2016 SCEC Report
Award Number 16049

Crustal Architecture of the Western Transverse Ranges, Southern California

Principle Investigator:

Thomas Rockwell
San Diego State University

TOTAL AMOUNT OF GRANT: $25,000

PROPOSAL CATEGORY: **C. Ventura SFSA**
DICIPLINARY ACTIVITY: **Earthquake Geology**
SCIENCE OBJECTIVES: **1a, 4a, 4b, 4c**

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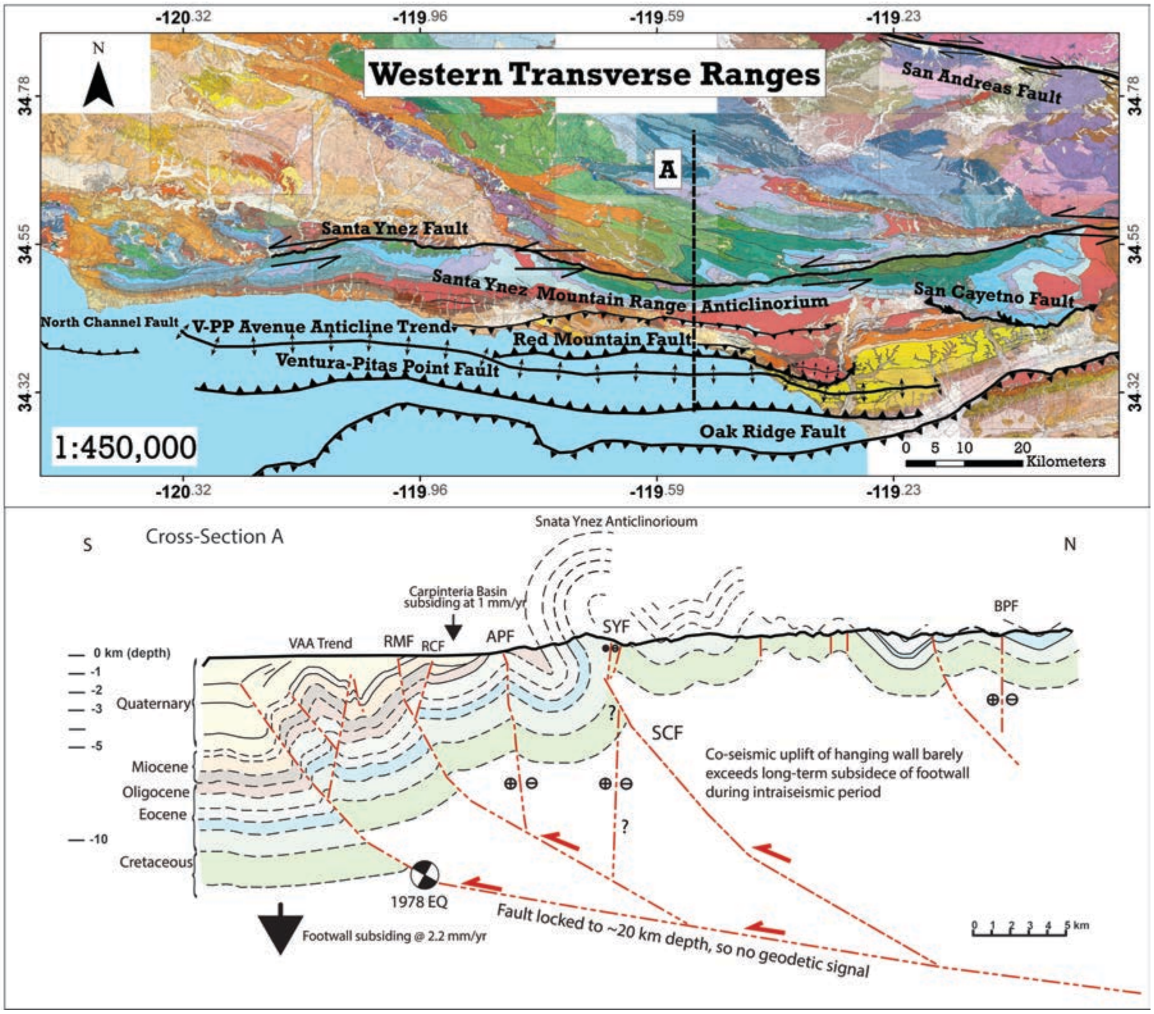
1. Abstract:

