Contributions to the SCEC Community Fault Model: Relating onshore-offshore stratigraphy and fault-fold activity beneath Santa Monica Bay

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We used industry seismic reflection data to map a blind N-dipping low-angle fault beneath central and eastern Santa Monica Bay, along 65 km of its strike (Figs. 1, 2). This fault could be called the tip of the Santa Monica Mountains thrust, the Shelf Projection thrust, or the San Pedro escarpment thrust. We interpret it to be a basal Miocene detachment associated with clockwise vertical-axis rotation of the Santa Monica Mountains. It is located south of and beneath the Santa Monica-Dume fault (Fig. 3). Several contractional structures indicate that it has been reactivated, with different structural styles for each. The western part, south and southwest of Pt. Dume, has been only slightly reactivated near its upper tip by post-Miocene folding. However, its downdip projection merges with or intersects the moderately-dipping Santa Monica-Dume fault. Any active folding of the Santa Monica Mountains anticlinorium absorbs a deep thrust slip component on these faults. The central and southeast part of the fault is overlain by the WNW-trending Palos Verdes anticlinorium, including a 20 km-wide offshore part beneath the Shelf Projection, located off of Manhattan Beach. The M5.0 1979 and 1989 earthquakes are spatially associated with the offshore part of this fold, but cross sections show them and many smaller quakes to be beneath the fault, unless it dips more steeply at depth (Fig. 3). The fault, or linked system of faults, then bends to the southeast, where its tip is beneath the base of San Pedro escarpment. The San Pedro escarpment is a dip slope associated with a SW-dipping fold limb, where the seafloor is almost as steep as the underlying strata. The NE-dipping fault segment that we mapped is aligned in 3D with the Compton thrust map from the Community Fault Model (Fig. 3C; Plesch and Shaw, 2002; Shaw and Suppe, 1996).

The Shelf Projection anticlinorium had previously been interpreted as en-echelon with, and distinct from, the Palos Verdes anticlinorium (Nardin and Henyey, 1978; Legg et al., in press). We remapped these anticlinoria and show that they are now a single structure. This single 40+ km-long anticlinorium, on both Palos Verdes Peninsula and at the Shelf Projection, include short-wavelength (1/2-1 km) folds. (Fig. 4; Dibblee, 1999; Fisher et al., 2003;). It is these folds that are en-echelon. The involved rocks are late Miocene (e.g., Nardin and Henyey, 1978), and we hypothesize that this short-wavelength folding predates the larger structure. This folding sequence may be common, as dated strata show that short-wavelength Pliocene folds precede long wavelength folding of the Channel Islands anticlinorium (Seeber and Sorlien, 2000).

We have two primary tasks before submitting and resubmitting manuscripts for publication. One is to more convincingly show the existence of (a) blind fault(s) beneath the Palos Verdes (includes Shelf Projection) anticlinorium. The other is to show whether or not this fault is active. There is not a single seismic reflection profile that will convince all readers that the fault exists. However, using numerous seismic reflection profiles from industry and USGS allows the interpreter confidence in the existence of the blind fault(s) (Figs. 2, 4). Relocated hypocenters of Hauksson (2000) and of Armbruster and Seeber do not show a single simple fault surface, and these hypocenters are mostly below the blind fault (but may be above a NE-dipping Miocene normal-separation fault whose seafloor trace is located farther to the southwest) (Fig. 3). Folds, in the absence of diapirism, are the product of slip on faults. Where faults strike parallel to contractional folds in their hanging-walls, a blind component of slip on underlying faults must be absorbed by the folds. Therefore, if there is an active Palos Verdes anticlinorium, there must be a responsible active fault. The fact that we have mapped the upper tips of a blind fault system is almost irrelevant to the existence of blind fault slip. So, the question becomes whether the Palos Verdes anticlinorium is actively folding, and if so, whether its offshore part beneath the Shelf Projection and across the Redondo Canyon fault is also actively folding. We call the underlying fault the Palos Verdes-Shelf Projection blind fault for now because it is premature and would cause confusion to call it the upper Compton blind fault.

Palos Verdes Peninsula has active surface and rock uplift (LaJoie, 1986). This uplift has been explained as the result of ~3 mm/yr right-lateral slip on the Palos Verdes fault, and a restraining segment (Ward and Valensise, 1994). While the restraining segment supplies a component of convergence, this convergence need not be accommodated solely on the Palos Verdes fault; the width of the fold suggests involvement of a low-angle fault (e.g., Shaw and Suppe, 1996). The uplift with respect to sealevel underestimates increase in structural relief if Santa Monica and San Pedro basins are subsiding, as we and others have proposed (Sorlien et al., 2003; Bohannon et al., submitted; see Pinter et al., 2003). Folding of San Pedro escarpment is not explained in cross sections by Shaw and Suppe (1996).

