Modeling blind fault slip from Quaternary growth of Palos Verdes anticlinorium, offshore Long Beach

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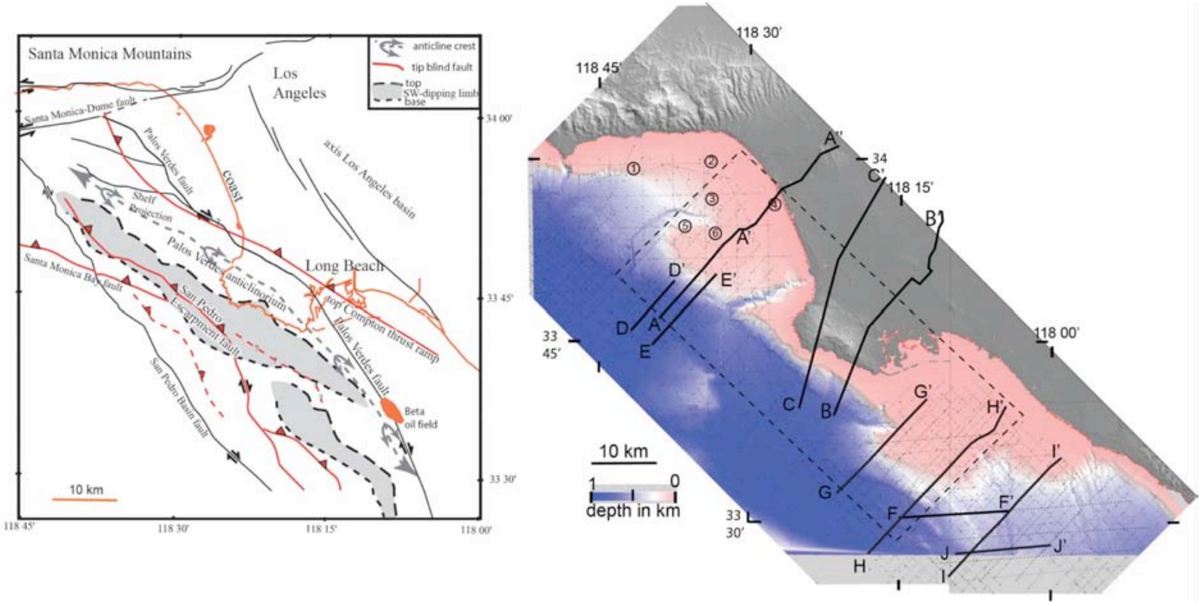

Figure 1: left: Map showing faults related to the Palos Verdes anticlinorium. Gray fill is the southwest limb of Palos Verdes anticlinorium. The Red curves with triangles on NE hanging-wall side represent parts of the same thrust system, respectively the tip of the San Pedro Escarpment fault and the top of the Compton ramp. The Compton is responsible for the regional NE-dipping fold limb that forms the southwest margin of LA basin. **Right**: Multibeam bathymetry and topography, with tracklines of seismic reflection data used in this project (fine lines). A, B, C, and F are shown in Figures 3 and 4. We have depth-converted A-A', G-G' and H-H' using sonic logs from wells (Broderick, 2006; Rigor, 2003).

Previous Structural Models for Palos Verdes anticlinorium

The five km-deep L.A. basin is isolated from other basins to the southwest by a 70 km-long anticline-ridge, the Palos Verdes Anticlinorium (PVA), (Davis et al., 1989; Figures 1, 2). There is little current agreement on any aspect of the PVA. This lack of agreement includes the scale and continuity of the structure, which faults are responsible for it, whether these faults are active, and even the dip direction and whether the southwest limb is undergoing extension or contraction. One set of models explains the visible, uplifting part of the PVA as due to oblique right-reverse slip along a restraining segment of the Palos Verdes fault (e.g., Nardin and Henyey, 1978). Alternatively, thrust slip on a SW-dipping roof thrust above a SW-directed tectonic wedge has been interpreted as the cause of folding and uplift of the PVA (Fig. 3; Davis et al, 1989; Shaw and Suppe, 1996). The position and depth of the tip of the wedge is very different in the two interpretations (B-B' vs. C-C' on Fig. 3). Both interpretations include a NE-dipping ramp beneath the southwest margin of Los Angeles Basin, with the Shaw and Suppe (1996) version named the Compton thrust.

