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Rheological Stratification of the Active Continental Lithosphere: Constraints from Space Geodesy

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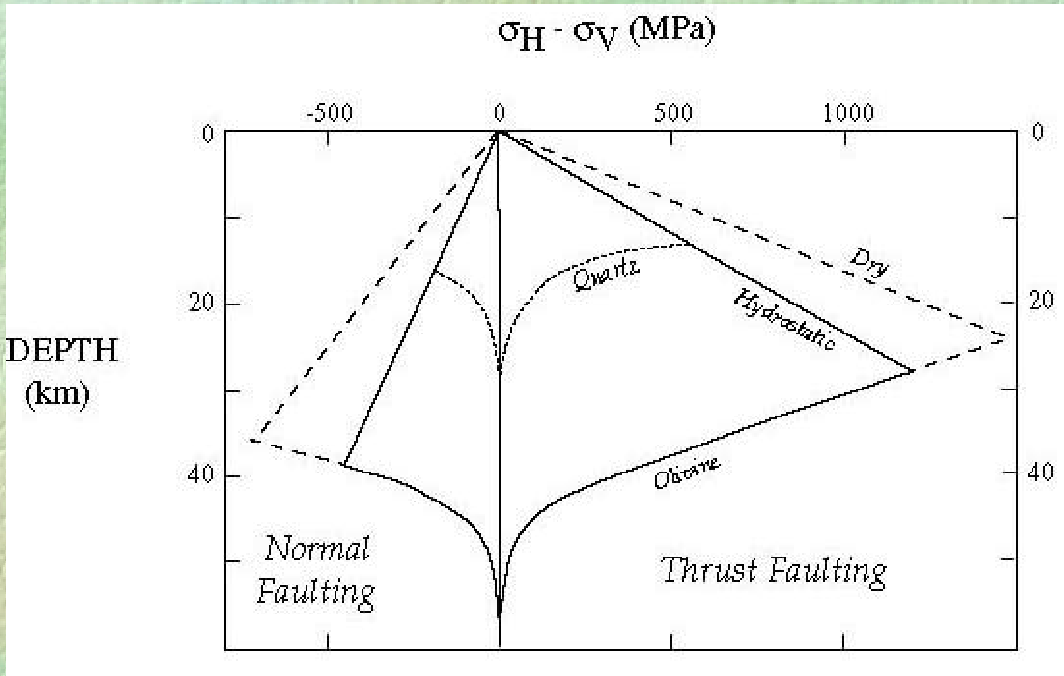
Georg Kaufmann & Falk Amelung, Tony Lowry

OUTLINE

- Review : Rheology of the Continental Lithosphere
  - Conventional view (e. g. Goetz & Evans, 1979; Brace & Kohlstedt, 1980)
  - Suggested refinements
- Post-Seismic Transient Deformation
  - <u>Western USA</u>--1959 M=7.3 Hegben Lake eq (Nishimura & Thatcher, 2002)
  - <u>Western USA</u>--1999 M=7.1 Hector Mine earthquake (Discussed by Dr. Pollitz)
  - <u>Intraplate Japan</u>--1896 M=7.5 Riku-u earthquake (Thatcher et al., 1980)
- Transient Deformation due to Surface Loading/Unloading
  - Isostatic rebound of Lake Bonneville, Utah (e.g. Bills et al., 1994)
  - Reservoir loading of Lake Mead, Nevada (Kaufmann & Amelung, 2000)
- Comparisons with Effective Elastic Thickness from Gravity/Topo (Lowry et al., 2000)
- Summary
  - Implications, questions, future work

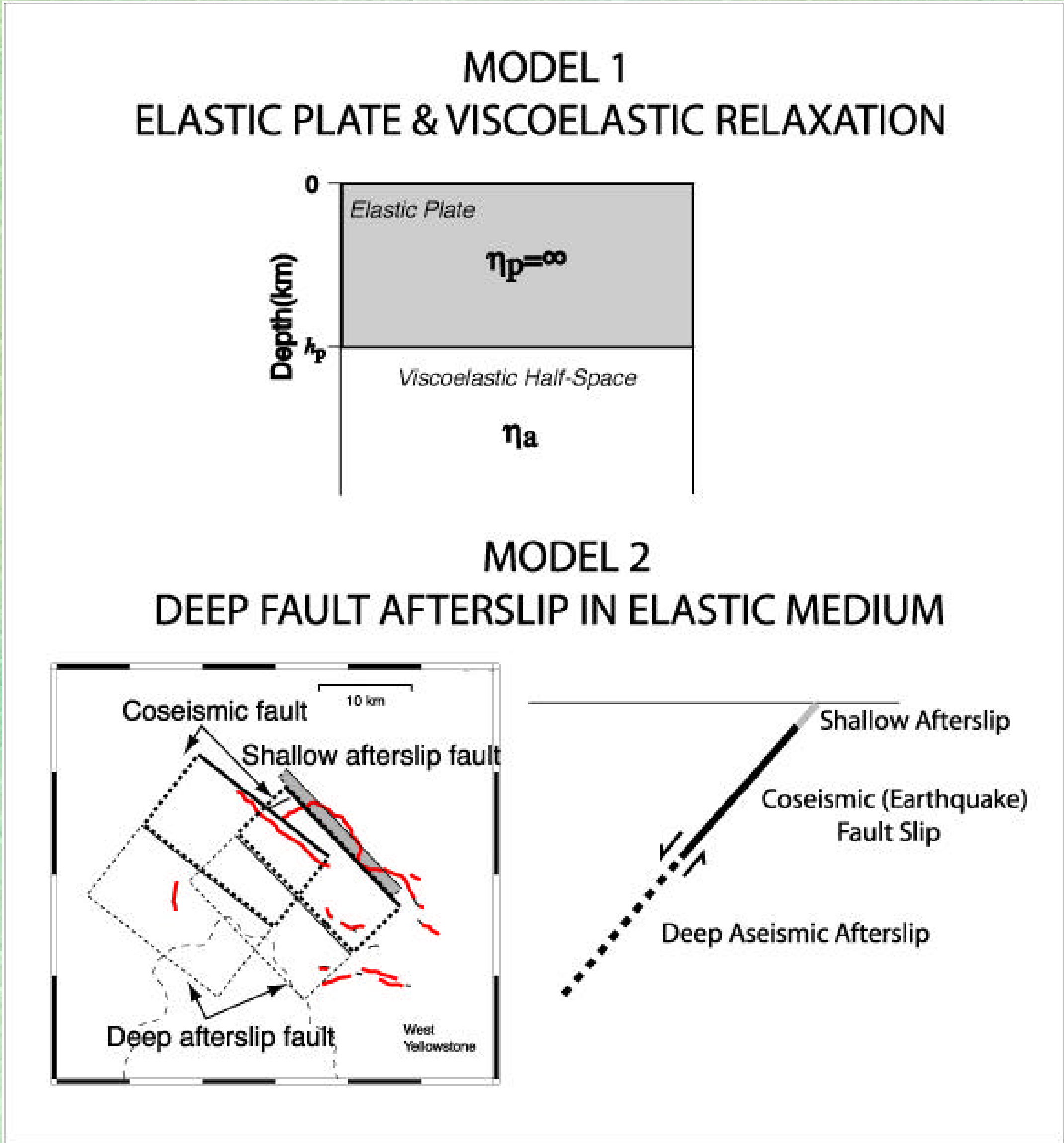
Review:
Rheology of Active Continental Lithosphere



