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Earthquakes ★ Floods ★ Hurricanes ★ Landslides ★ Tsunamis ★ Volcanoes ★ Wildfires

Faulting, Afterslip and Deformation Associated with the 24 August 2014 South Napa Earthquake (M 6.0)

Ken Hudnut, Ph.D. - U. S. Geological Survey

California Spatial Reference Center Semi-Annual Meeting
Ontario, California
1 October 2014

USGS network update

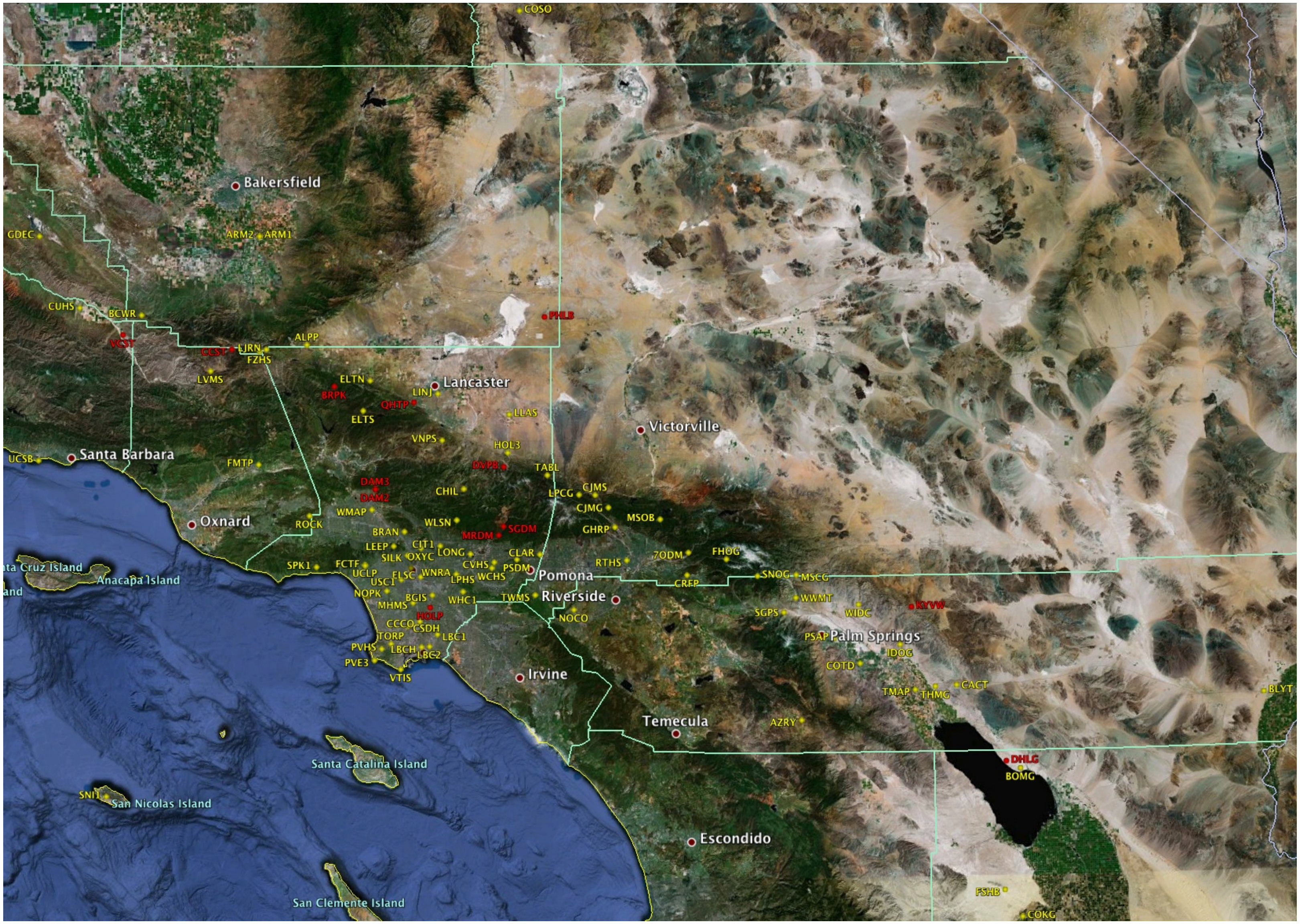
provided on behalf of Dan Determan and Aris Aspiotes

Nancy King retired

USGS SoCal Network UASI Upgrades Completed

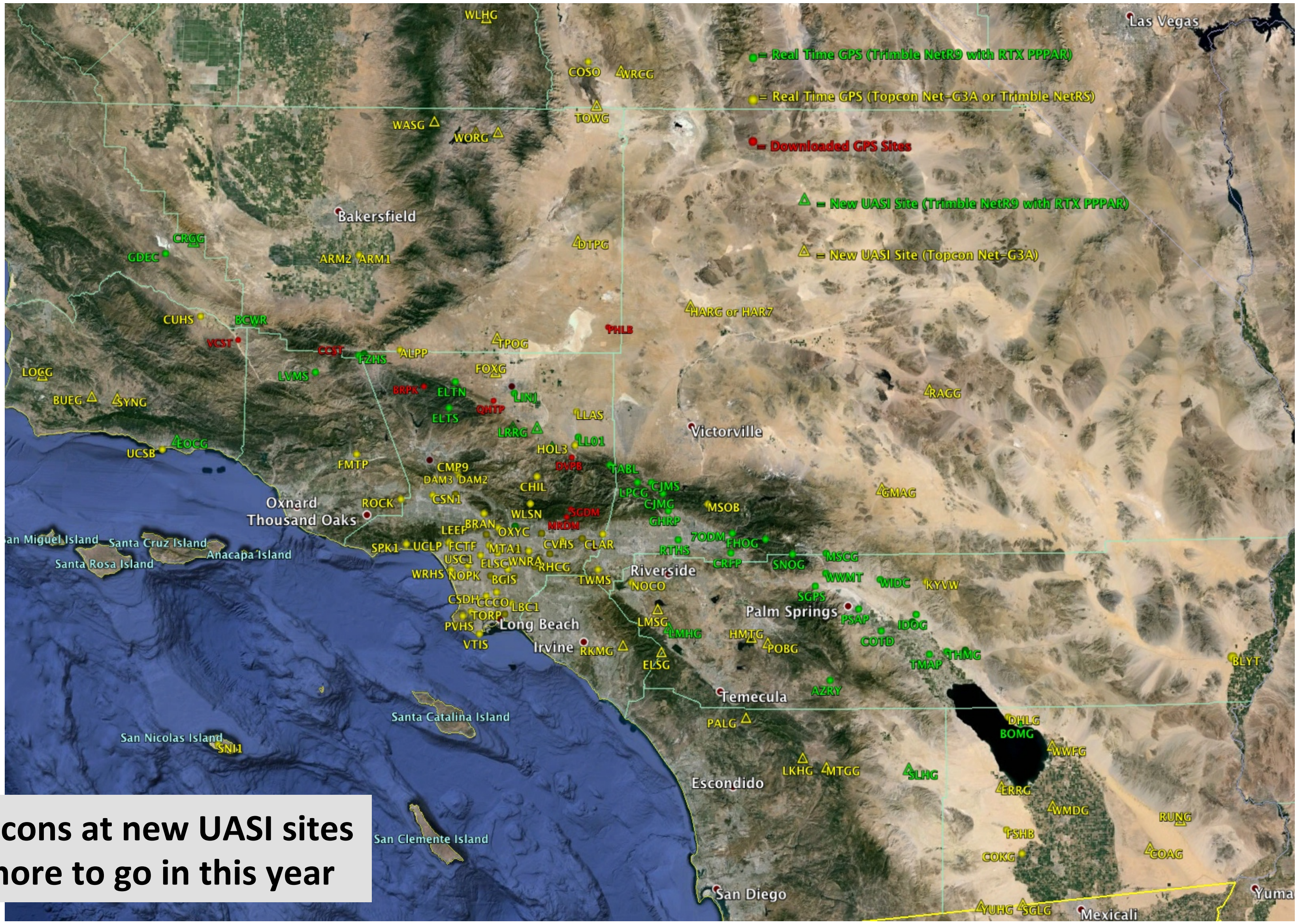
- Total GPS/GNSS stations
  - Before UASI = 104
  - After UASI = 142+
- Total co-located w/ seismic
  - Before = 23
  - After = 64+
- Real-time telemetered GPS/GNSS stations
  - Before = 96
  - After = 134+

USGS Status – Before UASI



USGS Status – After UASI

(41 RTX's; of these 34 at SoSAFz 'zipper', 7 at new UASI sites)



6 Topcons at new UASI sites
26 more to go in this year

Space geodesy, satellite & airborne imagery are powerful new methods for repair & recovery

- GPS is central to providing an absolute reference frame for correlating pre- to post-event imagery and observations.

- Geo-referenced pre-event imagery requires GPS control so that image-derived products showing changes may be highly accurate; we develop geodetic-quality differencing of LiDAR, EO and InSAR imagery through use of GPS global networks.

- Global sharing of GPS ground control station data in real-time facilitates disaster response.

- Global sharing of imagery makes rapid disaster response applications of imagery possible.

- USGS contributes to domestic & international efforts to use imagery to support response efforts (e.g., following earthquakes).





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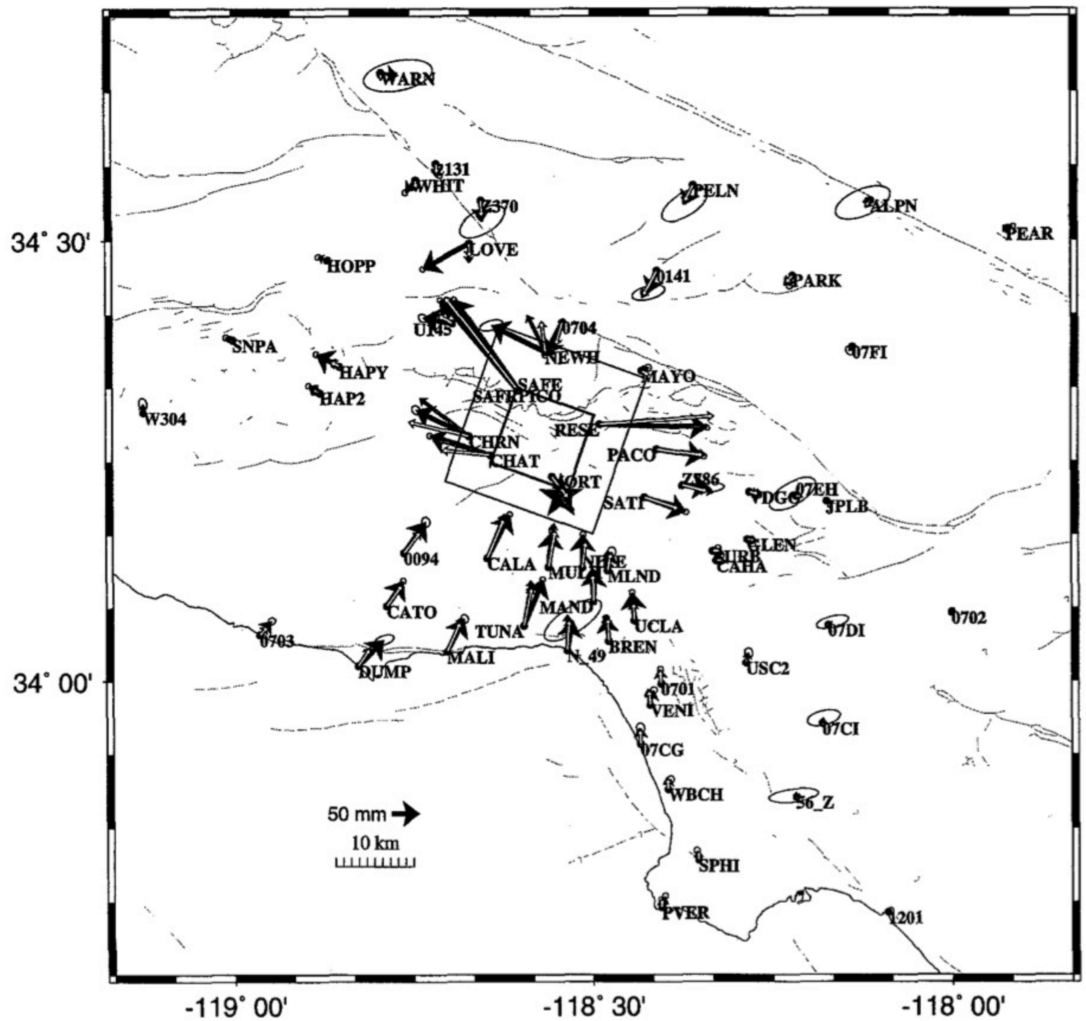
Northridge Co-Seismic Displacements

