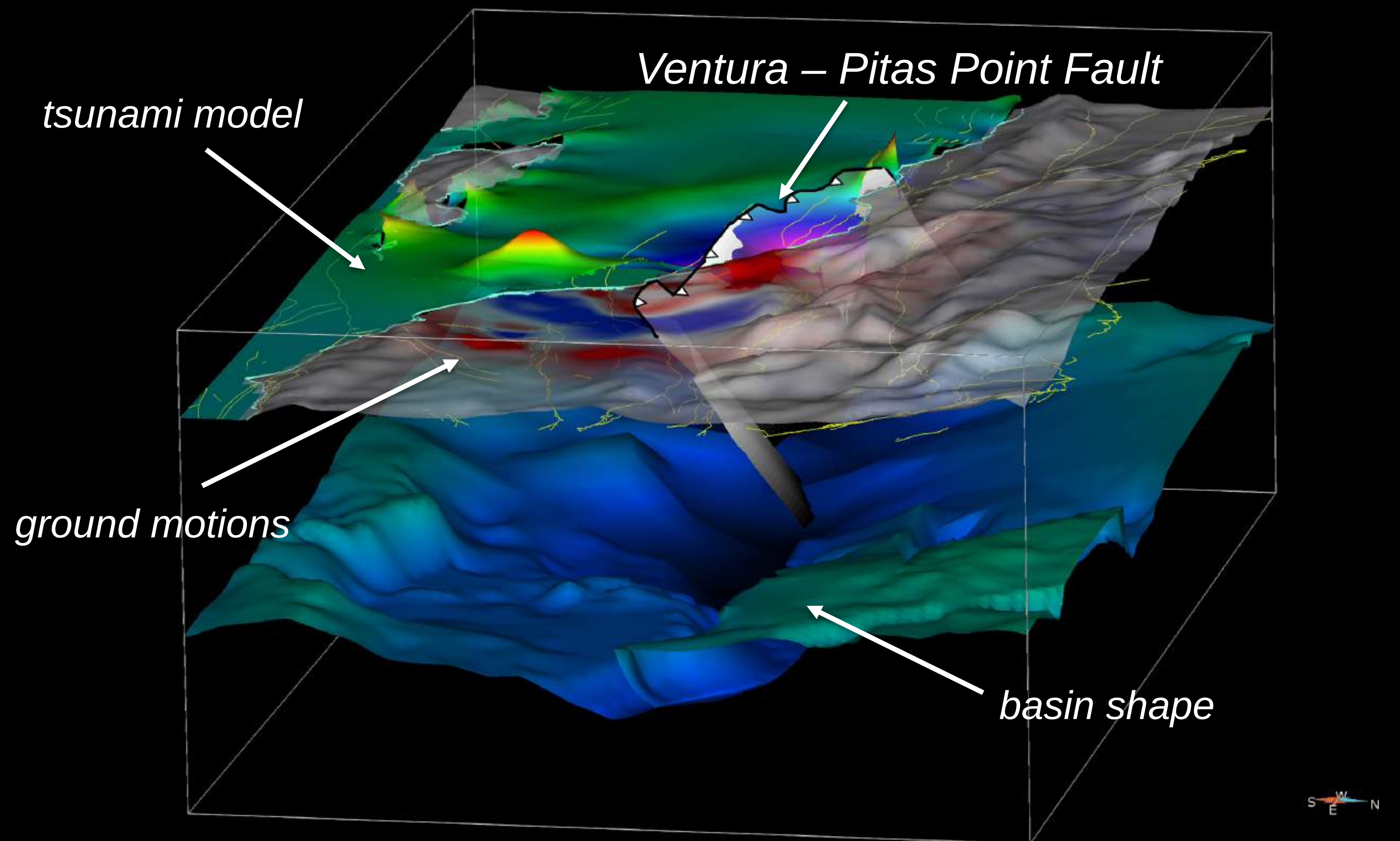
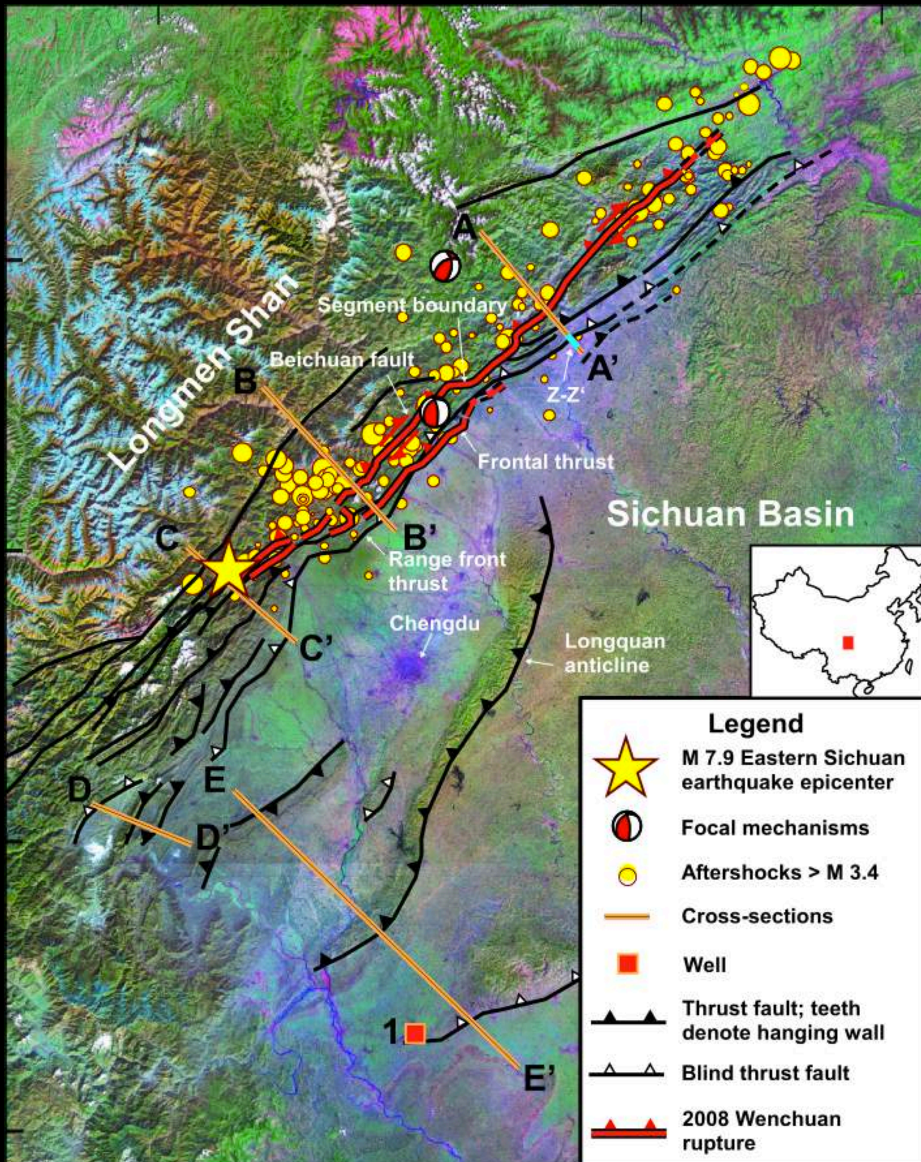
The Ventura Special Fault Study Area: *Assessing the potential for large, multi-segment thrust fault earthquakes and their hazard implications*

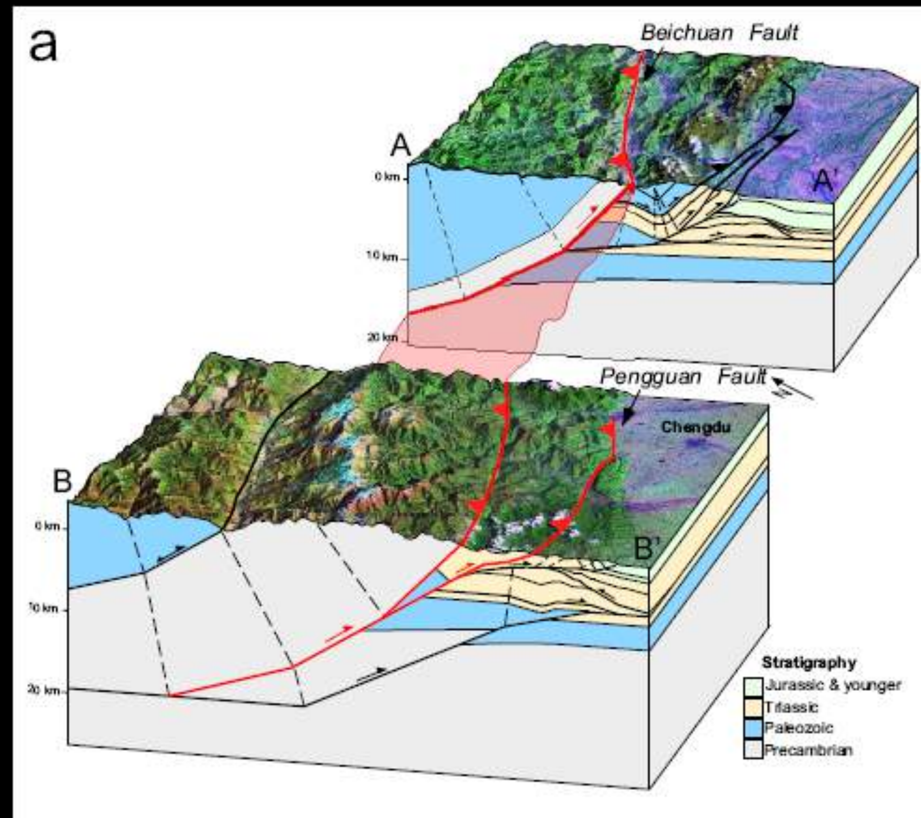


John H. Shaw, Michael Barrall, Reed Burgette, James F. Dolan, Eric Geist, Jessica Grenader, Thomas Gobel, William Hammond, Egill Hauksson, Judith A. Hubbard, Kaj Johnson, Yuval Levy, Lee McAuliffe, Scott Marshall, Craig Nicholson, David Oglesby, Andreas Plesch, Laura Reynolds, Thomas Rockwell, Kenny Ryan, Alex Simms, Christopher Sorlien, Carl Tape, Hong Kie Thio, and Steven Ward

Large (multi-segment) thrust fault earthquakes

2008 Wenchuan (M 7.9) earthquake

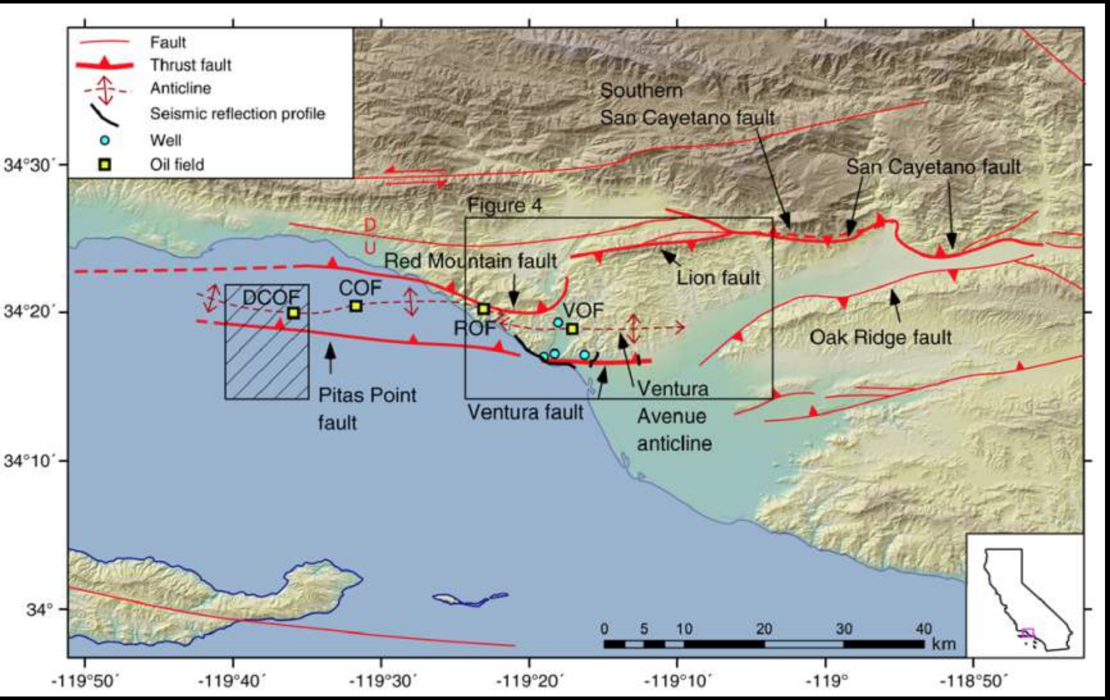


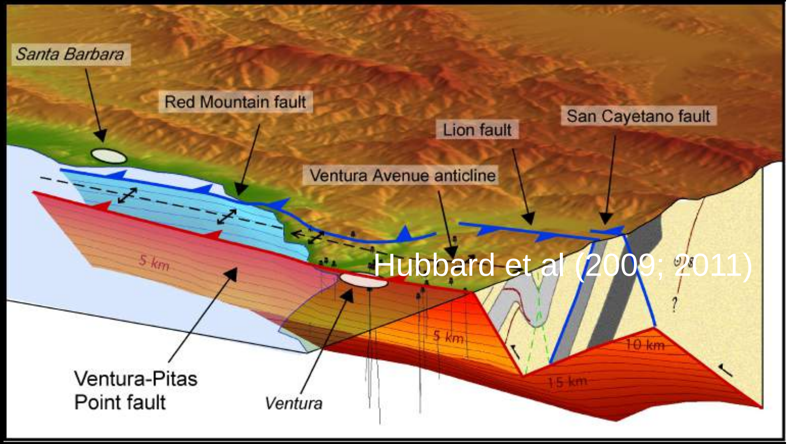


Hubbard et al (2009; 2011)

Large thrust fault earthquakes often involve multiple faults splays, including detachments, and breach lateral fault segment boundaries.

Why the Ventura Fault?





The Ventura fault lies at the juncture of some of the largest and fasting slipping thrust faults in California

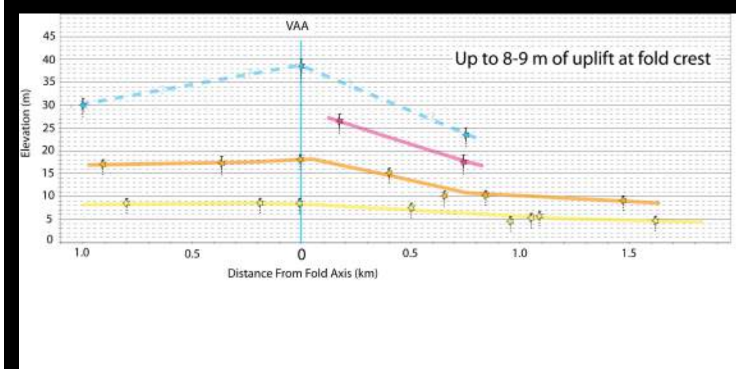
The overlying anticline is one of the fastest uplifting regions of the southern California coastline

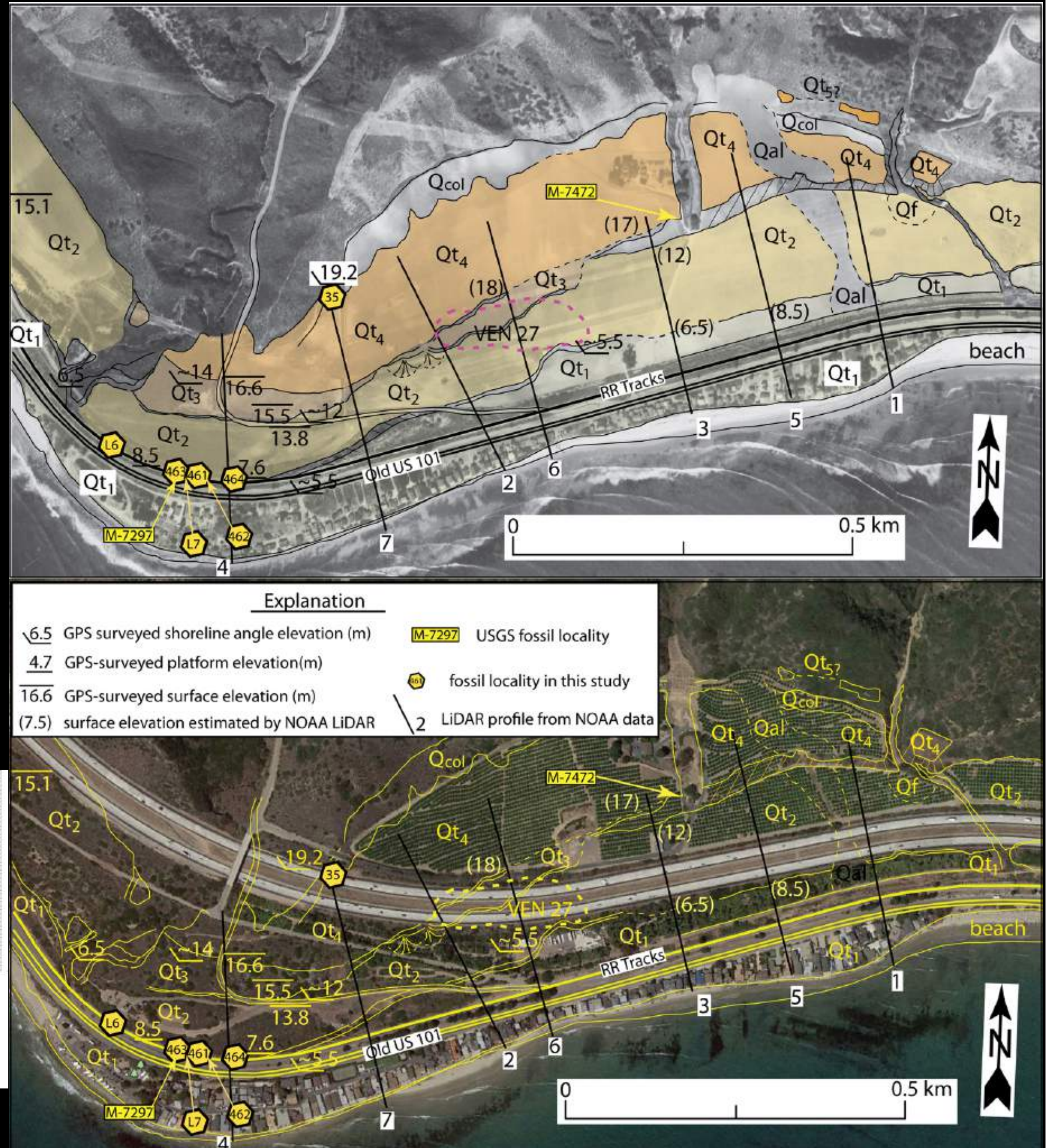
Ogle and Hacker, 1969 ; Sarna-Wojcicki et al., 1976 ; Yeats, 1982a ; Rockwell et al., 1988; Perry and Bryant, 2002; Hubbard et al, 2014.

Motivation - Pitas Point Holocene Emergent Terraces

Deformed marine terraces suggests the occurrence of four large Holocene earthquakes on the Ventura fault with up to 9 meters of uplift at the fold crest.

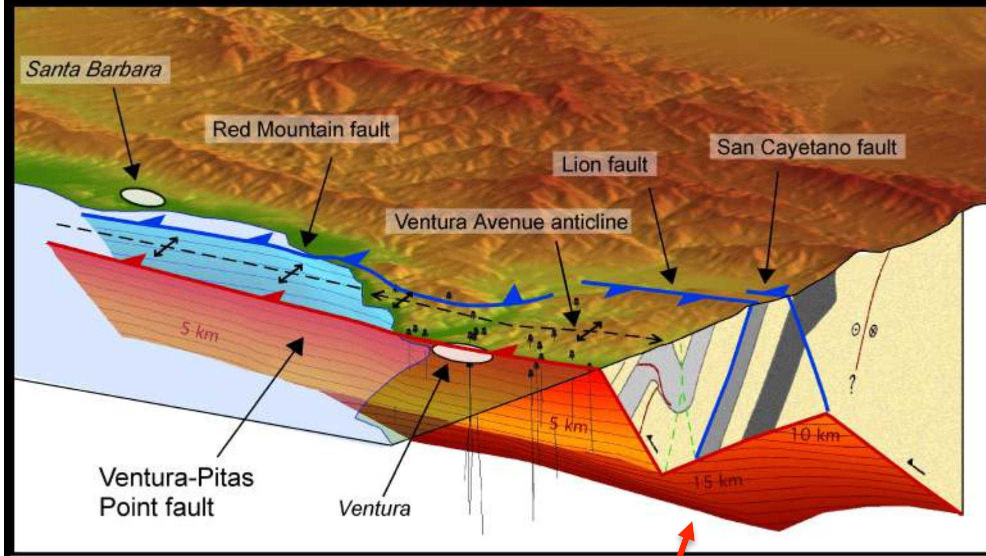
Such events seem to require multi-segment fault ruptures involving others thrust faults in the Transverse Ranges





Rockwell et al., (2012)

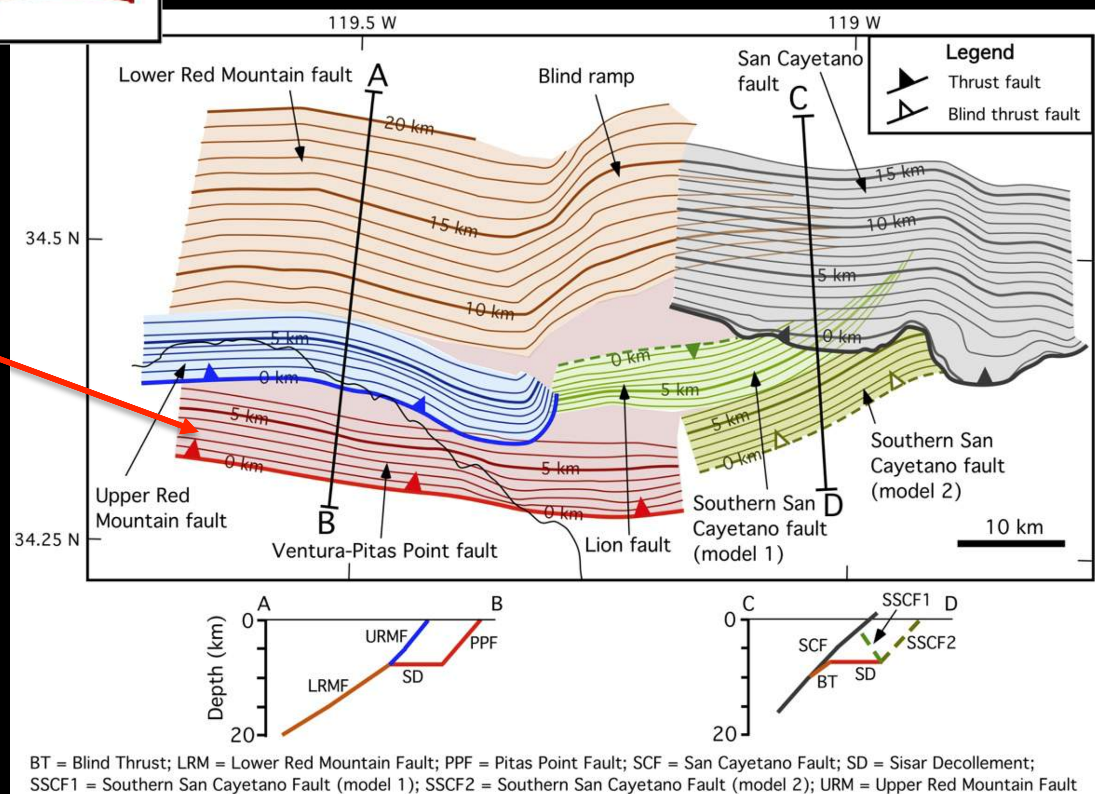
Motivation - Subsurface Structural Characterization



Subsurface structural analysis suggests that the Ventura fault represents a direct linkage between some of the largest, highest slip rate thrust faults in the Transverse Ranges, including the Pitas Point fault (left) and San Cayentano fault (below).