After Brace & Kohlstedt (1980)

- Brittle-elastic upper crust, where earthquake faulting occurs
- Weak, ductile lower crust (for quartz, feldspar composition!)
- Stronger upper mantle lithosphere (~olivine composition)
- SUGGESTED REVISIONS REPORTED HERE
  - Lower crust is strong and ~elastic for time scales up to ~10 ka
  - Upper mantle lithosphere is ductile and weaker than the crust

Alternative Mechanisms of Post Earthquake Deformation



VISCOELASTIC RELAXATION

- Elastic plate coupled to ductile underlying layer
- Earthquake or loading/unloading stresses relax by ductile flow
- Elastic plate thickness determines scale of surface deformation
- Effective viscosity determines time dependence

DEEP ASEISMIC AFTERSLIP

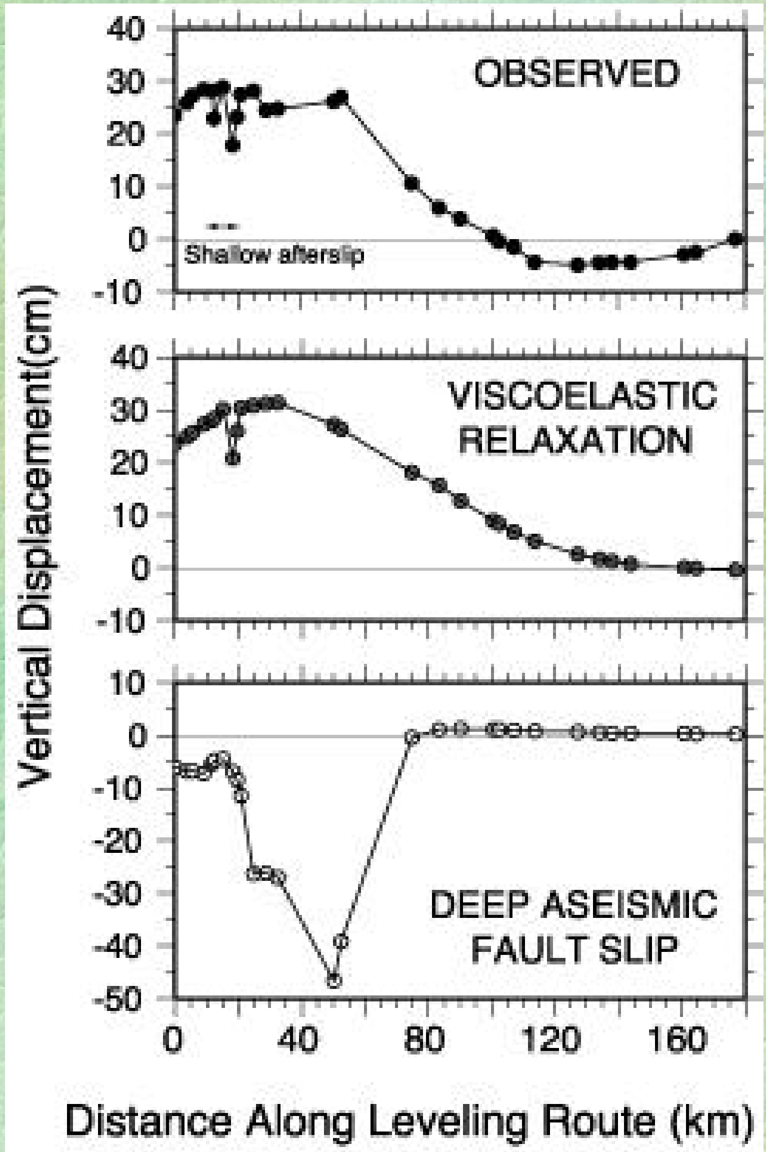
- On down-dip extension of earthquake fault plane
- Fault geometry and depth determine scale of surface motions
- Aseismic fault slip history determines time dependence

1959 M=7.3 Hegben Lake Earthquake

Nishimura & Thatcher 2002

- Normal faulting earthquake
- 30 km surface faulting
- Maximum 6 m slip
- 2-fault model (red boxes)
- Post-seismic leveling 1959-1987 (green lines)
- Constrains relaxation process
- Viscoelastic mantle required

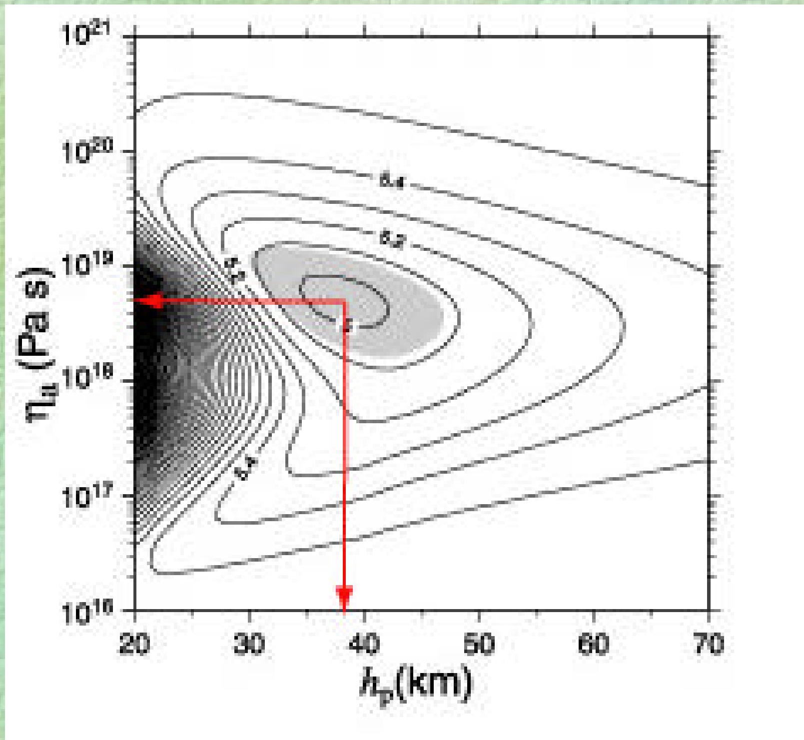
Hegben Earthquake Postseismic Leveling Favors Viscoelastic Relaxation Mechanism



Nishimura & Thatcher 2002

- Observed displacements show uplift
- Viscoelastic relaxation model predicts uplift, fits observed pattern
- Deep aseismic fault slip model predicts subsidence

