HARVARD UNIVERSITY

Kinematic evolution of the Palos Verdes restraining bend and 3-D architecture of the fault, Southern California

SCEC AN NSF+USGS CENTER

Franklin D. Wolfe, John H. Shaw, Andreas Plesch; Harvard University, Cambridge, MA; Contact: Franklin Wolfe (wolfe_franklin@g.harvard.edu)

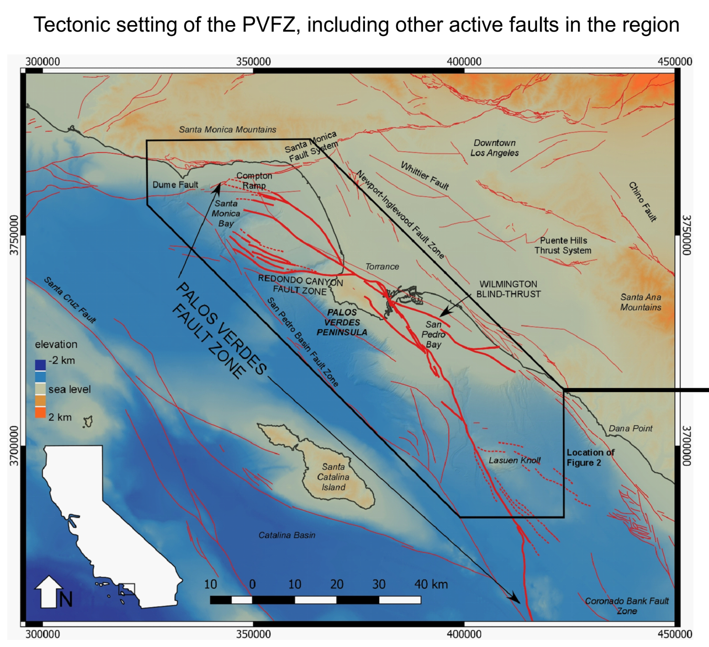
Abstract

The Palos Verdes Fault Zone (PVFZ) extends across the southwestern Los Angeles Basin and Inner Continental Borderland, California, and is considered capable of generating large, damaging earthquakes with short recurrence intervals. The 110-km-long fault zone is composed of vertical and moderately dipping segments that accommodate oblique, right-lateral reverse displacement. Onshore, the PVFZ undergoes a counterclockwise rotation, producing a major restraining bend that generates the Palos Verdes Peninsula. Here, we use well and seismic reflection data to develop kinematic models that show how folding of the PVFZ by the Wilmington blind-thrust formed the restraining bend. We use these insights to develop a new, comprehensive 3-D model of the PVFZ that incorporates results from prior studies in the San Pedro and Santa Monica Bays. North of the peninsula in Santa Monica Bay, debate persists over the extent, geometry, and activity of the PVFZ. Here, we analyze a dense grid of high-resolution seismic reflection data and present new mapping of the Santa Monica Bay segment of the PVFZ, including multiple active splays (e.g., Redondo Canyon Fault Zone) that occur within a very broad damage zone at the northern termination of the fault system. Together, these insights contribute to a new comprehensive model for the geologic evolution and 3-D geometry of the PVFZ that has important implications for the seismic hazard it poses to the broader Los Angeles metropolitan region.

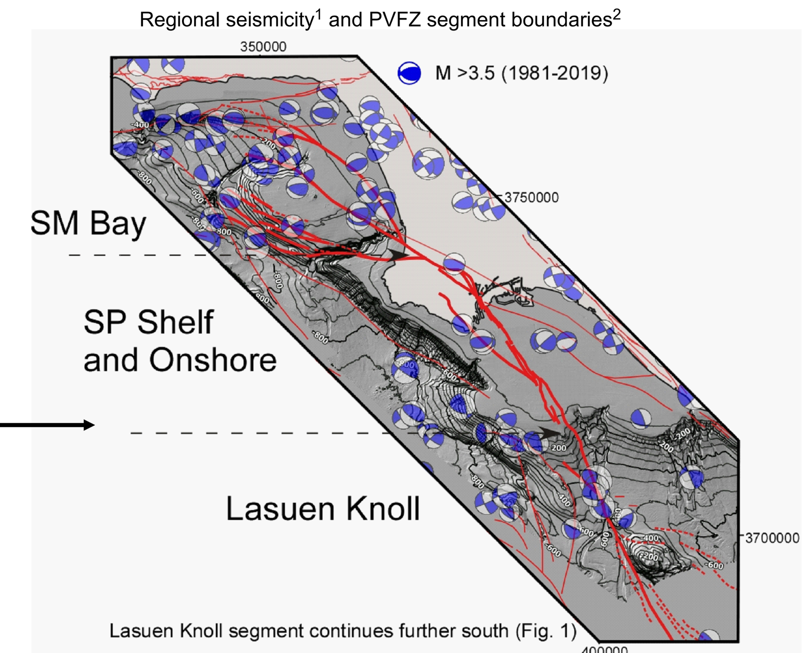
1 The Palos Verdes Fault Zone (PVFZ)

