Estimating Compliance of Fault Zones using Geodetic Imaging Observations

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Southern California Earthquake Hazard

- It has been widely argued that major faults in California, and in particular southern California, are overdue for large earthquakes
- Comprehensive probabilistic-hazard source models that integrate geological, geodetic, and observed seismicity data overestimate the number of expected earthquakes in California
- A 160-year long hiatus in great earthquakes along all major plate-boundary faults in southern California and in particular the southern San Andreas and San Jacinto faults, based on paleoseismic and historical data, increases the need to reduce errors on the earthquake budget and identify the relative potential of active fault zones
- Understanding the compliance of fault zones provides for a better accounting of the proportion of aseismic versus seismogenic strain accumulation

Earthquake Hazard

Large earthquakes cause billions of dollars in damage and extensive loss of life and property

Half of the US earthquake risk lies in California

Annualized earthquake losses are $5.3B in the US and $3.5B California

Resolution of the national hazard map is coarse

Is California Overdue for a Large Earthquake?

Earthquake moment rate discrepancy of ±20%

Over a century:

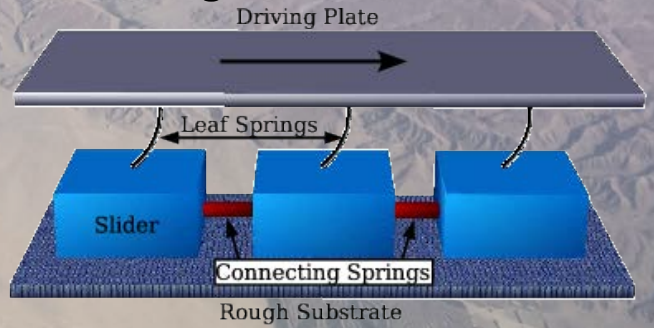
- Southern California should experience either one fewer or one more M~7.4 event
- Or a dozen Northridge sized earthquakes

The 1994 M6.7 Northridge earthquake killed 57 people and caused ~$25B in damage

The larger 1992 M7.2 Landers earthquake caused less damage

"The springs on the San Andreas system have been wound very, very tight. And the southern San Andreas fault, in particular, looks like it's locked, loaded and ready to go,"

-Tom Jordan, Past Director
Southern California Earthquake Center

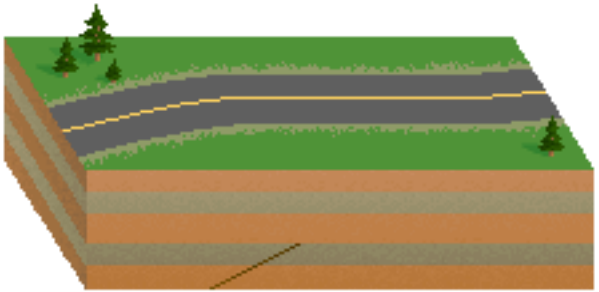


Earthquake Processes are Complex

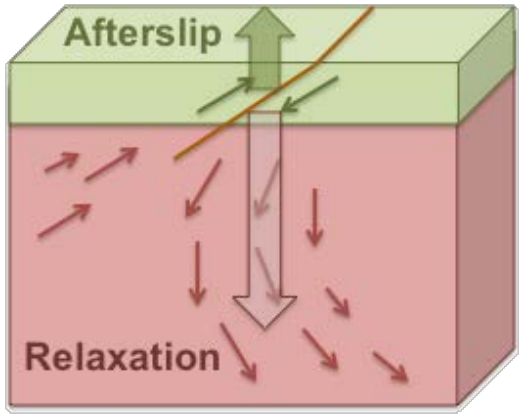
Wide range of spatio-temporal scales

Superposition of long-term tectonic motions and transient deformation

Variety of tectonic and non-tectonic sources

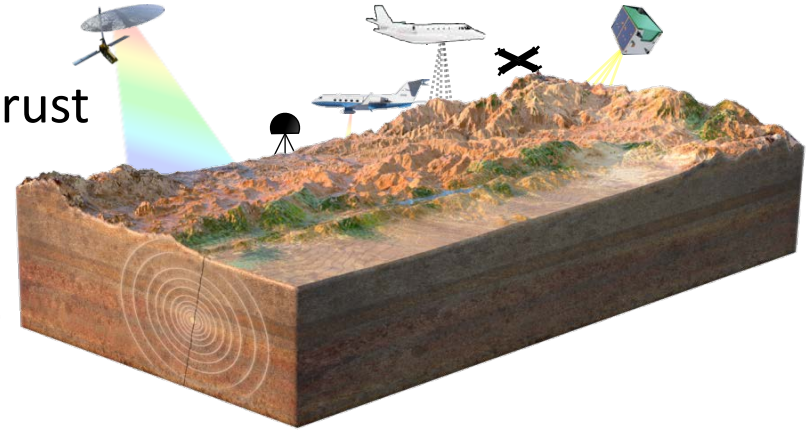


Coseismic



Geodetic Imaging

- Probes a wide range of measures of the spatio-temporal behavior of faults and the crust
- Useful for improving earthquake hazard assessment and forecasting
  - Reduce the uncertainty of potential earthquake location and magnitude

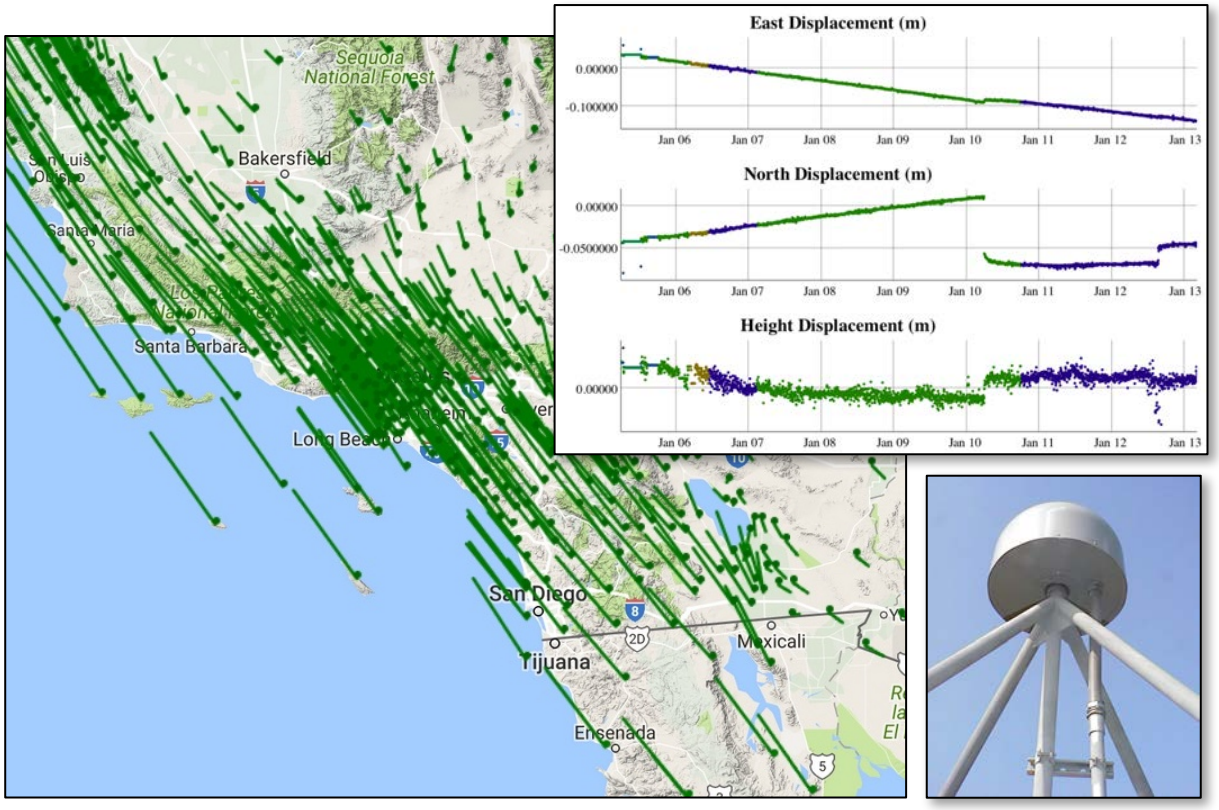


Technique	Measurement	Temporal Resolution	Measurement Accuracy	Spatial Resolution	Coverage
GPS	Velocity Displacement	5 min – daily ≤25 years	~1 mm ~1 mm/yr	~10 km	California Western US
UAVSAR	Displacement	3 – 12 months 8 years	1 cm	7 m	San Andreas fault system
Topography	Geomorphology Displacements	Baseline Yearly	5 cm – 2 m	5 cm – 2 m	Active California faults

GPS Measures Deformation to 1 mm/yr

Station spacing typically about 10 km in tectonically active parts of California

Rates of deformation are nonlinear following large earthquakes and can take years to decay

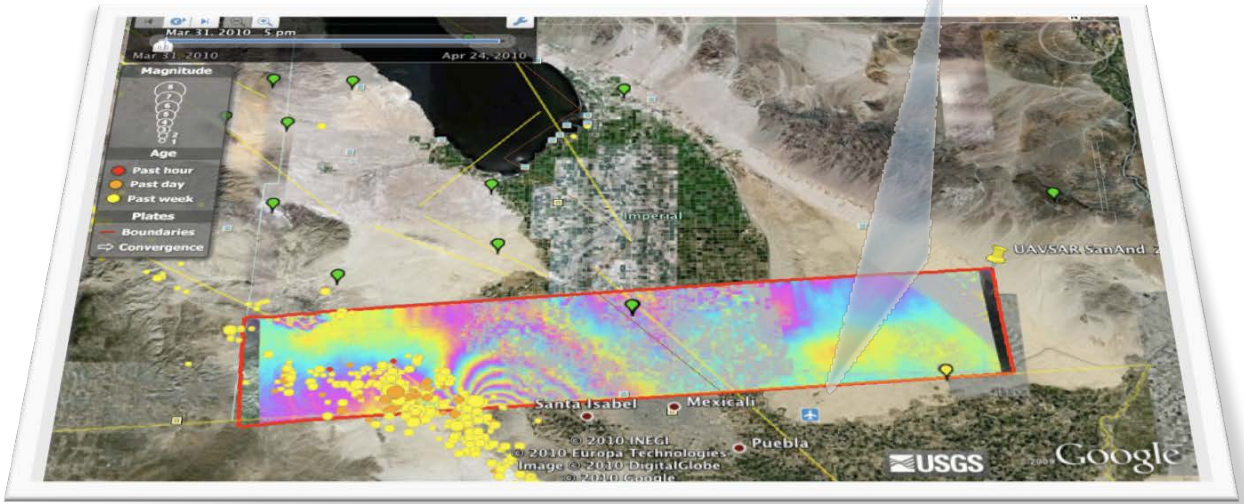


UAVSAR

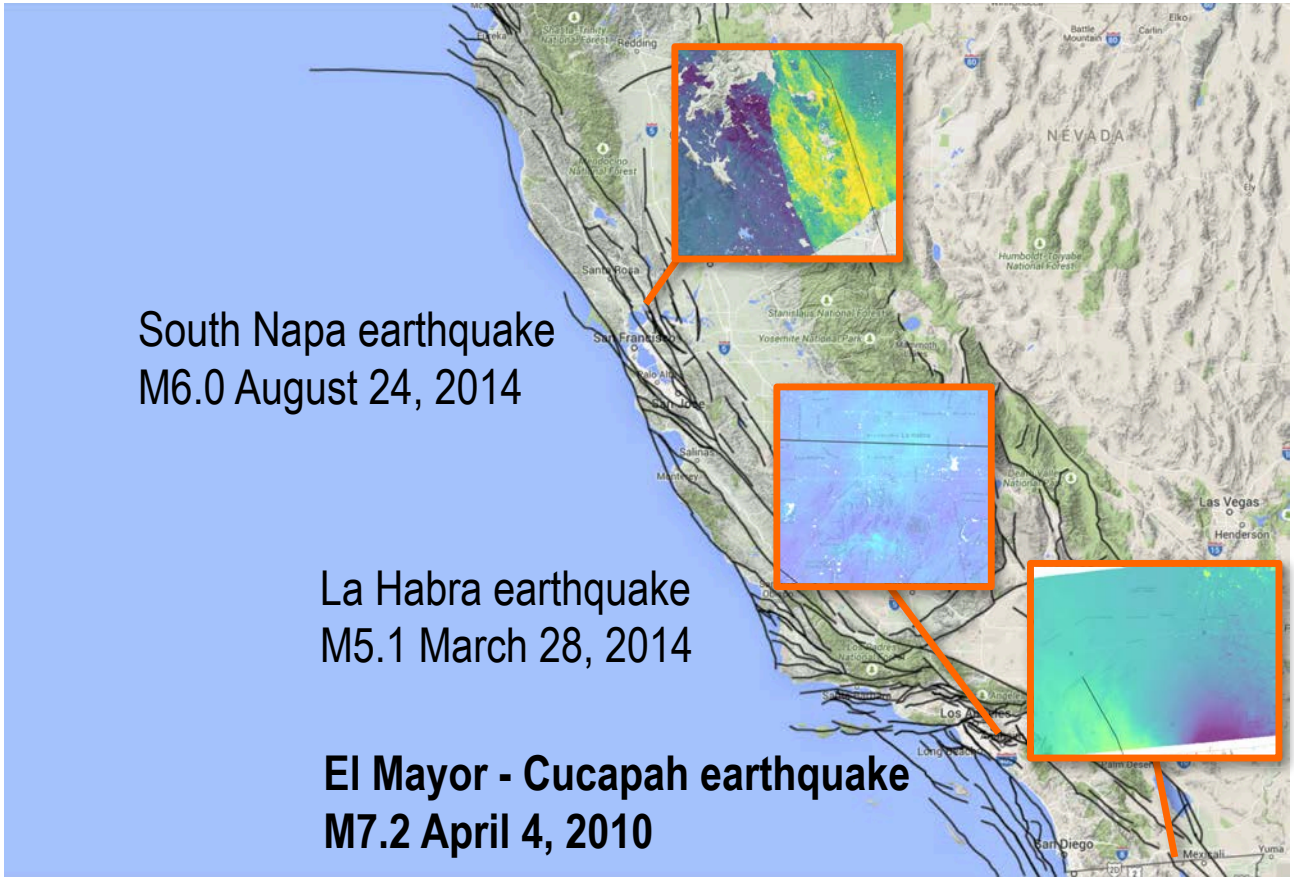
- Airborne Interferometric synthetic aperture radar (InSAR)
- Products provide ground changes in a line of sight direction to/from the instrument