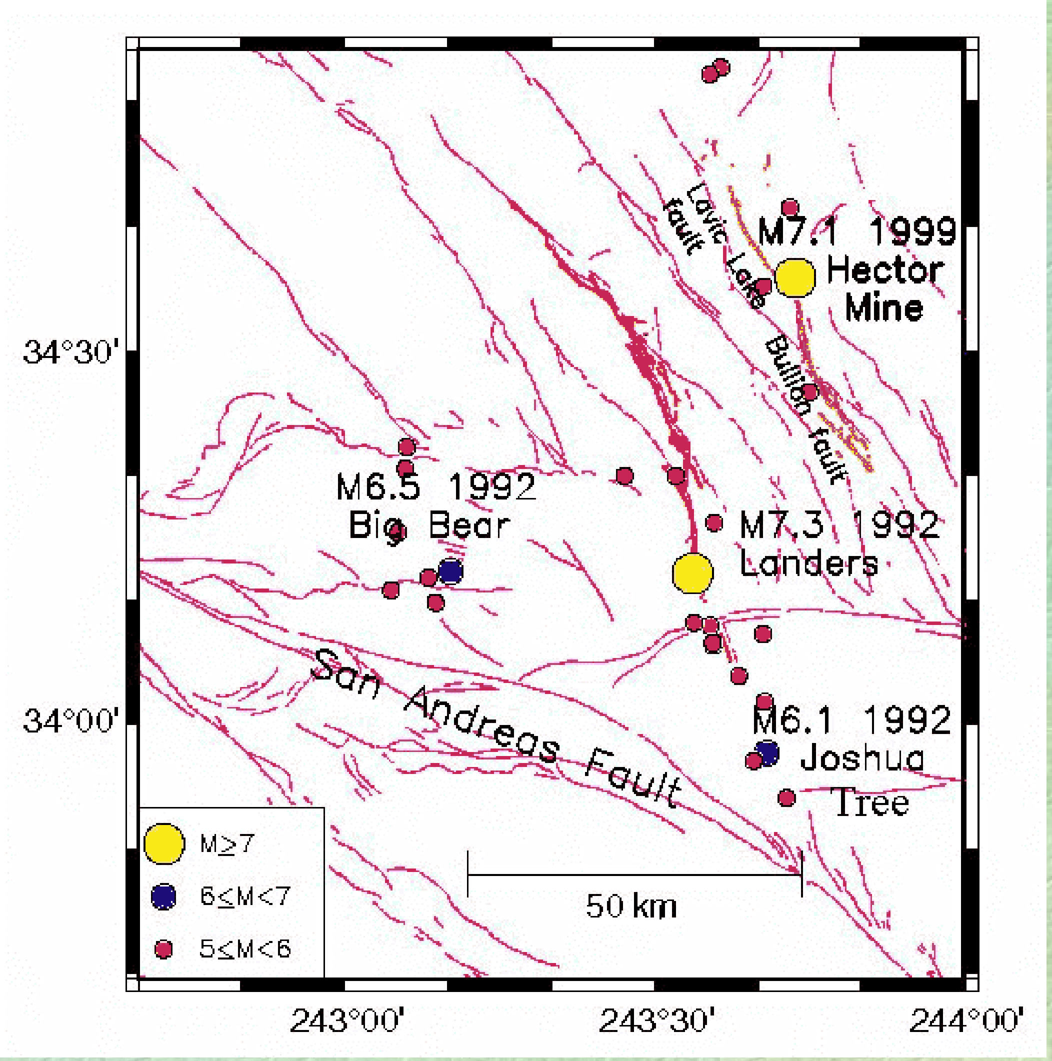
Best Fit Viscoelastic Model for Hegben Lake Postseismic Data



Nishimura & Thatcher 2002

- Upper mantle viscosity
  $\eta_a = 10^{18\pm0.5}$ Pa-s
- Elastic plate thickness
  $h_p = 38 \pm 8$ km
- Lower crustal viscosity must be > 10^{20} Pa-s

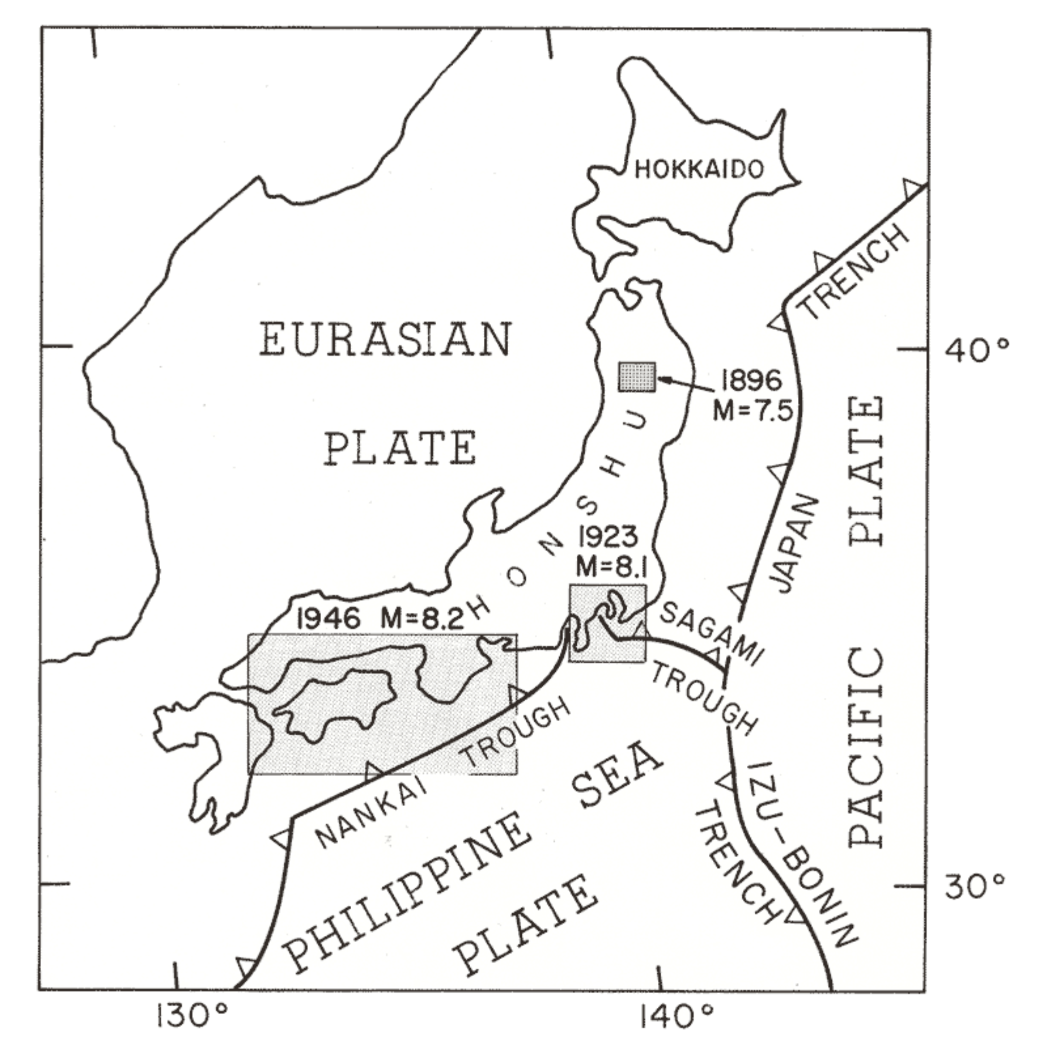
Post-Seismic Deformation from 1999 M=7.1 Hector Mine, California, Earthquake



Pollitz et al (2001)

