Separating Tectonic, Magmatic, Hydrological, and Landslide Signals in GPS Measurements near Lake Tahoe, Nevada-California

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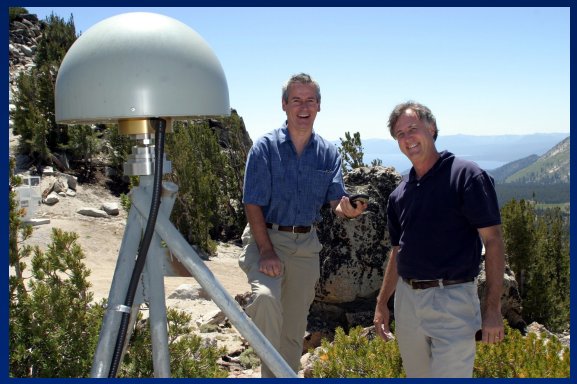
with thanks to Ken Smith and David Von Seggern

Separating Tectonic, Magmatic Hydrological and Landslide Signals

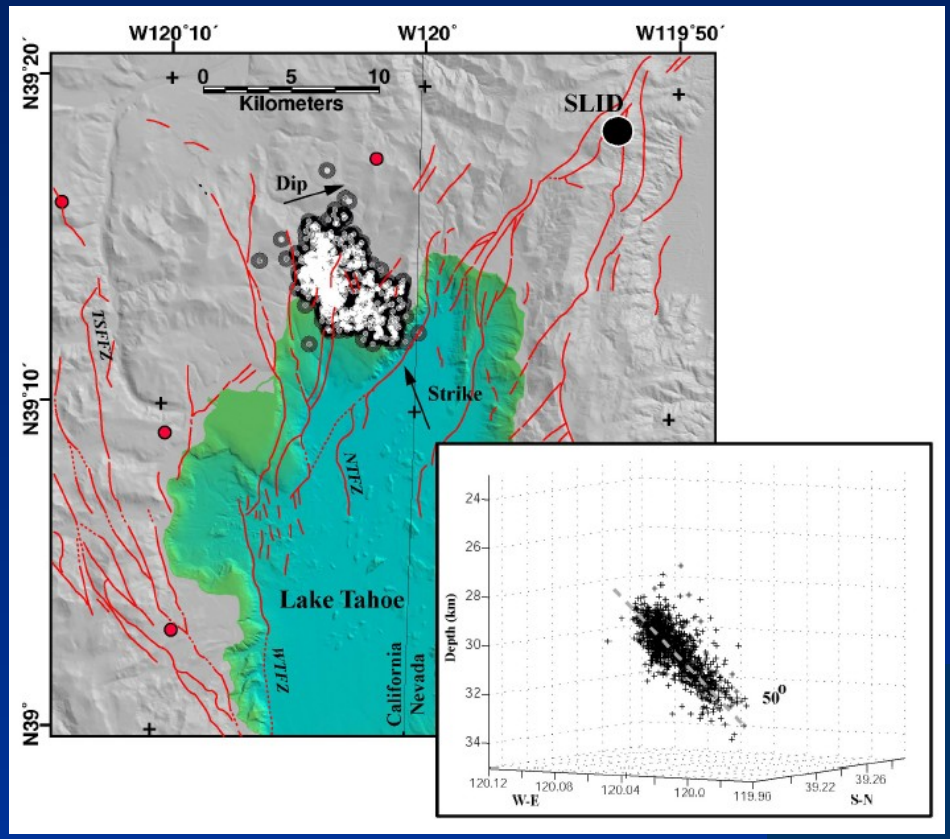
- Two case studies of GPS transients
  - Slide Mountain 2003
    - Smith et al., 2004, doi:10.1126/science.1101304
  - Mogul-Sommerset 2008



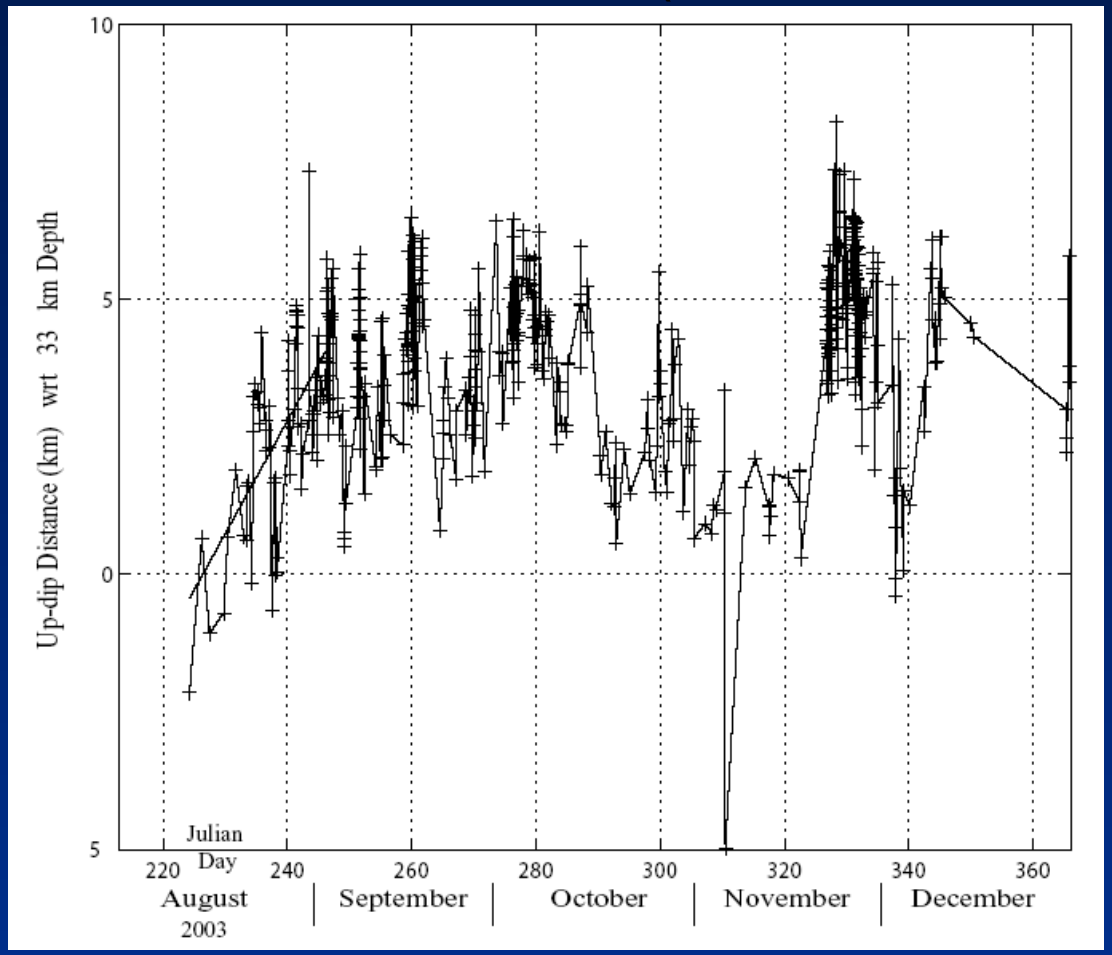
- Both transients coeval with earthquake swarms
  - Swarms of magmatic or tectonic origin?
  - Transients from crustal deformation or landsliding?
  - Transients complicated by hydrological effects

Summary of SLID Transient
August 2003 – January 2004

- Earthquake swarm under Lake Tahoe
  - 29-33 km deep → below seismogenic zone
    - Rheological implication → rapid stress change
  - Seismic moment M_w 3.8
- GPS transient at SLID
  - 3-D displacement ~12 mm
  - Geodetic moment M_w 6.1
    - Timing is the same as seismic
    - 99% aseismic
- Evidence → magmatic



Depth of Seismicity vs Time
(Smith et al., 2004)



1. Quakes are below typical seismogenic depth, which requires a very rapid stress transient

2. Seismic time series starts with upward trend at
   2.4 mm / second
   8.5 m / hour
   1.4 km / week

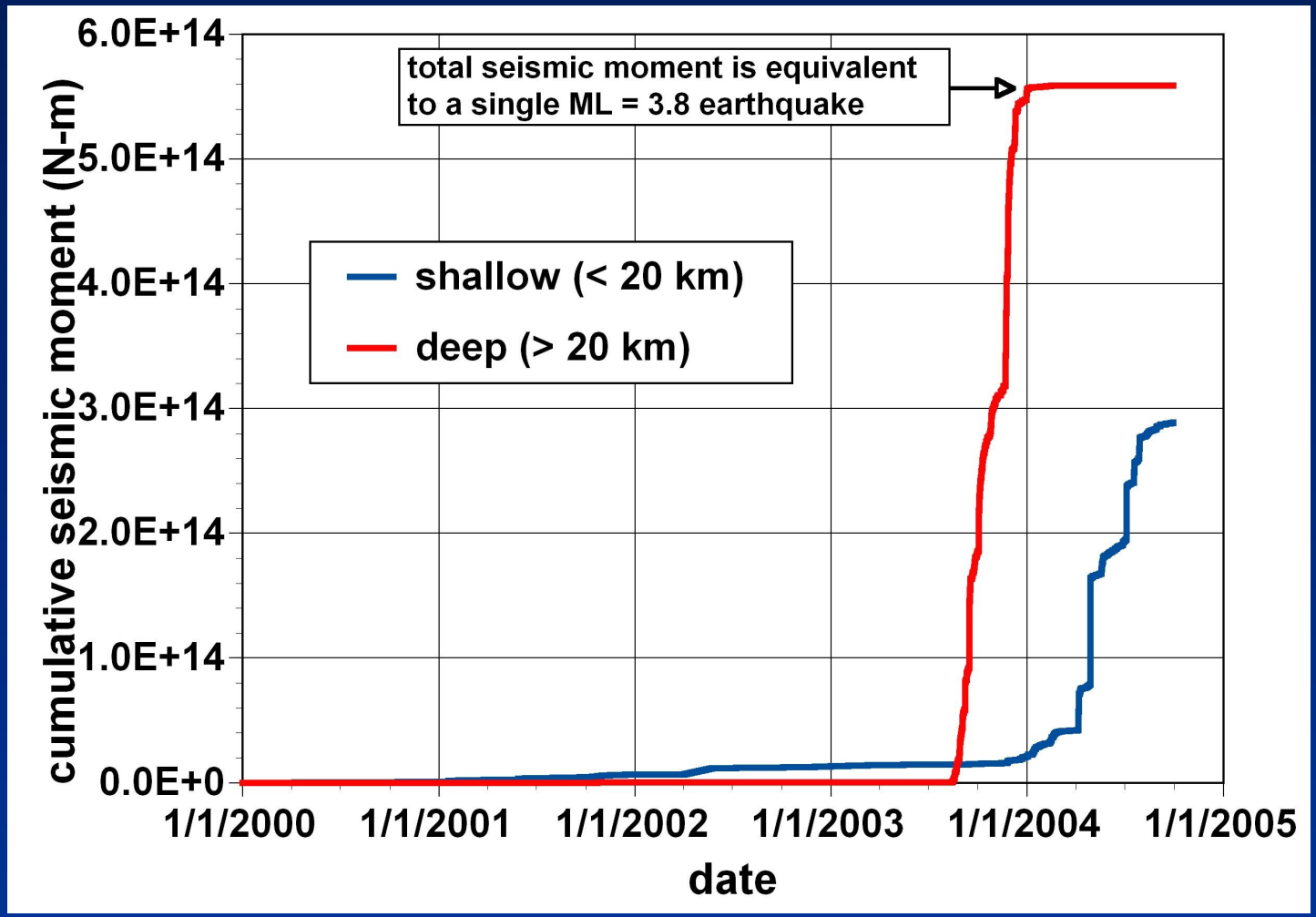
3. Supports hypothesis of lower crustal magmatic intrusion, migrating upward.