UAVSAR

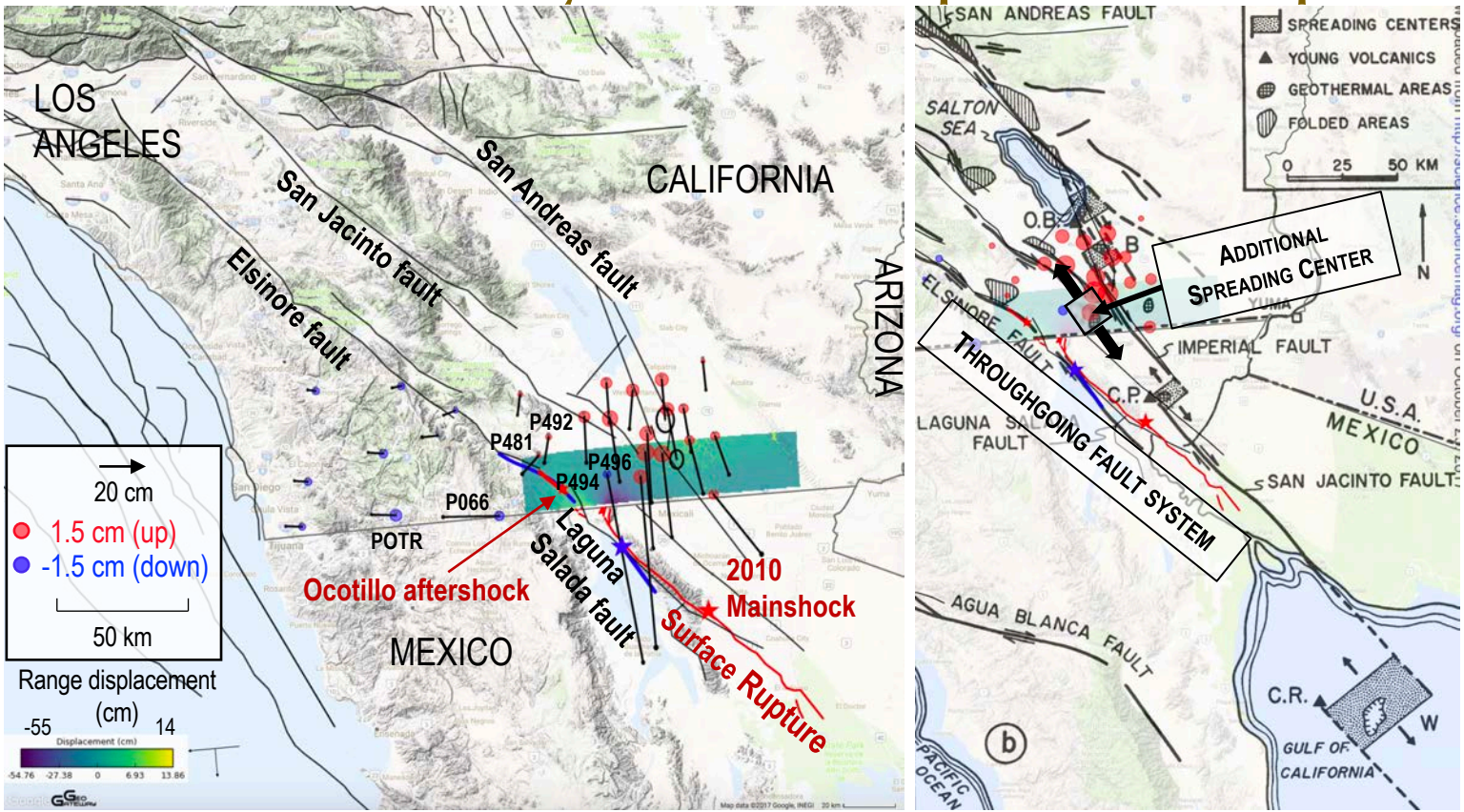
- Airborne InSAR
- L-band (24 cm wavelength)
- Repeat pass interferometry
- Flown on a Gulfstream III
- Color cycle is 12 cm



Earthquakes Observed with UAVSAR



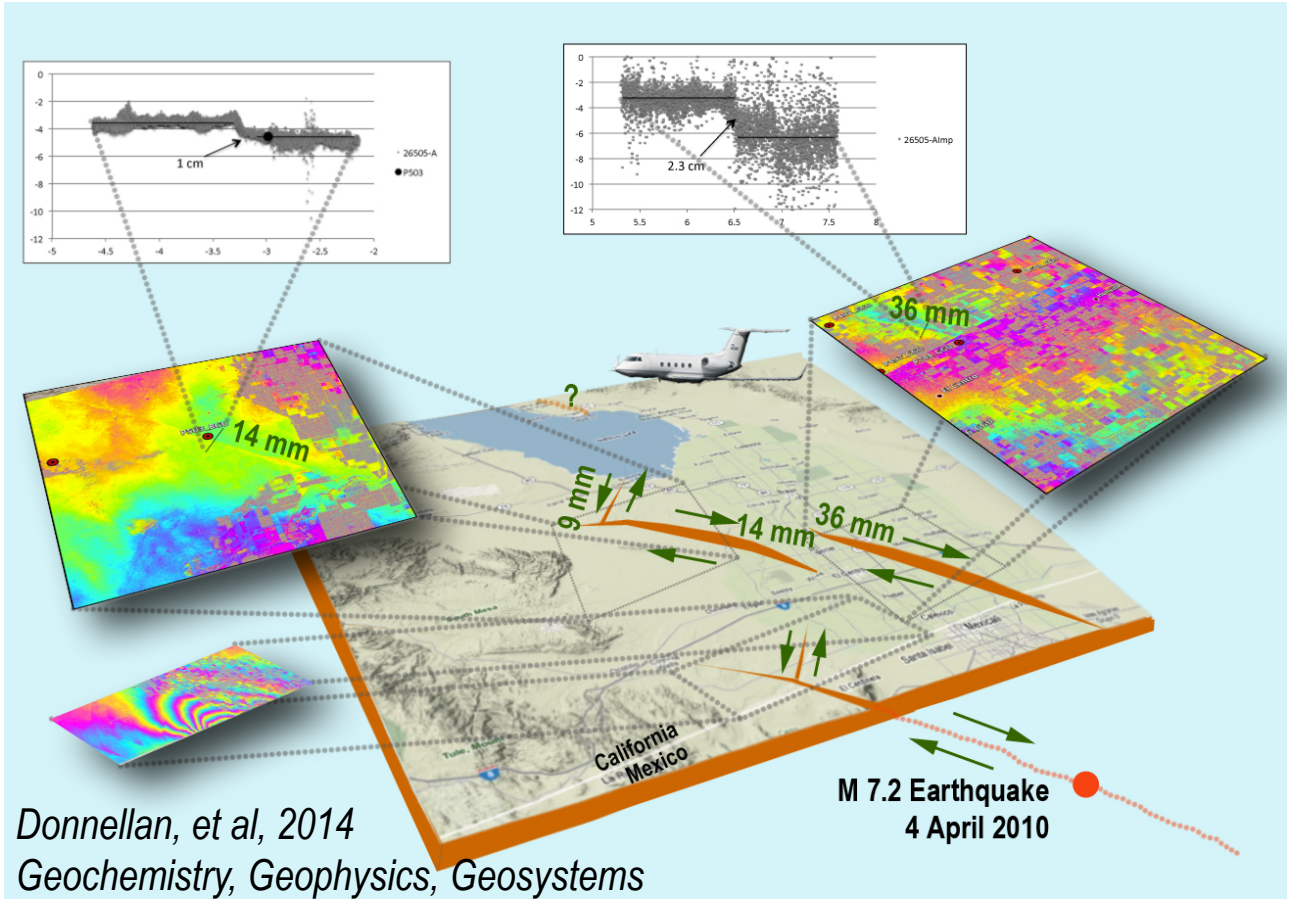
2010 M7.2 El Mayor – Cucapah Earthquake



Donnellan et al, Fracture Advancing Step Tectonics Observed in the Yuha Desert and Ocotillo, CA Following the 2010 M_w7.2 El Mayor – Cucapah Earthquake submitted to Earth and Space Science

Triggered Slip in Salton Trough

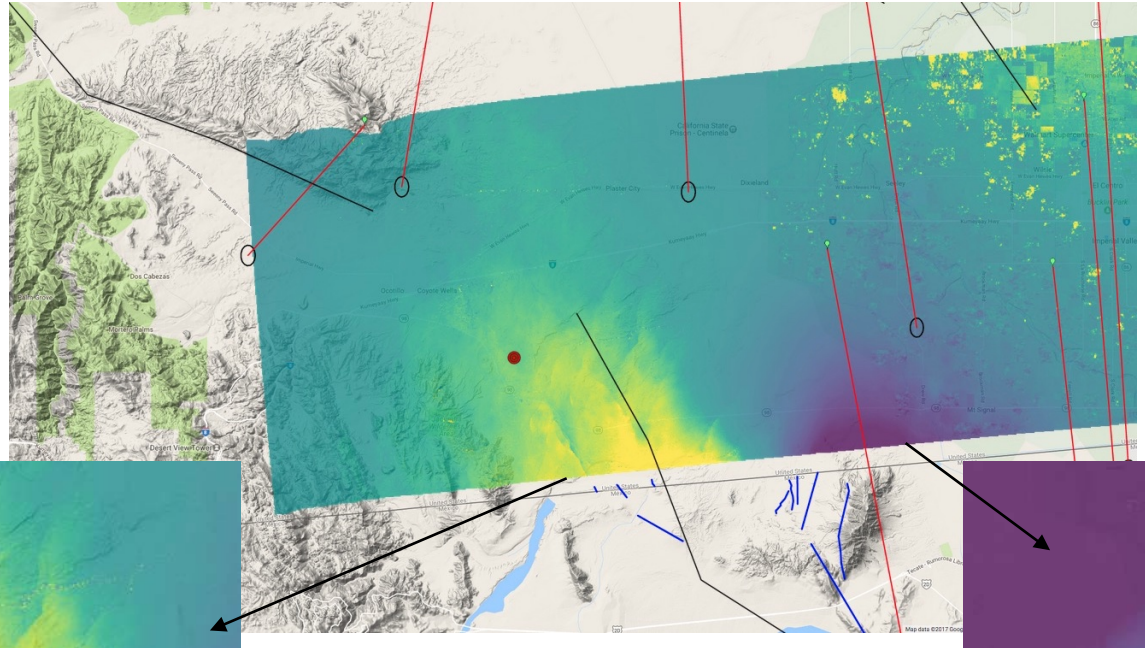
- Shallow slip triggered on a network of faults up to and including the San Andreas fault
- GPS too sparse to determine depth
- Slip decreases and depth increases toward Salton Sea



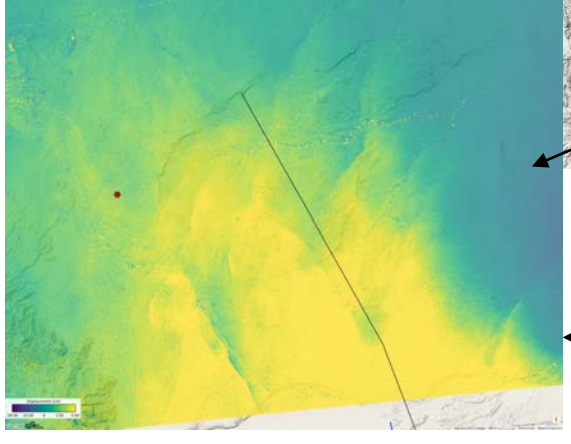
Donnellan, et al, 2014
Geochemistry, Geophysics, Geosystems

