

2017 SCEC Report
Award Number 8054

**Crustal Architecture of the Western Transverse Ranges, Southern California:
The Potential for Great Earthquake**

Principle Investigator:

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San Diego State University**

TOTAL AMOUNT OF GRANT: \$25,000

PROPOSAL CATEGORY: **Data Gathering and Products**
DISCIPLINARY ACTIVITY: **Earthquake Geology**
SCIENCE OBJECTIVES: **1a, 3a, 3b, 3e**

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1. Abstract:

Details of the subsurface structure of the Western Transverse Ranges (WTR) of southern California is still under ongoing debate. Recent work found evidence for large earthquakes. This evidence combined with the community's agreement that existing models can be improved, motivated us to study further the structure in the region. Our goal is to construct a balanced retro-deformable 3D model that will be in agreement with the full range of geologic and geodetic data. Towards achieving this goal, we initially constructed several shallow geologic cross-sections by compiling geologic data and reviewing / modifying existing models. These cross-sections have been added to with new sections to the west towards Point Conception, and together will be used to interpolate a 3D model. We then used the Trishear module in MOVE to forward model the structure of the range to compare to the geologic sections with the purpose of testing different deep structural geometries that consistently reproduce the surface structure. Our current interpretation is that the WTR, during the period of shortening that began in the Pliocene, developed thrust fronts which propagated southward over time, similar to other fold-and-thrust belts. We interpret the nearly continuous overturned Tertiary stratigraphy of the Santa Ynez Mountains as a large anticlinorium that formed as the first thrust front over the (mostly) blind San Cayetano thrust, and that the thrust front propagated south with time to the Red Mountain fault and eventually to the currently active thrust front, the southward-vergent Pitas Point-Ventura fault. Using fault-related folding methods, we predict vergence direction and geometry of the major faults at depth, and use these structures to model the evolution of the Transverse Range since the late Pliocene. The forward modeling predictions are in good agreement with the observed geology and deformation. Our results suggest that the Western Transverse Range is comprised of a southward verging imbricate thrust system, with the dominant faults dipping as a ramp-ramp to the north that steepen as they shoal from $\sim 20^\circ$ degrees at depth to $\sim 60^\circ$ near the surface. By including the full range of observations in our forward modeling efforts, we address fundamental questions regarding the structural geometry and kinematics of the region, which allows for a better understanding of earthquake and tsunami potential.

2. Technical report:

Summary of the Work Done During 2017

Our goal is to construct a reliable model for the subsurface structure of the western Transverse Ranges (WTR) of southern California (figure 1). The motivation for initiating this project was the evidence for very large and rapid uplift events that have occurred along the Pitas Point – Ventura fault system (Hubbard et al., 2014; McAuliffe et al., 2015; Rockwell et al., 2016), with the implication being that these are the result of very large earthquakes. There are several existing structural models of the Transverse Ranges, however they do not explain the full extent of observations, are in conflict with each other, and still stand in debate.

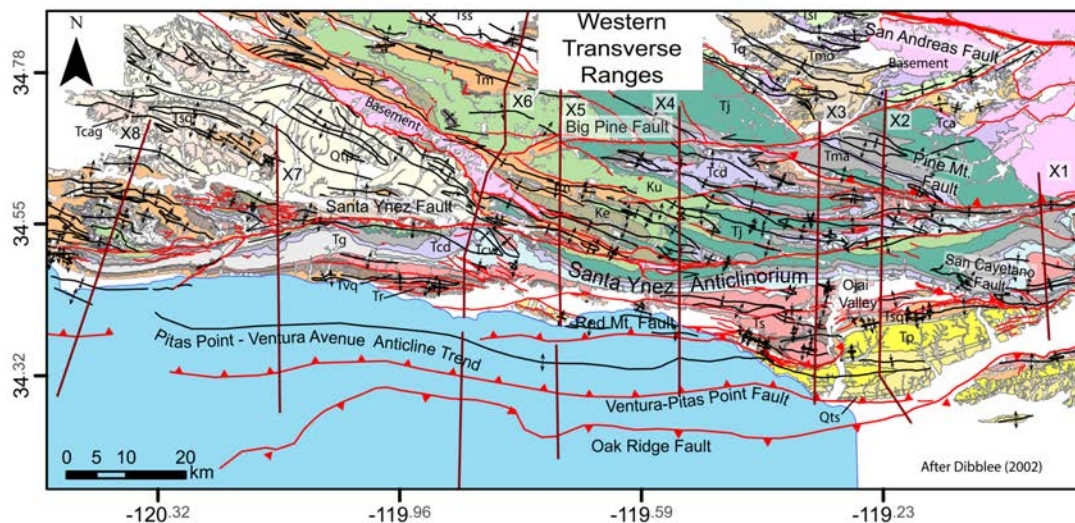


Figure 1. *Geology and structure of the western Transverse Ranges (WTR) in southern California (from Dibblee's maps (2002). Note the continuity of Tertiary stratigraphy along the Santa Ynez anticlinorium, which forms the backbone of the WTR. It also demonstrates the continuity of the deep thrust system. Completed cross-section locations are marked as dashed lines and presented in Figures 3, 4 and 5.*