Seismological Analysis

(Ken Smith & D. Von Seggern)

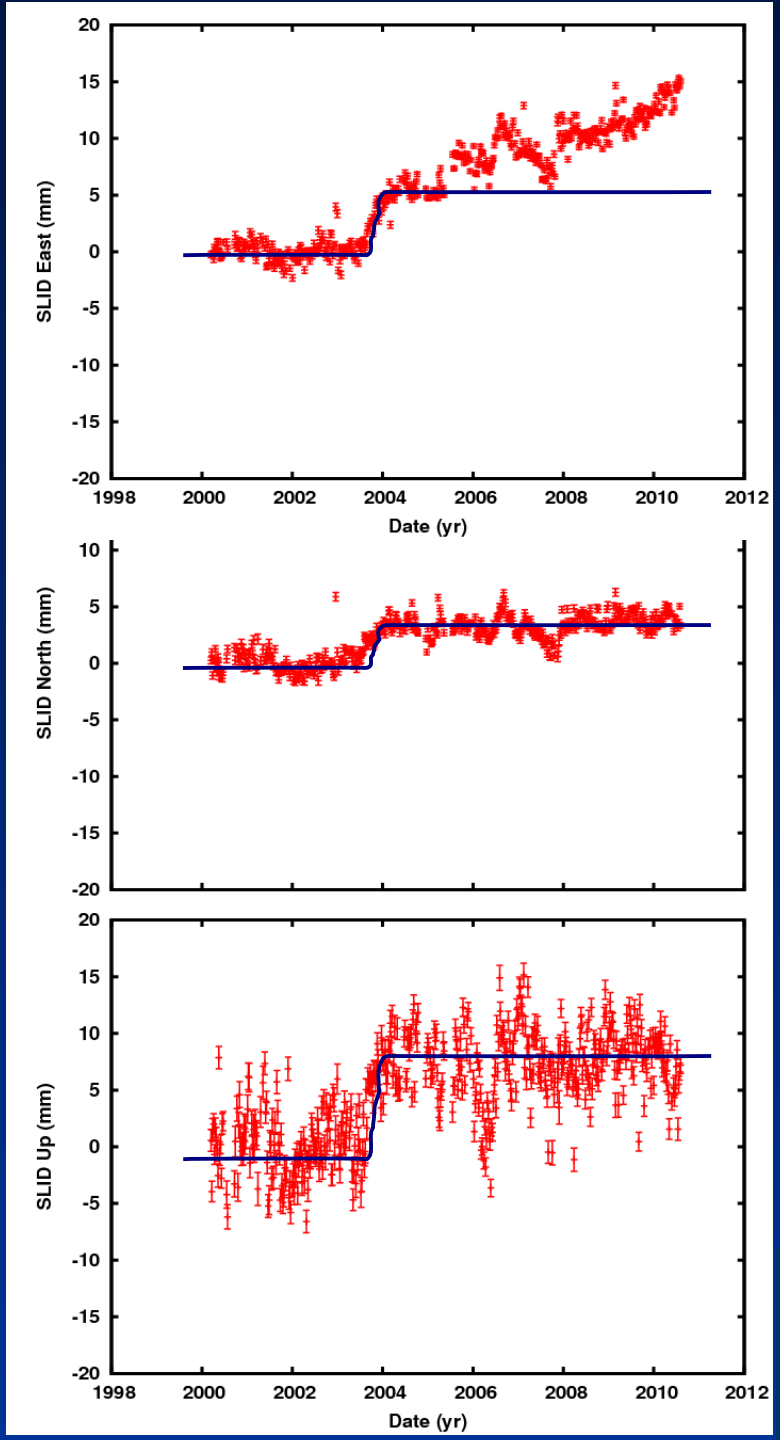
Deep event has clearly ended on Jan 1 2004

Shallow μ-seismicity follows deep Event – Brittle response



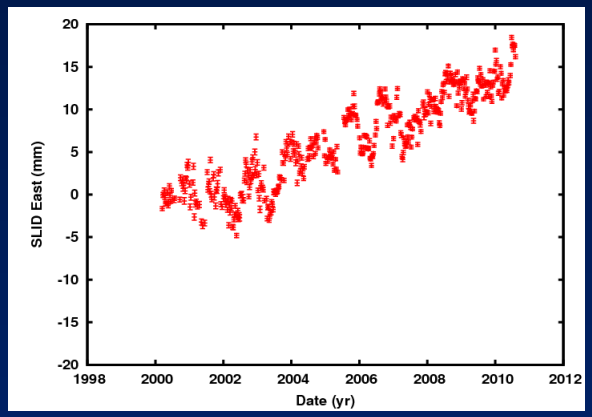
SLID GPS

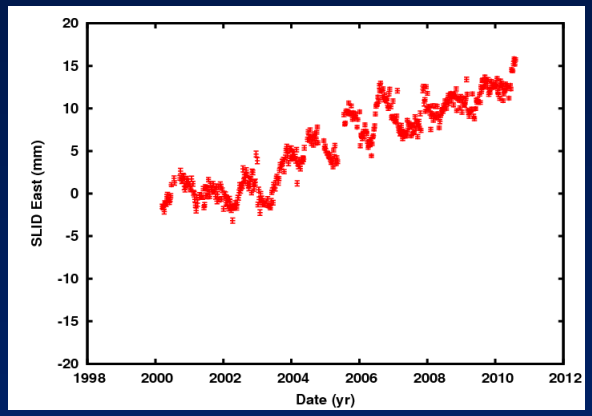
- GPS Method
  - seasonal and secular removed
  - model during seismic quiescence
- Fit to transient
  - Blue curve is not GPS!!
  - Cumulative moment from deep earthquakes
  - Curve scaled to fit GPS data
    - Δ N = 4 mm
    - Δ E = 6 mm
    - Δ U = 9 mm
- Okada model for tensile crack
  - moment M_w 6.1 → 99% aseismic
  - Earthquakes only a symptom of the process, not the cause
- East velocity changes!
  - Regional magmatics at work?

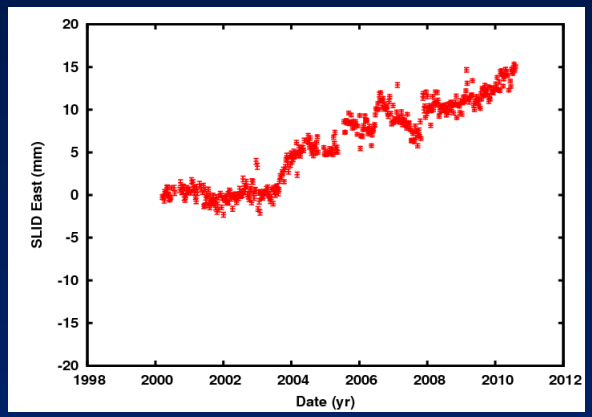


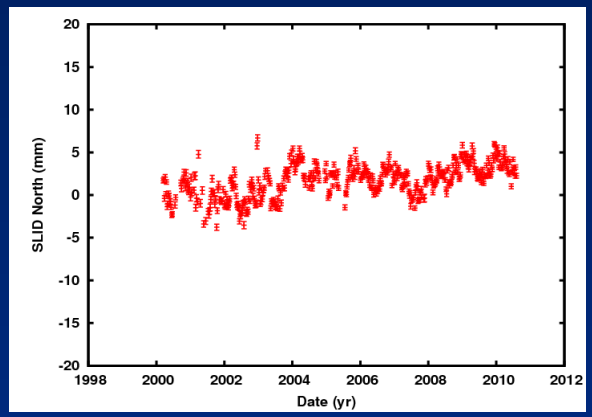
SLID Time-Series Filter (pre 2003.5)

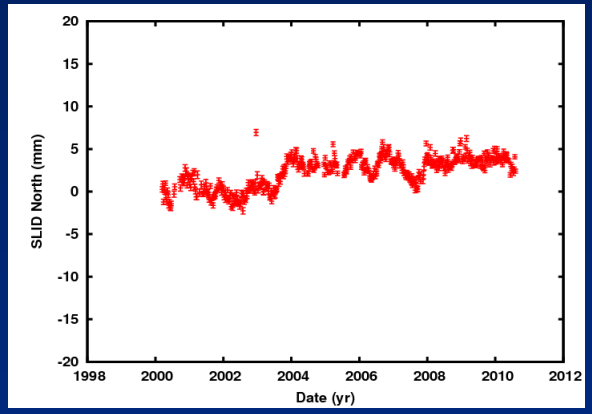
Global Frame → Western US Frame Seasonal Removed