- Excellent earthquake for post-seismic deformation imaging
- Good campaign and continuous GPS network coverage
- Good InSAR images of post-seismic deformation in ~year following earthquake
- Well-constrained coseismic fault slip model (GPS & InSAR)
- Unique constraints on mechanism of post-seismic relaxation
- Already discussed by Dr. Pollitz

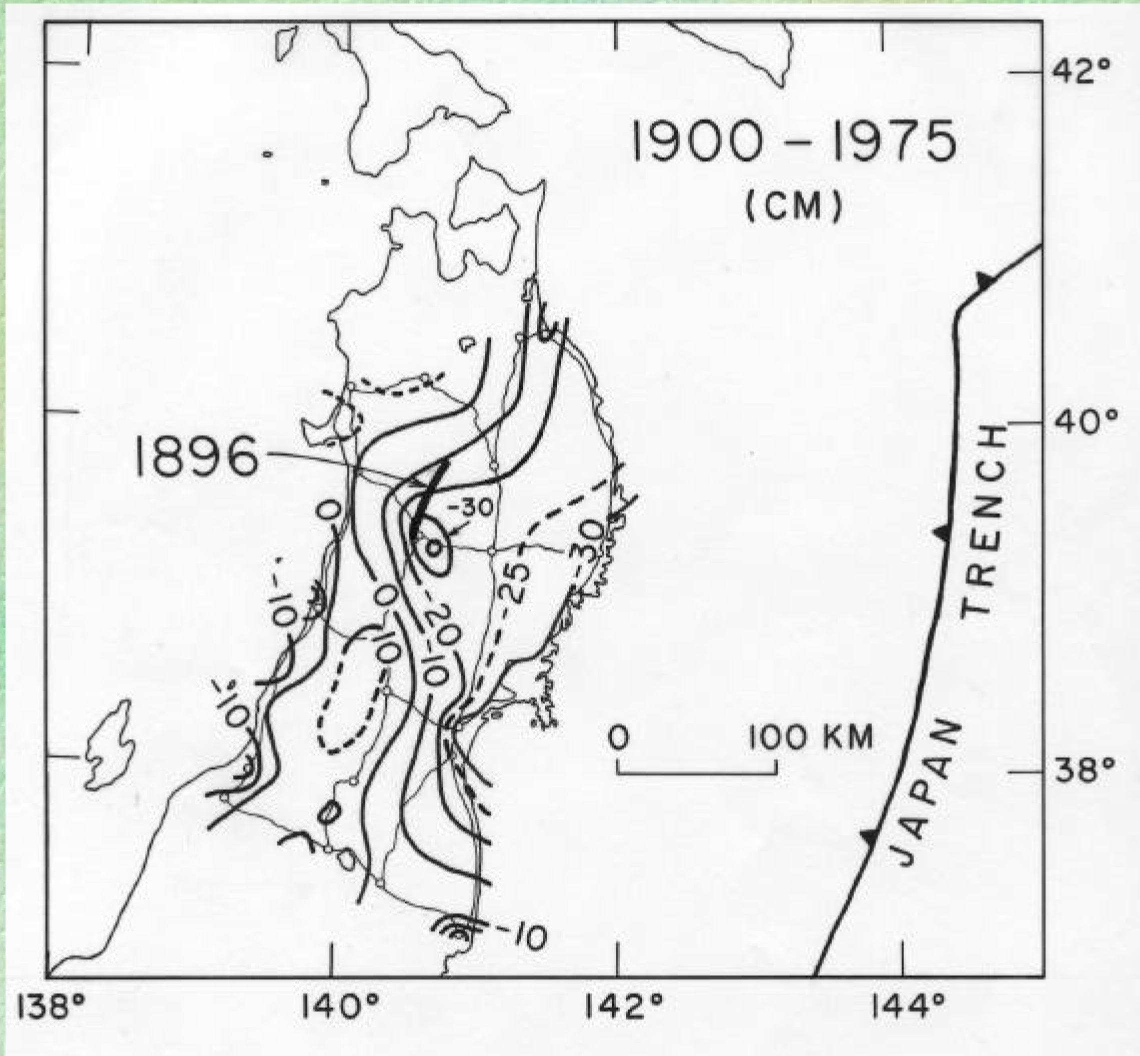
Post-Seismic Deformation from 1896 M=7.5 Riku-u, N. Honshu, Japan Earthquake



Thatcher, Matsuda, Kato & Rundle (1980)

- Intra-plate thrust faulting event
- Surface faulting ~40 km, with ~4m offsets on Senya fault
- Leveling network established in 1900 across epicentral zone
- Remarkable transient deformation centered on 1896 fault
- Requires viscoelastic relaxation mechanism to explain

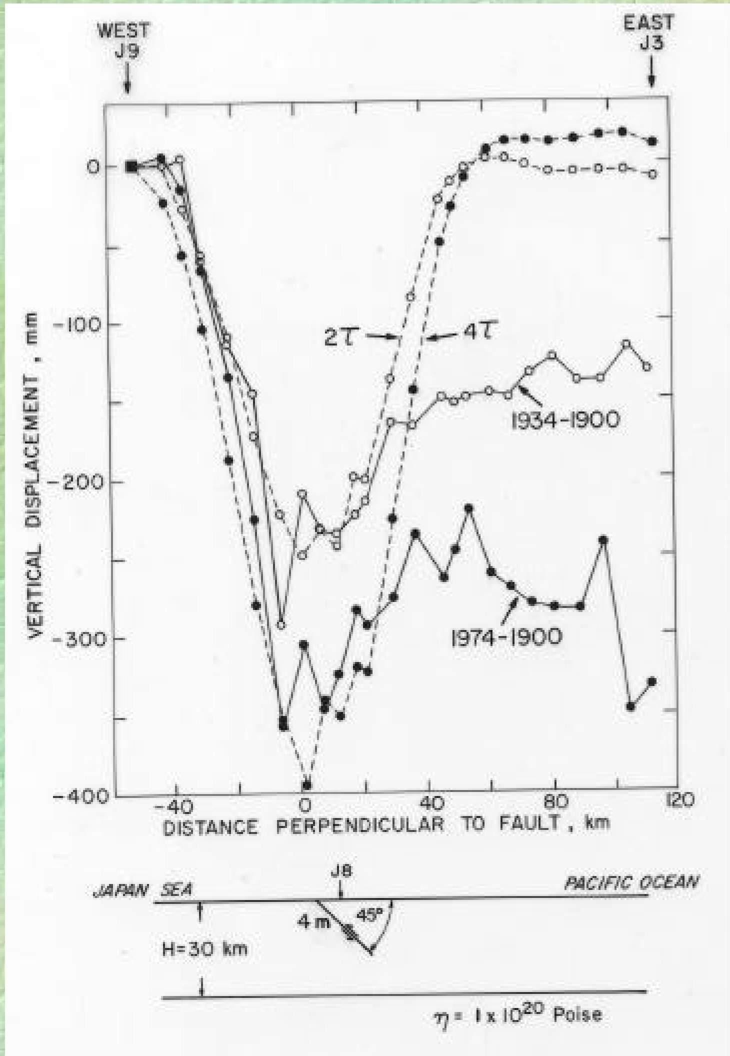
1900-1975 Level Changes Following 1896 M=7.5 Riku-u, N. Honshu, Japan Earthquake



Thatcher, Matsuda, Kato & Rundle (1980)

