SCEC Project 25139 Technical Report

Introduction and Project Objectives

The 29 June 1925 M6.5 Santa Barbara earthquake was a seminal event for the city of Santa Barbara and for the perception of earthquake hazards statewide in California. It enabled implementation of the now characteristic Spanish-Colonial style of architecture and first seismic-safety building codes for the city, and helped set the stage not only for the expansion of earthquake hazard perception into southern California, but the impetus for the first Uniform Building Code in 1927 that included lateral earthquake forces. The 100th anniversary offered an excellent and timely opportunity to re-evaluate and better understand the likely causative fault (or faults) for this and other major damaging earthquakes in the Santa Barbara-Ventura area, as well as important aspects of the active 3D fault geometry, the significance of variable uplift, fault slip and geodetic strain rates along the coast, and the more extensive, increased earthquake and tsunami hazard potential for this important active earthquake region with large urban populations at risk.

In 2012, SCEC established the Ventura Special Fault Study Area to promote interdisciplinary science investigating the prospects for large, multi-segment earthquakes in the western Transverse Ranges of California, and to address the hazards posed by these potentially devastating events. An initial concern was that large damaging, multi-segment earthquakes with magnitudes of M7.7 to M8.1 may have occurred in the Santa Barbara-Ventura area based solely on repeated Holocene uplift events of coastal marine terraces located around Pitas Point near Ventura (**Fig.1**)[*Rockwell,* 2011; *Rockwell et al.,* 2014, 2016]. The inferred principal location for these proposed events is believed to be the Pitas Point-Ventura fault (PP-VF) [*Hubbard et al.,* 2014; *McAuliffe et al.,* 2015; *Rockwell et al.,* 2016], part of the larger primarily offshore, N-dipping North Channel-Pitas Point-Red Mountain fault system [*Archuleta et al.,* 1997; *Kamerling et al.,* 2003; *Fisher et al.,* 2005; *Sorlien et al.,* 2014; *Nicholson et al.,* 2017] that extends farther west for over 120 km. It was owing to the increased hazard potential that such proposed large magnitude events would represent that the Santa Barbara-Ventura region was designated as the Ventura Special Fault Study Area (SFSA) for focused, integrated, multi-disciplinary research [*Dolan et al.,* 2012].

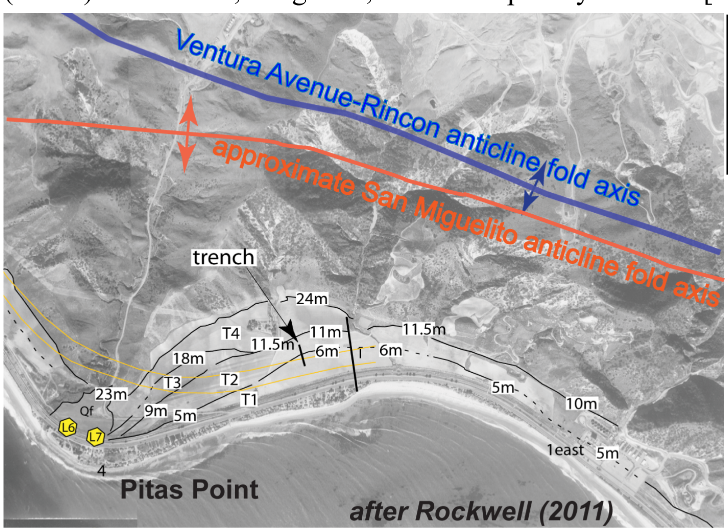
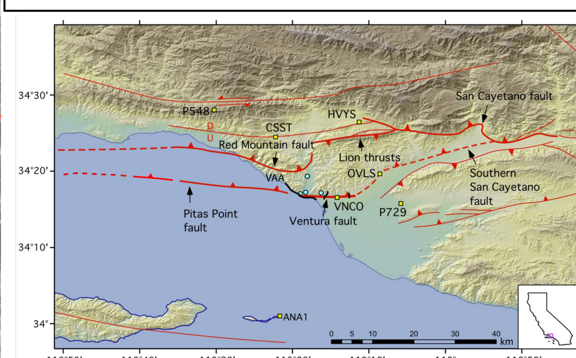


Figure 1. (left) Map of Holocene emergent terraces at Pitas Point [after *Rockwell,* 2011]. (below) Map of the eastern Santa Barbara Channel with the Pitas Point-Ventura fault.