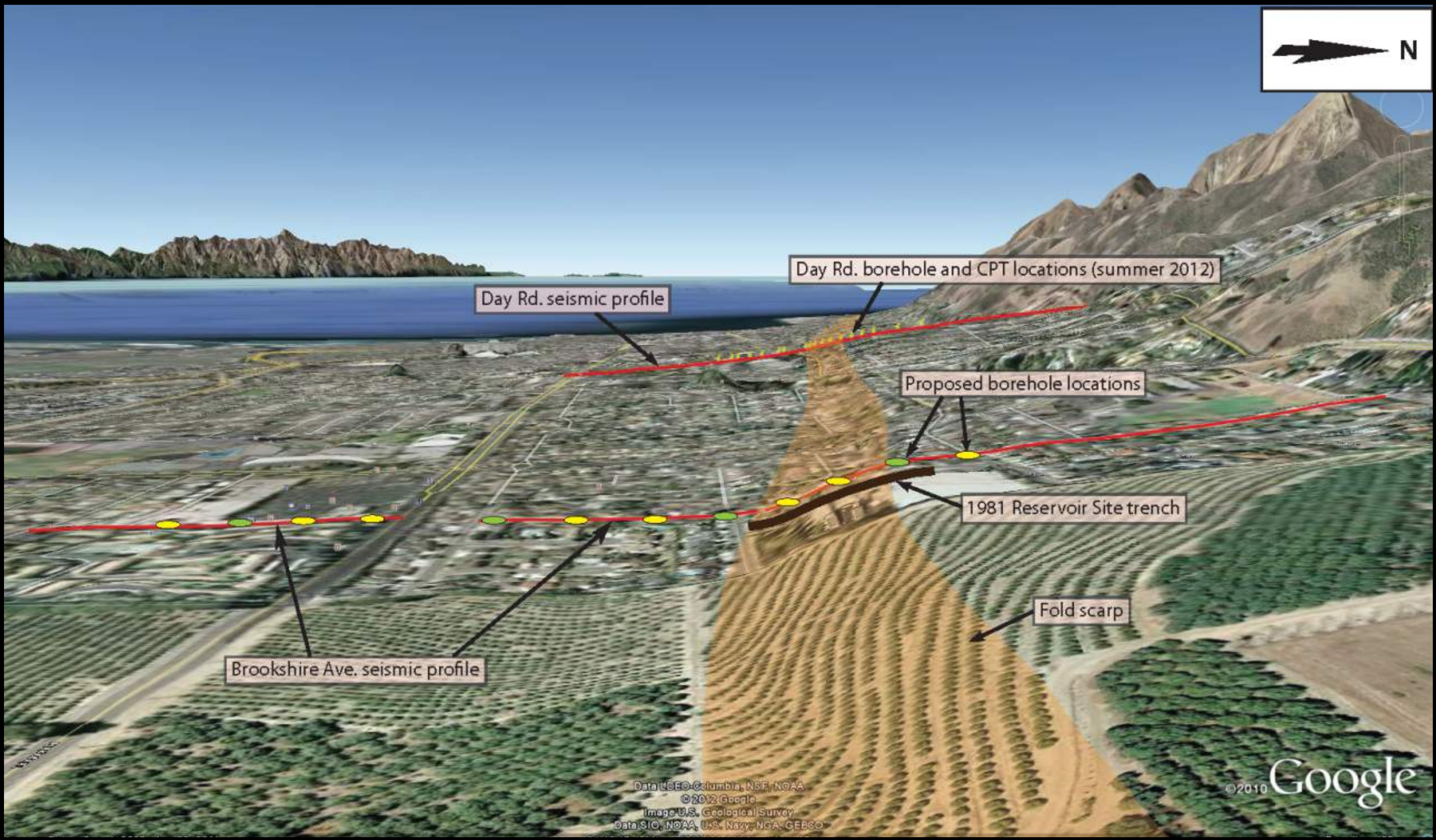
This may enable the large, multi-segment ruptures implied by the terrace records.

Ventura Fault



Hubbard et al., (2014, BSSA)

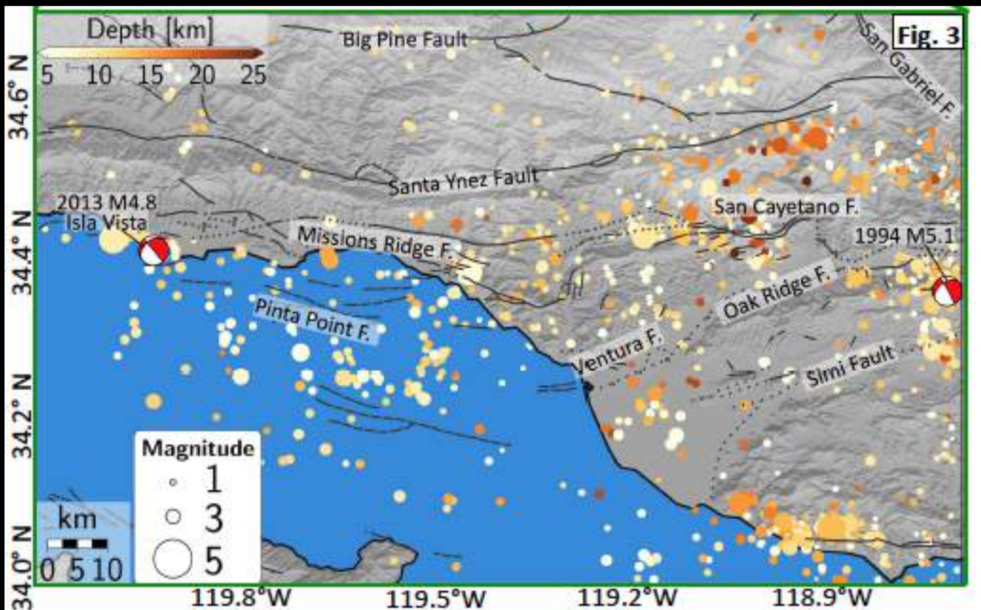
Motivation – Prominent fault & fold scarps in Ventura



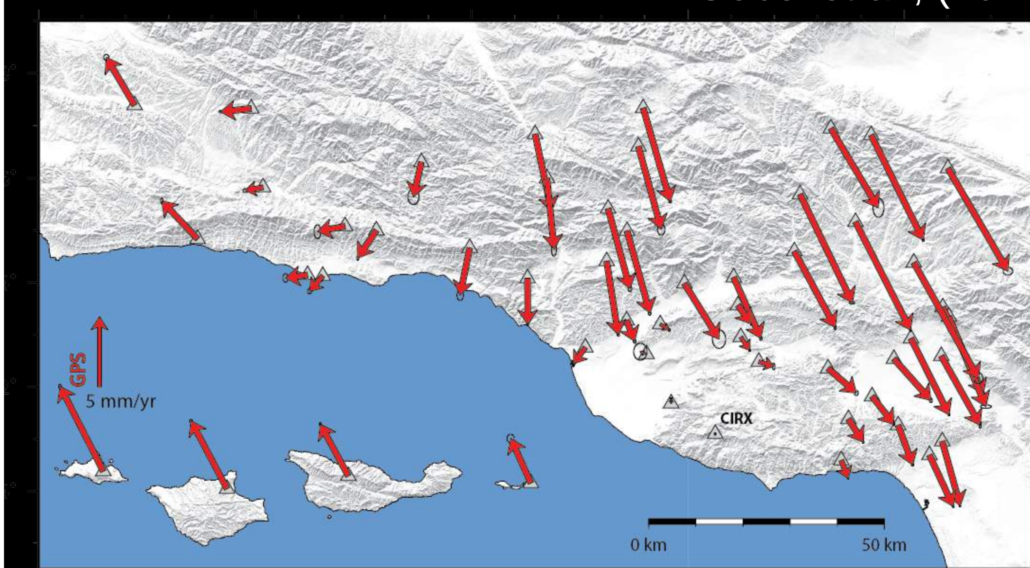
McAuliffe et al., (2015)

Surface manifestation of the fault forms a prominent scarp running through the city of Ventura – target for paleoseismic investigations.

Motivation – Evidence of ongoing deformation



Gobel et al., (2015)

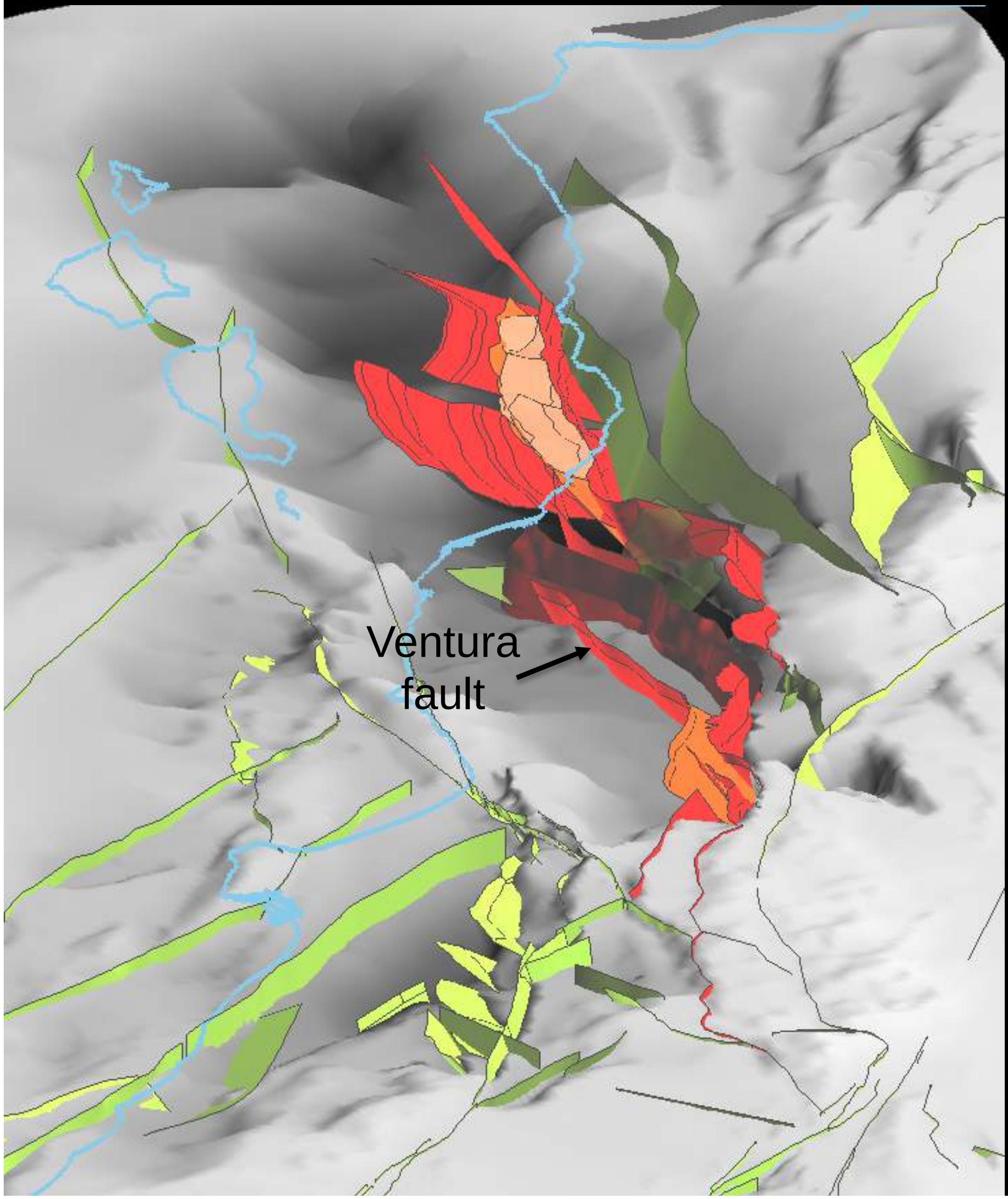


Marshall et al. 2013 (JGR)

Earthquake occur throughout the study region and over a large depth range

Rapid N-S convergence rates across the region

Motivation – Severe ground shaking and tsunami hazards



Proposed event magnitudes and sedimentary basin depth suggest potential for severe ground shaking.

Offshore extensions of these faults pose risks for local tsunamis.

Inaugural Ventura SFSA Workshop Field Trip (8/15-16/2013)

Goals for the Ventura SFSA (2013)

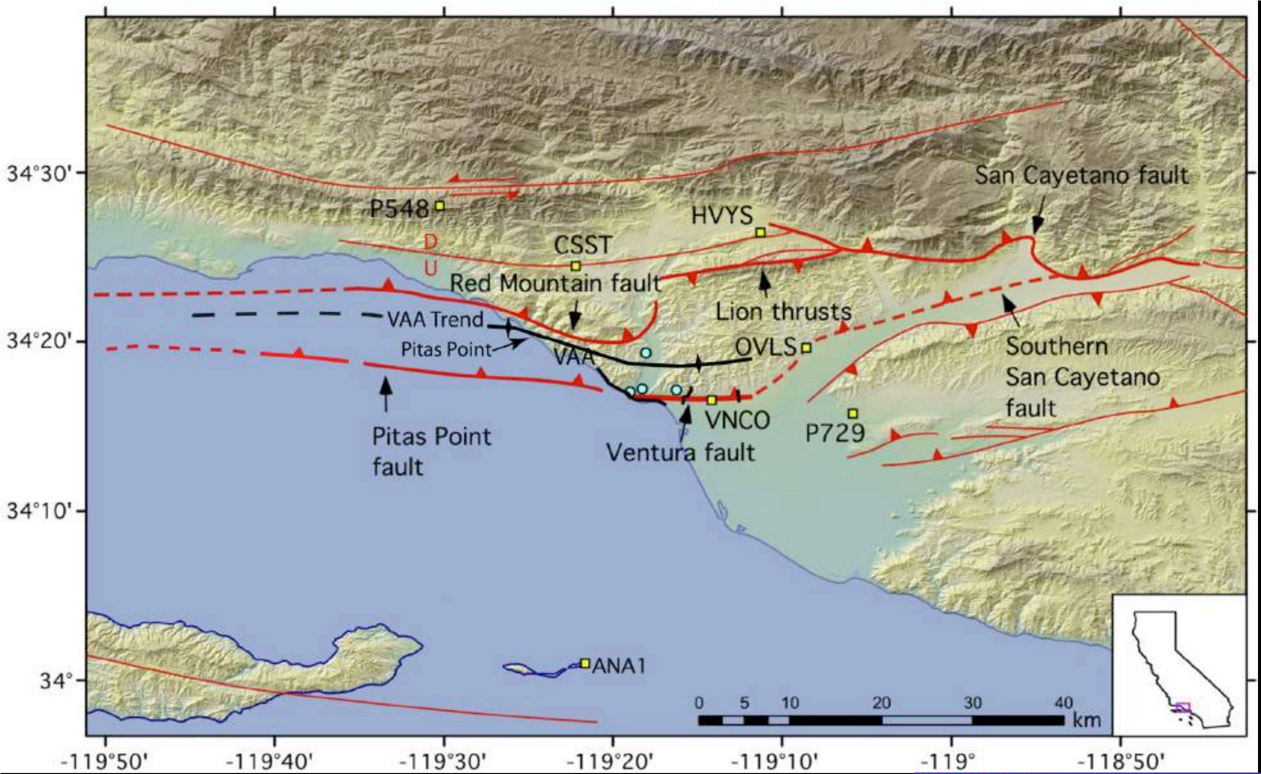
Test and refine the record of large multi-segment ruptures on the Ventura fault system along strike, and extend the record back in time.

Determine how slip and deformation are distributed in these large, multi-segment ruptures, and how might this vary over multiple earthquake cycles.

Characterize the interseismic strain accumulation along the Ventura thrust system.

Define a viable set of rupture scenarios with kinematic and dynamic rupture modeling, and evaluate these using the paleoearthquake record.

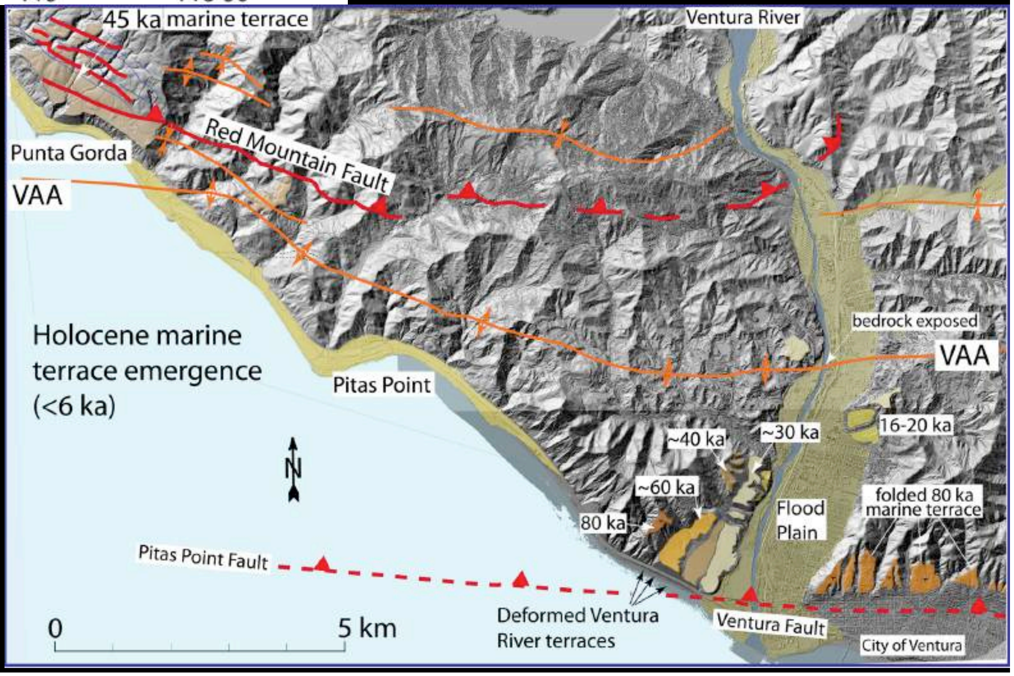
Define the intensity, duration, and distribution of strong ground shaking and tsunami runup we should anticipate for these events.



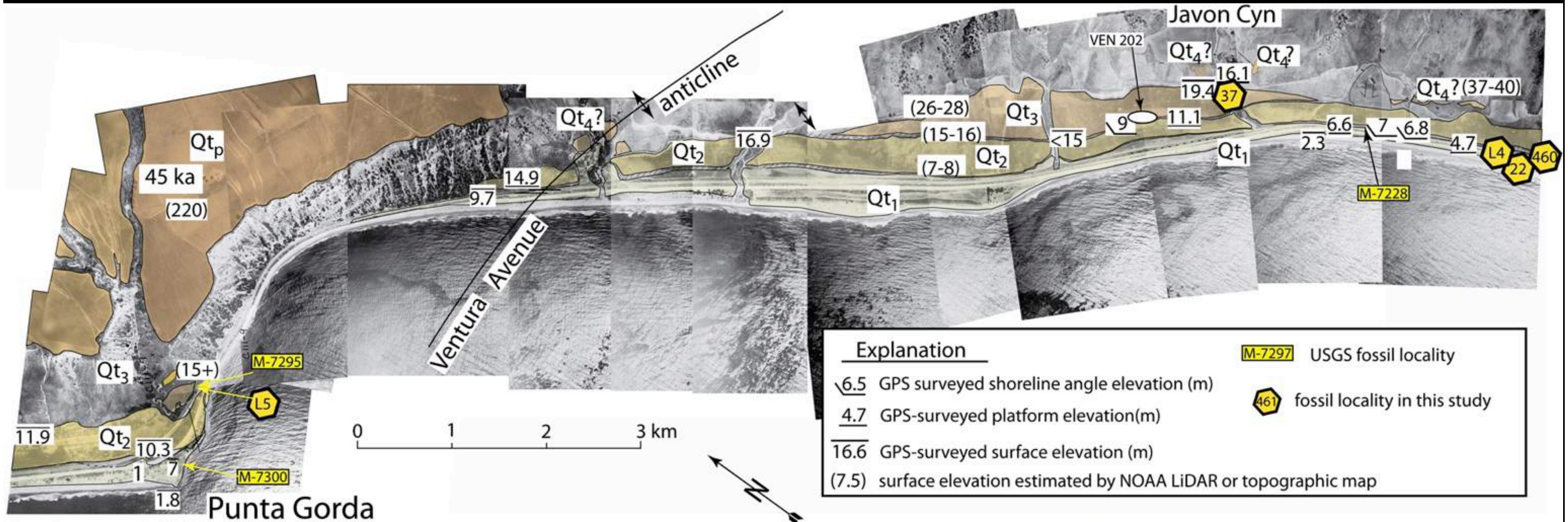
Refining the paleoseismic record from marine terraces

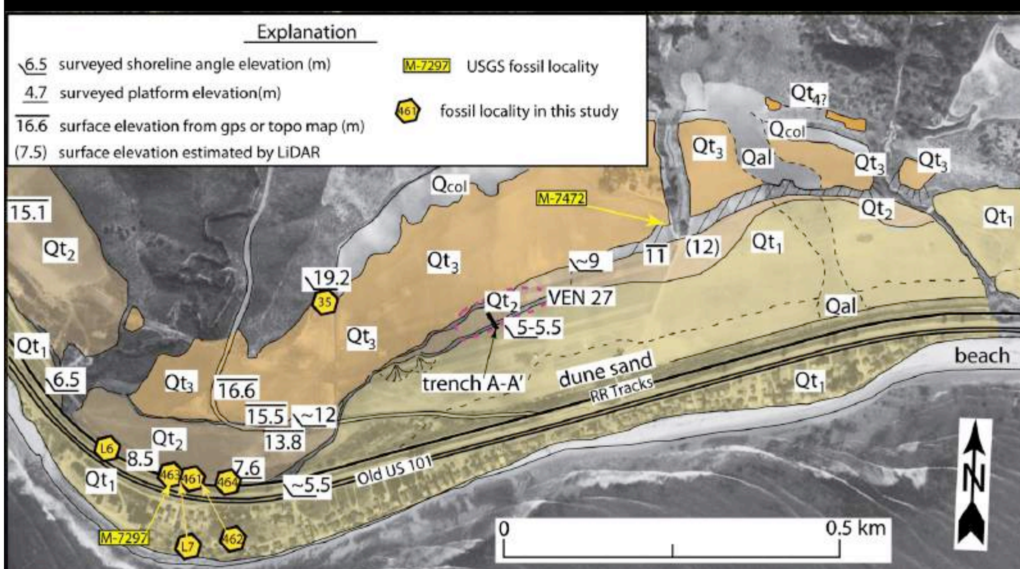
Rockwell et al., (2015)

Holocene coastal uplift between Ventura and Carpinteria is interpreted to reflect folding of the VAA and slip on the partially blind Ventura - Pitas Point fault, which are structurally linked.



