Anomalous Uplift at Pitas Point, California: Implications from Onshore & Offshore 3D Fault & Fold Geometry and Observed Fault Slip

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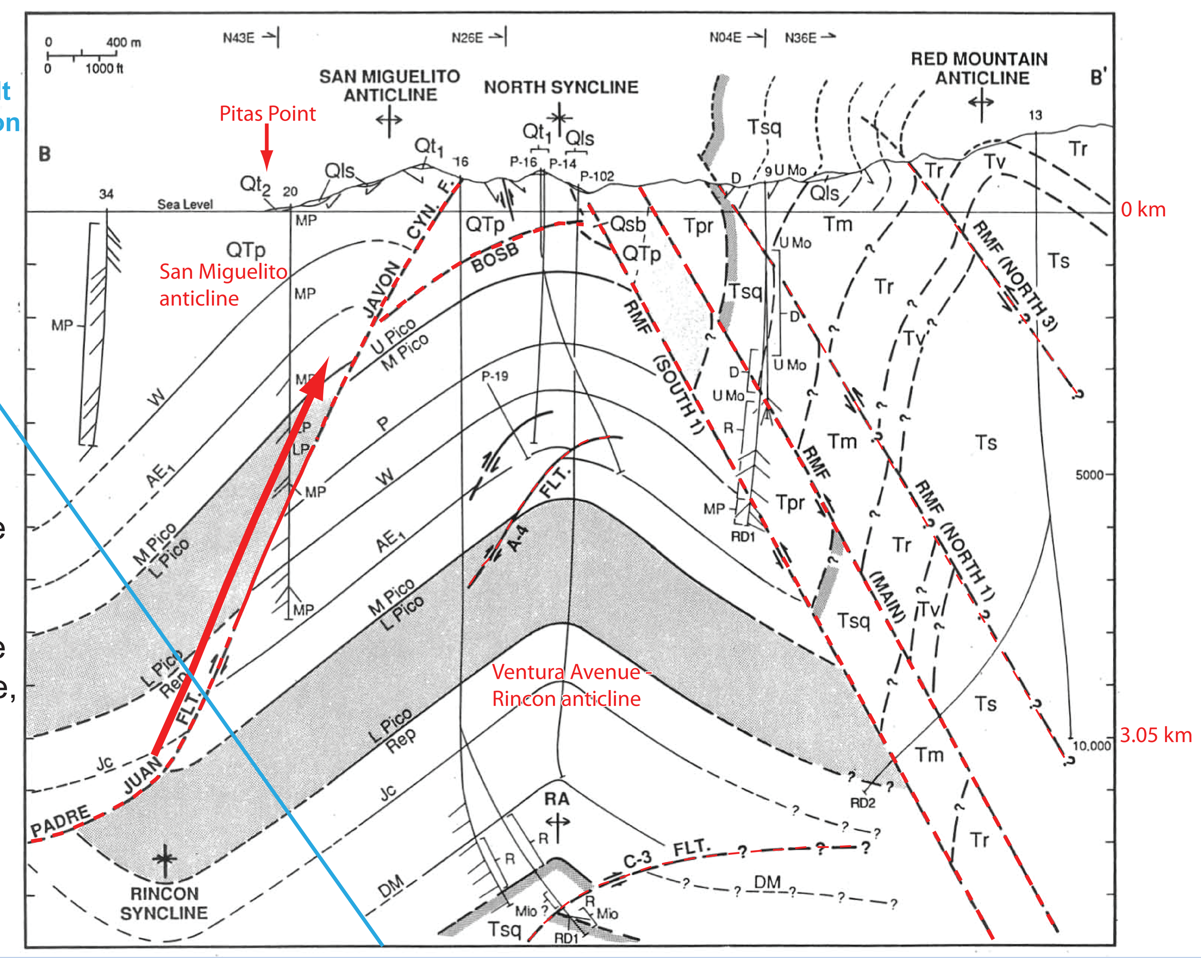
ABSTRACT