As a result of these on-going research activities, a number of important science issues and fundamental controversies were revealed related to the large uplift events at Pitas Point, their implications for earthquake hazard, alternative fault geometries of major fault systems, and important discrepancies and corroborations between various model predictions and observations. These issues or questions include:

Science questions the workshop hoped to address:

a) What are the primary, first-order data and observations that any model for the unusual uplift at Pitas Point or elsewhere along the coast, and the 3D subsurface geometry of active faults must satisfy?

b) Is the unusual uplift at Pitas Point representative of multiple M7.7+ earthquakes on the blind Pitas Point-Ventura fault, or is it anomalous and not indicative of M7.7+ events or the slip at depth farther along strike?

c) Is Pitas Point uplift driven primarily by slip on the S-dipping Padre Juan fault, N-dipping Ventura fault, or some combination? Are other factors like a cross fault and restraining bend also involved?
d) What are the likely source faults of the 1925, 1978 and 2013 Santa Barbara area earthquakes? What would be the expected ground motions for a repeat of 1925 or a much larger M7.4+ regional earthquake?
e) What is the first-order fault architecture driving Western Transverse Ranges deformation?
f) Are the principal faults (Red Mountain, Pitas Point, San Cayetano, Santa Ynez, etc.) detached at some shallow crustal level (7-10 km) or are they steeply dipping to depths of 15-18 km?
g) If detached, what is the geologic and geophysical evidence for the depth and dip of this detachment, or is this geometry simply model driven? If not detached, how is fault geometry properly modeled in 3D?
h) What does the presence of Precariously Balanced Rocks behind Santa Barbara and Montecito [*Brune,* 2009] tell us about the maximum magnitudes and ground motions the active faults can or have produce?
i) To what extent are measured geodetic strains elastic (and related to the seismic hazard), or can they also reflect inelastic processes related to basin subsidence, compaction, gravity-sliding and other processes?

To help address these questions, a field trip and workshop were held on the centennial anniversary of the 29 June 1925 Santa Barbara earthquake (https://www.scec.org/events/2025-santa-barbara-earthquake-workshop/). The half-day field trip visited several key geological and geophysical sites associated with the 1925 earthquake, the local onshore faults, and uplifted marine terraces running from UCSB to Pitas Point. The workshop consisted of short talks and interleaved poster sessions on the active fault systems and patterns of deformation. The objective was to bring together researchers, students and stakeholders in areas of earthquake history, offshore geophysics, crustal structure, seismicity, geodesy, fault modeling, tectonic geomorphology, paleoseismology, sedimentology, and dynamic rupture modeling to review and evaluate important observations relevant to these issues and the hazard potential for the Santa Barbara-Ventura area.

Sunday (June 29) Field Trip

The primary purpose of the field trip was to provide insight into the active tectonic geomorphology and related fault architecture (both onshore and offshore) responsible for the on-going deformation, as well as the various rates of fault slip, fault interaction, and marine terrace uplift along the Santa Barbara-Ventura coast and thereby put in proper perspective the uplift and fault slip rates observed at Pitas Point.

