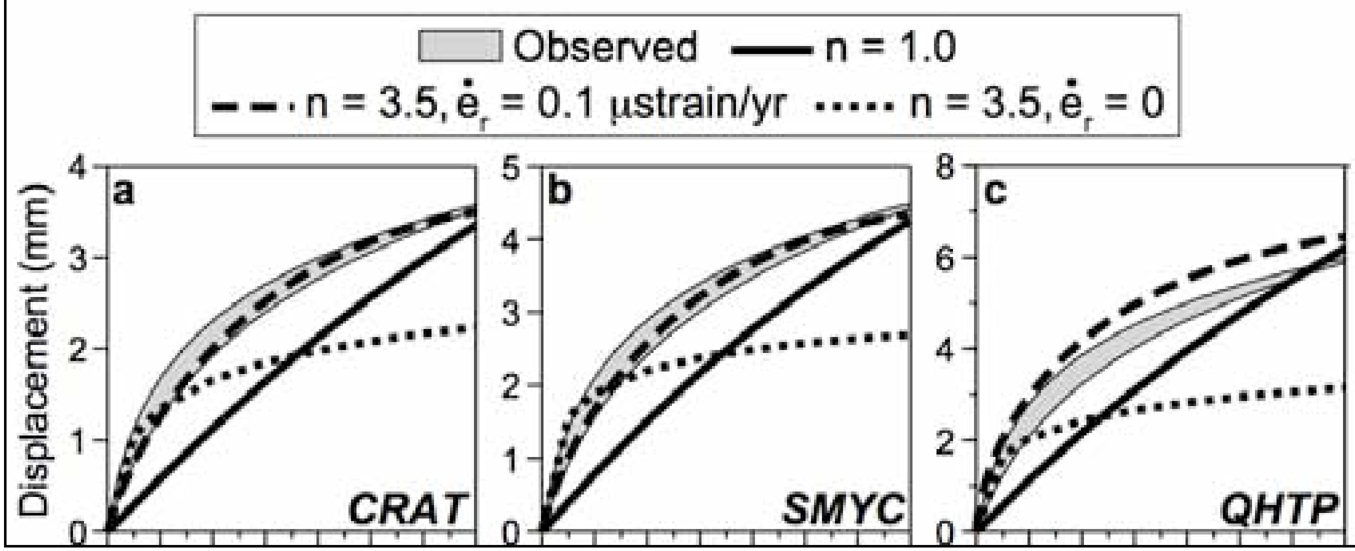




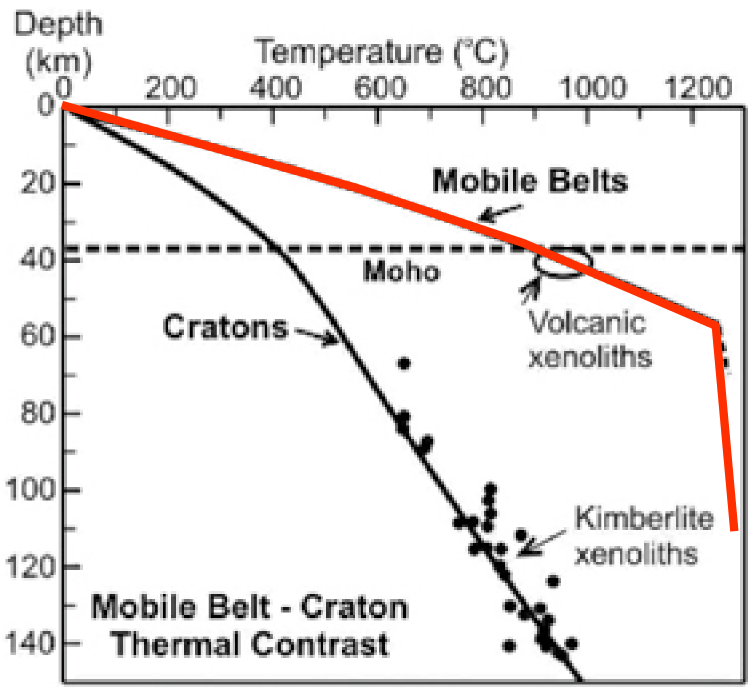
Conclusions

- Far-reaching transient motions after Mojave earthquakes require broad mantle flow beneath a strong crust
- Transient time-series is best explained by a flow consistent with wet olivine:
  - stress exponent n = 3.5-4.5
  - activation energy Q = 430-480 kJ/mol
  - regional strain rate of mantle is ~0.1 μstrain/yr $\varepsilon = A\,\sigma^n\, e^{-Q/RT}$

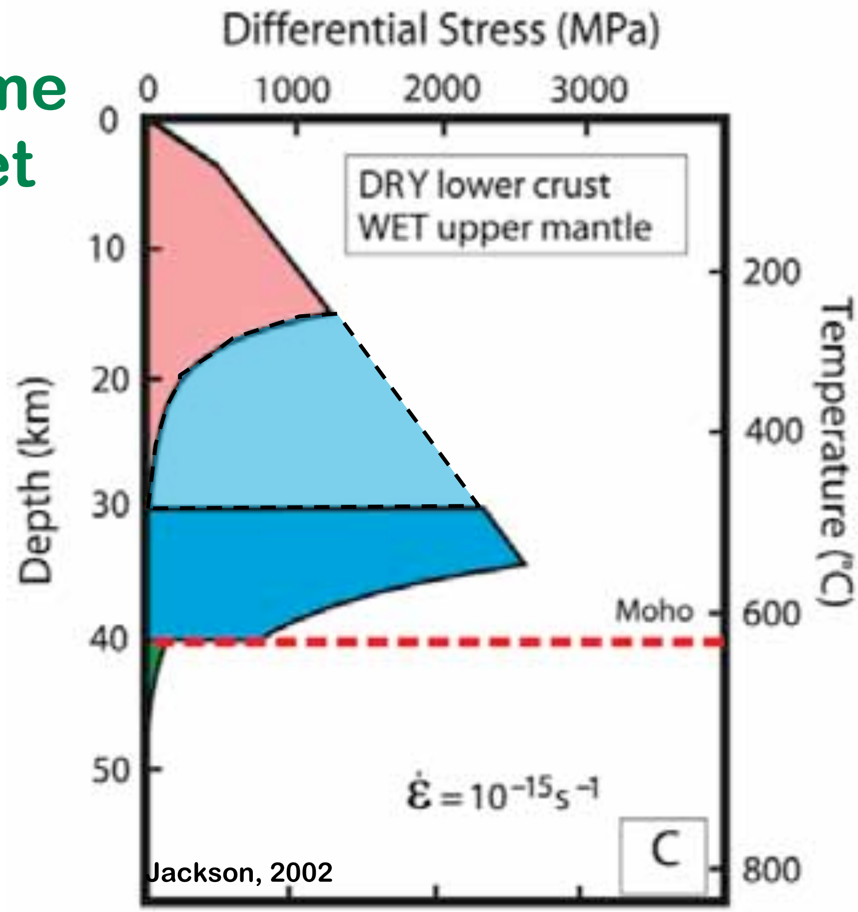




Mojave Dessert Tastes Like Crème Brûlée: Strong Crust - Hot & Wet Mantle in (former) Backarc

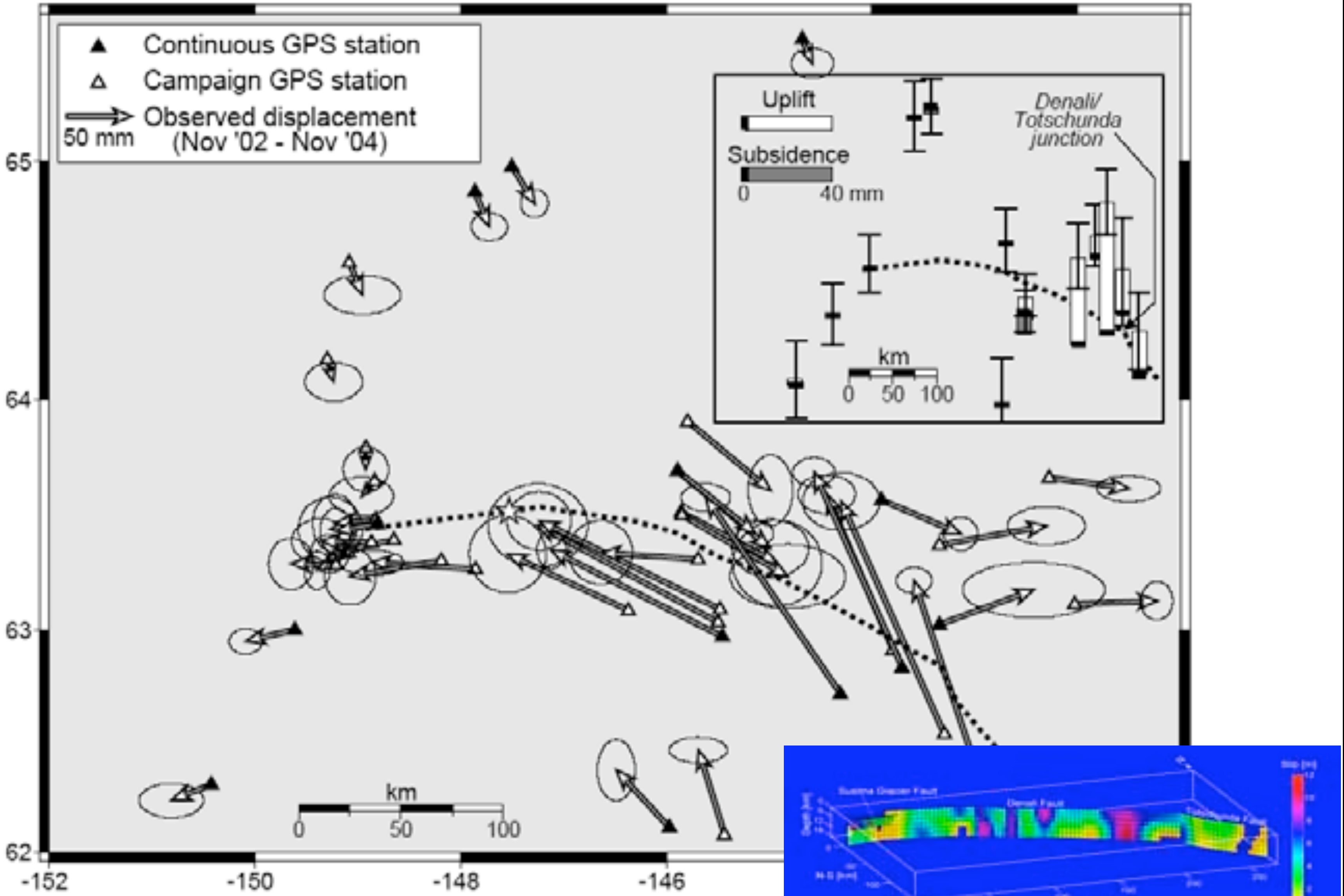


Hyndman, GSA Today 2005



- What gives in the crust?
  - Modest poroelastic rebound together with crustal afterslip and/or flow contribute (see Fialko, 2004; Perfettini & Avouac, 2007; Freed et al., 2004)

M_w 7.9 Denali Earthquake

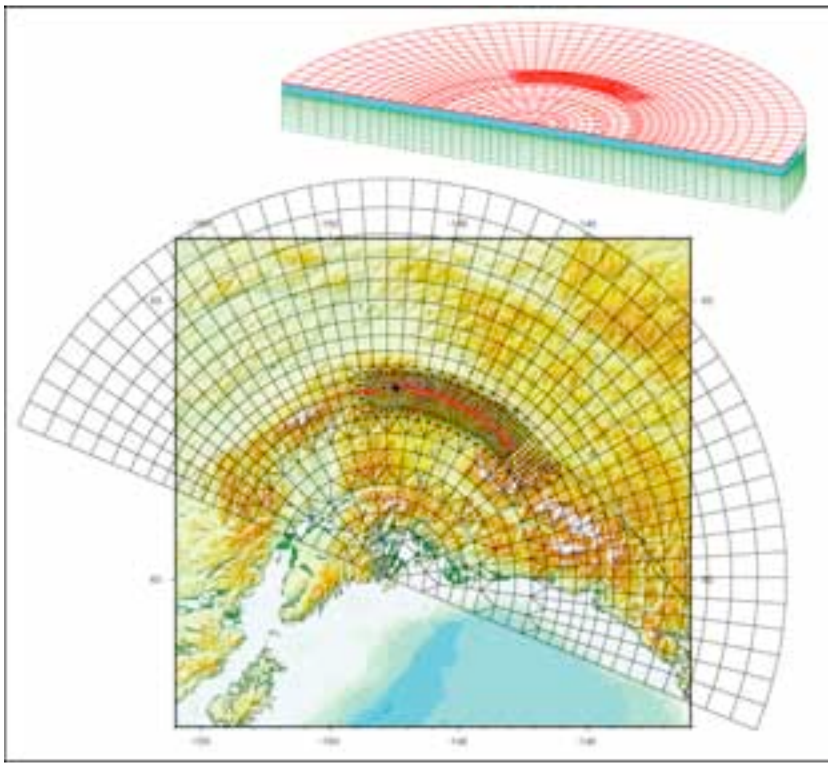


Freed et al., 2006, JGR

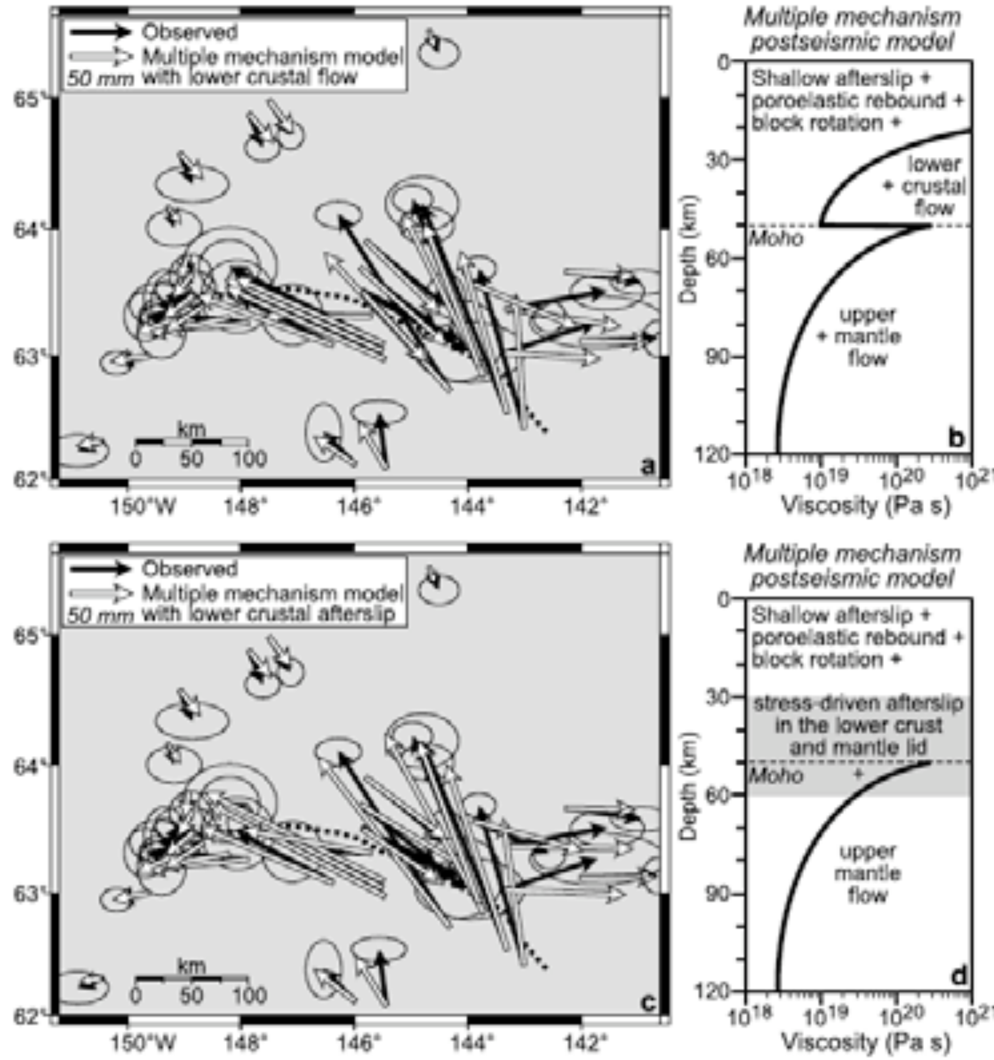
Hreinsdottir et al., 2006, JGR

Mantle Flow and Crustal Shear

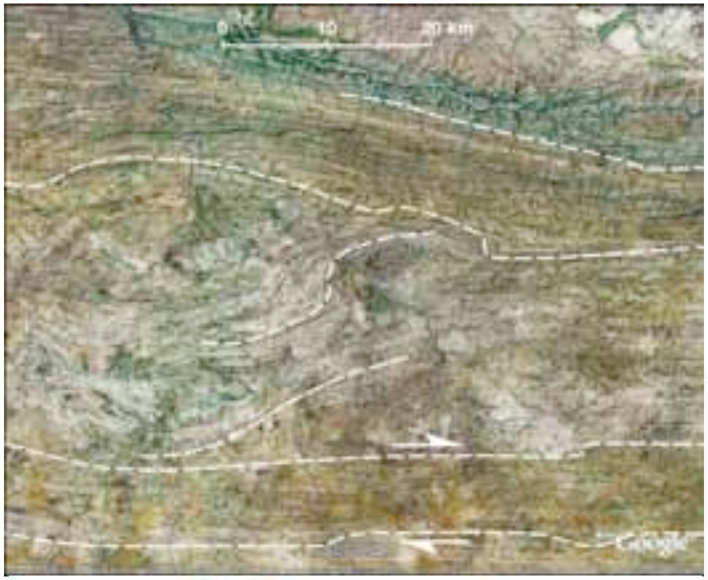
- **FEM models indicate upper mantle relaxation, as well as lower crustal flow or slip**