- Localized subsidence ~35 cm located near 1896 surface rupture
- Unrelated Pacific coast subsidence due to Pacific plate subduction at Japan Trench

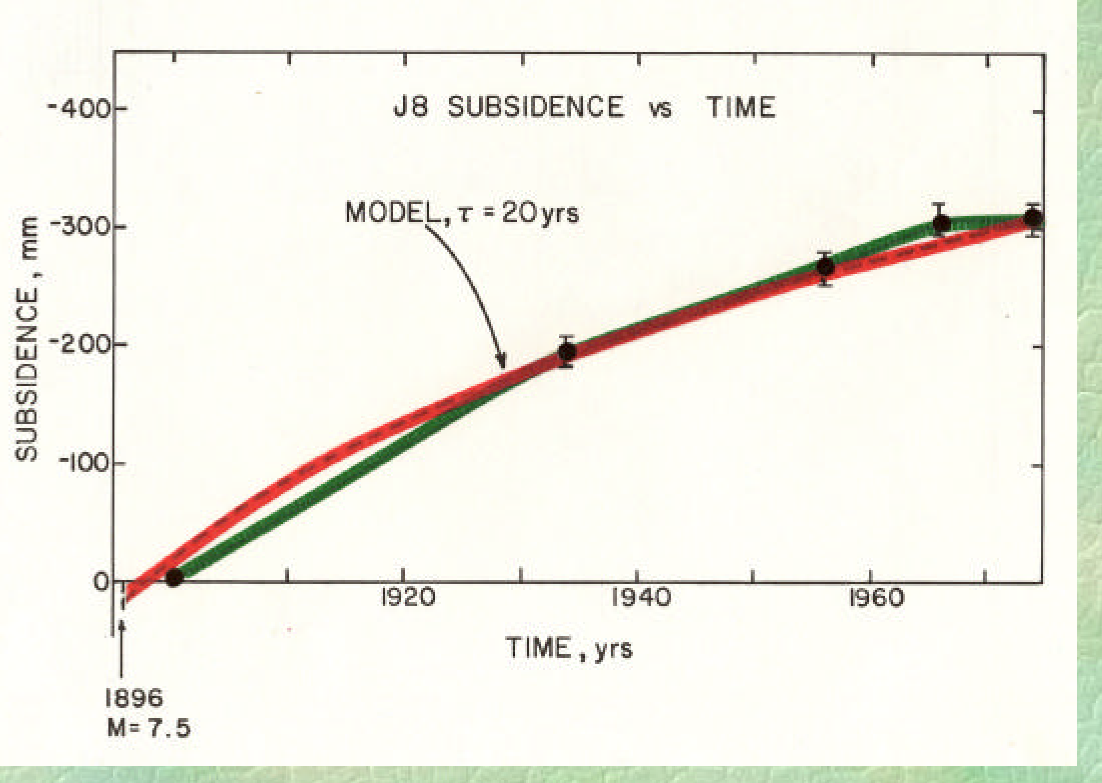
Observed versus Model-Predicted Vertical Displacements



Thatcher, Matsuda, Kato & Rundle (1980)

- Good agreement near 1896 fault
- Mismatch near Pacific coast due to Pacific plate subduction at Japan Trench
- Spatial pattern requires elastic crust 30 km thick
- Time decay of deformation (see next graph) requires effective viscosity of upper mantle to be 1×10^{19} Pa-s

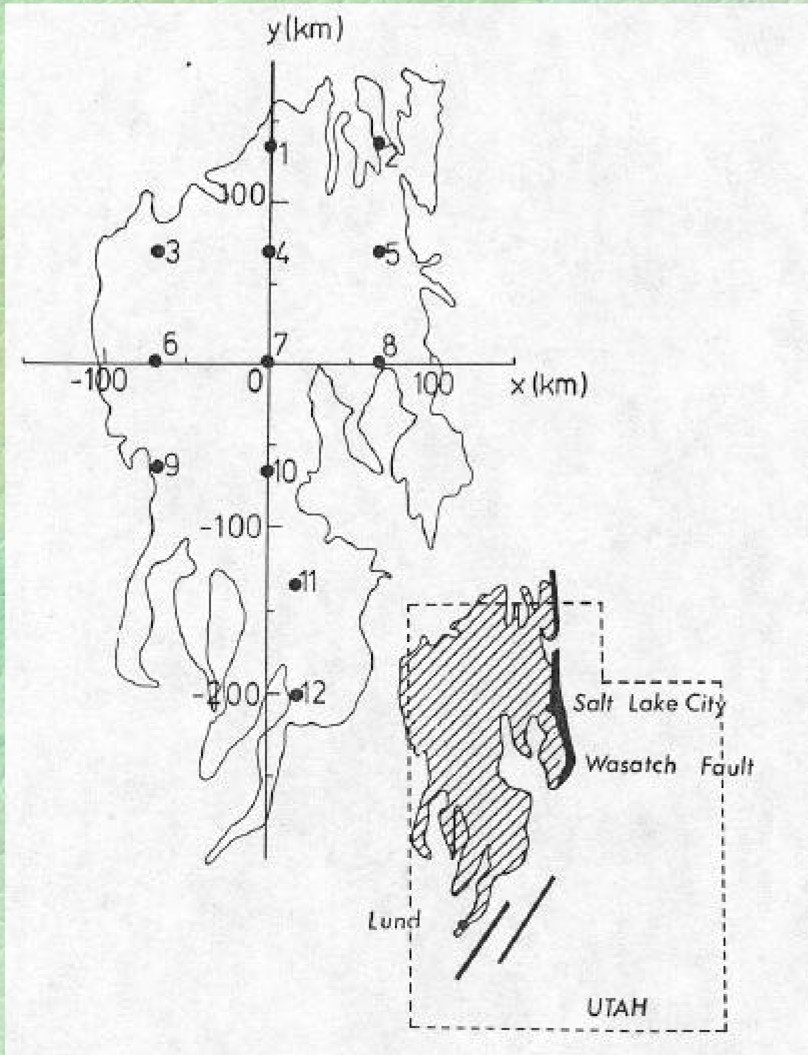
Observed versus Model-Predicted Vertical Displacement Time History at 1896 Fault



Thatcher, Matsuda, Kato & Rundle (1980)