Rockwell et al., (2015)

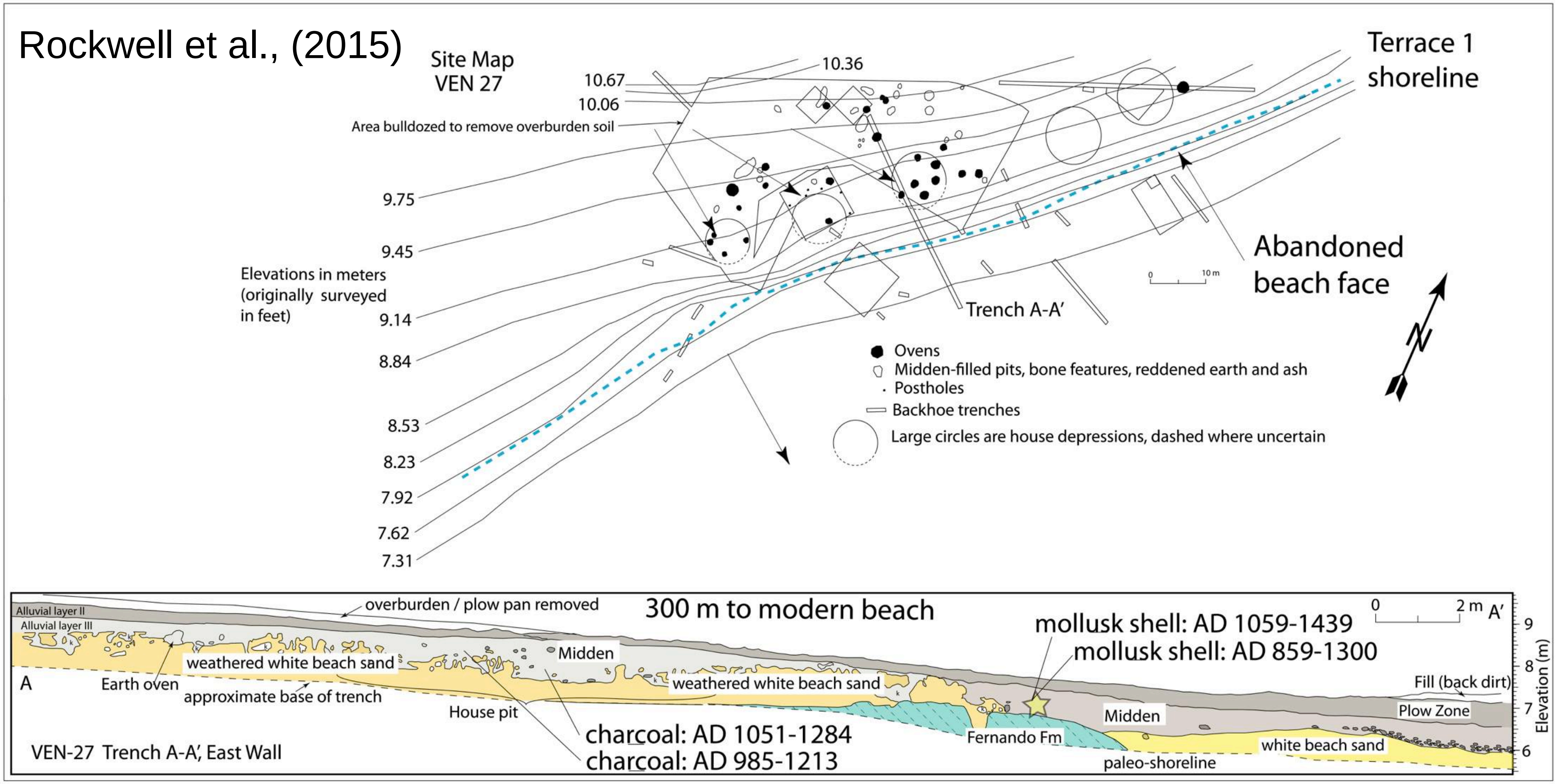


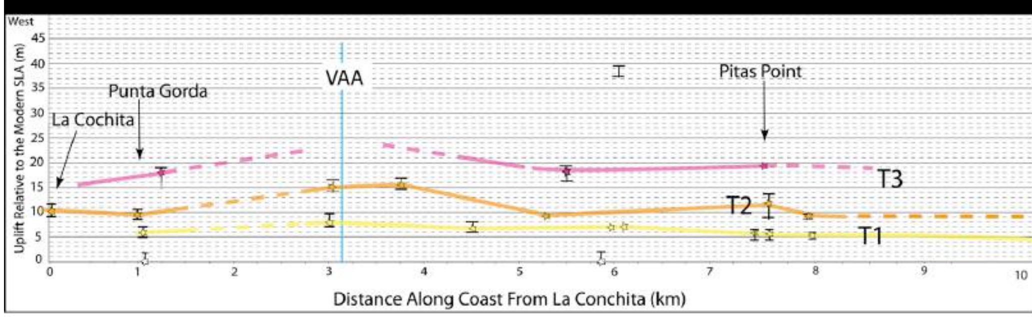


Terrace mapping has been refined using GPS surveys and Lidar.

Three (possibly 4) distinct marine terraces have been mapped across the structure, and dated using various methods.

Rockwell et al., (2015)

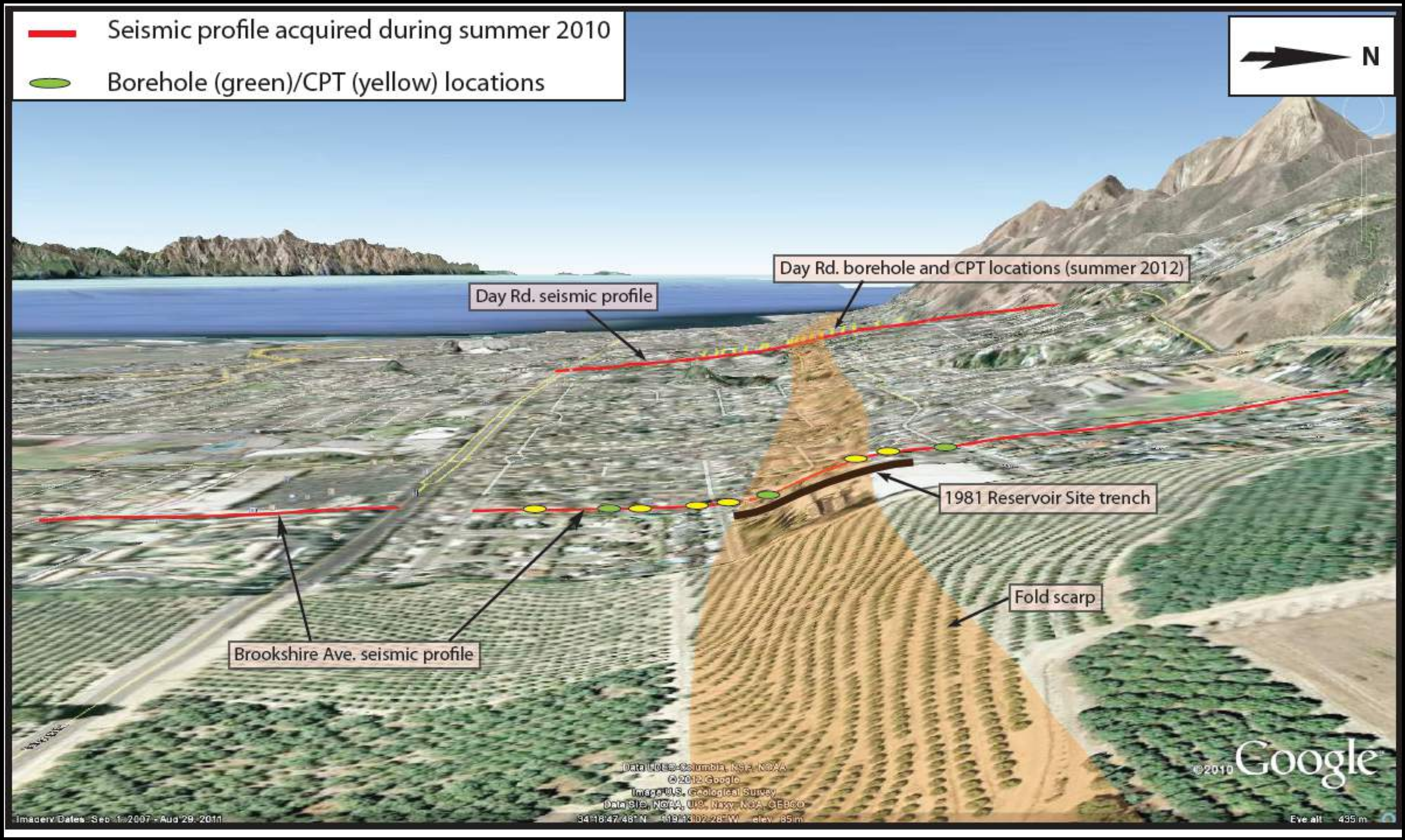




MRE ≈ 950 years ago, with 4-6 m uplift at Pitas Point and 7-8 m over fold crest.

Penultimate event ≈ 1950 years ago, with the third event between 4.2 and 4.7 ka (Based on terrace spacing, it is possible that evidence for an additional event is missing because of terrace erosion).

Testing and refining the paleoseismic record

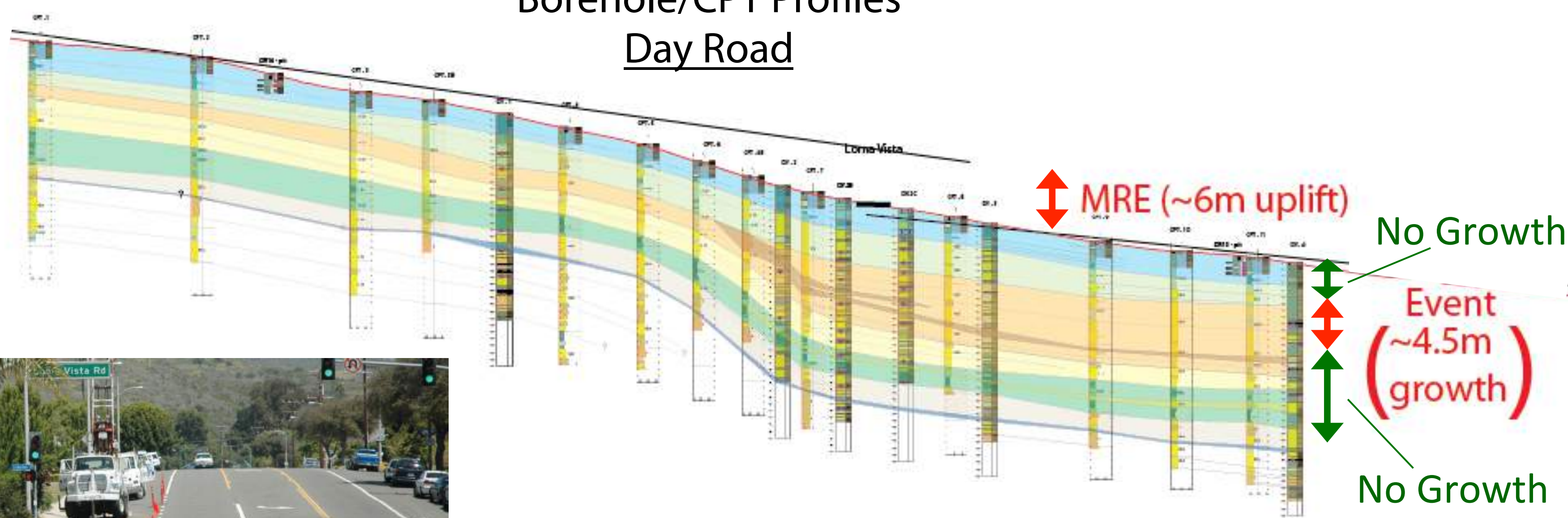


McAuliffe et al., (2015);
Grenader et al., (2015)

N

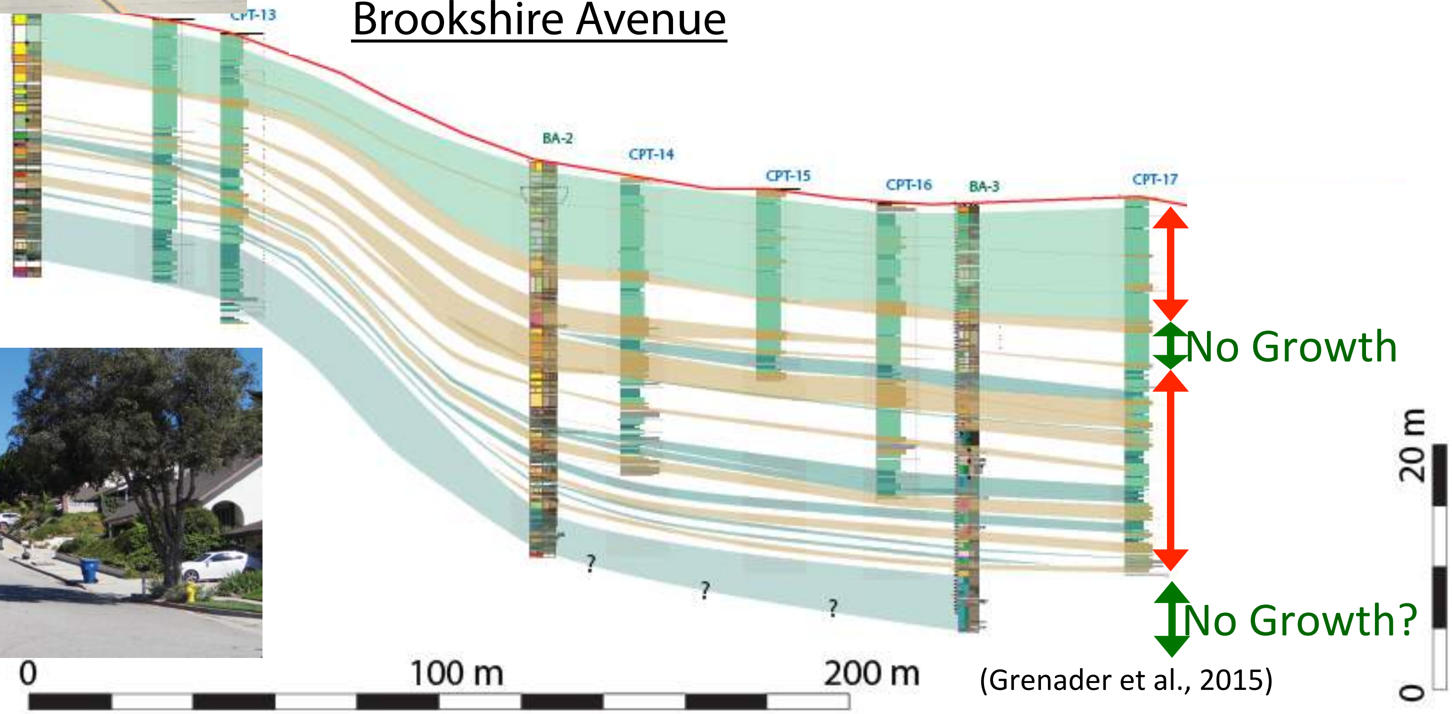
Borehole/CPT Profiles

Day Road



(McAuliffe et al., 2015)

Brookshire Avenue



(Grenader et al., 2015)

Paleoseismic results

McAuliffe et al., (2015); Grenader et al., (2015);

Both sites show evidence of two large Holocene uplift events.

The MRE is < 700-900 years ago and exhibits ≈ 6 m of uplift. *Can we constrain the age of this event more precisely?*

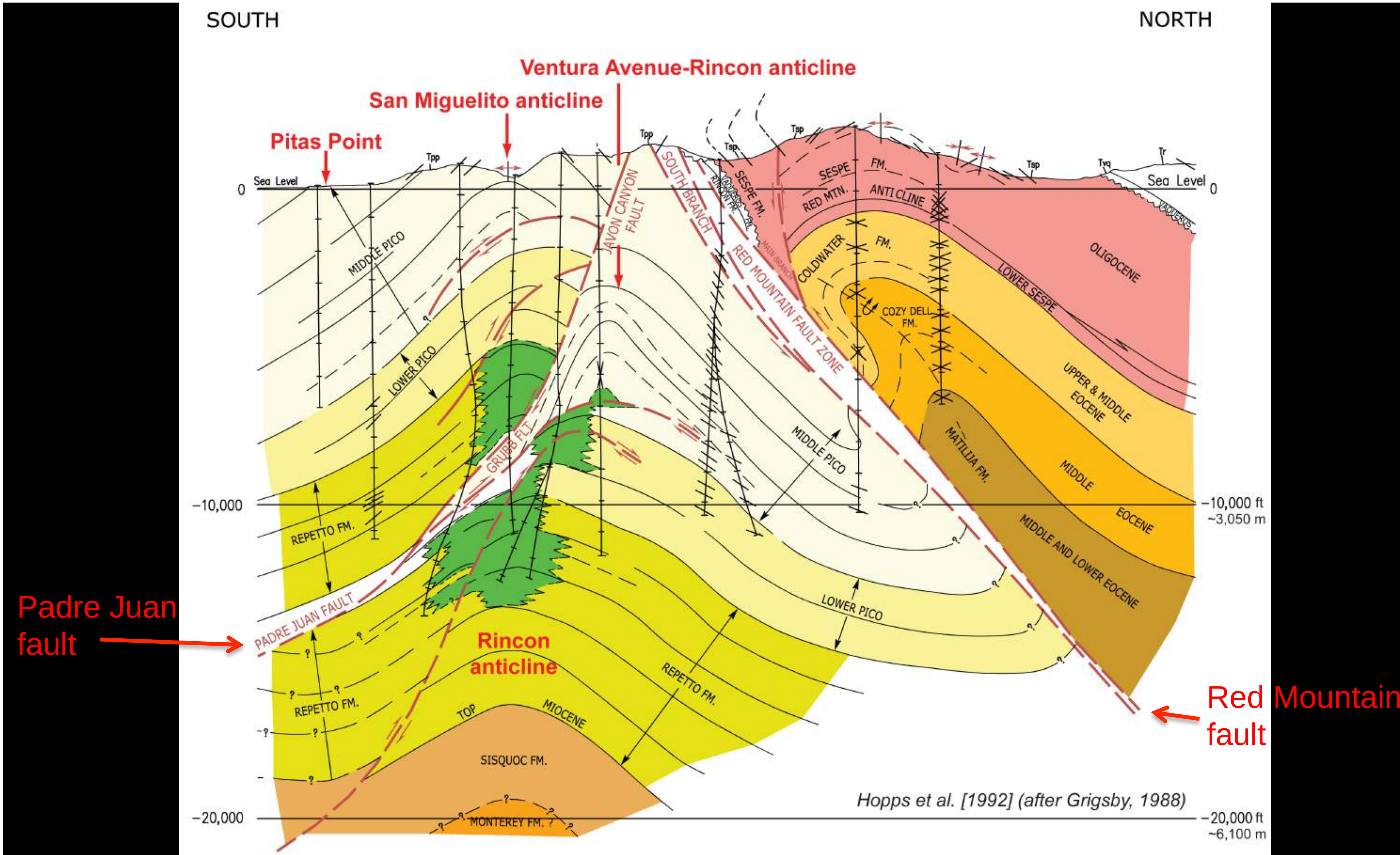
The second event is between 3 and 5ka, and exhibits ≈ 4.5 m of uplift at the Day Rd. site.

These events may be correlated with terrace uplift events (Rockwell et al.,), along the coast. *Can these events be correlated more precisely? Date of the MRE? Are there "missing" events?*

The Brookshire site records ≈ 18 m of total Pleistocene to Holocene uplift, suggesting the occurrence of other events.

Comparison of two sites suggest that slip rates are decreasing to the east, consistent with the plunge of the fold. *Is this consistent with geodetic and seismologic observations?*

Collectively, the magnitude of the inferred events suggest that they record large multi-segment thrust fault earthquakes. *How large? What segments do they involve?*

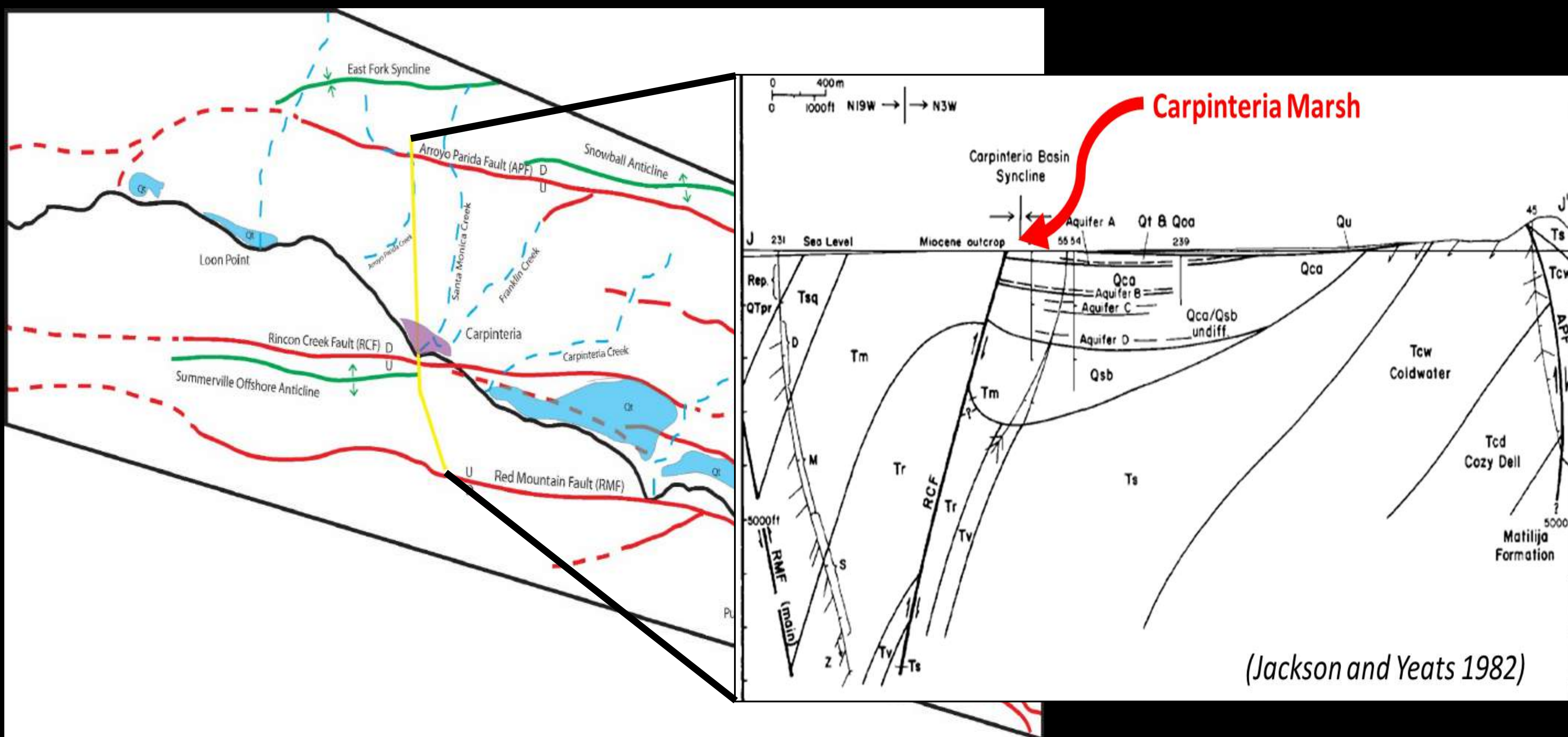


Pitas Point lies above not one but two anticlinal folds: the strongly N-verging, asymmetric San Miguelito anticline in the hanging wall of a S-dipping, listric Padre Juan fault, and the distinctly separate Ventura Avenue-Rincon anticline located in its footwall. As Pitas Point is above this S-dipping out-of-syncline thrust fault, uplift at Pitas Point is most likely the result of slip on the Padre Juan fault and not necessarily on the N-dipping Ventura fault.