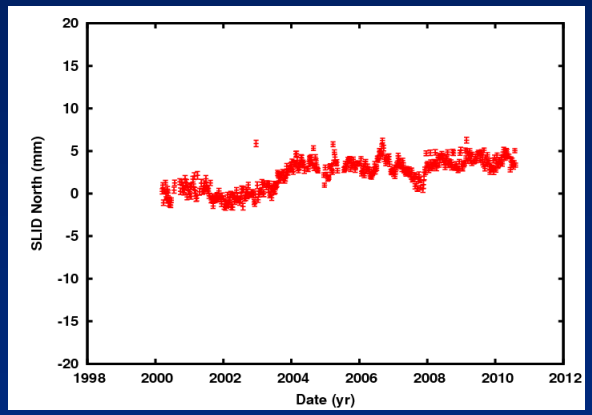


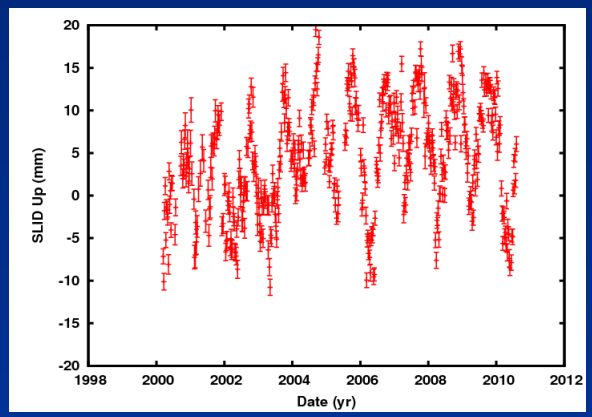


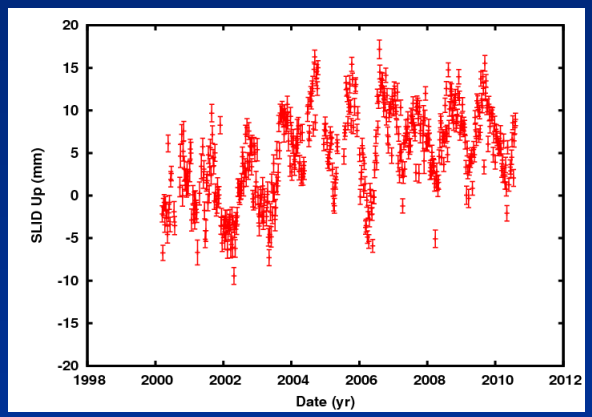


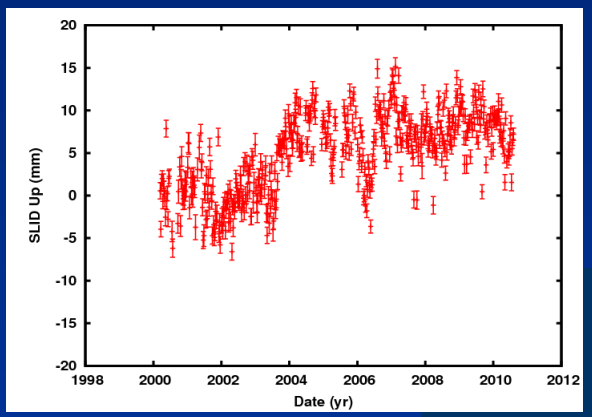






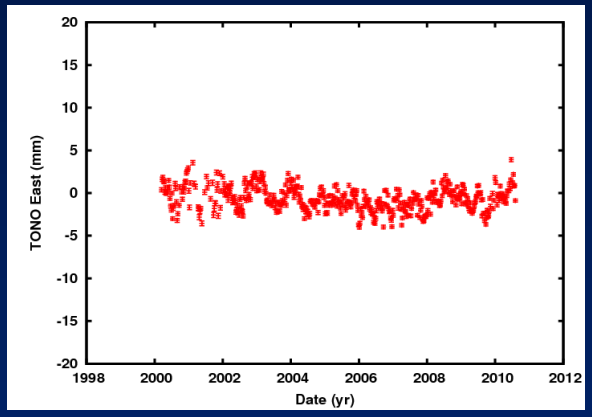


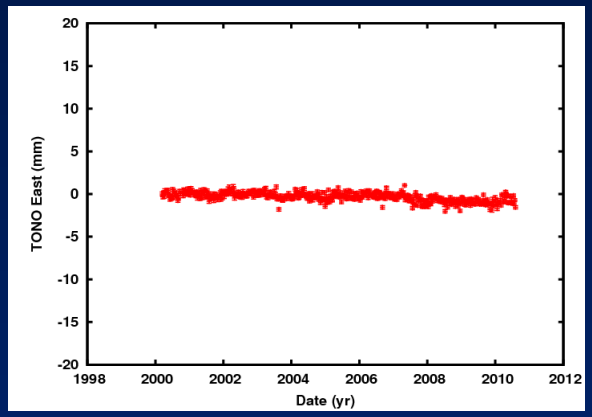


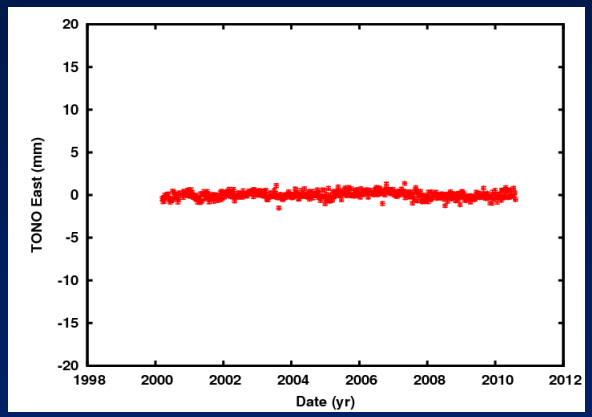


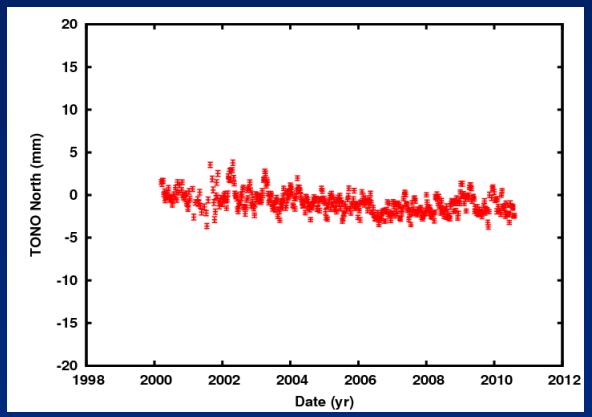
TONO (control) Time-Series Filter (pre 2003.5)

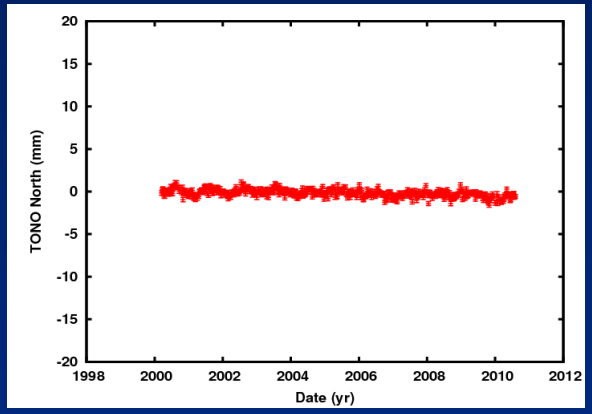
Global Frame → Western US Frame → Seasonal Removed

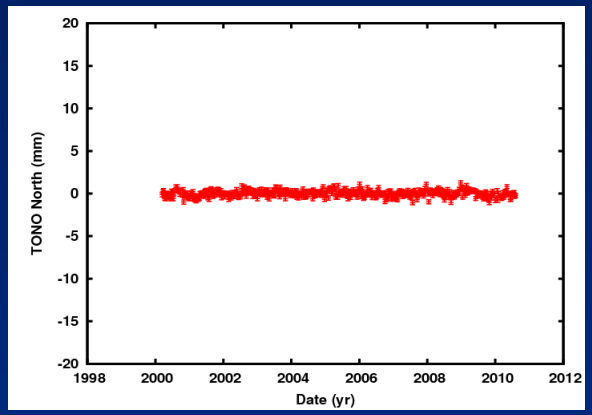


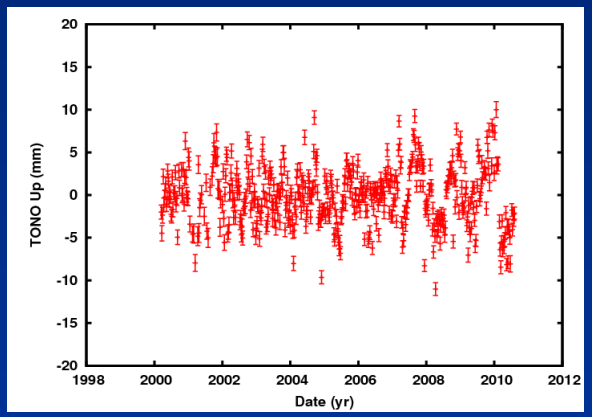


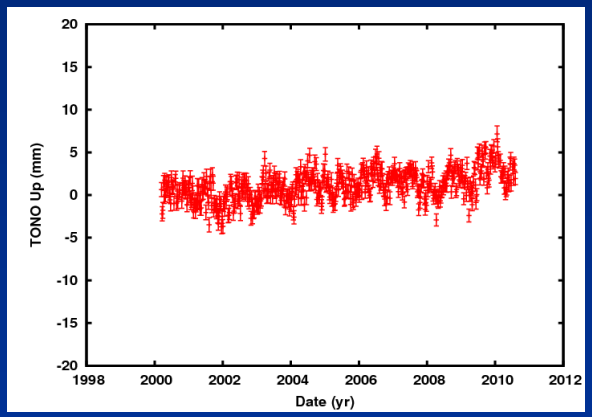


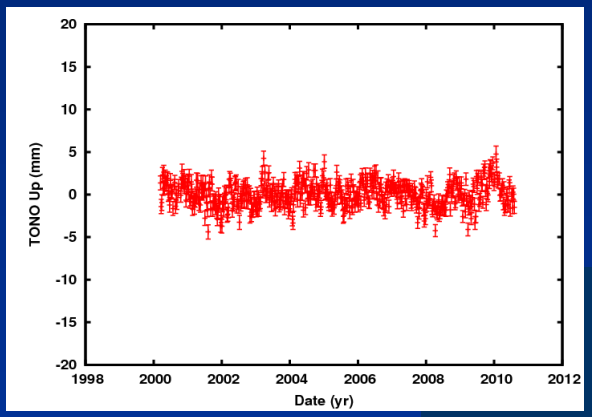






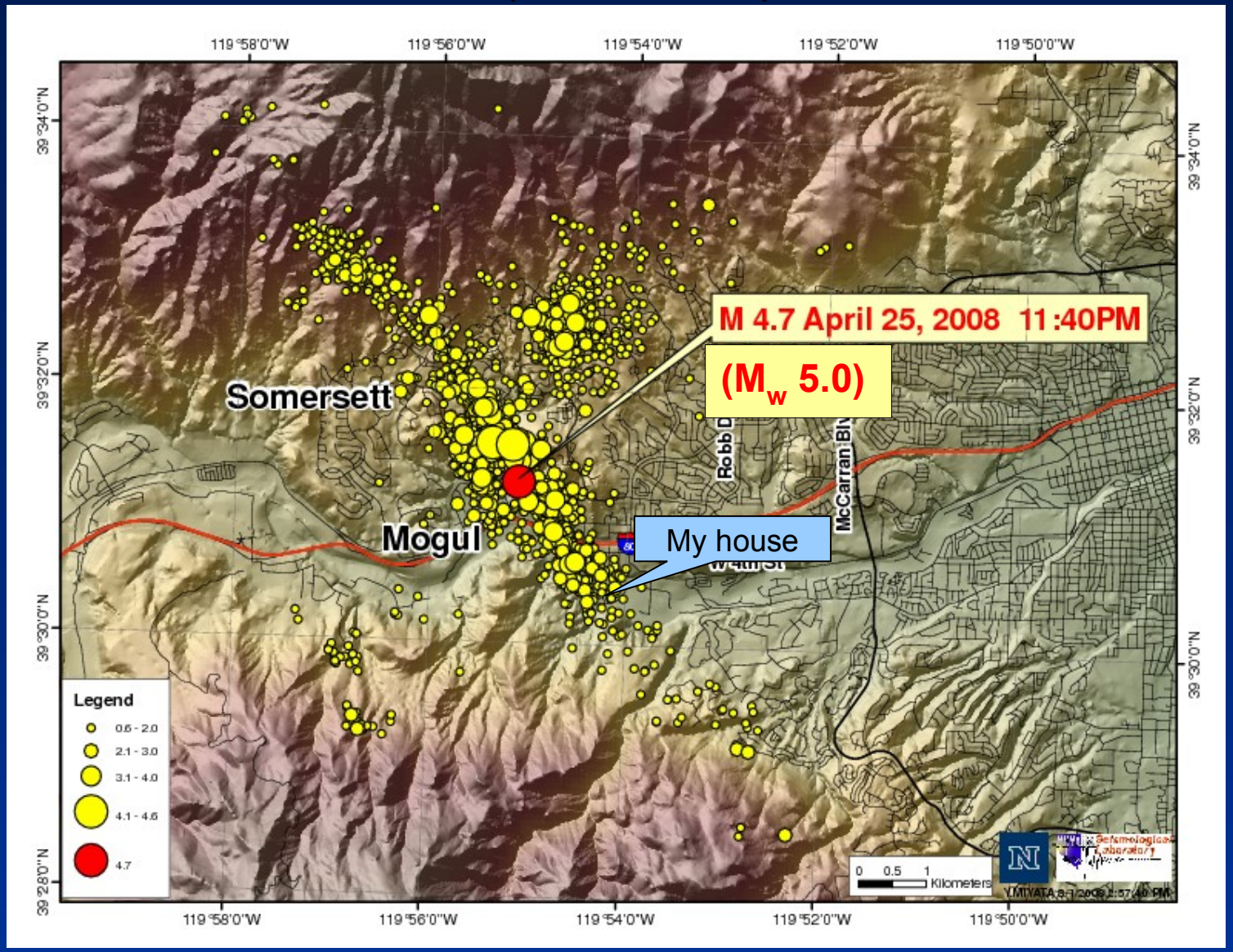






Mogul Earthquake Swarm, Feb-Aug 2008

(Ken Smith)