The deep 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, which will be in agreement with the full range of geologic, geodetic, and seismicity data. For achieving this goal we constructed several preliminary cross-sections by compiling data and reviewed existing models. We then expanded these sections based on regional geologic mapping. These cross sections will be used with additional surface data to interpolate the 3D model. Our current interpretation is that the WTR, during the period of shortening, developed thrust fronts which propagated southward in time, similar to other fold-and-thrust belts worldwide. We interpret the nearly continuous overturned Tertiary stratigraphy of the Santa Ynez Mountains as a large anticlinorium that formed as an early 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. We further suggest that the steep dip angle and continued activity of the Red Mountain fault, as observed near the surface, is a result of northward rotation of the fault in the backlimb of the Ventura Avenue anticline, which has caused it to flexurally slip in the near surface. The northward rotation is also responsible for continued folding to the north (Ayers Creek syncline) and back thrusting on the hanging wall of the Red Mountain fault (Arroyo Parida fault).

2. Exemplary image:



Map of the western Transverse Ranges showing the Santa Ynez Mountains anticlinorium, a continuous upright to overturned fold that extends from Point Conception to Fillmore. The continuity of the fault requires a continuous fault at depth, which is blid except where the San Cayetano is emergent in the east. The lower panel is a preliminary crustal-scale cross-section (location in the top panel). Compiled in MOVE (of Midland Valley) using surface geology (1986 Dibblee maps), offshore seismic data (USGS seismic survey repository), and well data (from Jackson and Yeats, 1982). Note the very large overturned anticline that comprises the Santa Ynez Mountains. This continuous fold strongly demonstrates that the deep thrust ramp is a continuous structural feature, and that it is located beneath (now north of) the Santa Ynez Mountains. This provides a framework within which to construct a series of balanced, kinematically consistent cross-sections from which the 3-dimensional character of the North Channel – Pitas Point – Ventura – San Cayetano thrust can be characterized and implemented in the SCEC CFM.

3. Technical report:

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Summary of the Work Done During 2016

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; Rockwell et al., 2016; McAuliffe et al., 2015), 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.