Asymmetric Pattern of Surface Disruption

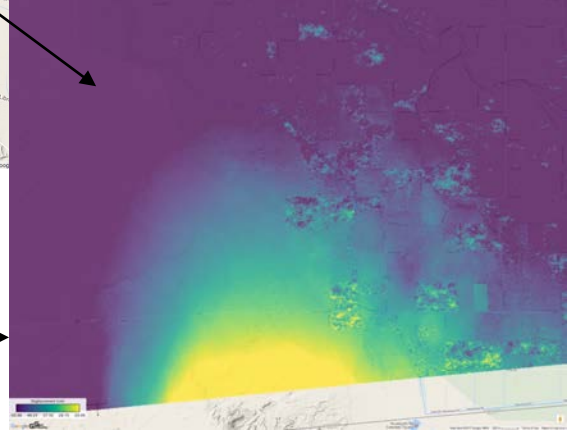
More surface fracturing to northwest

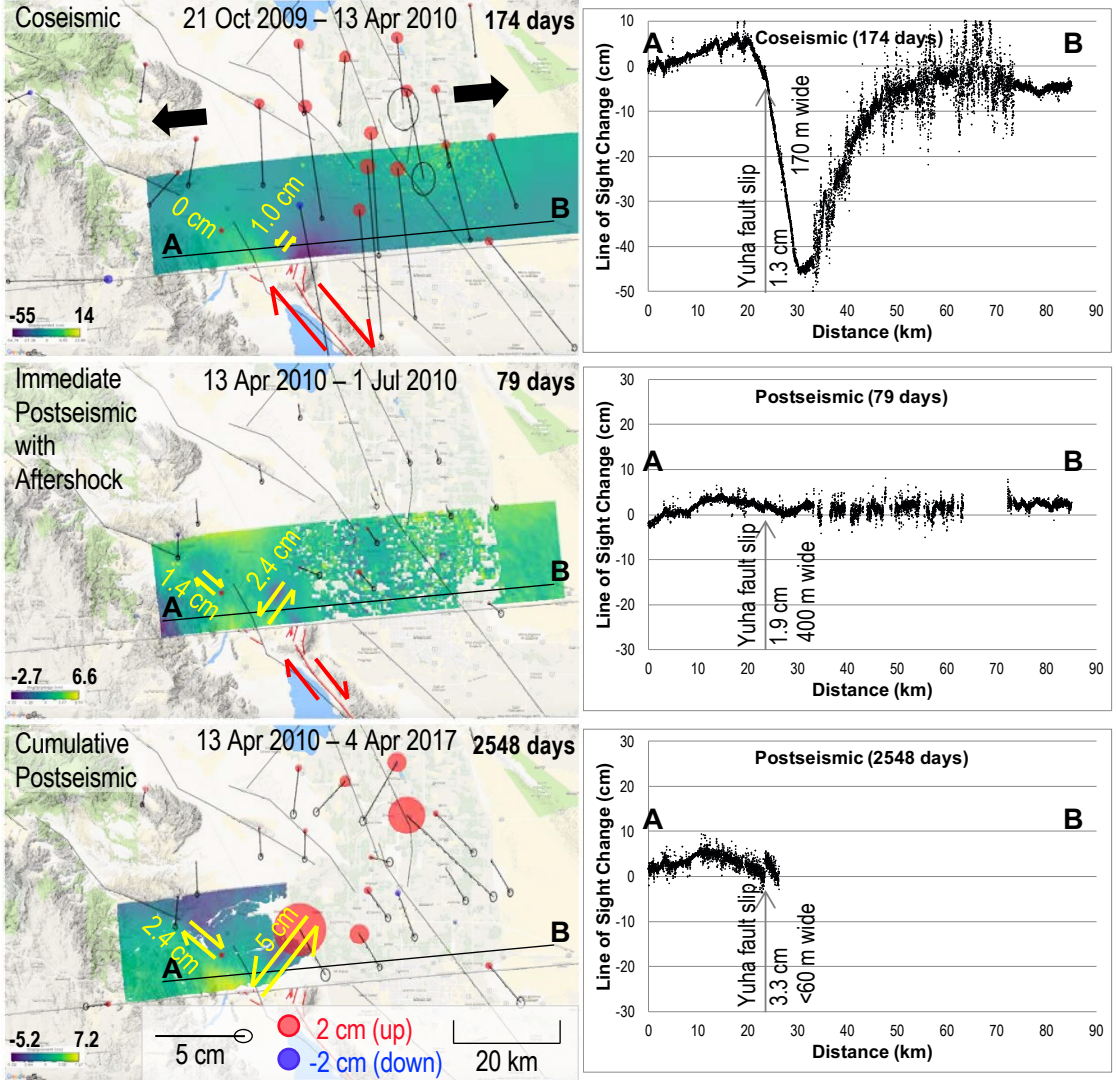


Smoother surface deformation to northeast but considerably more overall motion

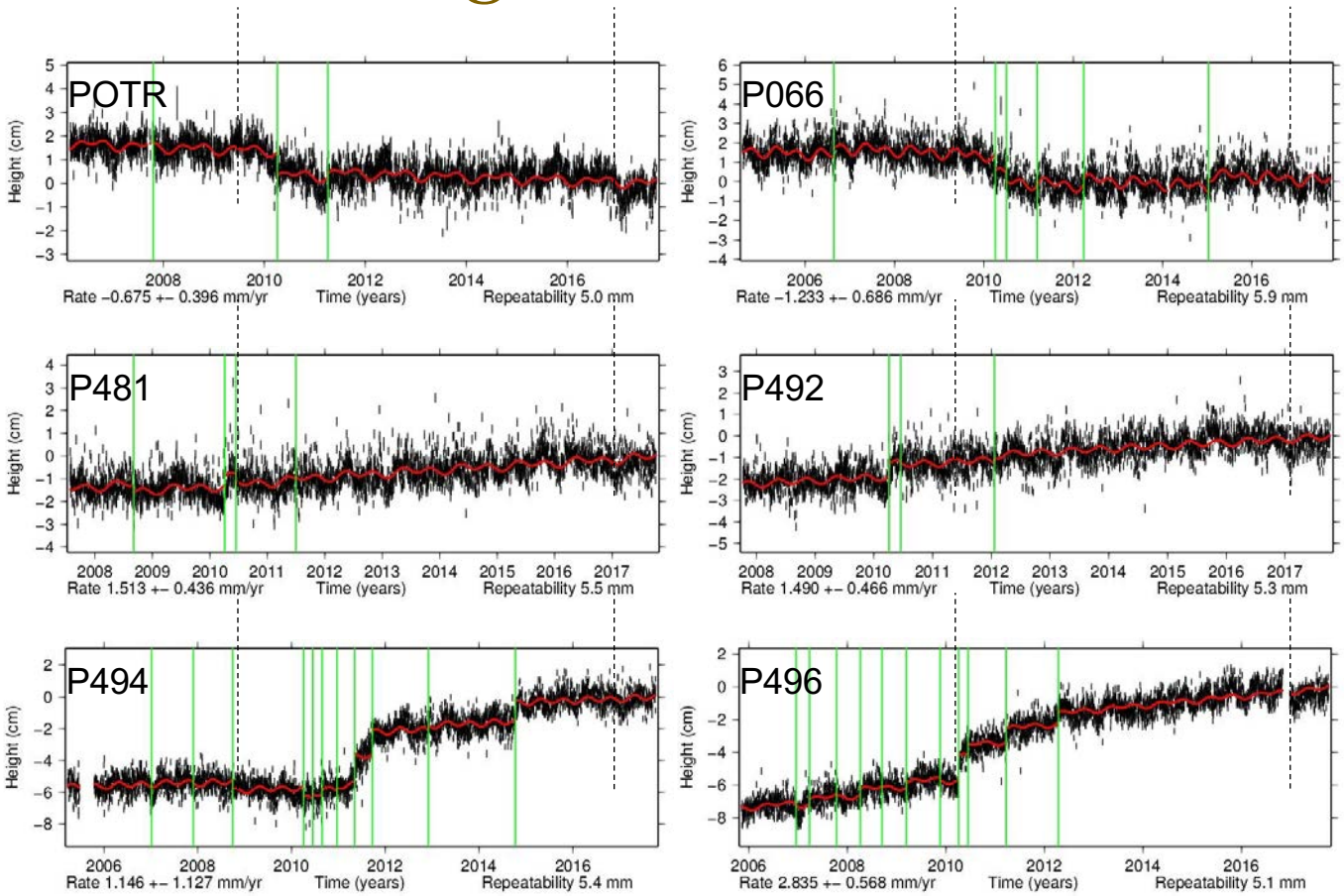


stretched color scale

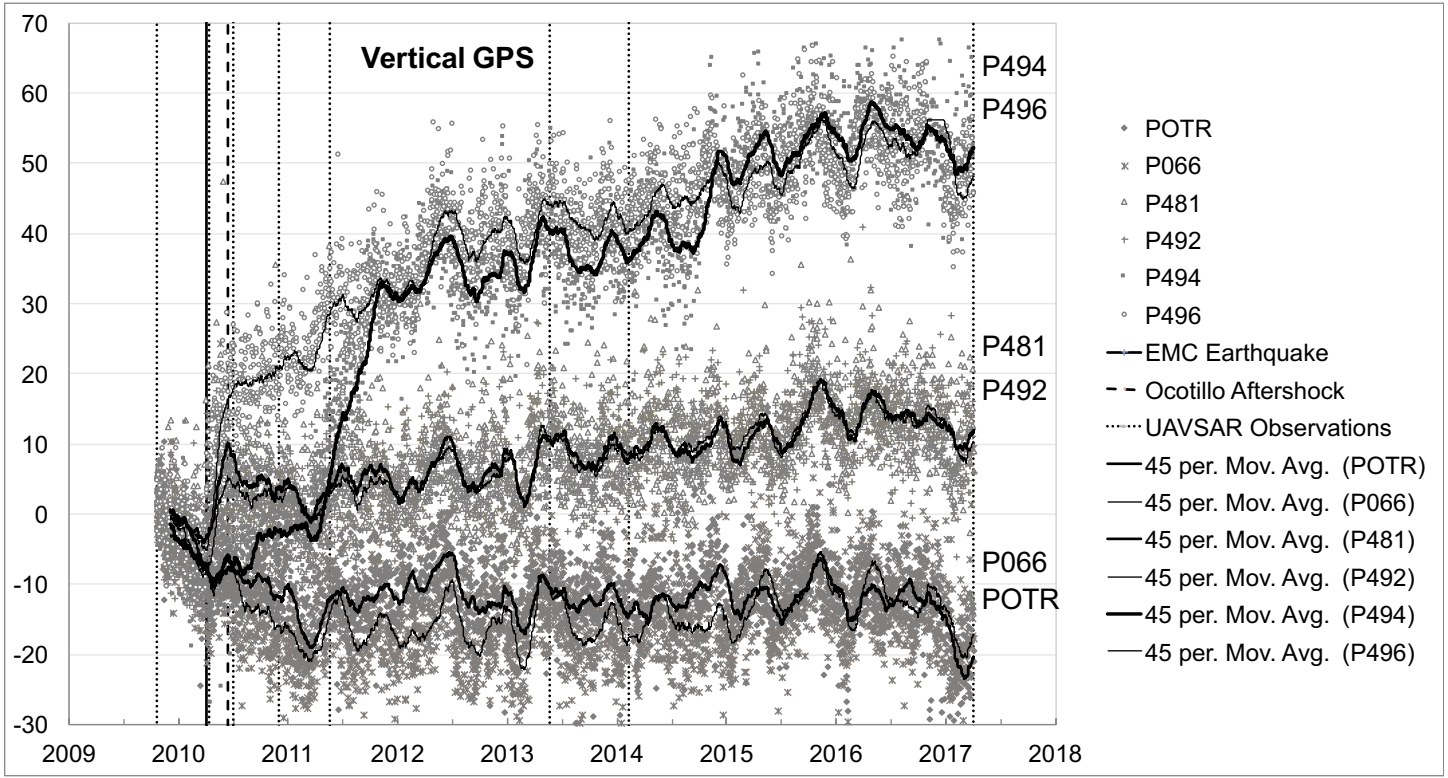



Coseismic
21 Oct 2009 – 13 Apr 2010
174 days
0 cm
1.0 cm
A
B
-55
14
Coseismic (174 days)
Line of Sight Change (cm)
Distance (km)
Yuha fault slip
1.3 cm
170 m wide
Immediate Postseismic with Aftershock
13 Apr 2010 – 1 Jul 2010
79 days
1.4 cm
2.4 cm
-2.7
6.6
Postseismic (79 days)
1.9 cm
400 m wide
Cumulative Postseismic
13 Apr 2010 – 4 Apr 2017
2548 days
2.4 cm
5 cm
-5.2
7.2
5 cm
2 cm (up)
-2 cm (down)
20 km
Postseismic (2548 days)
3.3 cm
<60 m wide