Ph.D. student Yuval Levy has constructed a number of cross sections (Figures 1 and 2) towards building a reliable 3-D model that will be implemented into SCEC's CFM, and that can be used by the modeling community. After the completion of the first few of these cross sections, an expansion of the work area farther north was deemed necessary in order to include the entire system for building a reliable retro deformable model. This work is being continued today, with the intention of adding a sufficient number of cross sections necessary for a valid construction of the 3D model that is retrodeformable through time. The intended model must account for the rates and styles of the observed vertical motions (ie., large uplift at Pitas Point and Ventura, interpreted as coseismic; a relatively high rate of uplift on the hanging wall of several back thrusts, rapid subsidence in Santa Barbara and Ventura basins, subsidence of sub-basins in the hanging wall of the thrust sheet at Carpinteria and Goleta Sloughs (Simms et al., 2016), uplift of fluvial terraces along the Ventura River and other drainages (Rockwell et al., 1984, 1988; Rockwell, 1988), uplift of marine terraces along the length of the coast (Rockwell et al., 1992; Gurrola et al., 2014; Rockwell et al., 2016), as well as match the observed decrease

in geodetic shortening rates westward from Ventura (Marshall et al., 2013). Our hypothesis is that there is a common-form structure connecting the thrusts at depth, and that the system has propagated southwards over time, which is based on both geomorphic and geologic observations combined with chronologic studies. Yuval developed a forward model using the Trishear module in MOVE in order to estimate the fault geometry at depth (Figure 2).

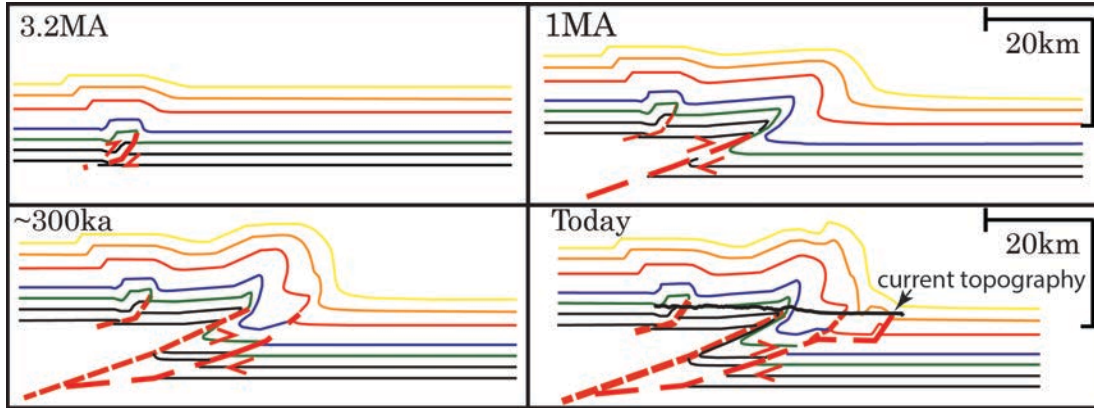


Figure 2. Our forward model demonstrating the evolution of the structure since late Pliocene. The thrust front is migrating south in the vergence direction. The black line in the final caption represents the topography. Preexisting, secondary or out of plane deformation is neglected.

Comparison of the forward modeling to the near surface geology shows that the model predictions capture the first order patterns of folding, and structural and stratigraphic relief (Figure 3, 4 and 5). Considering that the depth of the brittle-ductile transition in the WTR is as deep as 20 km, based on the D90 depth of microseismicity (Nazareth and Hauksson, 2004), this model argues that the surface area of the fault in the seismogenic zone may approach 10^4 km^2 if the entire 180 km of the system fails in a single event. Such a potential rupture area would support an earthquake in the M7.8-8 range, as argued from recent studies of coastal uplift, borehole excavations, and structural analysis (Hubbard et al., 2014; McAuliffe et al., 2015; Rockwell et al., 2016).