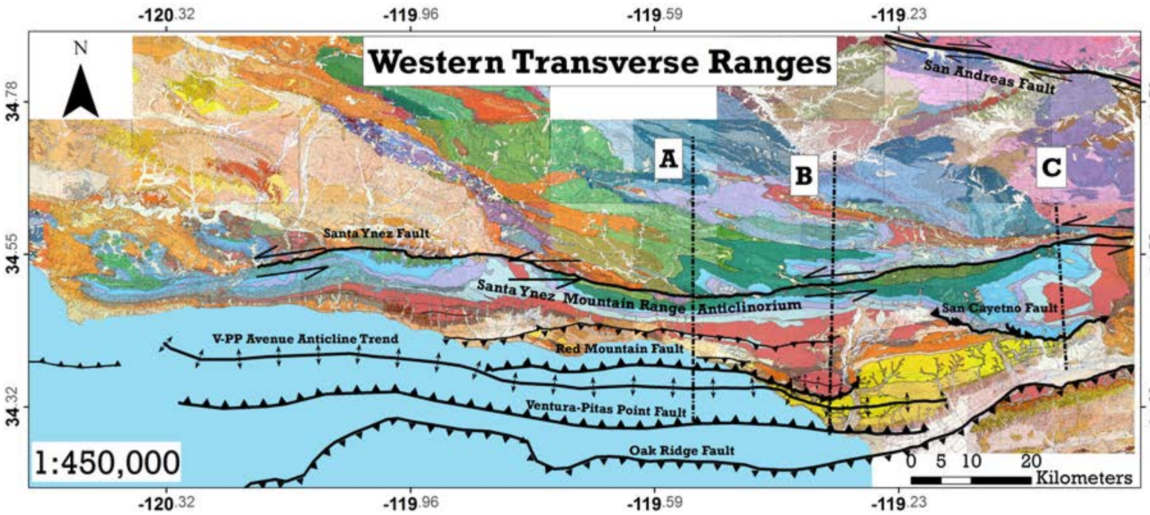

Figure 1. *Geology and structure of the western Transverse Ranges (WTR) in southern California (from Dibblee's maps (1986), with the offshore locations of faults and folds from Sorlien and Nicholson, 2015). Note the continuity of Tertiary stratigraphy along the Santa Ynez anticlinorium, which forms the backbone of the WTR. It also demonstrates the continuity of the deep thrust system. Locations of completed cross-section in year 1 are marked as dashed lines and presented in figure 2.*

Over the past year, Ph.D. student Yuval Levy has constructed a number of preliminary cross sections (Figure 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 and other rivers (Rockwell et al., 1984; 1988; Rockwell, 1988), uplift of marine terraces along the length of the coast (Rockwell et al., 1992; Metcalf, 1994; 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 preliminary results were presented in poster sessions at the AGU annual meeting 2015, SSA 2016 and SCEC 2016. In addition, at the SFSA workshop during SCEC 2016, Yuval gave a 15 minute presentation of his work.

Details of the results we present here will change as we progress, as the sections are not fully retrodeformable yet. However, our understating of this fault system has progressed and 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 (Figure 2). 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 2), as topography is being built to the north, which requires that the dominant vergence is to the south.

Our initial 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. 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. The hanging wall of the Rincon Creek fault is rising at about 1 mm/yr at Carpinteria (fig. 2A), based on the 45-50 ka marine terrace passing through sea level in downtown Carpinteria (Jackson & Yeats, 1982); the terrace was cut at about 50 m below sea level (Bloom et al., 1974). In contrast, the Carpinteria basin is subsiding at about 1.2 mm/yr (Simms et al., 2016), indicating a slip rate for the fault of about 2.2 mm/yr. The mere fact that the basin is subsiding and yet lies in the hanging wall of the thrust sheet requires explanation, and our currently favored hypothesis is that the offshore Ventura-Santa Barbara basin is subsiding at a much faster rate, known to be in the 2-3 mm/yr range, such that the entire thrust front remains below sea level. The sedimentation rate in the offshore of Carpinteria is high, with about 5 km of Quaternary sediment, which implies a long-term subsidence rate of about 2.5 mm/yr. To the east in central Ventura basin, the rate is even higher, with 3-4 km of sediment accumulated in the past 1 Ma (3-4 mm/yr)(Yeats, 1983; Rockwell, 1988). Any reliable model must account for these types of observations and be kinematically consistent along the length of the fold and thrust belt. In addition to the frontal thrust, the Red Mountain fault continues to show late Quaternary activity, in spite of its steep dip of 70^{o}. This may be explained by virtual of the observation that it rides in the backlimb of the Ventura Avenue anticline, which has been rotated by about 40^{o}. Considering that the Red Mountain fault must also be rotated by a similar amount, this explains both its continued activity due to flexural slip as well as its steep dip.