GPS Long-Term Time Series

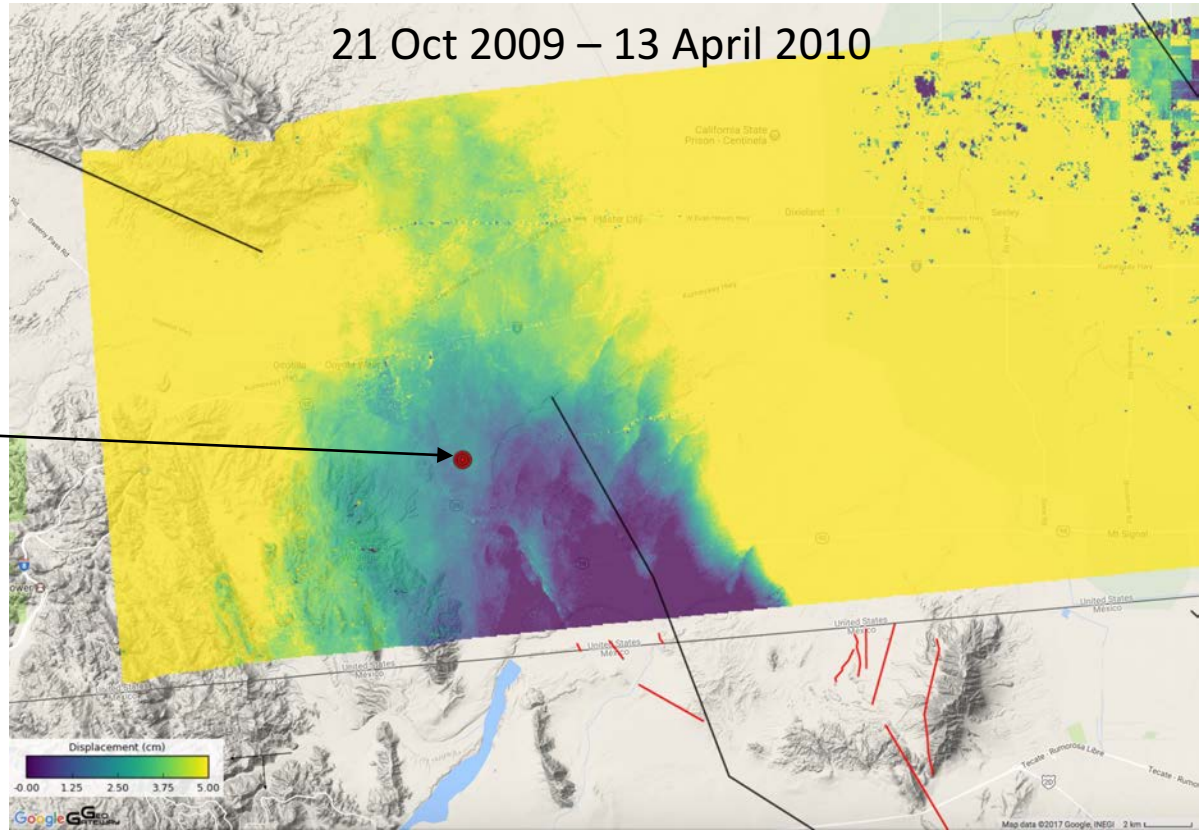


GPS Time Series 2009 – 2017



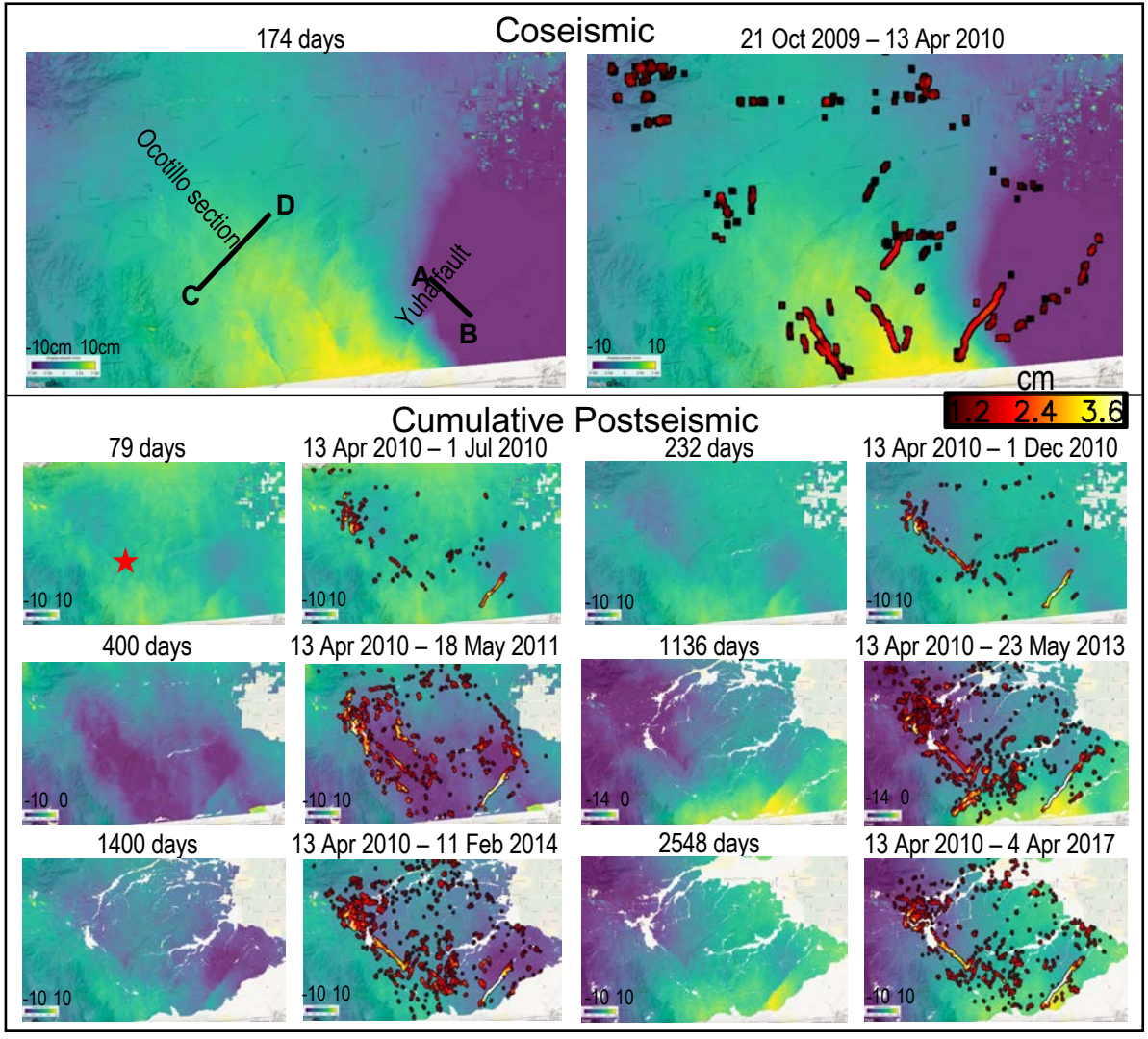
Coseismic Deformation Northwest of Rupture

Location of M5.7
15 June 2010
aftershock

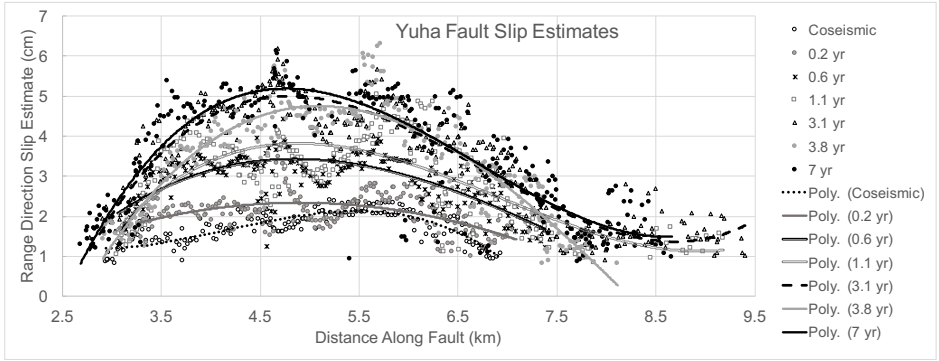


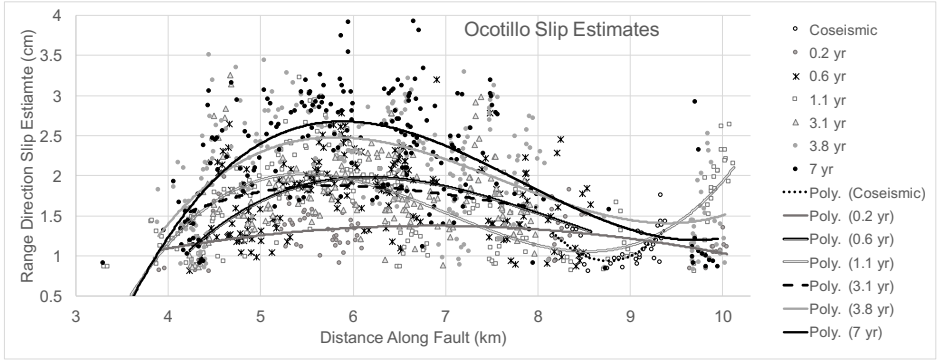
SanAnd_26501_09083-010_10028-000_0174d_s01_L090HH_C2