- The PVFZ is generally considered the fastest slipping fault in the Los Angeles Basin (~2-4 mm/yr). The fault zone is described relative to its geographic segments, such as the Santa Monica, San Pedro, and Lasuen Knoll regions.

Tectonic setting of the PVFZ, including other active faults in the region



Regional seismicity[1] and PVFZ segment boundaries[2]

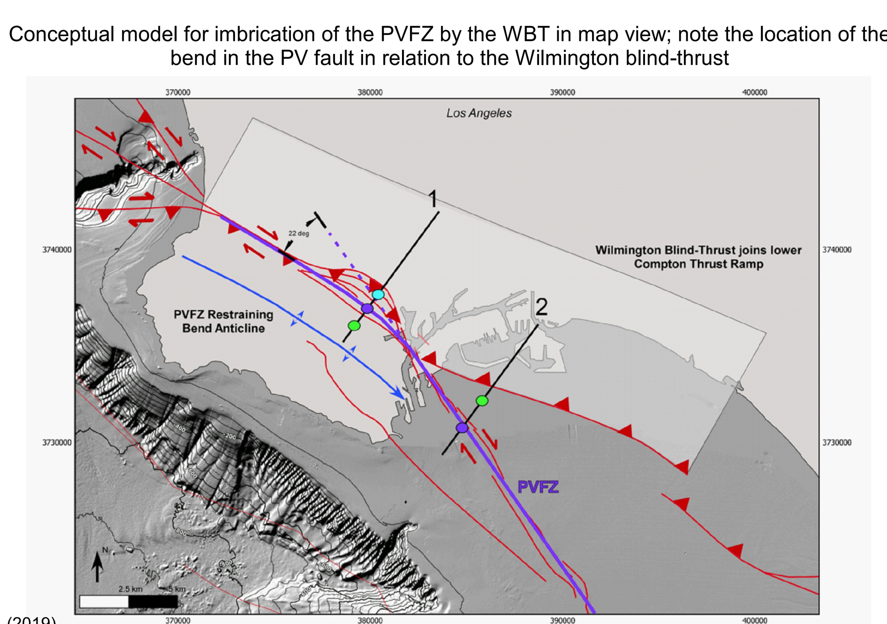


[1]Hauksson et al. (2012); [2]Brothers et al. (2015); Brankman and Shaw (2009)

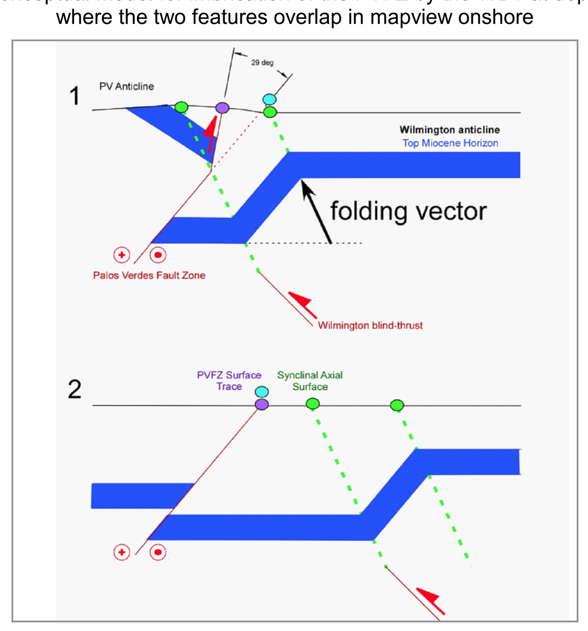
2 Conceptual Model for the Origin of the PV Pensinula