Based on four Recent ~8-10-m uplift events of coastal marine terraces at Pitas Point, many believe these represent earthquakes near M8 on the N-dipping Pitas Point-Ventura fault (PPVF), part of the larger primarily offshore North Channel-Pitas Point-Red Mountain fault system. However, this model of multiple Holocene M8 events on the PPVF has major problems, not the least of which are: failure of the 2D fold model used to properly infer subsurface fault-fold geometry, an implied Holocene slip rate for the blind PPVF that is inconsistent with offshore observations, and the marked lack of near-surface fault rupture or widespread tsunami deposits expected from such shallow (<15 km depth) M8 events that would extend 10's of km offshore. The reason for these discrepancies may be that uplift at Pitas Point is driven primarily by slip on the S-dipping listric Padre Juan fault (PJF), not solely by the PPVF. The PJF juxtaposes the strongly N-verging San Miguelito anticline in its hanging wall above the more symmetric Ventura Avenue-Rincon anticline in its footwall. Fault and fold geometry is well determined by industry wells that produce from the distinctly different upper San Miguelito and lower Rincon oilfields, and by imaging offshore with seismic reflection data. In the upper 3 km, the PJF exhibits up to 2.6 km of dip separation, in contrast to ~200 m of inferred separation on the Ventura fault at similar depths. Much of this PJF slip is syntectonic with growth of the Rincon anticline as PJF splays are folded by this lower fold. The timing and slip involved for San Miguelito fold growth and its emplacement against and deformation of the lower Rincon anticline, the specifics of infered Ventura fault propagation, and the geometry of the PJF and PPVF requires that much of this fault slip occurred while the PJF acted independently—not as a backthrust to the PPVF. A still active listric PJF can help account for the observed uplift at Pitas Point without recourse to M8 earthquakes. Regardless, its presence helps explain why the uplift at Pitas Point is so anomalous, and not necessarily indicative of the expected slip at depth either along strike of the PPVF or the average slip during large earthquakes. Rather, this uplift at Pitas Point is probably localized to where slip on the PJF predominates, or where the PJF and PPVF strongly interact, which limits the length & depth of possible seismic ruptures and the geohazard & tsunami potential of the active fault(s) involved.

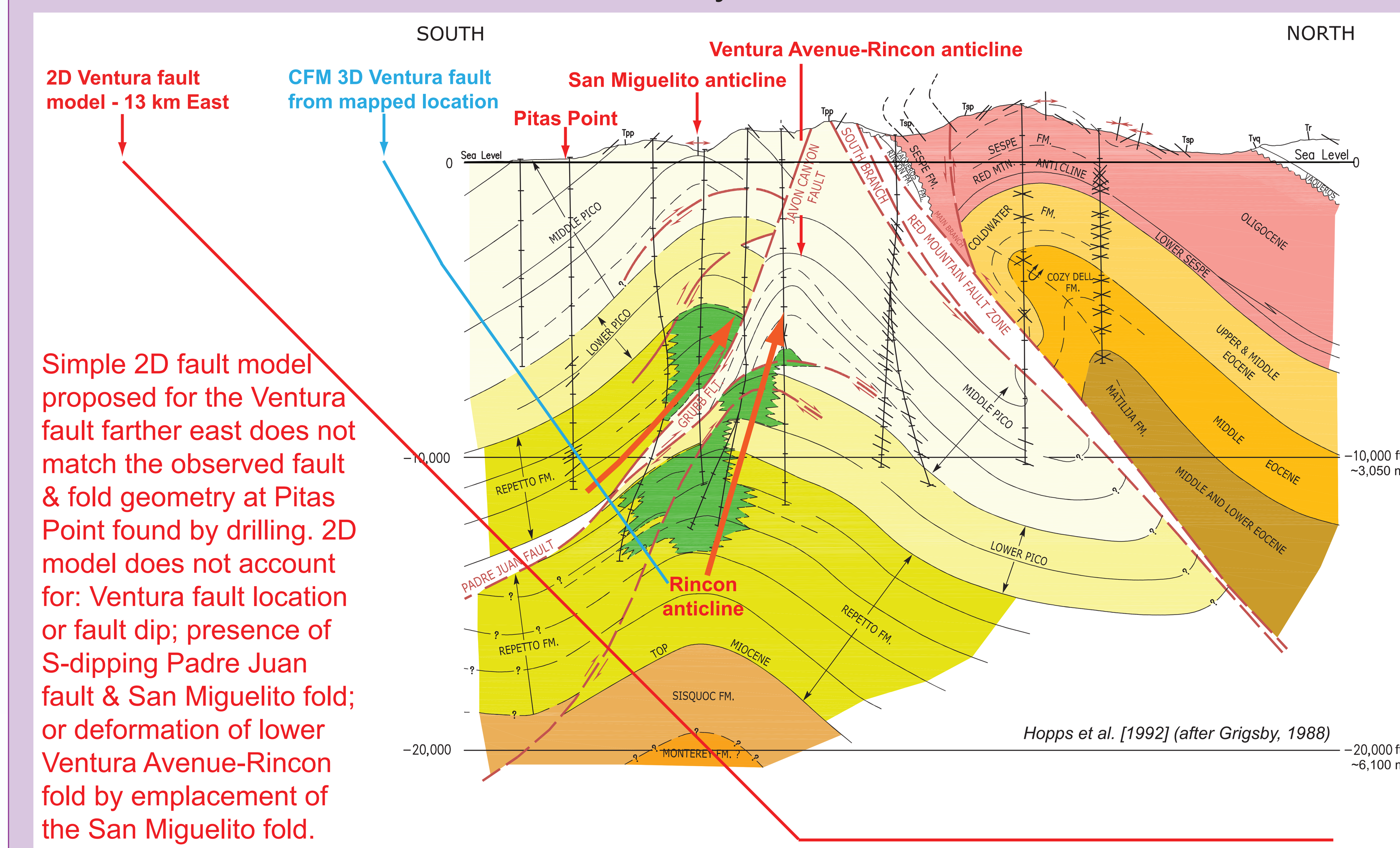
Structure Cross Section from Well Data 1km West of Pitas Point