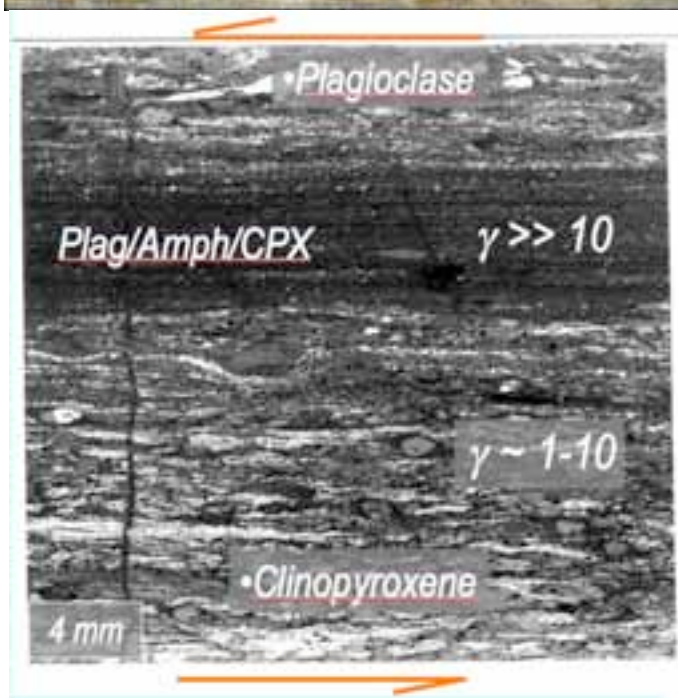


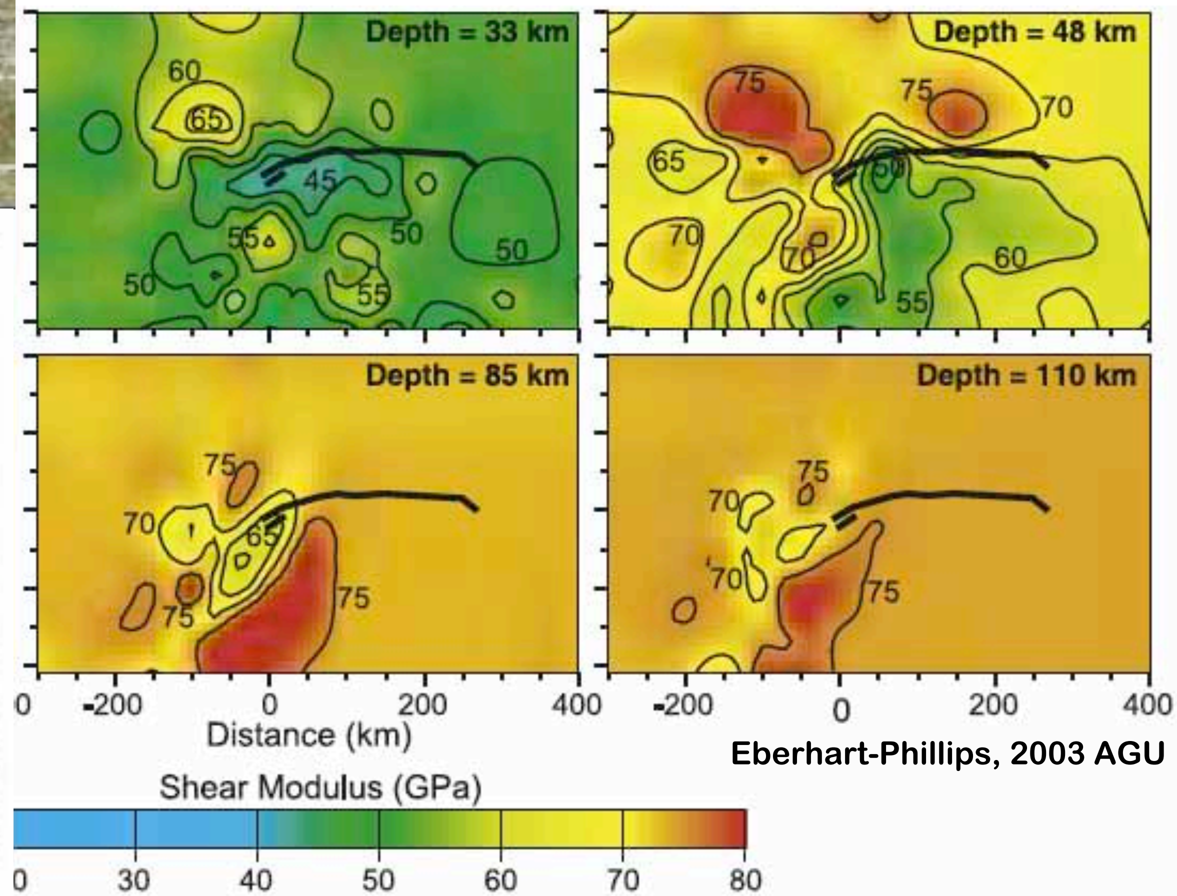
Freed et al., 2006 JGR



Localized Lower Crustal Shear

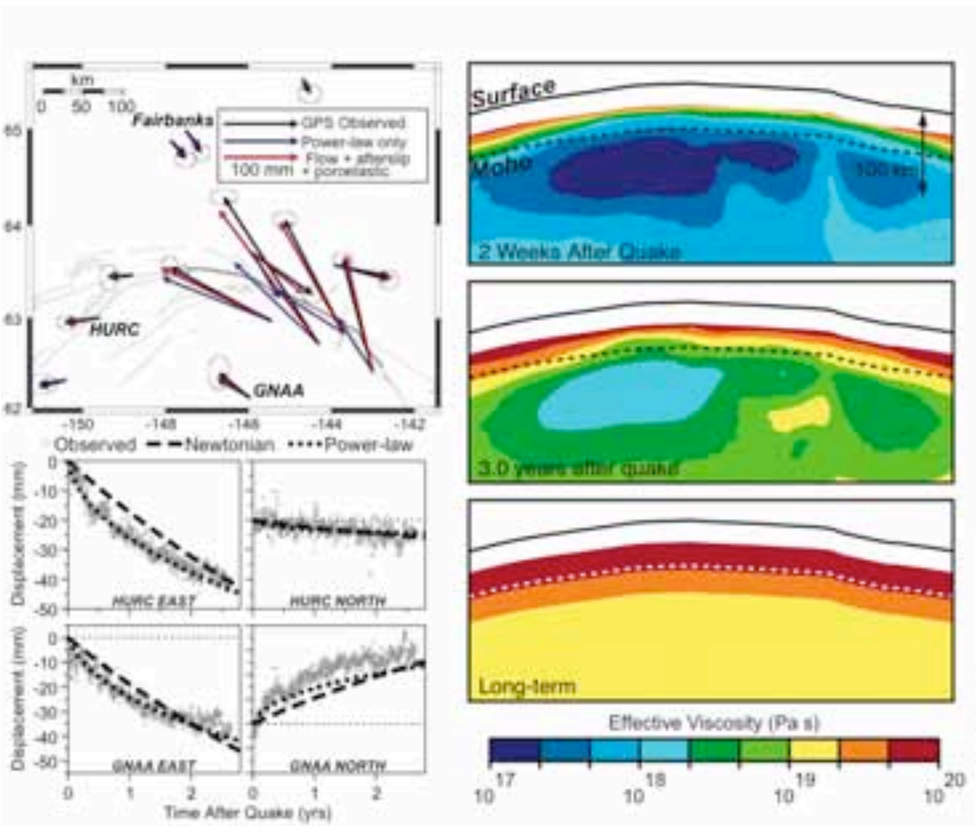




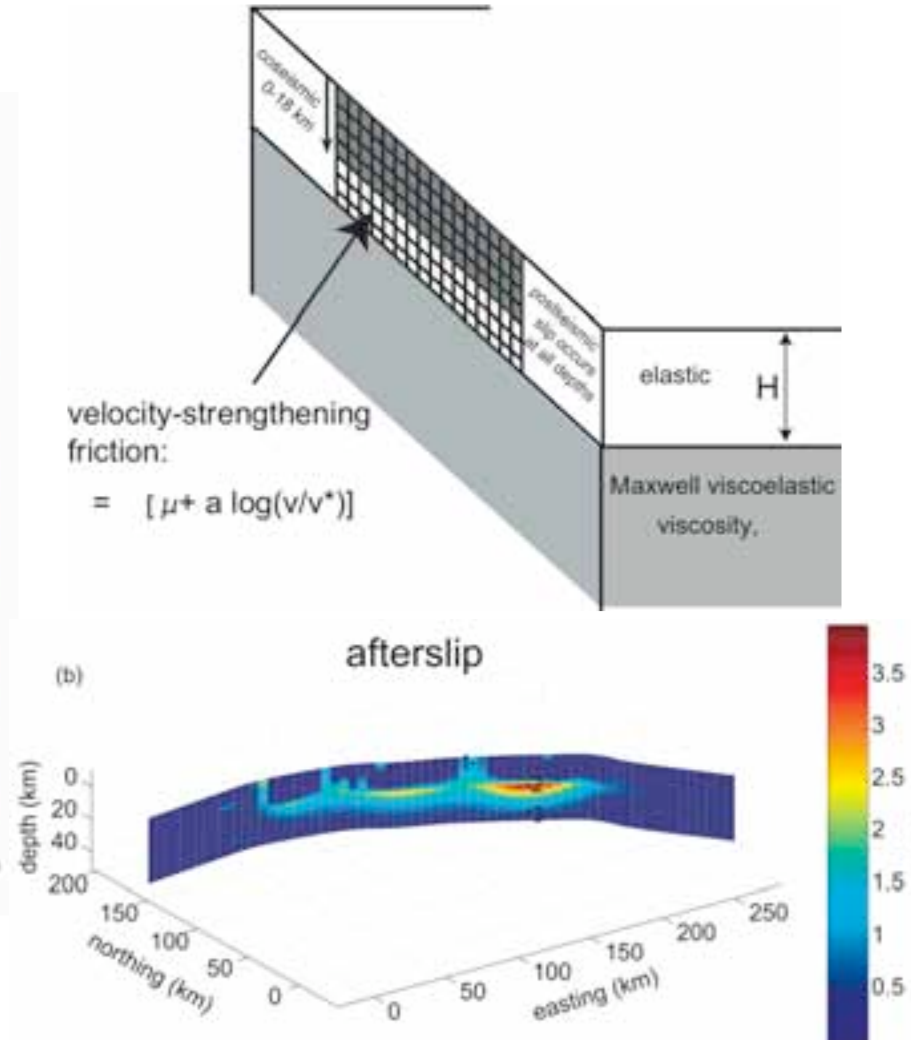


Eberhart-Phillips, 2003 AGU

Rheology of Lower Crustal Shear?



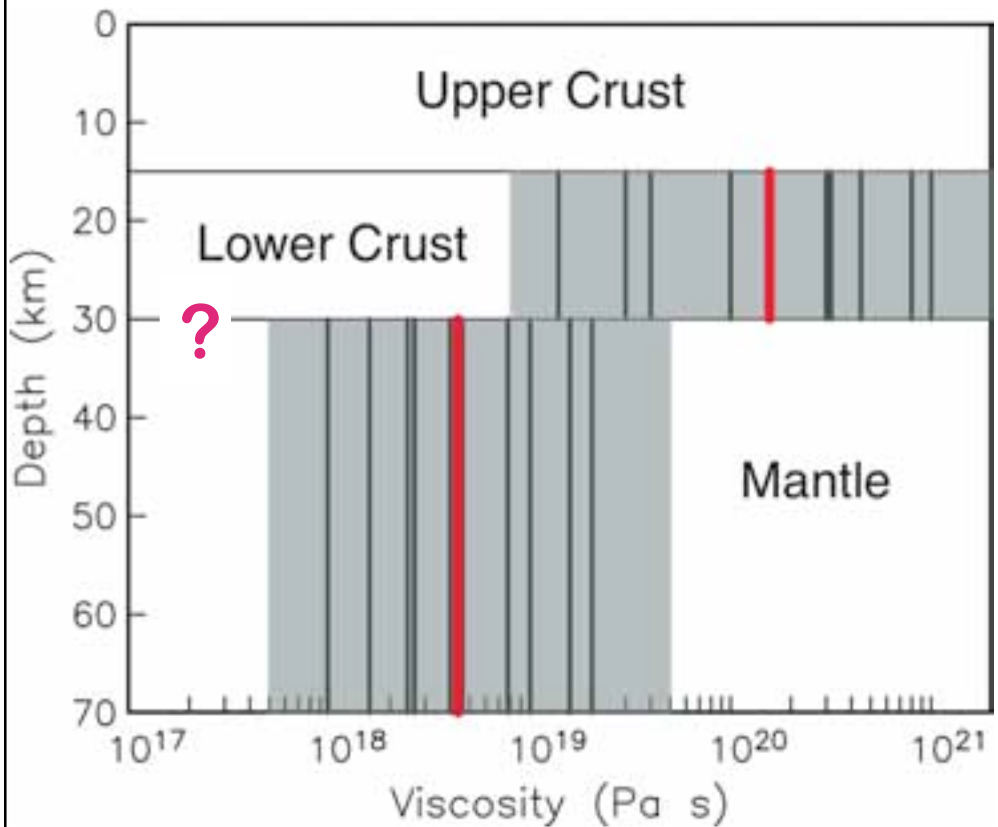
Freed et al., 2006 EPSL

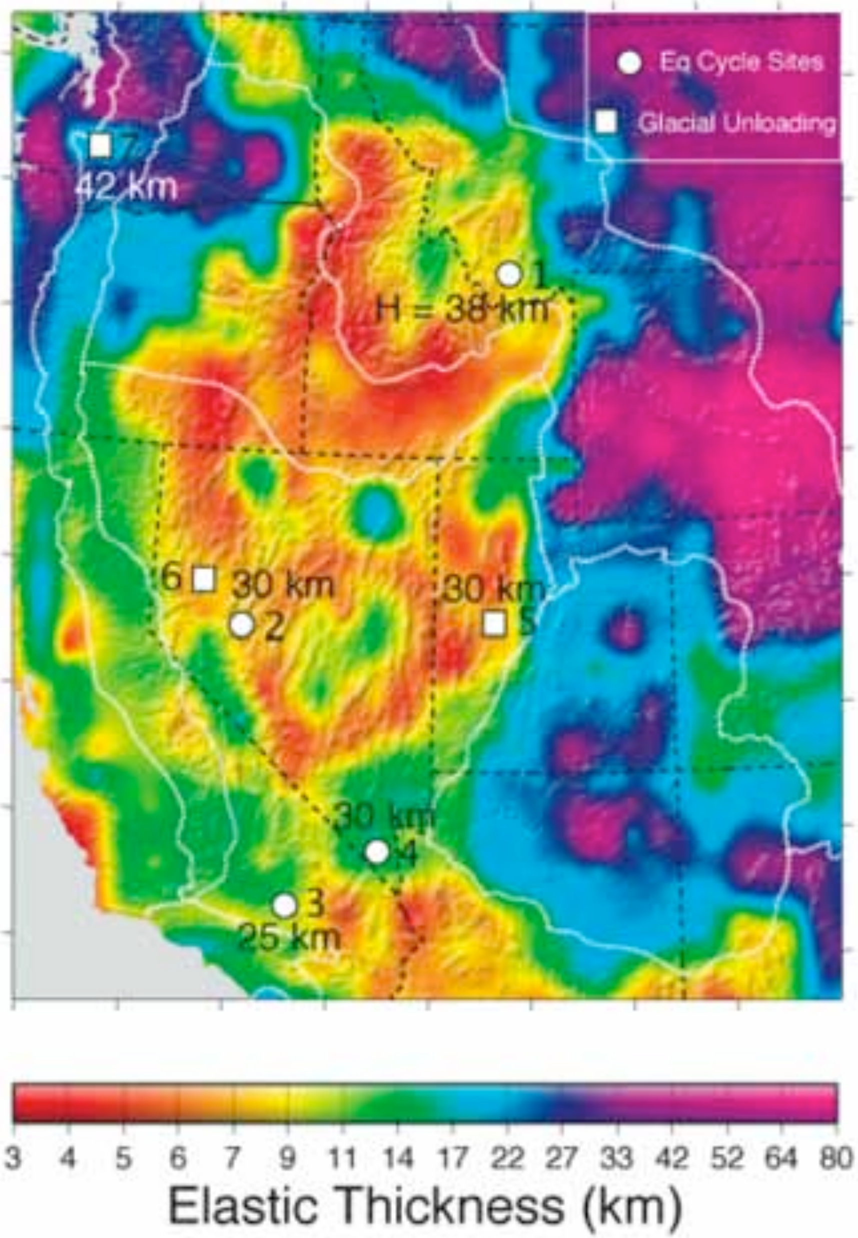


Johnson et al., 2008 GJI submitted

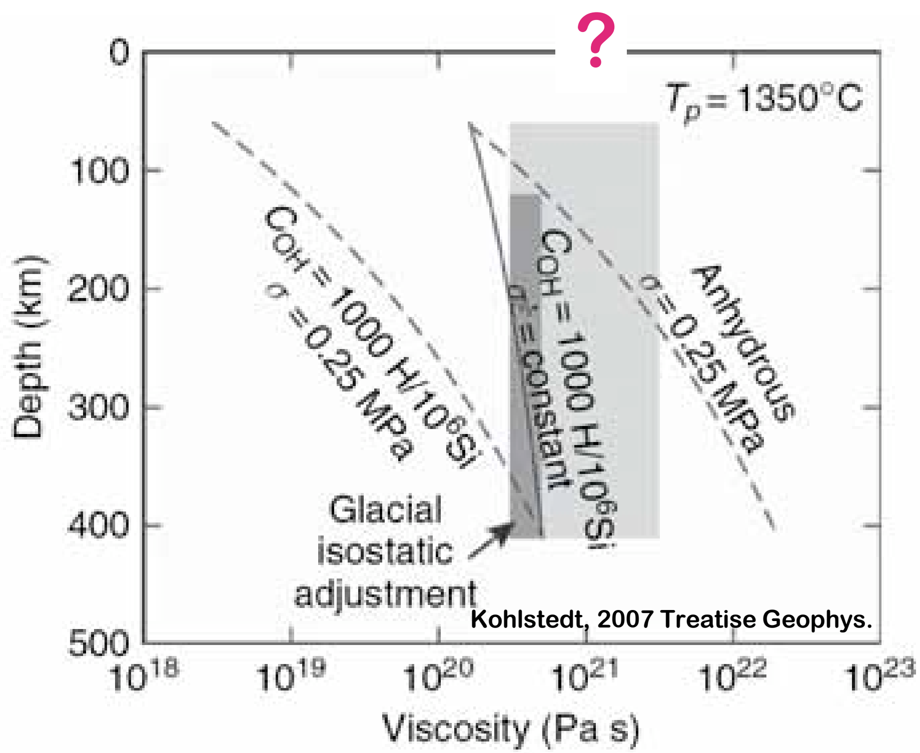
Plate Boundaries: Weak Mantle - Strong Crust