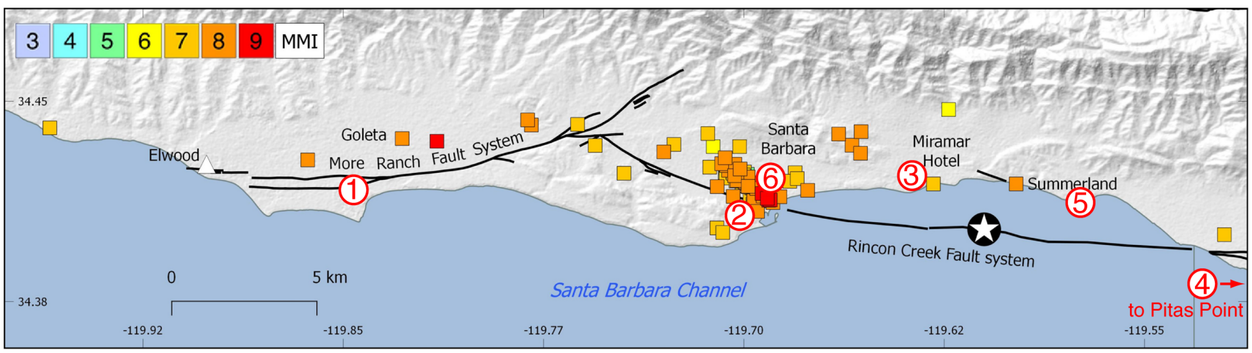


Figure 2. Intensities for the 1925 Santa Barbara earthquake and proposed possible 1925 rupture scenario along the Rincon Creek-Mesa and More Ranch faults [*Hough and Martin*, 2018]. Circle numbers are tentative fieldtrip stops. Stop #4 at Pitas Point [*Rockwell et al.,* 2014, 2016] is located about 30 km farther to the southeast.

1. UCSB/More Ranch fault/Campus uplift: Site provided perspective on the Campus raised marine terrace, age and uplift rate (2 mm/yr)[*Gurrola et al.,* 2014]; fault scarp and slip rate (1.4 mm/yr) for the steeply (60°-70°) S-dipping oblique-strike-slip More Ranch fault; and a cross section for how the S-dipping onshore faults merge with the N-dipping offshore oblique-reverse Pitas Point (PPF) and Red Mountain (RMF) faults based on seismic reflection imaging, seismicity and industry well data [*Nicholson et al.,* 2017].

2. SBCC/Mesa fault/Mesa uplift: Stop provided view of stepped S-dipping oblique-strike-slip Lavigia & Mesa fault uplift (1 mm/yr) and fault slip (0.6-2 mm/yr) rates; *John Iwerks* [2007] geologic cross section mural showing wedge geometry of S-dipping Mesa and N-dipping Pitas Point faults; and travel up and down Mesa fault scarp (124 m topographic expression) [*Keller and Gurrola*, 2000; *Gurrola et al.,* 2014].

3. Santa Barbara Lagoon: Evidence for two possible tsunami inundation deposits [*Simms et al.,* 2021] that may correlate with recent uplift events at Pitas Point; uplift rate (0.4 mm/yr) of adjacent Cemetery terrace.

4. Pitas Point/Pitas Point uplift: Evidence for four major 8-11 m uplift events at Pitas Point since 6.7 ka and related uplift rate (6-7 mm/yr)[*Rockwell et al.,* 2014, 2016]. Structure cross sections east [*Grigsby,* 1988; *Hopps et al.,* 1992; *Nicholson et al.,* 2017] and west [*Grigsby,* 1988; *Hsieh & Suppe,* 2020] of Pitas Point based on extensive industry well data confirm two independent anticlinal folds (San Miguelito and Ventura Avenue) are present, with Pitas Point uplift and San Miguelito fold development and displacement driven by the S-dipping, listric Padre Juan fault. Competing explanations for how and to what degree the S-dipping Padre Juan and N-dipping Ventura faults interact, and what other elements may be contributing to the unusually high rate of local marine terrace uplift were discussed but still not fully resolved.

5. Loon Point: Fault-related folding of Loon Point anticline and deformed marine terrace; terrace uplift rate (0.5 mm/yr) and oblique-strike-slip Loon Point fault slip rate (1 mm/yr)[*Gurrola et al,* 1988].