Note that Pitas Point is directly above the Padre Juan fault that is Quaternary active with a potential onshore slip rate of 10 mm/yr since ~250 ka. Offshore, the inferred long-term rate is much lower, ~2 mm/yr, like the offshore slip rate for the Pitas Point fault.

Industry wells define a strongly N-verging, asymmetric San Miguelito anticline in the hanging wall of a S-dipping, listric Padre Juan-Javon Canyon fault. The distinctly separate and more symmetrical Ventura Avenue-Rincon anticline is located in its footwall. In the upper 3 km, uplift and emplacement of the San Miguelito anticline involved 2.5 km of measured stratigraphic dip separation along the Padre Juan fault (red arrow). The Ventura fault shows only ~200 m of dip separation over this same depth interval. Uplift & emplacement of the San Miguelito fold necessarily occurred as slip on an independent Padre Juan fault as this would involve movement of material from the footwall to the hangingwall of the Ventura fault, if the Ventura fault was present at this depth when this slip occurred.

Structure Cross Section from Industry Well Data 3 km East of Pitas Point



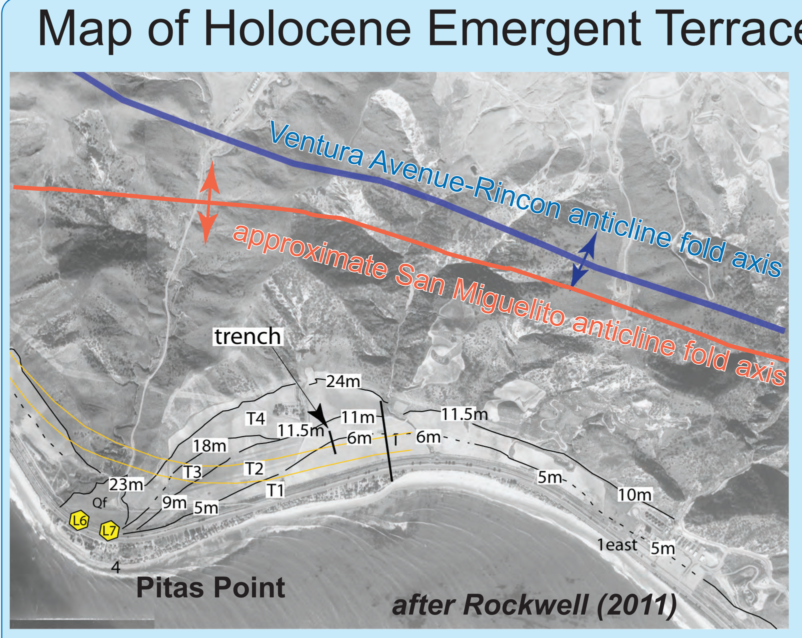
This deeper cross section near Pitas Point demonstrates that 1) timing of upper San Miguelito fold uplift along Padre Juan fault was contemporaneous with growth of lower Rincon anticline as emplacement deforms the lower fold and Padre Juan splays are also folded; 2) Padre Juan fault slip needed to emplace the San Miguelito fold is unrelated to the Ventura fault because this involves moving material from the footwall to the hanging-wall across the Ventura fault itself; and 3) the depth of either S-dipping Padre Juan or N-dipping Ventura fault below Pitas Point is only ~2.5 km. The fault slip needed to produce ~8-10-m uplift events at Pitas Point is ~10-12-m, but neither fault exhibits evidence for such large slip events or the required high fault slip rate at its mapped near-surface location.

