2021 SCEC Report

Developing comprehensive alternative CFM representations of active thrust systems in the Santa Barbara Channel and Ventura basins, Western Transverse Ranges

SCEC Award 21009

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Summary
We developed a comprehensive 3D representation of the active blind-thrust and reverse fault systems in the Santa Barbara Channel and Ventura basin for inclusion in the Community Fault Model (CFM). SCEC has made important contributions to our understanding of the prospect for large, multi-segment thrust fault earthquakes in the Transverse Ranges and the hazards these events pose to the coastal populations of southern California. In particular, emphasis has been placed on the Ventura-Pitas Point thrust system, and its interaction with the Red Mountain, San Cayetano, and other active structures in the southern Transverse Ranges (Hubbard et al., 2014; McAuliffe et al., 2015; Grenader et al., 2015; Sorlien et al., 2015; Rockwell et al., 2016; Marshall et al., 2017; Perea et al., 2017; Levy et al., 2019; Don et al., 2020, 2021). Our SCEC sponsored work in 2021 involved new analyses of geologic and geophysical datasets to refine our understanding of the 3D geometry and slip rates on these faults. We have integrated these results along with that of other SCEC investigators (Hubbard et al., 2014; Levy et al., 2019; Don et al., 2020, 2021) into a new, geometrically and kinematically viable 3D representation for the Ventura-Pitas Point, Midchannel, Red Mountain, Lion, Cayetano, and Southern San Cayetano faults. Collectively, these faults pose one of the largest deterministic seismic hazards in southern California, with some of the fastest Holocene uplift and slip rates in the Transverse Ranges, and evidence that they sourced large (M ≥ 7.5) paleoearthquakes (McAuliffe et al., 2015; Grenader et al., 2015; Rockwell et al., 2016). Our new fault model is currently under review as part of the CFM 5.3 evaluation, and based on the outcome of this assessment will be considered as the preferred or an alternative representation in CFM 6.0. This reflects the final culmination of our SCEC sponsored research on this fault system.

Background
The Western Transverse Ranges has long been recognized as an active fold-and-thrust belt formed by the "big bend" in the San Andreas fault. While historic thrust and reverse fault earthquakes (e.g., 1971 San Fernando M 6.6; 1994 Northridge M 6.7) and paleoseismic studies have documented the activity of many of the structures in this region, others were less well understood (Figure 1). Moreover, the subsurface geometry and potential linkages of these faults was largely unknown, limiting our ability to consider them in comprehensive regional hazard assessments. The Ventura fault represented one of the least understood of these features. The fault is overlain by the Ventura Avenue anticline, one of the fastest uplifting structures in southern California (Rockwell et al., 1988). However, the prevailing view less than a decade ago was that the Ventura fault represented a shallow structure that extended only a few hundred meters deep, and thus posed no significant hazard (e.g., Yeats, 1982). As a result, it was not included in early versions of the SCEC CFM. Recent efforts by SCEC investigators, in contrast, have come to a markedly different conclusion. Hubbard et al., (2014) showed that the blind Ventura fault extends from the southern margin of the fold to the base of the seismogenic crust through a north-dipping, ramp-flat-ramp geometry that is linked at depth to several of the largest and fastest slipping faults in the Transverse Ranges, including the Pitas Point, Red Mountain, and San Cayetano faults (Figure 1). Mechanical models have subsequently shown this architecture to be consistent with the geodetically observed surface deformation patterns (Marshall et al., 2017). Re-analysis of the Holocene marine terraces above the Ventura Avenue anticline suggest that it deforms in discrete 7-9 m uplift events, with the latest event occurring ~950 years ago (Rockwell et al., 2011; 2016). These are inferred to represent large (M ≥ 7.5) earthquake on the Ventura fault. Recent excavations across the fold scarp confirm this view, showing evidence for at least two large-displacement (4.5 to 6m uplift) paleo-earthquakes in the Holocene that appear to correlate with uplift of marine terraces along the coast (McAuliffe et al., 2015; Grenader et al., 2015). Geophysical studies of the larger fault system that extends offshore also document discrete Holocene seafloor deformation (Ucarkus et al., 2013; Perea et al., 2017). Finally, geodetic observations (GPS, InSAR, and leveling studies), and fault system models indicate rapid shortening (2.7 to 8 mm/year) and uplift (> 2 mm/yr) rates across portions of this structure (Burgette et al., 2015; Marshall et al., 2013; Marshall et al., 2017). Together, these results

support the heightened activity of the Ventura-Pitas Point fault, and its role in accommodating large thrust fault earthquakes in conjunction with other faults in the southern Transverse Ranges.