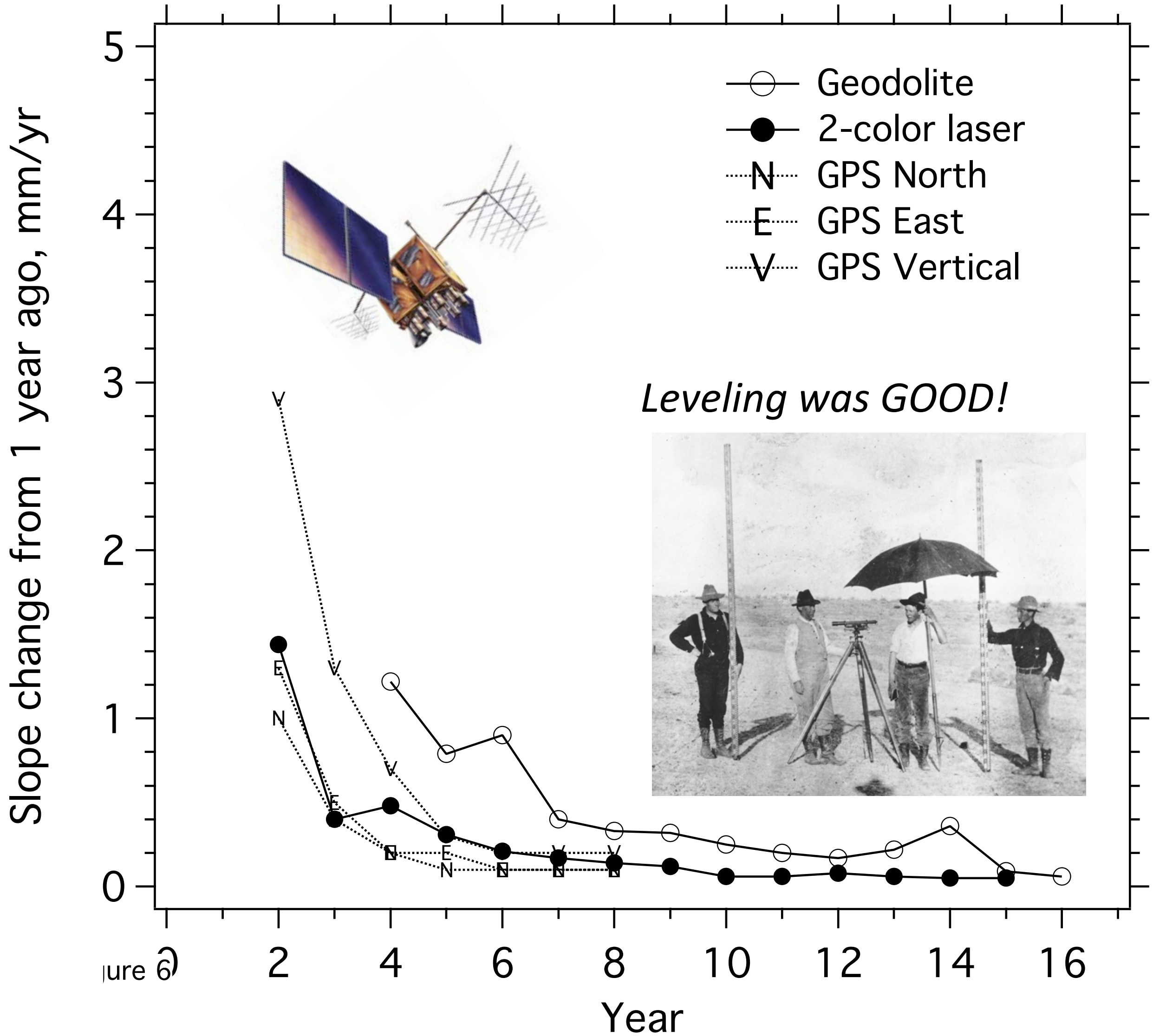


Hudnut et al.
BSSA, 1996

Northridge 1994

In 1994,
GPS was
still being
tested vs.
previous
methods

The GPS
constellation
had just
achieved
Initial
Operational
Capability

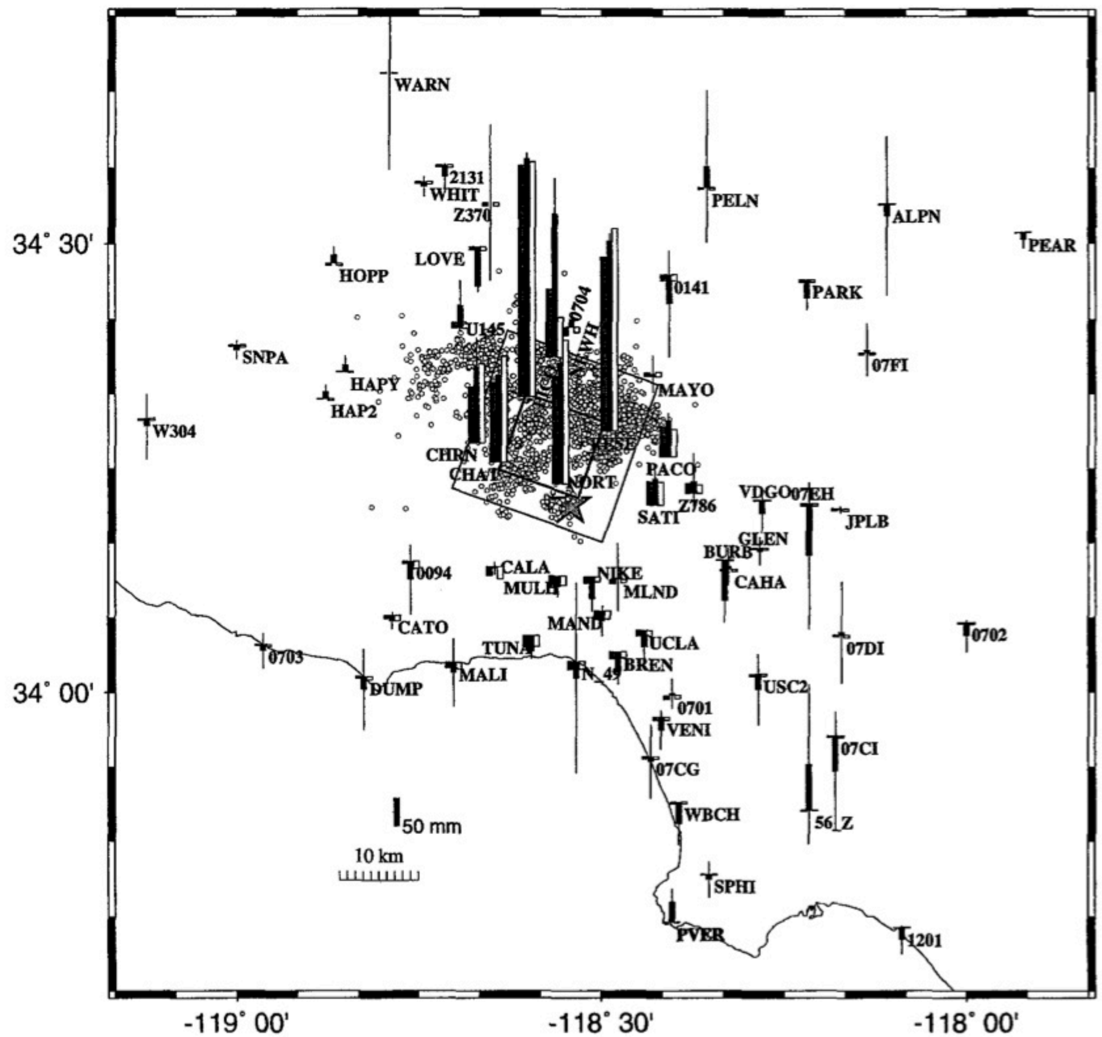


Northridge Earthquake GPS

- Initial focal mechanism – but fault rupture could have been on either plane; no surface rupture
  - 1971 dipped north, what about 1994?
  - Aftershocks of Northridge in first several days did not clearly delineate one plane or the other

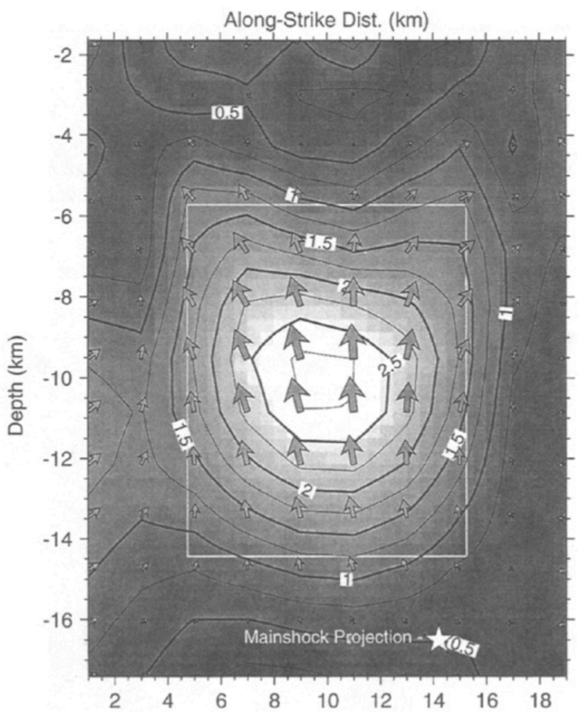
- GPS displacements showed a strong preference for a deeper hypocenter and a south-dipping fault plane; NORT moved SE and up – anomalous?
  - Displacement of station NORT proved not to be the only influential station in the solutions
  - Confidence in a south-dipping plane came from geodesy

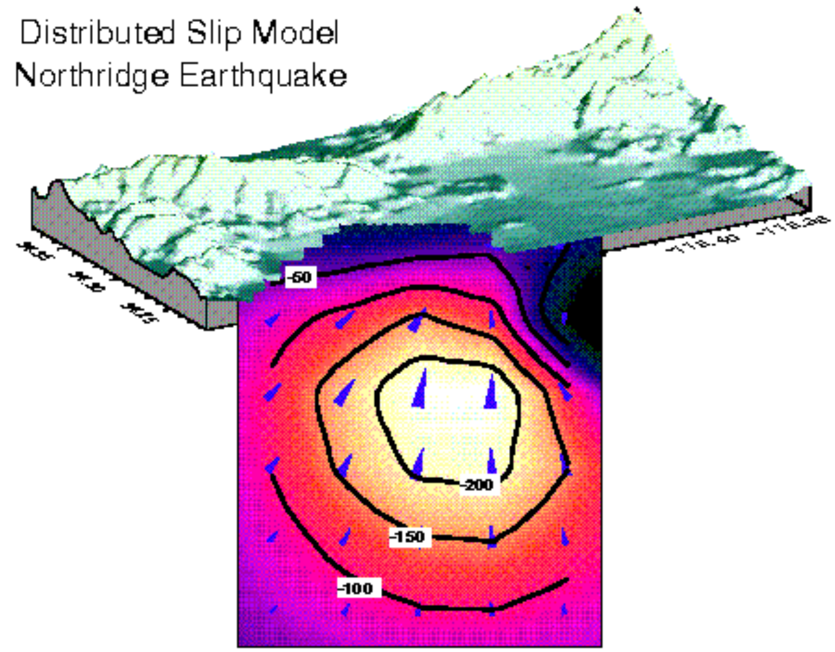
Northridge Co-Seismic Displacements



Hudnut et al.
BSSA, 1996

Northridge Co-Seismic Displacements

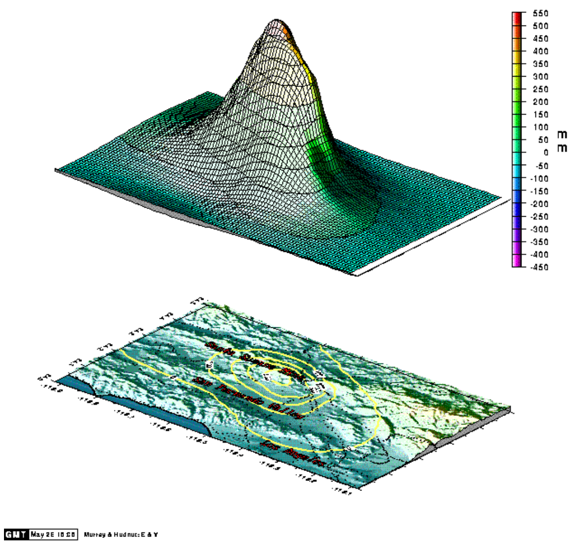




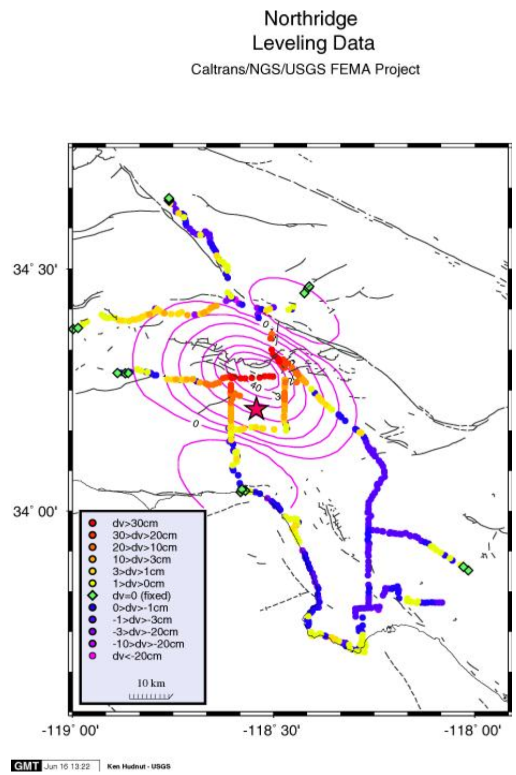
fault plane dips south
beneath San Fernando Valley