Nicholson et al, SCEC Poster #221

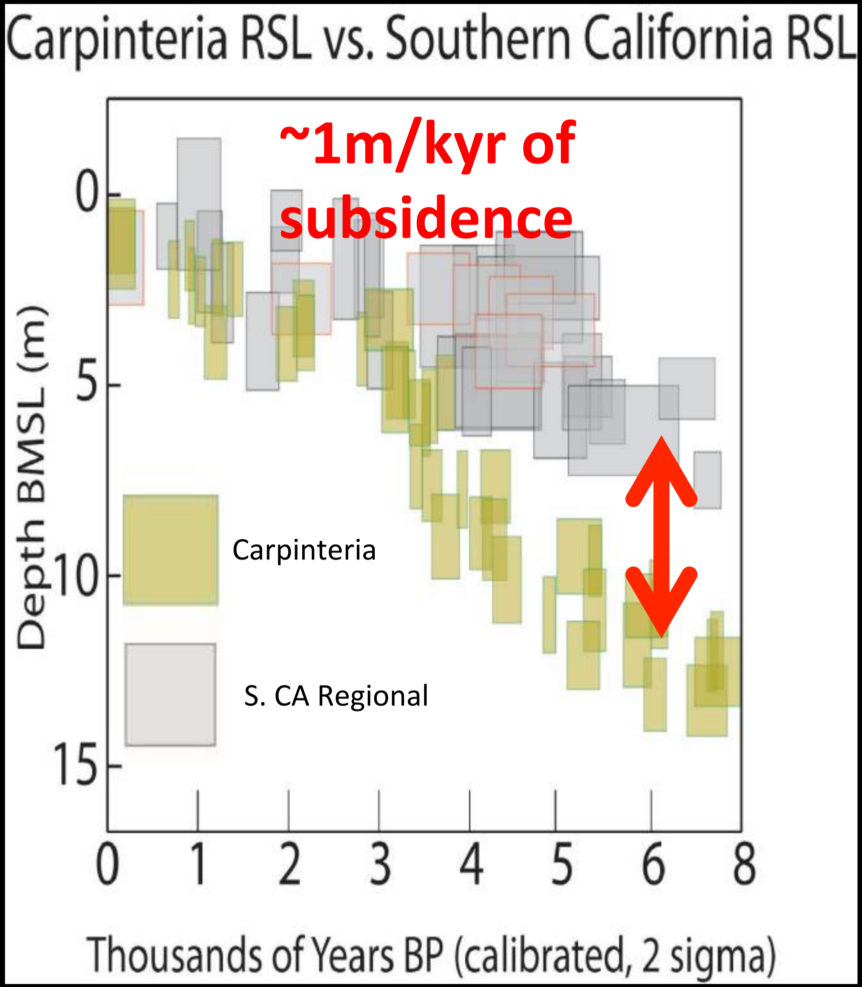
Evidence for Subsidence along the Rincon Creek Fault in Carpinteria Marsh, California

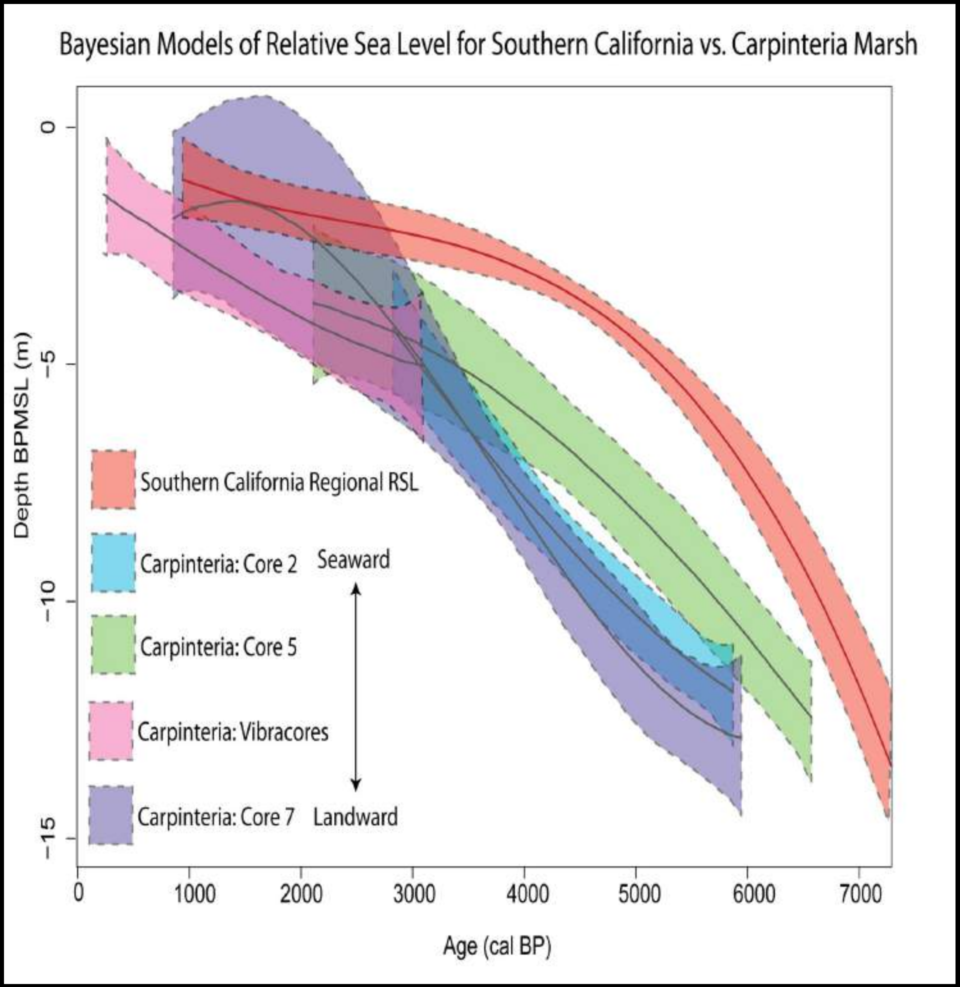
Reynolds, LC; Simms, AR; Rockwell, TK; Peters, R; Bentz, M



- Since 2012 we have taken over 39 vibracores up to 4m depth from Carpinteria Marsh, and 7 Geoprobe cores up to 15m depth below marsh surface.
- Carpinteria is located in the footwall of the Rincon Creek Fault, a potential backthrust off the Red Mountain or Ventura – Pitas Point faults.

Average Subsidence in Carpinteria Marsh





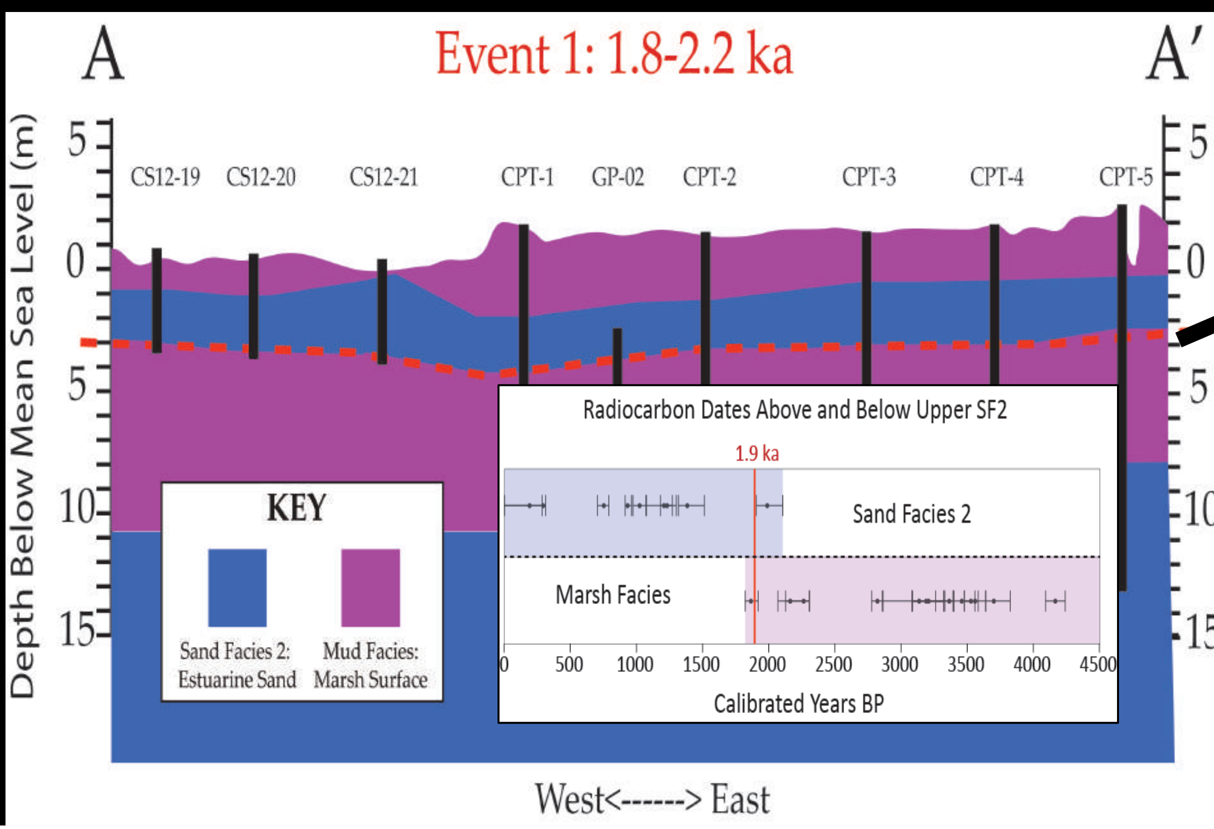
Comparing radiocarbon dated marsh deposits from Carpinteria to a regional record of relative sea level indicates Carpinteria has experienced ~1m/1000 yr of subsidence over the last 7000 years.

- Relative sea level curves generated from 4 different cores from Carpinteria shows subsidence varies temporally and spatially.
- Subsidence is therefore not simple compaction, and may be initiated in discrete events.

Reynolds, LC; Simms, AR; Rockwell, TK; Peters, R; Bentz, M

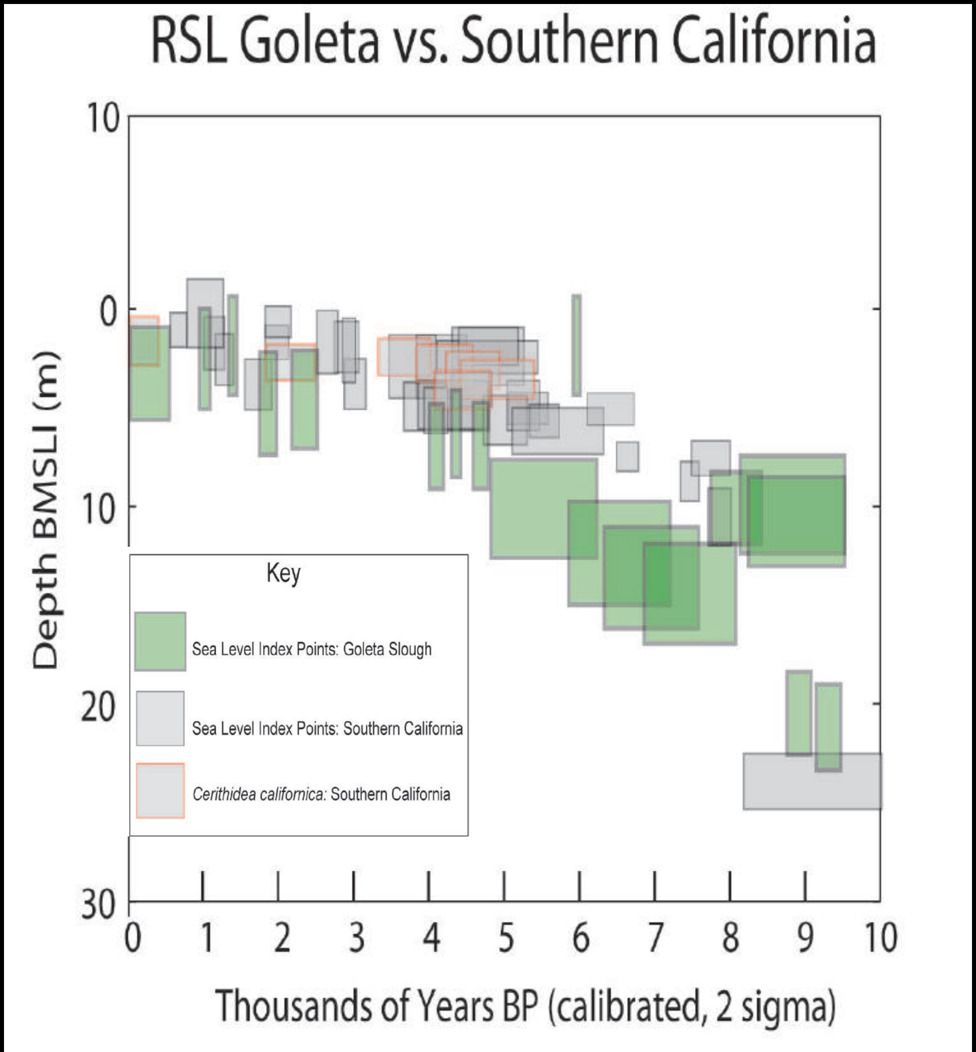
Candidate Subsidence Event One

- Marsh deposits are sharply overlain by subtidal sand 2-4m BMSL throughout the marsh.
- Interpreted as abrupt deepening event dated to 1.8-2.2ka. *This may correlate with event 2 at Pitas Point.*



Reynolds, LC; Simms, AR; Rockwell, TK; Peters, R; Bentz, M

Subsidence in Goleta Slough



- Goleta Slough also appears to be subsiding at ~0.75m/kyr.

- Preliminary stratigraphy indicates an abrupt deepening similar to that observed in Carpinteria at ~1.9ka.


https://farm4.static.flickr.com/3249/2536152807_60b8bd9d46.jpg

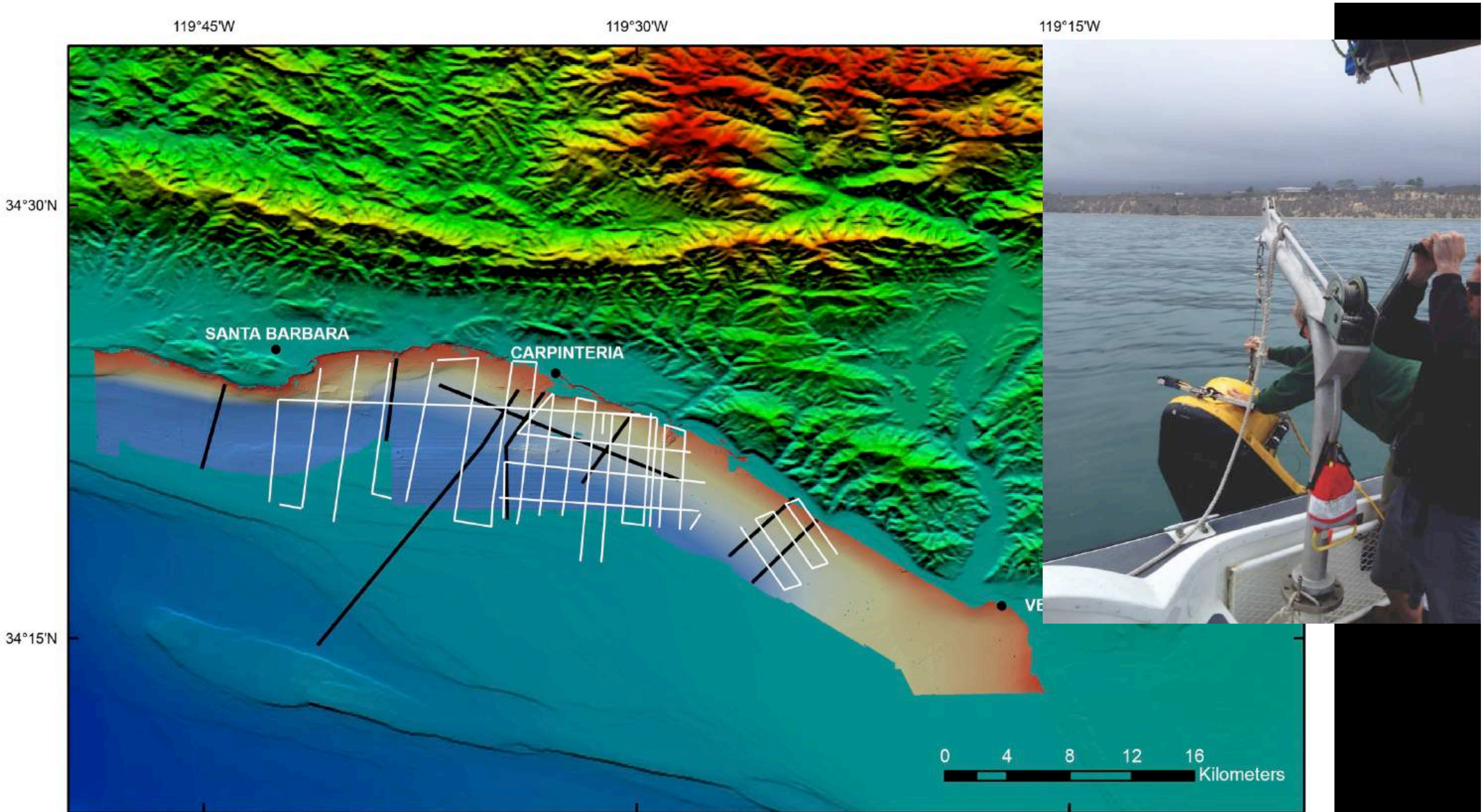
Reynolds, LC; Simms, AR; Rockwell, TK; Peters, R; Bentz, M

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

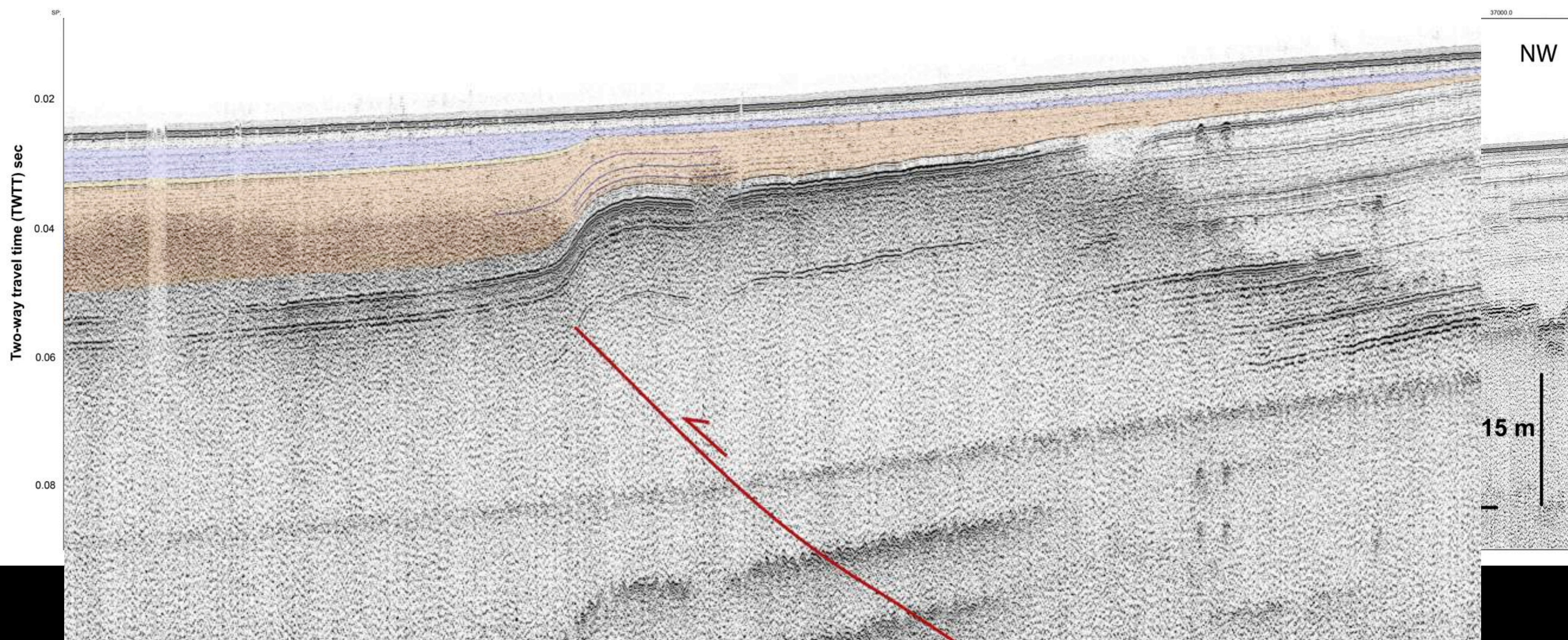
Active deformation associated with large uplift events offshore Western Transverse Ranges

Gülsen Ucarkus[1,2], Neal Driscoll[2], Daniel Brothers[3], Graham Kent[4], Thomas Rockwell[5], John Driscoll[2]

[1] Istanbul Technical University, Geology Department, Istanbul, Turkey
[2] Scripps Institution of Oceanography, University of California, San Diego
[3] Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz
[4] Nevada Seismological Laboratory, University of Nevada Reno
[5] Department of Geological Sciences, San Diego State University, San Diego

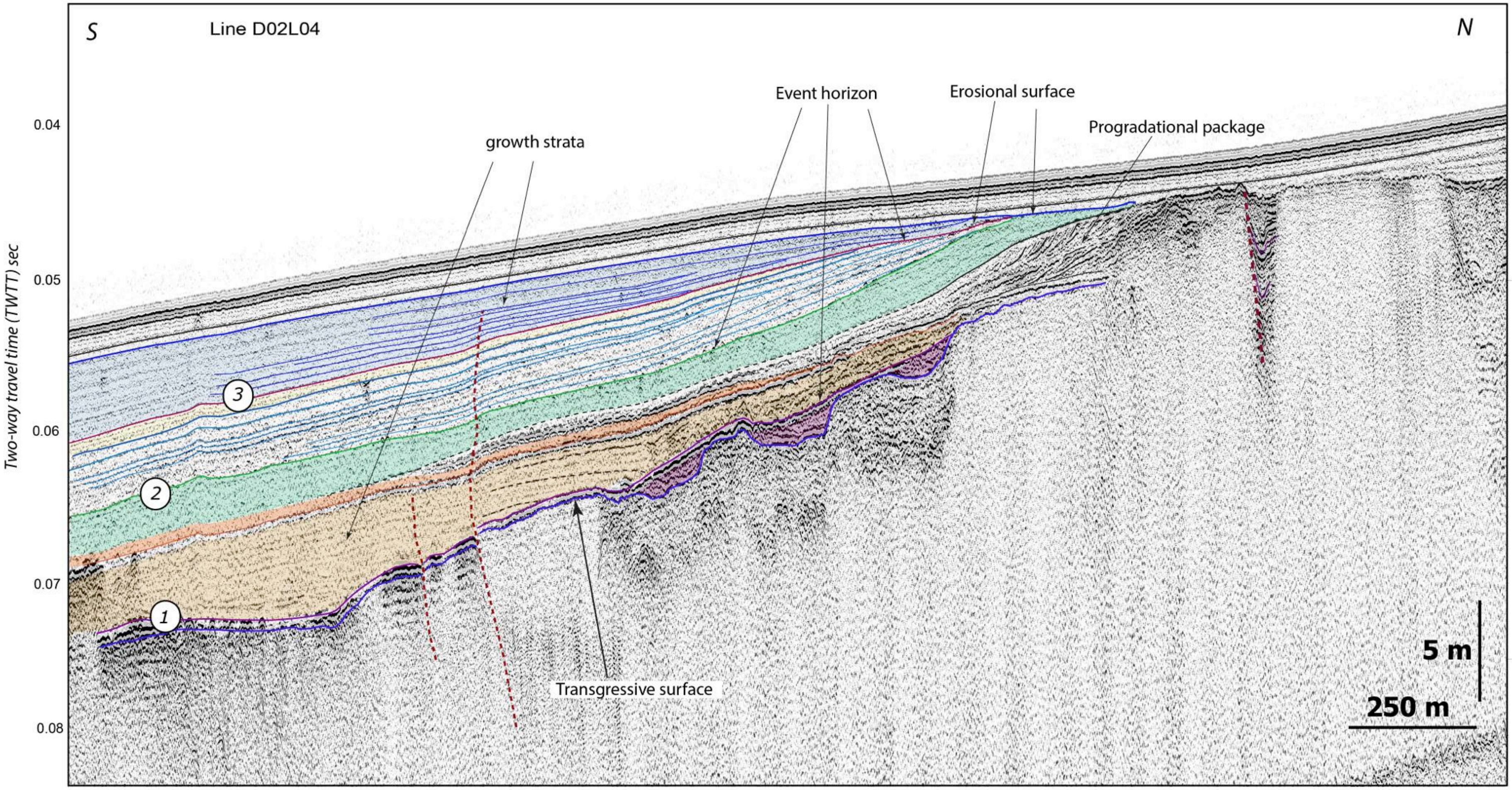


- ~240 km-long very high-resolution (decimeter) CHIRP seismic reflection data from offshore Santa Barbara in the west to Ventura in the east.
- High-Resolution Mini-Sparker Seismic-Reflection Data From the Southern California Continental Shelf—Gaviota to Mugu Canyon by USGS, Sliter et al. 2008.
- California State Waters Map Series by USGS-Bathymery offshore Santa Barbara, Carpinteria and Ventura. (2-m-resolution).