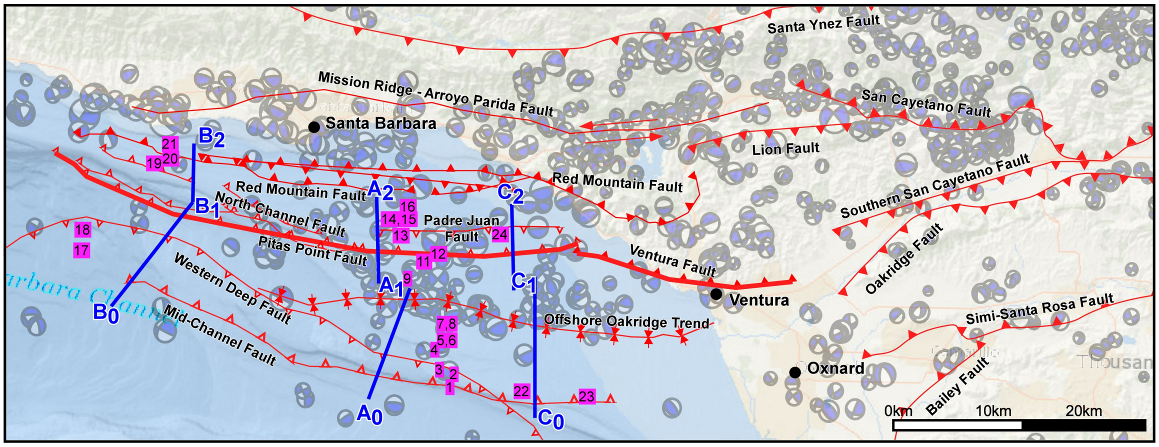

Figure 1: Map showing locations of major faults in the Ventura basin and Santa Barbara Channel, including the Ventura-Pitas Point, Southern San Cayetano, and Mid-Channel faults. The cross section shown in Figure 2 is indicated by blue trace A-A^2. Other sections are included in Don et al., (2021). Surface fault traces from Community Fault Model 5.3 (Plesch et al., 2016). Numbers are wells used for stratigraphic control in cross sections and 3D models (see Figure 2).

The magnitude of the inferred earthquakes involving the Ventura fault requires that it ruptures in conjunction with other faults in the Western Transverse Ranges. The most likely candidates for this linkage are the San Cayetano fault system to the east and the Pitas Point fault system to the west. Hubbard et al., (2014) proposed that the Ventura and San Cayetano faults share the same mid-crustal ramp and are therefore directly linked at seismogenic depths, despite a ≈ 10 km offset of the surface traces of these faults. This linkage occurs because the aforementioned non-planar fault geometry – with the Ventura fault dipping steeply northward from its surface trace, soling to a detachment in the Monterey-Rincon shale, then dipping northward on a lower crustal ramp (Hubbard et al., 2014; Levy et al., 2019). Levy et al. (2019) further documented the subsurface geometry and interaction of this and other regional fault systems, defining an imbricated, generally break-forward thrusting sequence that is consistent with the evolution of many comparable fold-and-thrust belts. Hubbard et al. (2014) also noted the likely connection between the Ventura fault with the offshore Pitas Point fault to the west, consistent with the along strike continuity of the overlying anticlinal structures (Sorlien et al., 2015). Recent marine geophysical studies have further documented the activity of the offshore Pitas Point fault but have also noted that displacement systematically decrease westward (Perea et al., 2018, 2019). This suggests two possibilities. First, many events that occur on the Ventura fault may not extend offshore or, if they do, would release significantly less slip, on average, than the onshore part of the fault system. This would have major implications for the tsunami hazards associated with the fault, as well as for other aspects of our understanding of fault system behavior and earthquake hazards in the region. A second alternative is that some large, multi-segment ruptures do not involve the Pitas Point fault above the mid-crustal detachment. Rather, slip on the detachment may approach the surface on another structure. Our research sought, in part, to address these questions, and results are described in the following section.