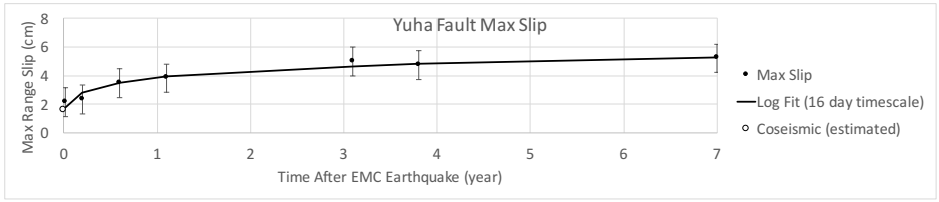
Automated Edge Detection

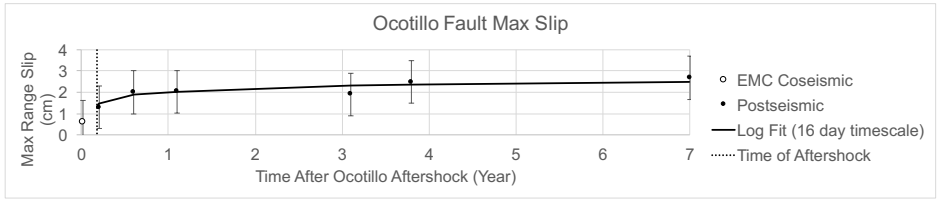


Automated Slip Estimates

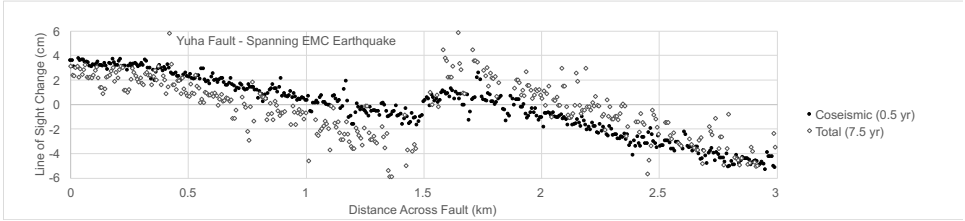


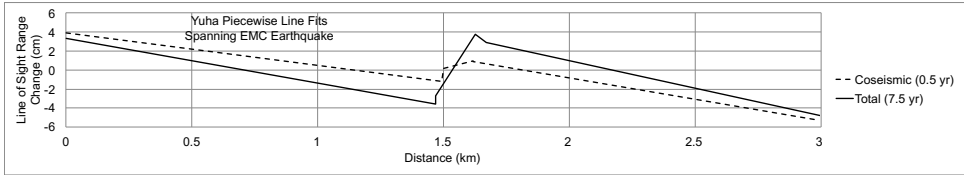


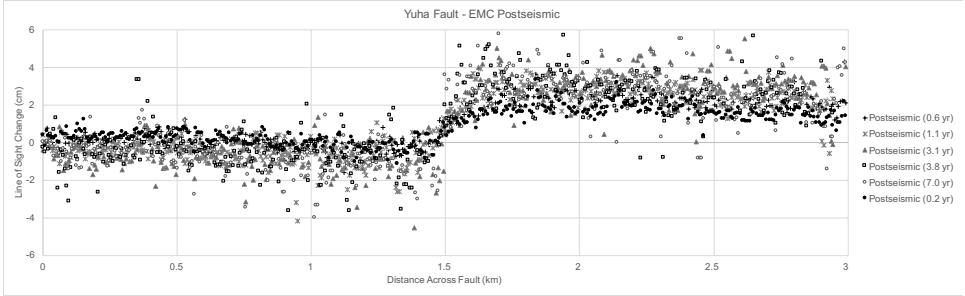


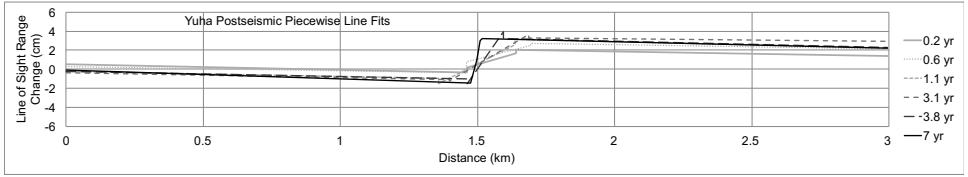


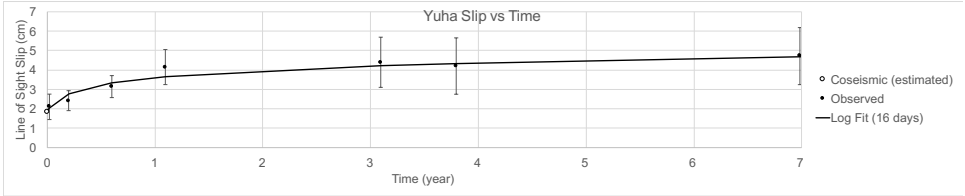
Yuha Fault Line of Sight Slip Estimates



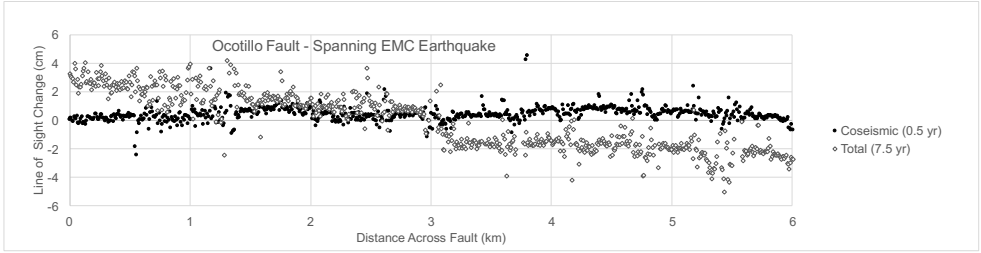


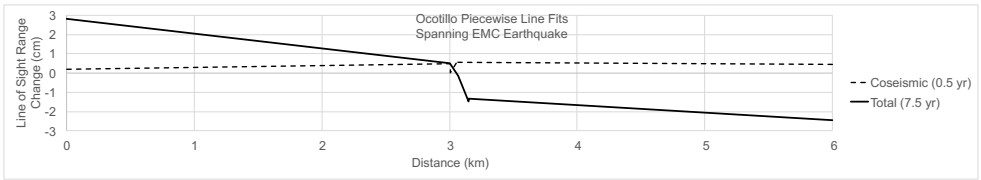


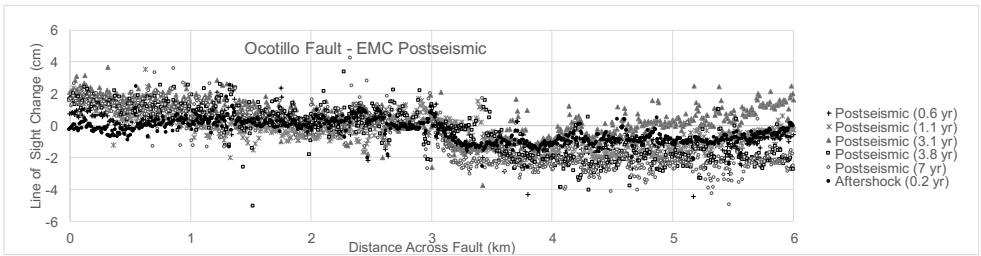


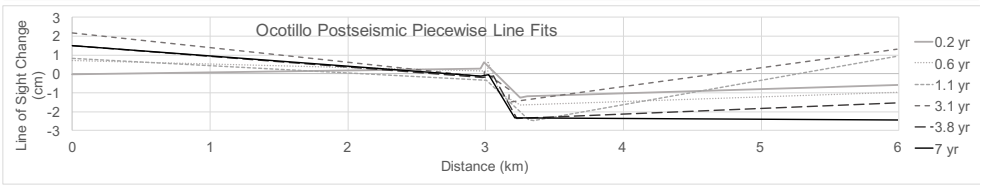


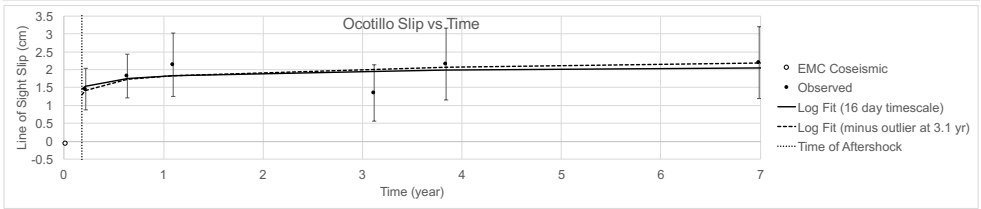
Ocotillo Section Line of Sight Slip Estimates