Thatcher & Pollitz, GSA Today 2008

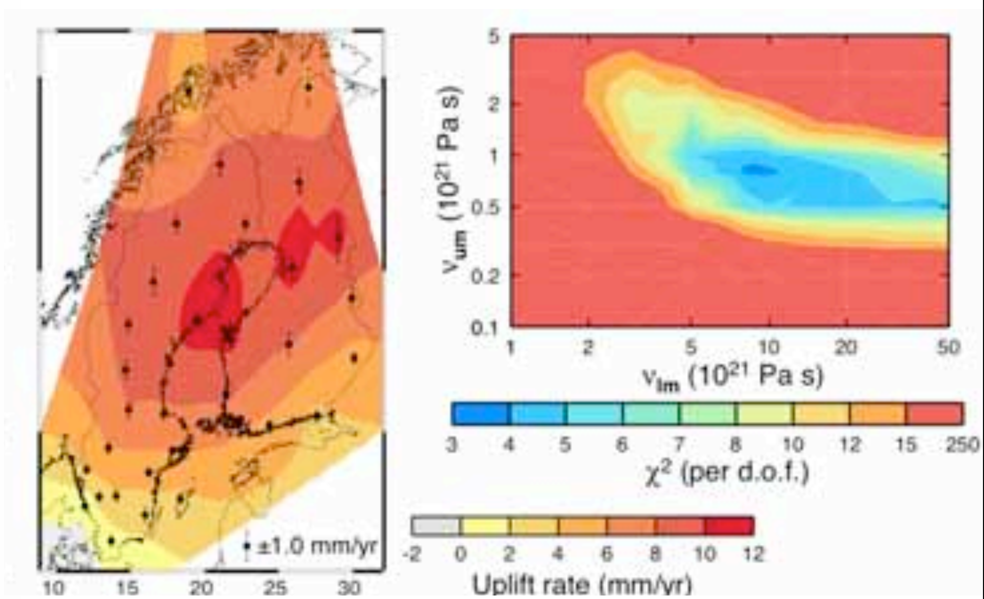




Cratonic Shields: Strong Crust and Mantle

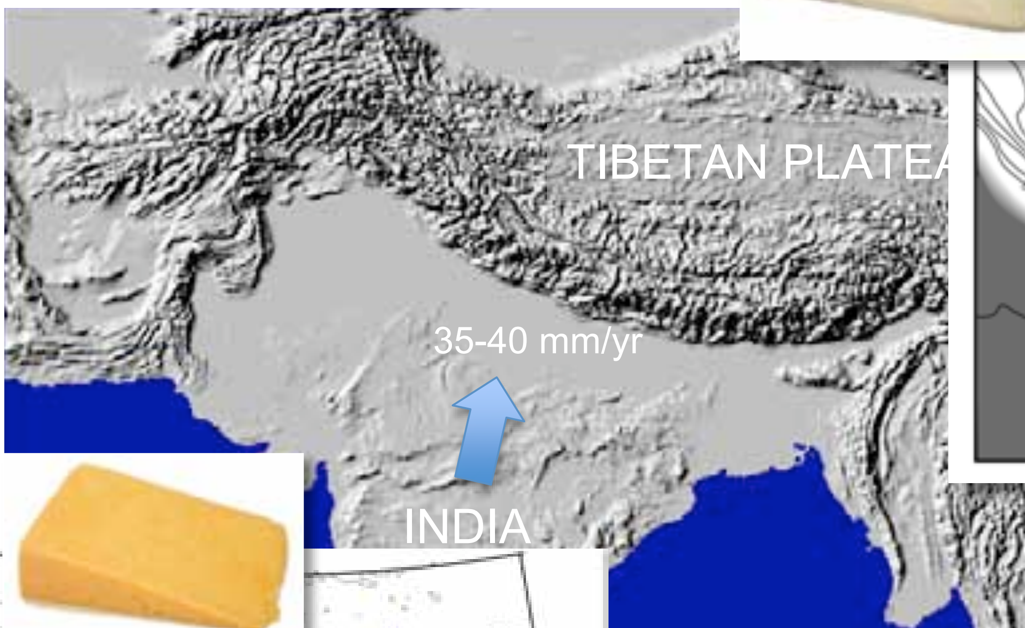


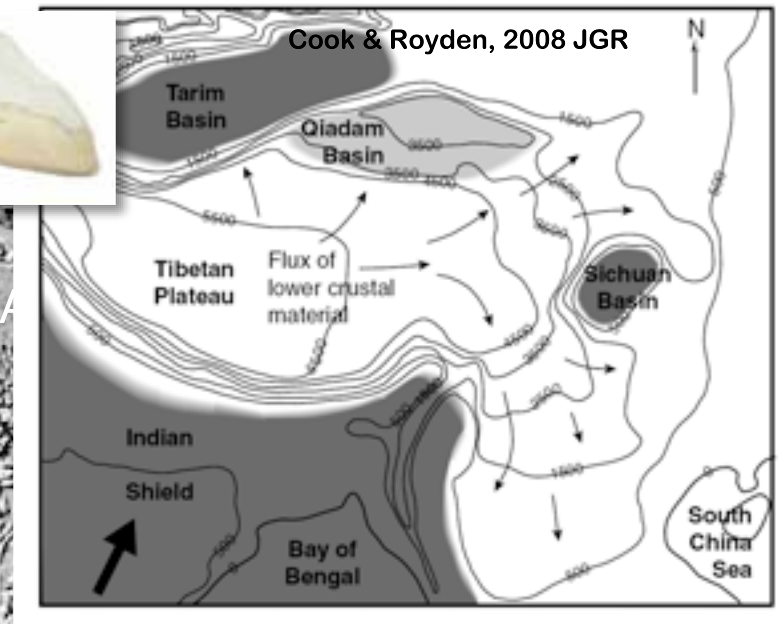
Kohlstedt, 2007 Treatise Geophys.

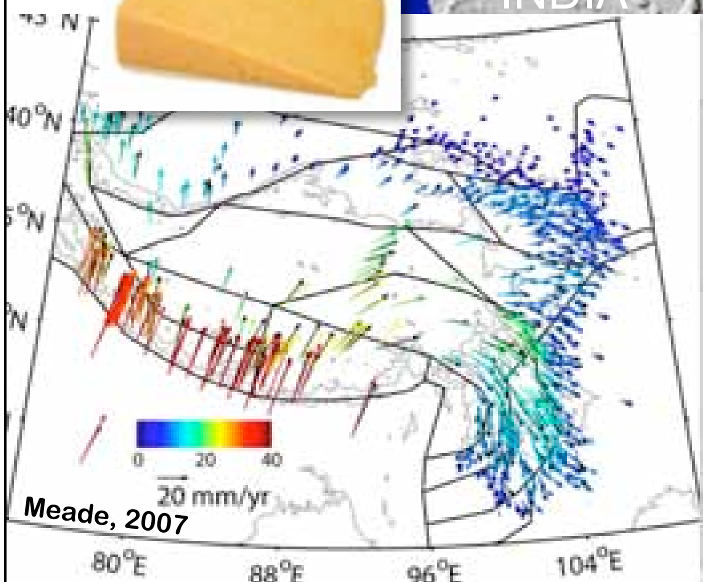


Milne et al., Science 2001

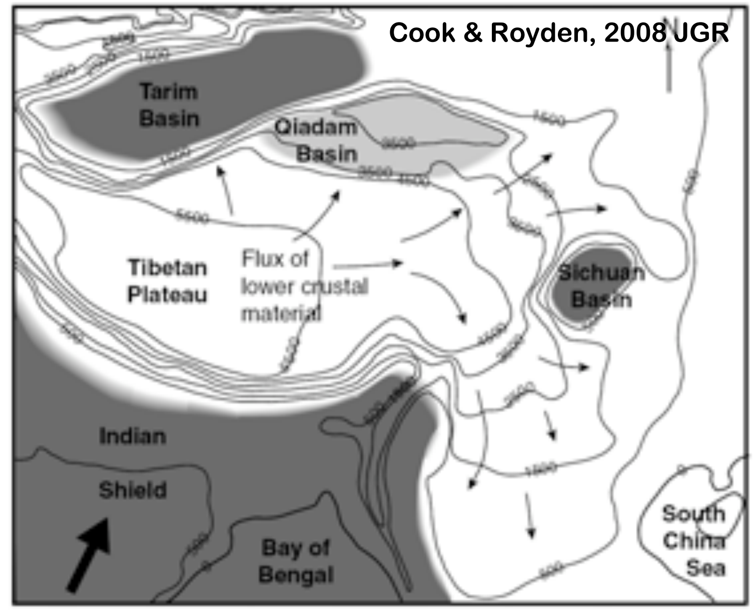
Weak Crust in Tibet: Cheddar or Brie?

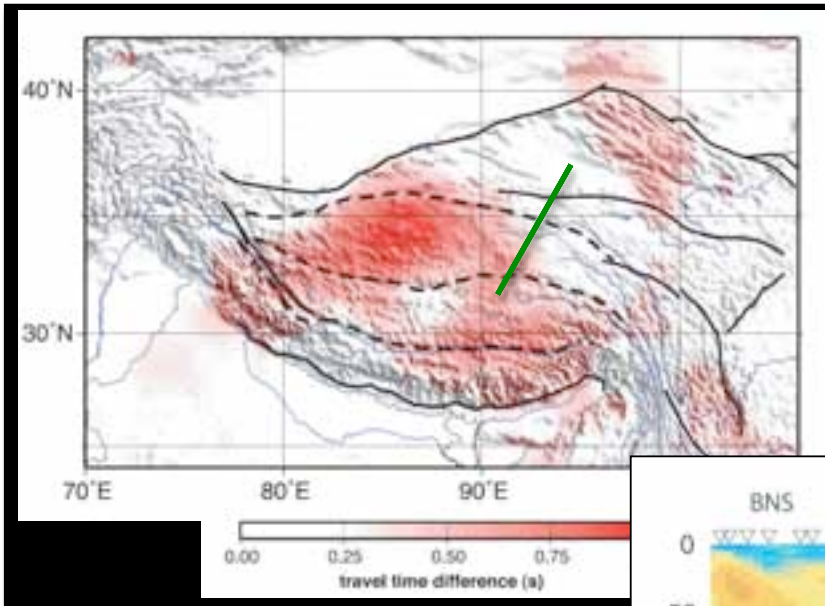




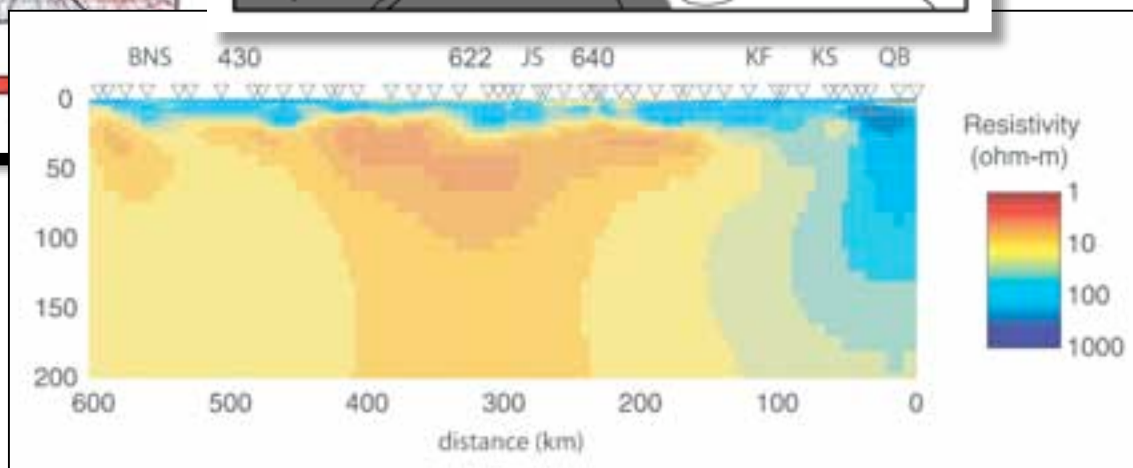


Evidence for Mid/lower Crustal Flow





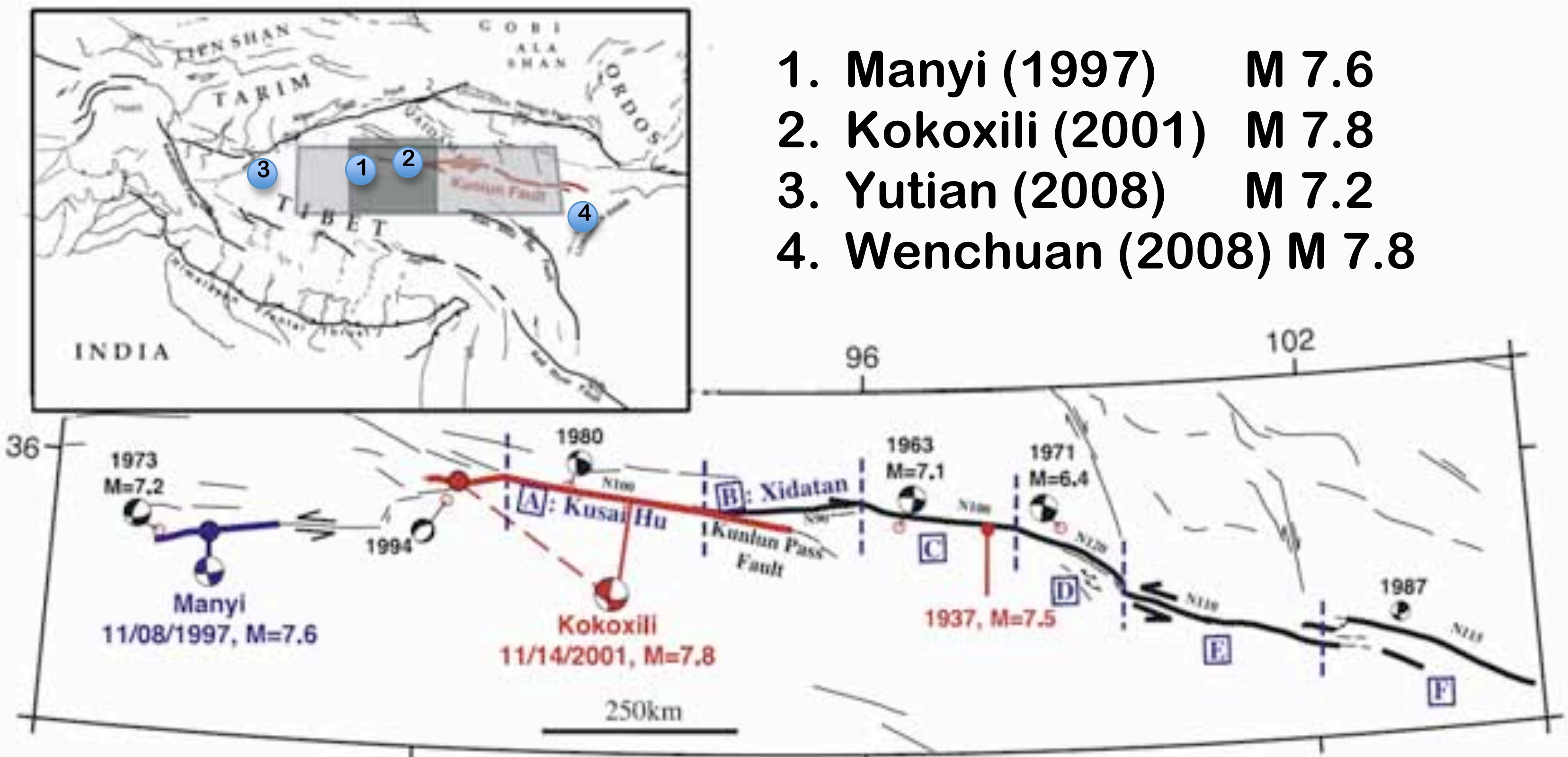
Shapiro et al. 2004: mid/lower crustal flow inferred from seismic anisotropy