Our data and approach

In order to resolve these diverse interpretations, we worked with several grids of industry multichannel seismic reflection data in combination with high resolution USGS multichannel and Minerals Management Service single channel reflection data (Fig. 1). These were interpreted together with stratigraphic data from industry wells, sea floor geology from bottom samples, and multibeam bathymetry data. These data were used to produce 3D digital representations of faults and folded stratigraphic horizons (Fig. 2).

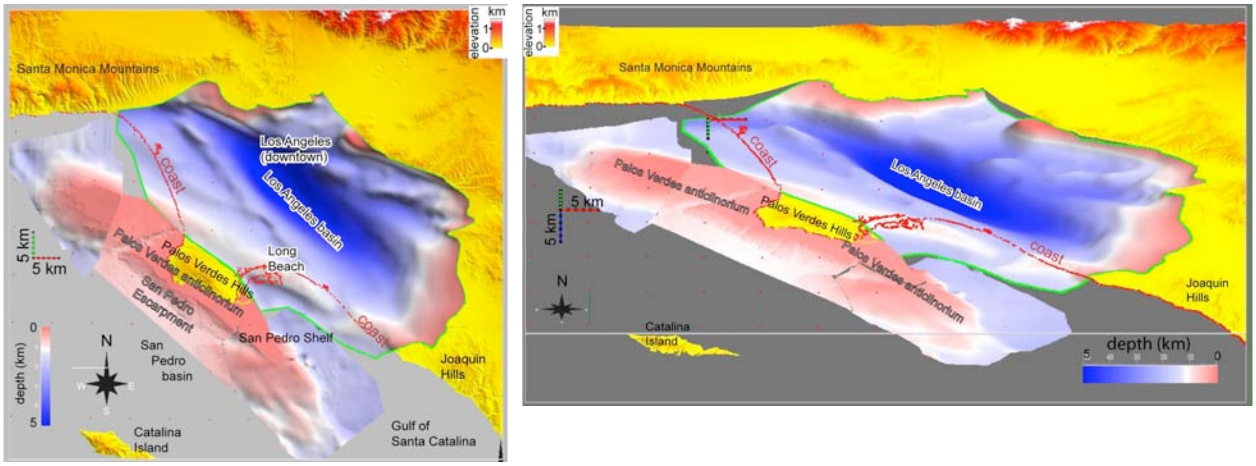

Figure 2: Near top Miocene subsurface stratigraphic horizon (blue to pink) and Digital Elevation Model (DEM) of Palos Verdes anticlinorium (PVA) and Los Angeles basin. The 70 km-long PVA is paired with subsiding, 5 km-deep Los Angeles basin, with the regional fold limb between them growing above blind regional thrust faults. Interpretation of part of the San Pedro Escarpment is incomplete and multibeam bathymetry is shown there (Dartnell and Gardner, 1999). The subsurface of the onshore Los Angeles basin is digitized from Wright (1991). The offshore sub-bottom is from our mapping. **Left:** Plan view. **Right:** Oblique view towards the north.