- The peninsula is expressed onshore as a doubly plunging anticline with an emergent portion 400 m in height.
- The peninsula occurs where the PVFZ undergoes a major counterclockwise rotation, producing a restraining bend architecture where the PVFZ and Wilmington blind-thrust are interpreted to overlap in map view.
- At depth, this interaction suggests the PVFZ is in the hanging wall of the Wilmington blind-thrust[3] (WBT) and above the forelimb of the Wilmington anticline onshore.

Conceptual model for imbrication of the PVFZ by the WBT in map view; note the location of the bend in the PV fault in relation to the Wilmington blind-thrust



Conceptual model for imbrication of the PVFZ by the WBT at depth where the two features overlap in mapview onshore

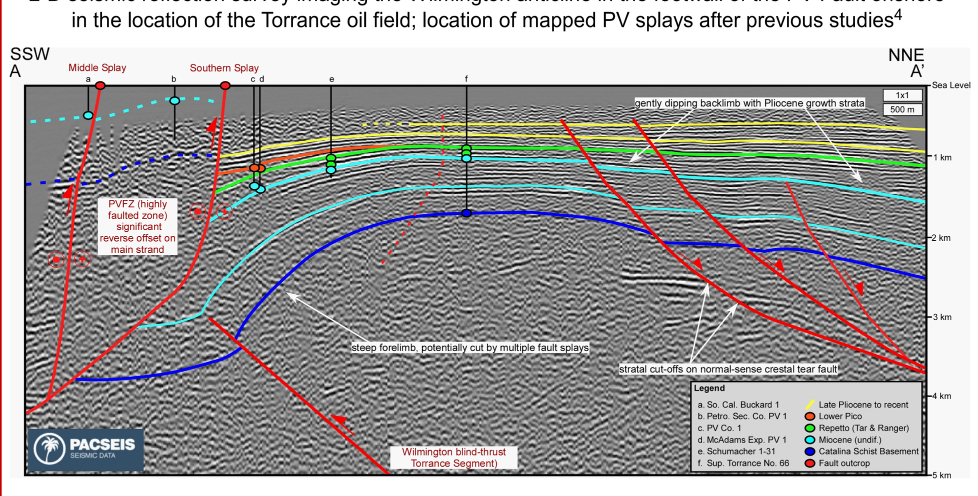


[3]Wolfe et al. (2019)

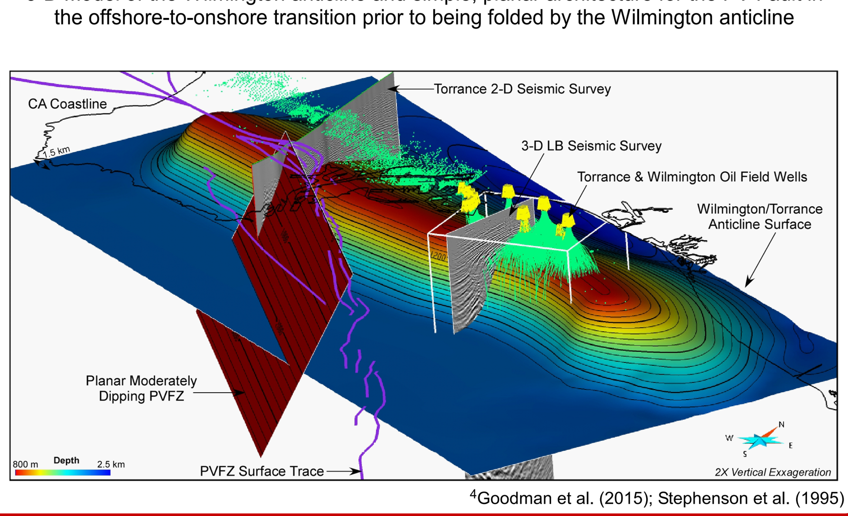
3 Kinematic Model Set-up and Data Constraints