This is NOT the Ventura Avenue Anticline!

It is the distinctly separate San Miguelito Anticline!

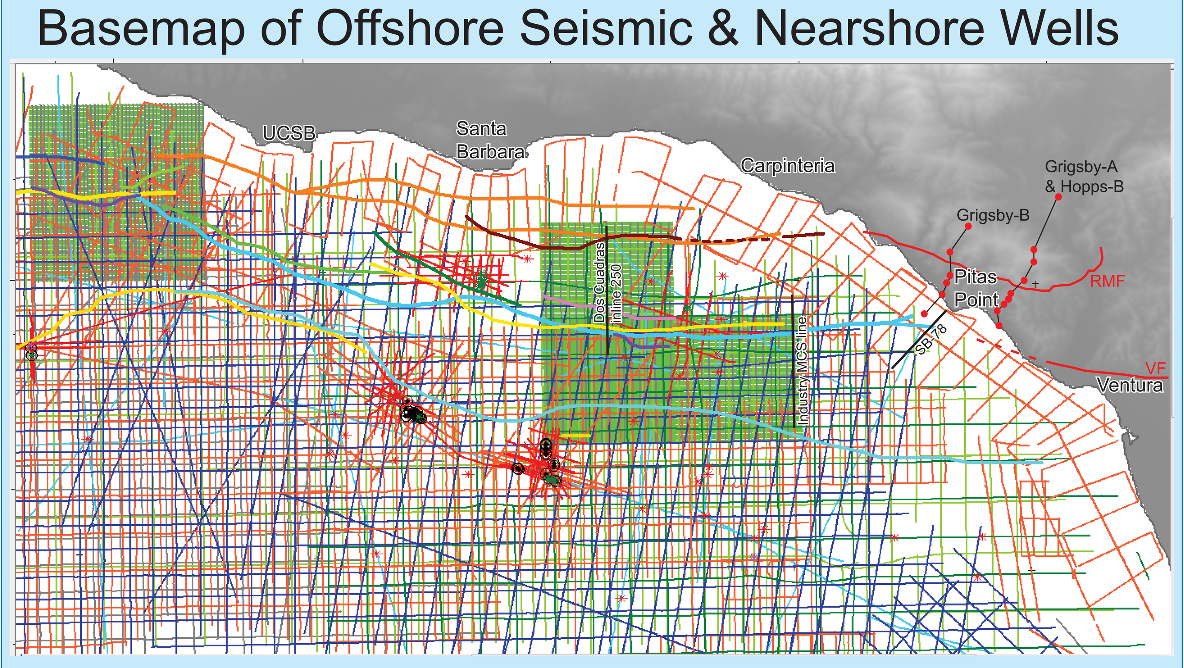
This classic amphitheatre photo looking west is often mistaken for the Ventura Avenue anticline, which is farther along trend to the east. However, this is the N-verging San Miguelito anticline and oilfield. Photo credit Art Sylvester.