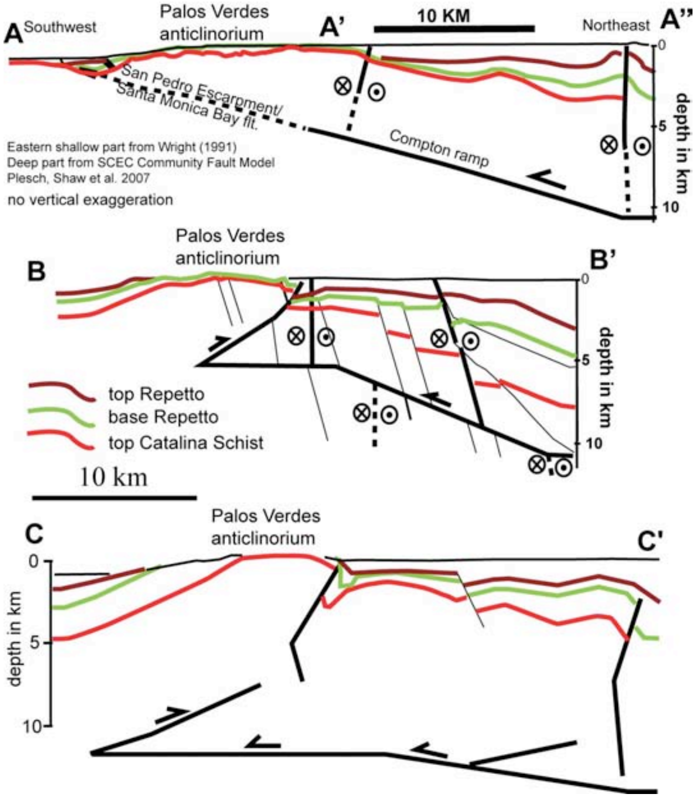

Figure 3. Cross sections, all at same scale with no vertical exaggeration, located on Figure 1. **A:** Our interpretation across the northwest plunge of Palos Verdes anticlinorium (PVA), combining offshore depth-converted seismic profile, a cross section from Wright (1991) and the SCEC Community Fault Model (Plesch, Shaw et al., 2007). **B:** Simplification of cross section from Shaw and Suppe (1996). SW-dipping roof thrust explains uplift of crest of PVA, but does not explain the SW-dipping offshore fold limb. **C:** Simplification of cross section from Davis et al. (1989). This interpretation explains the southwest limb of PVA as a backlimb above a SW-dipping roof thrust. The San Pedro Escarpment fault (A) could project directly to the deep ramp shown in C-C', could merge with flat if the ramp is as shallow as in B-B', or could project beneath the southern Compton ramp and merge with a basal decollement.

Thrust slip beneath Palos Verdes anticlinorium

The onshore restraining segment of the Palos Verdes fault contributes locally some contraction that may account for enhanced uplift of the Palos Verdes Hills (Ward and Valensise, 1994; also Woodring et al., 1946), but cannot account for the major part of the PVA. Broad contractional folding is inconsistent with the young extension near a releasing double bend on the sub-vertical Palos Verdes fault (Fig. 4). The offshore anticlinorium can instead be explained by the NE-dipping San Pedro Escarpment fault (SPEF), which aligns in 3D with the Compton thrust ramp of Shaw and Suppe (1996) and may be the same fault (Fig. 3).

The PVA's southwest limb has over 1 km of relief at F-F' (Fig. 2). A simple model of motion of the hanging-wall up a fault ramp can be used to calculate 1.6 mm/yr slip for a fault dipping 20º, or 1.1 mm/yr for a fault dipping 30º.