- To explore is folding of the PVFZ by the Wilmington anticline is a plausible model for the origin of the PV Peninsula, we developed a detailed structural model involving new seismic reflection data onshore, hundreds of oil and water wells, published cross sections, and surface and subsurface maps.
- Our PV model is simple and includes moderately westward dipping fault segments within the dip range defined by Brankman and Shaw (2009)

2-D seismic reflection survey imaging the Wilmington anticline in the footwall of the PV Fault onshore in the location of the Torrance oil field; location of mapped PV splays after previous studies[4]



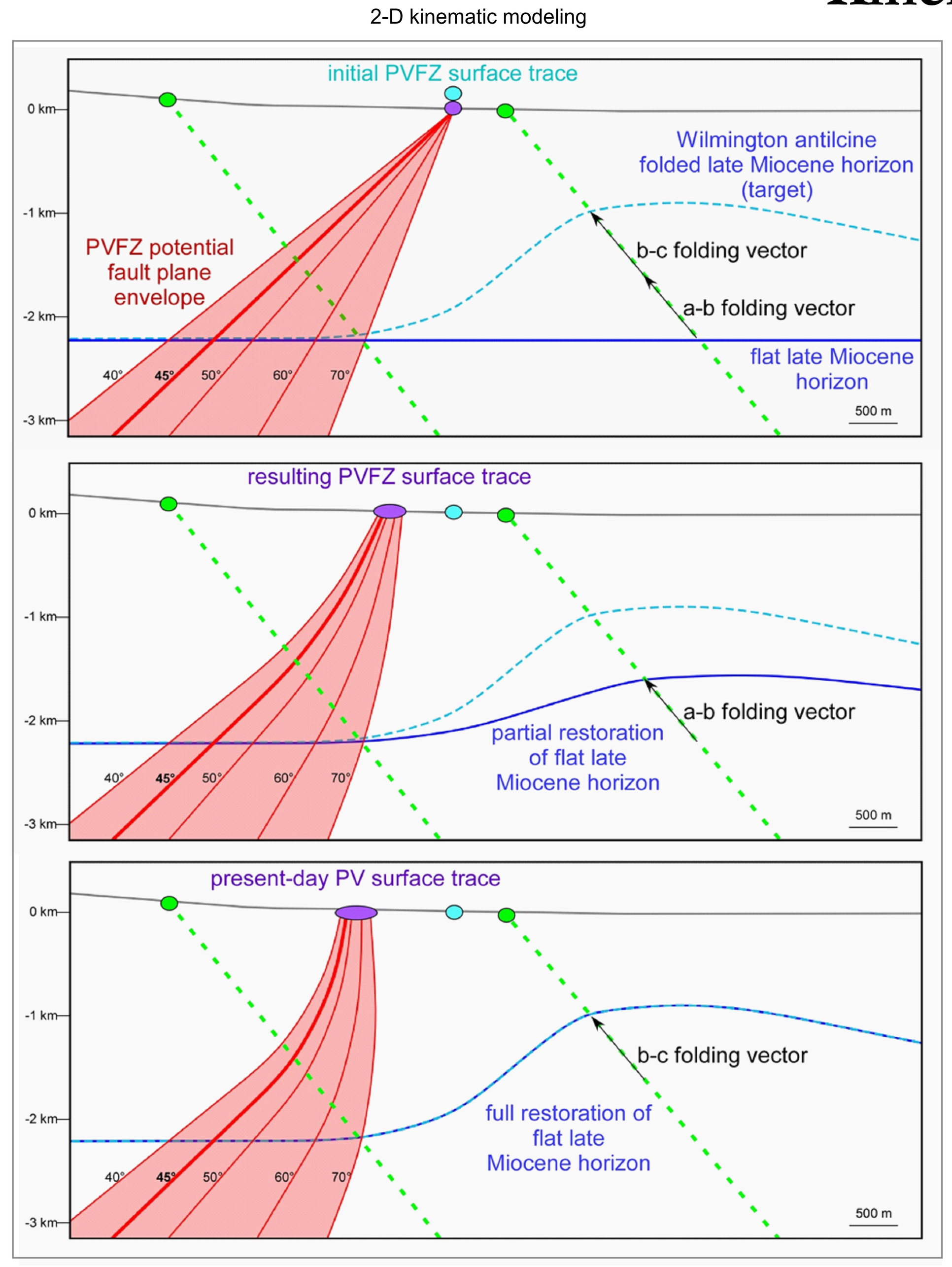
3-D Model of the Wilmington anticline and simple, planar architecture for the PV Fault in the offshore-to-onshore transition prior to being folded by the Wilmington anticline