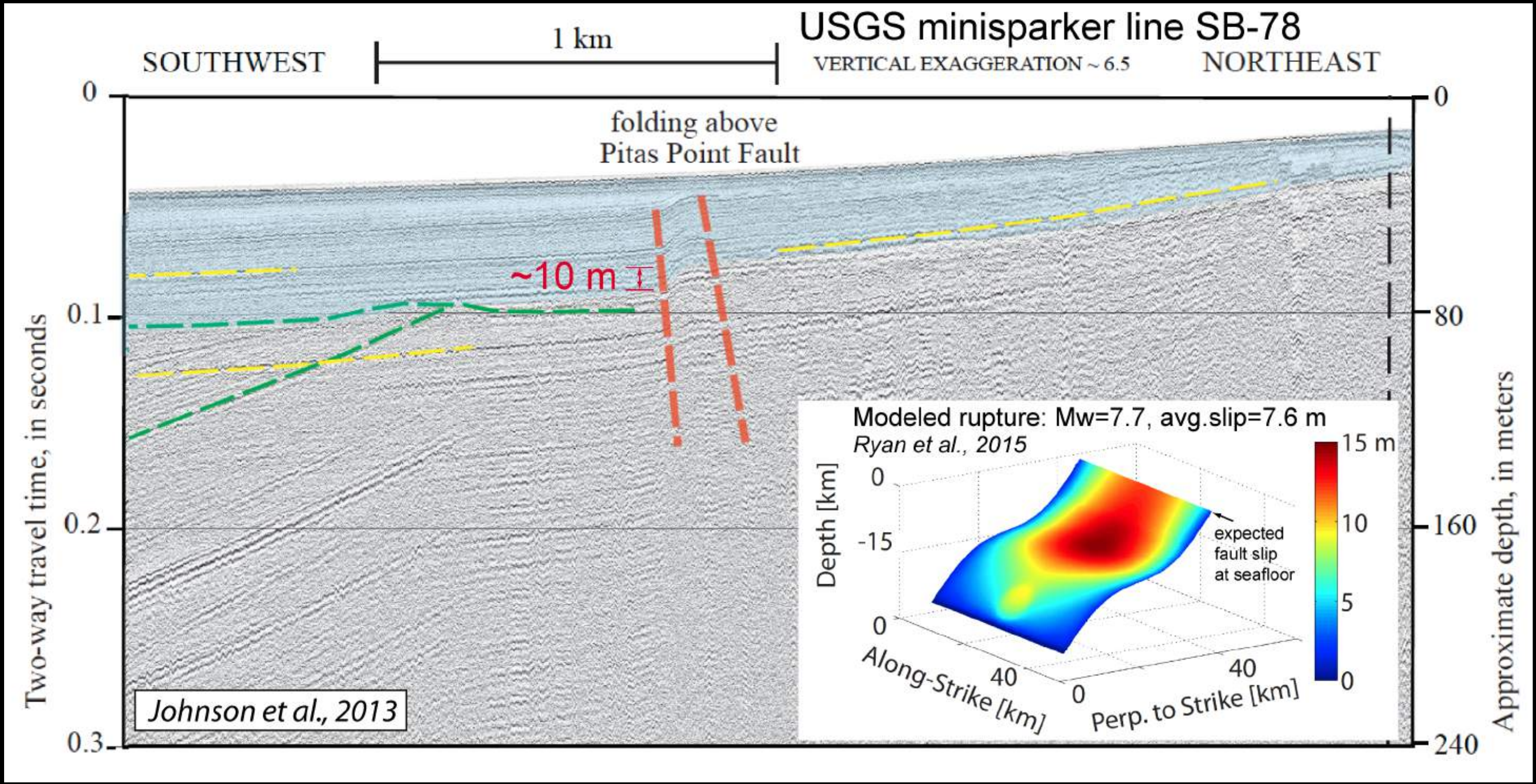
SP:
37000.0
NW
Two-way travel time (TWTT) sec
0.02
0.04
0.06
0.08
15 m

3 discrete onlap events



High-Resolution Marine Seismic Reflection Data Across Pitas Point Fault

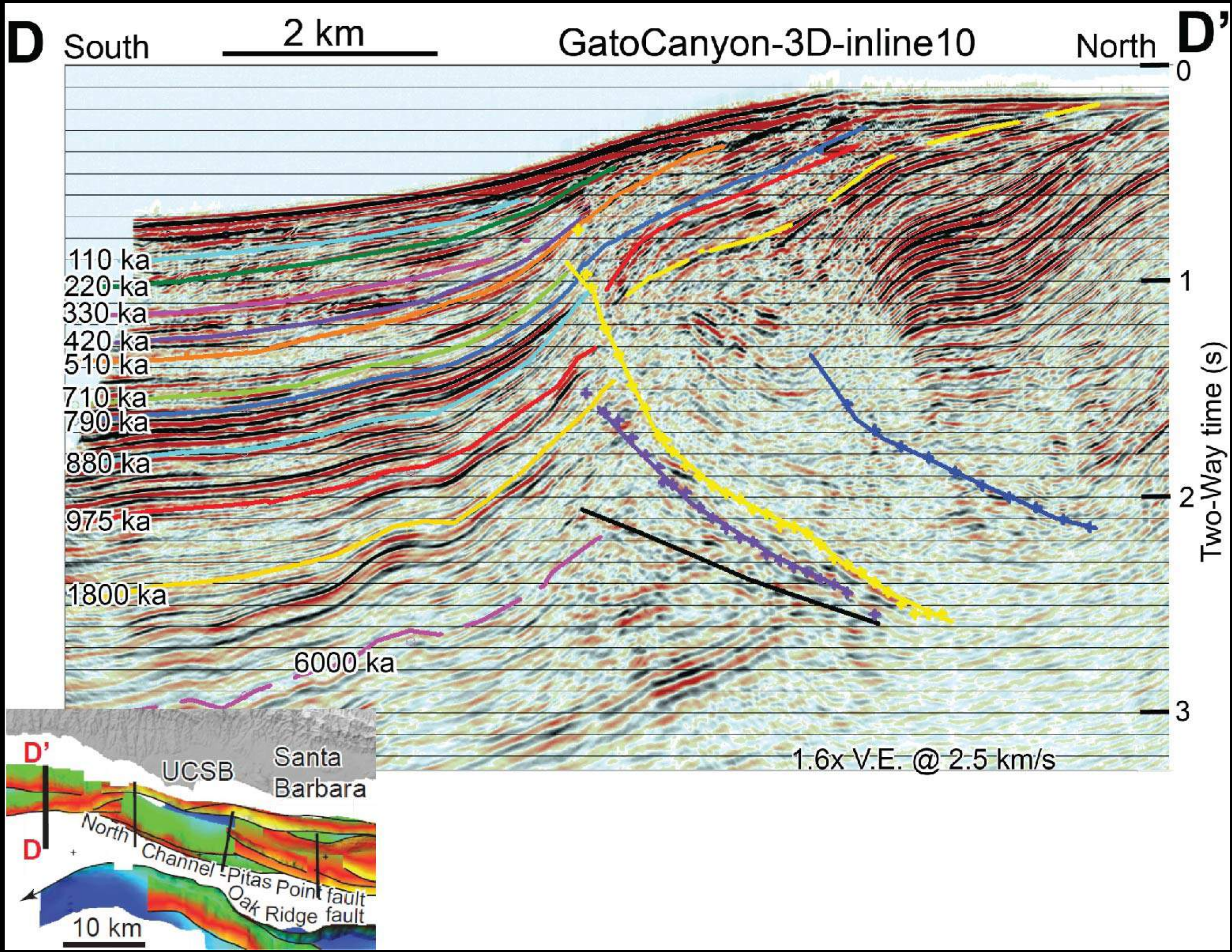
Nicholson et al, SCEC Poster #221



USGS minisparker line southwest of Pitas Point [*Johnson et al.,* 2013]. At the fault, sediments younger than the Last Glacial Maximum (blue shaded) that are ~12 ka exhibit ~10 m of vertical structural relief, sediments at ~3 ka show ~5 m, and younger sediments are little deformed.

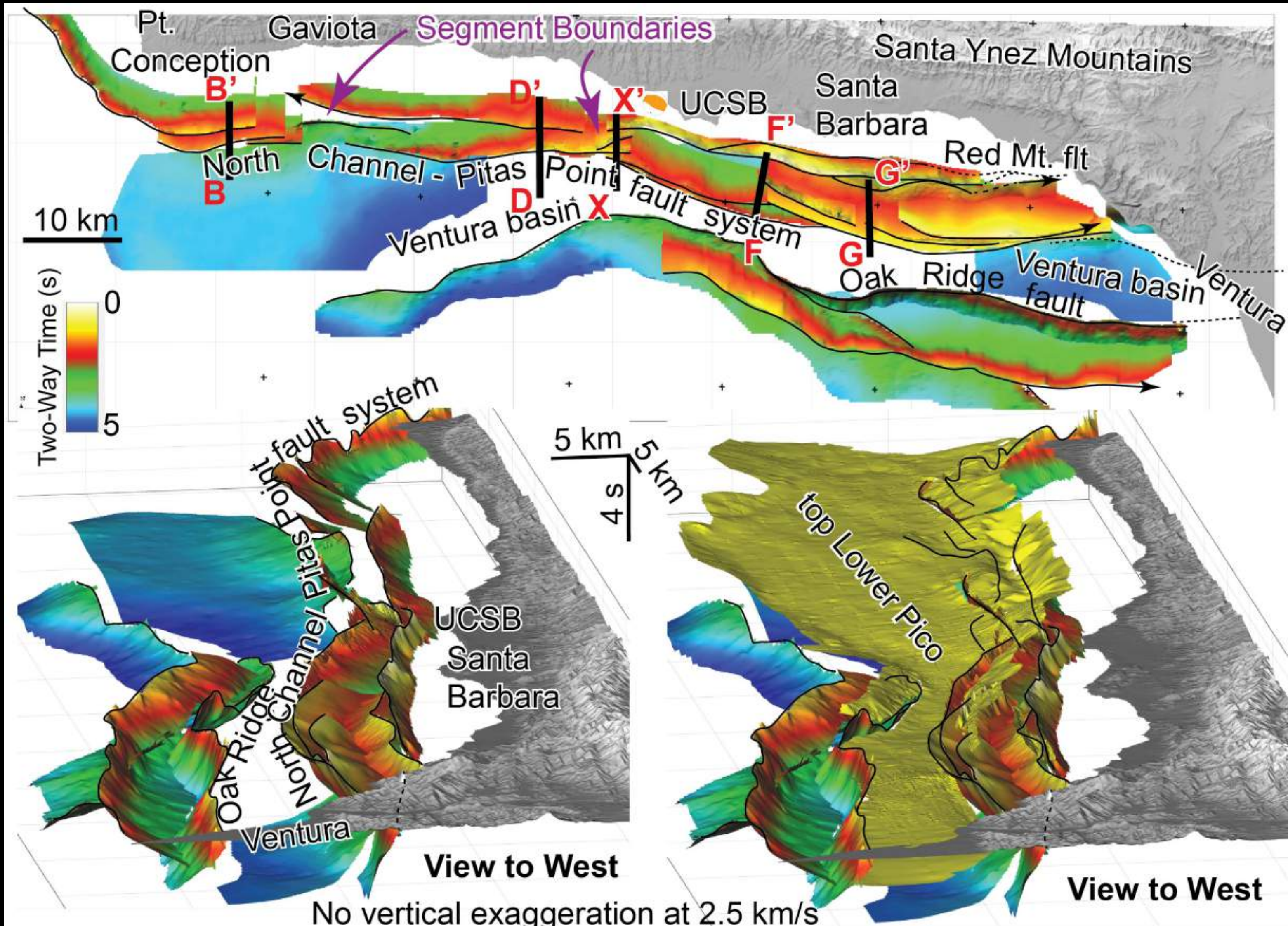
This constrains the magnitude and/or frequency of large displacement events involving this part of the fault.

Investigating the offshore extent of the fault system



Sorlien, C. C., C. Nicholson, R. J. Behl, C. J. Marshall, and J. P. Kennett, 2014.
Sorlien, Nicholson, Kamerling. Behl ,2015 (SCEC abstract).

Investigating the offshore extent of the fault system



Sorlien, C. C., C. Nicholson, R. J. Behl, C. J. Marshall, and J. P. Kennett, 2014.
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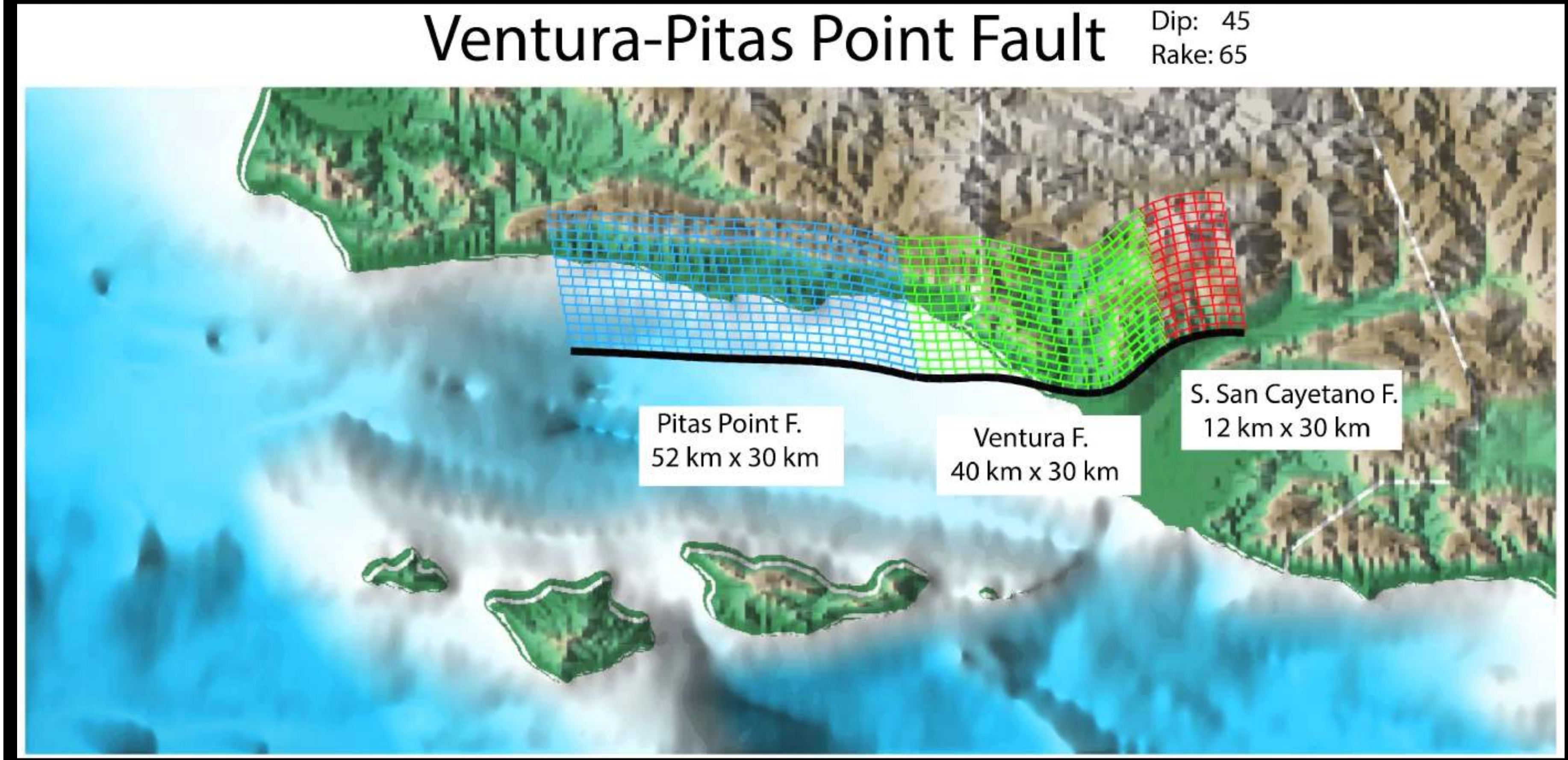
Earthquake simulators – Steve Ward



Goals for the Ventura SFSA (2013)

Test and refine the record of large multi-segment ruptures on the Ventura fault system along strike, and extend the record back in time.

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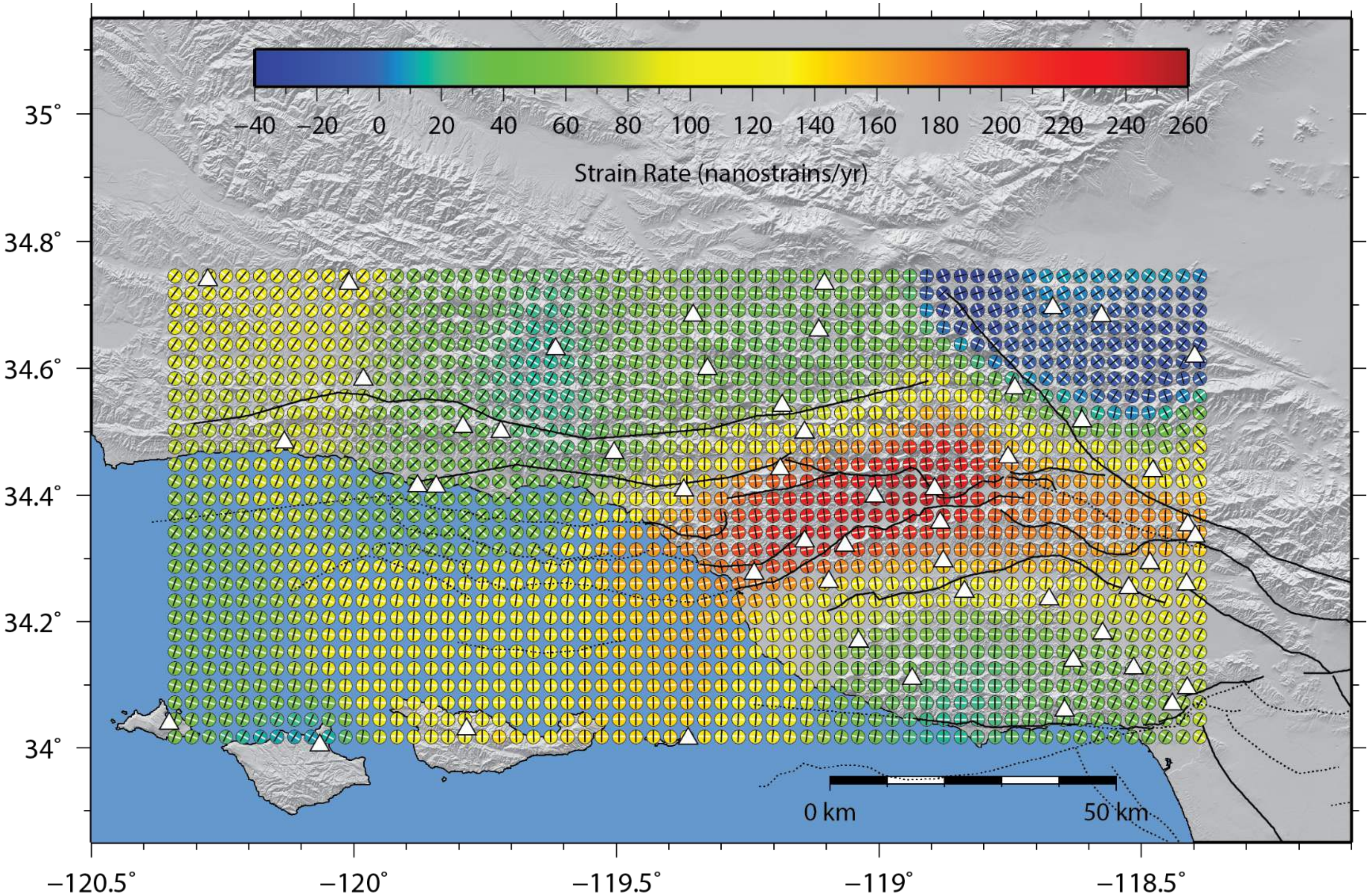
Define a viable set of rupture scenarios with kinematic and dynamic rupture modeling, and evaluate these using the paleoearthquake record.