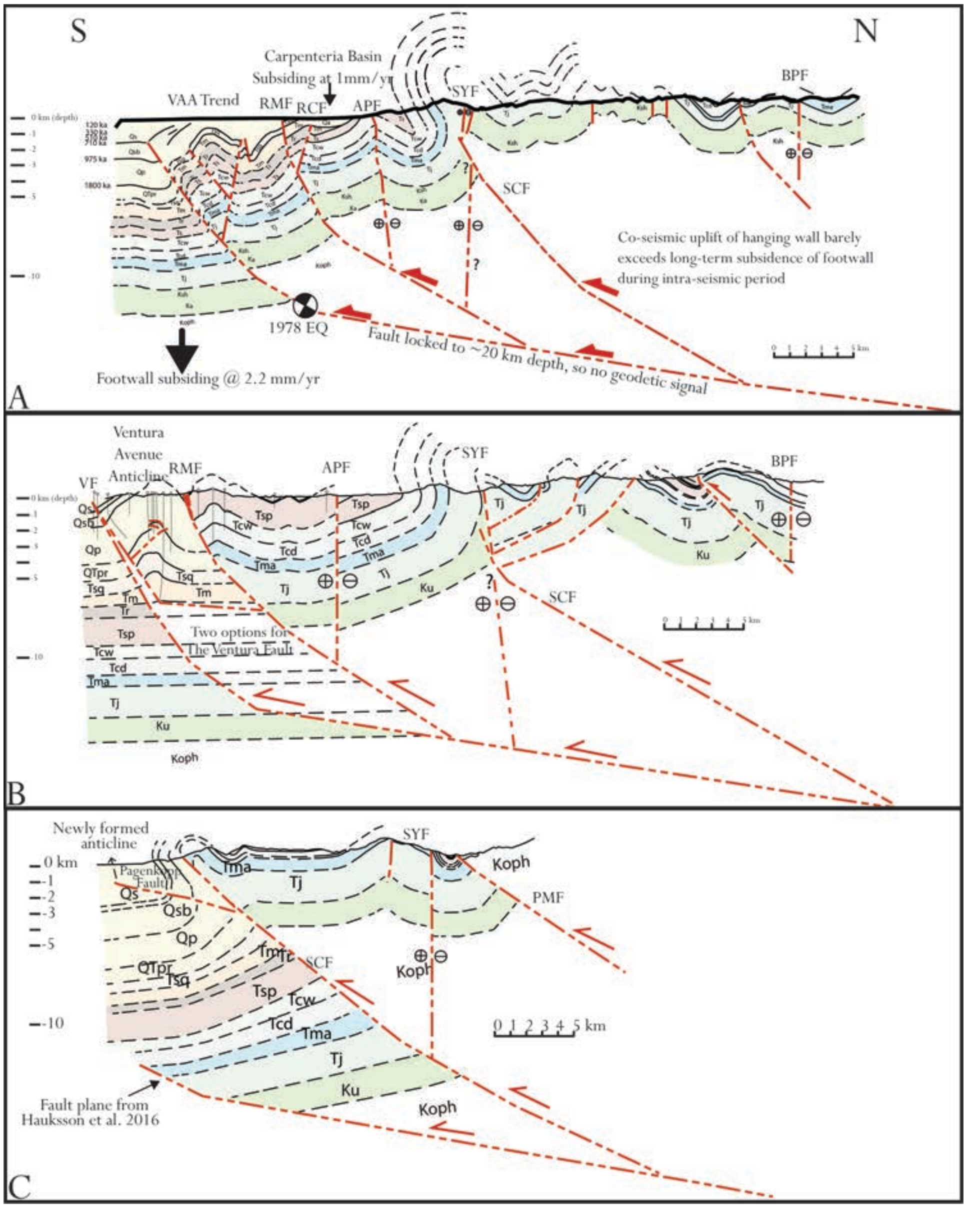

Figure 2. *Preliminary crustal-scale cross-sections (location on figure 1). Compiled in MOVE (of Midland Valley) using surface geology (1986 Dibblee maps), offshore seismic data (USGS seismic survey repository), and well data (from Jackson and Yeats, 1982; Isaacs, 1992). Note the very large overturned anticline that comprises the Santa Ynez Mountains. This continuous fold (Figure 1) strongly demonstrates that the deep thrust ramp is a continuous structural feature, and that it is located beneath (now north of) the Santa Ynez Mountains. This provides a framework within which to construct a series of balanced, kinematically consistent cross-sections from which the 3-dimensional character of the North Channel – Pitas Point – Ventura – San Cayetano thrust can be characterized and implemented in the SCEC CFM.*

The back thrusts are a particular problem, as they seem to have been in a stable position for the past couple of hundred thousand years in the Santa Barbara area (More Ranch fault) and Carpinteria area (Rincon Creek fault). Back-thrusts have been modeled as resulting from fault bends (Mitra, 2002) or from a wedge thrust (Medwedeff, 1989, 1992), but neither apply in the case of the More Ranch and Rincon Creek faults, and eastward to the Arroyo Parida fault. We invoke a geology-based model that these back-thrusts result from a space problem when the thrust front propagates south and folding above the new frontal thrust deforms older structures in its back-limb. In the cross-sections (Figure 2 A and B), folding of the back-limb of the Ventura Avenue anticline forces the Red Mountain fault to steepen, resulting in flexural slip long the fault, and this also results in the formation of a stationary back-thrust north of the Red Mountain fault (Figure 3). This suggested model explains the observations of Rockwell et al. (1984) of Holocene folding south the Arroyo Parida and uplift without tilting to the north of it.