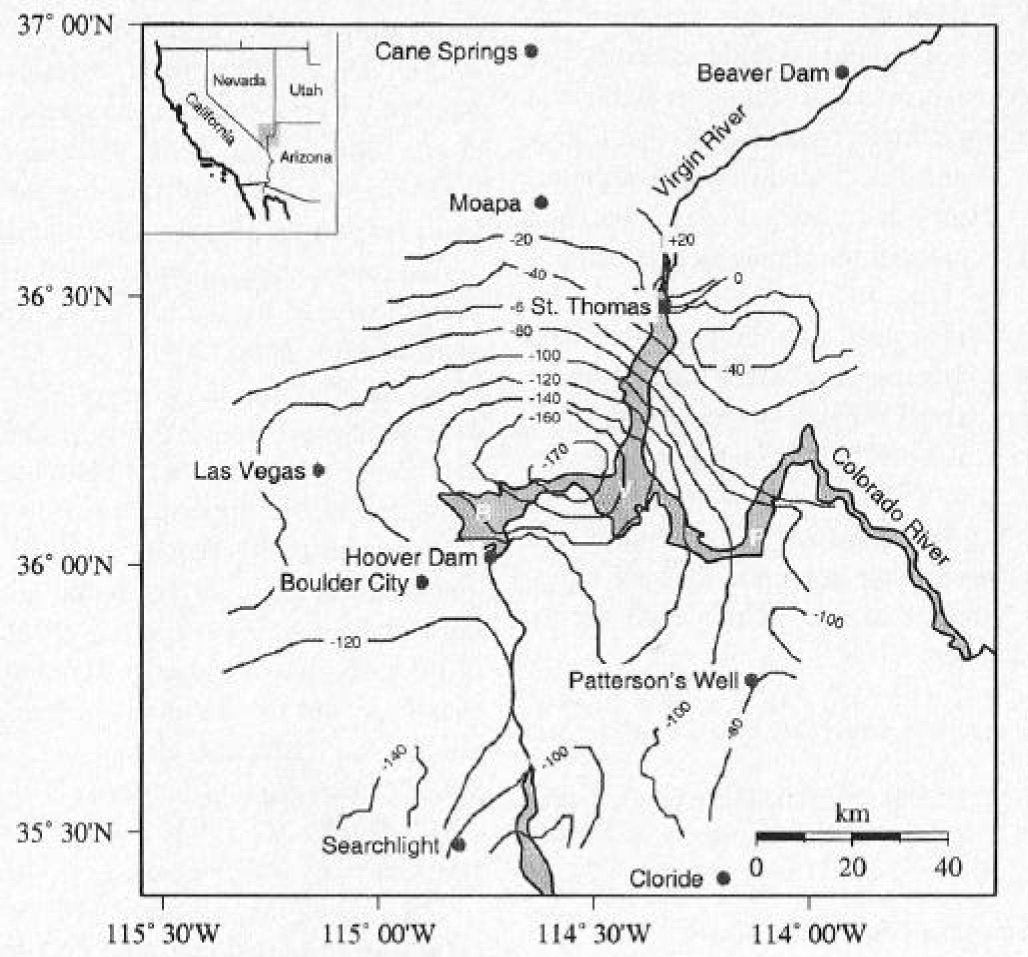
- Time decay of deformation requires viscoelastic model relaxation time of 20 years and effective viscosity of upper mantle to be 1×10^{19} Pa-s

Isostatic Rebound of Lake Bonneville Utah, Western USA



- Sudden draining of pluvial lake ~12,000 & 14,000 yrs BP
- Uplifted shorelines record rebound of lithosphere
- Models (many studies) require:
  - Elastic crust ~30 km thick
  - Upper mantle viscosity 1-3 x 10^{19} Pa-s
    - (or as low as 2 x 10^{18} Pa-s if thin low viscosity layer)

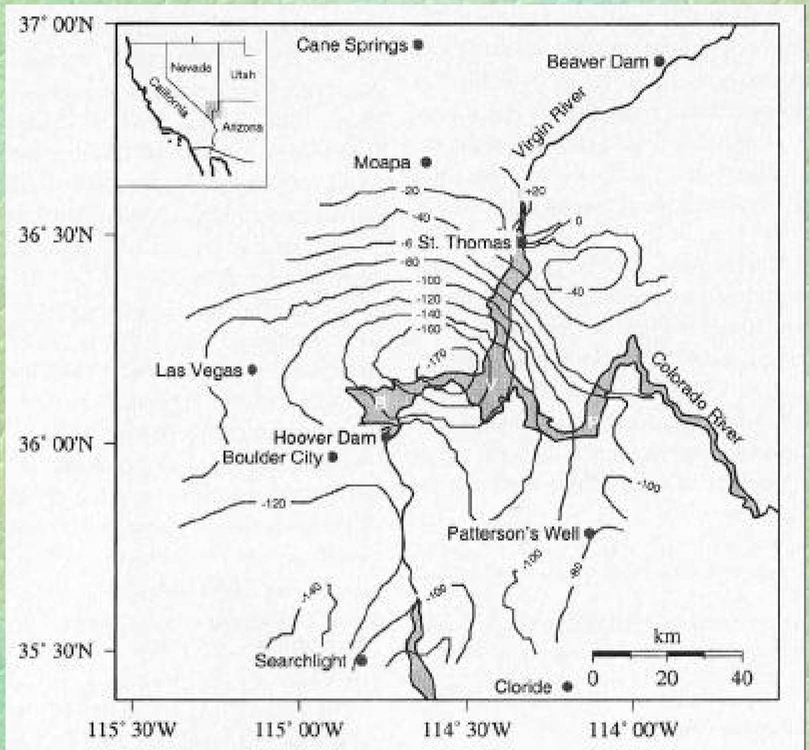
Time-Dependent Subsidence Due to Filling of Lake Mead, Nevada, in 1934

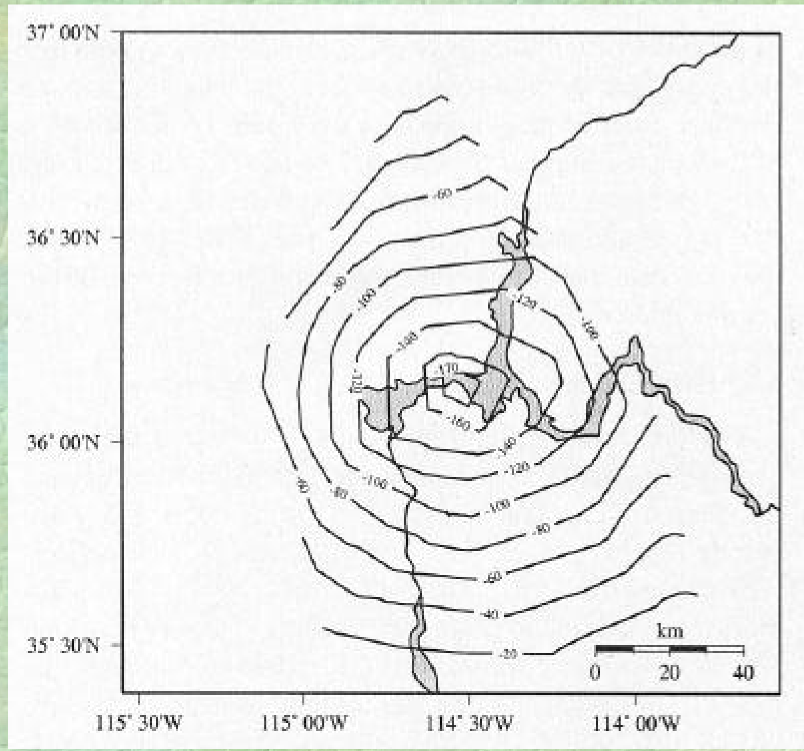


Kaufmann & Amelung, (2000)

- Loading of 635 km^2 by reservoir up to 220 m deep
- Leveling in 1935, 1941, 1950 & 1963
- Spatial pattern & time dependence of the deformation constrain lithosphere rheology