Define the intensity, duration, and distribution of strong ground shaking and tsunami runup we should anticipate for these events.

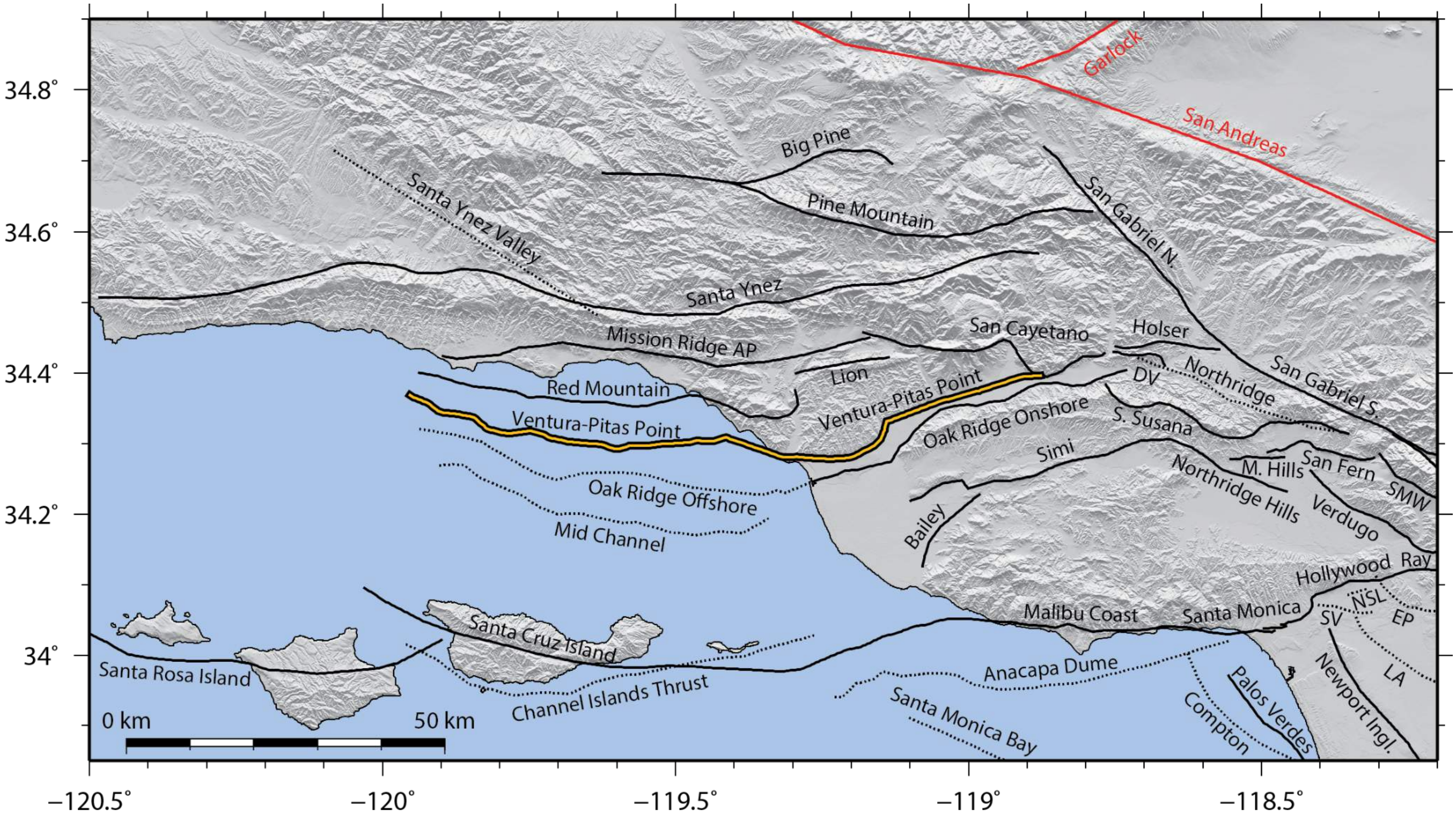
Ventura Geodetic Contraction Rates



- Principal contraction rates from smoothed inversion of PBO GPS velocities
- Shortening is localized in the Ventura basin. Little strain elsewhere.

From Marshall et al. (2013, JGR)

Ventura Regional Faults



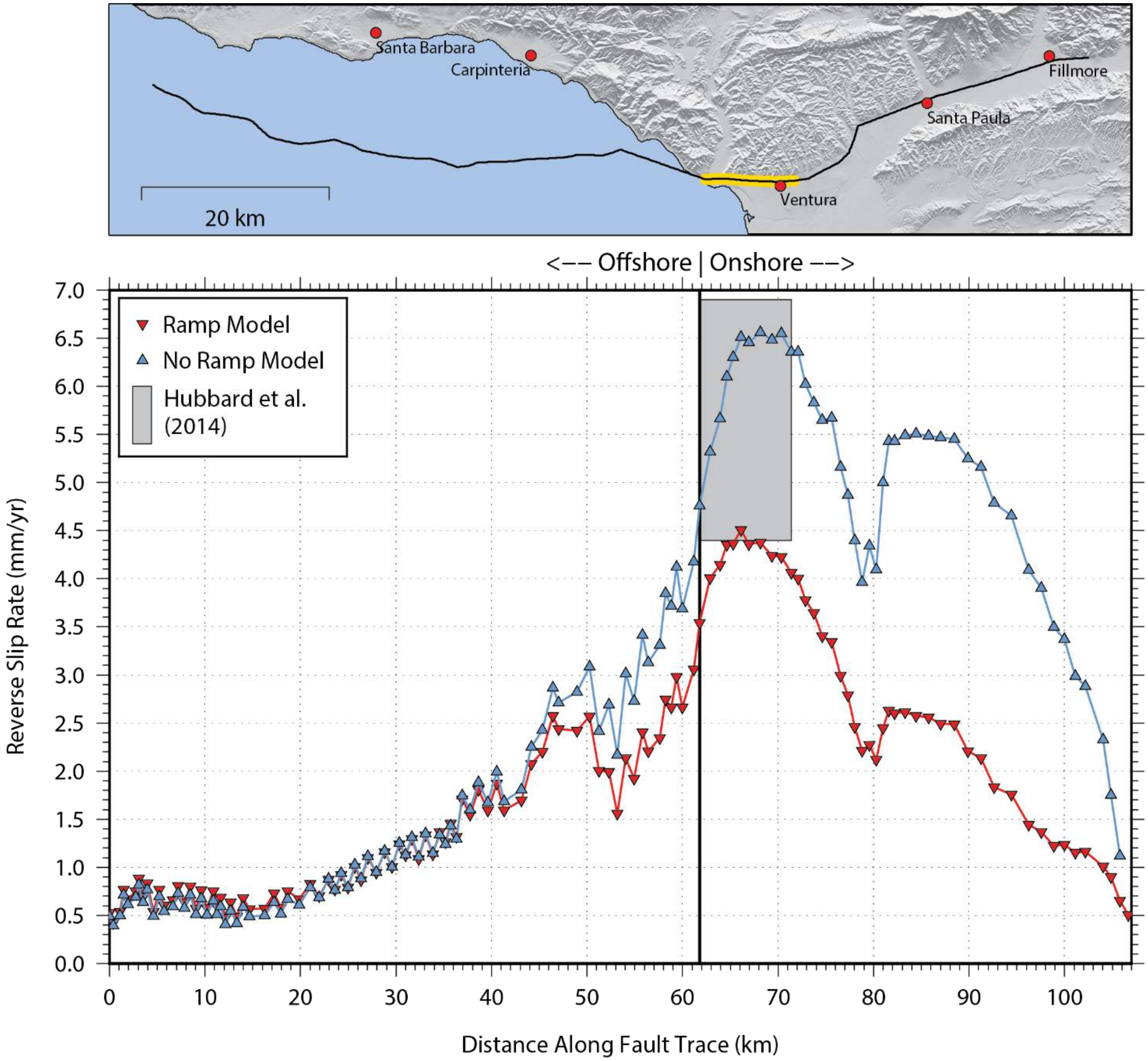
- Map of Ventura regional fault traces from CFM5.0
  - Ventura fault highlighted in gold. Model is driven by geodetic shortening rates.
  - Modeled geometry is complex. All faults mechanically interact.

Scott Marshall, Gareth Funning, Susan Owen (in prep)

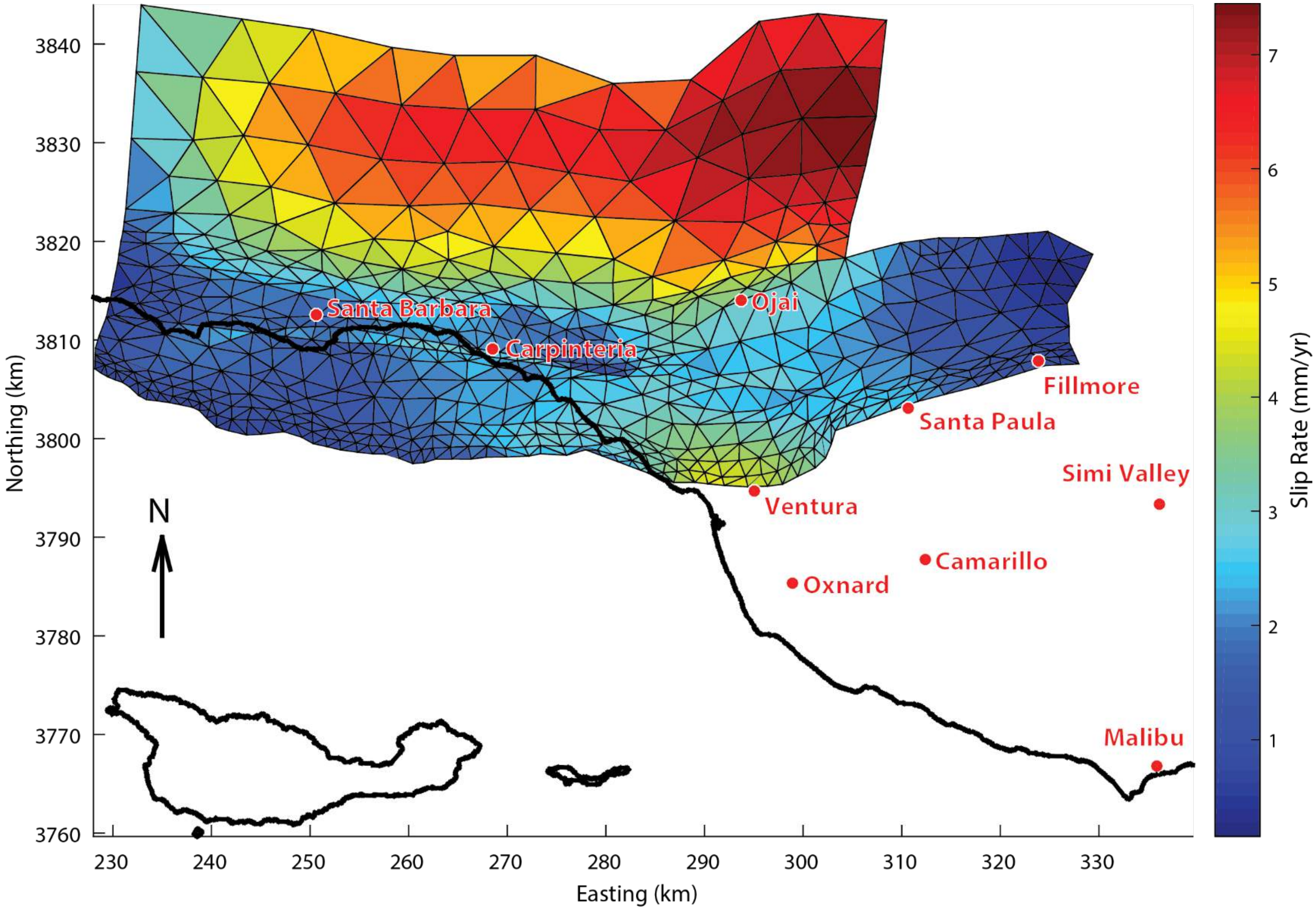
3D Mechanical Model: Ventura Fault Slip Rates

- Tested two fault models
  - Ramp/Constant Dip
- Slip at the surface of Earth fits best with constant dip model
  - both overlap Hubbard et al. (2014) slip rates
- Existing estimates overestimate slip rate
  - Studies at sites of anomalously fast slip
- Both models predict similar avg slip
  - 3.3-3.4 mm/yr

From: Scott Marshall, Gareth Funning, Susan Owen (in prep)



Ramp Model: 3D Slip Distribution



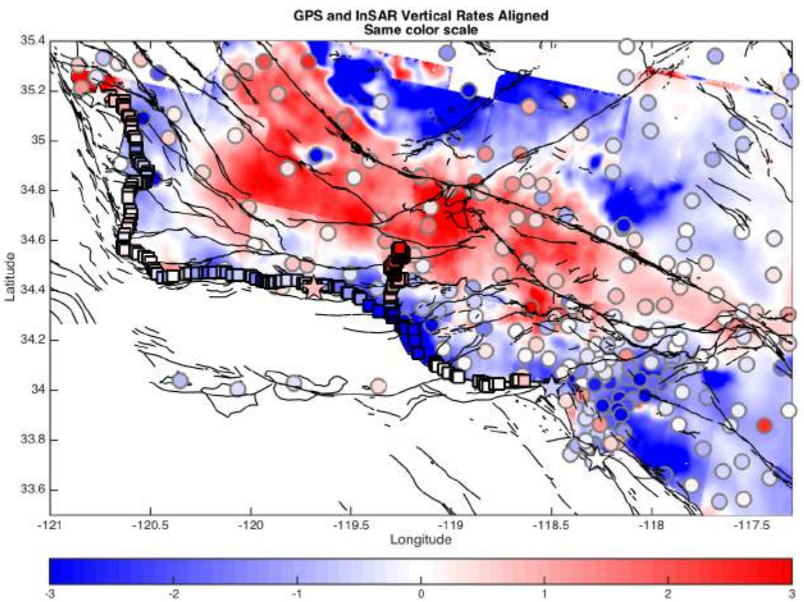
- 3D Distribution of slip is complex
  - Slip rates are fast near coast where large paleo-uplift events have been found
  - Max slip is on lower ramp at depth, which agrees with Hubbard et al., (2014)

From: Scott Marshall, Gareth Funning, Susan Owen (in prep)

Observations of vertical deformation across the western Transverse Ranges and constraints on Ventura area fault slip rates

Reed Burgette, Bill Hammond, Kaj Johnson

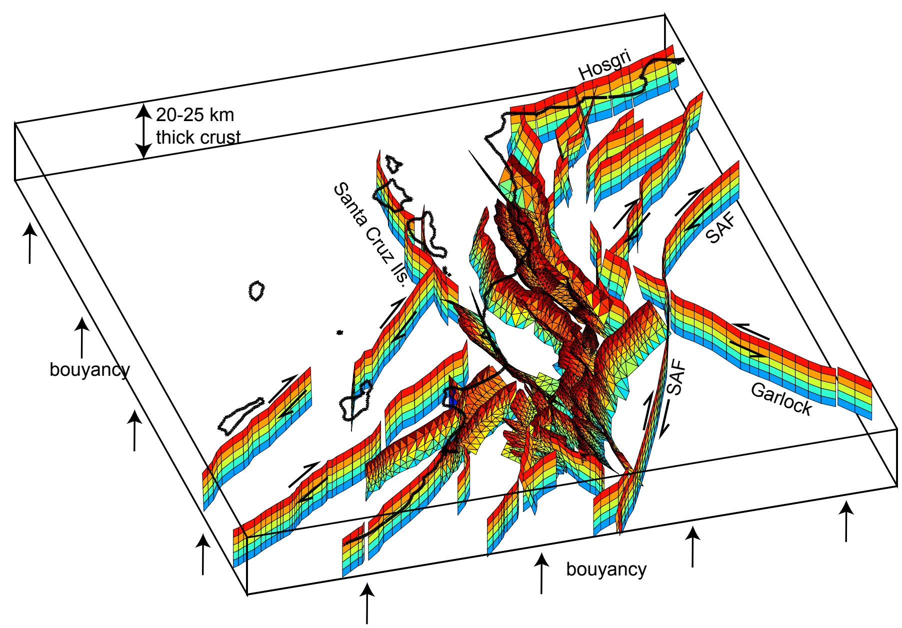
New vertical velocity field

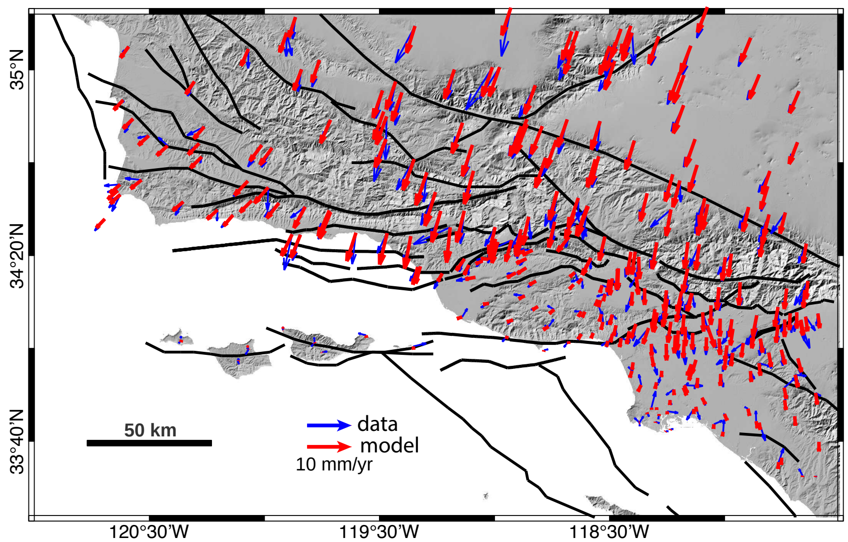


- Constrained by repeated leveling, tide gauges, InSAR, and GPS
- Rates from terrestrial techniques and InSAR are aligned with the space-based GPS rate field.
- Agreement between techniques emphasizes part of signal that has been steady over the past century

Deformation Model

- Horizontal (GPS) and vertical deformation fields modeled with faults in an elastic plate under gravitational restoring forces
- Kinematic model – slip rates imposed
- Invert for slip rate and locking depth using MCMC techniques

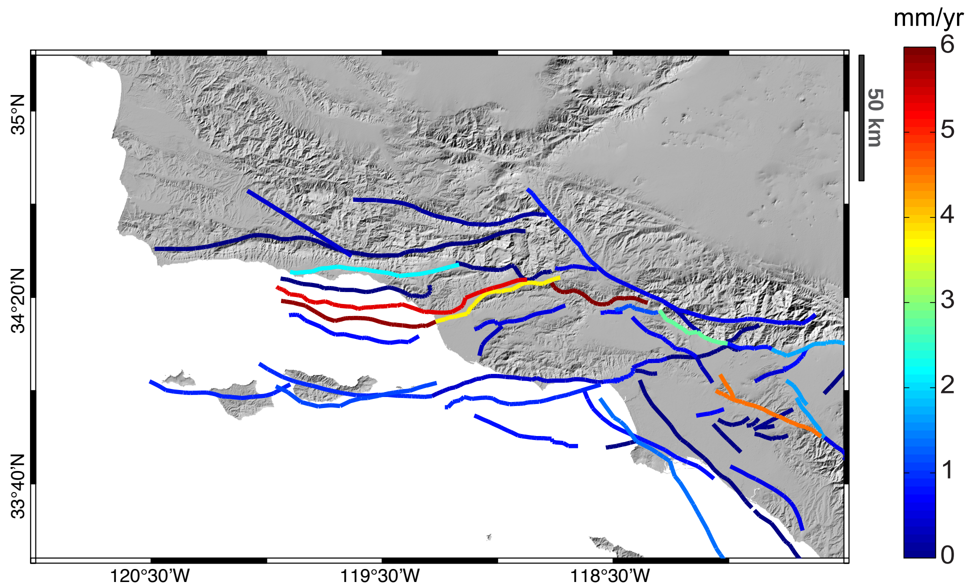




Predicted and observed horizontal velocities

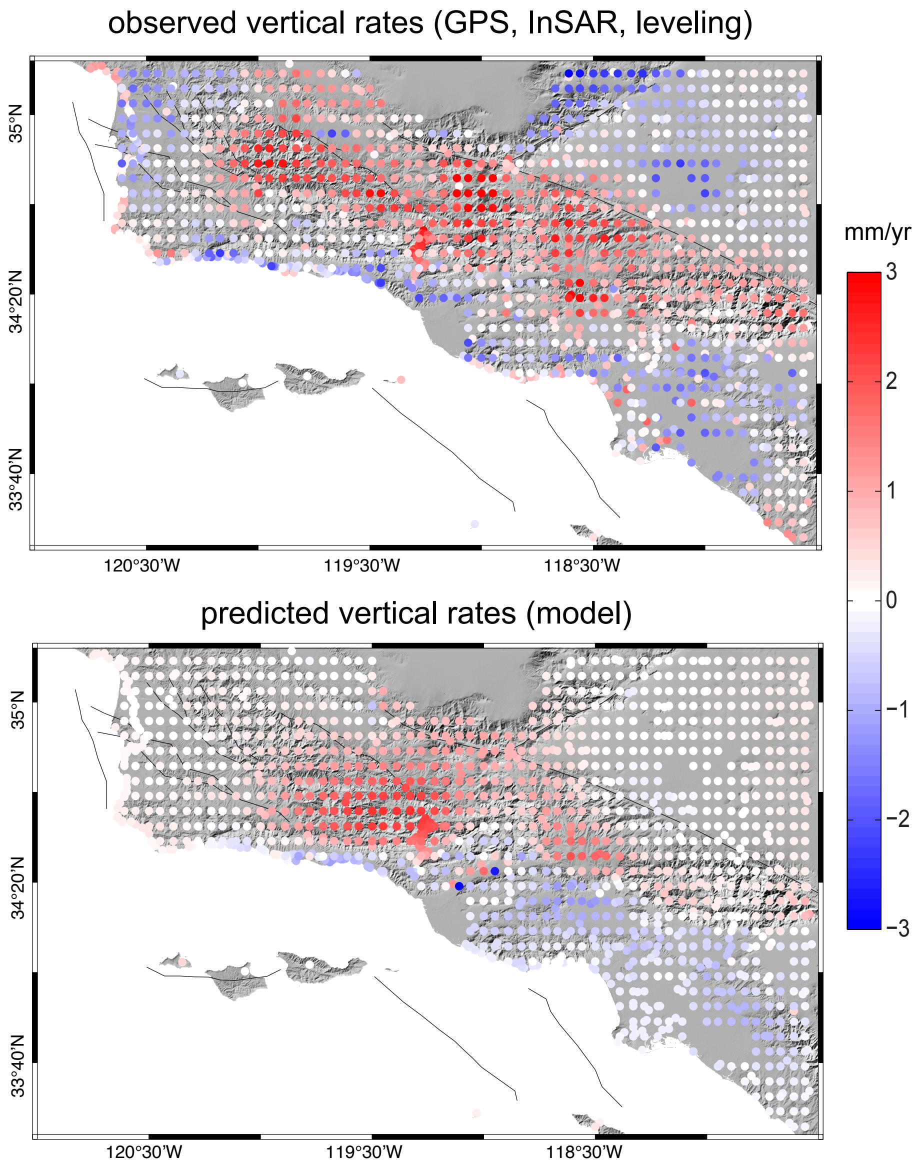
(after removing all deformation sources outside of Transverse Ranges)

- ~10 mm/yr of total shortening rate
- ~6-7 mm/yr shortening rate across Ventura Basin (on land)



Estimated dip-slip rates on Transverse Range faults

~11 mm/yr total slip rate across Ventura/Pitas Point fault and Oakridge



Observed and predicted vertical rates.