6. Downtown Santa Barbara: Short walking tour of buildings that suffered major damage (and still show residual effects) from the 1925 earthquake [*Sylvester and Mendes*, 2011; *Gurrola*, 2025; https://eq25.org/].

Principal observations relevant to fault modeling and hazard potential include: a) major onshore faults (Mission Ridge-More Ranch, Mesa) are steeply (60°-70°) S-dipping oblique-strike-slip faults with slip rates on the order of 1-2 mm/yr; b) these S-dipping onshore oblique-strike-slip faults merge at depth with the offshore N-dipping oblique-reverse faults (Pitas Point, Red Mountain) to create a master oblique-slip fault (not a thrust) at depth; c) uplift rates of raised marine terraces systematically decrease eastward from UCSB (2 mm/yr) to Summerland/Loon Point (0.5 mm/yr) but increase dramatically at Pitas Point (6-7 mm/yr); d) uplift rate at Pitas Point is thus anomalous and not found elsewhere along the coast; and e) at Pitas Point, there are two independent anticlinal folds (not one), with Holocene displacement necessarily occurring on the S-dipping, listric Padre Juan fault [*Nicholson et al.,* 2017, 2020; *Hsieh & Suppe,* 2020]. These observations contradict previously published models that rely exclusively on or exhibit only one active anticlinal fold (Ventura Avenue) and only Holocene slip on the N-dipping Ventura fault at shallow depths [*e.g., Hubbard et al.,* 2014; *McAuliffe et al.,* 2015; *Rockwell et al.,* 2016; *Levy and Rockwell,* 2020].

Monday (June 30) Workshop

A workshop was held at UCSB Marine Science Institute that consisted of 14 invited oral presentations together with 12 poster presentations by researchers that have contributed to the SFSA or who are working on similar complex tectonic problems. The workshop program is posted on the SCEC workshop webpage (https://www.scec.org/events/2025-santa-barbara-earthquake-workshop/). The workshop focused on recent research results in four thematic and interleaved poster sessions, with an introduction to highlight and summarize the field trip and some of the important unresolved questions and controversial issues at stake:
Session 1: Seismological Aspects
Session 2: Geological Aspects
Session 3: Geodetic and Physical Models of the Western Transverse Ranges
Session 4: Summary Debate & Synthesis

Introduction and Summary of Controversial Issues

Tom Rockwell summarized the field trip and identified important regional characteristics of the western Transverse Ranges (WTR). Older ages and lower uplift rates characterize the marine terraces at stops west of Pitas Point; uplift at Pitas Point reflects four 8-11 m uplift events since 6.7 ka and an uplift rate of 6-7 mm/yr. The S-dipping Padre Juan fault drives uplift and folding of the San Miguelito anticline at Pitas Point, which he interprets as a back-thrust off the N-dipping Pitas Point fault. Regional considerations must account for the development of the 180-km long Santa Ynez anticlinorium, the topography, geology, and southward propagation of folds on inferred blind thrust faults, and the emergent San Cayetano fault.

Craig Nicholson identified other important observations that any viable fault, hazard or regional tectonic model must accommodate, as well as some of the controversial issues that have yet to be resolved. These include: rotation of the WTR; major faults exhibit seismicity, inherited steep (>50°) dips and oblique-slip to depths of 15-18 km; uplift at Pitas Point is anomalous; the Pitas Point-Ventura fault (PP-VF) is blind;

and datasets indicate the S-dipping Padre Juan fault is Holocene active. Controversial issues include: a) if the uplift events at Pitas Point represent M7.7+ earthquakes, how can such multiple large magnitude events occur at shallow depths on blind faults, given dynamic rupture modeling would predict surface or seafloor offsets of 10-12 m per event? and b) how can one reconcile the 2D fold-and thrust models that have low-angle detachments at 7-8 km with the seismicity that defines steeply dipping planar faults to 15-18 km?