Map of Holocene Emergent Terraces at Pitas Point



Uplifted marine terraces at Pitas Point reflect at least four ~8-10-m uplift events dated at 0.95 ka, 2.09 ka, 4.4 ka & 6.7 ka [*Rockwell et al.*, 2016]. These raised terraces indicate a localized uplift rate of 6-7 mm/yr, which is significantly higher than observed along trend to the east or west where uplift rates are typically about 2 mm/yr.

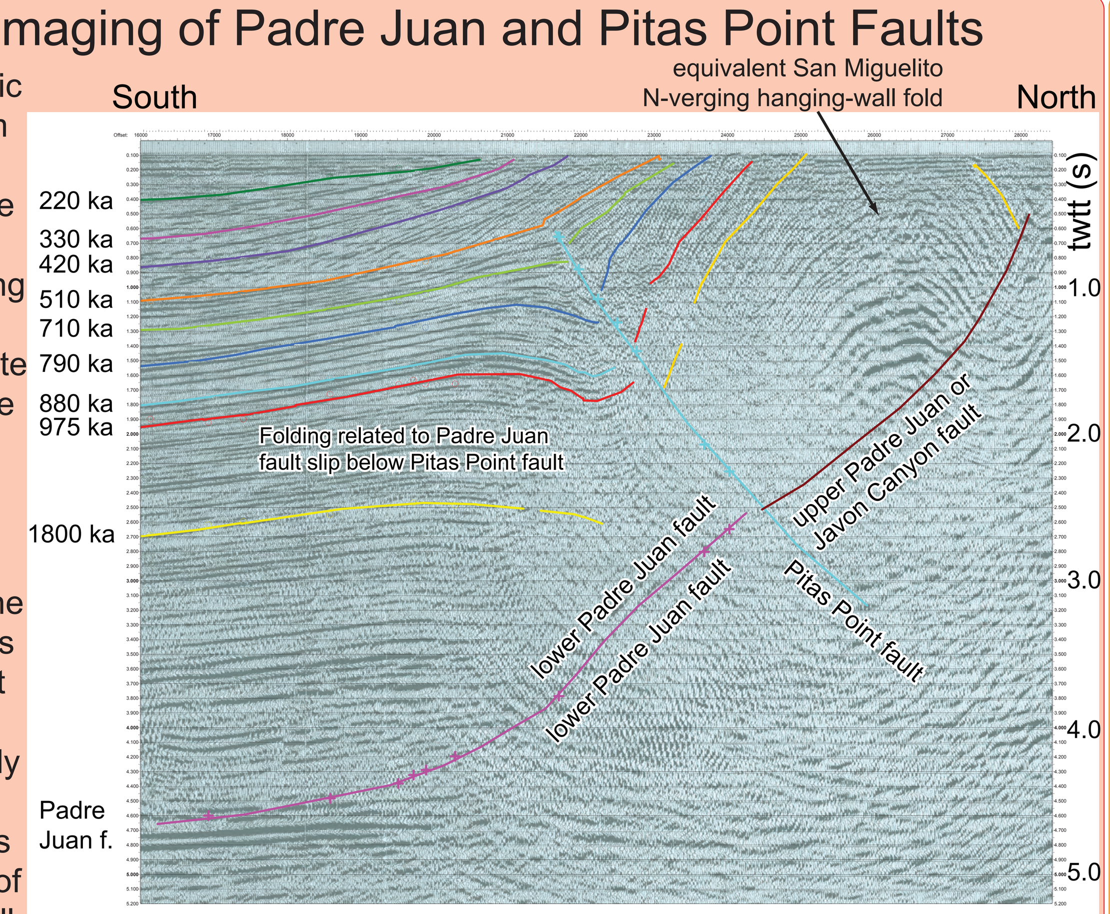
Basemap of Offshore Seismic & Nearshore Wells