Some general patterns of observed vertical velocity field predicted by the model:

- 0.5-1.5 mm/yr uplift of San Gabriel Mountains
- Present-day subsidence along Ventura-Santa Barbara coast
- ~3 mm/yr of tilt from Ventura to Santa Ynez Mountains, due in part to ~6 mm/yr of slip on Ventura/Sisar ramp-flat system

Geodetic results

Marshall et al., 2013; Marshall, Funning, and Owen (in prep);
Burgette, Hammond, Johnson (in prep), and others.

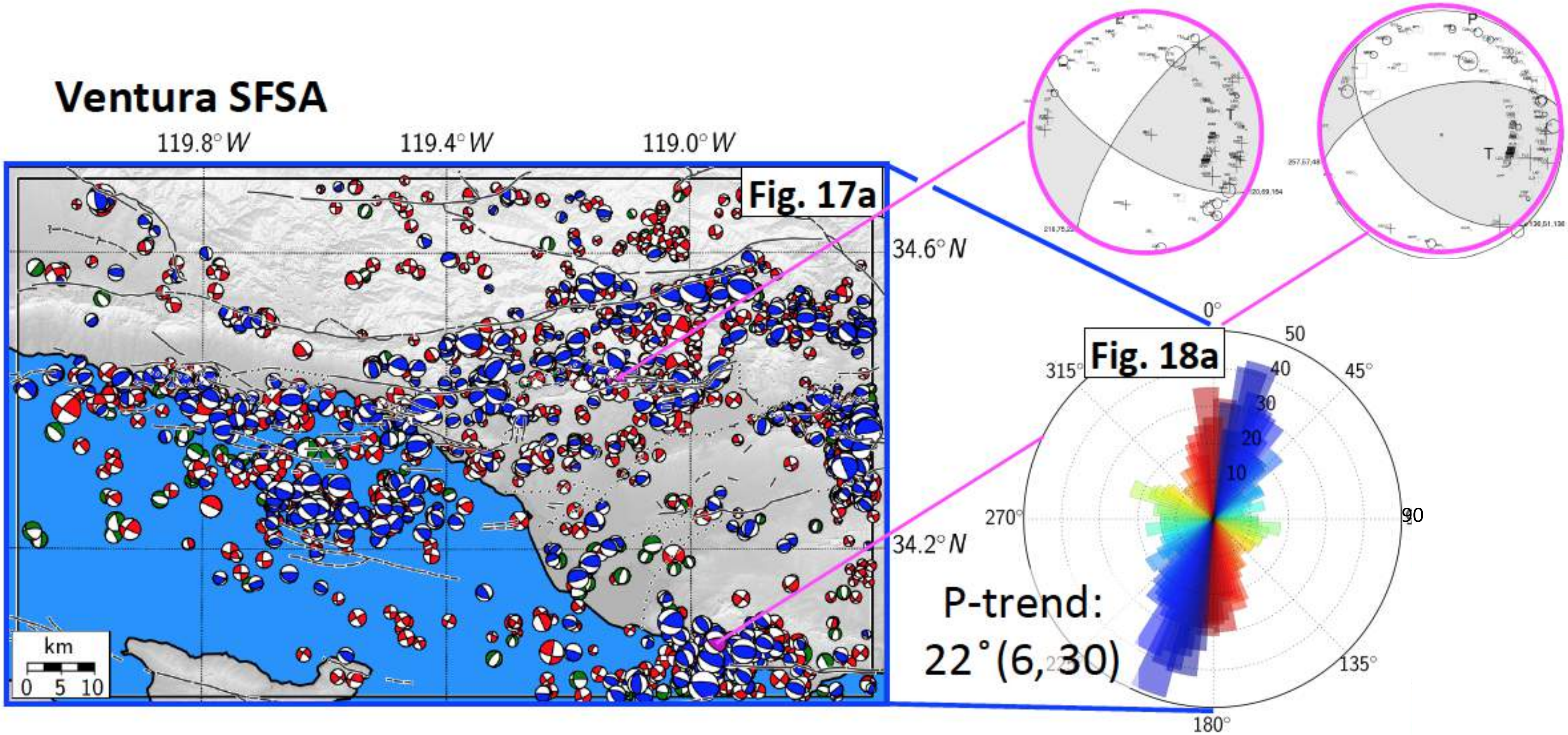
Large horizontal contraction rates across the Ventura region*. To what degree are these localized in the basin?*

Uplift localized in the mountains to the north and east of the Ventura fault. Many coastal areas are subsiding*. What do these vertical deformation rates tell us about interseismic strain accumulation on the Ventura – Pitas Point fault?*

Large (≥ 4 mm/yr) maximum dip slip rates centered on the Ventura fault. Decreasing slip rate to the east and west. *Are these gradients consistent with along-strike changes in geologic rates?*

Fault geometry has a significant impact on fault geometry at depth in the seismogeneic zone. *How can we further constrain these fault geometries?*

Seismicity statistics and stress in the Ventura SFSA



Gobel, Hauksson, Plesch, and Shaw (2014)

- Both thrust and strike-slip events occur throughout the region, with thrust events concentrated in a band running north of the Ventura basin.
- Focal mechanisms are consistent with NNE-SSW s1.
- Stress drops are lower and show less variation than in other regions of SoCal (SGP SFSA).

Goals for the Ventura SFSA (2013)

Test and refine the record of large multi-segment ruptures on the Ventura fault system along strike, and extend the record back in time.

Determine how slip and deformation are distributed in these large, multi-segment ruptures, and how might this vary over multiple earthquake cycles.

Characterize the interseismic strain accumulation along the Ventura thrust system.

Define a viable set of rupture scenarios with kinematic and dynamic rupture modeling, and evaluate these using the paleoearthquake record.

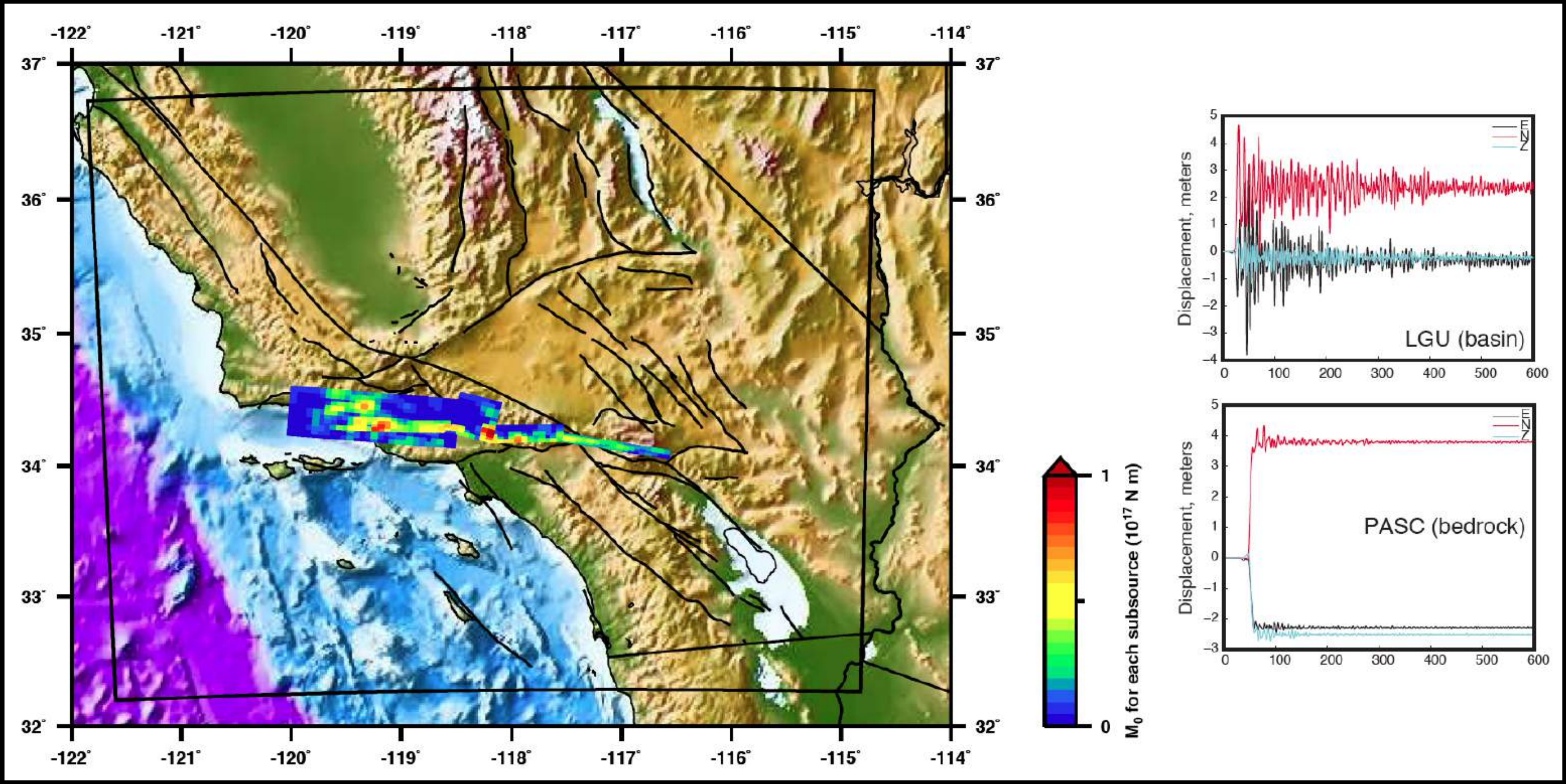
Define the intensity, duration, and distribution of strong ground shaking and tsunami runup we should anticipate for these events.

Kinematic rupture simulations

Source model

- Mw 7.9 Wenchuan earthquake (Chen Ji)
- 70,587 subsources, each characterized by hypocenter, origin time, rise time, and moment tensor (double couple assumed)

SPECFM simulations using SCEC USR



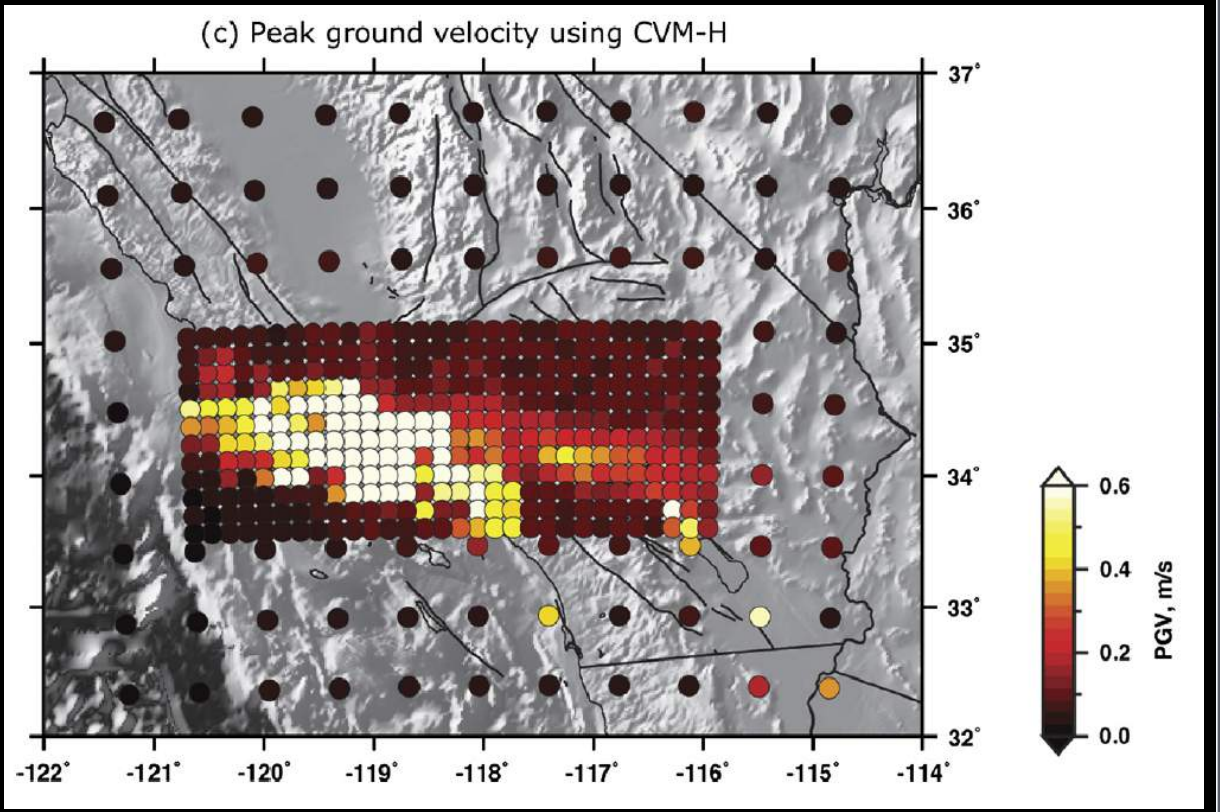
Tape et al., (in prep)

Kinematic rupture simulations

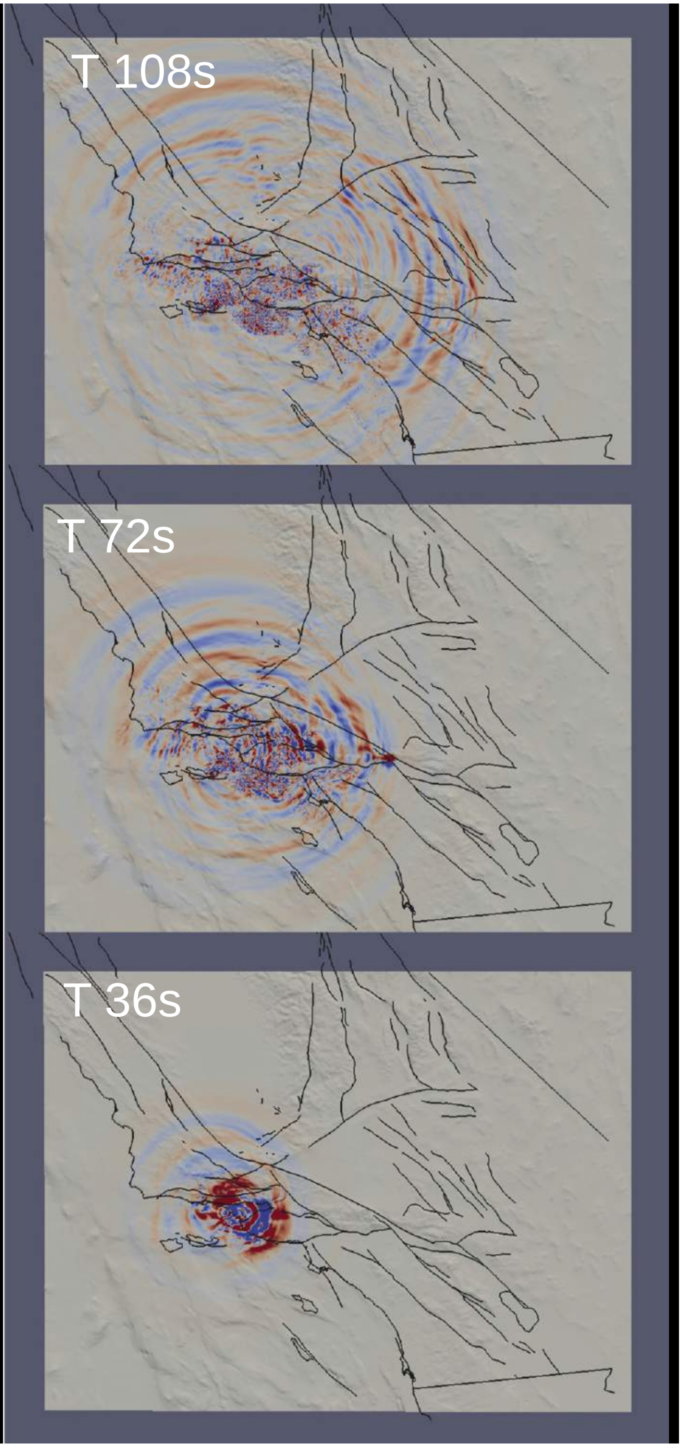
Simulation results

• PGV exceed 0.5 m/s over a large region of coastal southern California

• Significant basin amplification, resonance, and long duration shaking

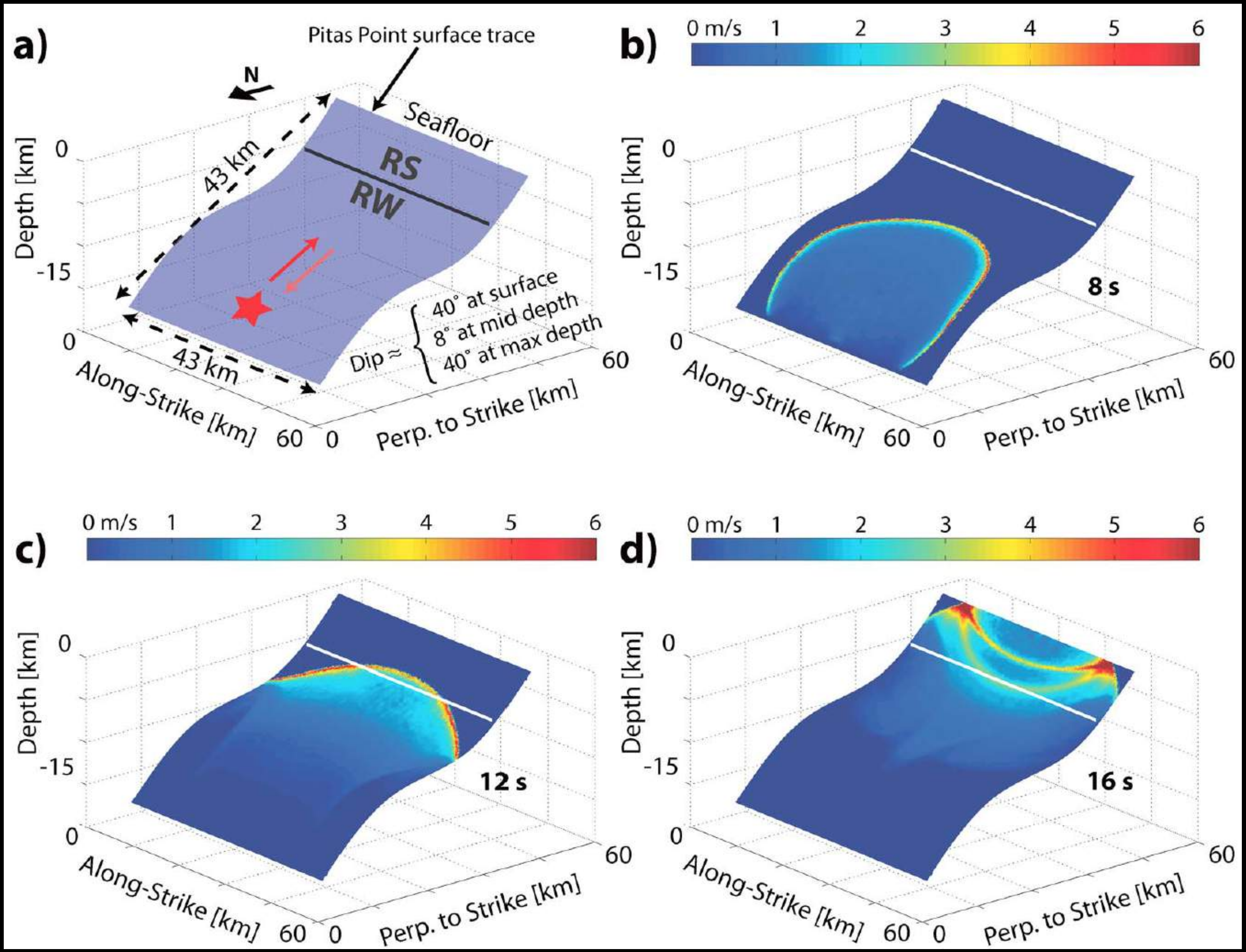


Shaw et al., 2015; Tape et al., (in prep)



Dynamic rupture and tsunami modeling

Ryan, K. J., E. L. Geist, M. Barall, and D. D. Oglesby (2015)



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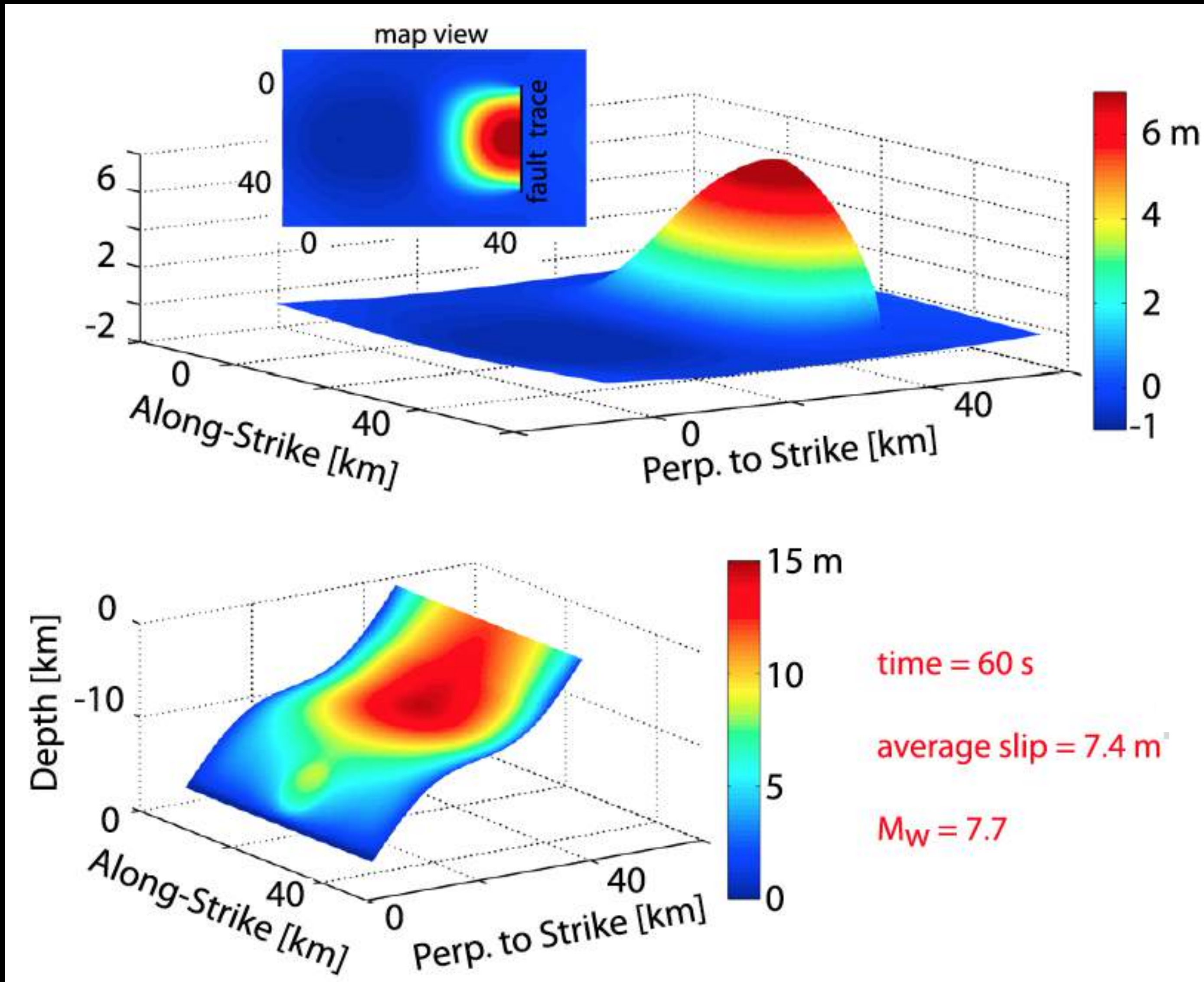