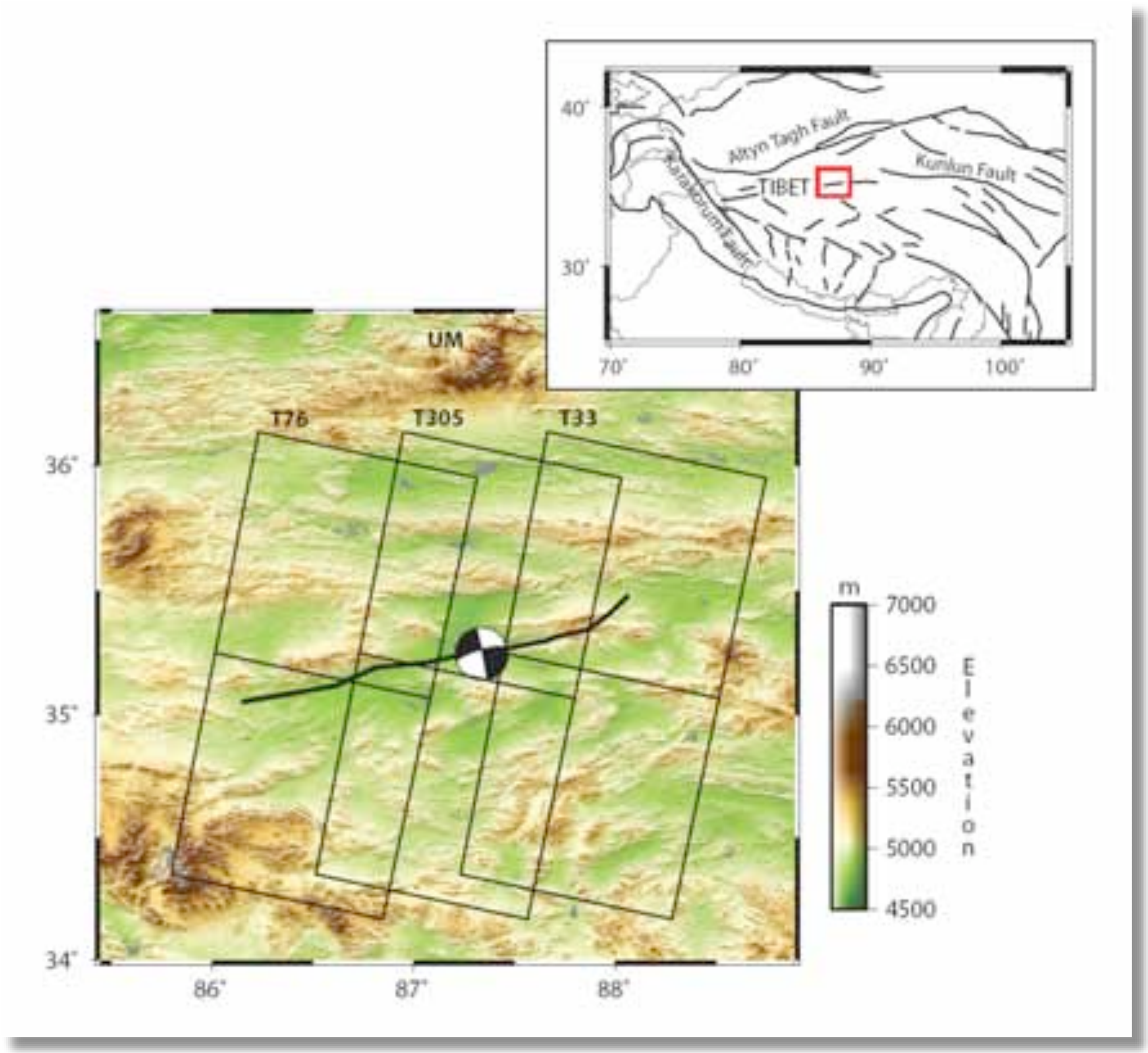
Unsworth et al. 2004: mid/lower crustal flow inferred from high conductivity measured by MT

Four Large Earthquakes in 11 Years

1. Manyi (1997) M 7.6
2. Kokoxili (2001) M 7.8
3. Yutian (2008) M 7.2
4. Wenchuan (2008) M 7.8

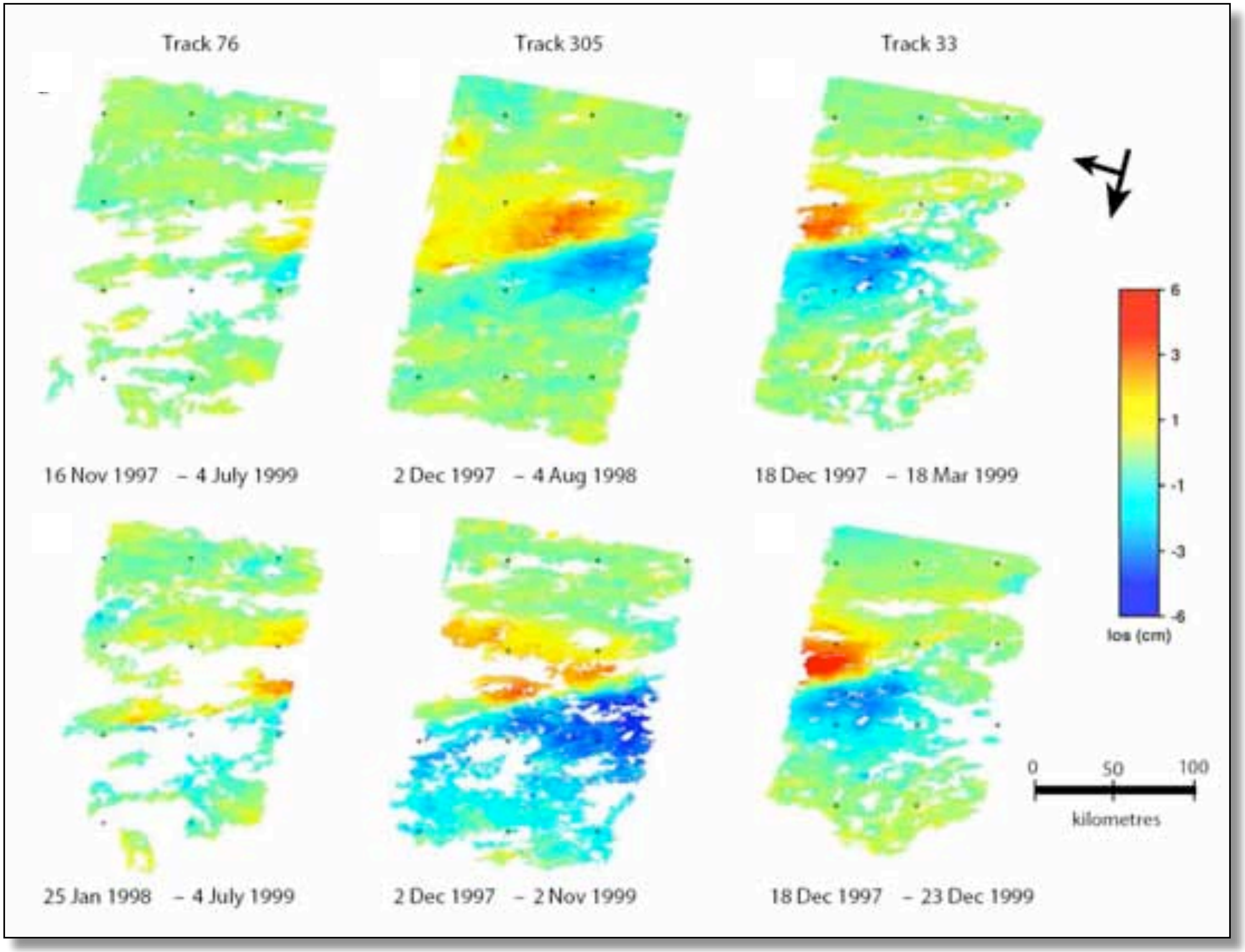


1997 Manyi Earthquake



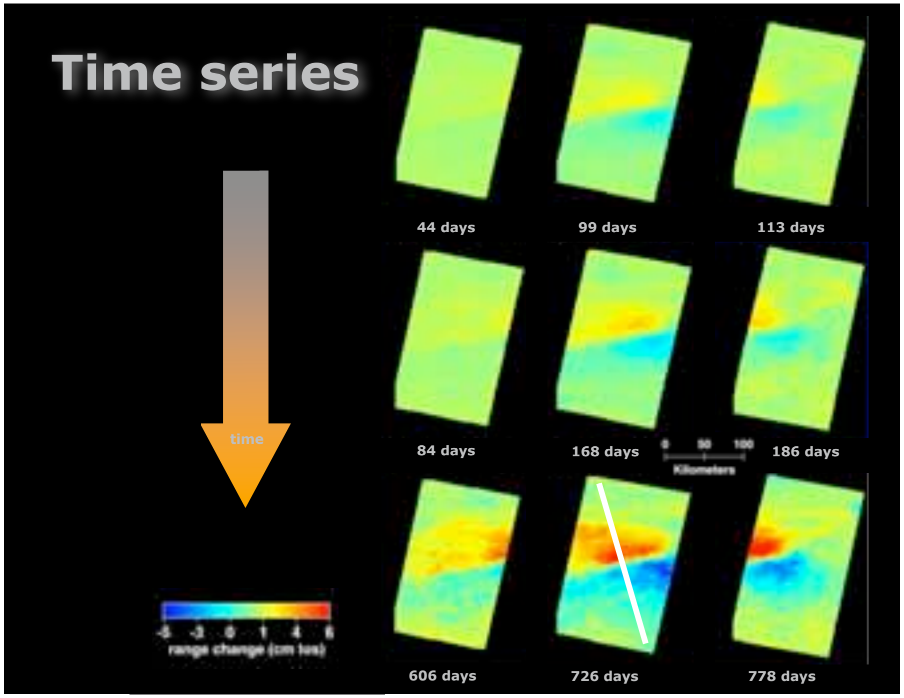
November 8 1997, M 7.6 left-lateral strike-slip on 200 km long rupture with up to 8 meters of slip