Hudnut et al.
BSSA, 1996

Northridge Co-Seismic Displacements

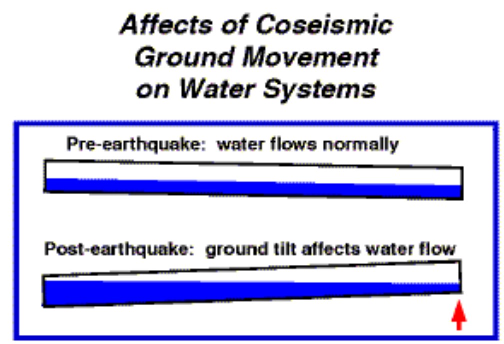


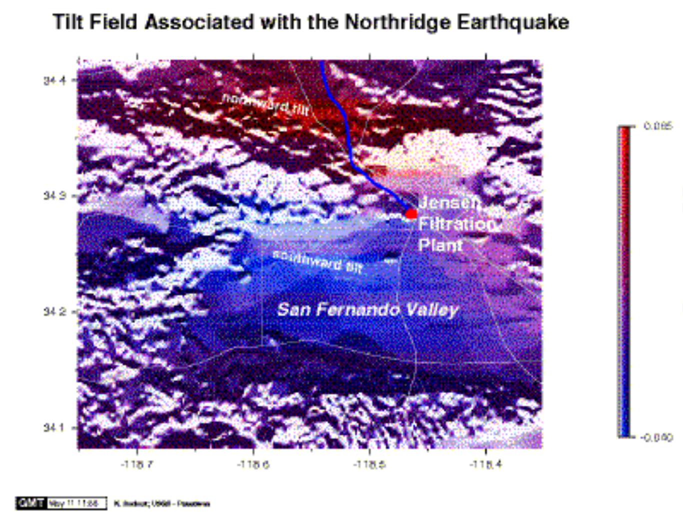
Caltrans
MWD & LADWP
needed
vertical
deformations

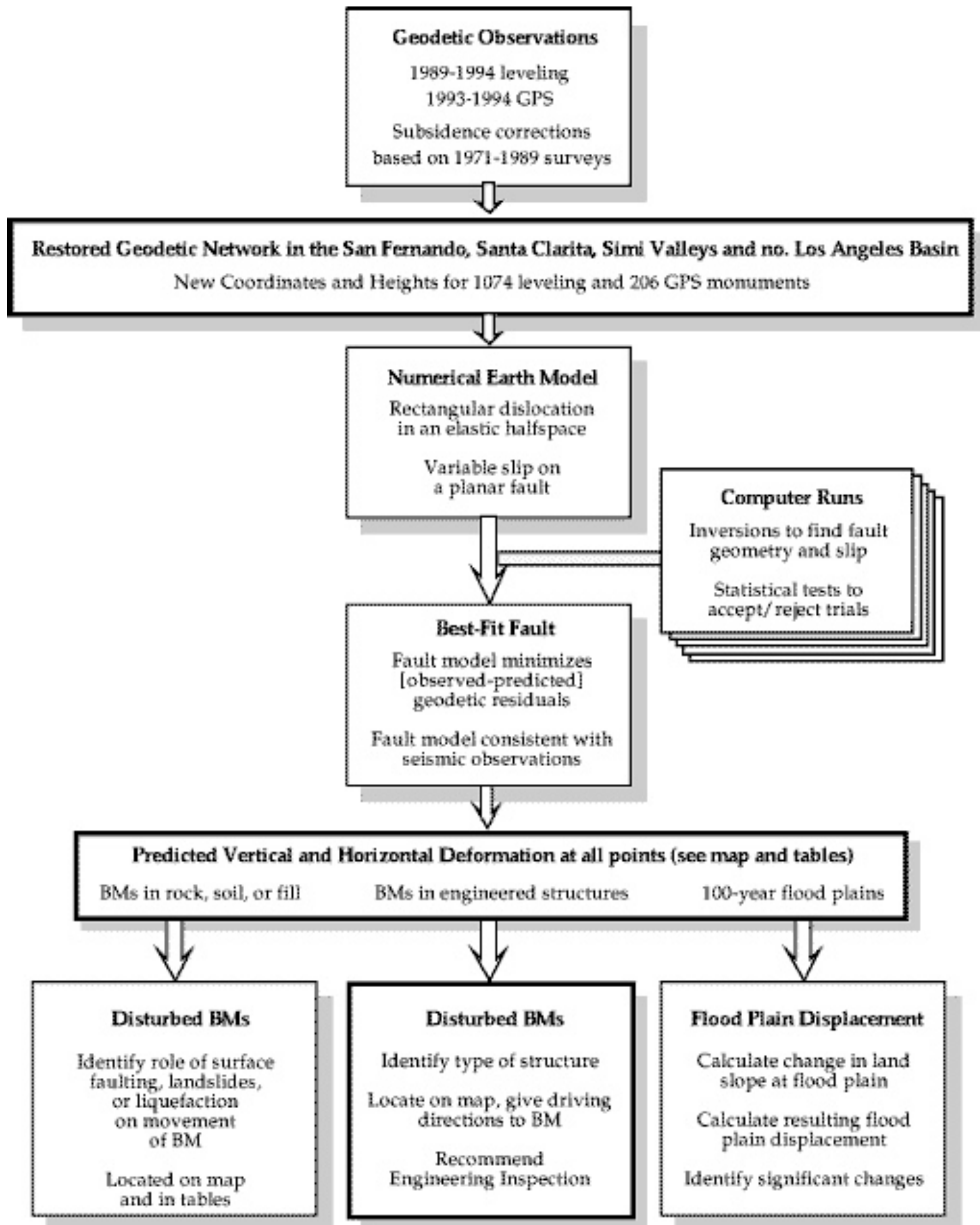


tilt of 40 cm
in 10 km

Impacts – Water!

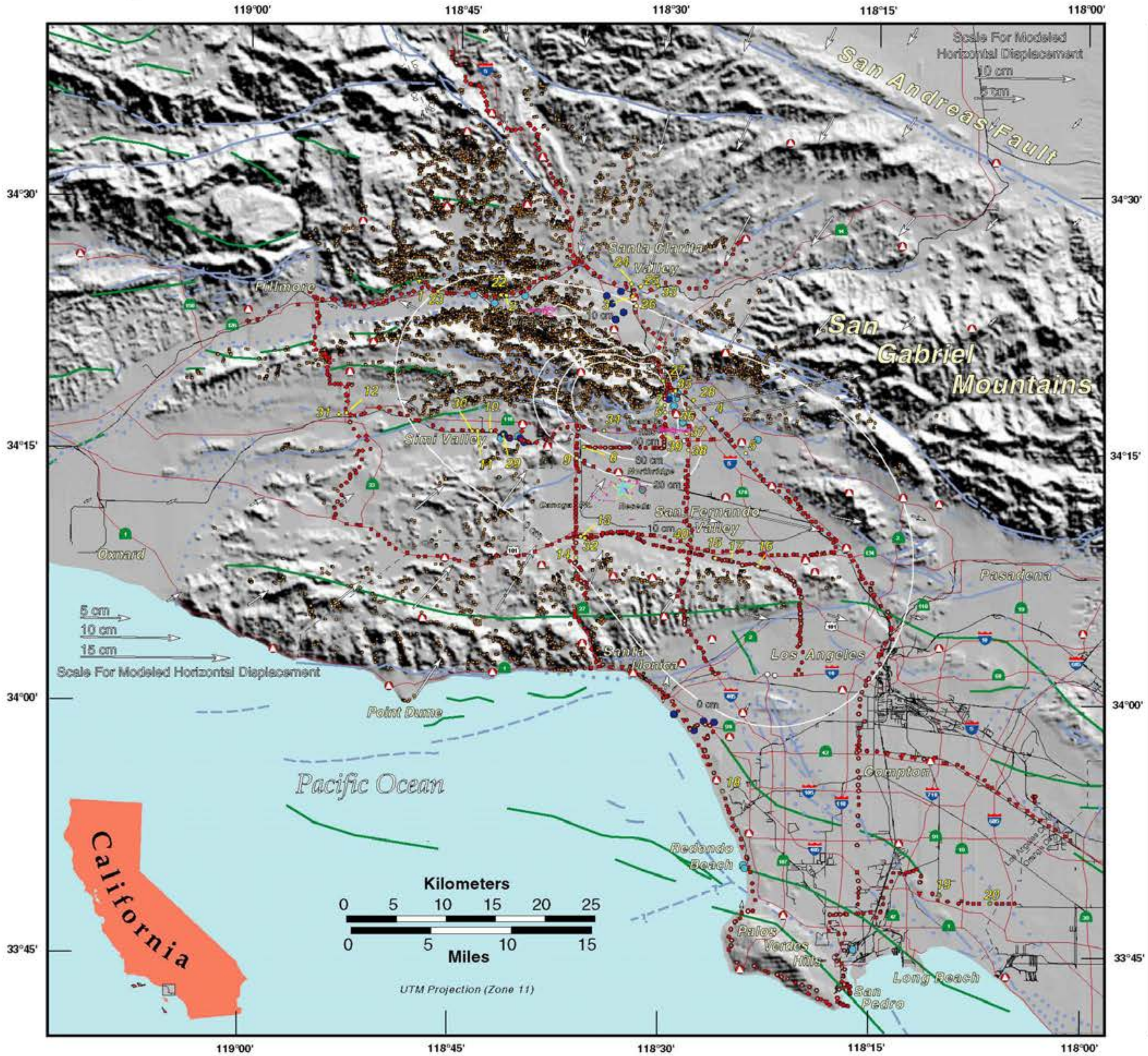






Geodetic Observations
1989-1994 leveling
1993-1994 GPS
Subsidence corrections
based on 1971-1989 surveys
Restored Geodetic Network in the San Fernando, Santa Clarita, Simi Valleys and no. Los Angeles Basin
New Coordinates and Heights for 1074 leveling and 206 GPS monuments
Numerical Earth Model
Rectangular dislocation
in an elastic halfspace
Variable slip on
a planar fault
Computer Runs
Inversions to find fault
geometry and slip
Statistical tests to
accept/reject trials
Best-Fit Fault
Fault model minimizes
[observed-predicted]
geodetic residuals
Fault model consistent with
seismic observations
Predicted Vertical and Horizontal Deformation at all points (see map and tables)
BMs in rock, soil, or fill
BMs in engineered structures
100-year flood plains
Disturbed BMs
Identify role of surface
faulting, landslides,
or liquefaction
on movement
of BM
Located on map
and in tables
Disturbed BMs
Identify type of structure
Locate on map, give driving
directions to BM
Recommend
Engineering Inspection
Flood Plain Displacement
Calculate change in land
slope at flood plain
Calculate resulting flood
plain displacement
Identify significant changes

Damage and Restoration of Geodetic Infrastructure Affected by the 1994 Northridge, California, Earthquake



Explanation

The 17 January 1994, M=6.7 Northridge earthquake permanently distorted the ground surface, displacing geodetic monuments used by engineers and surveyors to construct and monitor the urban infrastructure. New coordinates and heights for 979 monuments displaced by the earthquake, as well as 100 new monuments are given in the accompanying report, restoring the accuracy and integrity of the network.