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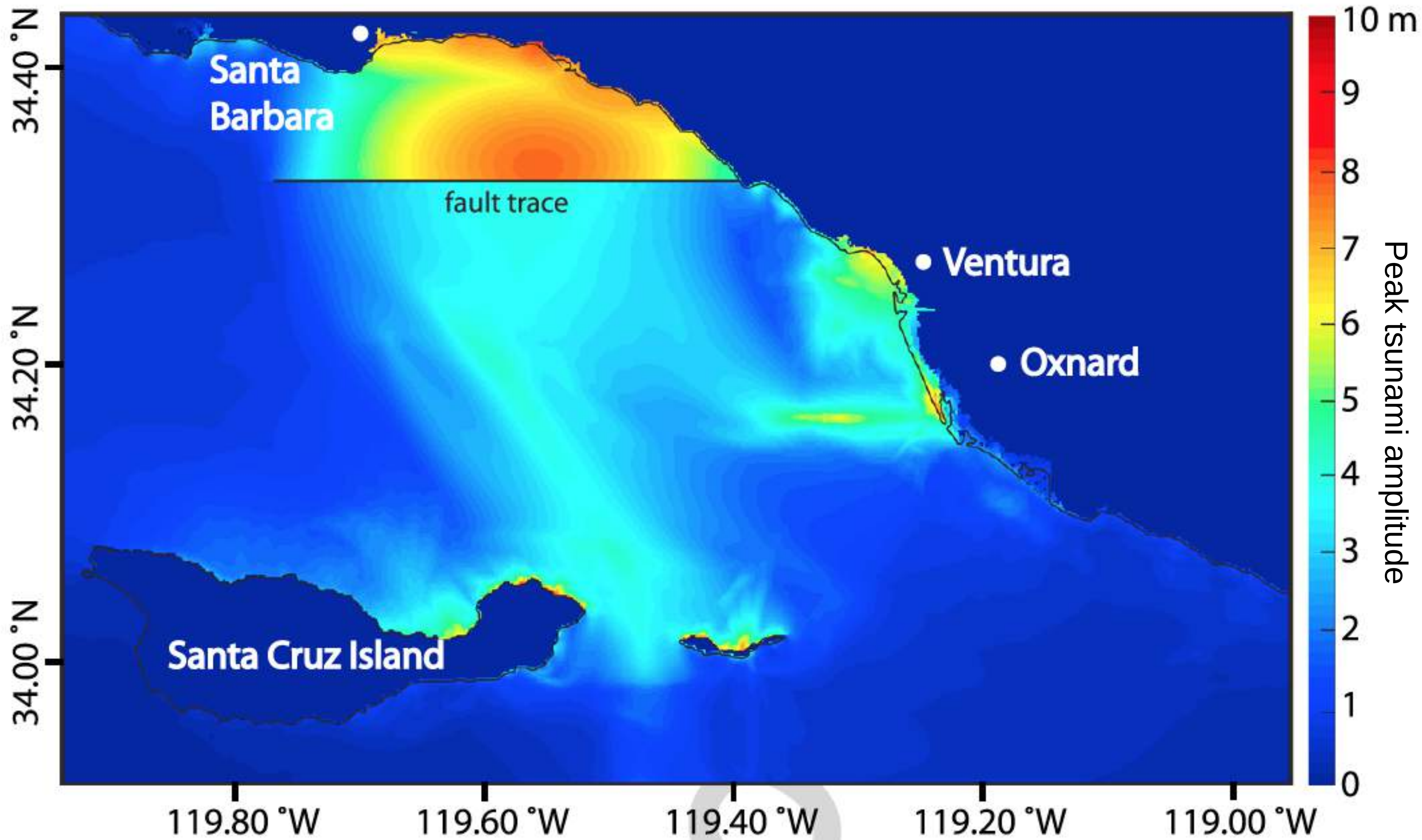
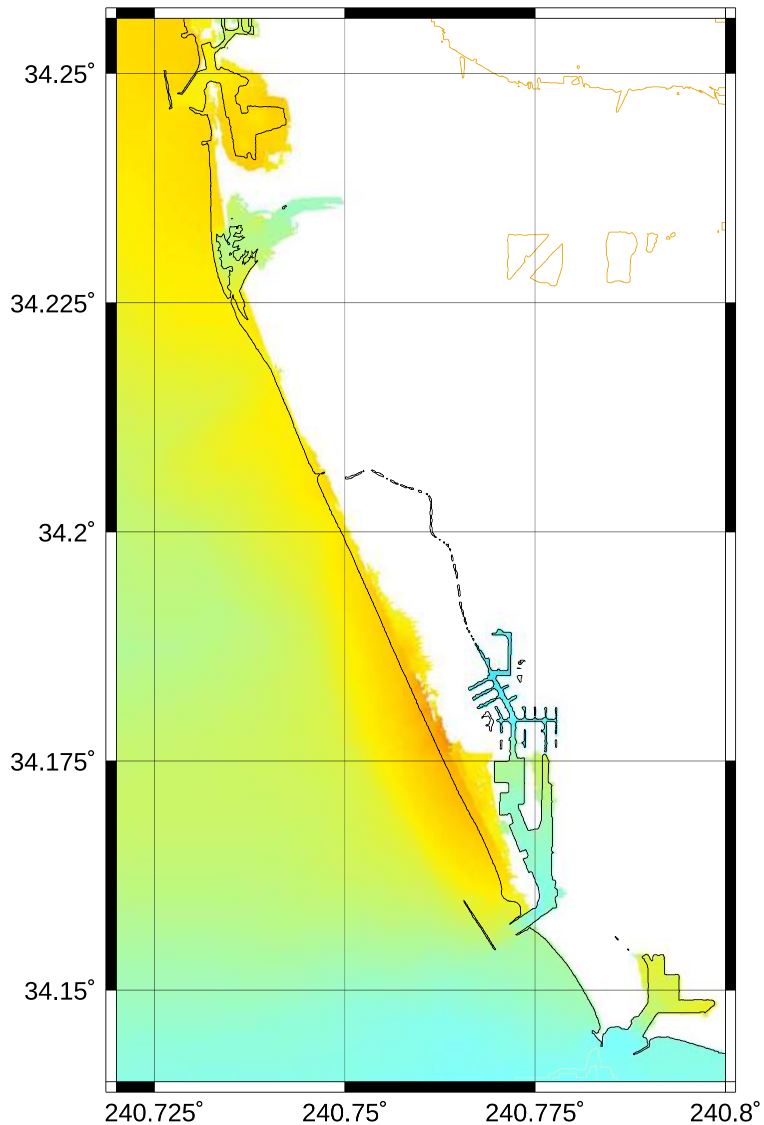
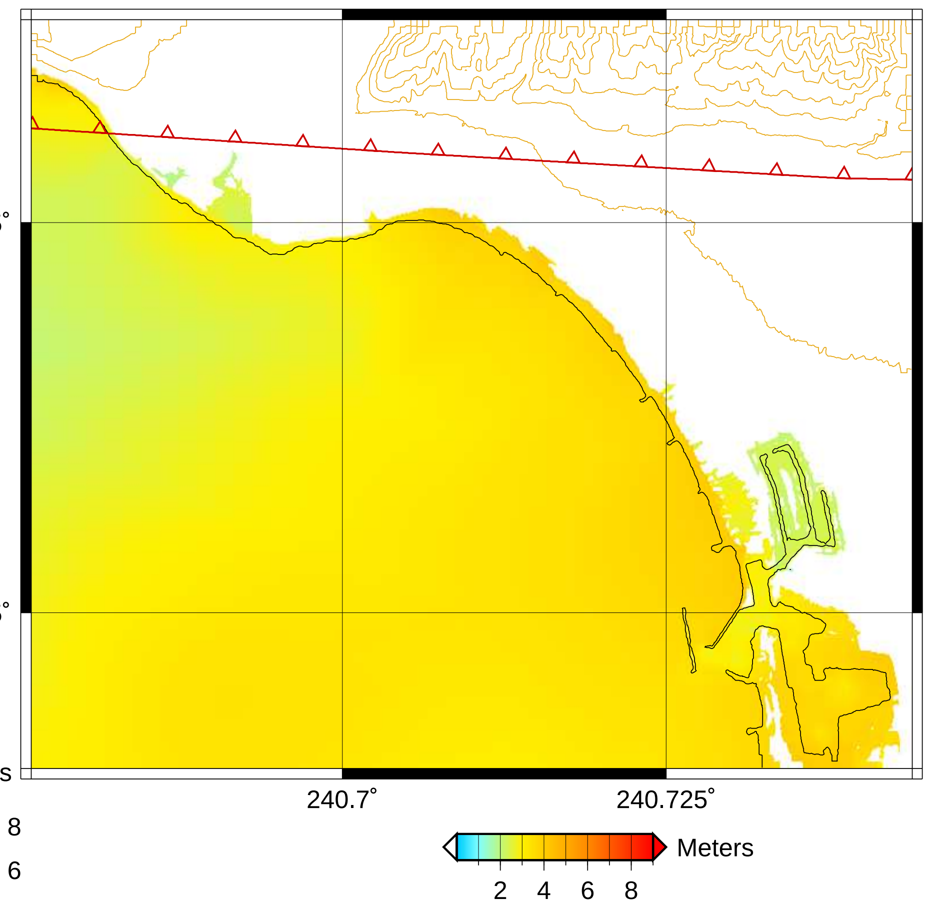
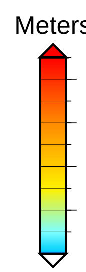


Ventura-Pitas point scenario





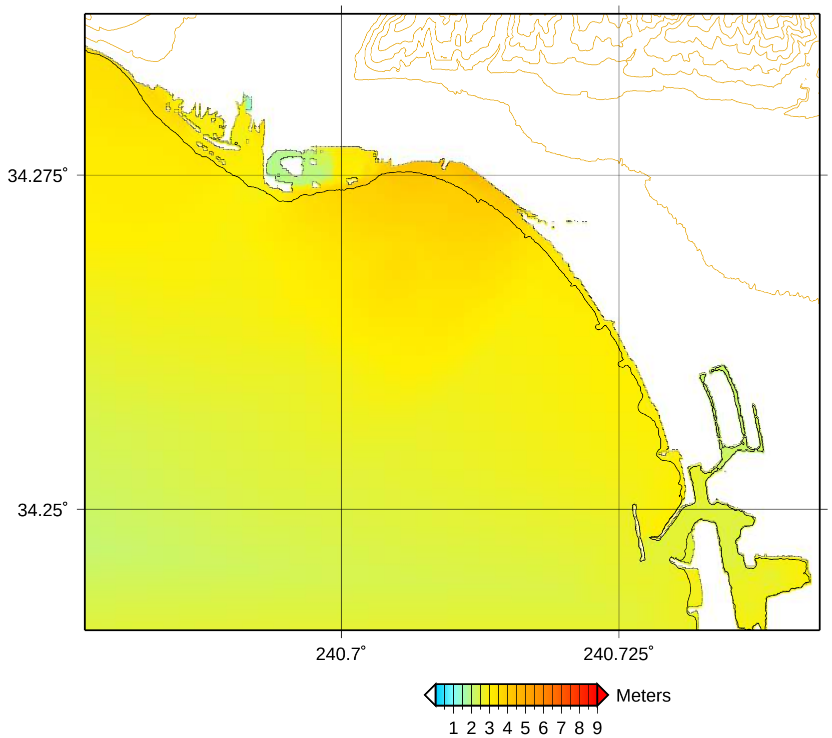


Inundation in the Ventura (top) and Oxnard (left) areas.

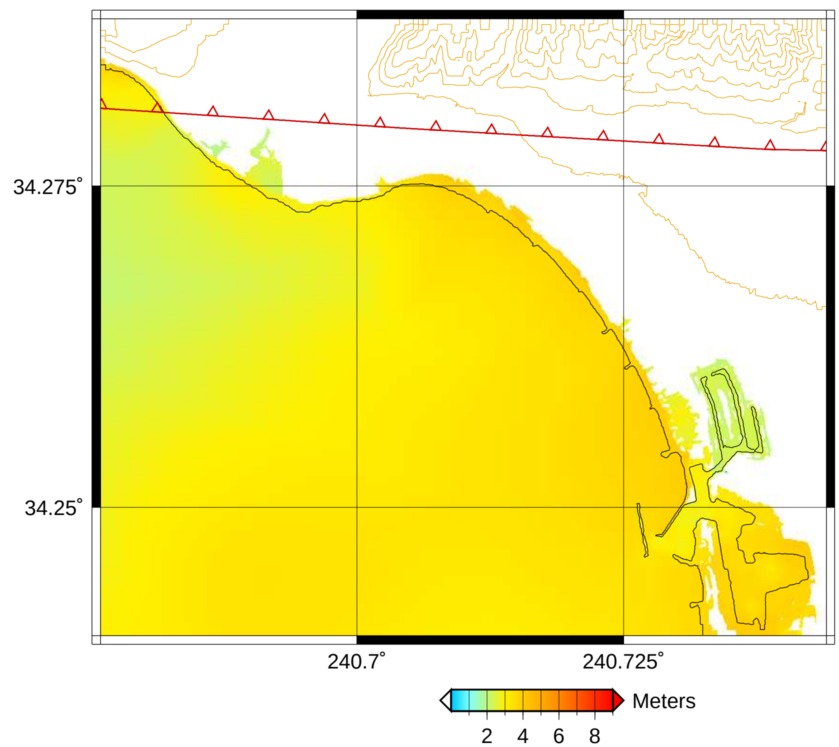
Thio et al., (2015)

Ventura-Pitas point vs. Oak Ridge fault

Oak Ridge



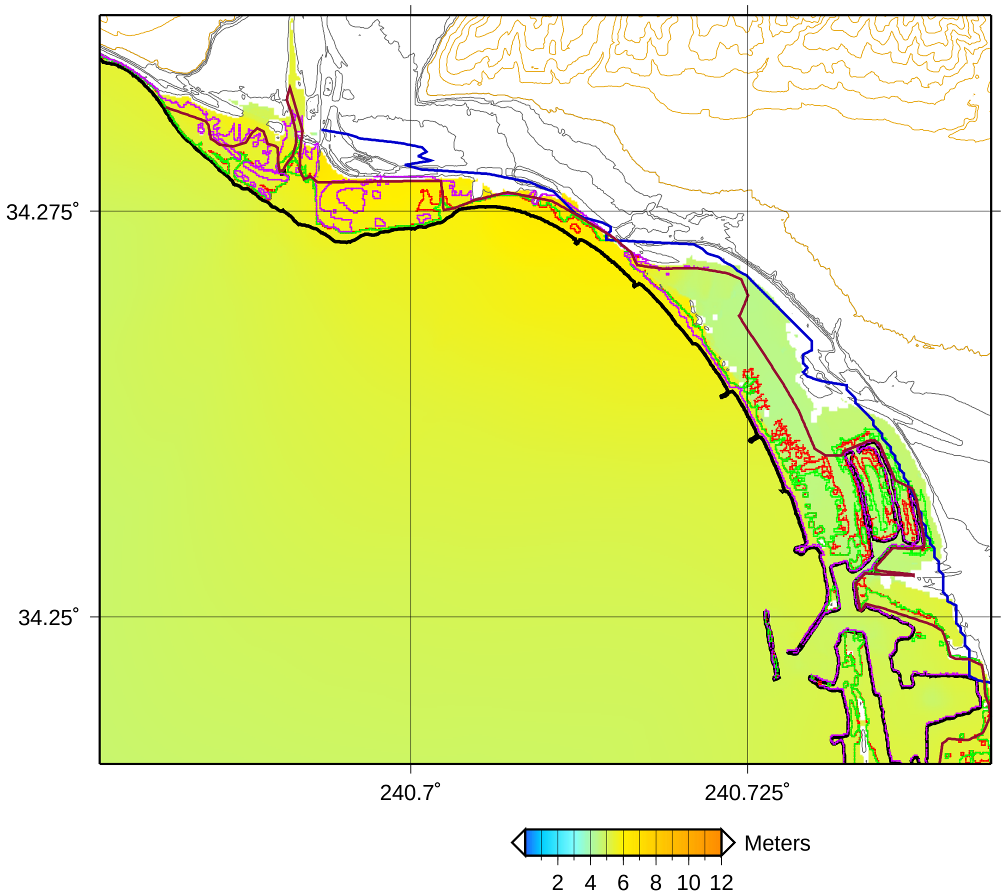
Ventura-Pitas point



For similar-sized events, the Oak Ridge fault causes more significant inundation in the Ventura area than the Ventura Pitas point fault due to the uplift of the Ventura area and the orientation of the Oak Ridge source relative to Ventura

Thio et al., (2015)

Comparison to the existing and future tsunami hazard maps

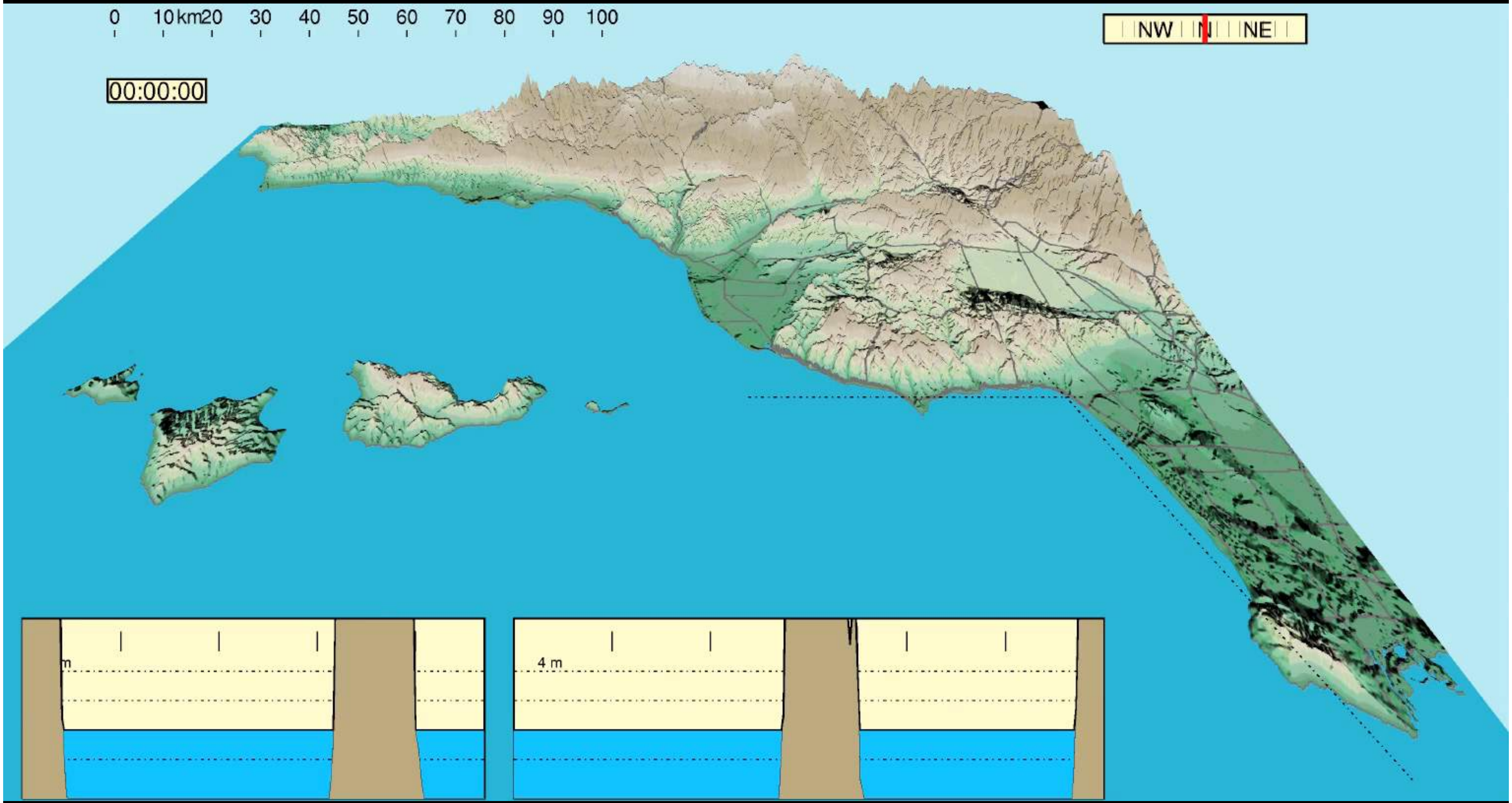


- Basemap: preliminary draft probabilistic tsunami hazard map
- Blue: current CGS tsuami emergency planning map
- Maroon: Ryan et al (2015)
- Purple: Oak Ridge
- Red and Green: Ventura-Pitas point

Thio et al., (2015)

Tsunami modeling

Steve Ward



Results of the Ventura SFSA (2015)

Large, multi-segment Holocene earthquakes involving the Ventura fault have been documented at multiple sites using a variety of methods.

Earthquake simulators show a complex range of single and multi-segment events, but do not currently reproduce the largest proposed earthquakes.

Activity of the fault system has been documented offshore. Do we need better offshore paleoseismology?

Episodic coastal subsidence events suggest large earthquakes on south-dipping faults that may or may not be associated to Ventura –Pitas Point fault ruptures.

Progress has been made in refining our understanding of the geometry and linkages among the various fault segments that comprise the Ventura – Pitas Point – North Channel fault and nearby structures. Questions remain – and these geometries have an impact on our assessment of possible event magnitudes.

Results of the Ventura SFSA (2015)

Large amounts of horizontal shortening occur across the Ventura – Pitas Point fault system, implying fast slip rates.

Vertical deformation is localized to the north and northeast of the Ventura fault trace. Horizontal contraction may be localized in basin.

Earthquakes are widely distributed, dominated by thrust mechanisms, show low stress drops, and are consistent with NNE-SSW directed s1.

Kinematic and dynamic rupture simulations forecast significant ground motions over a large area of coastal southern California.

Tsunami simulations suggest that peak amplitude is related to maximum surface displacement. Scenario events show the prospect for large run-ups – especially in the footwall of the thrust sheet.