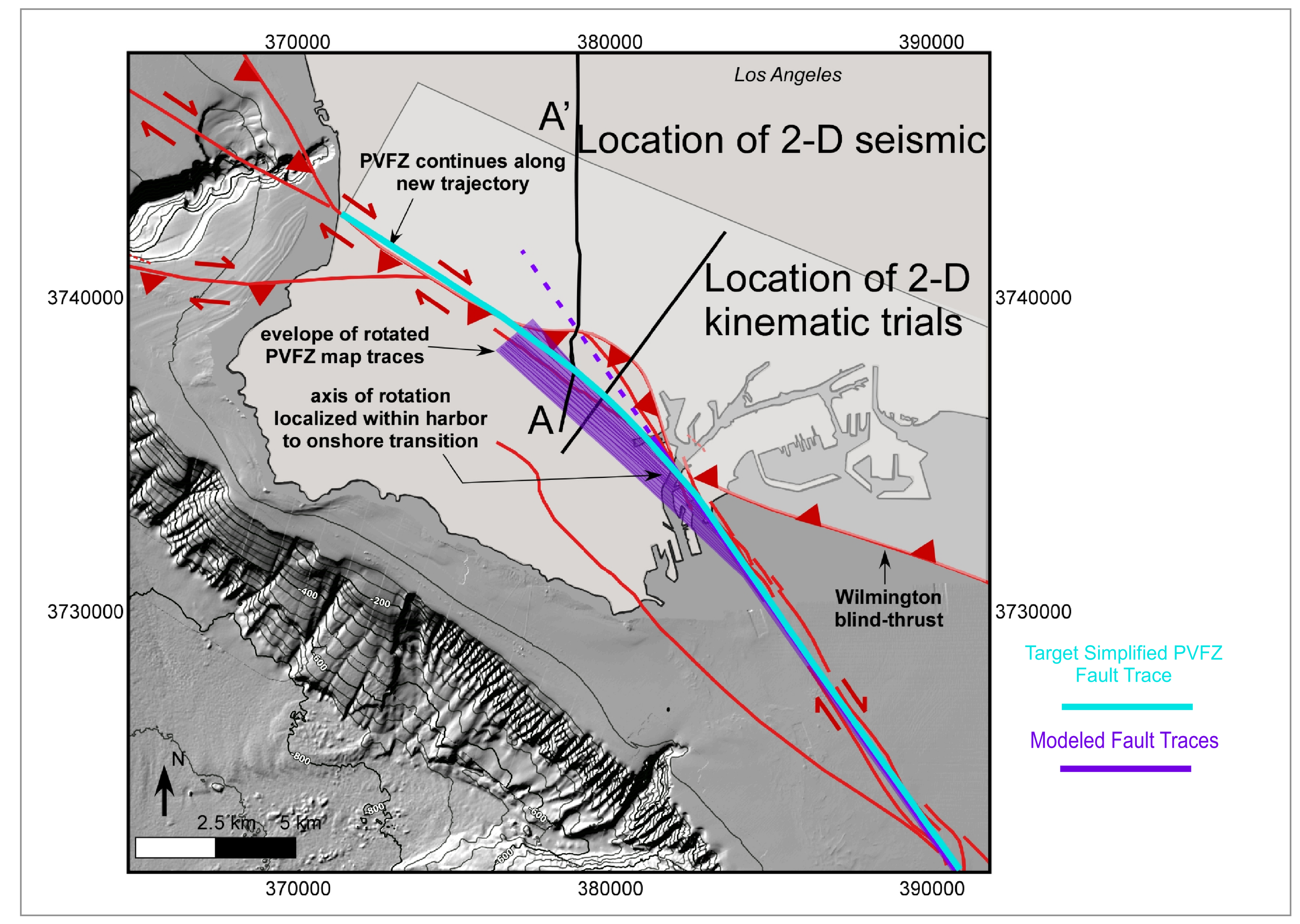
[4]Goodman et al. (2015); Stephenson et al. (1995)