Modeling Subsidence Due to Filling of Lake Mead



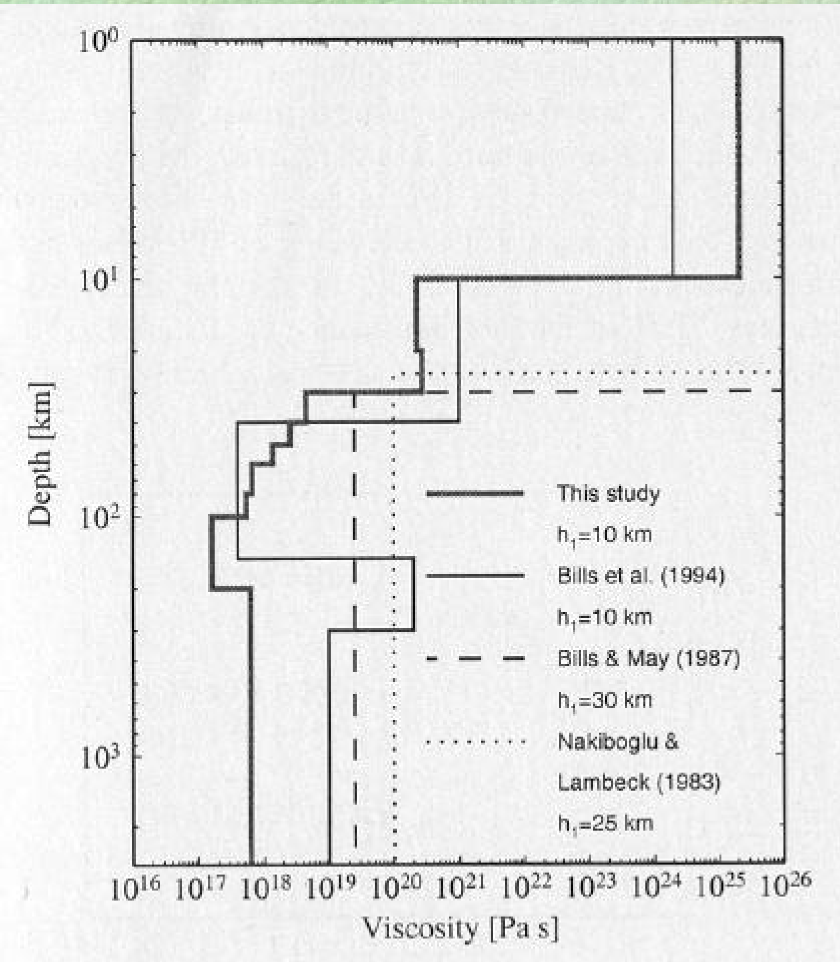


Kaufmann & Amelung, (2000)

- Elastic layer ~ crustal thickness 28 ± 3 km

- Upper mantle viscosity ~1.5 x 10 ^{18} Pa-s

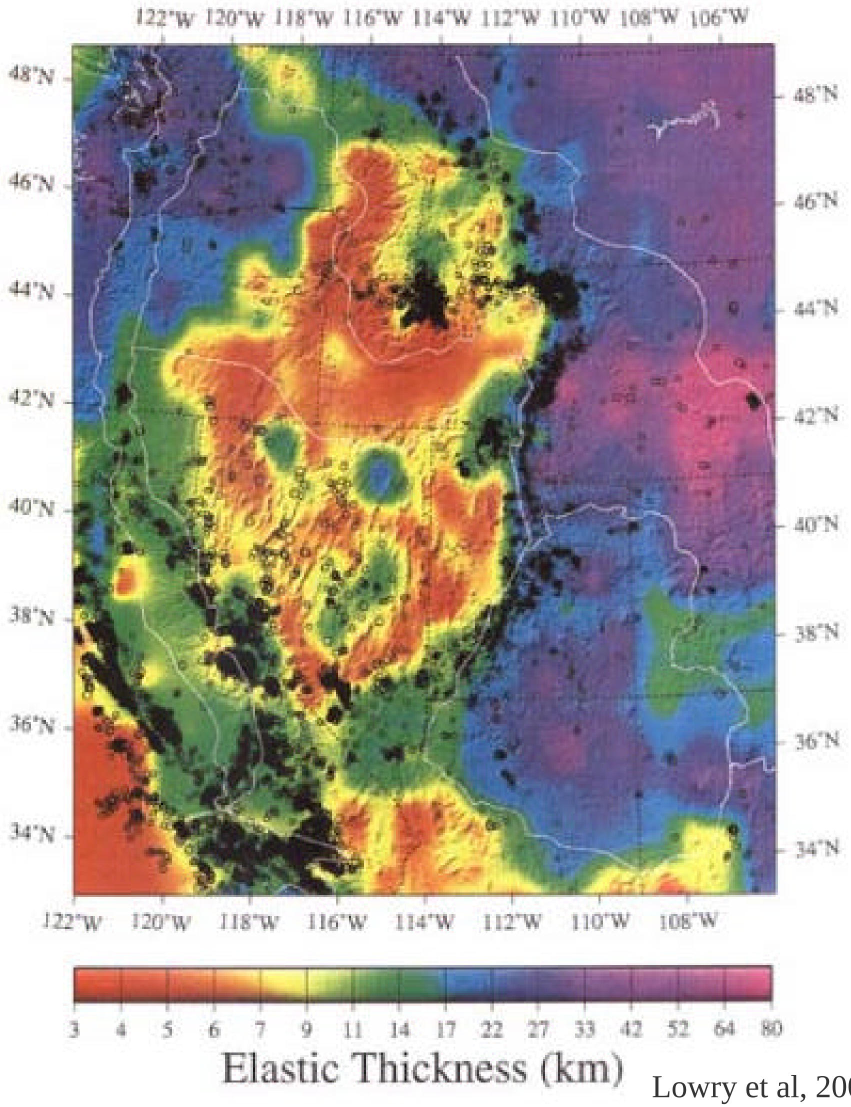
Lithospheric Viscosity Profiles from Modeling Loading/Unloading Deformation in Western USA



Kaufmann & Amelung, (2000)

- Strong ~elastic crust (lower crust *might* be slightly weaker, $\eta > 10^{20}$ Pa-s)
- Upper mantle viscosity range 10^{18} - 10^{19} Pa-s

Western US Elastic Lithosphere Thickness from Gravity-Topography Correlation



Lowry et al, 2000

- In active western USA
  T_e ~ 5 - 15 km

- Generally T_e factor of 2 - 4 thinner than 'geodetic' estimates
  - Hegben: 9 km vs 40 km
  - Mojave: 15 km vs 30 km
  - Bonneville: 7 km vs 30 km
  - Lake Mead: 15 km vs 30 km

- Why?
  - Lower crustal stress relaxation for time scales > ~10 ka?
  - Transient rheology different?
  - Acknowledged & unacknowledged errors in both methods?

Implications, Issues & Questions

Strength of Lower Crust

- Post-seismic results suggest strong ~elastic crust to Moho depths (~30 km)
- Consistent with isostatic rebound of Lake Bonneville & Lake Mead loading
- No ‘jelly sandwich’ rheological layering in Western USA at present?
- Long term lower crustal stress relaxation?

Does Lower Crustal Flow Occur Only in Very Hot Crust?

- Metamorphic core complexes pre-heated by magmatism?
- Overthickened orogens (Tibet, Andes) with hot lower crust at ~30-70 km depth?