Details of the results we present here will likely change as we progress, however we believe that our understating of this fault system has progressed and that the general structure is correct. In the community, there is an agreement that the active fold and thrust belt system in the WTR involves the San Cayetano, Red Mountain and the Pitas Point-Ventura faults, the associated Ventura Avenue anticline trend offshore to the south and west, with faulting and folding westward to Point Conception (Figure 1). This is demonstrated by the nearly continuous system of folds and thrusts for a lateral distance of at least 180 km, and by the continuous anticlinorium of the Santa Ynez Range, which comprises the “backbone” of the rooted thrust system (Figure 1). This is also supported by seismic imaging in the offshore (Fisher et al., 2009; Sorlien and Nicholson, 2015), where a nearly identical structural style for the frontal thrust system is evident for the length of the offshore WTR. The continuous fold structure of the Santa Ynez Mountains argues that the fault structure at seismogenic depth may be much simpler than the complex fault array in the upper few kilometers. In fact, if the observations of large displacement are correct, a typical simpler fold and thrust fault structure at depth makes sense. This kind of structure seems to be in agreement with the first order observations of topographic and stratigraphic relief (Figure 3, 4 and 5), as topography is being built to the north, which requires that the dominant vergence is to the south.

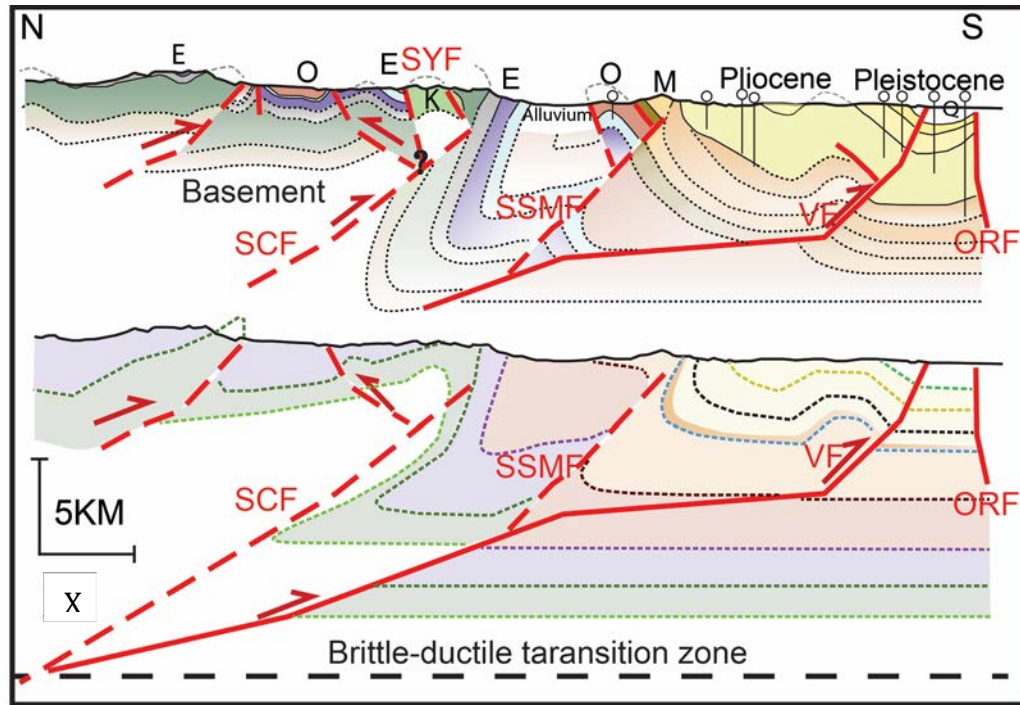


Figure 3. Comparison between data (upper cross section) and forward model (lower cross section) for cross section 2 (Figure 1) showing a good first order match between the two. Interpretation of the deeper data part is based on stratigraphic thickness from maps and Dibblee (1982). Ages are specified with black letters K - Cretaceous, E - Eocene, O - Oligocene, M - Miocene. Faults are specified with red letter: SCF - San Cayetano fault, SYF - Santa Ynez fault SSMF - South Sulfur Mountain fault, VF - Ventura fault, ORF - Oak Ridge fault. Black dashed line marks the brittle-ductile transition zone.