4 Kinematic Results (2- and 3-D)

2-D kinematic modeling



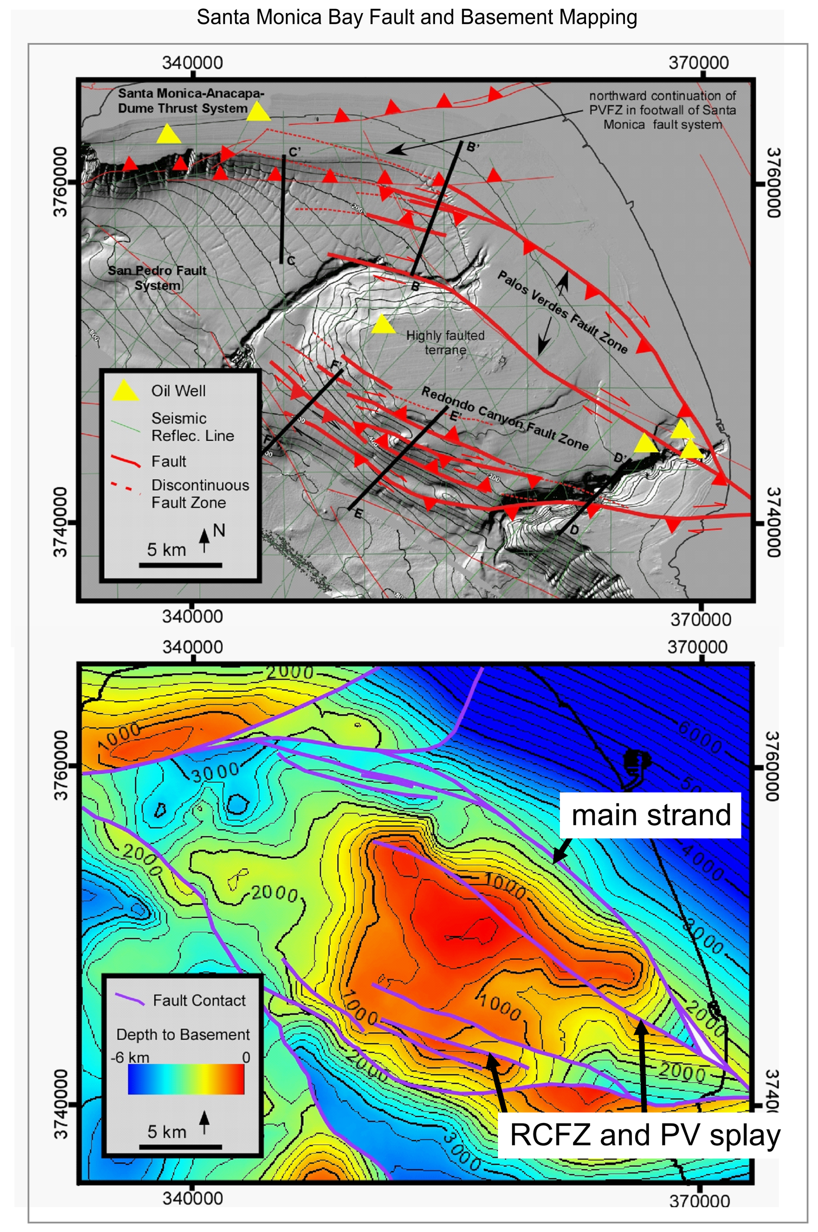
Results from numerous 3-D kinematic modeling trials (mapped surface traces of folded PV fault plotted)