Results

Our work has focused on analysis of 2- and 3-D industry seismic reflection data and extensive well control, including dipmeter logs and horizon tops, to constrain the geometry and kinematics of the Ventura-Pitas Point and Mid-Channel thrusts (Redin et al., 1998; Shaw and Suppe, 1994; Sorlien et al., 2015; Don et al., 2019, 2020). Based on these data constraints, we generated a series of balanced cross sections using both inverse and forward modeling based on fault-related folding theories. One of these sections is shown in Figure 2. These sections demonstrate that the offshore fold geometries are consistent with a ramp-flat-ramp geometry for the Pitas Point fault, with the mid-crustal flat located in the Miocene Monterey/Rincon shales. This geometry is nearly identical to that of the onshore Ventura fault (Hubbard et al., 2014), and thus supports the proposed linkage of the Ventura and Pitas Point faults.

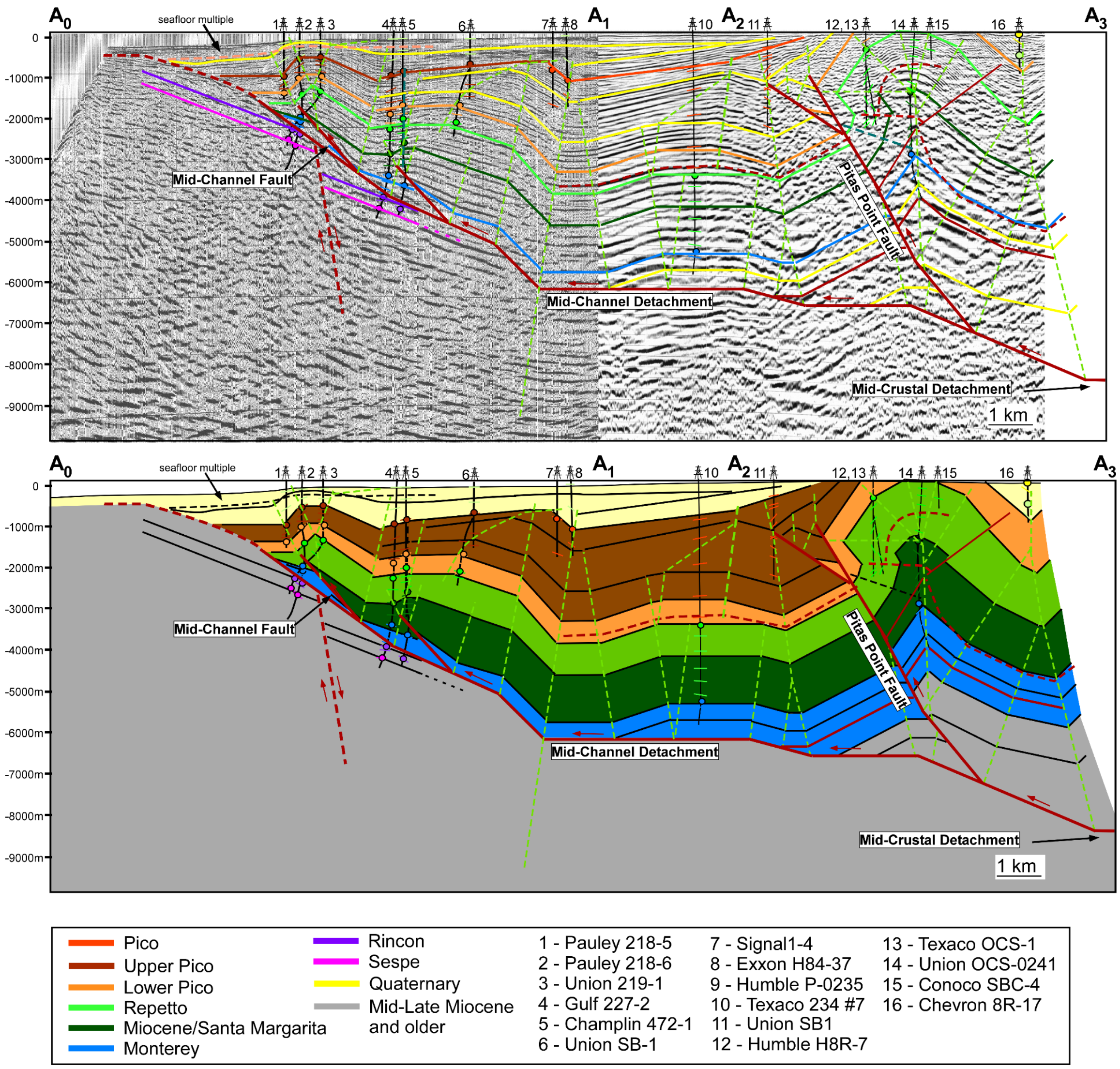

Figure 2: Cross section showing offshore geometry of the Pitas Point fault system and its linkage with the Mid-Channel fault system (location Figure 1). A) Seismic reflection profile showing data projected from nearby wells. Dip changes, cutoffs, and discontinuous reflectors constrain the location of the Mid-Channel and Pitas Point thrusts. B) Interpretation of Dos Cuadras anticline / Pitas Point fault, Pitas Point anticline / Mid-Channel fault, and Mid- Channel anticline / Mid-Channel fault. Red lines are faults, with arrows indicating slip sense. Dark blue-green dashed lines are axial surfaces. Horizons colored based on stratigraphy (see legend). Dashed red lines are inactive faults or bedding parallel thrusts.

We recognize, however, that there is an important distinction between the onshore (Ventura) and offshore (Pitas Point) character of the fault systems. While all of the slip on the onshore fault system extends upward along the Ventura fault ramp, a significant amount of the slip on the offshore mid-crustal detachment extends south of the Pitas Point