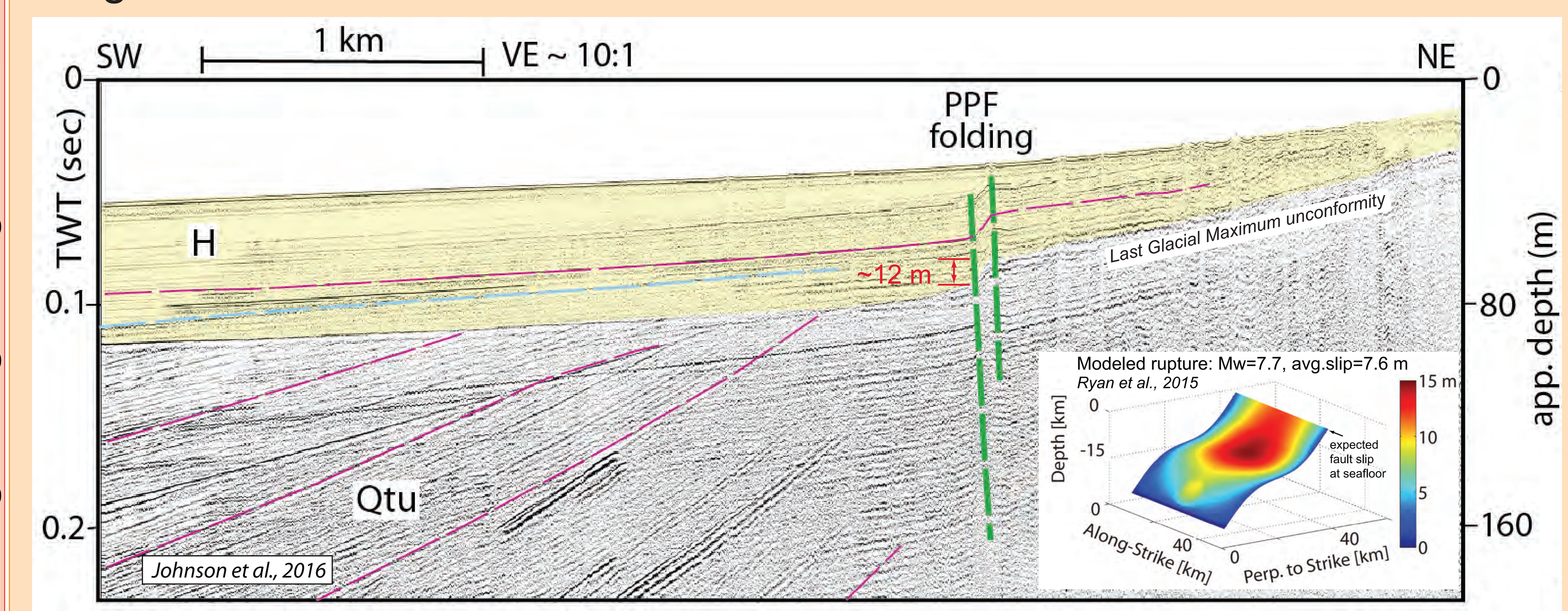
Grids of 2D & 3D seismic surveys and nearshore wells used to map offshore faults and reference horizons in 3D and correlate to onshore cross sections.

Offshore MCS Imaging of Padre Juan and Pitas Point Faults

Industry multichannel seismic (MCS) reflection line ~10 km west of Pitas Point used to map faults & dated reference horizons in 3D. S-dipping, listric Padre Juan & N-dipping Pitas Point faults are well imaged. Both faults contribute to the uplift and folding of the N-verging hanging-wall fold, which exhibits progressive fold-limb rotation and tilting indicative of diminishing slip updip along the faults, but the lower Padre Juan also drives folding below the Pitas Point fault. At this location, the Pitas Point fault is completely blind, and exhibits no fault rupture of shallow sediments since ~500 ka, or evidence of discrete Recent hanging-wall folding events. Thus, the large, localized ~8-10-m uplift events at Pitas Point are unlikely to be representative of the seafloor offset or slip at depth farther west along the offshore Pitas Point fault.