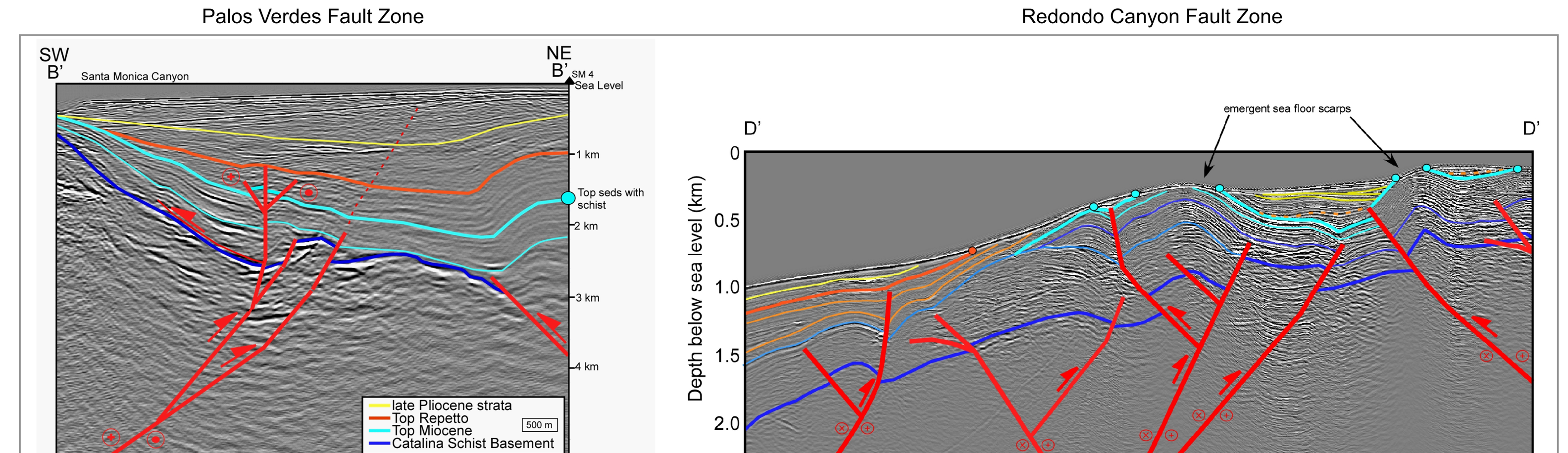


- The growth of the Wilmington anticline steepens the near-surface portion of the PVFZ and rotates the surface trace to the south, similar to what is observed today.
- The axis of rotation is localized in the inner harbor region.
- The modeled change in fault dip and trend onshore would enhanced the vertical component of deformation onshore, producing the PV Pensinsula uplift.

5 The Santa Monica Bay Segment of the PVFZ

Santa Monica Bay Fault and Basement Mapping





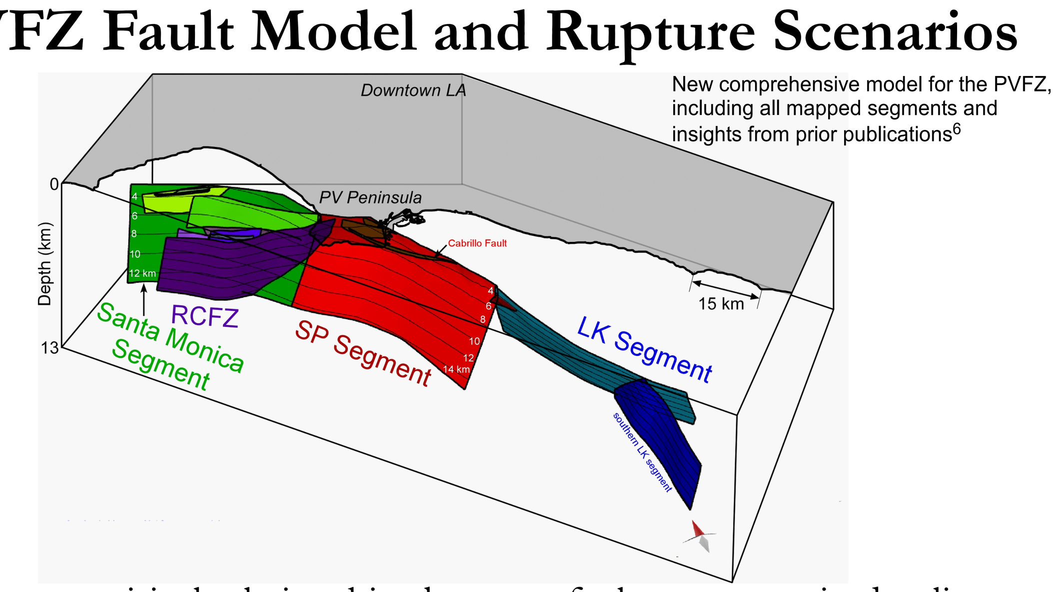
Miocene strata thicken towards fault, indicative of an earlier extensional phase of deformation prior to present-day transpressional regime