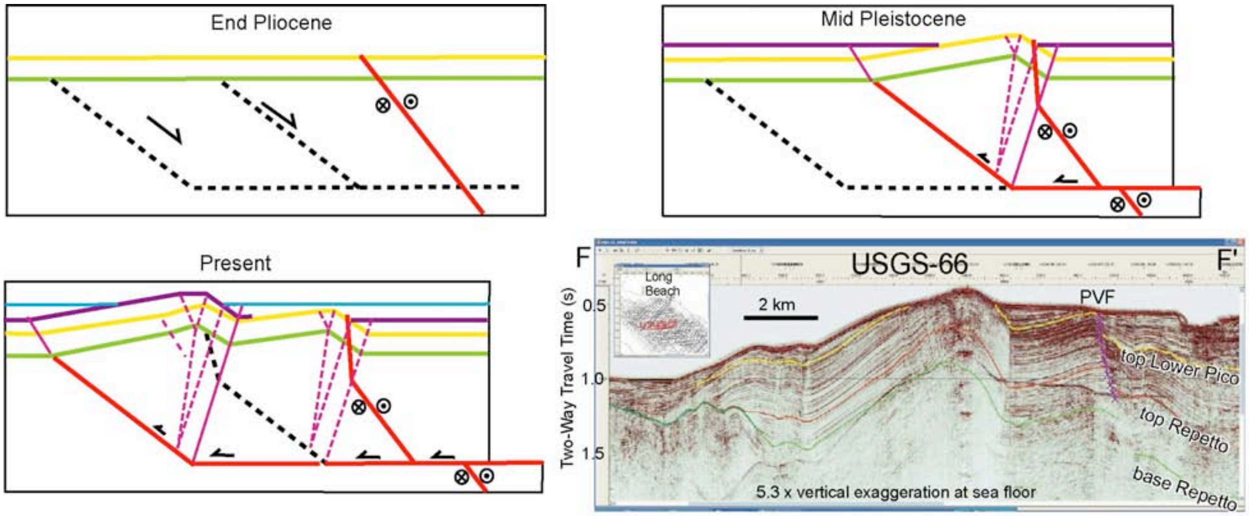

Figure 4: Model for growth of a complex broad forelimb, similar to the southeast part of Palos Verdes anticlinorium (PVA). Ages are given for comparison to the reflection profile F-F'. The folding was copied directly from Figure 3A of Wickham (1995); his Figure 3A was then shifted to the left and subsequent folding also directly traced. **Top left**: End Pliocene (yellow). Right-dipping dextral fault is active, but normal slip on the two other faults had ended previously, by end Miocene (green). **Top right**: Mid Pleistocene (violet). One of the normal faults is reactivated as a thrust. The forelimb is much wider than the backlimb in this displacement gradient fold model (Wickham, 1995, in contrast to widely-applied fault propagation fold models (e.g., Suppe and Medwedeff, 1990). **Bottom left**: Present. Reactivation propagated forward to the outer fault. **Bottom right**: Migrated USGS multichannel seismic reflection profile F-F', located on Inset and Figure 1. The interval between top Repetto (~2.5 Ma, brown) and top Lower Pico (~1.8 Ma, yellow) does not thin on the southwest dipping limb, while Quaternary strata onlap the lower fold limb, suggesting it did not start folding until the beginning of Quaternary time. The entire Pliocene section pinches out beneath the modern bathymetric basin; we interpret the footwalls of NE-dipping Miocene normal-separation faults to have remained relatively high-standing through Pliocene time there. The right-lateral Palos Verdes fault dips northeast away from the crest of the anticlinorium and has normal separation, and thus does not explain the folding.

Thrust-fold models for Palos Verdes anticlinorium

The southwest-dipping limb of PVA has been interpreted as a backlimb above a SW-dipping roof thrust by both Davis et al (1989) and by Shaw and Suppe (1996). Considering only the PVA southwest of the Palos Verdes fault, its southwest limb is wider than its northeast limb (Fig. 3). The most prominent anticline within the southeast part of the PVA also has a broad SW-dipping limb and a short, steeper NE-dipping limb (Fig. 4). Kink-band migration models such as fault bend folds of Suppe (1983) and fault propagation folds of Suppe and Medwedeff (1990) have backlimbs that are wider than forelimbs. Presumably, a SW-dipping thrust was inferred to explain the observed asymmetry of PVA without violating these specific models. However, displacement gradient folds (Wickham, 1995) can have forelimbs much wider than backlimbs, so asymmetry of an anticline does not determine fault dip direction. These displacement gradient (cumulative slip) and slip rate gradient (instantaneous slip rate) folds may be especially appropriate for thrust reactivation of pre-existing faults. NE-dipping faults are imaged and large SW-dipping faults are not imaged on seismic reflection profiles beneath San Pedro Escarpment. Unlike published interpretations, we interpret the southwest limb of the PVA to be a forelimb above NE-dipping thrust faults that dip beneath San Pedro Escarpment. The difference in fault geometry and predicted slip distribution during an earthquake has strong consequences to strong ground motion and tsunami generation immediately offshore of Los Angeles Harbor.

Other SCEC-related Efforts

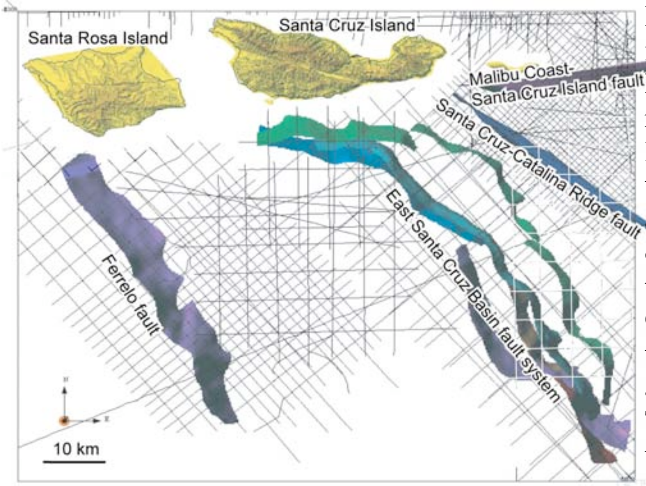

Figure 5: Map of 9 pieces of depth converted faults supplied to the SCEC Community Fault Model (CFM). Black lines are the seismic reflection profiles used in the mapping. The left-lateral Malibu Coast-Santa Cruz Island fault and the right-lateral Santa Cruz-Catalina Ridge fault are sub-vertical and not yet depth-converted. The other faults are northeast-dipping thrust or oblique thrust faults that fold the sea floor and inferred Quaternary strata. All faults were interpreted together with graduate student Sarah Schindler in an NSF-funded project lead by Craig Nicholson. The depth conversion was done using interval velocity layers following geologic horizons. This and coordinate transformations were done specifically for the CFM.

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