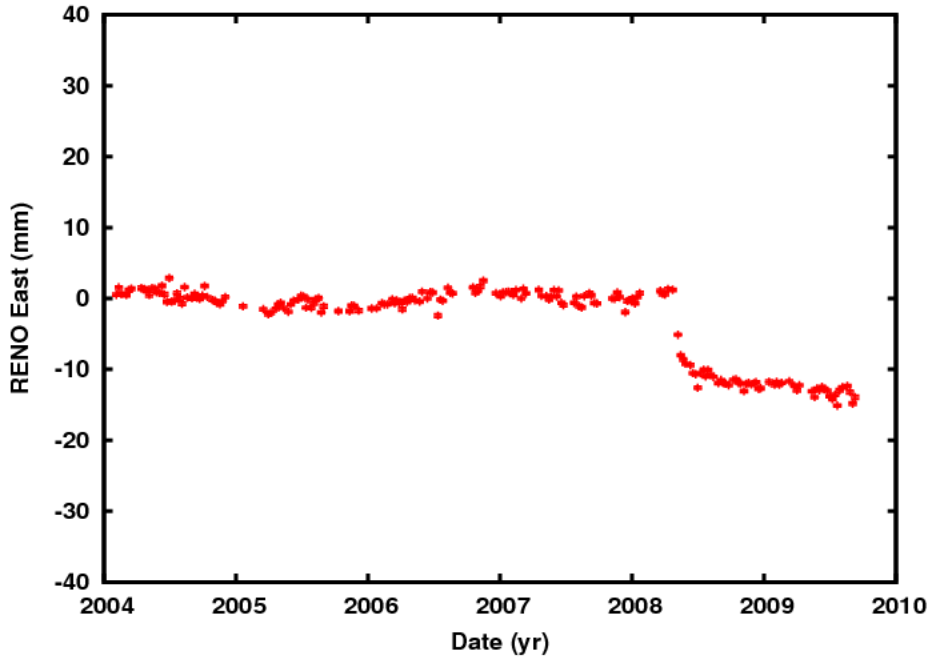


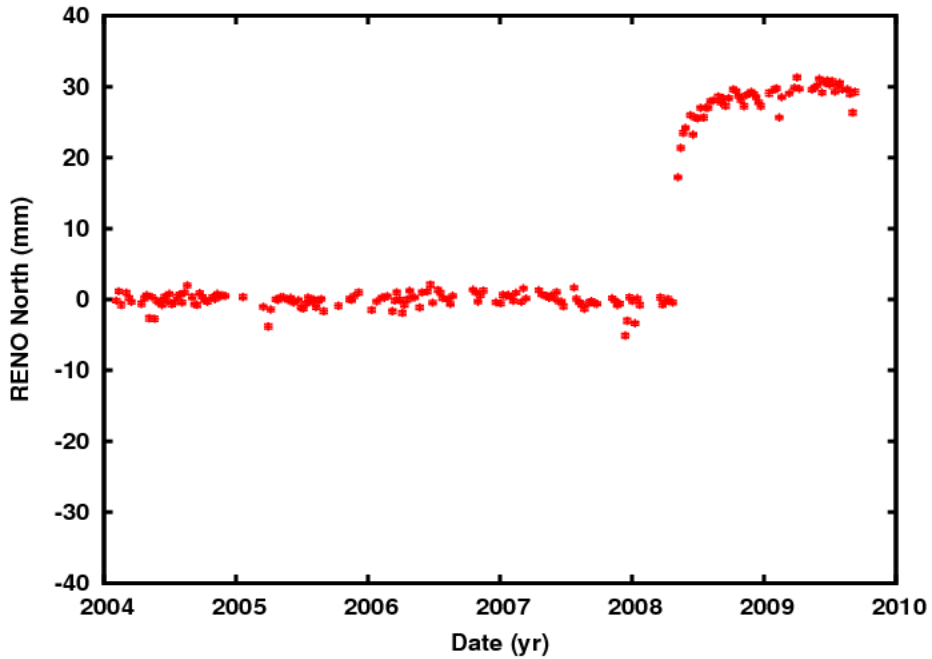
GPS Site RENO
Installed January 2004

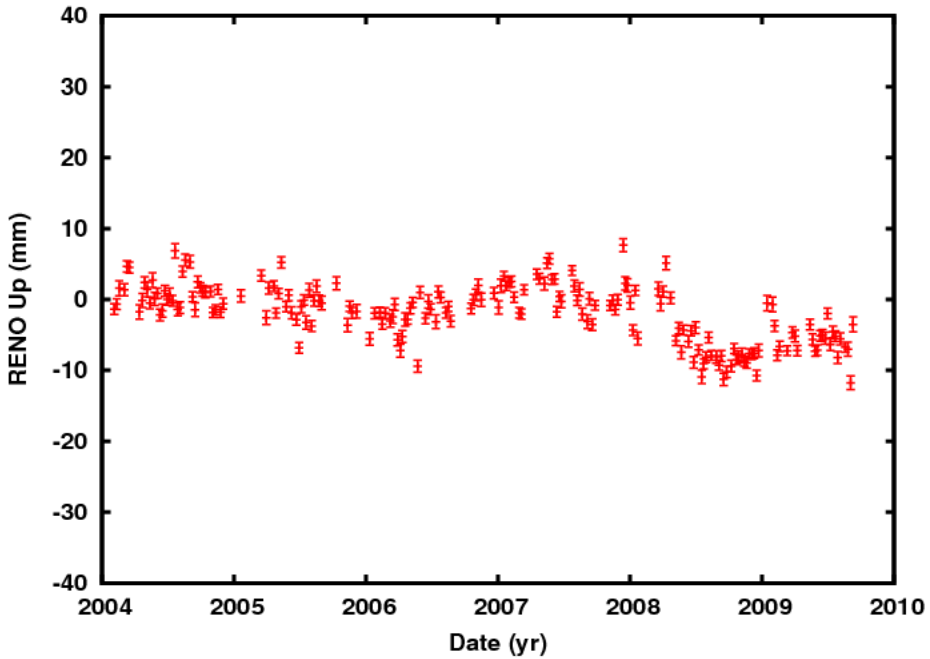
- Installed January 2004
  - MAGNET network
  - Now > 300 stations
- Fortuitous Location
  - Within Mogul swarm
  - 200 meters from M_w5.0 mainshock, April 2008!
- Smallest earthquake measured by GPS

RENO GPS

- Co-seismic offset
  - M_w 5.0, 25 April 2008
- No pre-seismic signal
- Large post-seismic slip





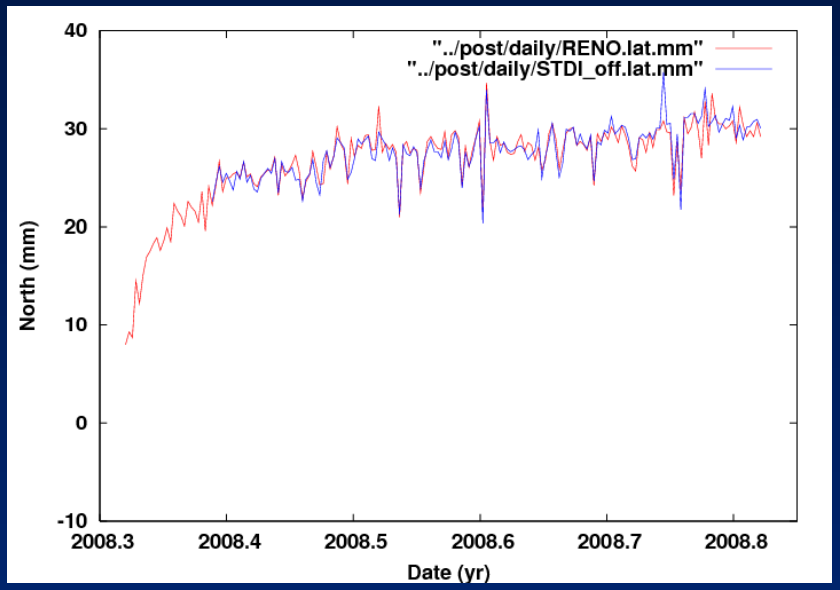


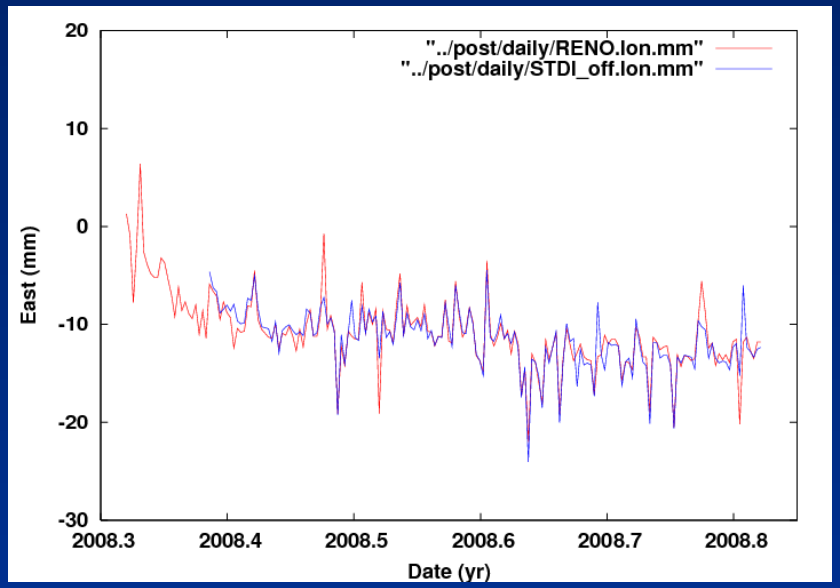
Tectonic or Triggered Landslide?

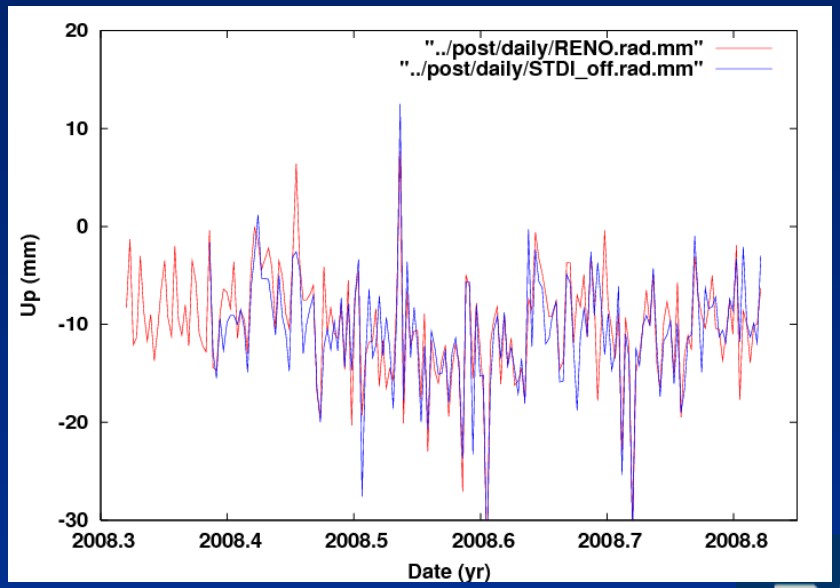
- The Mogul Landslide
  - Active ~100,000 yr
    - Last slide ~1900 induced by irrigation ditch
  - RENO
    - GPS site lies above the eastern headwall
  - STDI
    - Installed 20 May 2008
    - Above southern headwall
    - 296 m from RENO