fault. Specifically, Don et al., (2019; 2021; 2022) proposed that the slip on this detachment extends toward the seafloor along the Mid-Channel thrust where it is consumed by a south-vergent, fault-propagation fold (Mid-Channel anticline) (Figure 2). Based on analysis of nine Pleistocene horizons ranging in age from 120 ka – 1.05 Ma (e.g. Kennett and Ingram, 1995; Hopkins, 2006; Nicholson et al., 2006; Marshall, 2012; White et al., 2013; Dean et al., 2015; Behl *et al.*, 2016), we use patterns of uplift in the Mid-Channel anticline to define that the fault became active at 650 ka (510-710 ka). This analysis yielded a 2.1 ± 0.2mm/yr slip rate on the Mid-Channel fault, which suggests that it may accommodate about one third of the observed geodetic contraction across the basin (Don et al., 2022).

Don et al., (2019; 2022) proposed three alternative architectures for the Mid-Channel fault at depth, based on possible modes of interaction with the adjacent Offshore Oak Ridge, Western Deep, and Ventura-Pitas Point faults. The mapped detachment level for the Mid-Channel fault within the Miocene Monterey-Rincon shales is identical to that inferred for the crustal detachment (flat) in the Ventura-Pitas Point system. This provides a mechanism to link the two fault systems, whereby slip that is fully consumed by the onshore Ventura fault would be partitioned offshore between the Pitas Point and Mid-Channel faults (Figures 1 & 2). This offers an explanation for the apparent decrease in recent activity and slip rate on the Pitas Point fault (Nicholson, 2017; Perea et al., 2018, 2019), despite its clear linkage with the onshore Ventura fault. Specifically, some earthquake ruptures may have all of the displacement extend upward along the Pitas Point fault, whereas others may partially or completely bypass the Pitas Point fault and send displacement to the south along the detachment to the Mid-Channel fault. This would result in a lower slip rate for the Pitas Point fault, as some of the fault motion is transferred to the Mid-Channel system.