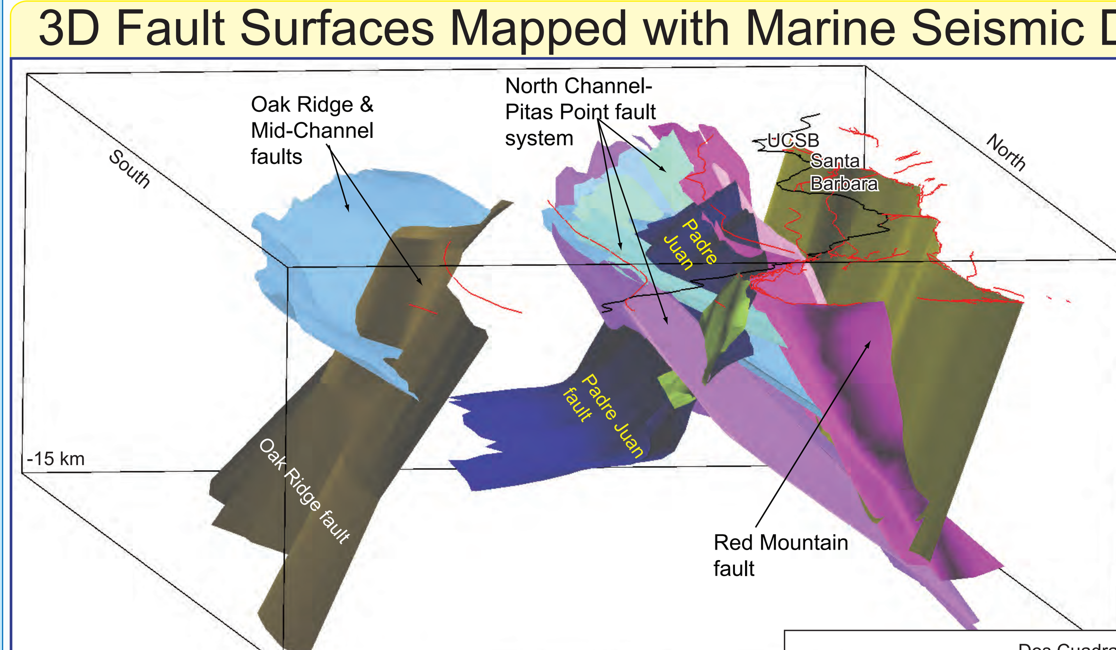


High-Resolution Marine Seismic Reflection Data Across Pitas Point Fault



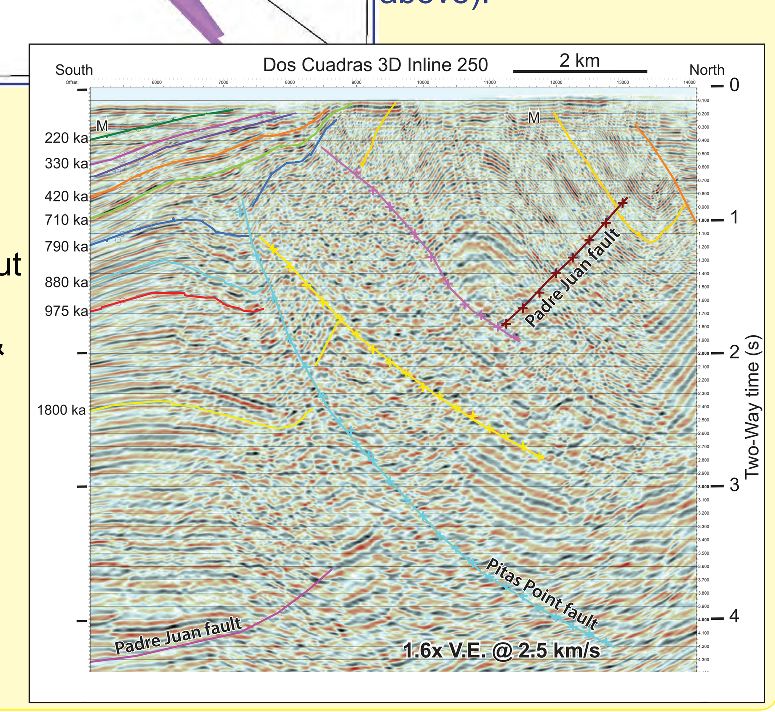
USGS minisparker line SB-78 2.5 km southwest of Pitas Point. At the fault, sediments younger than Last Glacial Maximum (yellow) dated at ~10-12 ka exhibit ~12 m of vertical structural relief, but no fault rupture. Green lines are fold axes not faults. Maximum vertical relief of the LGM unconformity is ~20-24 m, but decreasing westward, indicating a slip rate of the Pitas Point fault of ~2 mm/yr. The expected multiple 10-12-m seafloor fault offsets at the Pitas Point fault [*inset*] predicted by dynamic rupture models used to explain the uplift events at Pitas Point since 7 ka are not observed. More importantly, late Quaternary sediments (Qtu) south of and below the Pitas Point fault also show progressive tilting & fold-limb rotation likely related to continued slip on the S-dipping Padre Juan fault.