Mogul Landslide Experiment

- RENO-STDI (296 m)
- Red = RENO
- Blue = STDI

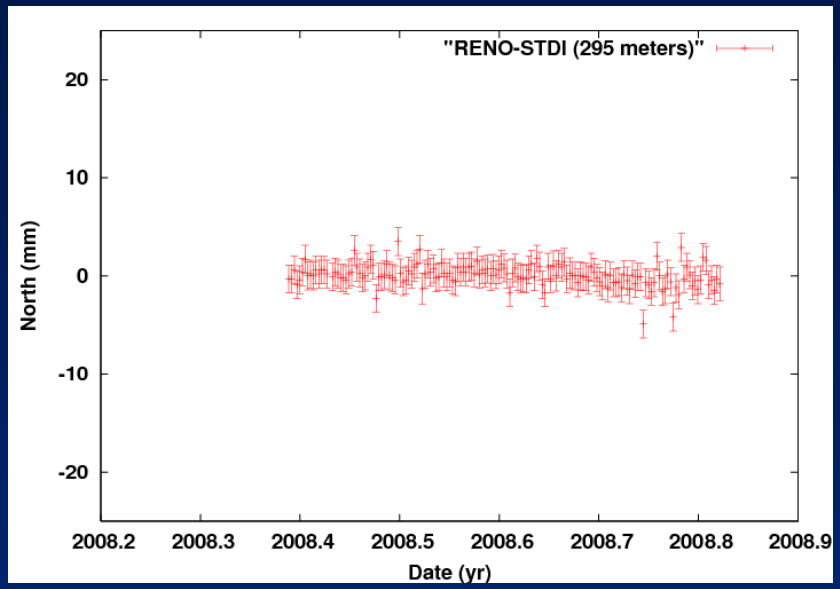


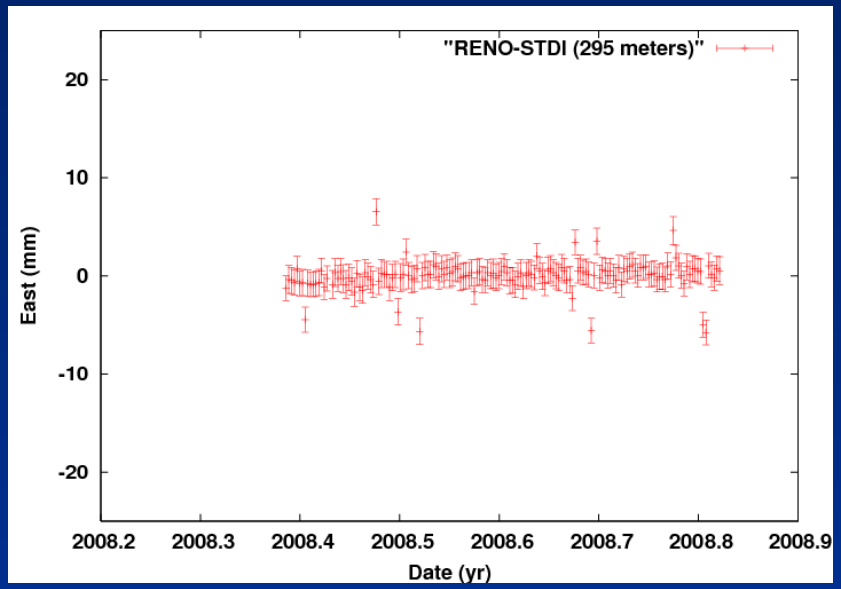


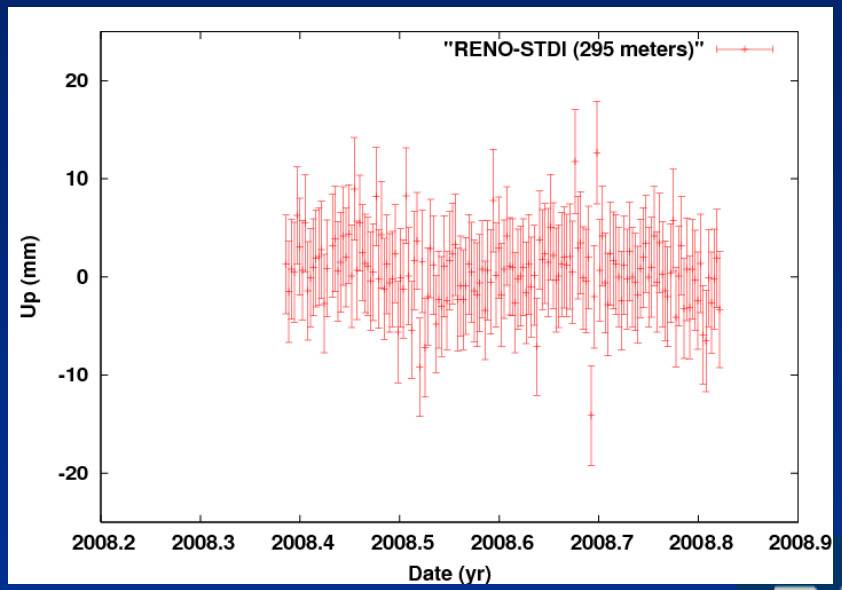


Mogul Landslide Experiment

- RENO-STDI (296 m)
- Rel. Motion << 1 mm
- Clearly no landsliding

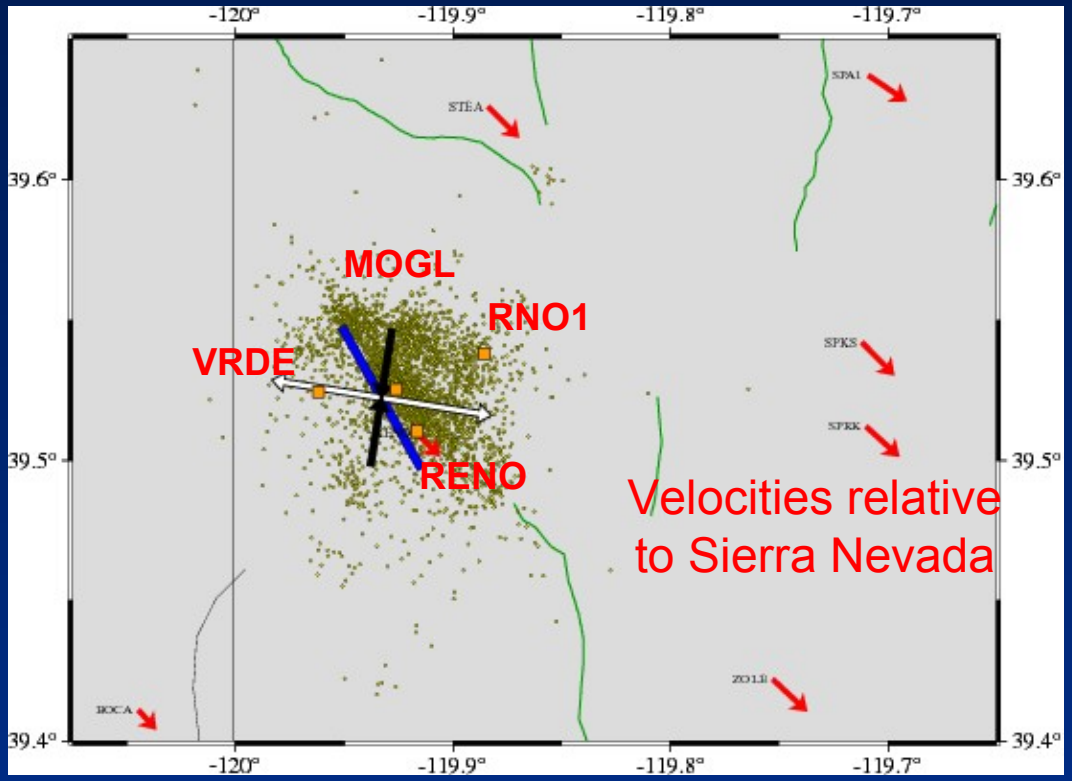






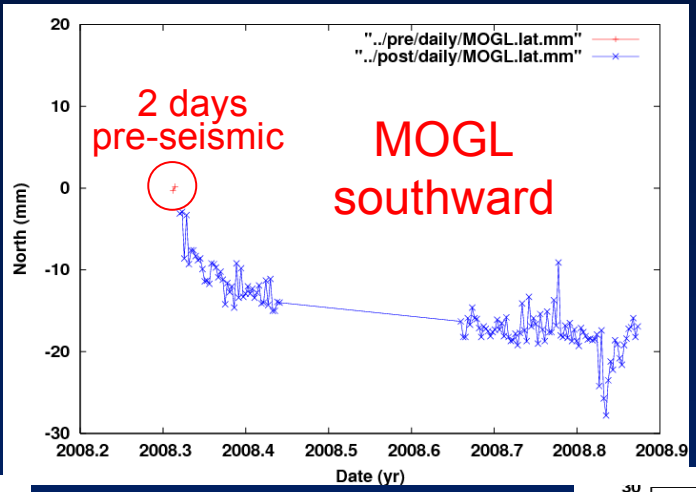
GPS Regional Strain-Rate Tensor

Pre-Seismic

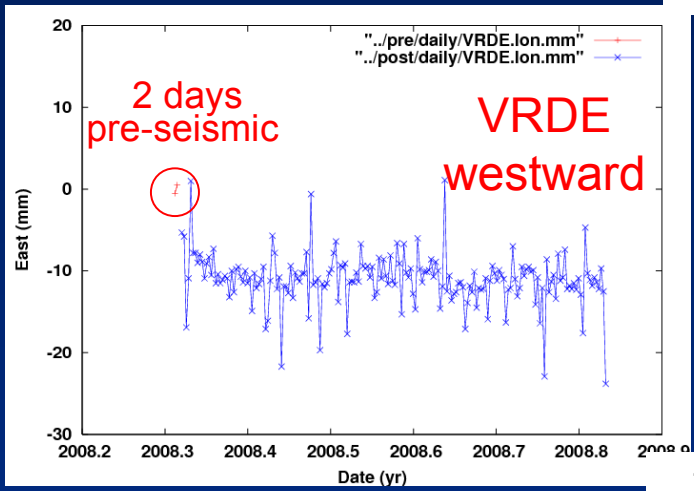


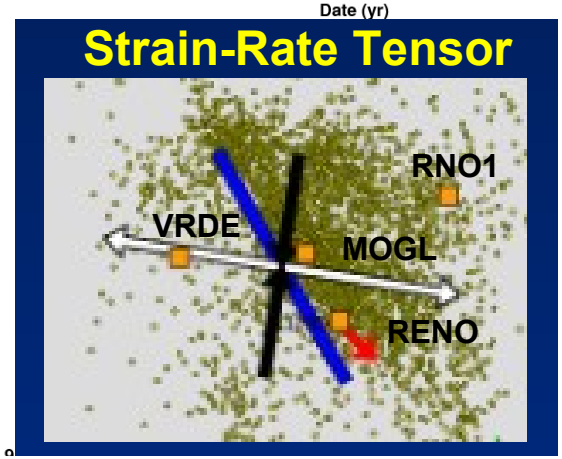
- Transtensional Strain = Shear + E-W Extension
- "No-length change" aligns with strike-slip seismicity
- Indicates tectonic response → not magmatic