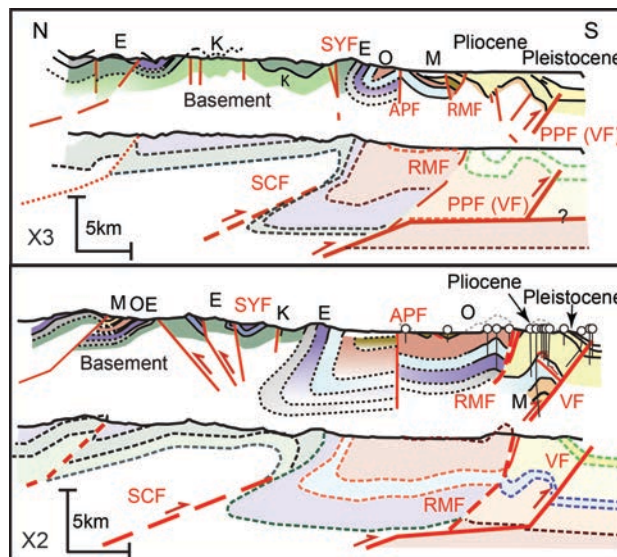


Figure 4. Comparison between data (upper cross section) and forward model (lower cross section) for cross section 3 and 4 (Figure 1) showing a good first order match between the two. For ages abbreviations see Figure 3. SCF - San Cayetano fault, SYF - Santa Ynez fault, RMF - Red Mountain fault, VF - Ventura fault, PPF - Pitas Point fault APF - Arroyo Parida fault.

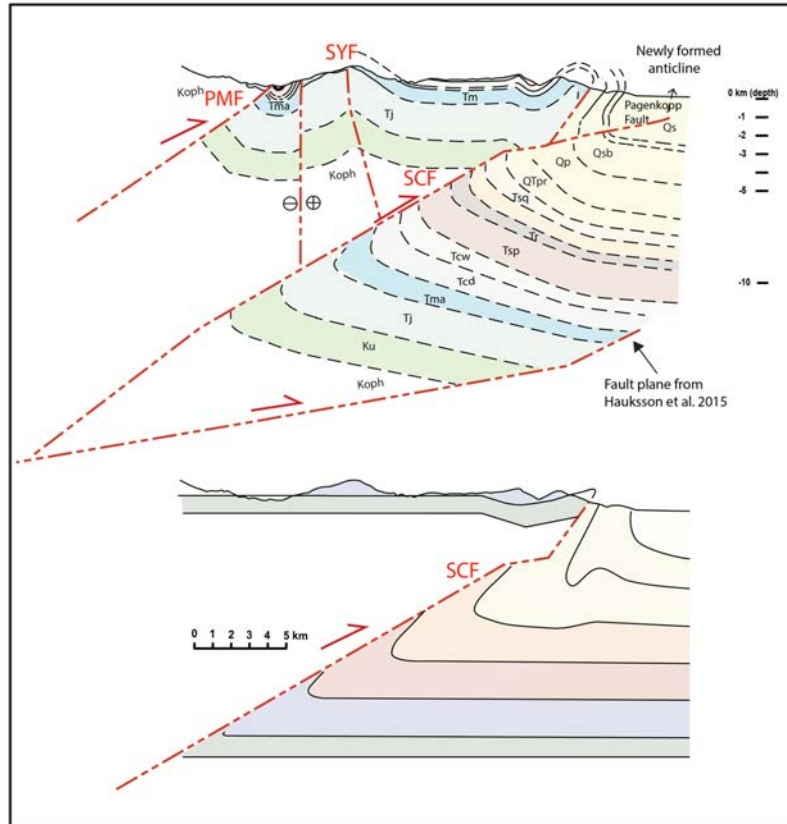


Figure 5. Comparison between data (upper cross section) and forward model (lower cross section) for cross section 1 (Figure 1) showing a good first order match between the two. SCF – San Cayetano fault, SYF – Santa Ynez fault, RMF – Red Mountain fault, PmF – Pine Mountain fault.

These sections are drawn through the southern thrust front (the Ventura/Pitas Point thrust and associated hanging wall anticline (Ventura Avenue anticline trend), the Red Mountain fault and its associated hanging wall fold, the Rincon Creek “back-thrust” fault, the Santa Ynez anticlinorium, and other structures to the north.

Our recent results were presented in poster sessions at the SCEC 2017 and SAA 2018 annual meeting. In addition, we submitted a paper to *Geology* and it is being reviewed (Levy et al., In review). The SCEC publication number is 8054.

We have already started applying this and similar models, in collaboration with John Shaw’s group, to explain the complex structures in the hanging wall of the thrust sheet. We are also about to begin testing the model against geodetic data in collaboration with Scott Marshall.