The earthquake shaking also damaged engineered structures and caused surface cracking, liquefaction and landslides. A geophysical model of the permanent earthquake deformation (shown by white contours and vectors) closely corresponds to the displacement of most monuments. The 40 monuments with displacements that differ from this model by more than 3 cm (1.2") are identified as anomalous; half of these are located in engineered structures; others are in engineered fill. The affected structures and fill may thus be in a weakened state as a result of the shaking, making them vulnerable to future earthquakes.

MOVEMENT OF LEVELING BENCH MARKS

Undisturbed (fits model) | Anomalous, with identifier

- Bedrock or Sediment Sites
- Bridge Spans, Piers and Abutments
- Building Foundations
- Catch Basins
- Culverts and Retaining Walls
- Tower Foundations

Identifier, PIDs and anomaly in cm (+ uplift - subsidence)

1	EW9465	-3.6	21	EW0960	-8.1
2	EW6667	4.3	22	EW6670	-9.6
3	EW6895	8.0	23	EW0886	3.1
4	EW2515	3.3	24	EW5493	6.2
5	EW2673	-4.3	25	EW5496	6.2
6	EW6850	4.3	26	EW7951	7.5
7	EW6854	4.4	27	EW6965	-11.6
8	EW6792	-3.4	28	EW6889	-11.6
9	EW6427	-3.9	29	EW6942	-5.8
10	EW5628	4.0	30	EW6548	3.0
11	EW5625	-3.0	31	EW6937	5.0
12	EW6630	5.0	32	EW6321	-4.1
13	EW6326	-3.5	33	EW5932	-4.4
14	EW6346	3.2	34	EW9541	3.5
15	EW2212	4.6	35	AA3228	-9.2
16	EW2256	9.1	36	AA3231	-13.9
17	EW2245	-8.3	37	AA3234	-13.9
18	DY2495	-4.8	38	AA3236	10.4
19	DY2535	-11.6	39	EW6944	-13.9
20	DY2538	-4.6	40	AA3256	4.1

Global Positioning System monuments with coseismic observations of the ground displacement caused by the earthquake.

10 cm / 5 cm — Modeled uplift (contours) and selected horizontal displacements (computed for points at the tail of the arrows) caused by the Northridge earthquake (see accompanying report and Wald, D., Heaton, T., and K. Hudnut, *Bull. Seism. Soc. Am.* 86, No. 1B, p. 549-570, 1996).

EARTHQUAKE EFFECTS

17 January 1994 M=6.7 Northridge Mainshock

Location of bridges with major damage (I.G. Buckle, National Center for Earthquake Engineering Research, *Technical Report* NCEER-94-0008, 1994)

Landslides (E. L. Harp and R. W. Jibson, *USGS Open File Report*, 95-213, 1995)

Site of liquefaction inferred from subsurface studies (Holzer, T. Bennett, J., Tinsley, J., Ponti, D., and R. Sharp, Conference Proceedings, National Center for Earthquake Engineering Research, Tokyo, June 11-13, 1996.)

Site of liquefaction (Staff of U.S. Geological Survey, *USGS Open File Report*, 96-263, 1996; J.C. Tinsley, USGS, in prep. 1996)

Site of possible liquefaction (Staff of U.S. Geological Survey, *USGS Open File Report*, 96-263, 1996; J.C. Tinsley, USGS, in prep. 1996)

Groundcracking associated with the Northridge Earthquake.
GRANADA HILLS: Hecker, S., Ponti, D., Garvin, T., Powers, J., Fumal, T. Hamilton, J., Sharp, R., Rymer, M., Prentice, C., and F. Cinitl, *USGS Open File Report* 95-62, 1995.
POTRERO CANYON: Ponti, D. in prep. 1996.
NORTHRIDGE-RESEDA-CANOGA PARK: J. Sloson, J. Johnson, R. McCarthy, and T. Sloson, Calif. Seismic Safety Comm., in prep. 1996.

MAP BASE

County boundary
Railroad

Active Geological Structures

Faults, well located
Faults, inferred
Faults concealed by younger deposits
(C. W. Jennings, Geologic Data, Map 6, Calif. Div. Mines & Geol., 1994)

Fold formed above blind thrust faults (R. S. Stein and R. S. Yeats, *Scientific American*, 1989)

Highway Types

U. S. Interstate
U. S. Federal
State

This map and the accompanying report were funded by the Federal Emergency Management Agency as a Mission Assignment to the U. S. Geological Survey, with participation by the National Geodetic Survey, California Department of Transportation, and California Institute of Technology. This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards. Any use of trade, product or firm names is for descriptive use only and does not imply endorsement by the U. S. Government.

Map prepared by Anne Lilje (California Institute of Technology), Kathleen M. Hodgkinson (U. S. Geological Survey, Menlo Park), Kenneth W. Hudnut (U. S. Geological Survey, Pasadena), and Ross S. Stein (U. S. Geological Survey, Menlo Park).

U. S. Geological Survey Open File Report 96-517 (1996)

24 August 2014; S. Napa Eq. M 6.0

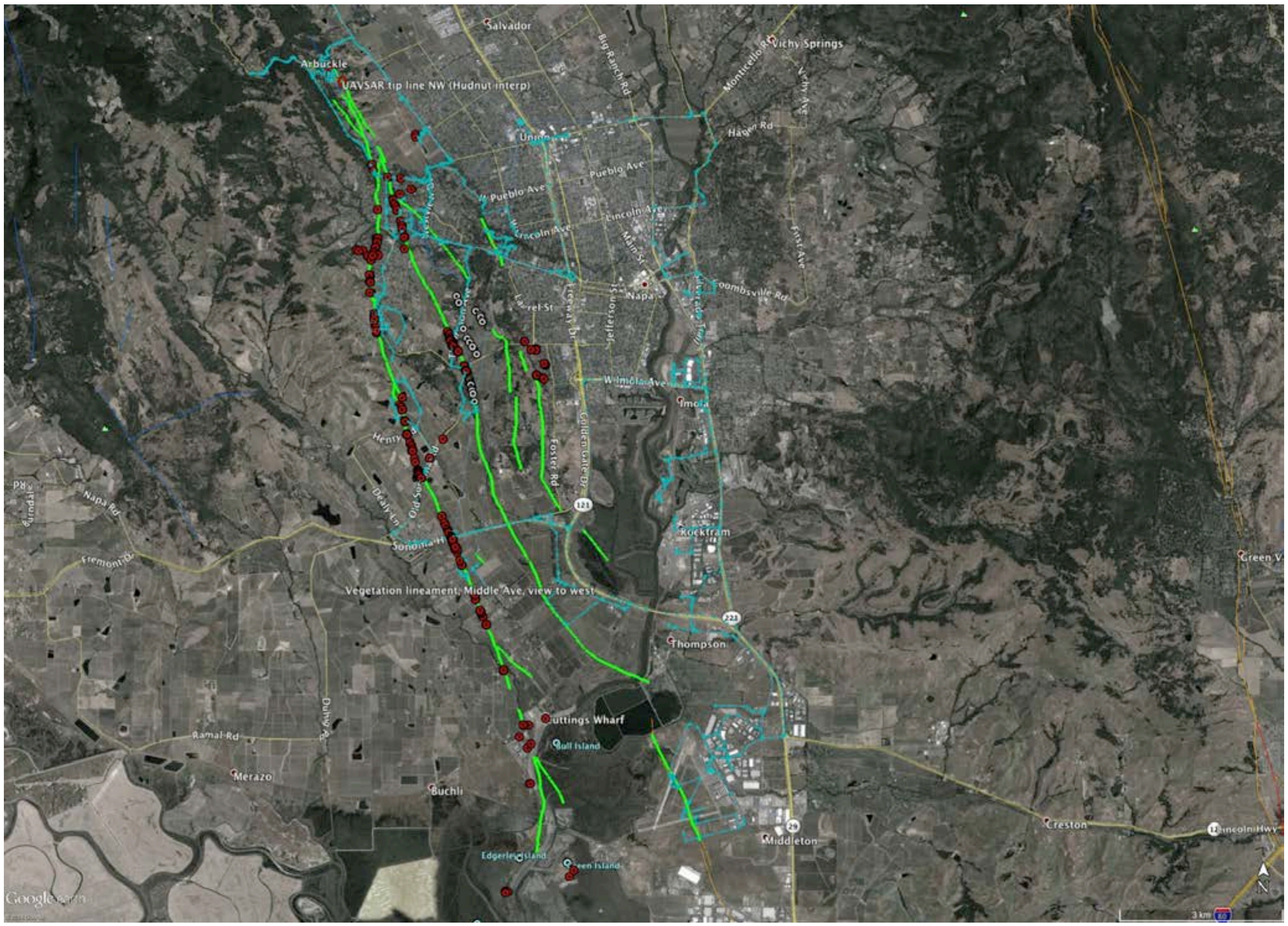
- Epicenter near Cuttings Wharf (south end)
- Rupture propagated towards the northwest and came up shallower on the fault as it went
- This resulted in energy being directed at the City of Napa, so damage was concentrated
- Fault rupture through residential suburban neighborhood of Browns Valley caused extensive damage that is still being repaired
- Critical lifeline infrastructure damage occurred along the surface rupture; identified by initial aerial recon

Maximum Fault Offset 46 cm


CAUTION

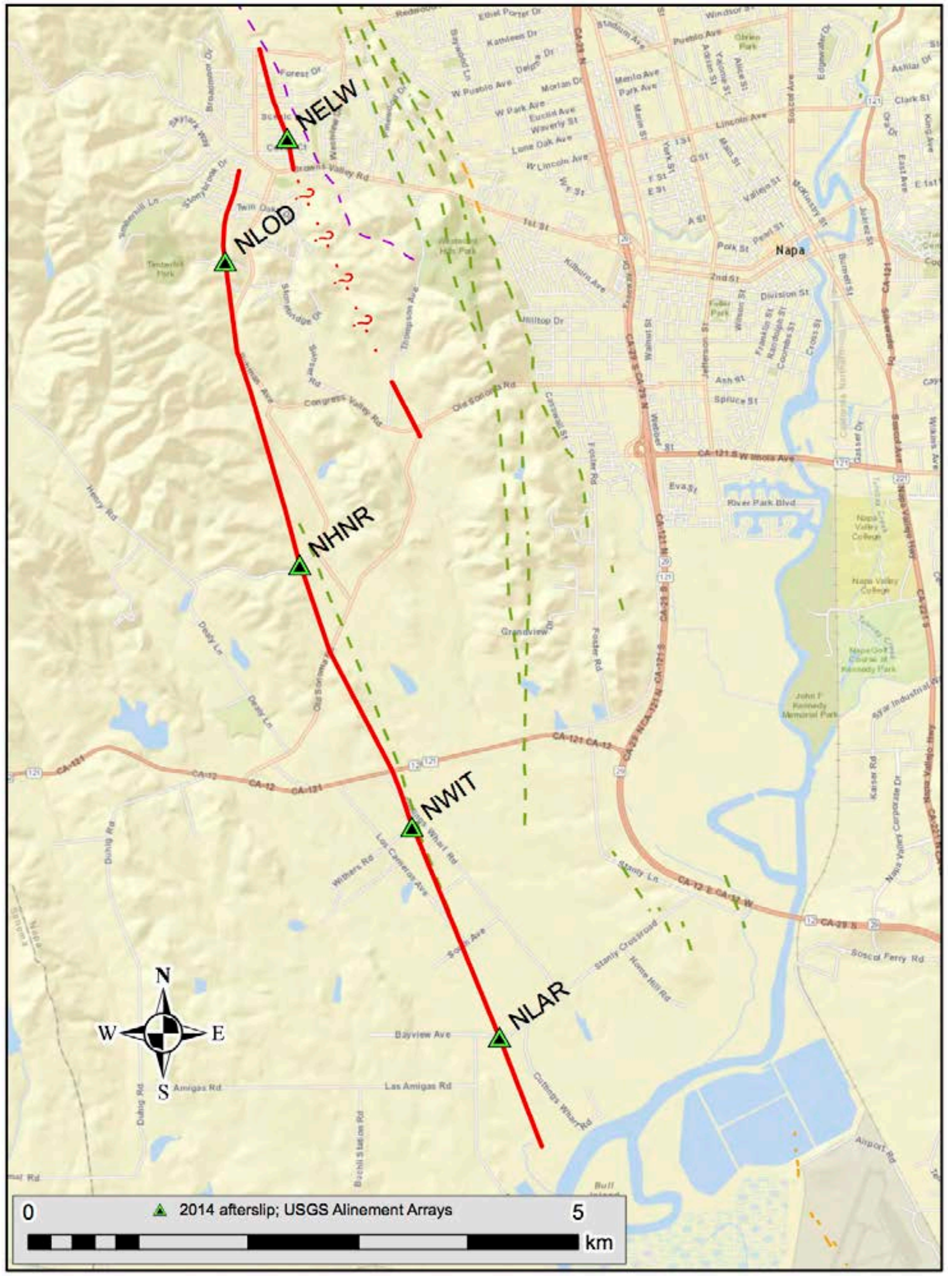
Two days ago (Tues., 9/30/2014) new observations of rupture next to house (Buhman Ave.)