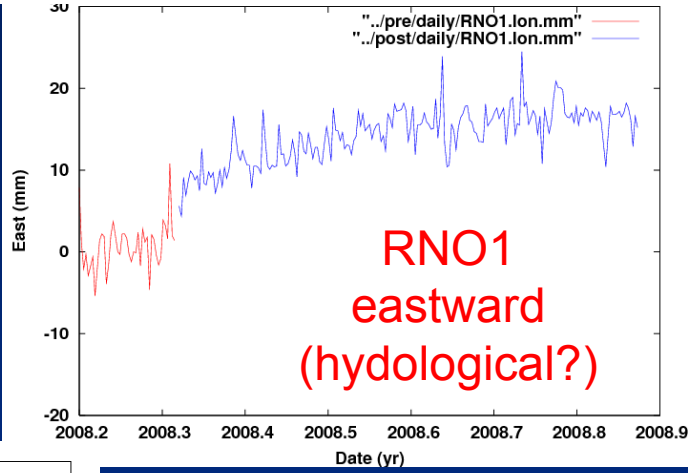
GPS Signals over few km

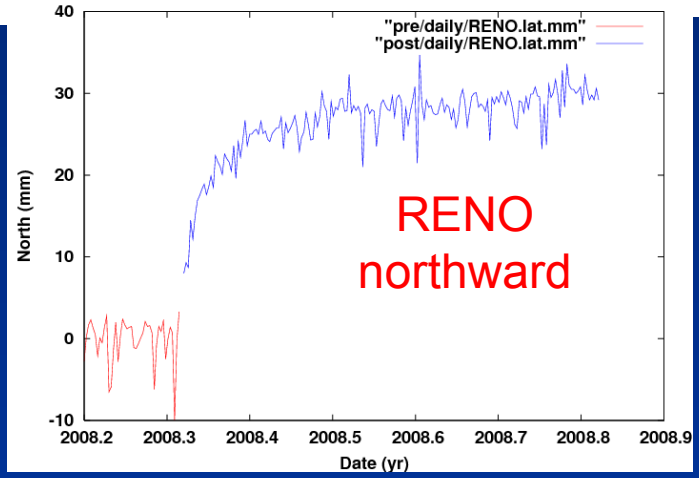


Consistent with regional inter-seismic strain tensor

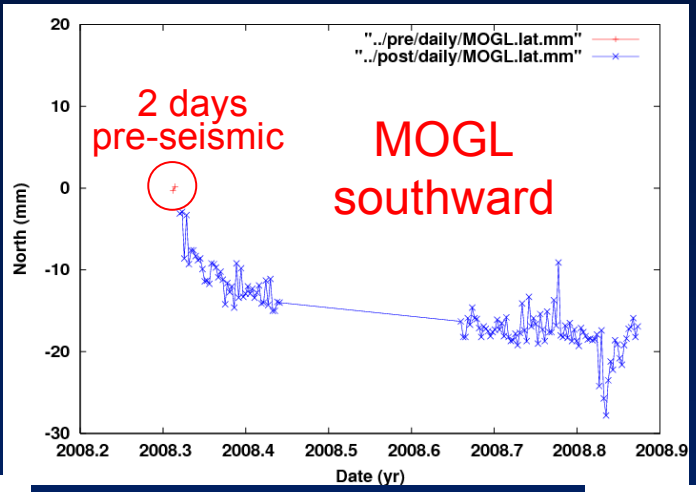




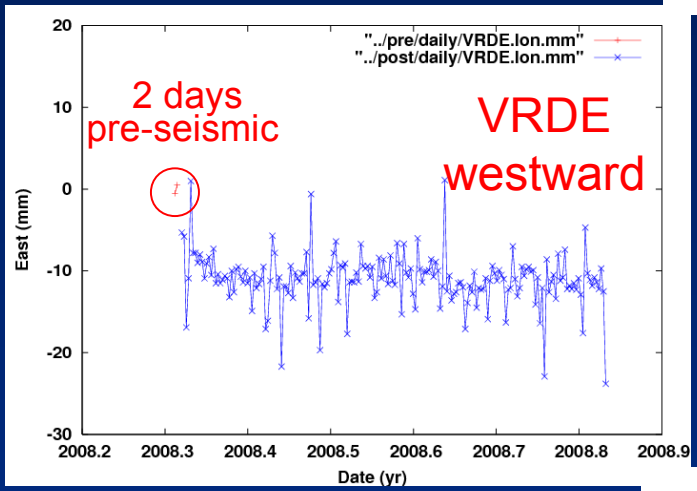


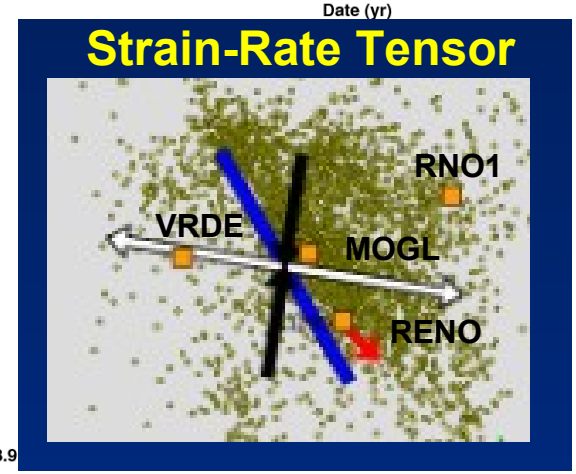


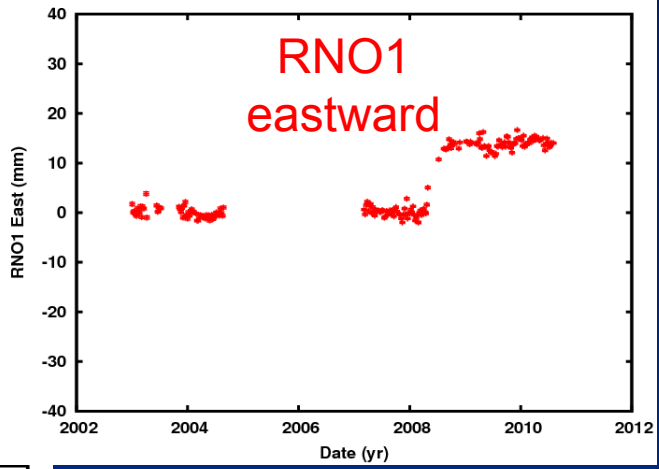
GPS Signals over few km

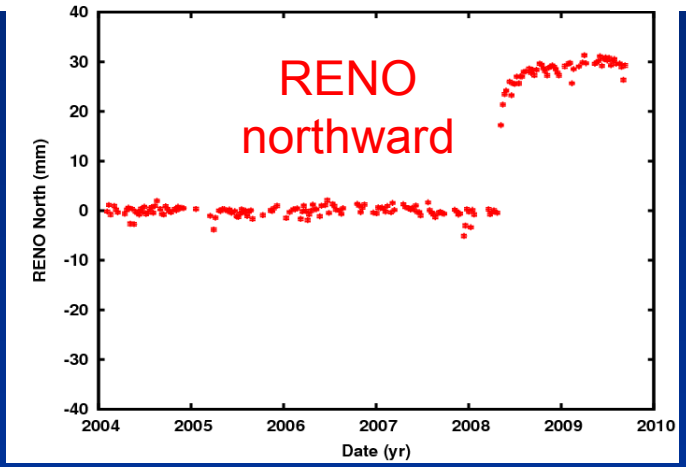


Consistent with regional inter-seismic strain tensor



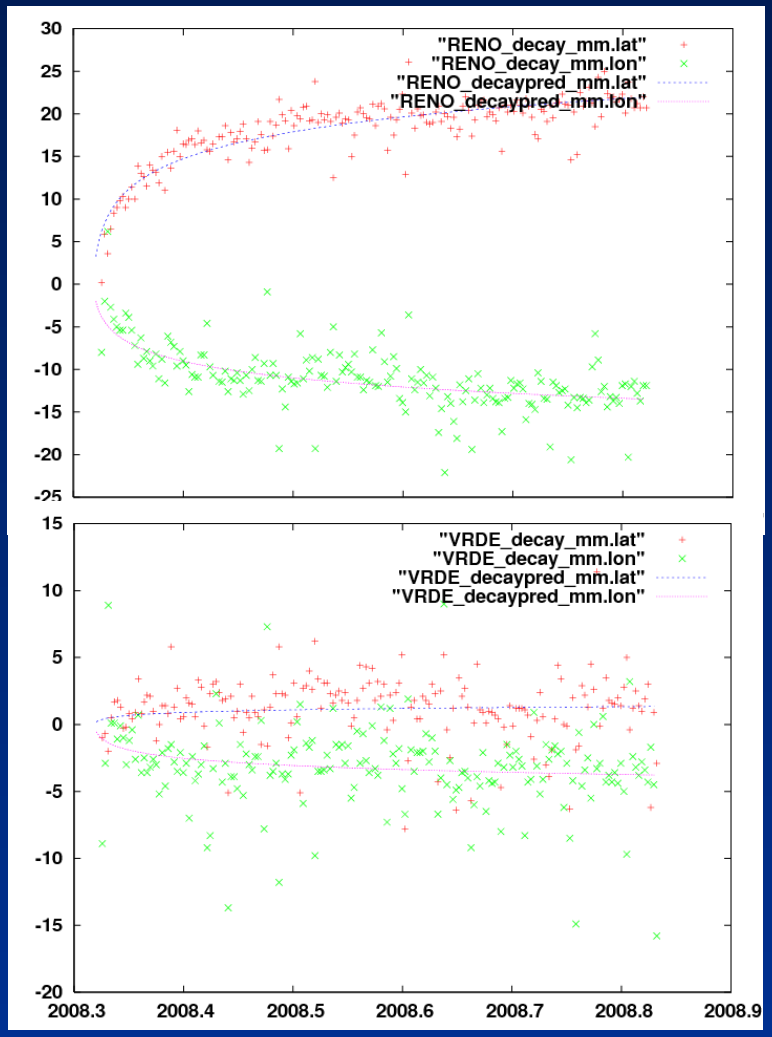


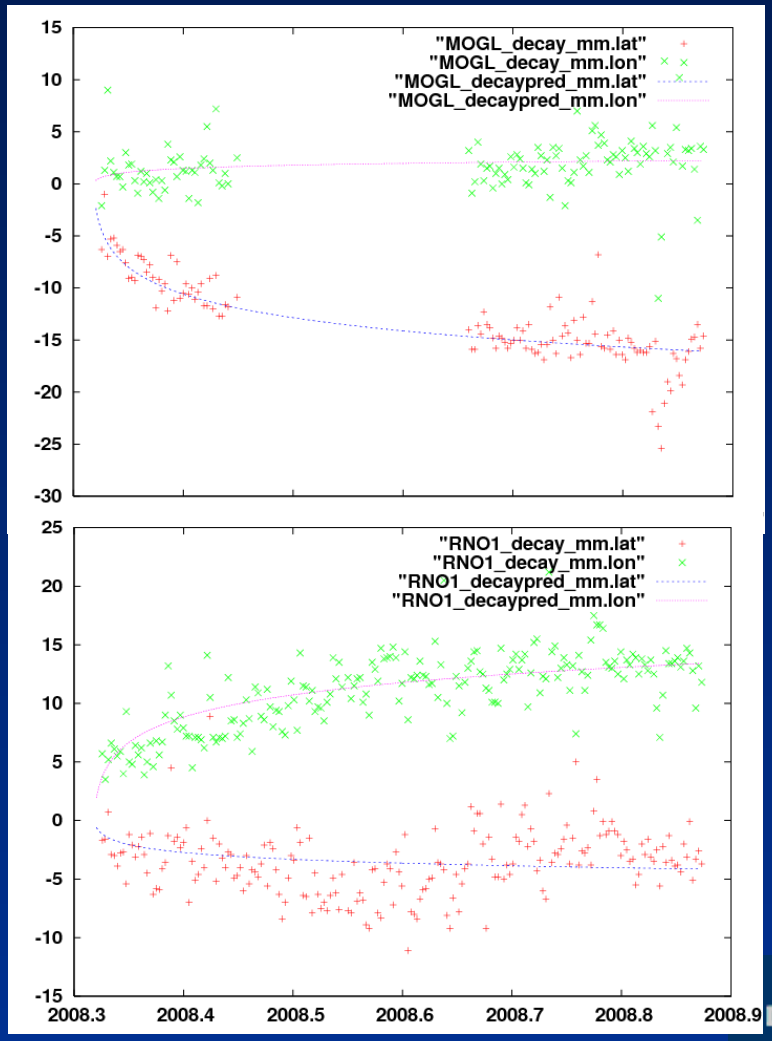