Is Upper Mantle Weak in Tectonic Regions? Why?

- Role of water in weakening mantle lithosphere?

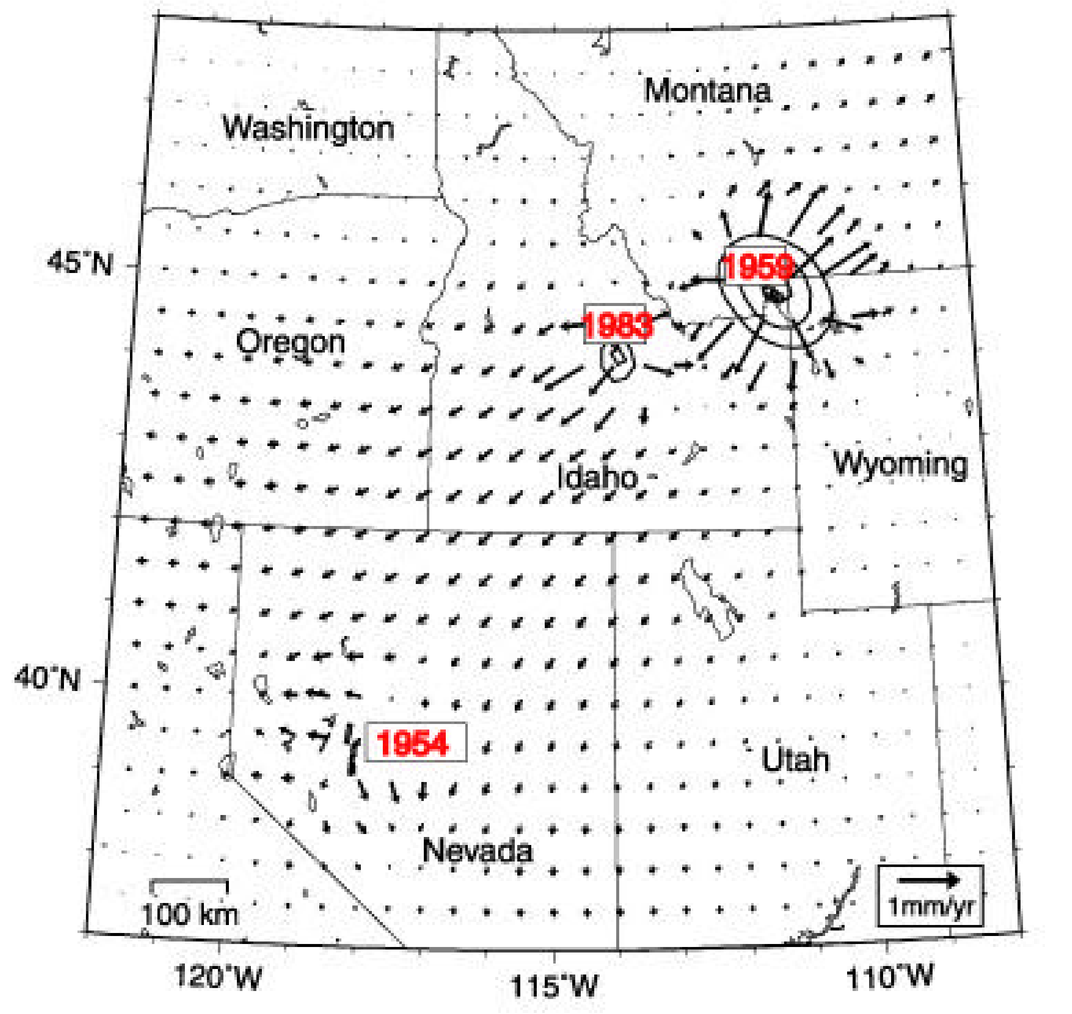
Likely Complexities & Unresolved Issues

- Role of lower crust is unknown--slow ductile flow or narrow shear zone?
- Are there lateral rheology variations near active fault zones?
- Regional variations in rheology? (Is San Andreas different from Mojave faults?)

New Research Directions

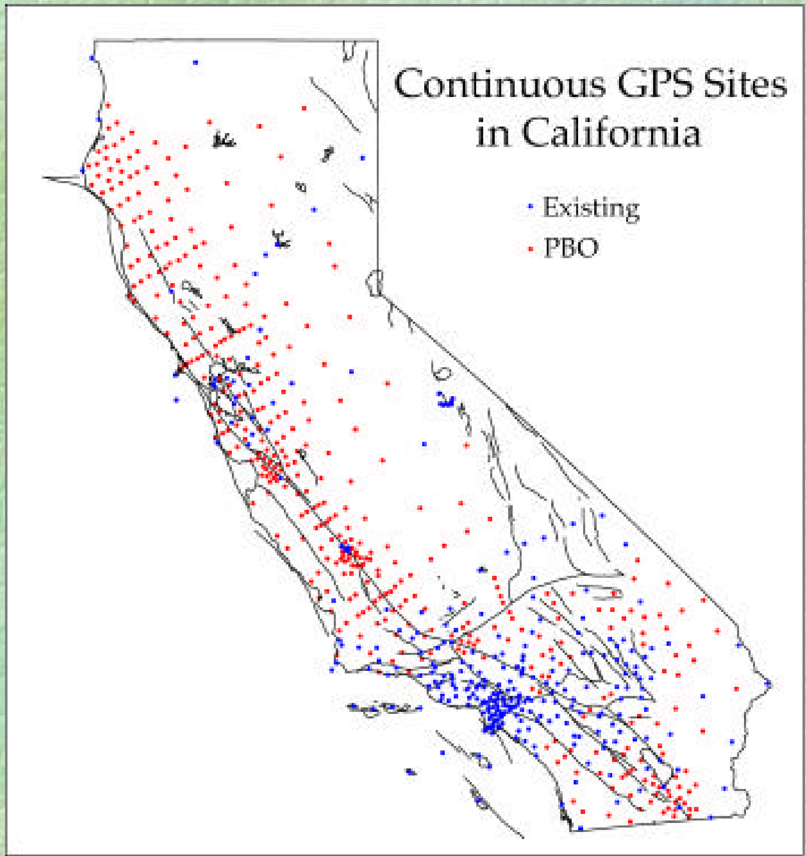
- More case histories of post-seismic relaxation worldwide
- Assess importance of other time-dependent relaxation processes

Western US Synthetic GPS Velocity Field in 2002 Due to Relaxation from 1954, 1959 & 1983 Earthquakes



- Assume Hegben Lake Relaxation Model
- Calculate 2002 postseismic transient velocity due to:
  - 1954 Dixie Valley, Nevada M=7.3
  - 1958 Hegben Lake,Montana M=7.3
  - 1983 Borah Peak, Idaho M=7.1
- Expected effects are measurable with high precision GPS

How EarthScope Will Contribute to Better Constraints on Crust-Upper Mantle Rheology



- More high resolution case histories of post-seismic transient deformation
- Long-term (>decade) stress relaxation from large (M>7) western US earthquakes from PBO continuous GPS networks
- Seismology--can connect crust/upper mantle structure to lithospheric rheology estimates with USArray
- InSAR will give 24-day snapshots of post-seismic deformation worldwide
- Better understanding of post-seismic stress transfer process