3D Fault Surfaces Mapped with Marine Seismic Data & Seismicity



Listric, out-of-syncline S-dipping Padre Juan fault is imaged by industry MCS data in the footwall & hanging wall of the Pitas Point fault, it is Quaternary active, it merges into the Rincon Shale at about 7 km depth, and it strongly influences the N-verging, asymmetric anticline found above it (see above).

Inline 250 from Dos Cuadras 3D seismic survey. This line farther west shows the Pitas Point fault is blind deeper and offsets the Padre Juan fault. Lower Padre Juan becomes less well imaged, but is still Quaternary active as indicated by folding below the Pitas Point fault. Farther east, upper & lower Padre Juan faults tend to merge, and may become more locally active, where the fault may help drive the localized high uplift rate at Pitas Point. At the coast is also where both the Pitas Point-Ventura fault and the Ventura Avenue-Rincon anticline axis step 2 km north.



Critical Observations Related to the Uplift at Pitas Point

- ***The high uplift rates of raised marine terraces observed at Pitas Point are anomalous.*** The uplift rates found at Pitas Point (~6-7 mm/yr)[*Rockwell et al.*, 2016] are not continued farther west along the Santa Barbara-Ventura coast [*Gurrola et al.*, 2014, ~2 mm/yr], and are not observed to the east for the Ventura Avenue anticline itself, where recent geodetic data [*Sylvester*, 2005] indicate an average uplift rate of ~2 mm/yr. The high inferred shortening rates at Pitas Point are not observed farther west offshore where the shortening rate measured across the Pitas Point fault to the S-branch of the Red Mountain fault is ~3 mm/yr [*Sorlien & Kamerling*, 2000]. Holocene slip rates inferred for the PItas Point fault from local folding above the blind fault tip are about ~2 mm/yr. This folding decreases westward owing to increasing fault tip depth.

- ***At Pitas Point, there is not one but two anticlinal folds:*** the upper N-verging, asymmetric San Miguelito anticline in the hanging wall of the S-dipping, listric Padre Juan fault, and the distinctly separate lower Ventura Avenue-Rincon anticline in its footwall [*Grigsby*, 1988]. Neither the N-verging fold, nor the Padre Juan fault are represented in the 2D fault-related fold model [*Hubbard et al.*, 2014] or the subsequently derived dynamic rupture model [*Ryan et al.*, 2015].

- ***S-dipping, listric Padre Juan fault is independently Quaternary active.*** The fault exhibits ~2.5 km of dip separation and much of this slip occurred during Ventura Avenue fold growth. Because emplacement of the San Miguelito fold was synchronous with Ventura Avenue folding and would involve moving material from the footwall to the hanging-wall of the Ventura fault if it was present, this fault slip must have occurred on the Padre Juan fault acting independently. Both high-resolution and deep-penetration MCS reflection data indicate continued folding, progressive limb rotation, and tilting in the footwall of the Pitas Point fault, indicating that the S-dipping Padre Juan fault is Quaternary active.

- ***Both the offshore Pitas Point fault and onshore Ventura fault are blind.*** Within the resolution of the seismic reflection data, the Pitas Point fault has not exhibited near-seafloor fault rupture in most places since 500 ka, although its hanging-wall does exhibit progressive limb rotation and tilting [*Sorlien et al.*, 2015] indicating that fault slip consistently diminishes updip. The large seafloor offsets [*Ryan et al.*, 2015] and widespread tsunami deposits expected from the inferred multiple, shallow ~M8 earthquakes on the Pitas Point-Ventura fault [*Rockwell et al.*, 2016] are not observed. Globally, the 10-12-m of fault slip at 2.5 km depth needed to explain the ~8-10-m uplift events at Pitas Point always produces surface rupture.

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