Contractional features are tightly spaced within the Redondo Canyon Fault Zone exposing eroded fold crests at the sea floor

- North of the PV Peninsula, multiple splays of the PVFZ are well-imaged in marine seismic reflection data and produce mappable basement offset.
- Overall, the fault zone separates a highly faulted basement high from an east-dipping basement low covered by undeformed sediment to the northeast.
- The PVFZ main strand has a moderate dip at depth and shows evidence for accommodating both reverse and strike-slip displacement.
- The deformation signature in the Santa Monica Bay is much more subtle than where it produces the PV Peninsula onshore. Thus, it is likely the PVFZ transfers some of its slip to other faults in the SM Bay, including the Redondo Canyon Fault Zone (RCFZ).
- The RCFZ is a northwest oriented zone of faulted anticlines located above moderately dipping fault segments. Some produce subtle seafloor scarps indicative of recent activity.
- This model is similar to that previously proposed by others[5]

[5]Bohannan et al. (2004); Nardin and Henyey (1978)

6 PVFZ Fault Model and Rupture Scenarios



New comprehensive model for the PVFZ, including all mapped segments and insights from prior publications[6]

- Based on empirical relationships between fault area, magnitude, slip rate, and recurrence interval[7], the PVFZ is capable of the following:

Single Segment Rupture	Magnitude	Avg. Recurrence Interval
Lasuen Knoll	M 7.1	574 yrs.
San Pedro	M 7.0	554 yrs.
Santa Monica Bay	M 7.0	556 yrs.
Redondo Canyon	M 6.9	491 yrs.

[6]Brothers et al. (2015); Brankman and Shaw (2009); [7]Biasi and Weldon (2006); Hanks and Bakun (2008); Wells and Coppersmith (1994)

7 Key Take-Aways

- The PV restraining bend is due to structural imbrication of the PVFZ onshore by the underlying Wilmington blind-thrust.
- The Santa Monica Bay segment of the PVFZ is a broad damage zone, including numerous active transpressional faults (e.g., Redondo Canyon Fault Zone)
- The new comprehensive model and seismic hazard assessment for the Palos Verdes Fault Zone, so. California suggests the fault zone is capable of larger events than previously expected. These would occur relatively frequently given the fault's fast slip rate.

References:

Biasi, G.P., and R.J. Weldon, 2006, Estimating surface rupture length and magnitude of paleoearthquakes from point measurements of rupture displacement, BSSA, 96, no. 5, 1612-1623.

Bohannan et al., 2004, Holocene to Pliocene tectonic evolution of the region offshore of the Los Angeles urban corridor, southern California, Tectonics, 23, no. 1.

Brankman, C.M, and John H. Shaw, 2009, Structural geometry and slip of the Palos Verdes Fault, Southern California: Implications for earthquake hazards, BSSA, 99, no. 3, 1730-1745.

Brothers et al., 2015, The Palos Verdes Fault offshore Southern California: Late Pleistocene to present tectonic geomorphology, seascape evolution, and slip rate based on AUV and ROV surveys, JGR, 120 no. 7, 4734-4758.

Goodman et al., 2015, Strain partitioning along the onshore Palos Verdes Fault Zone; New constraints on the geometry, distribution and kinematics of Quaternary deformation, SSA, poster

Hanks, T.C., and W.H. Bakun, 2008, M-logA obsevations for recent large earthquakes, BSSA, 98, no. 1, 490-494

Hauksson et al., 2012, Waveform relocated earthquake catalogue for Southern California (1981 to June 2011), BSSA, 102, no. 5, 2239-2244.

Nardin, T.R., and T.L. Henyey, 1978, Pliocene-Pleistocene disastrophism of Santa Monica and San Pedro shelves, California Continental Borderland, AAPG, 62, no.2, 247-272.

Stephenson et al., 1995, Seismic reflection and geomorphic characterization of the onshore Palos Verdes fault zone, Los Angeles, California, BSSA, 85, 943-950.

Wells, D., and K. Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, BSSA, 84, 974-1002.

Wolfe et al., 2019, The Wilmington blind-thrust fault: An active concealed earthquake source beneath Los Angeles, California, BSSA, 109, no. 5, 1890-1906.