Overview of Surface Faulting



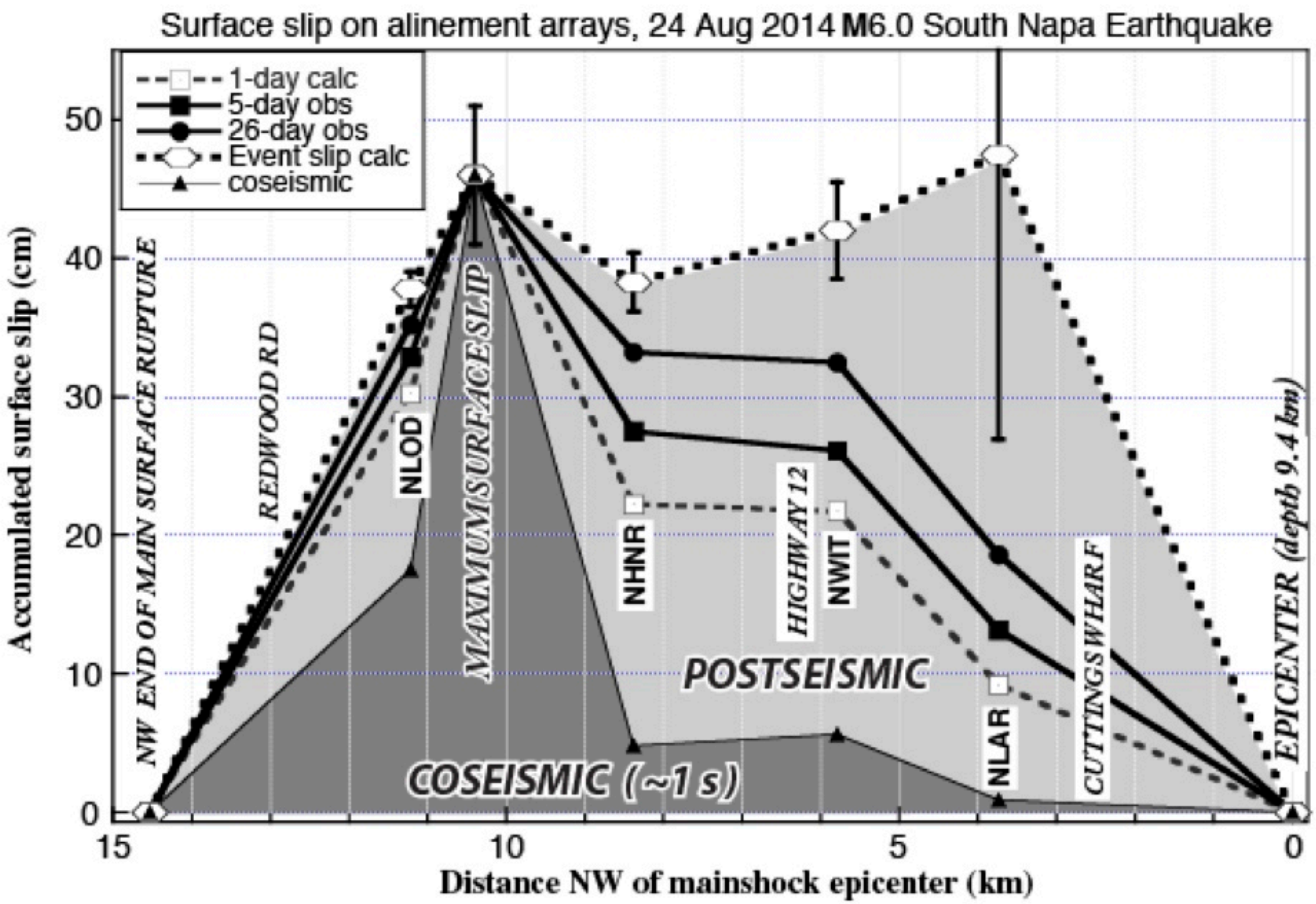
Need to assess afterslip

Fault is continuing to slip; predictable but uncertain. Could a gas pipeline break?



Map of alinement arrays installed across surface ruptures of the M6.0 South Napa Earthquake that occurred at 3:20 AM PDT on Aug. 24, 2014.

Courtesy of Jim Lienkaemper, USGS



Courtesy of Jim Lienkaemper, USGS

Airborne LiDAR Coalition formed rapidly as a result of California Earthquake Clearinghouse DWR, PEER-GEER, CGS and USGS prioritized post-earthquake airborne LiDAR

GEOTECHNICAL EXTREME EVENTS RECONNAISSANCE (GEER) ASSOCIATION

Turning Disaster into Knowledge

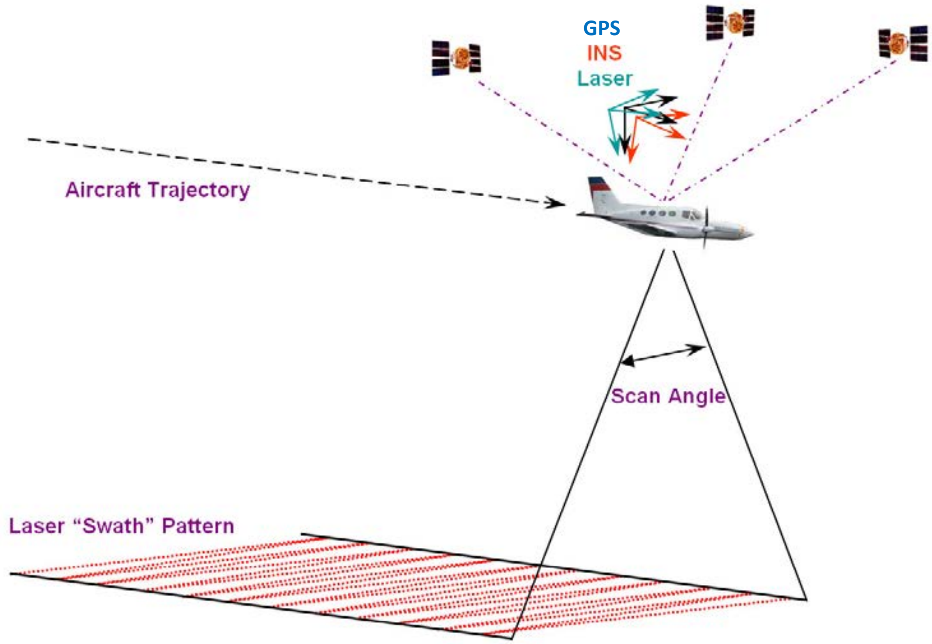
Geotechnical Engineering Reconnaissance of the August 24, 2014 M6 South Napa Earthquake

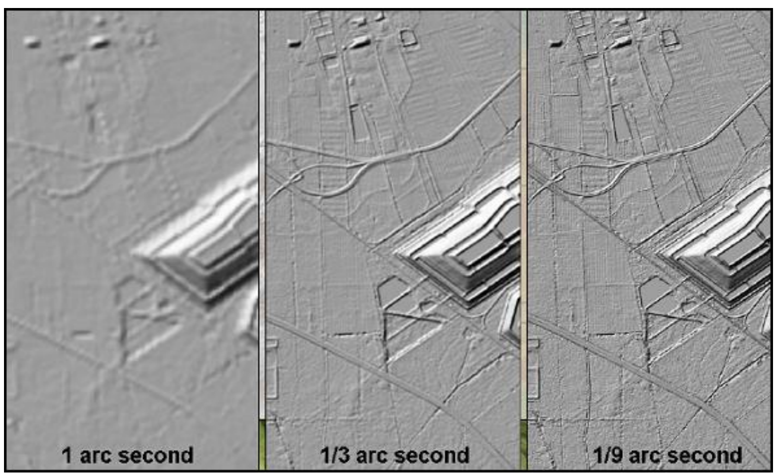
Report of the NSF Sponsored GEER Association Team, California Geological Survey, Pacific Earthquake Engineering Research Center, and U.S. Geological Survey

Editors:
Jonathan Bray, Julien Cohen-Waeber, Tim Dawson, Tadahiro Kishida, and Nicholas Sitar

Lead Authors:
Christine Beyzaei, UC Berkeley; Jonathan Bray, UC Berkeley; Julien Cohen-Waeber, UC Berkeley; Tim Dawson, CGS; Les Harder, HDR; Ken Hudnut, USGS; Keith Kelson, U.S. Army Corps of Engineers; Tadahiro Kishida, PEER; Robert Lanzafame, UC Berkeley; Roberto Luque, UC Berkeley; Dan Ponti, USGS; Michelle Shriro, GEI Consultants; Nicholas Sitar, UC Berkeley; Nathaniel Wagner, UC Berkeley; John Wesling, State of California, Office of Mine Reclamation

GPS is used to provide precise positions of airborne sensors so that highly accurate base geospatial data products such as high resolution terrain (elevation) data and ortho-rectified imagery can be produced efficiently. With pre- and post-event data difference products such as maps of vertical deformation, tilt and strain can be produced quickly and are useful for damage assessment.





Highly accurate terrain elevation data is replacing older, lower resolution data

Example of high resolution orthorectified imagery acquired in
Partnership between USGS and other Federal, State, and Local government agencies