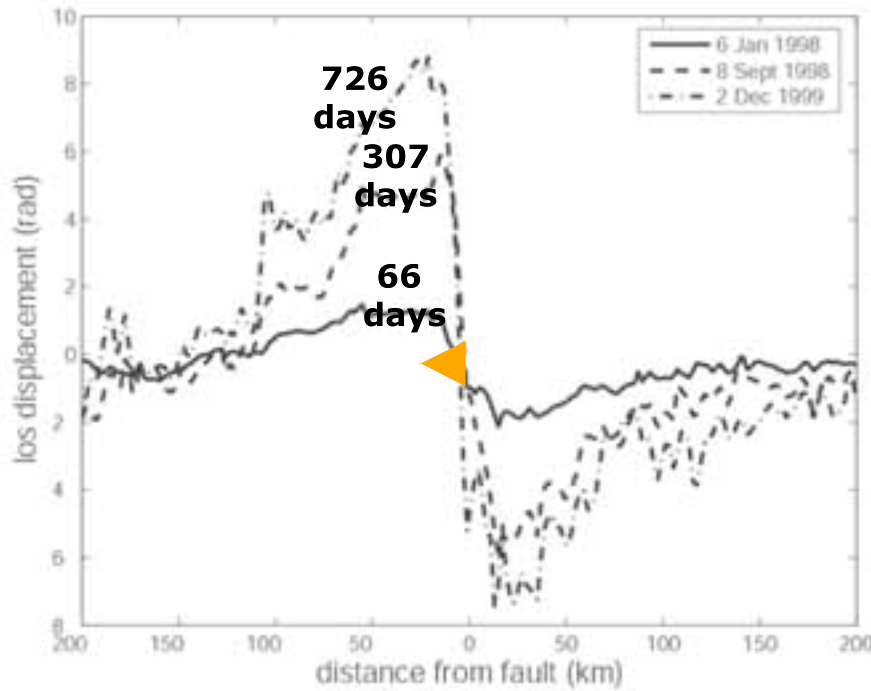
Post-Manyi Interferograms



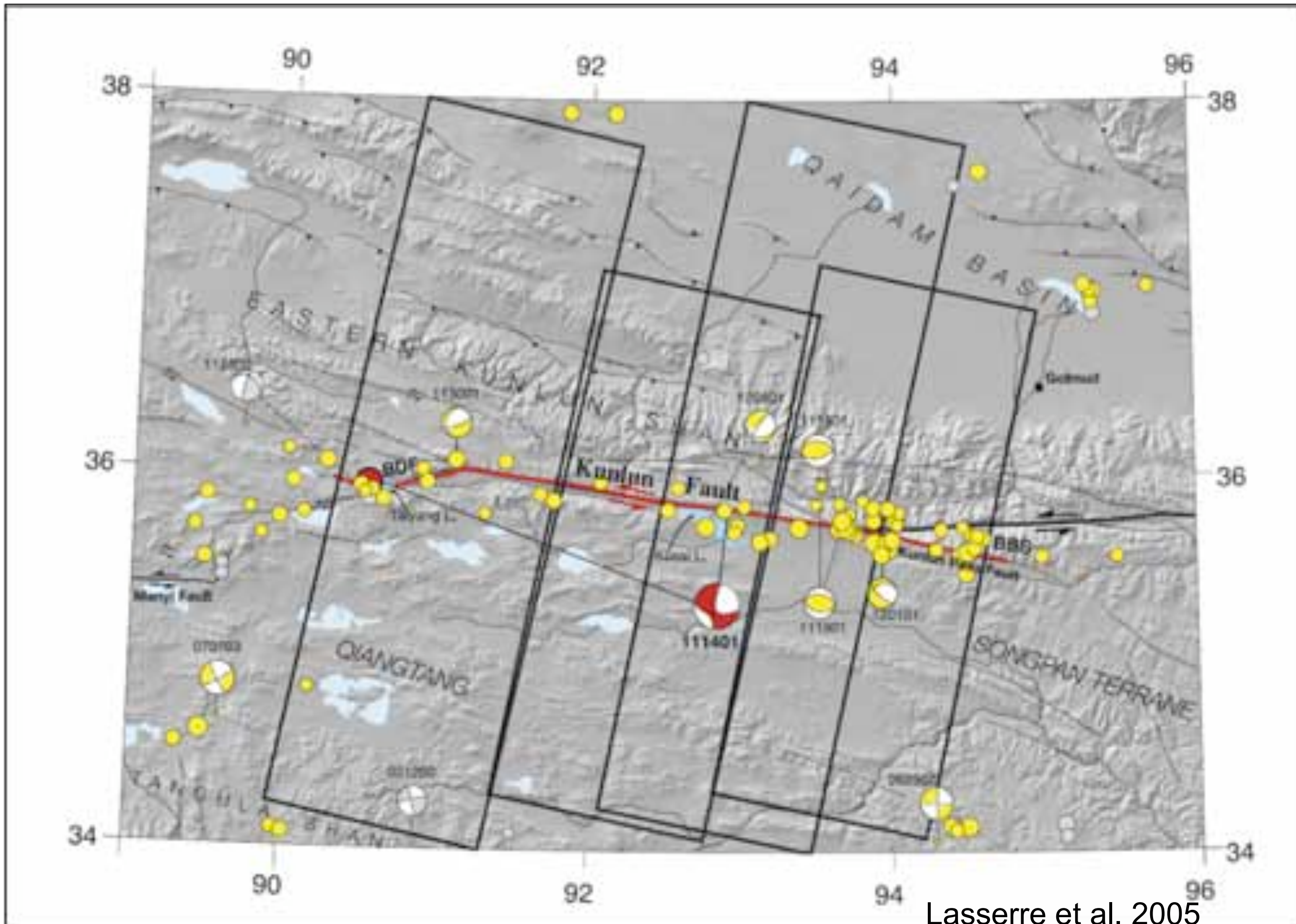
Ryder et al., 2007 GJI

Post-Manyi InSAR Time Series





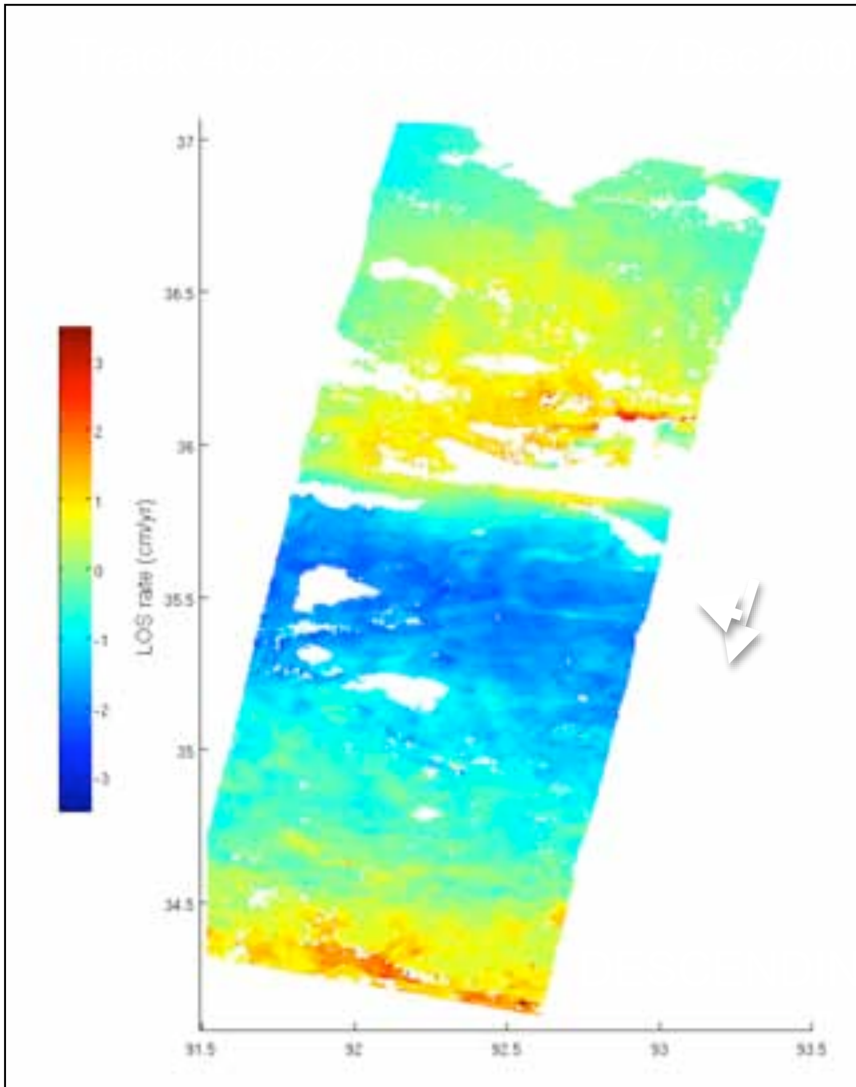
2001 Kokoxili Earthquake

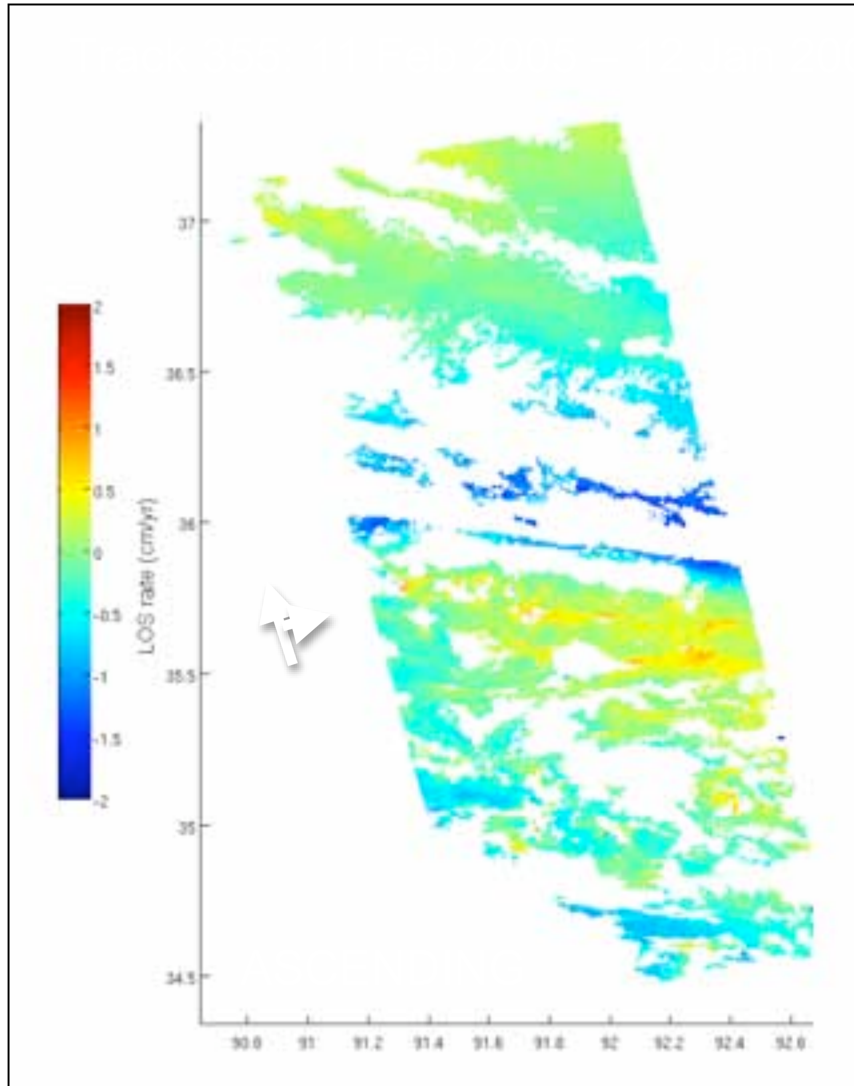


Lasserre et al. 2005

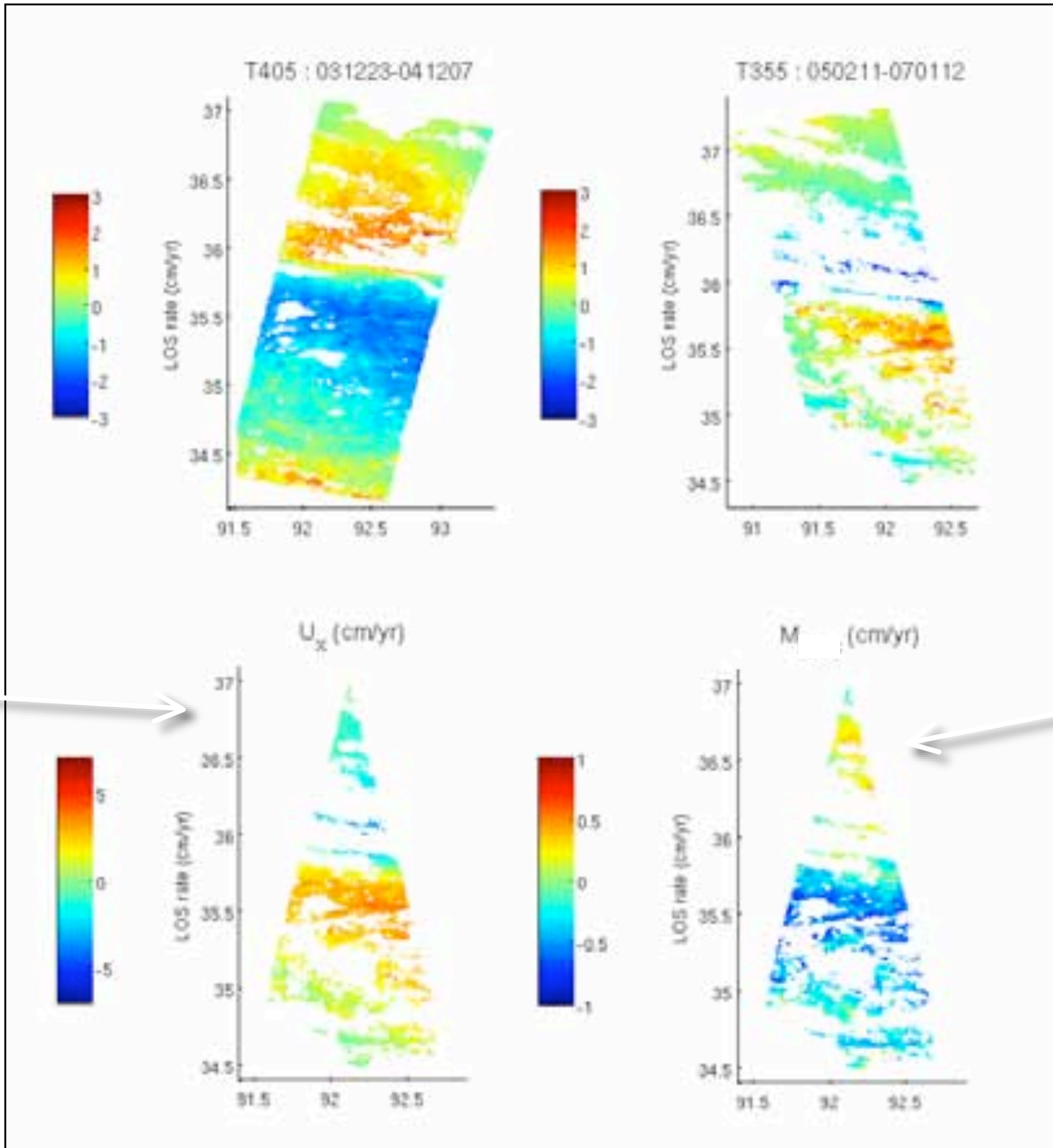
14 November 2001, M 7.8 left-lateral, 400-km-long rupture with up to 8 m of slip

Postseismic Interferograms





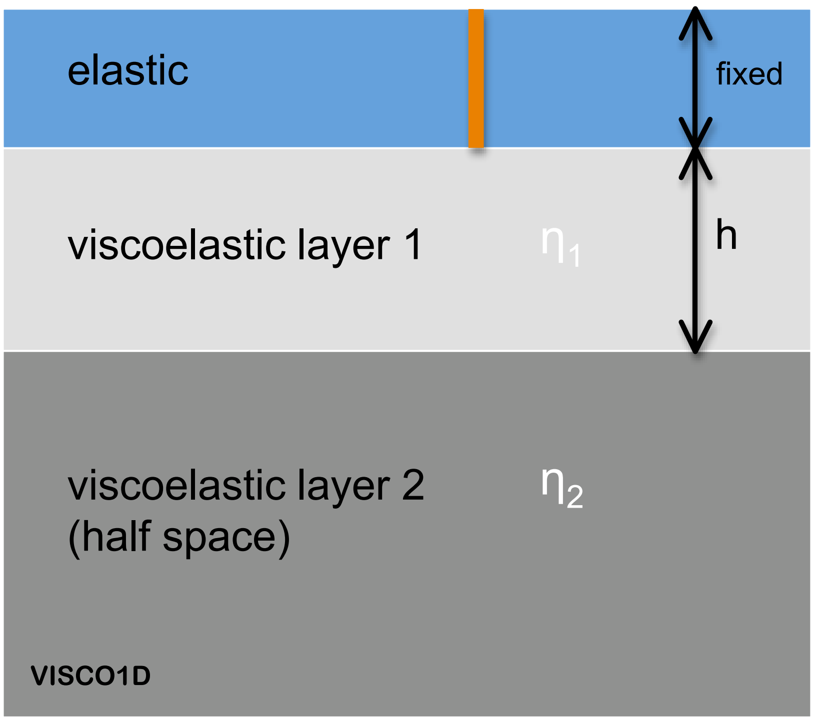
Descending and Ascending Orbit Data

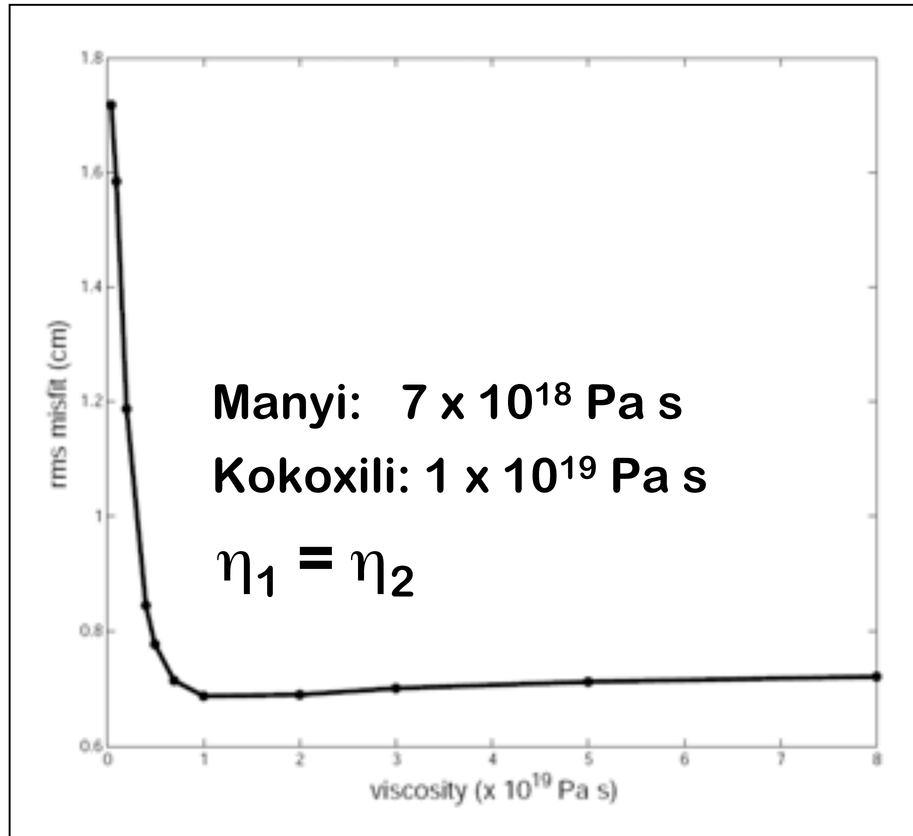


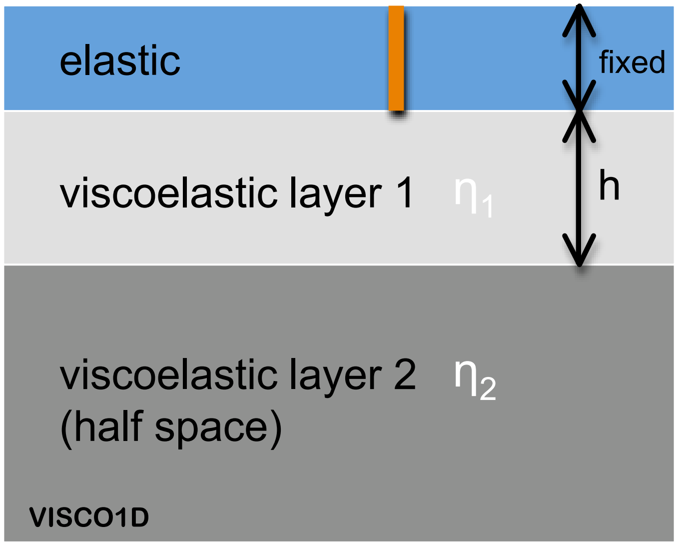
East-west component of horizontal displacement

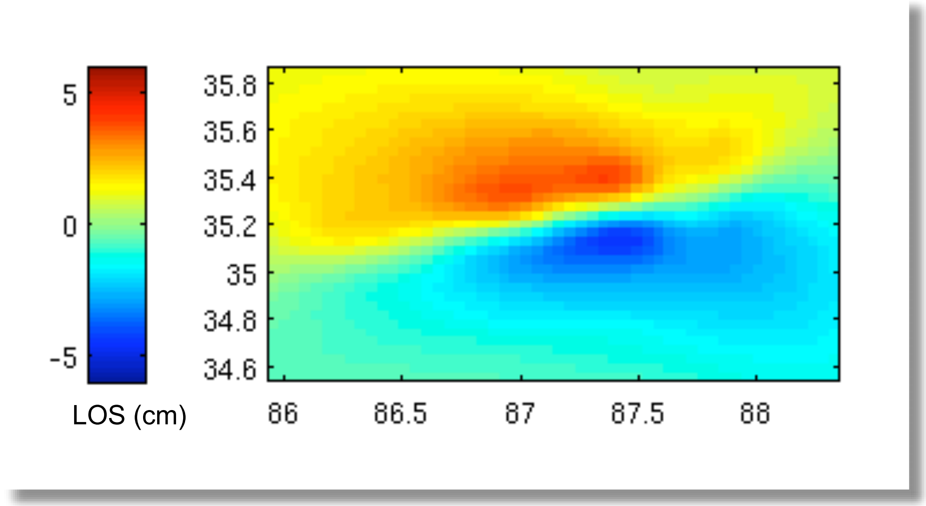
Composite of north-south horizontal and vertical components