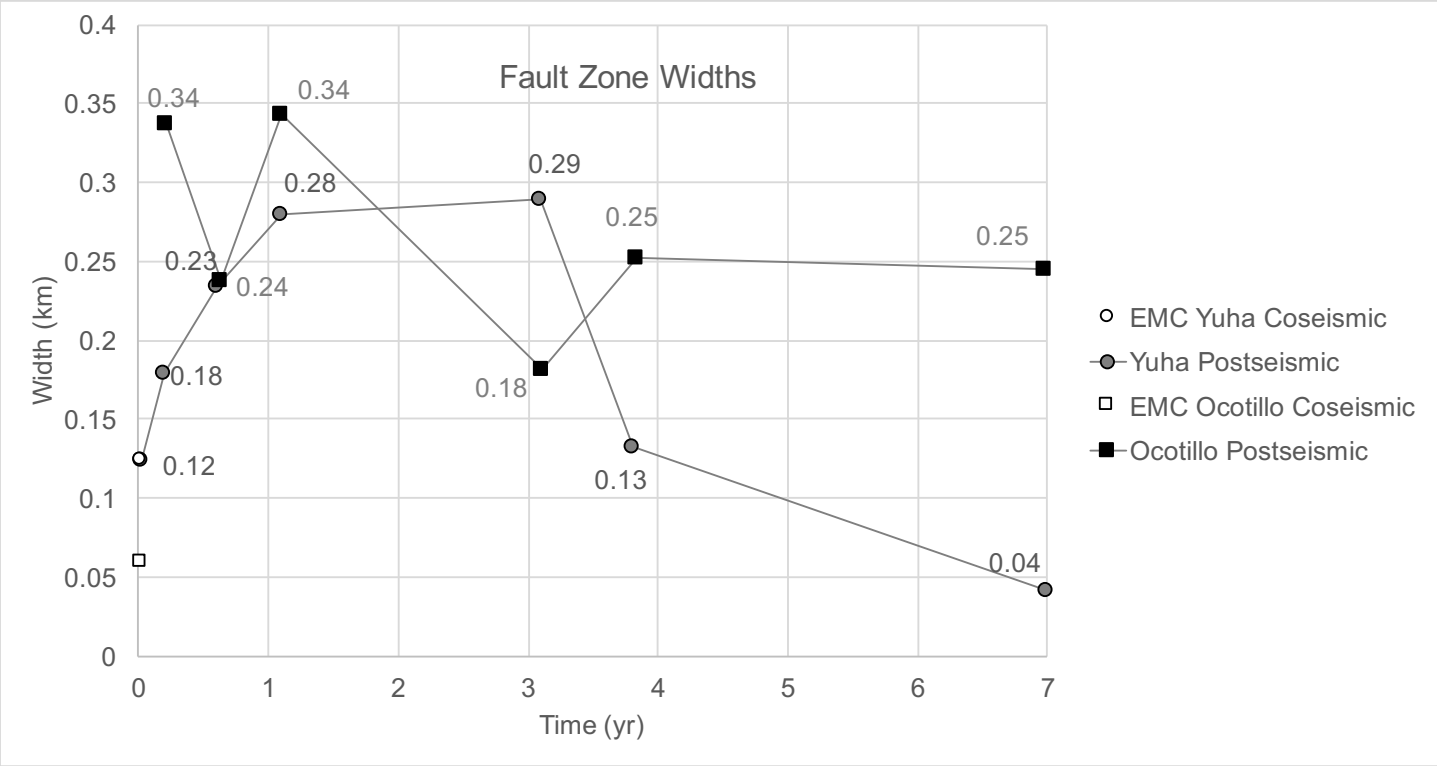




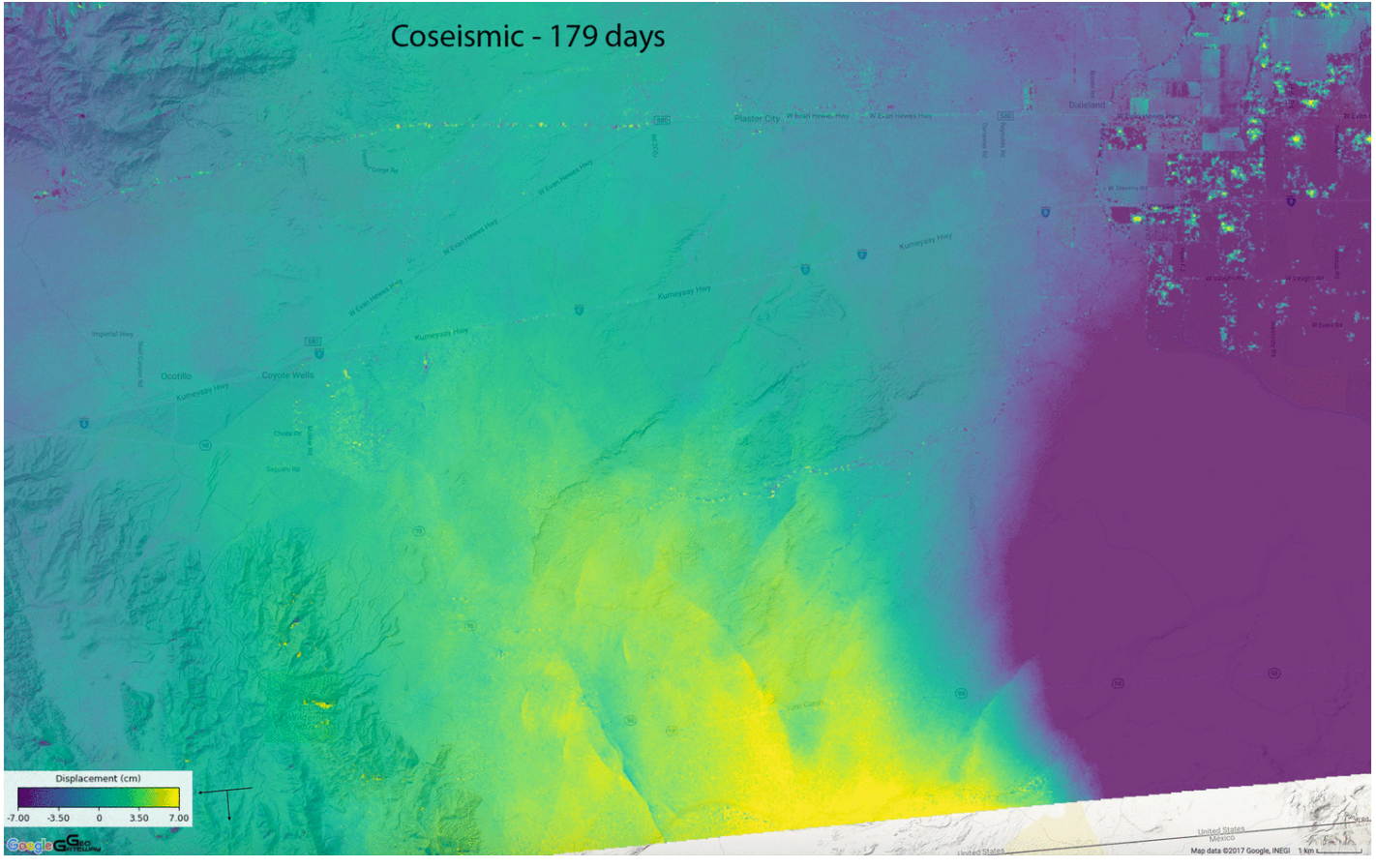




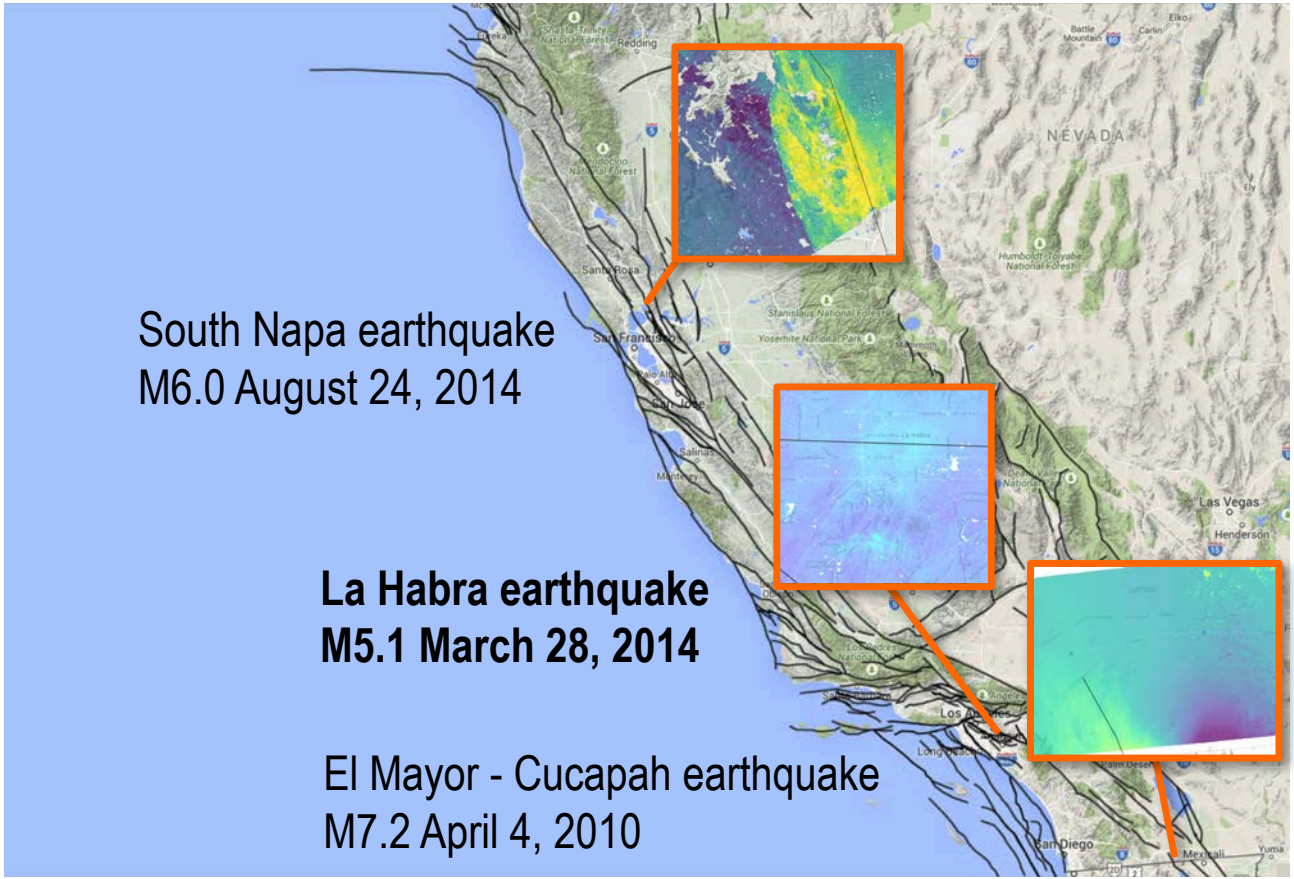
Fault Zone Widths



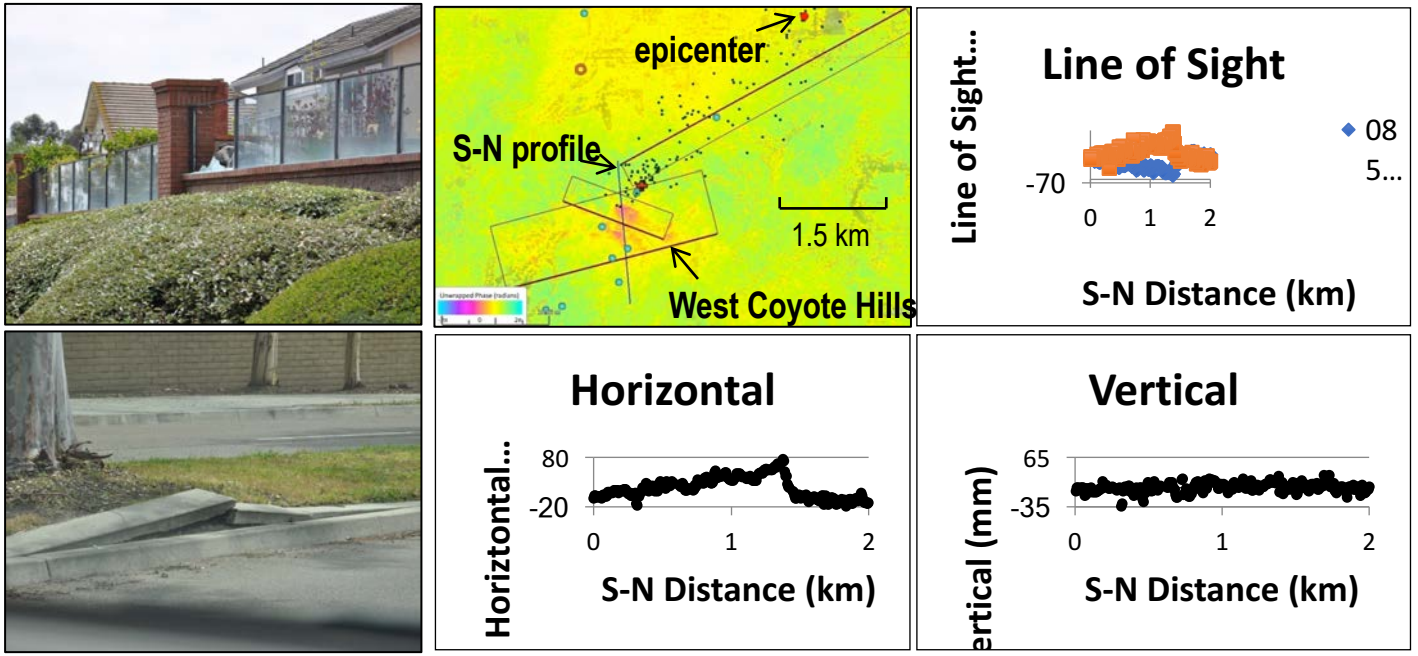
UAVSAR Yuha/Ocotillo Deformation



Earthquakes Observed with UAVSAR



2014 M 5.2 La Habra Earthquake



West Coyote Hills Slid Northward on an unconformity at about 500 m depth

Implications of Triggered Slip

Identify active faults

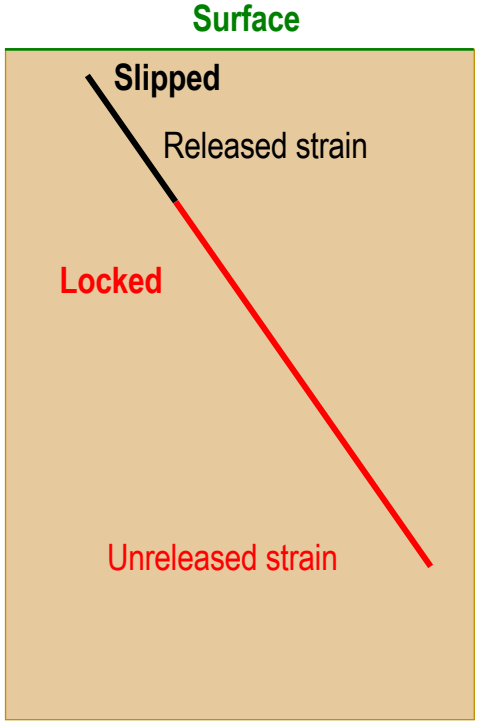
Estimate earthquake potential on locked segments of the faults

La Habra:

Seismic moment 82% of total geodetic moment released

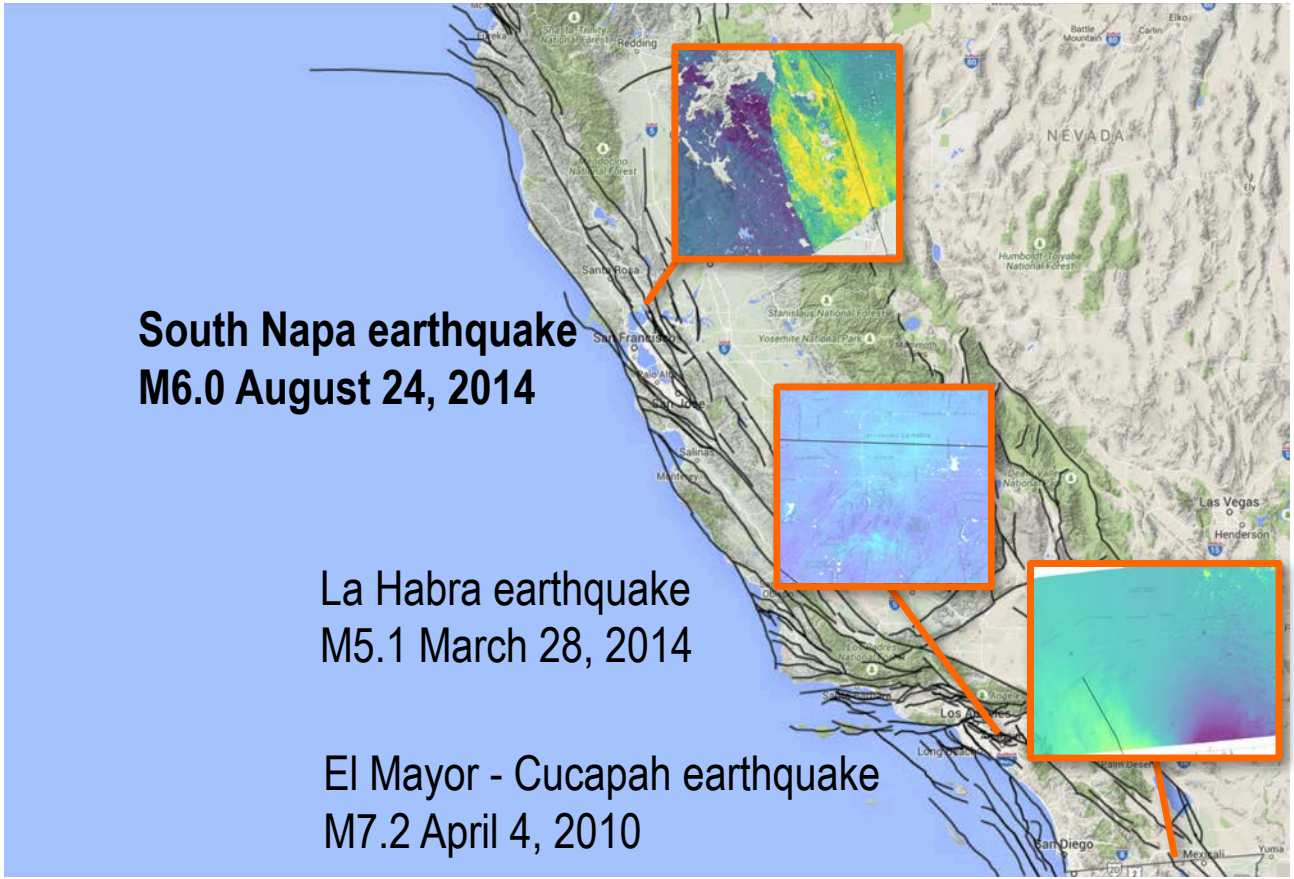
Future M6.1–6.3 earthquake would account for the accumulated strain