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4. Exemplary image:

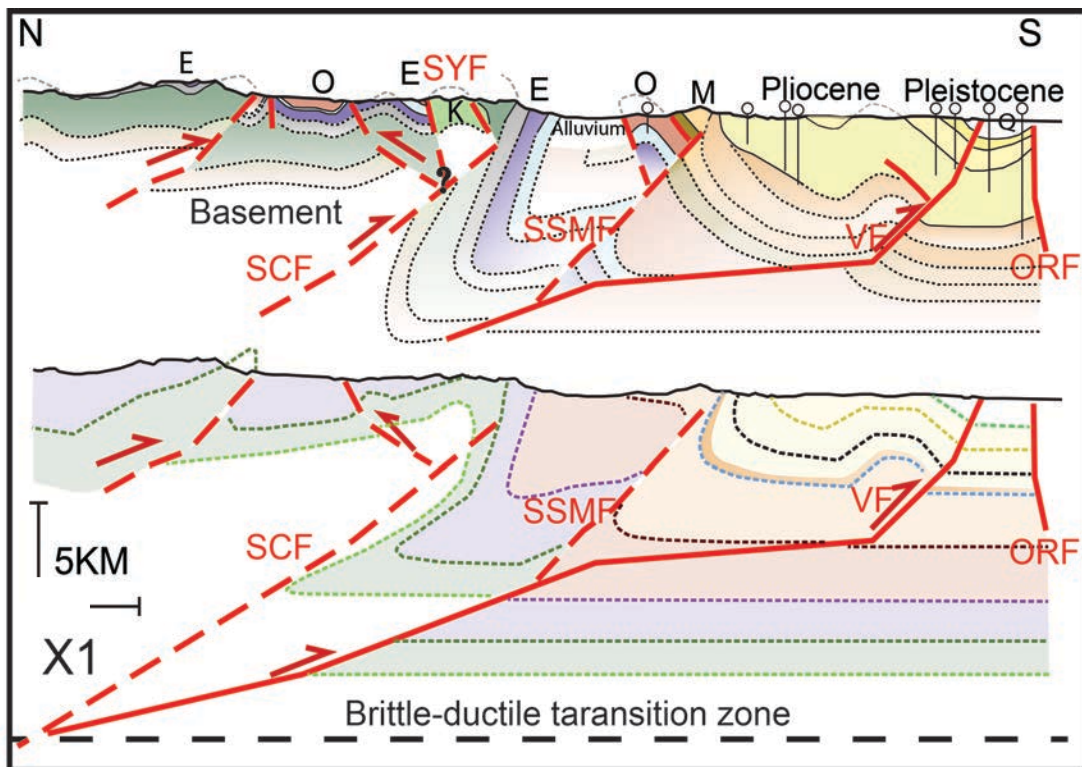


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5. Information on intellectual merit and impact:

The results of this work will provide a more consistent 3D model of the entire western Transverse Ranges for inclusion in the SCEC CFM, thereby providing a platform for modeling earthquakes in the Western Transverse Ranges. By doing so it will have a direct impact on an area in California which is inhabited by two million people. An additional contribution is the furthering of our understanding the 4D evolution of this region. A manuscript was submitted to Geology and is now in Review (Levy et al., In review).

6. List of presentations:

Conference name	Year	Location	Title	Type
Seismological Society of America annual meeting	2018	Miami, Florida, United States of America.	Subsurface Structure of the Western Transverse Ranges and Potential for Large Earthquakes - Trishear Forward Model	Poster
Southern California Earthquake Center annual meeting	2017	Palm Springs, California, United States of America.	Subsurface Structure of the Western Transverse Ranges and Potential for Large Earthquakes - Trishear Forward Model	Poster
Southern California Earthquake Center annual meeting	2016	Palm Springs, California, United States of America.	Subsurface Structure of the Western Transverse Ranges and Potential for Large Earthquakes	Workshop talk
Southern California Earthquake Center annual meeting	2016	Palm Springs, California, United States of America.	Subsurface Structure of the Western Transverse Ranges and Potential for Large Earthquakes	Poster
Seismological Society of America annual meeting	2016	Reno, Nevada, United States of America.	Activation of Dead Thrust Faults and Formation of Stable Back Thrust due to Back Limb Rotation after Thrust-Front Propagation: An Example from the Western Transvers Ranges, Southern California	Poster
American Geophysical Union annual meeting	2015	San Francisco, California, United States of America.	Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes	Poster

Submitted Manuscript: Levy, Y., Rockwell, T.K., Shaw, J.H., Plesch, A., Driscoll, N.W., and Parea, H., 2018 in review Structural Modeling of the Western Transverse Ranges: An Imbricated Thrust Ramp thrust Architecture? Submitted to Geology, may 2018,. (SCEC #8054)