The final phase of our study involved developing a comprehensive 3D representation of the active blind-thrust and reverse faults in the Santa Barbara Channel and Ventura basin that integrates our findings with those of other SCEC investigators. Specifically, we developed triangulated surface representations of these faults that are geometrically and kinematically compatible with existing faults in the CFM (Figure 3). Currently, the CFM contains both steeply dipping (Hopkins, 2006; Nicholson et al., 2007; Sorlien et al., 2015) and ramp-flat-ramp geometries for the Ventura-Pitas Point fault (Hubbard et al., 2014). To the north of this system the CFM includes representations of the Red Mountain fault; to the south it includes the Western Deep, Offshore Oak Ridge, and Channel Islands thrusts. Levy et al., (2019) has also contributed alternative representations for the Red Mountain fault and others structures in the southern Transverse Ranges. Our new representation of the Ventura-Pitas Point fault is a refinement of the flat-ramp-flat geometry, and we add a 3D representation of the Mid-Channel thrust to this fault system (Figure 3). In addition, our new model refines the representations of other faults to ensure that they are compatible with the updated Ventura-Pitas Point fault system.

These new fault representations are now being considered as part of the peer-evaluation process for CFM 5.3. Based on the outcome of this assessment, this new fault representation will be considered as the preferred or an alternative representation in CFM 6.0. Improving our understanding of these fault systems will important implications for earthquake hazards, including potential future earthquake magnitudes, recurrence estimates, as well as resulting strong ground motion and tsunami hazards.

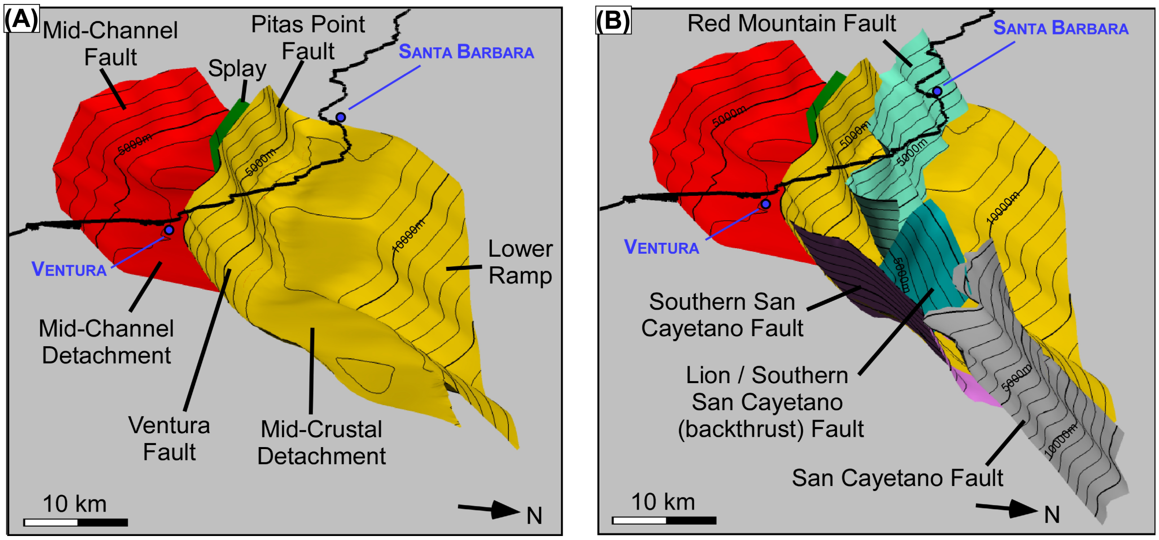

Figure 3: 3D view of the Ventura-Pitas Point fault system. (A) View showing linkage of Venutra and Pitas Point faults with the ramp-flat-ramp geometry and the Mid-Channel fault extending south into the Santa Barbara Channel. (B) View showing linkage of the Ventura-Pitas Point fault system with other regional fault systems. Red Mountain, Lion/Southern San Cayetano backthrust, and San Cayetano faults after Hubbard et al. (2014). View is approximately to the east. Contour interval = 1km. California coast show in black.

Application to SCEC5 Goals

This research addresses SCEC's explicit goal of refining our understanding of fault geometry and activity to improve assessment of regional earthquake hazards. This work contributes to the following goals outlined in the SCEC RFP:

P1.a. Refine the geologic slip rates on faults in Southern California, including offshore faults....

P3.a. Refine the geometry of active faults across the full range of seismogenic depths, including structures that link and transfer deformation between faults.

Moreover, we anticipate that our work can help contribute our understanding of rupture dynamics on complex fault systems:

P2.e. Describe how fault geometry and inelastic deformation interact to determine the probability of rupture propagation through structural complexities...

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