Session 1: Seismological Aspects

Sue Hough documented how the 1925 Santa Barbara earthquake played a pivotal role on urban planning, building code (UBC) development, earthquake-resistant design and public perception; the seismological characteristics and alternative source models (S-dipping Rincon Creek-Mesa-More Ranch, N-dipping Pitas Point) for 1925; and preliminary 1925 rupture models and simulated intensities from Rob Graves.

Egill Hauksson presented relocated seismicity with his regional velocity model showing planar seismicity trends below the major faults (Santa Ynez - SYF, San Cayetano - SCF, Red Mountain - RMF, Oak Ridge - ORF) to depths of 15-18 km; major seismicity trends in the Ventura basin and Santa Barbara Channel representing footwall deformation below the SCF, PP-RMF and ORF; relocation of the 1978 Santa Barbara sequence that moves farther south; and comparison of Ventura and San Gorgonio Pass SFSA.

Julian Lozos presented dynamic rupture model results comparing the alternative models in the CFM for the Pitas Point fault (ramp-flat and steeper dipping). Owing to different maximum fault model depths, the ramp-flat model yields a M7.5, while the steeper fault model yields a M7.7. Magnitude is highly dependent on initial stress, but in all cases, the steeper model had higher magnitude, stress drop and near-surface slip.

Alex Simms, together with a poster by Laura Reynolds, presented the record of tsunami and subsidence events in the Santa Barbara Channel with two possible Holocene tsunami deposits in the geologic record. These two inundation events potentially correlate with the two youngest uplift events at Pitas Point.

Chen Ji presented a poster modeling the waveform records at UC Berkeley for the 1925 earthquake using the 2013 M4.8 Isla Vista earthquake as an empirical Green's function. This modeling confirmed a moment magnitude of M6.5 for 1925 and a similar focal depth (10-12 km) and plausible focal mechanism as 2013.

Session 2: Geological Aspects

Marc Kamerling documented how inherited structures from WTR fault evolution helped define cross faults that limit earthquake ruptures on E-W-striking faults, and the more steeply dipping to overturned, reactivated fault and fold geometry exhibited by the Pitas Point-Red Mountain and Oak Ridge fault systems.

Chris Anthonissen documented results of 3 transects across the Ventura and shallow Southern San Cayetano faults showing in general lower amounts and rates of uplift, two roughly consistent Holocene events, and two older uplift events since 13.6 ka as compared with the 4 dated Holocene uplift events at Pitas Point.

Jared Kluesner presented mapping results of the western North Channel-Pitas Point (NC-PPF) fault system using 3D and 2D seismic surveys to show a complex network of *en echelon* splay faults that define a distinct NC-PPF deformation zone with increasing strike-slip to the west and controlling incipient seafloor failures.

Sam Johnson presented mapping results using high-resolution seismic reflection, multibeam bathymetry and seafloor imaging data that show minor folding above a blind PP-VF that decreases westward due to increasing fault or rupture tip depth and ~30 m of post-LGM uplift of the outer shelf above the NC-PPF.

Hector Perea presented further results from high-resolution CHIRP and mini-sparker seismic data of minor post-LGM folding above a blind, continuous PP-VF, a disconnect between the onshore and offshore RMF, and evidence for 3 Holocene uplift/fold events that seem to match the 3 younger dated events at Pitas Point.

Chris Sorlien presented a poster mapping the NC-PPF system from Ventura to Pt. Conception (120 km) and multiple dated stratigraphic horizons to document blind fault strands, associated progressive tilting of the hanging-wall fold forelimb, and no evidence of lateral or updip fault propagation in Quaternary time.