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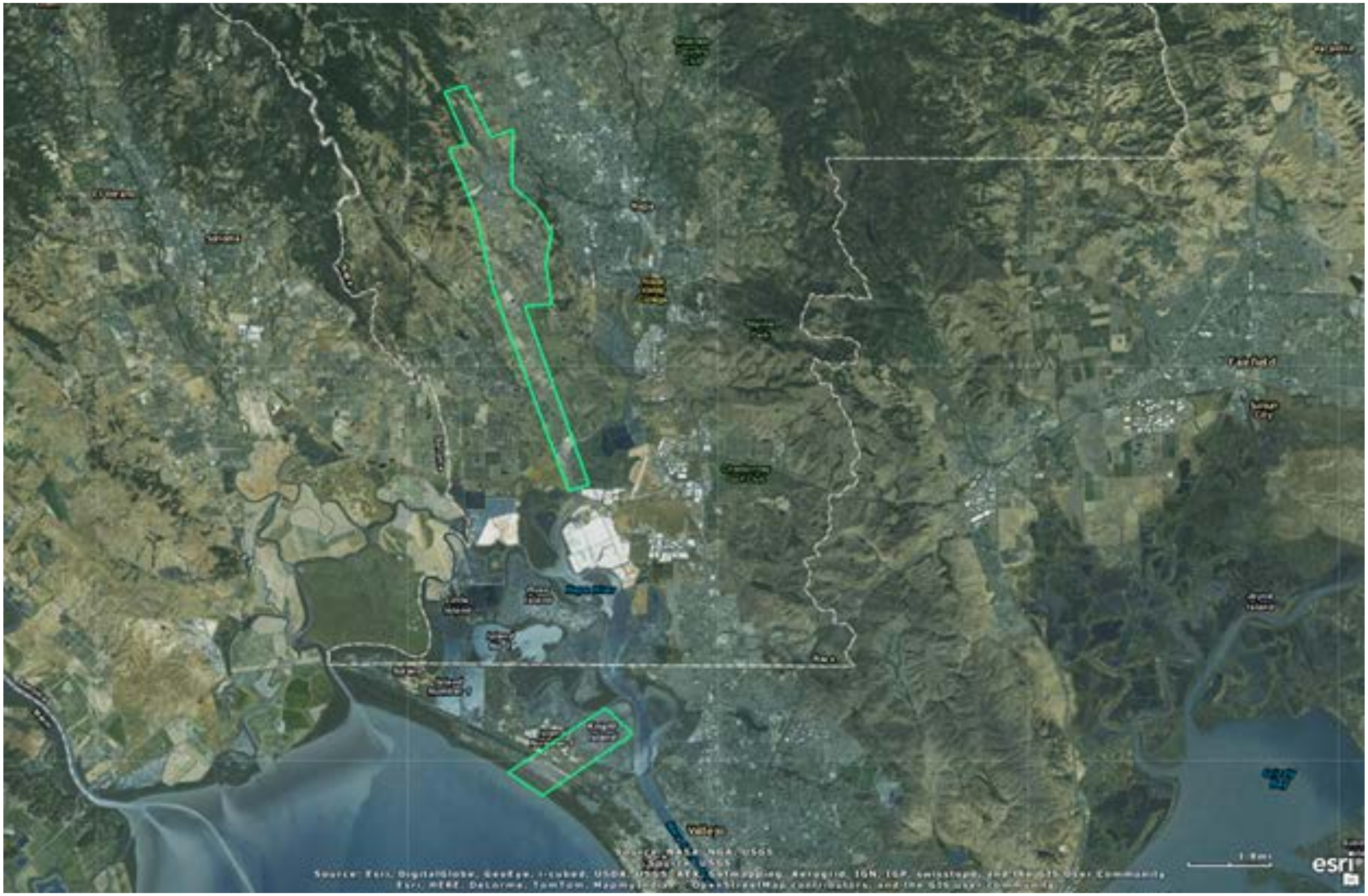
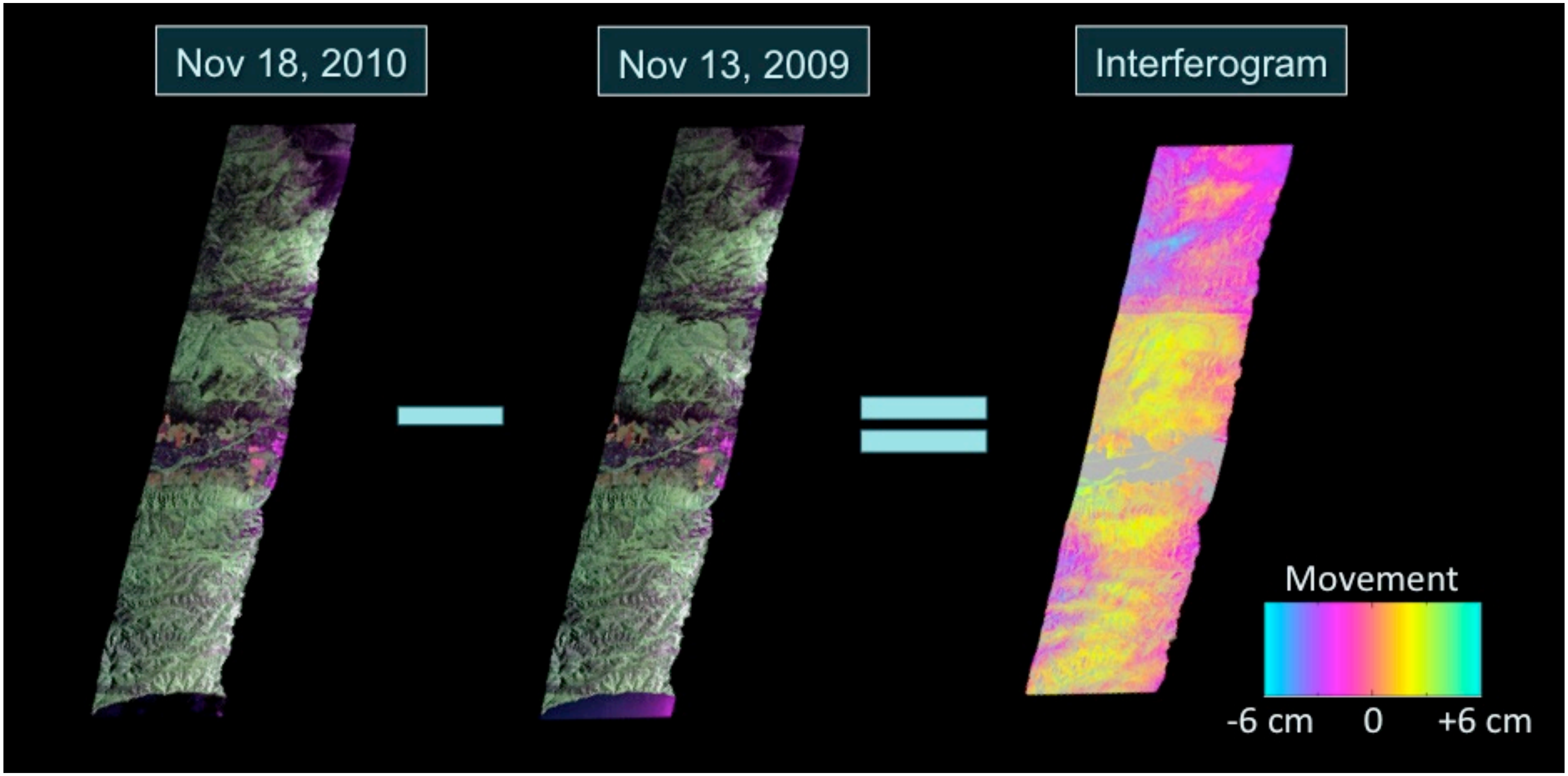
‘Phase I’ airborne LiDAR (9/9/2014)
Cost-share; DWR, CGS, PEER-GEER, USGS



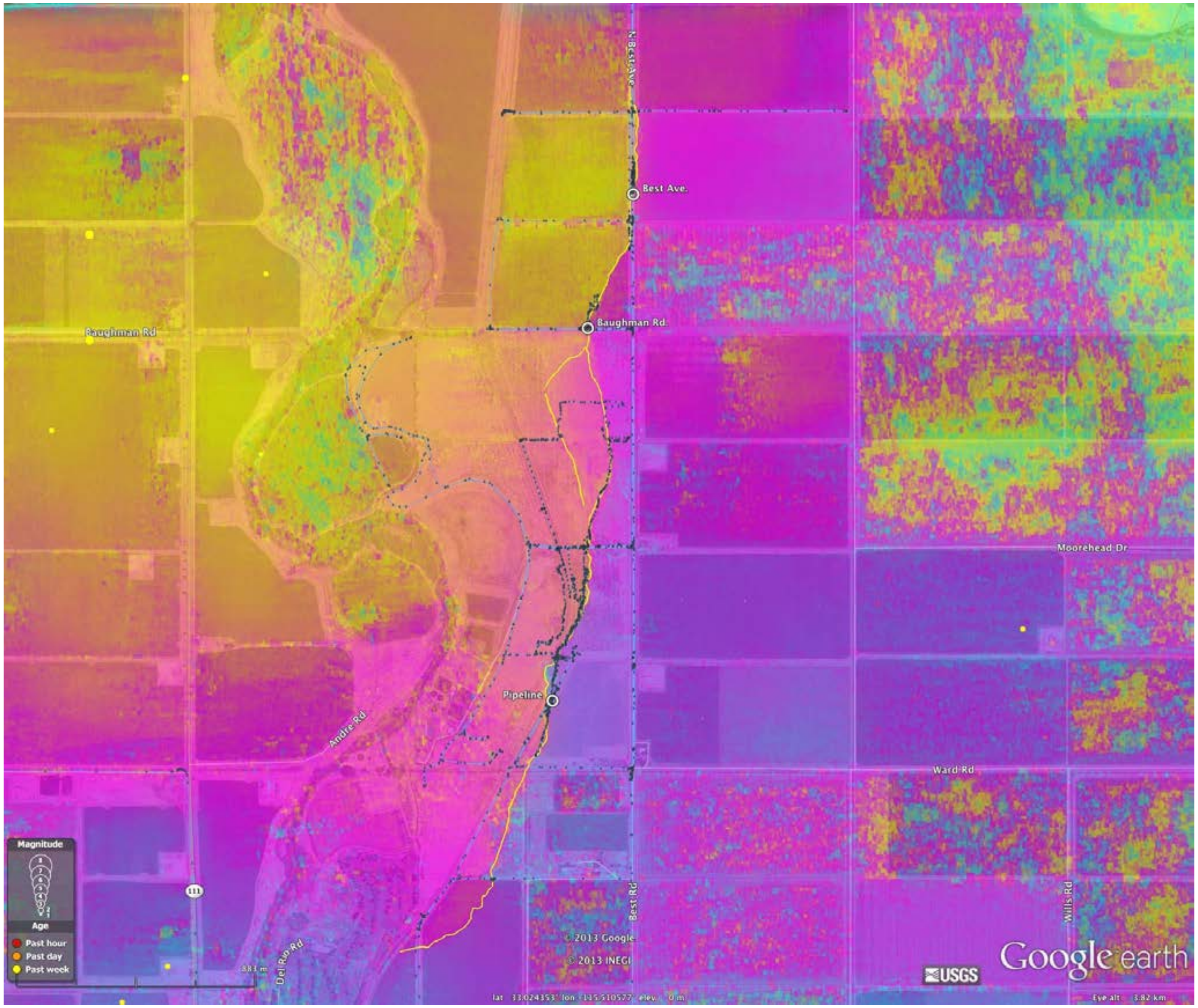
A very limited area of coverage was all that could be acquired due to limited funds.

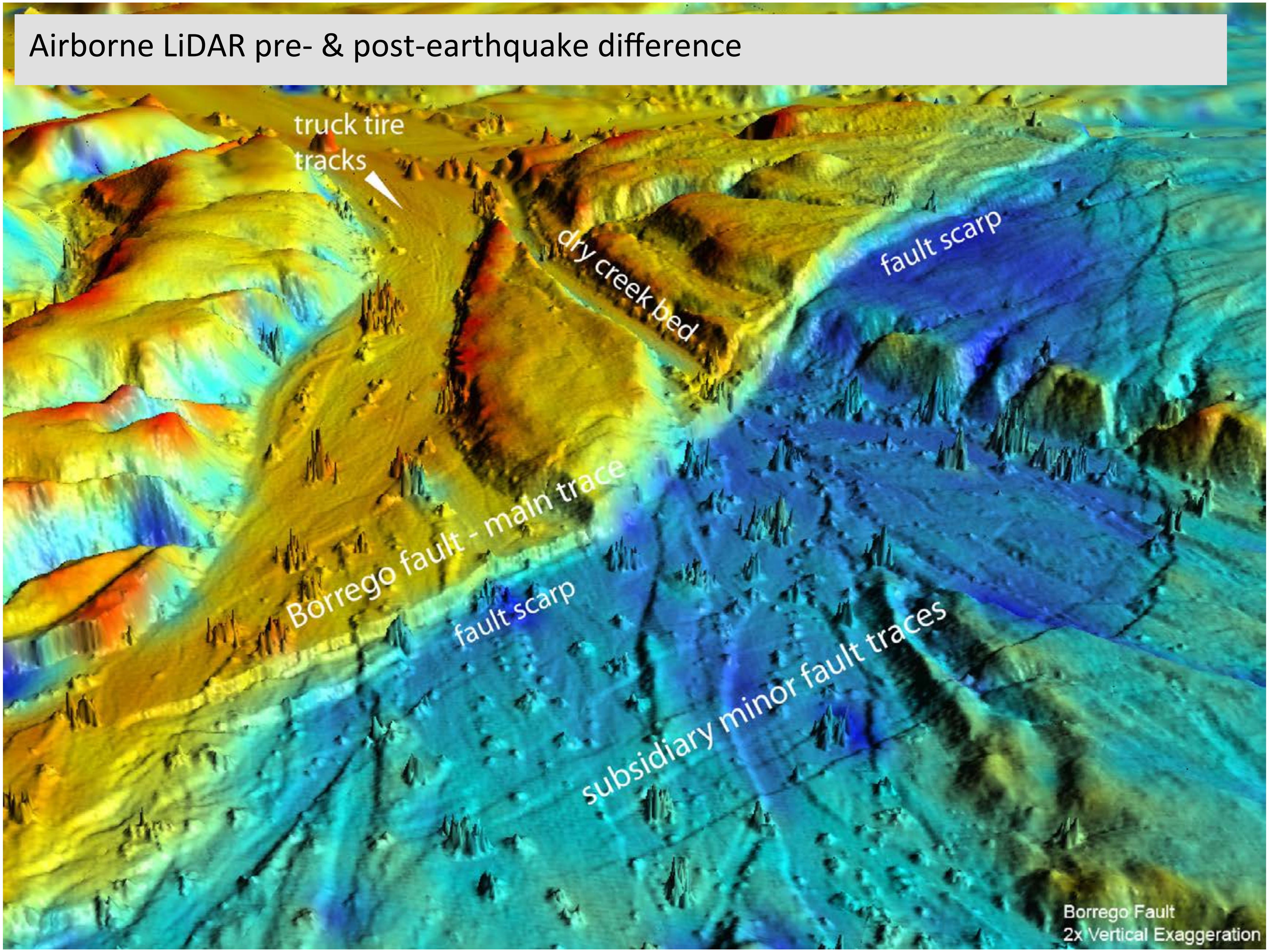
UAVSAR example interferogram (L-band)



Similar to satellite InSAR, but airborne so it has higher resolution and more control over flight planning for rapid response uses

Aug. 2012 Brawley, CA Swarm – UAVSAR (NASA/JPL)





Courtesy of Mike Oskin, UC Davis

“Phase II” airborne LiDAR – why a larger AOI?