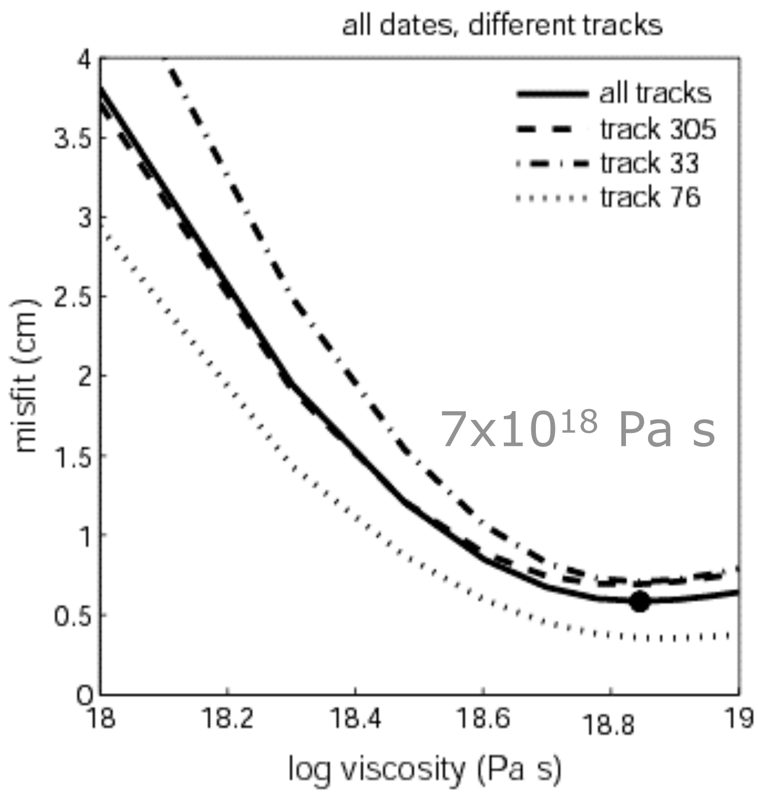
Uniform Viscosity in Mid- and Lower Crust

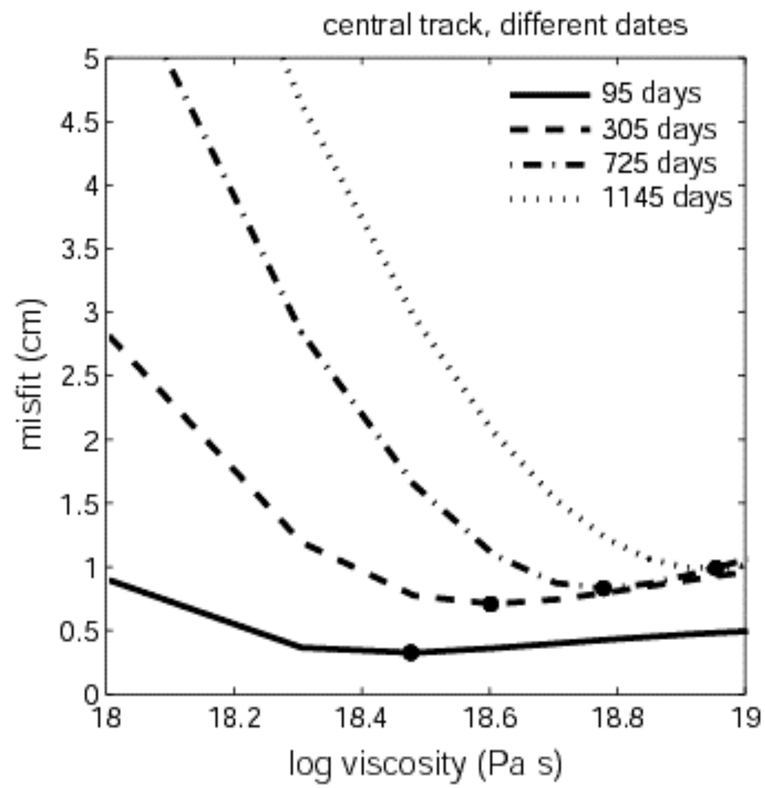






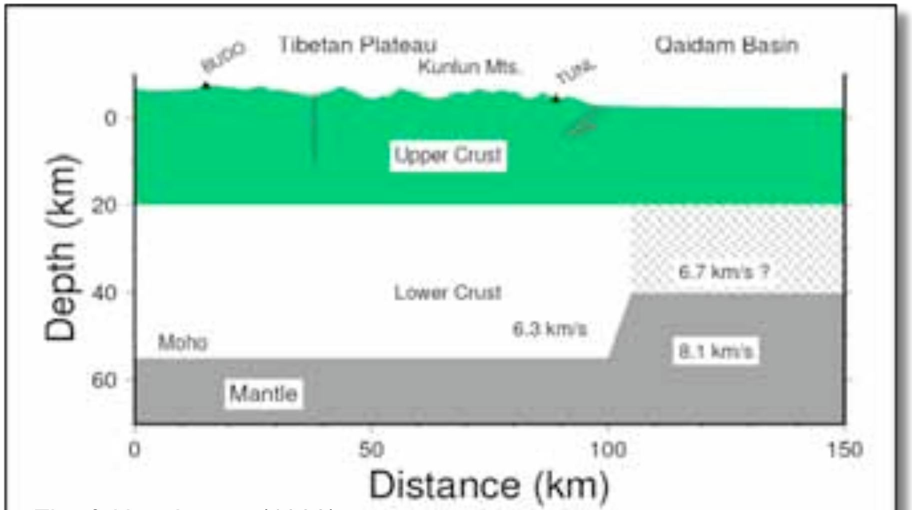




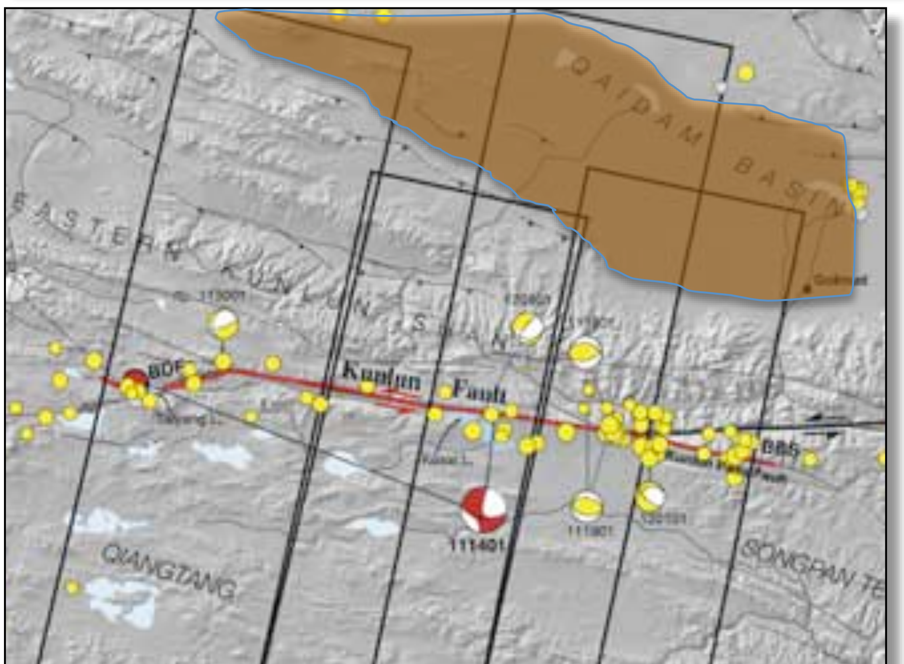


Ryder et al., 2007 GJI

Ongoing Work

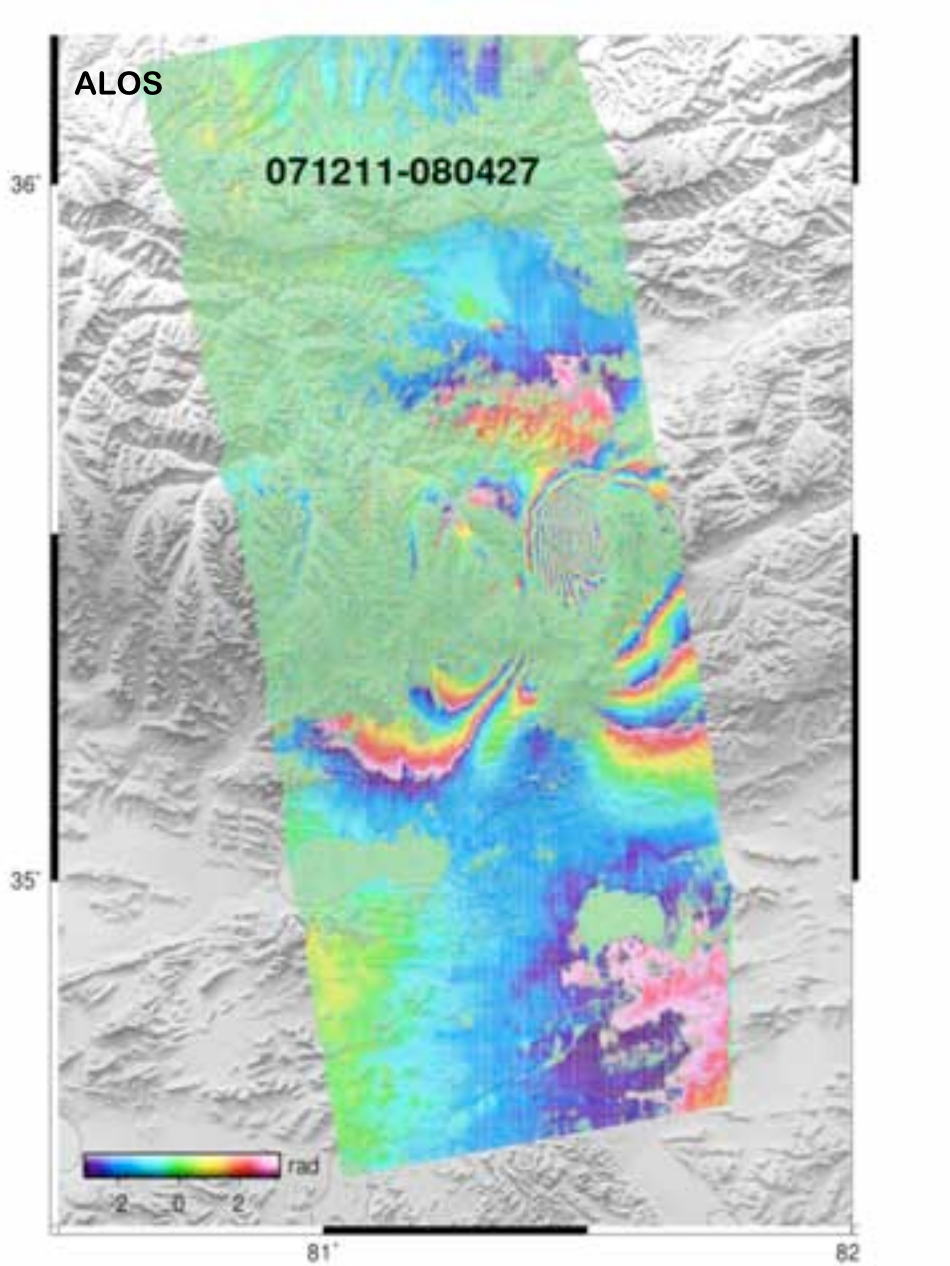


Zhu & Helmberger (1998)

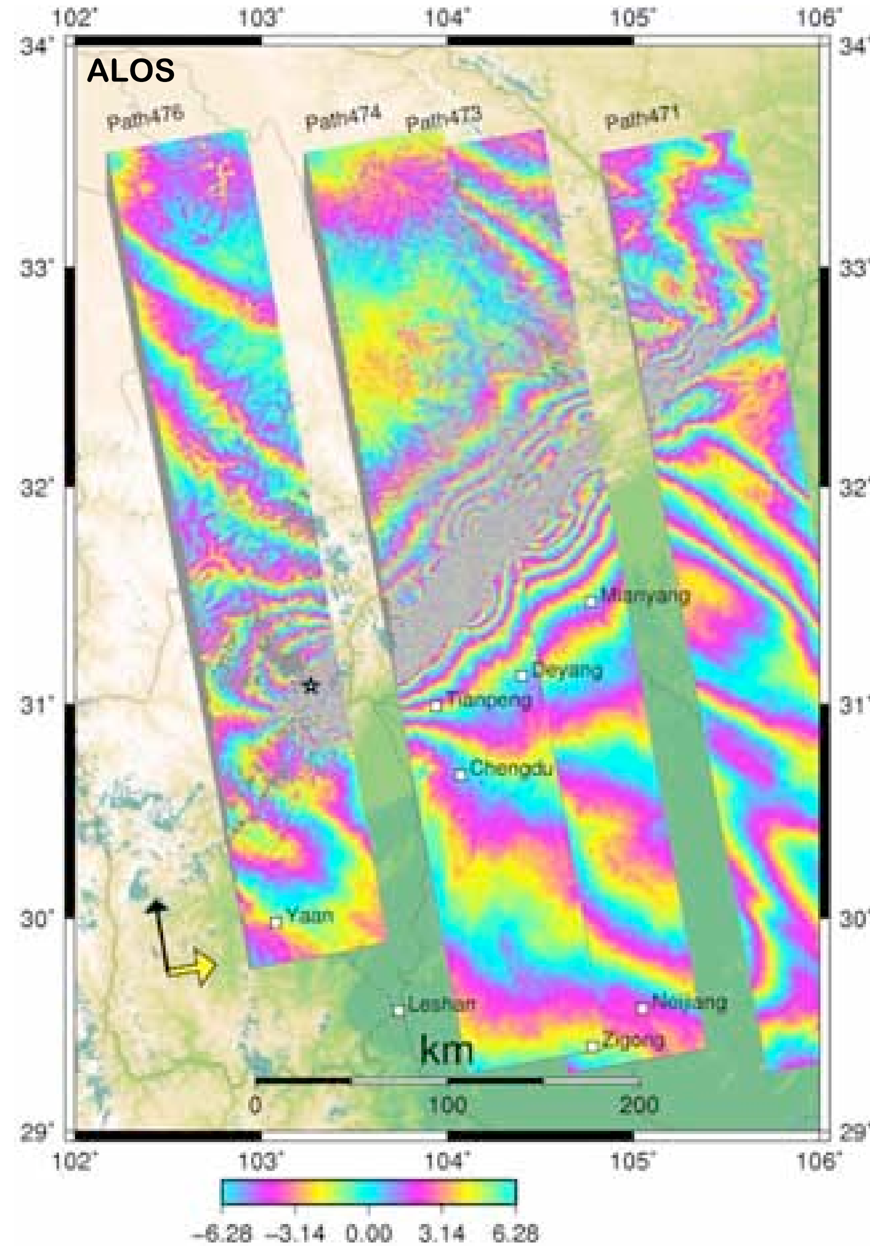


- More interferograms (ascending, ALOS)
- Use GPS time series of early post-Kokoxili deformation
- Dynamic afterslip modeling
- Finite element modeling to assess effect of lateral heterogeneity (e.g. crustal thickness, Qaidam basin)
- Investigate Yutian and Wenchuan postseismic transients