Session 3: Geodetic and Physical Models of the Western Transverse Ranges

Tom Rockwell reiterated that the 180-km Santa Ynez anticlinorium requires a blind fold-and-thrust model with southward propagation of faults and folds, and shortening that decreases westward. Forward trishear modeling [*Levy et al.,* 2020] can match much of the observed geology with fault geometry characterized by dominant N-dipping faults that steepen as they shoal. Dip and depth of the detachment is model driven.

Kaj Johnson presented results on geodetic deformation and structure models showing a broad pattern of uplift north of the Santa Ynez fault (SYF) [*Hammond et al.,* 2018], 4-5 mm/yr of differential vertical motion across the PP-VF, but 1-3 mm/yr of left-slip on the Red Mountain (RMF) and PPF [*Johnson,* 2024], indicating faults are oblique (not thrust). Santa Barbara coastline is subsiding at 1-3 mm/yr likely due locking of the PP-VF and potential inelastic components of basin sediment compaction.

Yu-Huan Hsieh, together with a poster by John Suppe, presented a preliminary model for the San Cayetano fault defined by the top of a low-angle (20°), 15-km wide low-velocity channel in the regional tomography model of *Wang et al.* [2020], and to some extent by seismicity, similar to thrust faults found in Taiwan.

Session 4: Summary Debate & Synthesis

Summary discussion was a bit less structured than desired, and important controversial issues remained to some extent unresolved. Important questions raised included: What is the fault architecture driving WTR deformation? Other than proposed models, what evidence is there to connect the PP-RMF and San Cayetano fault (SCF) systems or document how these systems may interact? If fault-related fold models require the crust be detached, what independent geologic or geophysical evidence is there for the depth and dip of the detachment? Current models have the detachment at 7-8 km depth, while the depth of major recorded earthquakes (including 1925, 1978 and 2013), earthquakes with low-angle nodal planes, and bulk of the seismicity is occurring at 10-12 km. What is the geometry of active faults driving the pattern of surface and seafloor uplift? For example, at Pitas Point, published models show only one anticline and infer slip on only the N-dipping VF, while structure cross sections from industry well data show two active independent anticlines and slip on the VF and S-dipping Padre Juan fault [*Nicholson et al.,* 2017; *Hsieh & Suppe,* 2020].

Other additional questions that were raised include: What happens during a major earthquake if the major active PP-VF is blind and fault slip decreases updip towards the buried fault tip? What is the potential for seafloor uplift, offset or tsunami generation if fold uplift is primarily onshore and the offshore fault is blind?

The general consensus of the participants was that the deformation at Pitas Point (four 8-11 m uplift events) [*Rockwell*] and the evidence onshore farther along strike (four 5-6 m displacement events) [*Anthonissen*] and offshore (three 1-3 m folding events) [*Perea*] all argue for the occurrence of multiple large magnitude earthquakes. The problem or discrepancy is that, other than at Pitas Point, the evidence for 3-6 m slip events is typically associated with M7.0+ earthquakes [e.g., *Perea et al.,* 2021] not necessarily M7.7+ earthquakes, and in several cases, event correlation is not consistent. For example, possible tsunami inundation events may correlate with the two youngest (1^{st} and 2^{nd}) uplift events at Pitas Point [*Simms*], but the older events are not observed; at Day Road on the VF, four inferred paleo-earthquakes seem to correlate with the 1^{st} and 3^{rd} Pitas Point events and with another two older than 7 ka [*Anthonissen*]; and offshore closest to Pitas Point above the blind PPF, deformation indicates 3 not 4 folding events [*Perea*]. The four uplift events found at Pitas Point are not all replicated elsewhere, and older deformation events found elsewhere (i.e., Day Road) are not observed at Pitas Point. This implies that uplift events at Pitas Point are local and to some extent anomalous, and not representative of the fault slip at depth farther along strike regardless of whether the N-dipping VF or S-dipping Padre Juan fault is driving the uplift. If the uplift events at Pitas Point are indicative of shallow M7.7+ earthquakes, if even 1 or 2 can remain otherwise hidden, this calls into question the completeness of the paleoseismic record derived from the various other regional sites or studies.