State agencies have concerns after they learned of more widespread effects

- bridge damage can be subtle (e.g., Northridge Eq. FEMA report)
- inspectors need aiding and guiding from imagery differencing in large area

- levee damage in Solano County at a greater distance (Grizzly Island)
- Sacramento River delta is susceptible to saline water, levees are crucial

Cost share in ‘Phase I’ seems to have depleted agency resources significantly

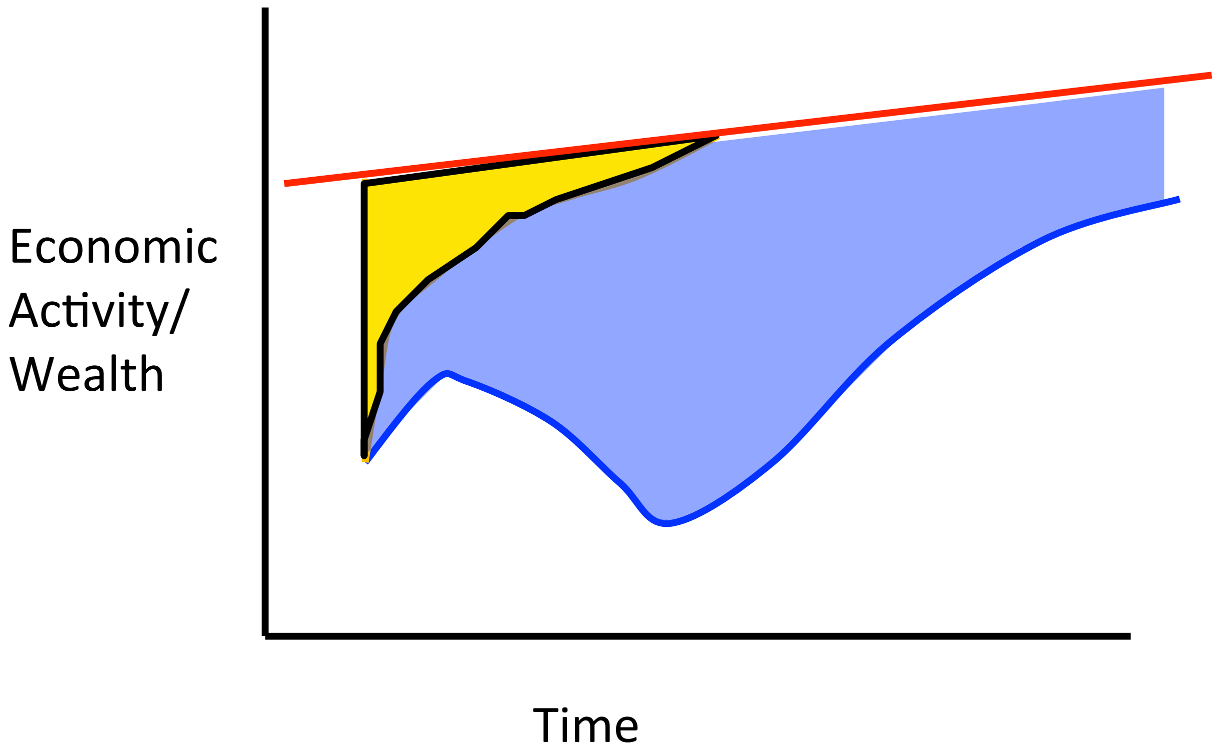
Identified a need for coverage of a larger area, but cost-share is a challenge

Uplift & subsidence pattern partially understood, more detailed info required

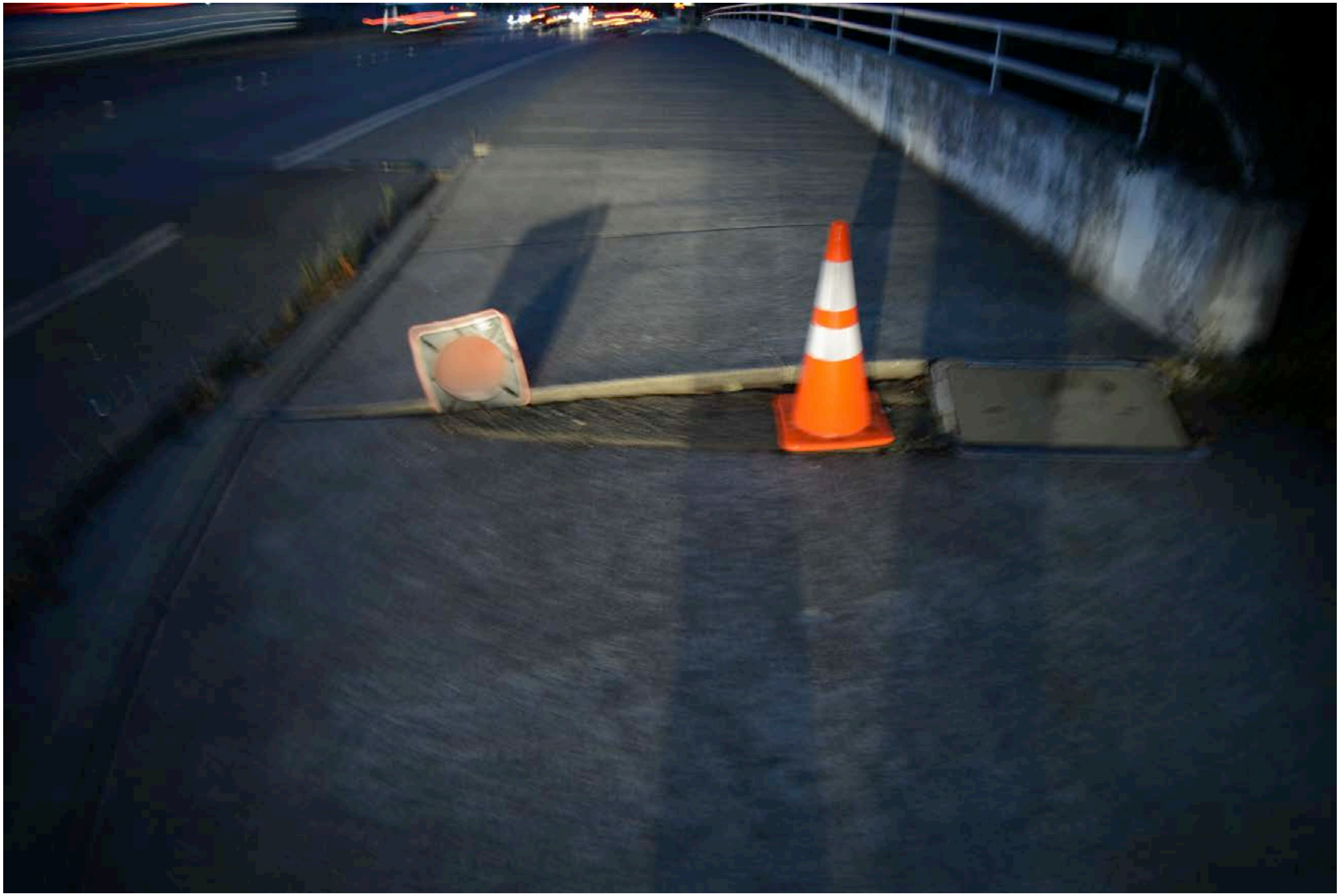
Stress change on faults such as the Green Valley fault and increased activity

Disaster vs. Catastrophe

- What made ‘Katrina’ a catastrophe? cascade of events …
- What if afterslip causes a pipeline rupture, or if a levee fails, or if another earthquake hits …
- Need to repair and restore geodetic infrastructure (as was done with GPS after 1992 Landers earthquake, GPS & leveling after 1994 Northridge earthquake, and with GPS & model by USMC after 1999)



Bridge and overpass damage, repairs and ongoing assessments by Caltrans, others



Levee damage at Grizzly Island; Solano County

Reported by Don Ryan, Solano County Sheriff / Emergency Management

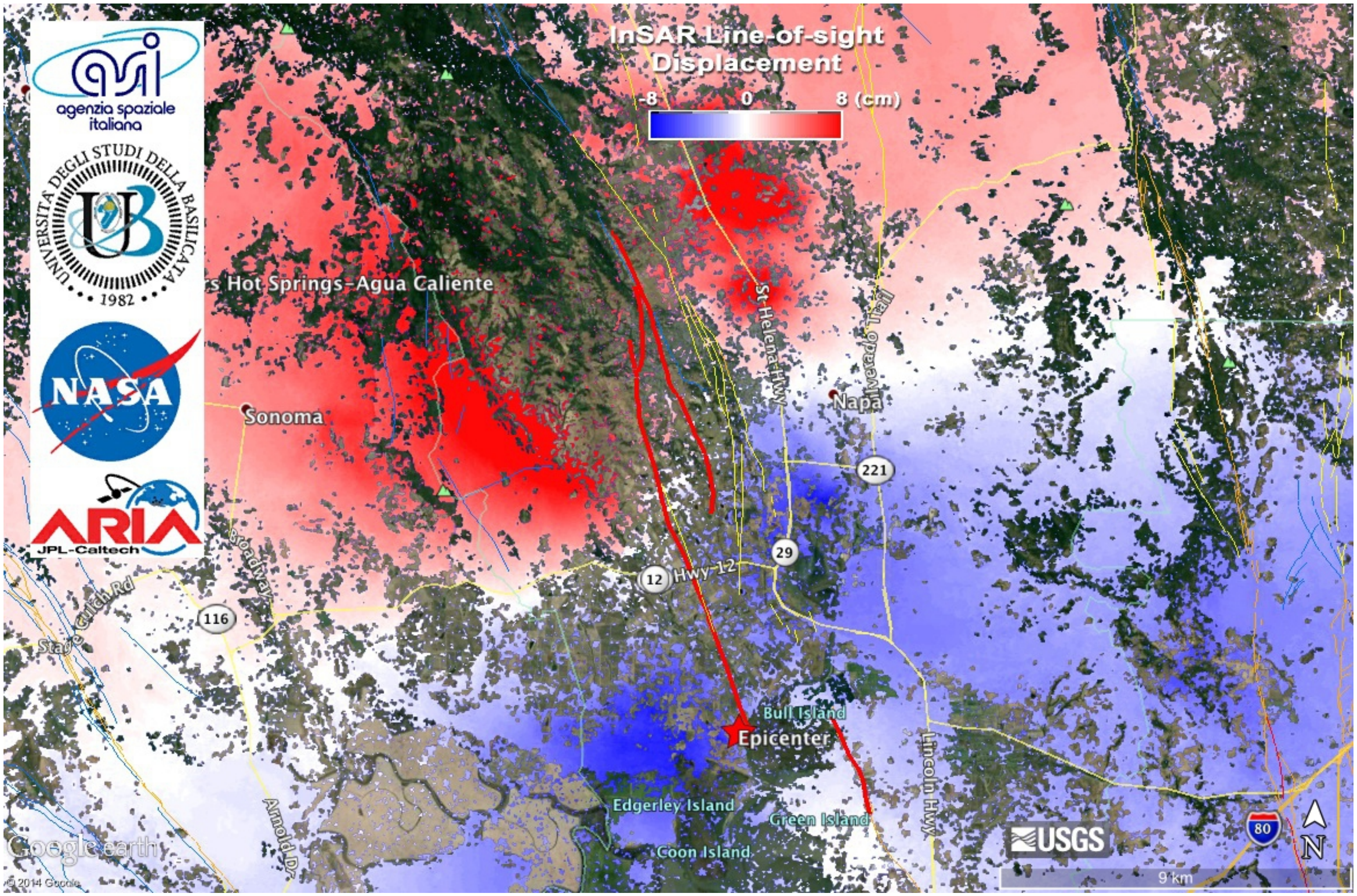
he requests assistance in assessing levee damage

repaired overtopping location approximately one mile west of the Van Sickle Rd/Gum Tree Road intersection in Solano County - more subsidence suspected further west of repair