2008 Yutian and Wenchuan Earthquakes



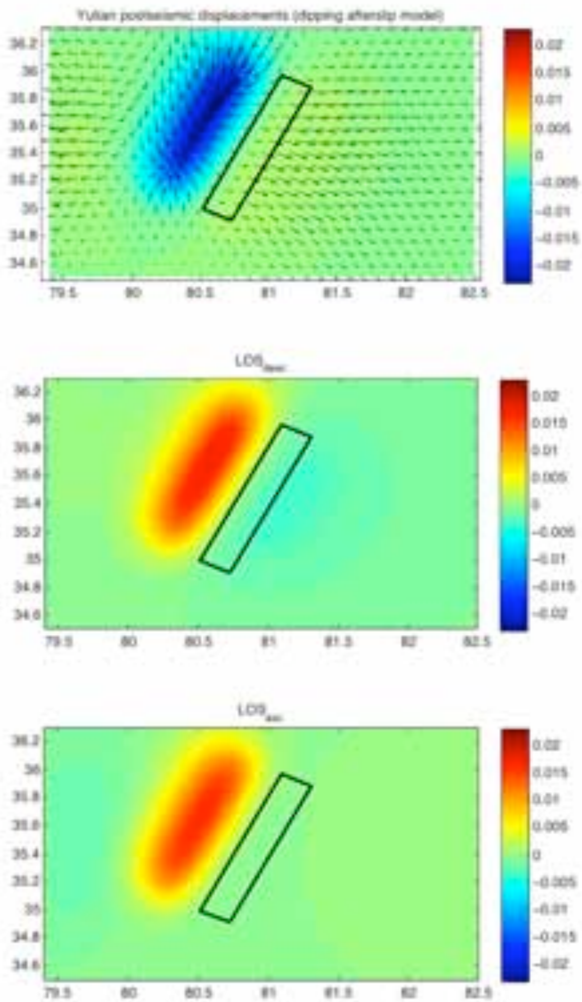
Isabelle Ryder, 2008



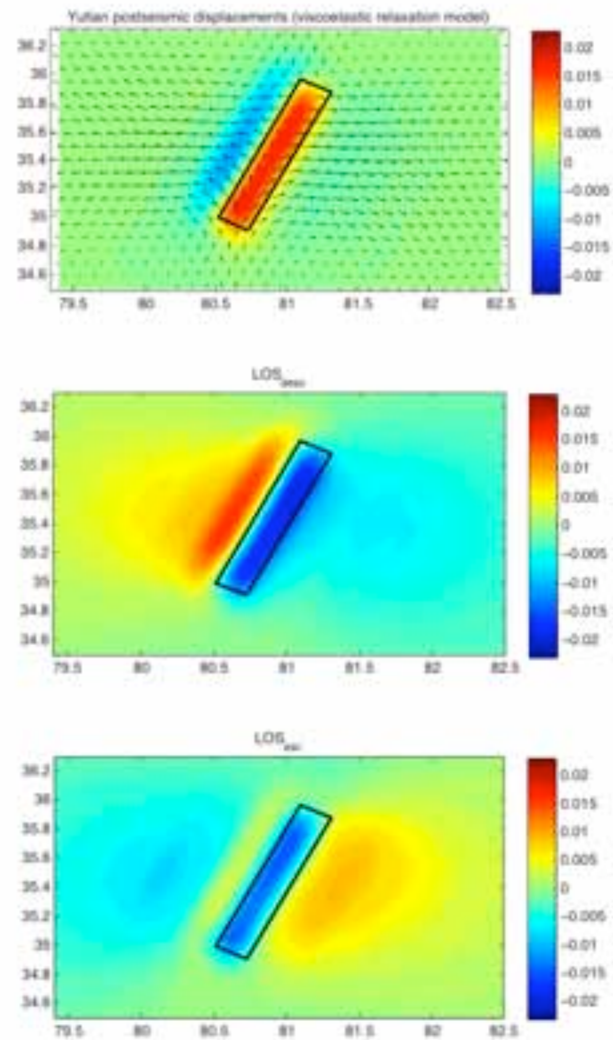
Manabu Hashimoto, 2008

Future work

Afterslip

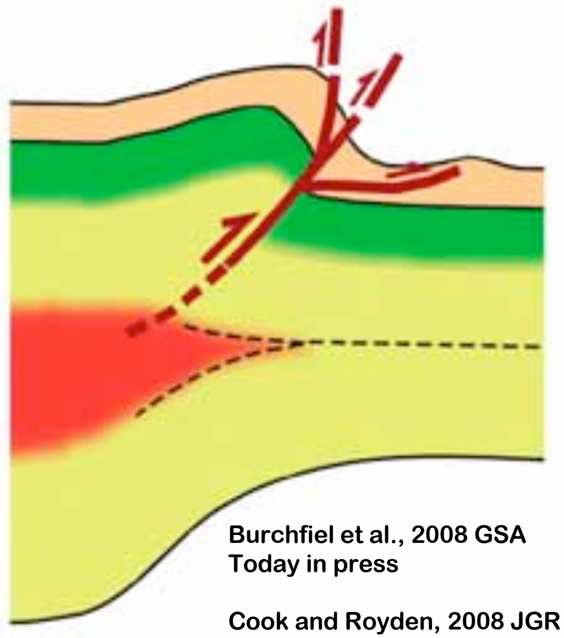


Viscous flow



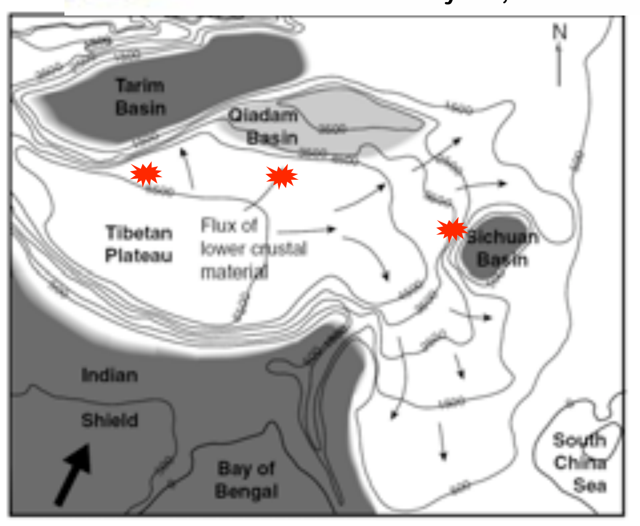
Dip-slip earth-quakes probe the deep rheology (of Tibet) with more unique patterns of deformation

Future work

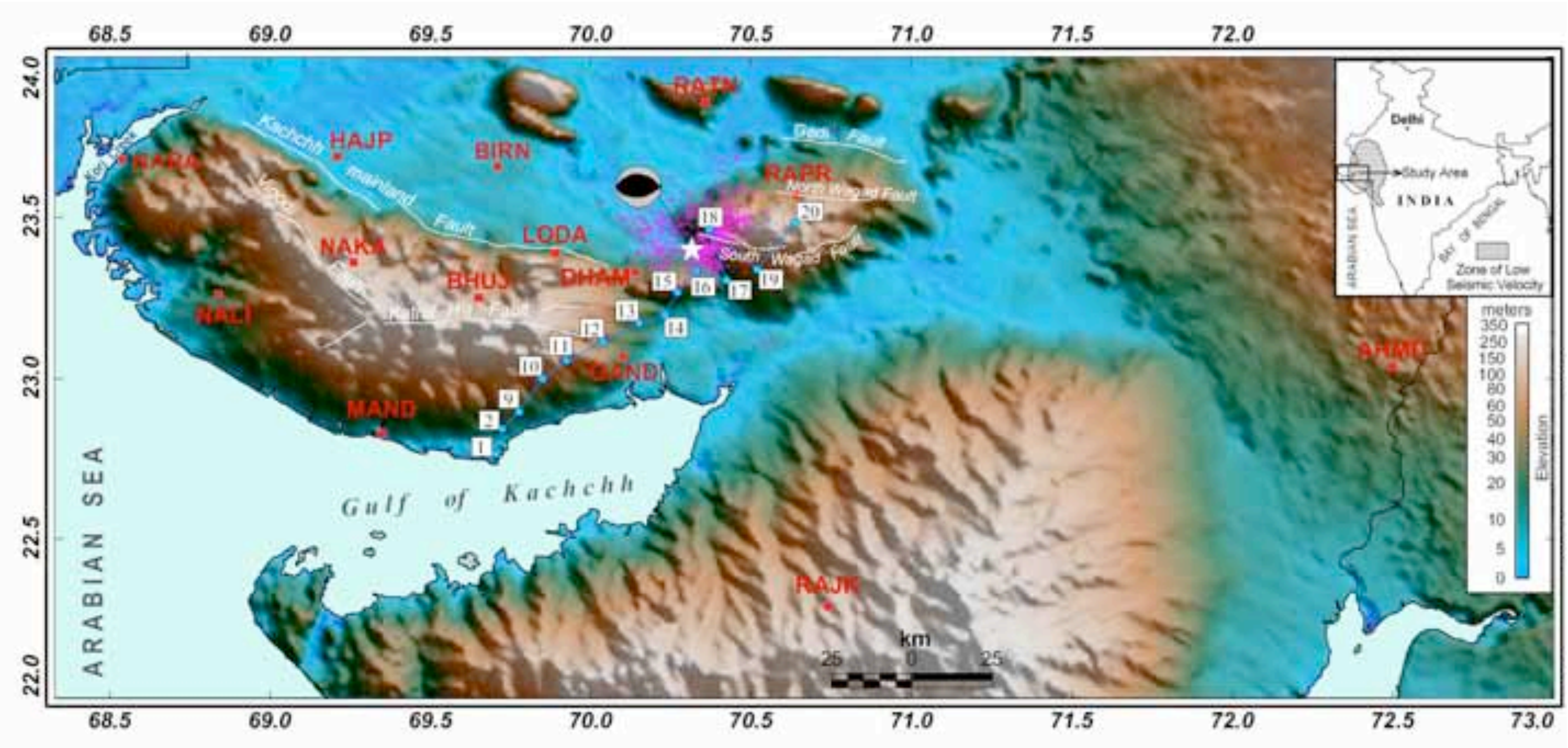


Burchfiel et al., 2008 GSA Today in press

Cook and Royden, 2008 JGR

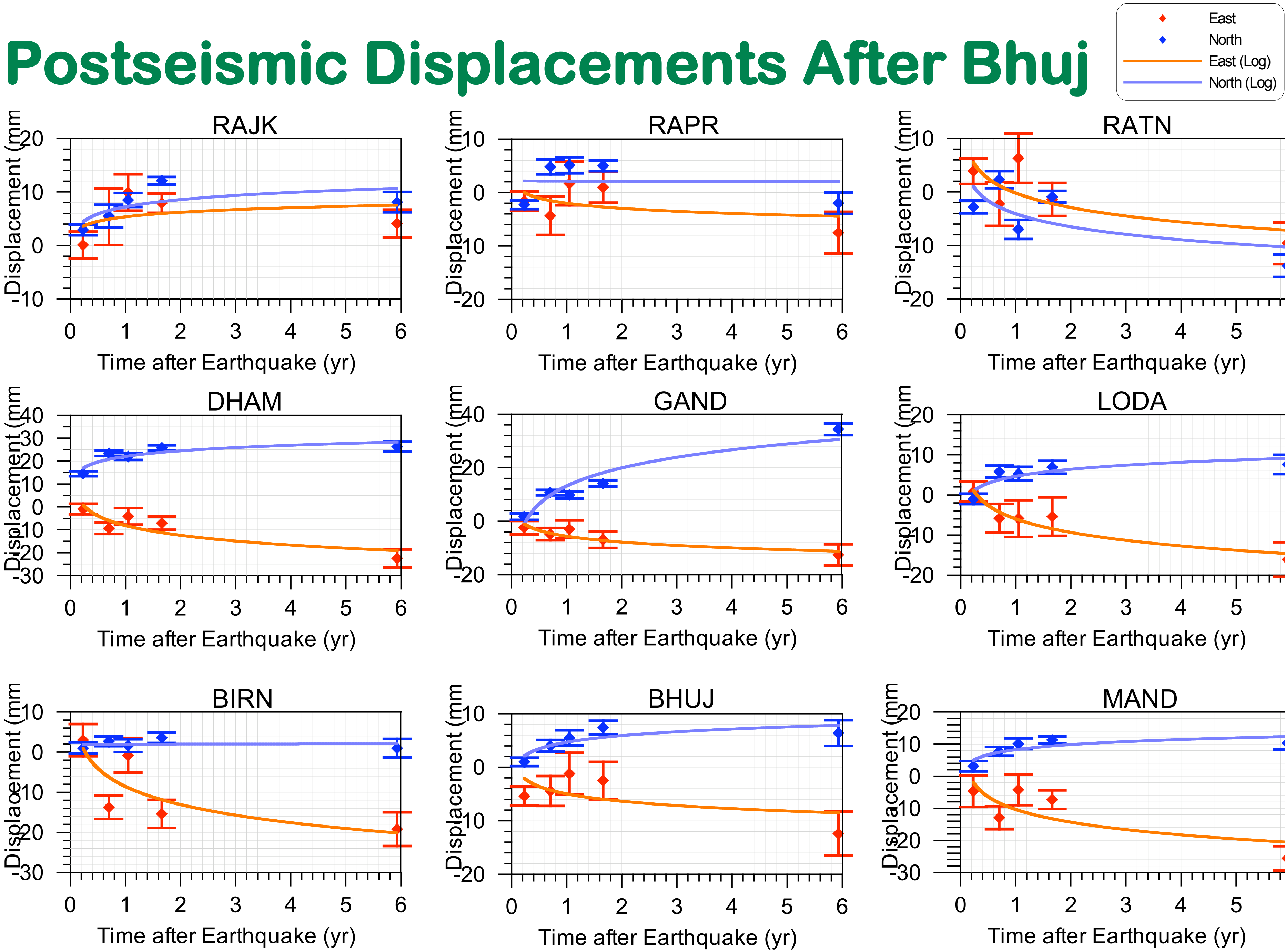


M 7.8 2001 Bhuj Earthquake: First Large Intra-plate Event in Space Geodetic Era



Chandrasekhar et al., 2008 in prep.

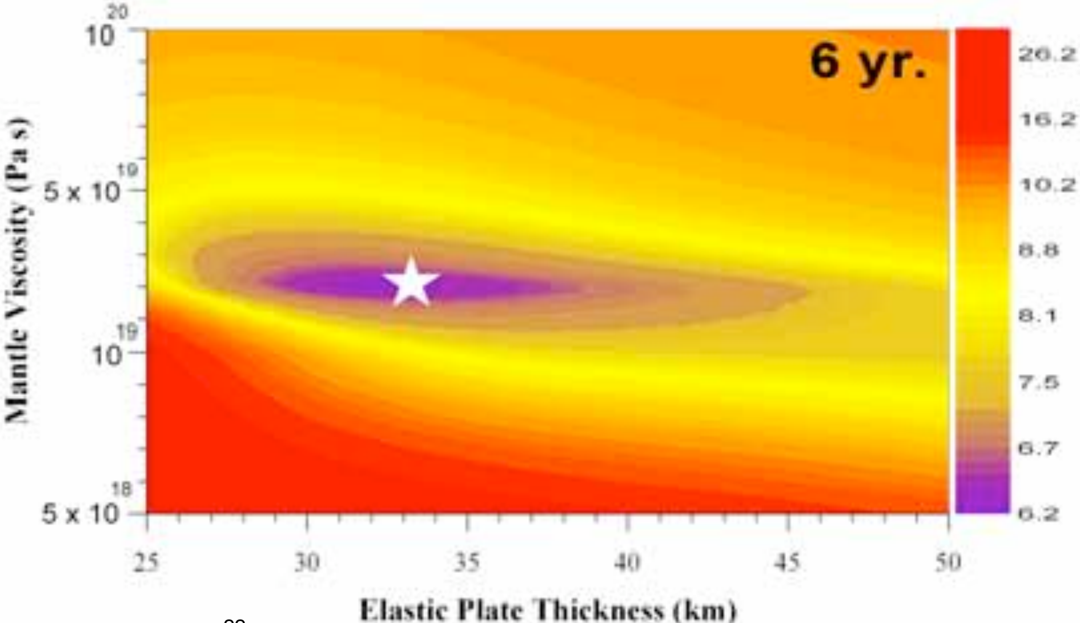
Postseismic Displacements After Bhuj

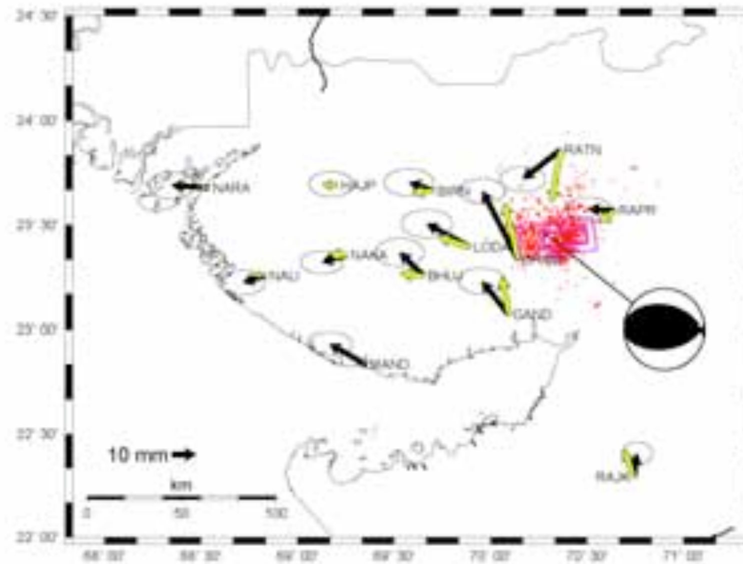


Chandrasekhar et al., 2008 in prep.