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, which will then allow for retrodeformation of the cross-sections through time.

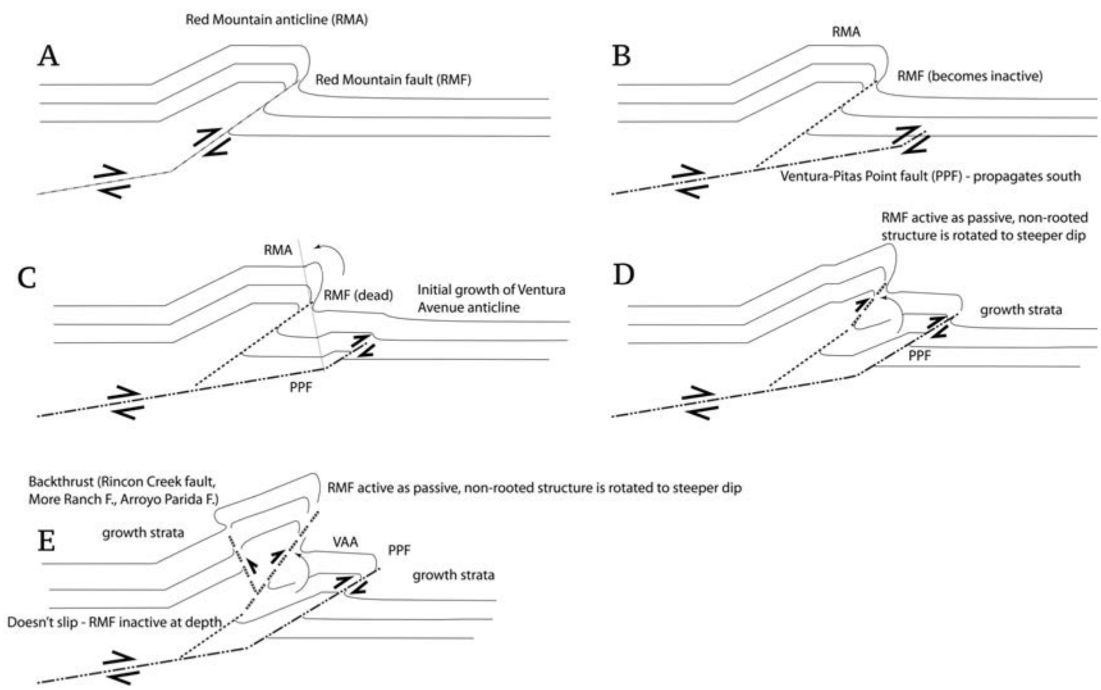

Figure 3. *Evolutionary model to explain the observation of spatially stable back-thrusts in the Santa Barbara fold belt using FaultFold Forward v. 6 (Allmendinger, 2014). In this model, the Red Mountain fault (RMF) was the earlier representation of the thrust front. Once the thrust propagated south, the RMF was forced to rotate northward in the back-limb of the growing Ventura Avenue anticline, which resulted in the formation of a back-thrust. The RMF continued to slip at the surface due to the rotation (flexural slip), but is cut off from the primary fault at depth. A generalized version of this model explains the presence and activity of the Arroyo Parida fault and other high-angle back-thrusts that now accommodate strike slip in the hanging wall due to slip partitioning.*

References Cited

Allmendinger, R.W. (2014) FaultFold Forward v.6. @geo.cornell.edu/geology/faculty/RWA/programs/faultfoldforward.html

Dolan, J.F. and T.K. Rockwell (2001). Paleoseismologic evidence for a very large (Mw>7), post-1660 A.D. surface rupture on the eastern San Cayetano fault, Ventura County, California: Was this the elusive source of the damaging December 21, 1812 earthquake? *Bull. Seismo. Soc. Am.*, **91** (6), 1417-1432.