Looking NW from repaired location at suspected subsidence area
needs further inspection

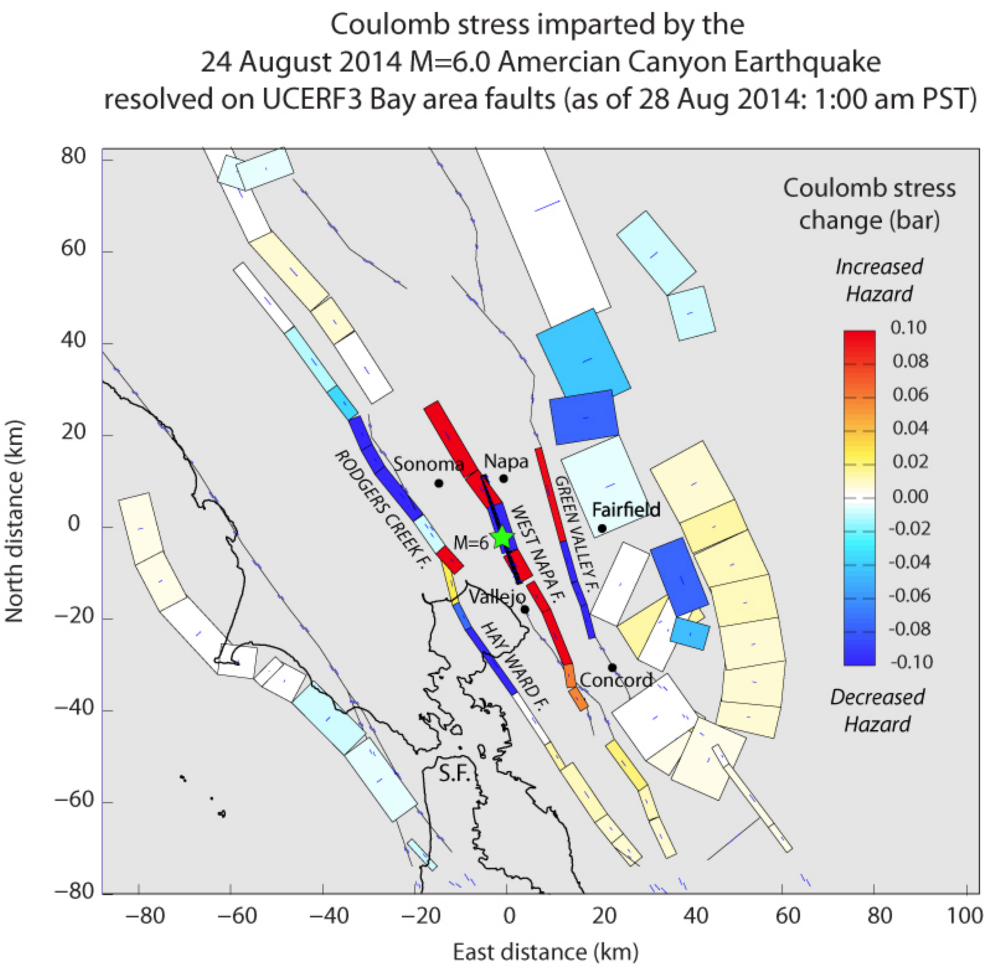
Uplift (red) and subsidence (blue)

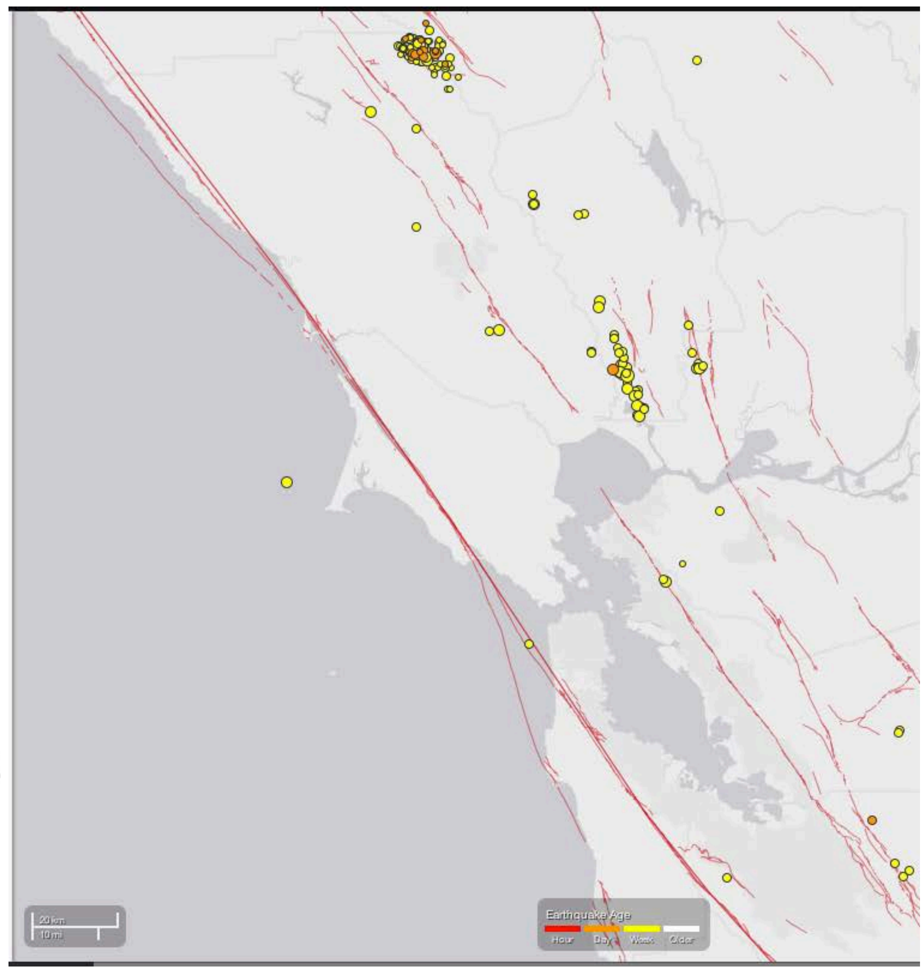
heavy red line is surface fault rupture



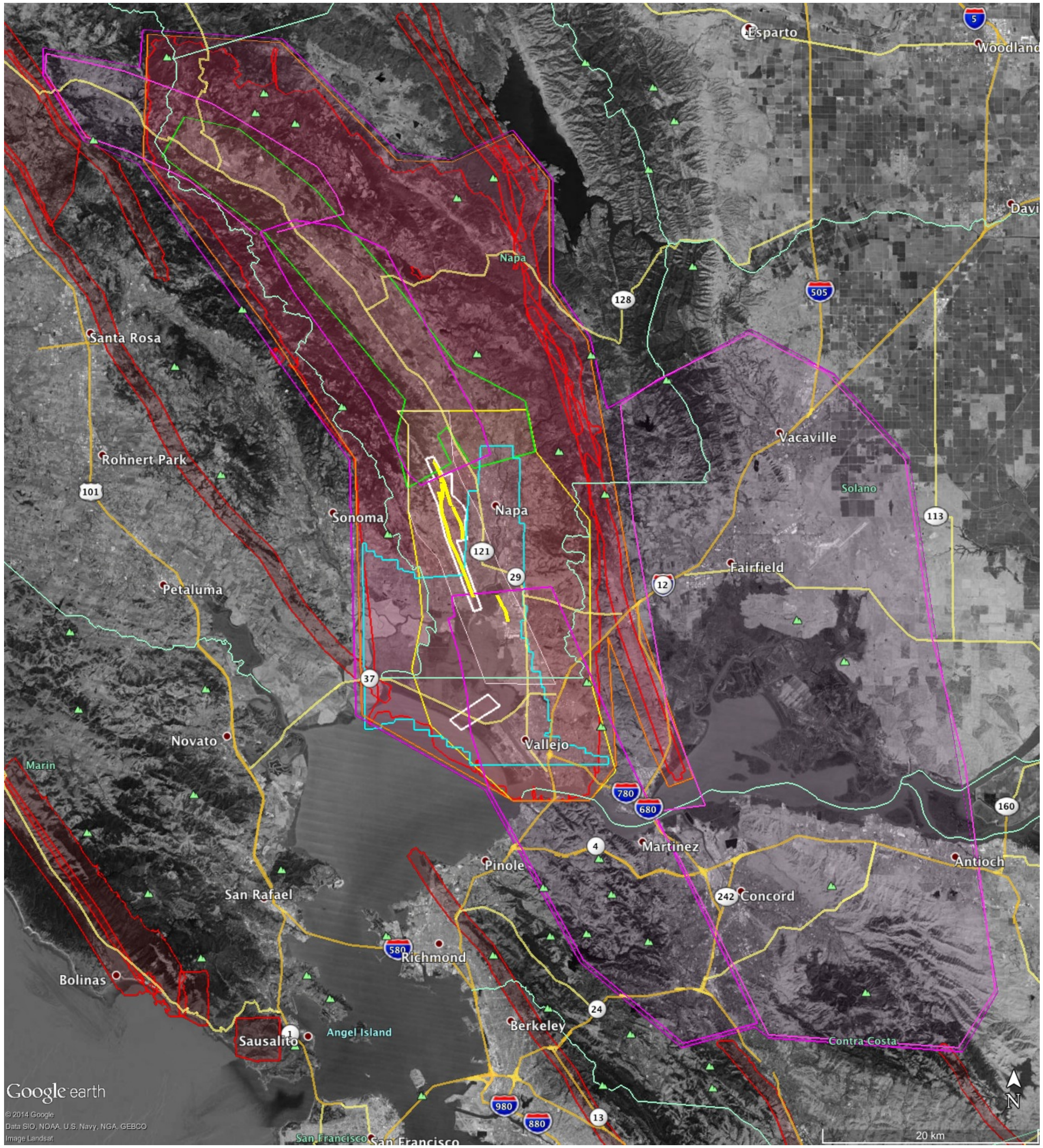
De-correlated in close proximity to the fault rupture zone; cannot see what happened

Triggered slip on Green Valley fault?





source: Ross Stein & Jian Lin



Esparto
Woodland
Davi
Napa
Santa Rosa
Rohnert Park
Sonoma
Napa
Vacaville
Solano
Fairfield
Petaluma
Novato
Marin
Vallejo
Martinez
Pinole
Concord
Antioch
San Rafael
Richmond
Bolinas
Sausalito
Angel Island
Berkeley
Contra Costa
San Francisco
San Francisco
Google earth
© 2014 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
20 km
N

GPS & imagery for hazards management

- GPS and rapid imagery analysis (especially differential repeat pass) is an essential enabling technology for the mapping and precise monitoring needed to accomplish science missions in support of hazard warnings and other societal needs.
- In the aftermath of a significant disaster event, re-mapping and establishing a grid and geo-referenced incident data is essential in support of immediate response (e.g., Urban Search & Rescue) as well as for long-term recovery (e.g., organizing debris removal).

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Before and after image differencing provides rapid characterization of earthquake ground deformation needed to assess patterns of subsidence, uplift and lateral shift that causes strain across pipelines

- Application to assessing damage to storm drains, sanitation lines and all other gravity fed water systems; identify subtle damage.
- Application to assessing subtle damage to engineered structures such as bridges, overpasses, and lifelines.
- Application to assessing damage to levee system in western Sacramento River delta; close and fragile enough to be damaged, even though shaking was not very strong at this distance range; how widespread? Verify and validate claims.
- What is the expected tectonic fault slip signal? How much afterslip is occuring and after several years how much more will accumulate? Geodetic and geospatial information must be accurate, and extrapolated slip values must be accurate.

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