Seismogenic faults may not have been identified by geologic surface mapping

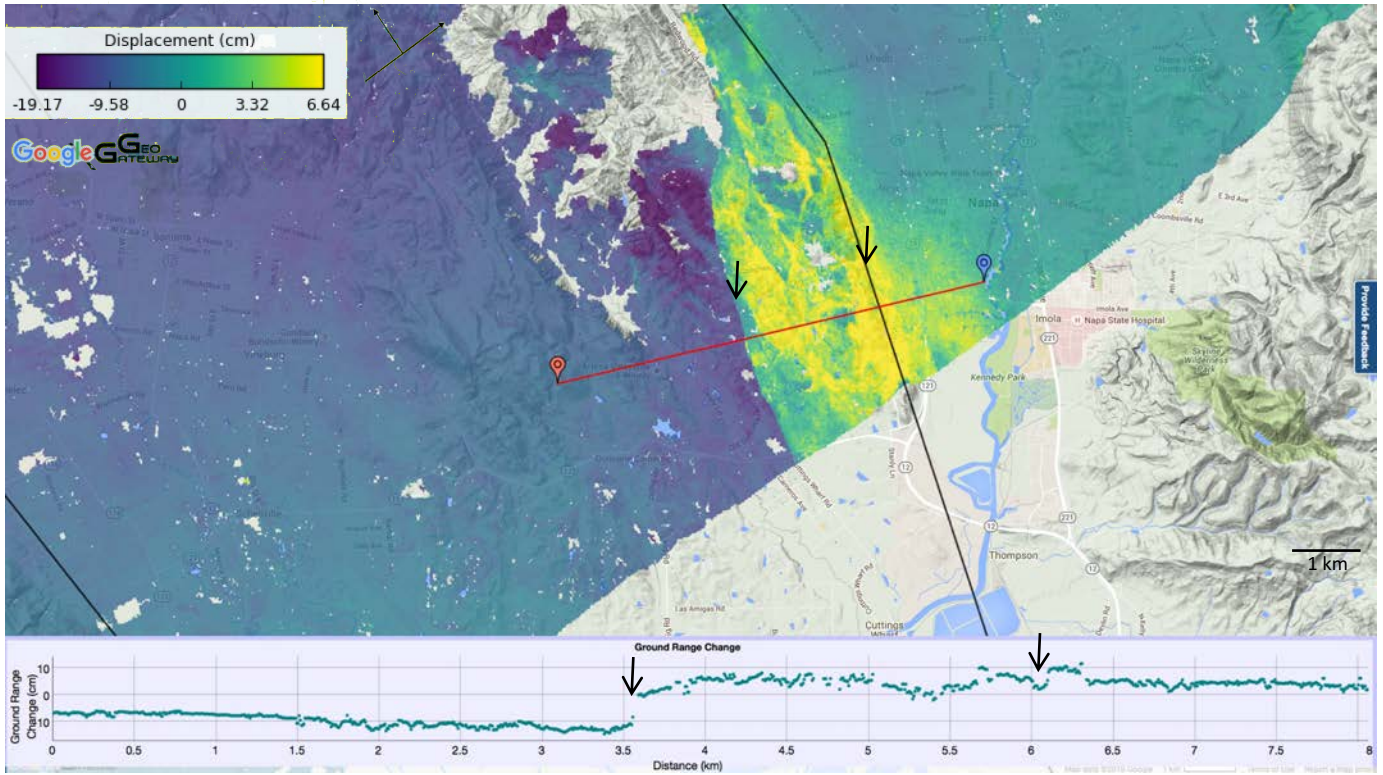


Donnellan et al, 2015
Earth and Space Science

Earthquakes Observed with UAVSAR

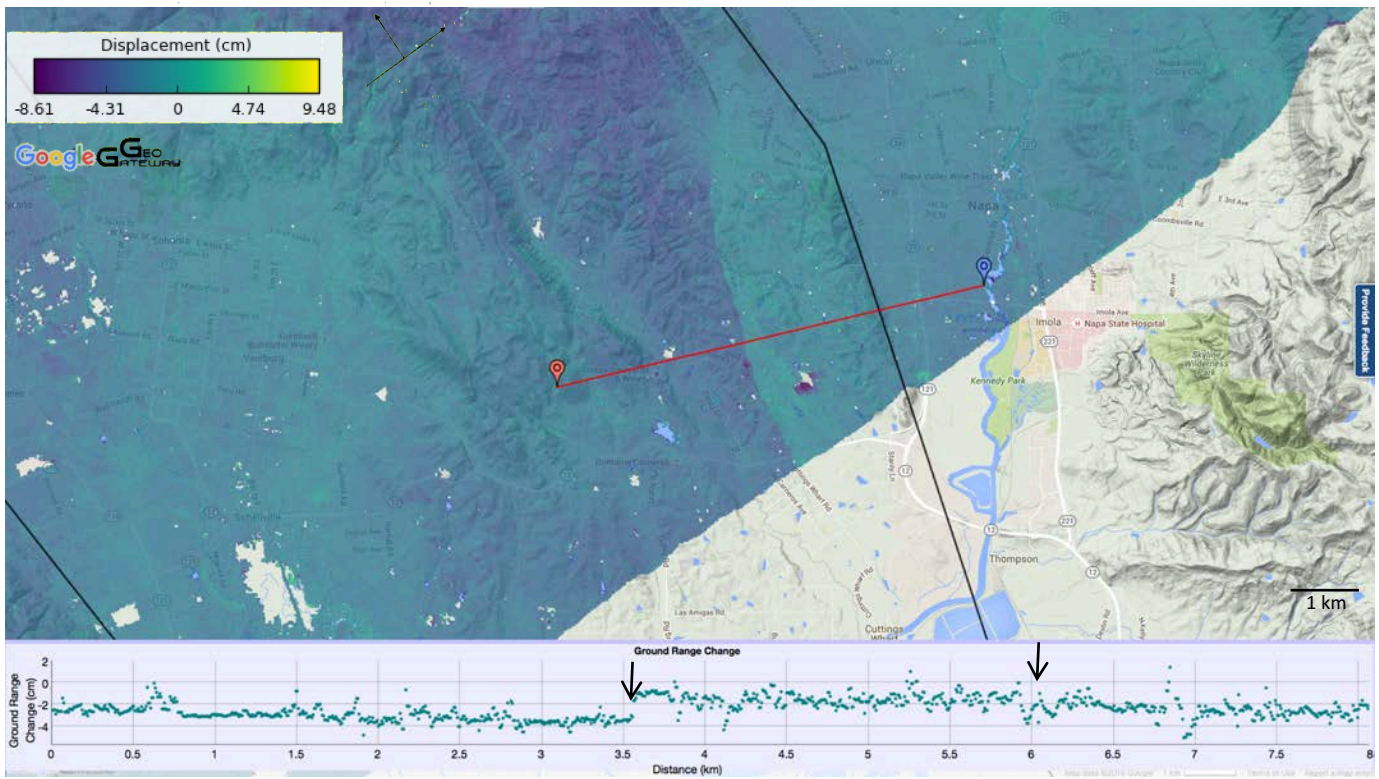


South Napa Earthquake Ruptured 3 km West of Mapped Trace



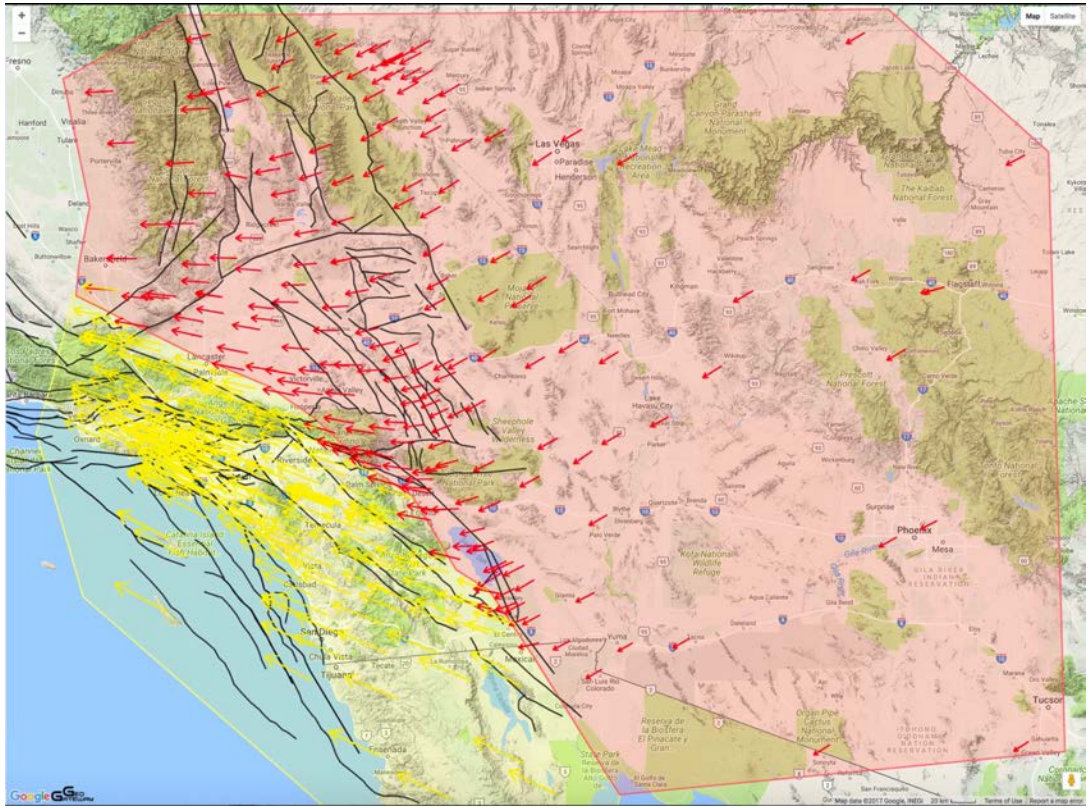
Slip on multiple structures but off the main mapped fault