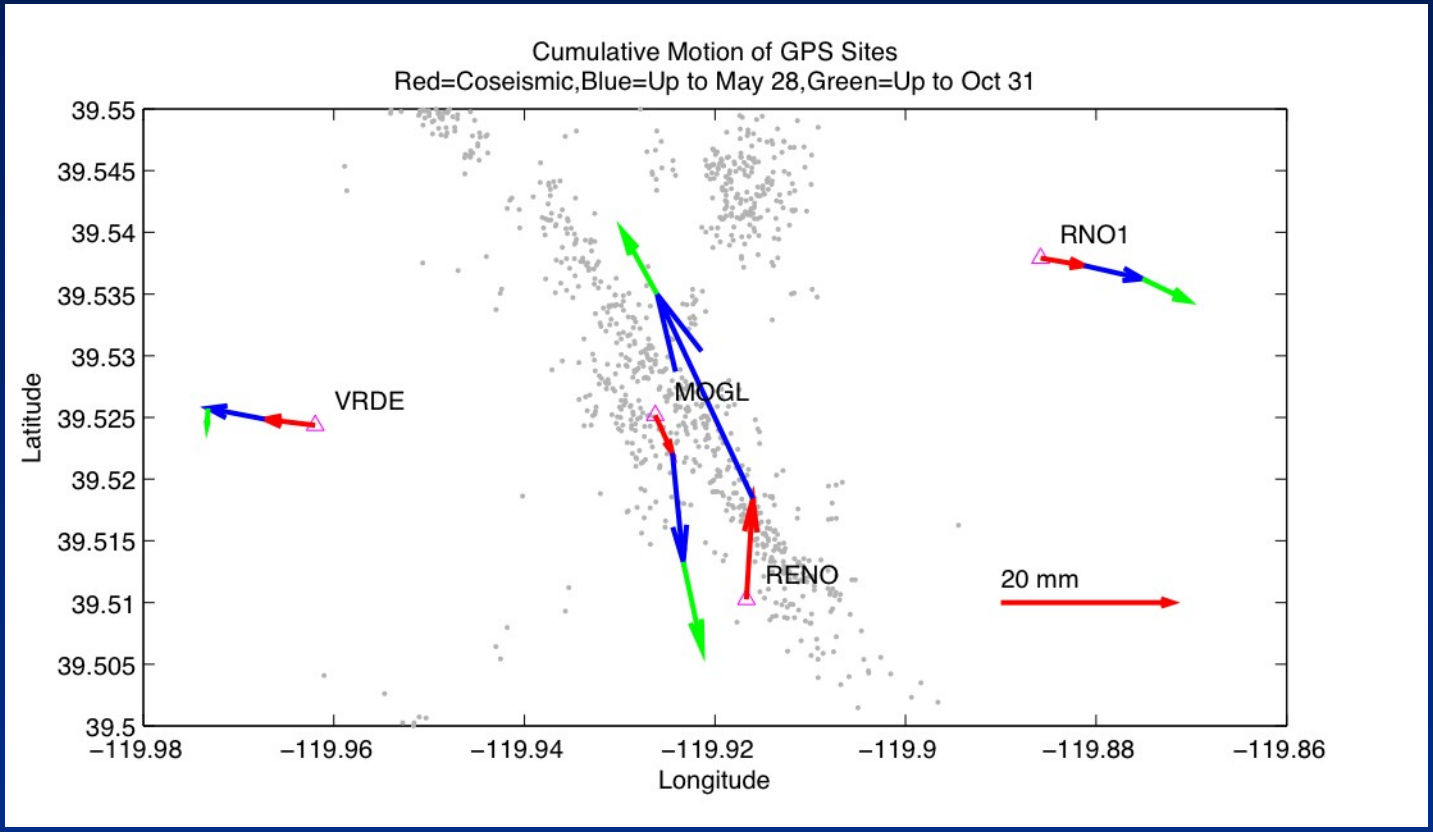
Post-Seismic After-Slip Model

- Estimated logarithmic time constant = 0.9 days

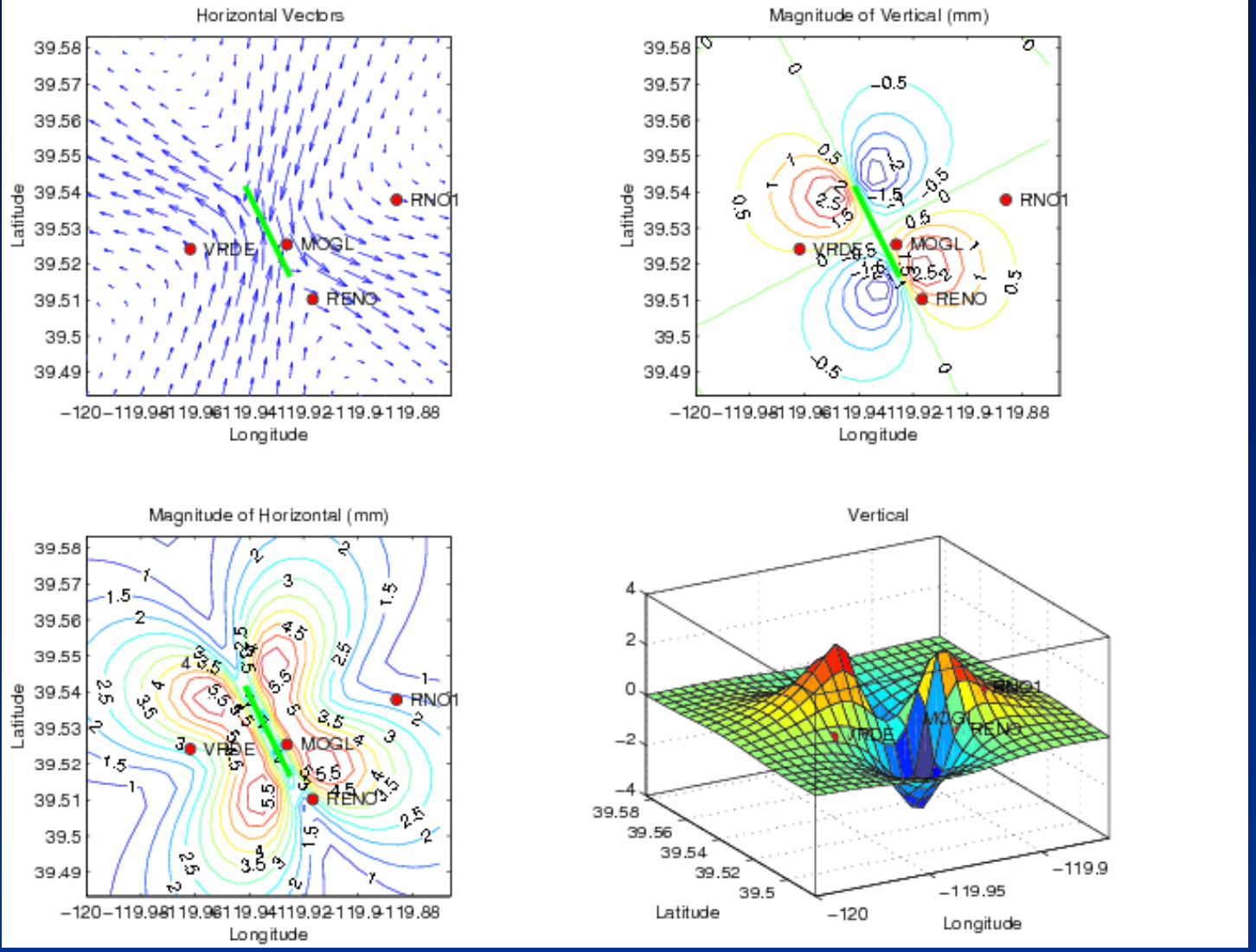




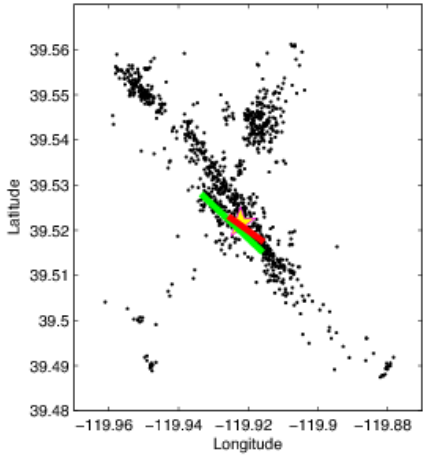
Co- and Post-Seismic Motion are closely aligned



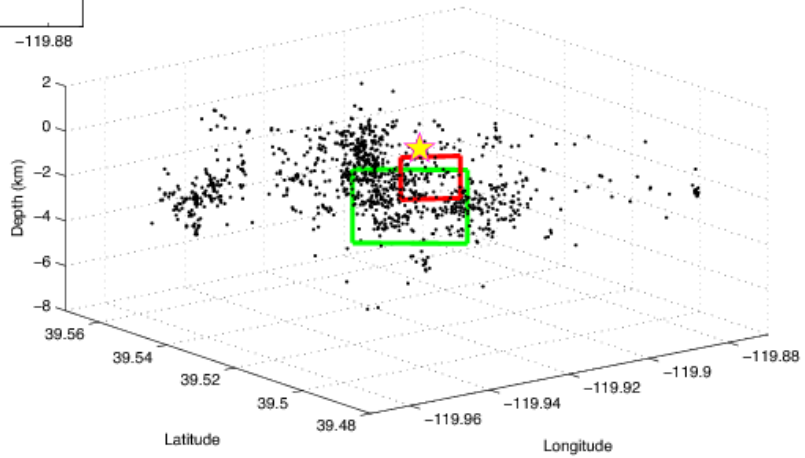
Dislocation Model



Co- and Post-Seismic Slip Model

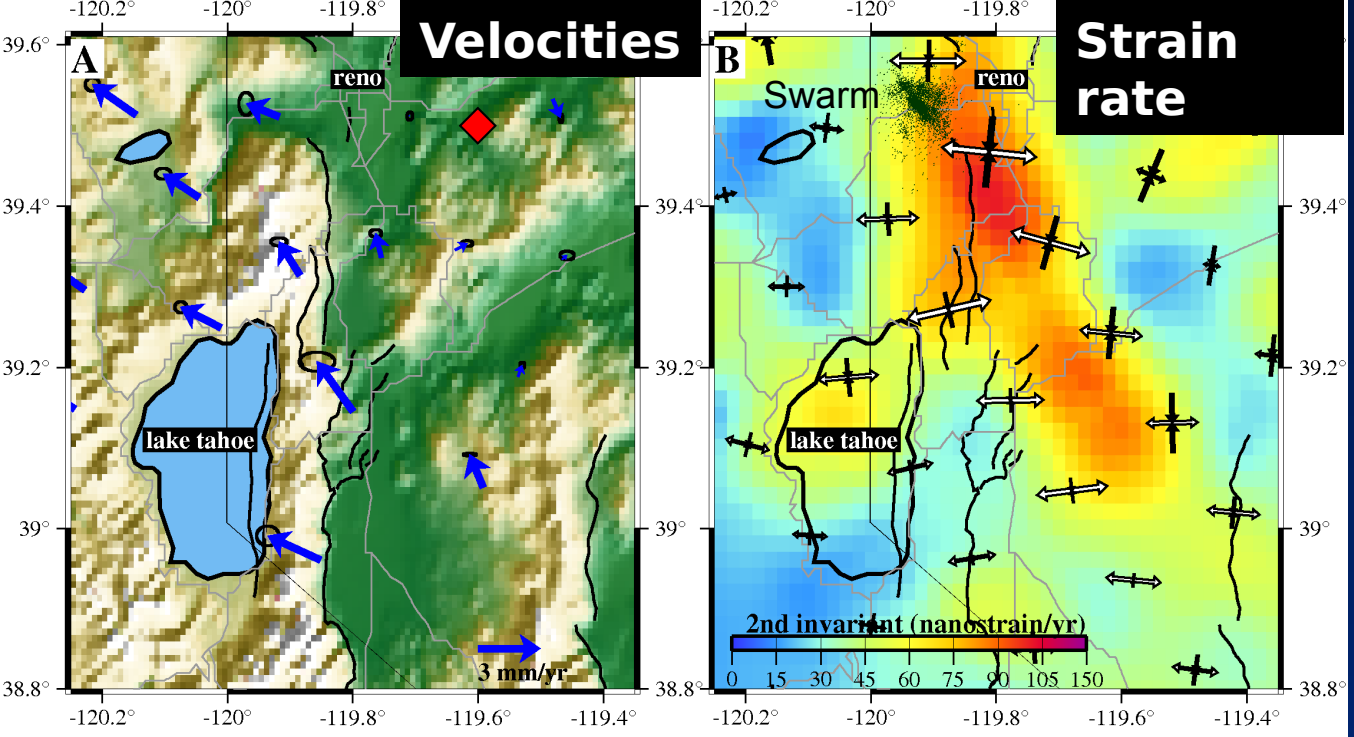


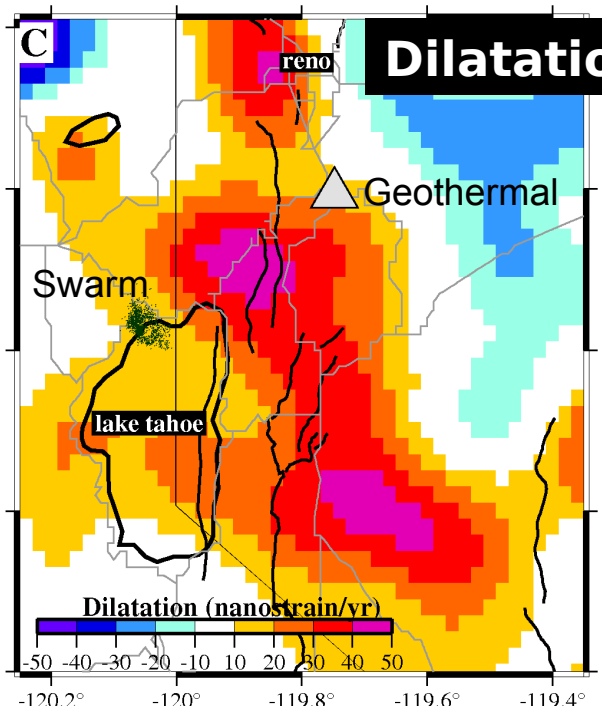
- Green:
  co-seismic (Apr 26)
- Red:
  post-seismic (to May 19)