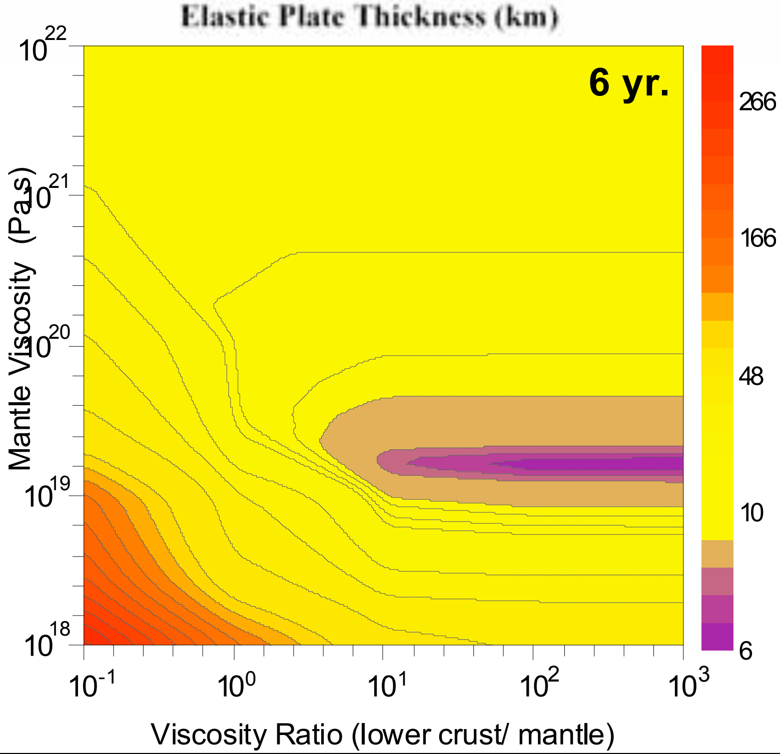
CIG June 24, 2008

Elastic Plate and Viscoelastic Asthenosphere



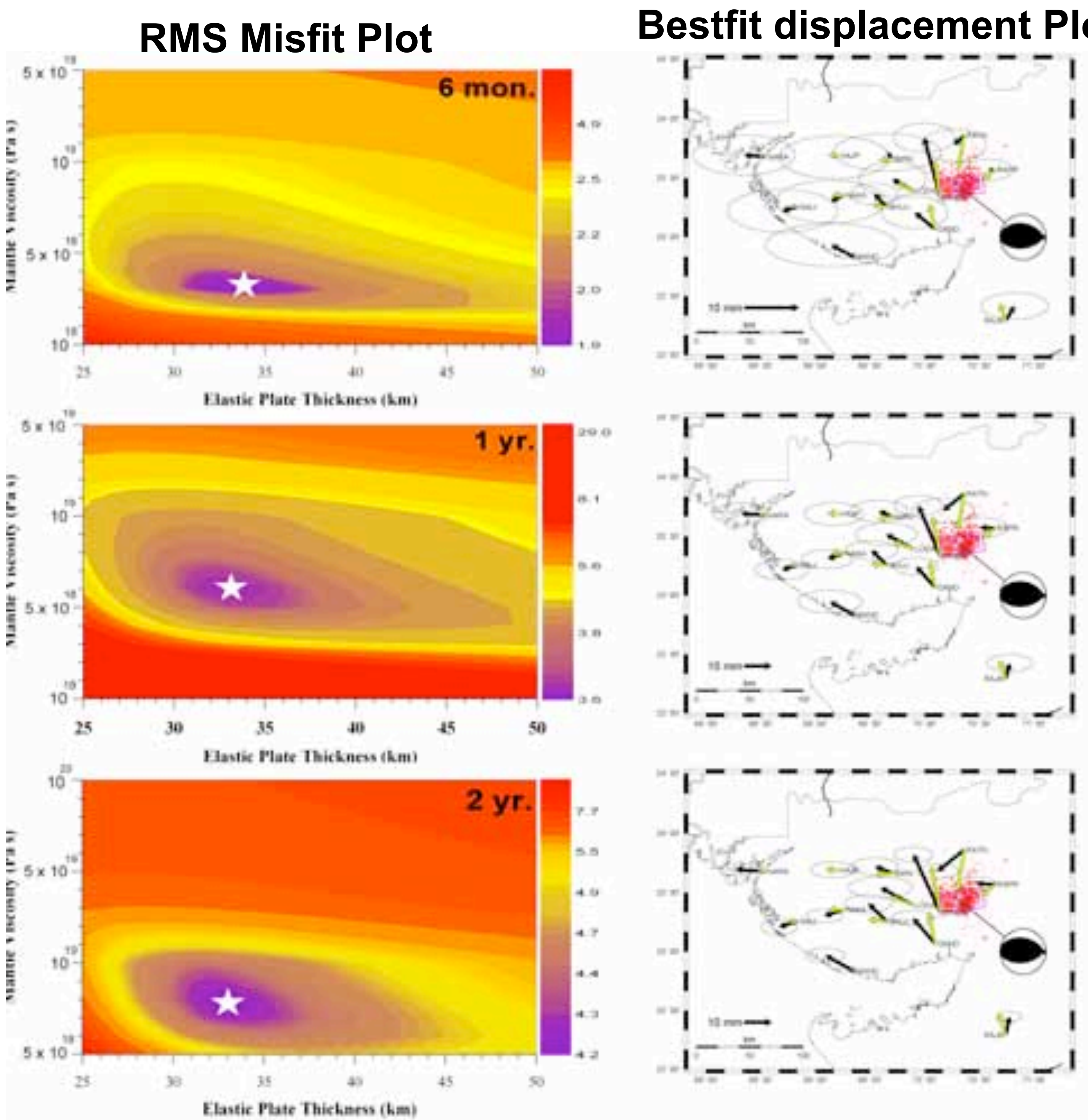


Chandrasekhar et al., 2008 in prep.

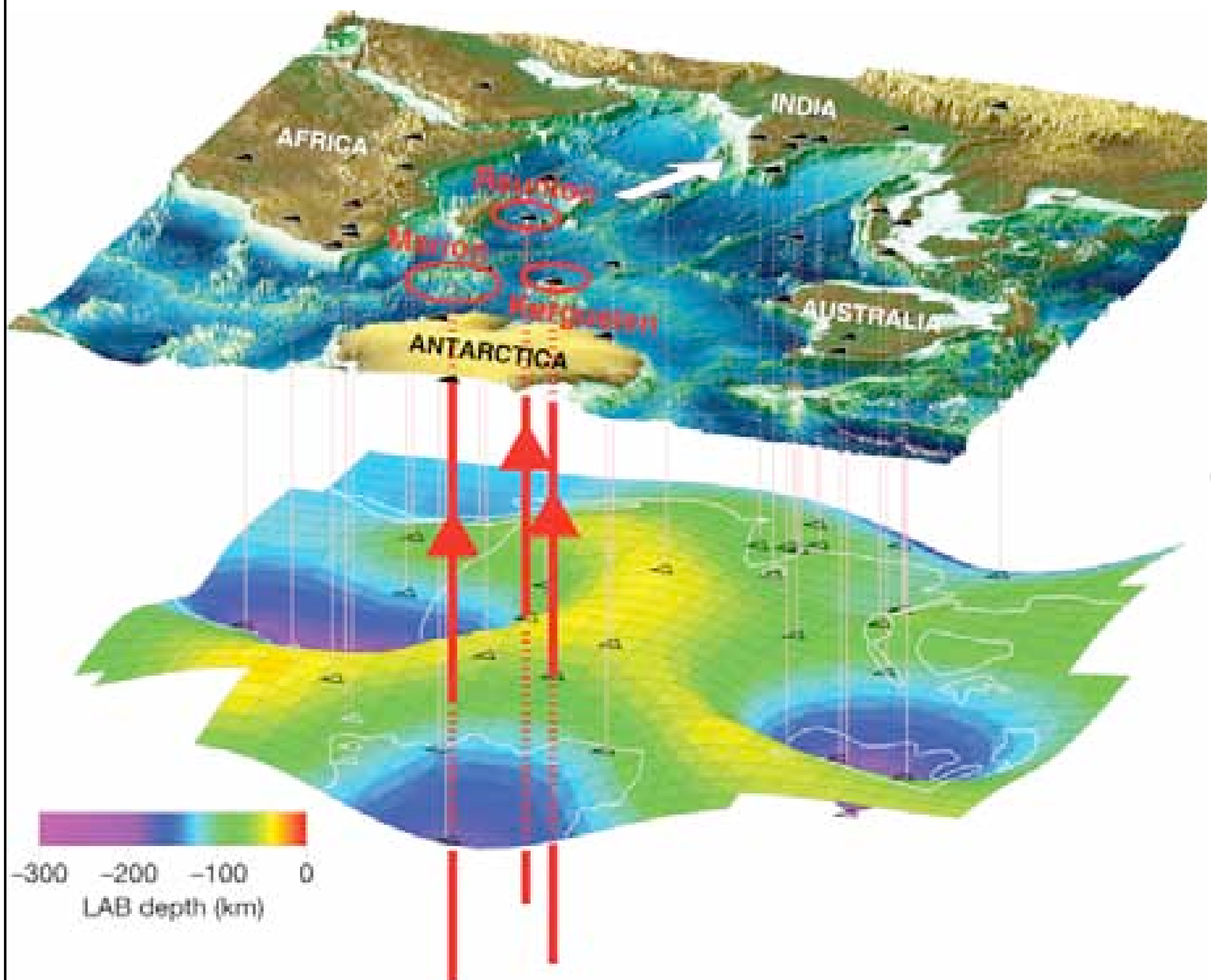


- **Mantle relaxation dominates**
- **Lower crust stronger than mantle**
- **Afterslip and poroelastic rebound not evident**

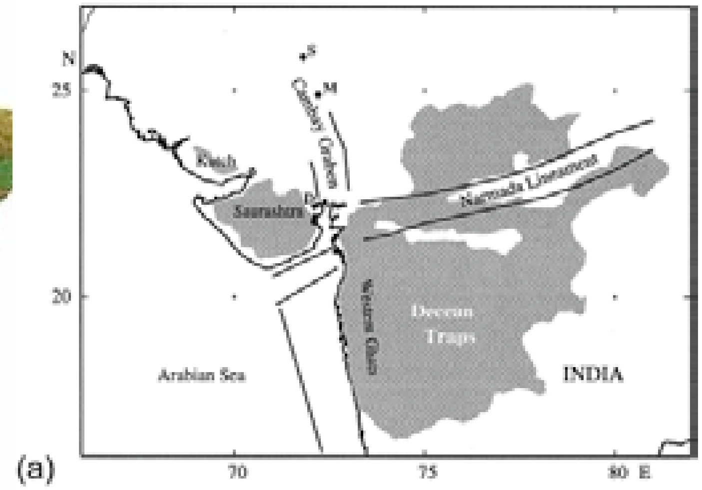
Effective Viscosity Increases With Time

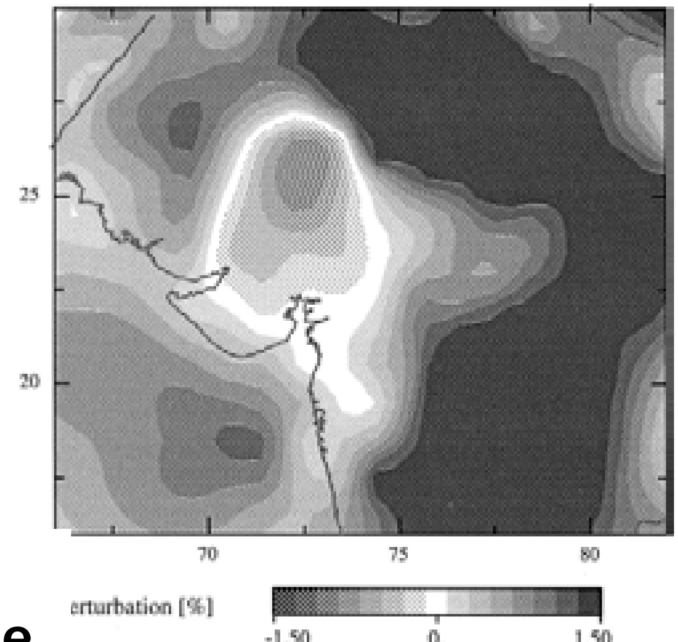


Strong Crust, Surprisingly Weak Mantle



Kumar et al. 2007, Nature



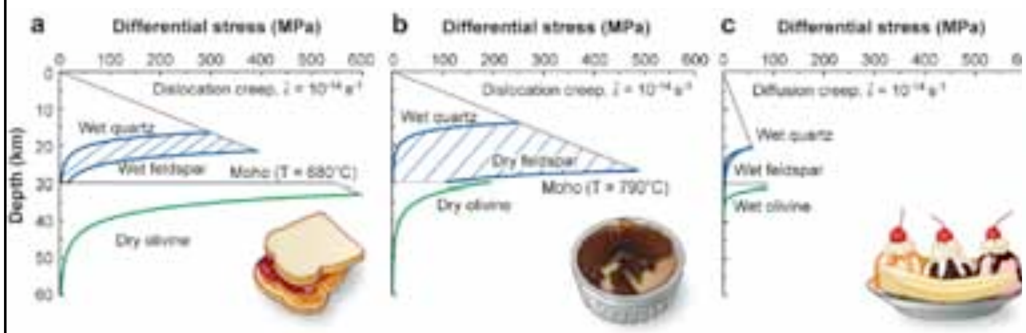


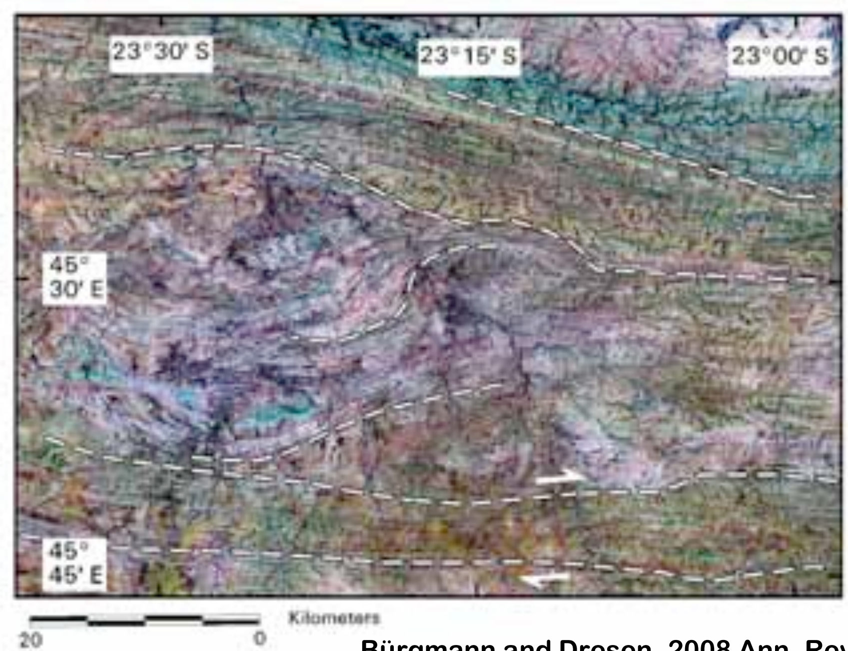
Kennett & Widiyantoro, EPSL 1999

- **Mantle under NW India is weakened by Deccan plume**

Some Answers, More Opportunities

- Lithospheric strength and rheology strongly differ as a function of the makeup, tectonic evolution, and environment of a region.
- In (former) backarc regions, the upper mantle is viscously weaker than the lower crust owing to high temperatures and possibly the addition of water.
- Mature fault zones are weak, and deformation along them is localized to varying degrees throughout the crust. Strain weakening and localization are ubiquitous at all scales.

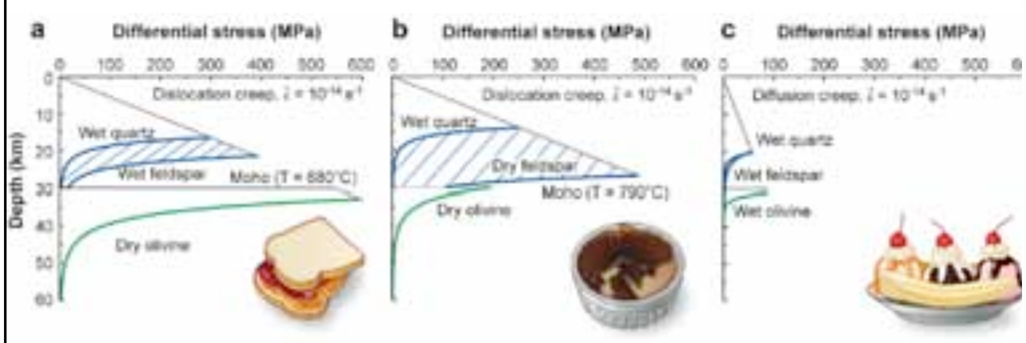


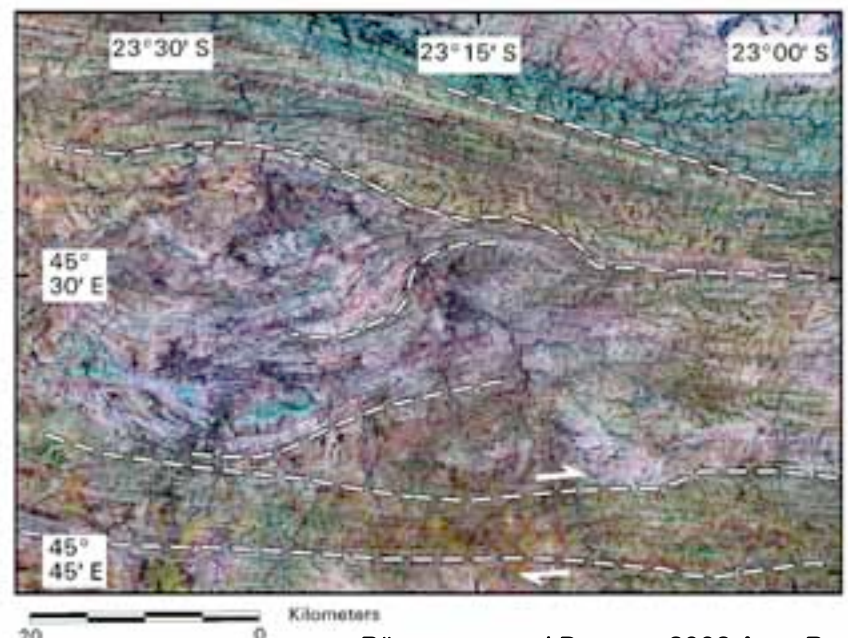


Bürgmann and Dresen, 2008 Ann. Rev.

Some Answers, More Opportunities

- **Future postseismic studies should be focused on resolving mid- to lower-crustal processes, and geophysical imaging tools need to be sharpened to better illuminate the deep architecture of active faults.**
- **Postseismic studies need to consider deformation early and late in the earthquake cycle.**
- **Transients in mechanical response due to abrupt or slow changes in loading or strain need to be explored.**
- **More post-loading studies of all types are needed to better explore the distribution of lithospheric rheology across the continents and plate boundary zones.**





Bürgmann and Dresen, 2008 Ann. Rev.