South Napa Earthquake Postseismic

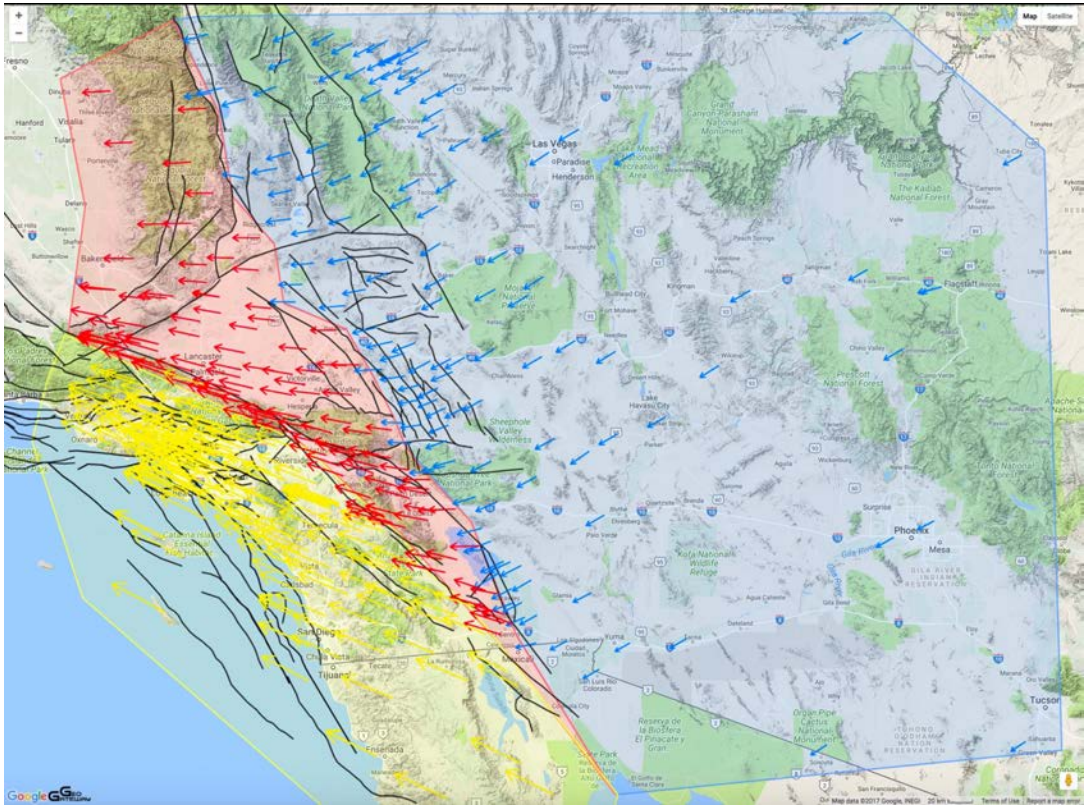


Afterslip confined to main rupture plane

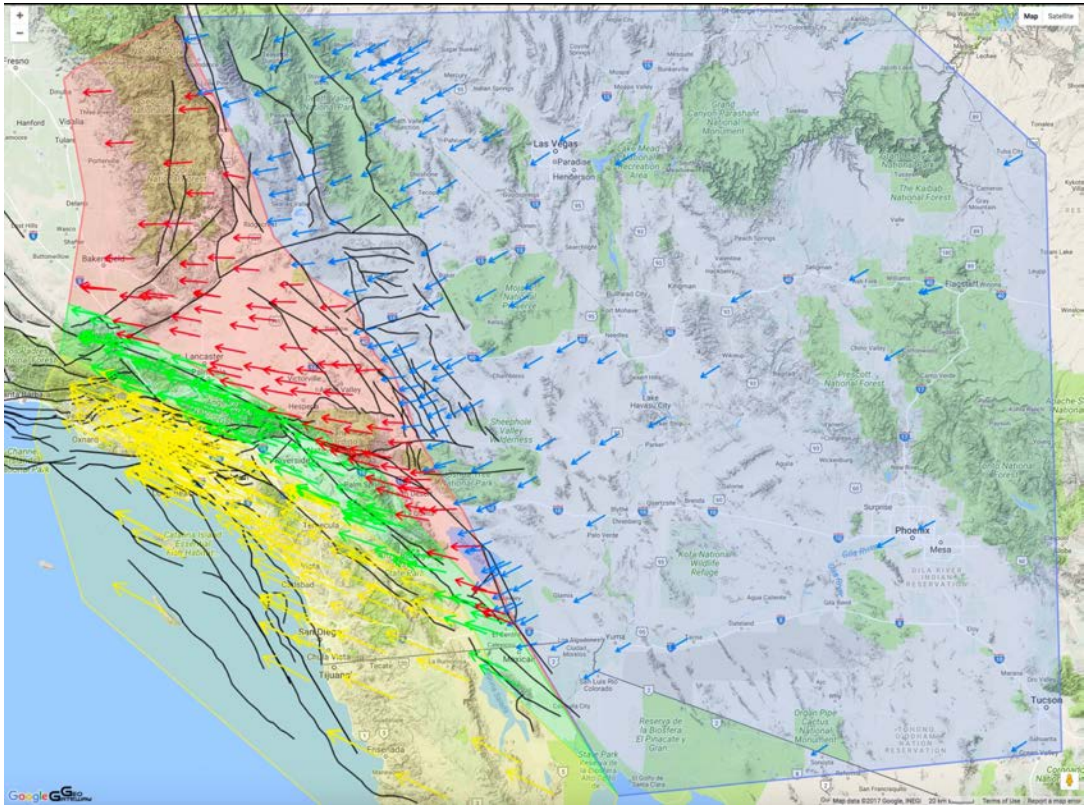
GPS Velocities: 2 classes



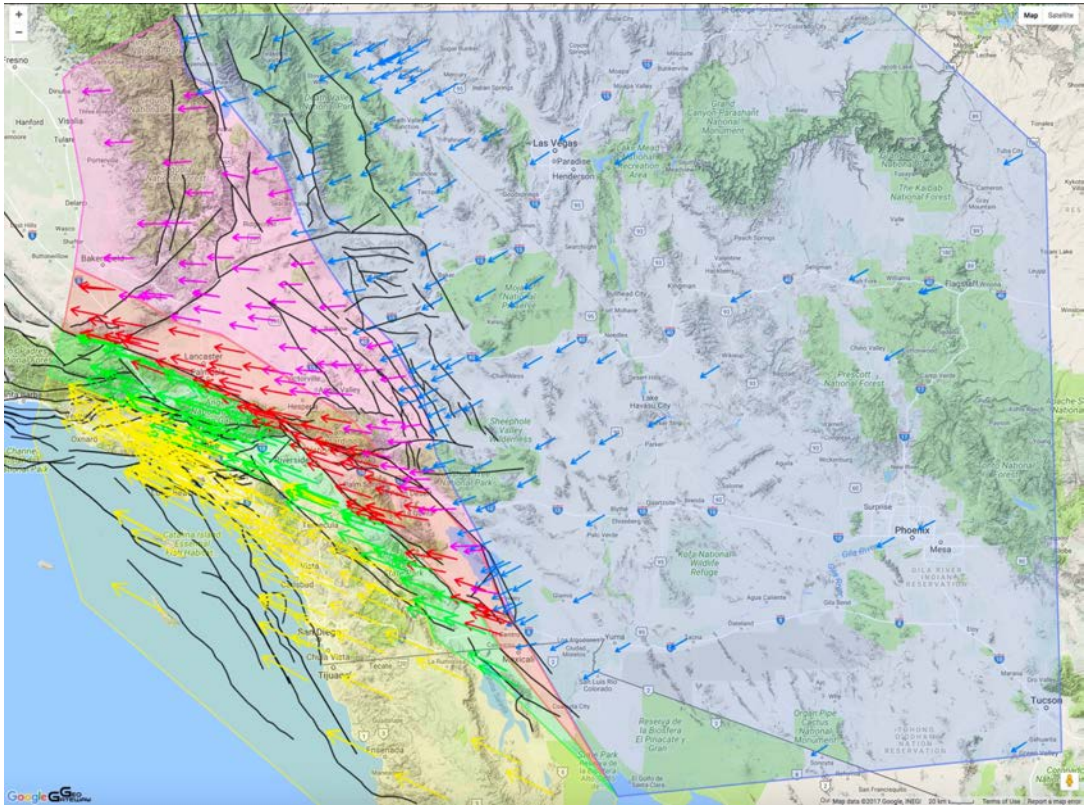
GPS Velocities: 3 classes



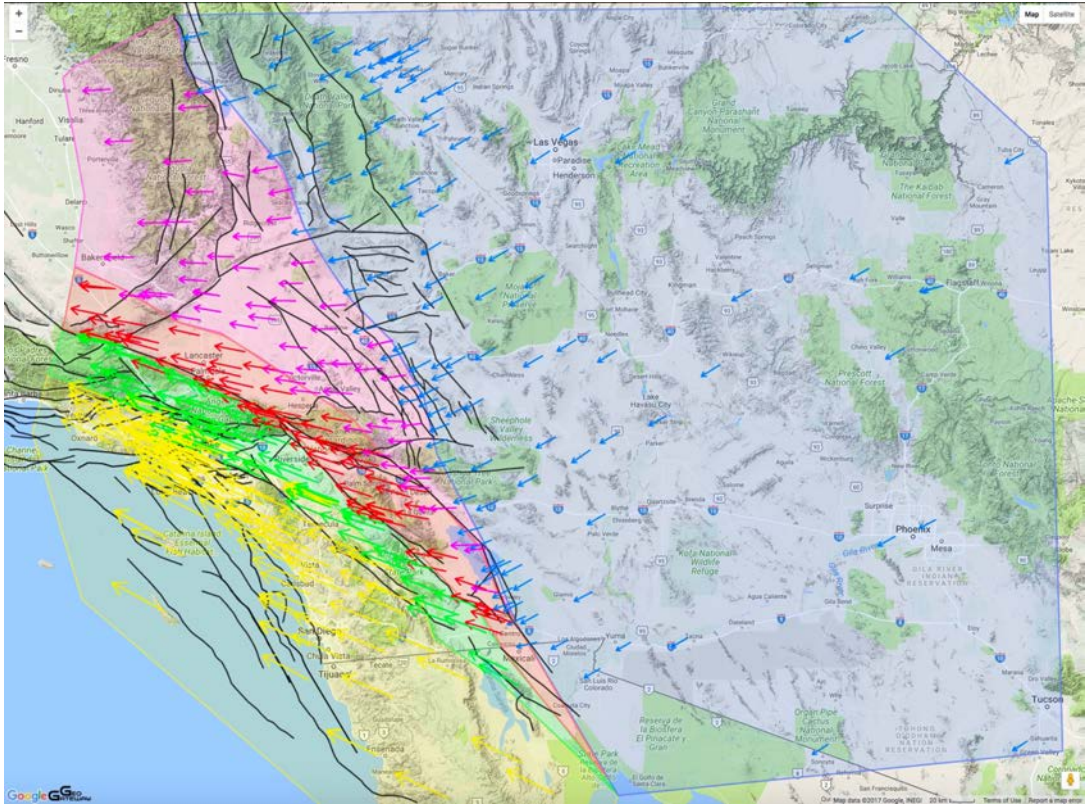
GPS Velocities: 4 classes

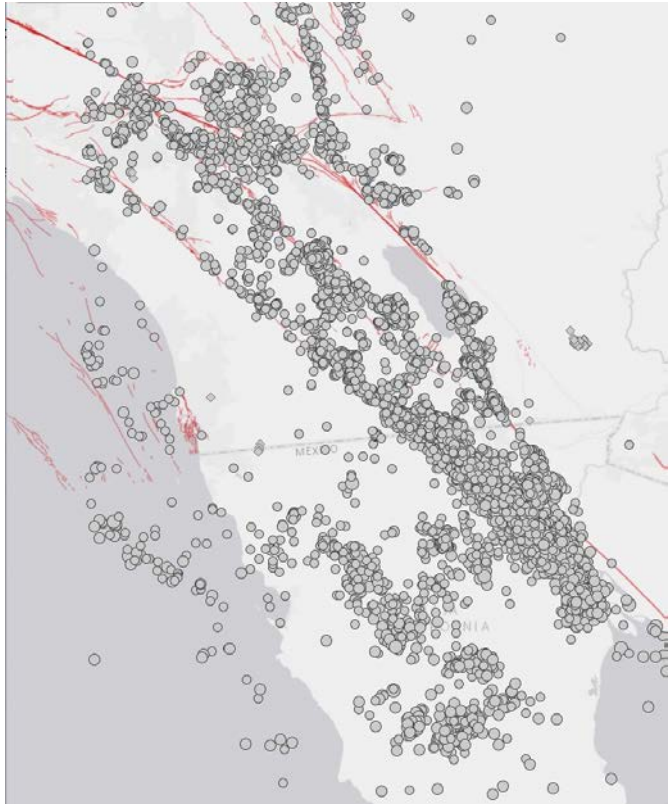


GPS Velocities: 5 classes



Consistent with Seismicity



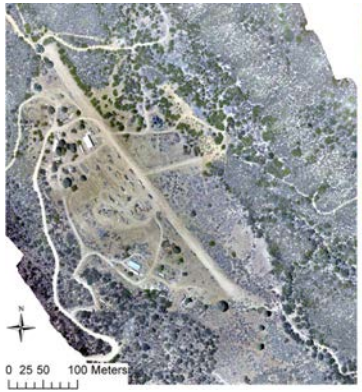


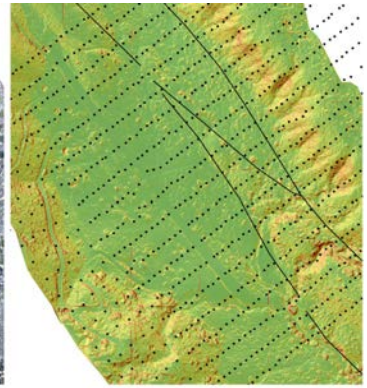
Structure from Motion

San Andreas Fault imagery, and topography



San Jacinto Fault imagery, topography, seismic stations, and faults

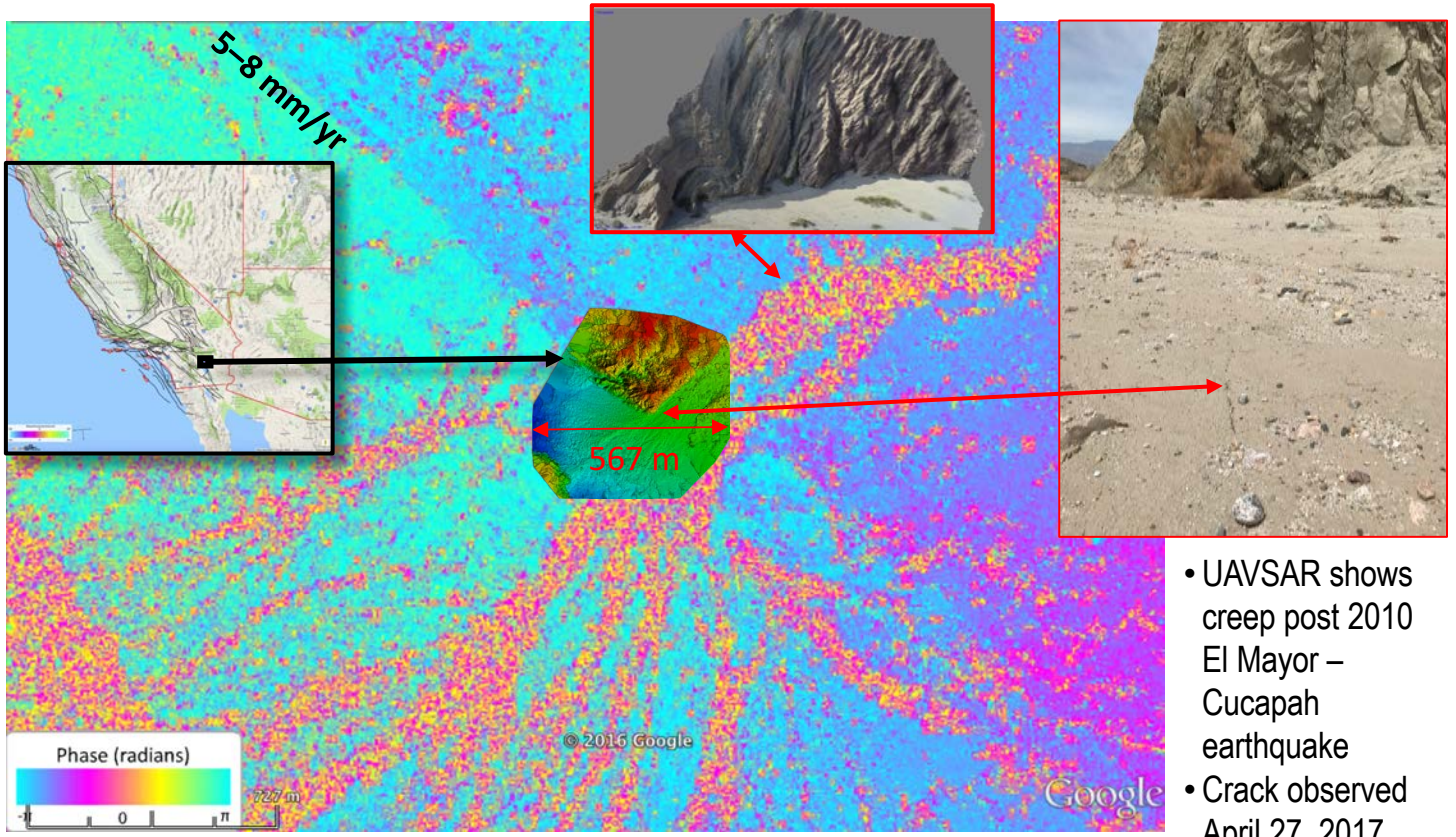




0.04 m/pix orthophoto

0.15 m/pix digital terrain model (ground classified using lastools; colored by slope over hillshade)

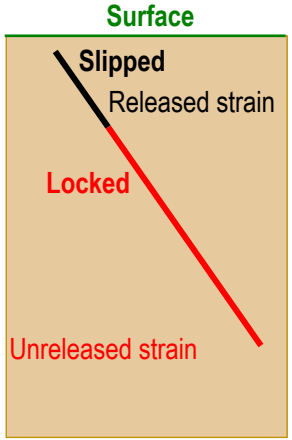
Triggered Slip on Southern San Andreas fault persists for years after earthquakes

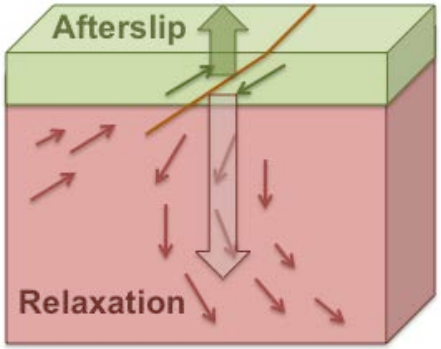


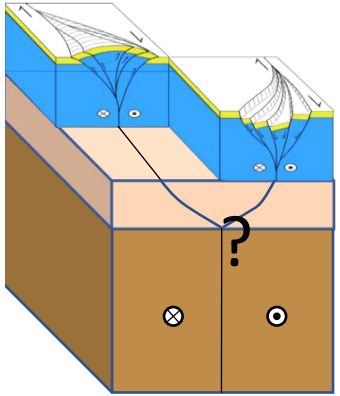
- UAVSAR shows creep post 2010 El Mayor – Cucapah earthquake
- Crack observed April 27, 2017

Implications

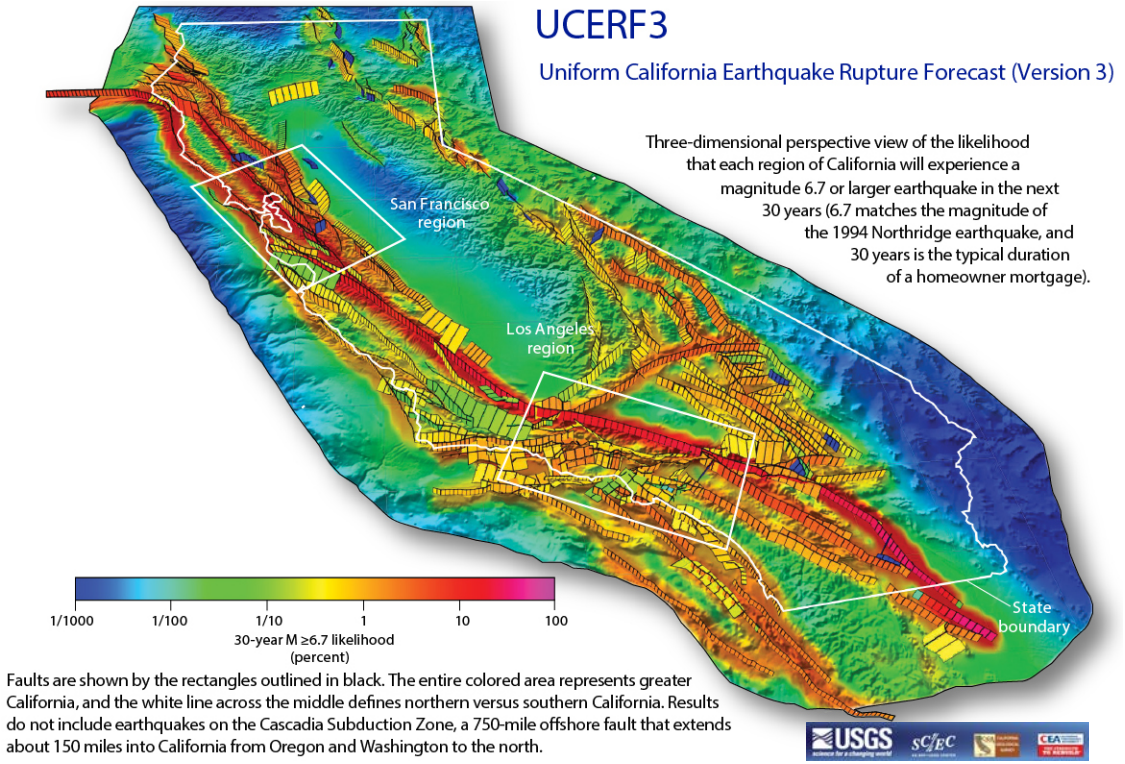
- Aseismic release of strain accumulation
  - Shallow slip can reflect strain accumulation on still locked deeper structures
  - Deeper slip may relieve strain locally but load neighboring faults
  - May reduce overall earthquake hazard – depends on the magnitude and area of slip
- Things to pursue
  - What is the depth of triggered slip?
  - Can damage asymmetry be inferred from geodetic imaging of the surface?
  - Does crustal deformation correlate with nowcasts based on seismicity?







Geodetic Imaging is Improving Forecasts



Crustal deformation measurement identifies tectonically active areas