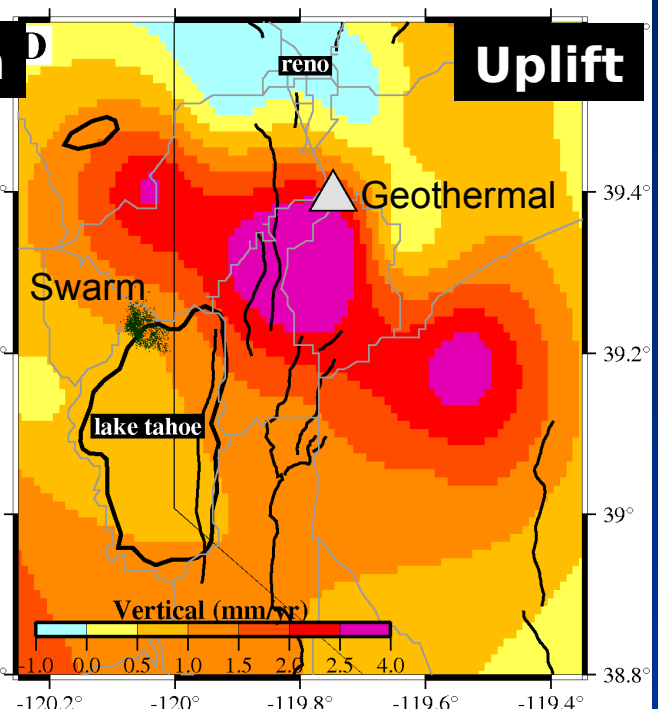


Mogul Swarm Summary

- Co-seismic displacements of M_w5.0 main shock
  - Measured at 4 GPS stations
  - Landsliding not responsible for detected GPS signal
  - Displacement pattern consistent with
    - regional strain tensor
    - swarm seismicity pattern
  - Post-seismic consistent with after-slip
- Evidence → tectonic source, not magmatic
- Hydrological signals may confound RNO1
  - "Bad" GPS site – not attached to bedrock
  - Large seasonal signal estimated and removed
  - Residual signal consistent with tectonics

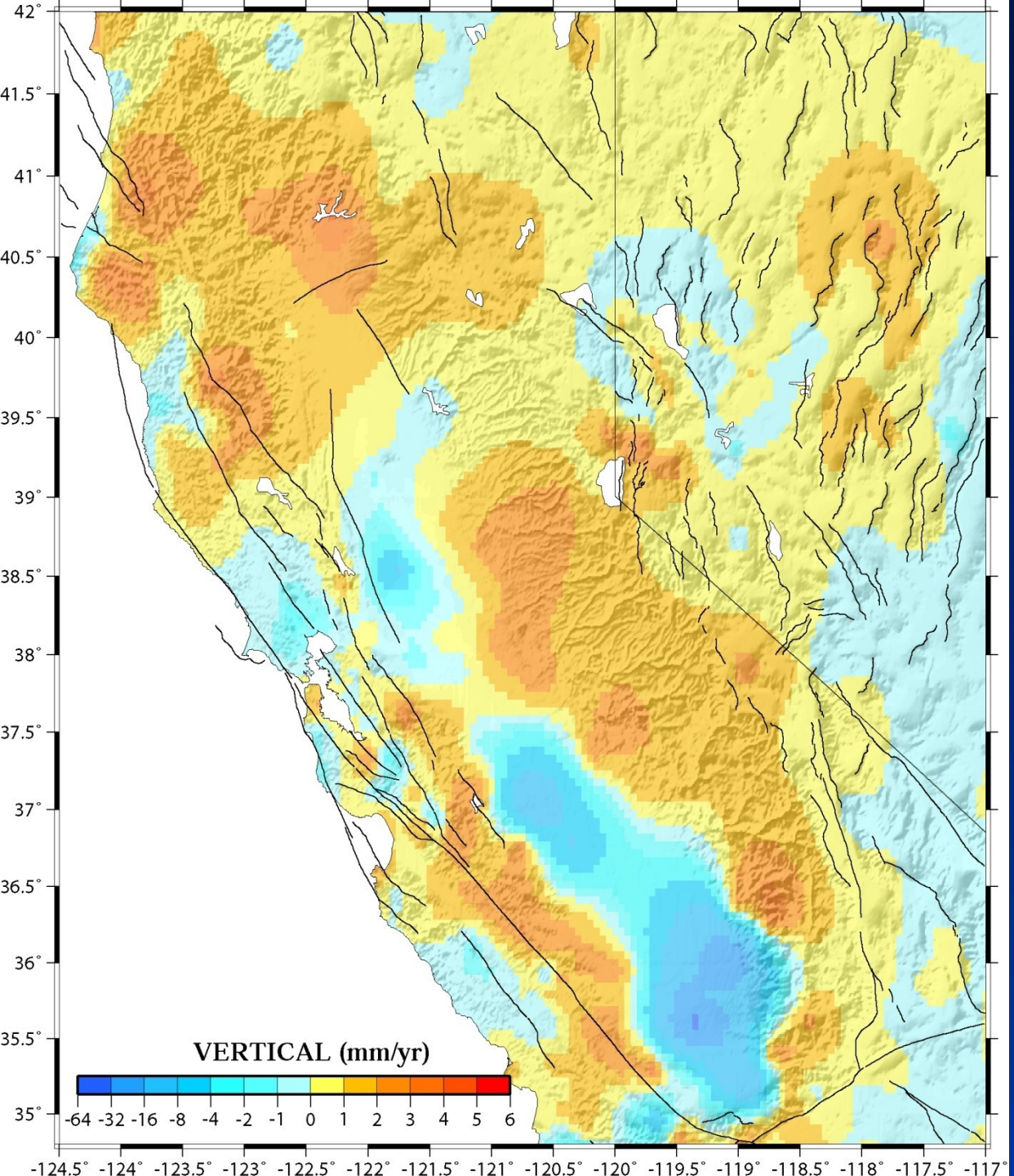






Reno-Tahoe Regional Deformation

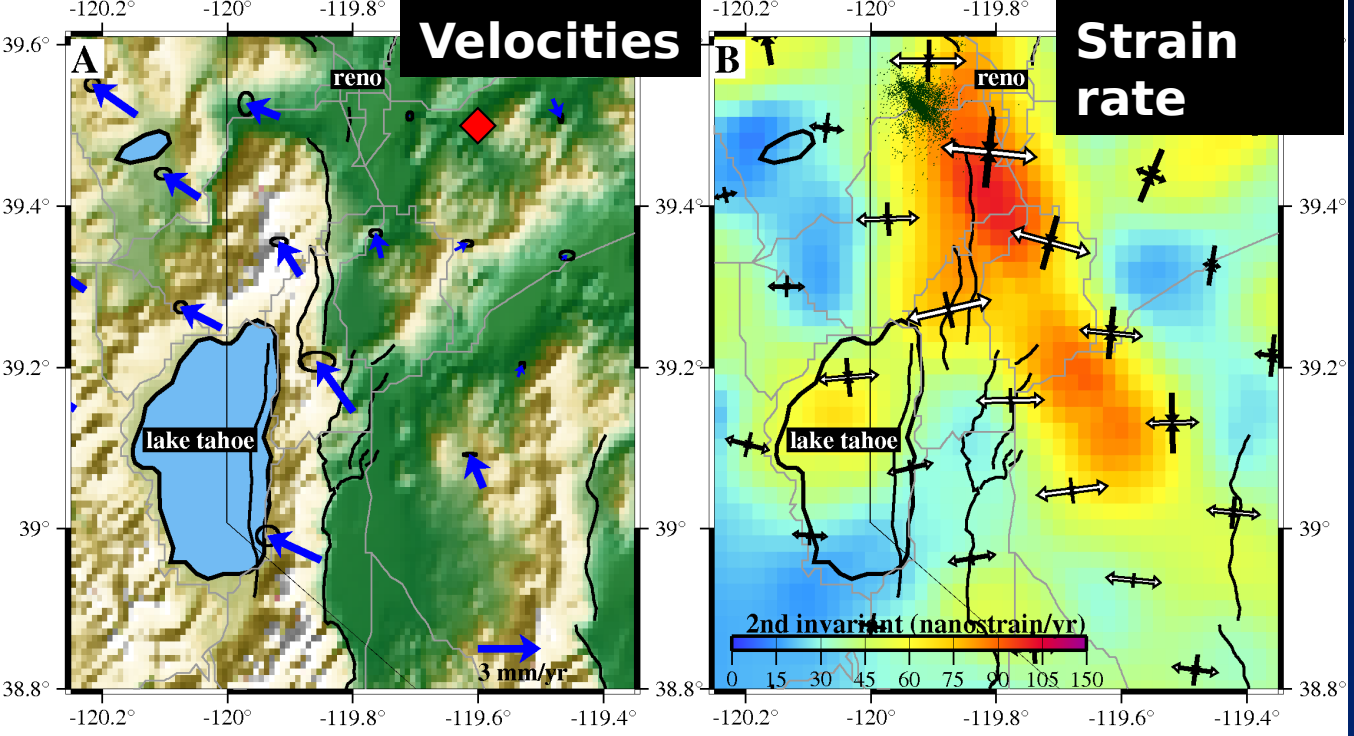
- Mix of shear and extension
- Mogul swarm consistent with high shear localized on Mount Rose fault
- Incipient fault propagation?
- Tahoe swarm consistent with magmatics
- Uplift associated dilitational stress
- Geothermal area is magmatic?

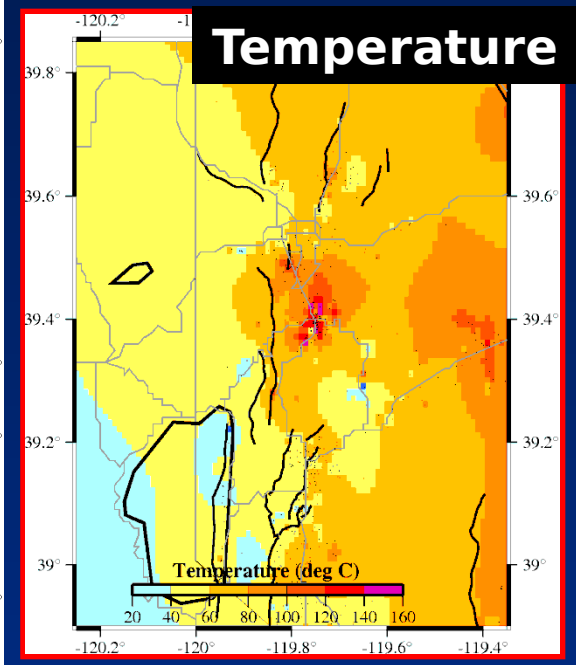


GPS Vertical Velocity Map

- Great Valley
  - Huge subsidence
  - “Bad” stations included
  - Hydrological effects
- Areas of Uplift
  - Sierra Nevada
  - Mt Lassen, Mammoth
  - CNSB (postseismic)
  - San Andreas
- Reno-Tahoe Uplift
  - Geothermally active
  - Magmatic evidence

Deformation in Reno-Tahoe Area





Extensional-magmatic relationship? (crustal doming)

Separating Signals: Lessons Learned

1. GPS+micro-seismology is powerful combination
   - Pattern + timing
   - Use all evidence to construct displacement model
2. Exploit data during relative seismic quiescence:
   - GPS Velocities → Regional Tectonics → Process(t,x)?
   - GPS Seasonal Signals → Hydrological Loading
   - Identify hydrological effects @ “bad” GPS sites
3. Consider greater regional context
   - What is typical or unusual?
4. These techniques identify magmatic-tectonic interaction in the Reno-Tahoe area