List of Workshop Participants

Chris Anthonissen, Aris Aspiotes, Jeng Hann Chong, Shyane Cornell, Timothy Dawson, James Dolan, Eileen Evans, Alice Gabriel, Rob Graves, Larry Gurrola, Ruth Harris, Egill Hauksson, Phil Hogan, Susan Hough, Yu-Huan Hsieh, Ken Hudson, Chen Ji, Kaj Johnson, Samuel Johnson, Marc Kamerling, Kathleen Marsaglia, Caje Kindred Weigandt, Jared Kluesner, Julian Lozos, Andy Lutz, Gareth Mills, Kevin Milner, Leyla Namazie, Craig Nicholson, David Oglesby, Ann Olesh, Brian Olson, Nate Onderdonk, Hector Perea, Laura Reynolds, Thomas Rockwell, Sandy Seale, Alexander Simms, Christopher Sorlien, John Suppe, Taka'aki Taira, Ashley Walsh, Clara Yoon, Eilon Zach.

Reference List of Workshop Presentations (oral and poster)

Oral

- Tom Rockwell, Field Trip Summary and Important Regional Characteristics
- Craig Nicholson, Controversial Issues Related to Earthquake Hazards in the Santa Barbara-Ventura Area
- Sue Hough, The 1925 M6.5 Santa Barbara Earthquake: A Pivotal Event
- Egill Hauksson, Recent Seismicity and Seismotectonics in the Santa Barbara-Ventura Area
- Julian Lozos, Implications of dynamic rupture models for the Santa Barbara-Ventura Area
- Alexander Simms, The record of tsunami in the Santa Barbara Channel
- Marc Kamerling, The Santa Barbara Channel in Four Dimensions
- Chris Anthonissen, Active tectonics and seismic hazards of the southern San Cayetano and Ventura-Pitas Point fault system
- Jared Kluesner, Western extent of the Pitas Point-North Channel fault system
- Sam Johnson, Marine geomorphic and seismic-reflection evidence for latest Pleistocene to Holocene tectonic activity, northern Santa Barbara Channel
- Hector Perea, Faulting and folding of the Transgressive Surface offshore Ventura records deformational events in the Holocene
- Tom Rockwell, Architecture of the Western Transverse Ranges
- Kaj Johnson, Present geodetic deformation and structure models of the western Transverse Ranges
- Yu-Huan Hsieh, Multiscale transects of the western Transverse Ranges

Posters

- Craig Nicholson, Anomalous Uplift at Pitas Point: Implications from Onshore & Offshore 3D Fault & Fold Geometry and Observed Fault Slip
- Chen Ji, Waveform modeling of the 1925 M6.5 Santa Barbara earthquake
- Larry Gurrola, Mapping onshore active faults, style of faulting, and rates of uplift along the Santa Barbara coastal piedmont
- Laura Reynolds, The record of tsunami and subsidence events in the Santa Barbara area
- Christopher Sorlien, The Pitas Point-North Channel fault-fold system through Quaternary time
- Eileen Evans, Modeling geodetic deformation in the Western Transverse Ranges
- Nate Onderdonk, Episodic uplift and deformation in the Santa Maria Basin and implications for long-term earthquake hazards in the western Transverse Ranges
- Kevin Milner, Santa Barbara area faults in the USGS NSHM: multi-fault ruptures, segmentation, and uncertainties
- John Suppe, Developing multiscale transect models of the western Transverse Ranges
- Ken Hudson, Anisotropic path and site effects' influences on strong ground motion records in the Santa Barbara region
- Alice Gabriel, The complex rupture dynamics of an oceanic transform fault: supershear rupture and deep slip during the 2024 Mw7.0 Cape Mendocino Earthquake
- Jeng Hann Chong, A creeping anticline above the Rakhine-Bangladesh megathrust: InSAR observations of an aseismic fold accommodating geodetic shortening

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