Fisher, M.A., C.C. Sorlien, and R.W Sliter (2009). Potential earthquake faults offshore southern California, from the eastern Santa Barbara Channel south to Dana Point, Geol. Soc. Am. Spec. Pap. **454**, 271-290.

Gurrola, L.D. (2005). Active tectonics and earthquake hazards of the Santa Barbara fold belt, California

[unpub. Ph.D. thesis]: Santa Barbara, University of California, 206 p.
Gurrola, L.D., and M. Kamerling, (1996). Role of cross faults as tears in thrust ramps in the Ventura and Santa Barbara Fold Belts, California, SCEC Annual Meeting Abstr. p. 49.
Gurrola, L.D., J.H. Chen, E.A. Keller, and J.G. Metcalf (1996). Dating of emergent marine terraces and rate of uplift for the western Santa Barbara Fold Belt, California: Geol. Soc. Am. Abstr. with Prog., **28** (7), A-301.
Gurrola, L.D., Chen, J.H., and Keller, E.A. (1997). Uranium series age and rate of uplift of the Mesa marine terraces, Santa Barbara Fold Belt, California: Southern California Earthquake Center Annual Meeting, October 1997, p. 64.
Gurrola, L.D., E.A. Keller, J.H. Chen, L.A. Owen, and J.Q. Spencer (2014). Tectonic geomorphology of marine terraces: Santa Barbara fold belt, California, *Geol. Soc. Am. Bull.* **126** (1-2), 219-233.
Hubbard, J., J.H. Shaw, J. Dolan, T. Pratt, L. McAuliffe, and T.K. Rockwell **(**2014). Structure and seismic hazard of the Ventura Avenue anticline and Ventura fault, California: Prospect for large, multi-segment ruptures in the western Transverse Ranges. Bull. Seismo. Soc. Am., **104** (3), 1070-1087. doi: 10.1785/0120130125
Hauksson, E., Andrews, J., Plesch, A., Shaw, J. H., & Shelly, D. R. (2016). The 2015 Fillmore Earthquake Swarm and Possible Crustal Deformation Mechanisms near the Bottom of the Eastern Ventura Basin , California. *Seismological Research Letters*, *87*(4).
Isaacs, C.M. (1992). Preliminary petroleum geology background and well data for oil samples in the cooperative Monterey organic chemistry study, Santa Maria and Santa Barbara-Ventura basins, California, U.S.G.S. Open File Report 92-539F, 40 p.
Jackson, P.A. and R.S. Yeats (1982). Structural evolution of Carpinteria basin, western Transverse Ranges, California, *AAPG Bulletin* **66** (7), 805-829.
Marshall, S.T., G.J. Funning, and S.E. Owen (2013). Fault slip rates and interseismic deformation in the western Transverse Ranges, California, *J. Geophy. Res.* **118**, 1-24.
McAuliffe, L.J., J.F. Dolan, E.J. Rhodes, J. Hubbard, J.H. Shaw, and T.L. Pratt (2015). Paleoseismologic evidence for large-magnitude (Mw 7.5-8.0) earthquakes on the Ventura b;lind thrust fault: Implications for multifault ruptures in the Transverse Ranges of southern California, Geosphere **11** (6), doi:10.1130/GES01123.1
Medwedeff, D. A. (1989). Growth fault-bend folding at southeast Lost Hills, San Joaquin Valley, California, *Am. Assoc. Pet. Geol. Bull.* **73**, 54–67.
Medwedeff, D.A., 1992. Geometry and kinematics of an active, laterally propagating wedge thrust, Wheeler Ridge, California. In: Mitra, S., Fisher, G.W. (Eds.), Structural Geology of Fold-and-Thrust Belts. Johns Hopkins University Press, Baltimore, MD, pp. 3–28.
Metcalf, J.G. (1994). Morphology, chronology, and deformation of Pleistocene marine terraces, southwestern Santa Barbara County, California, unpublished M.A. thesis, University of California, Santa Barbara, 167 p.
Mitra, Shankar (2002) Fold-accommodation faults. *Am. Assoc. Petr. Geol. Bull.* **86** (4) 671-693.
Namson, J. (1987). Structural transect through the Ventura basin and western Transverse Ranges, in Structural Evolution of the Western Transverse Ranges, Guidebook 48A. Pacific Section, T. L. Davis (Editor), Society Economic Paleontologists and Mineralogists, Los Angeles, California, 29–41.
Namson, J., and T. Davis (1988). Structural transect of the western Transverse Ranges, California: Implications for lithospheric kinematics and seismic risk evaluation, Geology **16**, 675–679.
Rockwell, T.K., E.A. Keller, and M.N. Clark (l984). Chronology and rates of faulting of Ventura River terraces, California, *Geol. Soc. Am. Bull.*, **95**, 1466-1474.
Rockwell, T.K. (1988). Neotectonics of the San Cayetano fault, Transverse Ranges, California: *Geol. Soc. Am. Bull.*, **100** (4), p. 500-513.
Rockwell, T.K., E.A. Keller, and G.R. Dembroff (1988). Quaternary rate of folding of the Ventura Avenue anticline, western Transverse Ranges, southern California: *Geol. Soc. Am. Bull.*, **100** (6), 850-858.

Rockwell, T. K., Nolan, J. & Ana, S. (1992). Ages and deformation of marine terraces between Point Conception and Gaviota Western Transverse Ranges California. SEPM Spec. Publ. 333–341.

Rockwell, T.K., K. Wilson, L. Gamble, M. Oskin, E. Haaker, and G. Kennedy (2016). Large Transverse Ranges earthquakes cause coastal upheaval near Ventura, southern California, *Bull. Seismo. Soc. Am*.

Ryan, K.J., E.L. Geist, M. Barall, and D.D. Oglesby (2015). Dynamic models of an earthquake and tsunami offshore Ventura, California, *Geophys. Res. Ltrs.* **42**, doi: 10.1002/2015GL064507.

Simms, A., Reynolds, L. C., Bentz, M., Roman, A., Rockwell, T., & Peters, R. (2016). Tectonic Subsidence of California Estuaries Increases Forecasts of Relative Sea-Level Rise. *Estuaries and Coasts*, *39*(6), 1571–1581. article. http://doi.org/10.1007/s12237-016-0105-1

Sorlien, C.C., J-P Gratier, B.P. Luyendyk, J.S. Hornafius, and T.E. Hopps (2000). Map restoration of folded and faulted late Cenozoic strata across the Oak Ridge fault, offshore Ventura basin, California, *Geol. Soc. Am. Bull.* **112** (7), 1080-1090.

Sorlien, C.C. and C. Nicholson (2015). Post-1 Ma deformation history of the Pitas Point-North Channel-Red Mountain fault system and associated folds in the Santa Barbara Channel, California, Final Technical Report for USGS grant G14AP00012, 24 p.

4. Intellectual Merit and Broader Impact:

The potential for great earthquakes in the Western Transverse Ranges is a critical question to resolve, as such an earthquake would likely produce broad regional damage, including in the Los Angeles Basin. The results of this work will be incorporated into the SCEC CFM, to be used to model the observed deformation field in the Western Transverse Ranges. An additional contribution will be furthering the understanding of the geologic evolution of the Western Transverse Ranges, as well as fold and thrust belts worldwide. This project supports one Ph.D. student (Yuval Levy).

5. List of publications:

- Invited talk: Levy, Y., Rockwell, T.K., Shaw, J.H., Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes. Southern California Earthquake Center annual meeting 2016 – SFSA Workshop.
- Levy, Y., Rockwell, T.K., Shaw, J.H., 2015. Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes. Poster presented at: Southern California Earthquake Center annual meeting 2016. Poster number: 082.
- Levy, Y., Rockwell T.K., Activation of dead thrust faults and formation of stable back thrusts due to back limb rotation after thrust-front propagation: an example from the Western Transverse Ranges, southern California. Poster presented at: Seismological Society of America annual meeting, 2016. Abstract number: 16-294.
- Levy, Y., Rockwell, T.K., Shaw, J.H., Driscoll N.W., Kent G.M., Ucarkus, G., Structural Architecture of the Western Transverse Ranges and Potential for Large Earthquakes. Poster presented at: American Geophysical Union annual meeting, 2015. Abstract number: 67800.