The part of the Palos Verdes anticlinorium beneath the Shelf Projection had been proposed to be active between 3 and 1 Ma. (Nardin and Henyey, 1978). Industry and USGS seismic reflection profiles appear to image the upper few hundred meters of strata onlapping the fold. Our reprocessing of USGS data attenuated multiples and images progressively-tilted Pliocene strata on the north limb of the fold. Rapid (.28-.58 mm/yr) Holocene sedimentation shown in cores (Sommerfield and Lee, 2003), and an unconformity imaged at ~~300 m below sea floor on the seismic, suggests that the non-tilted strata are younger than 0.5 to 1. million years, or younger if sedimentation rates have been higher during glacial periods. We correlated a reflection from ~50 ka strata at the base of ODP site 1015 to the south limb of the anticlinorium (Shipboard Scientific Party, 1997; Normark and McGann, 2003). Strata beneath the post-50 ka package, but above any unconformity, can be followed about 300 vertical meters up the south fold limb (Fig. 4). Barring drape by erosion of the Shelf Projection during sea level eustatic lowstands, it appears that this limb is actively folding. Our mapping shows the right-lateral Palos Verdes fault to split up and die out within northeast Santa Monica Bay (Fig. 1; see also Fisher et al., 2003). We also mapped the right-lateral San Pedro Basin fault, which has 40 m structural relief of the 50 ka horizon. Part of the contraction that forms the Palos Verdes-Shelf Projection anticlinorium is due to a restraining left stepover between these two right-lateral faults.

Conclusions

The Palos Verdes anticlinorium extends 20+ km west-northwest into Santa Monica Bay, beneath the Shelf Projection. The offshore part includes a progressively-tilting north limb, and a steeper south limb that folds probable late Quaternary strata. A blind fault mapped beneath a large area of Santa Monica Bay projects beneath this structure and into the Compton thrust ramp. Although upper parts of this fault may not be active, the scale of the active Palos Verdes-Shelf Projection anticlinorium suggests a ~800 square km underlying active fault-and we have not included possible offshore continuations south of Palos Verdes Hills. We also provided a 3D representation of 30 km of the right-lateral San Pedro Basin fault, and of 25 km of a steep fault that cuts the San Pedro escarpment; both faults continue southeast beyond out study area.

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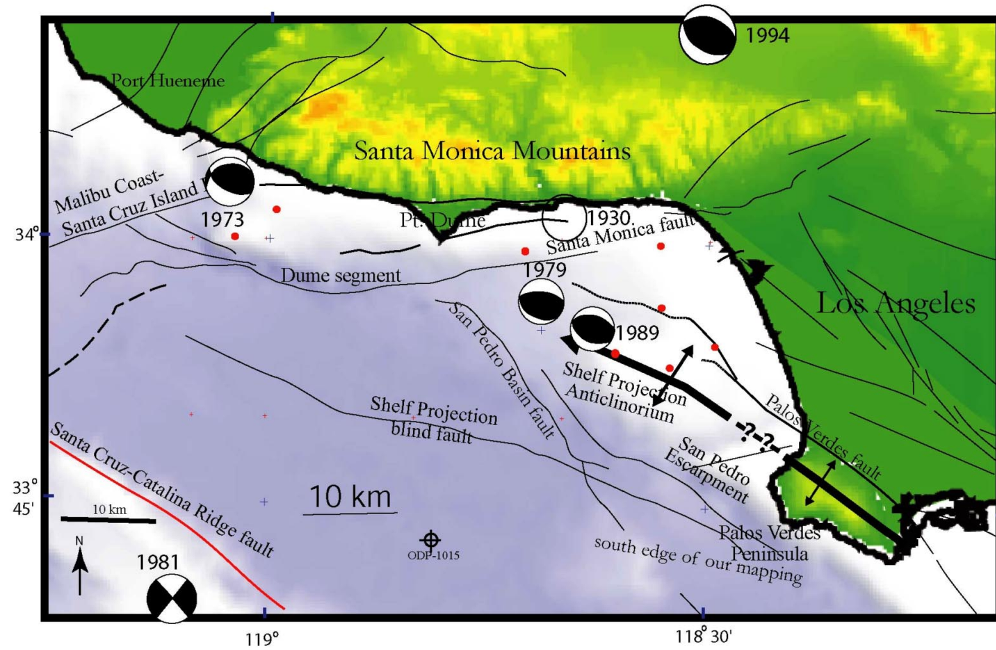


Figure 1: Fault map of Santa Monica Bay and vicinity. Focal mechanisms from USGS and SCEC (1994) and Haukkson and Saldivar (1986). Red dots are those wells used in the project (others exist). The Palos Verdes anticlinorium extends WNW beneath the Shelf Projection.

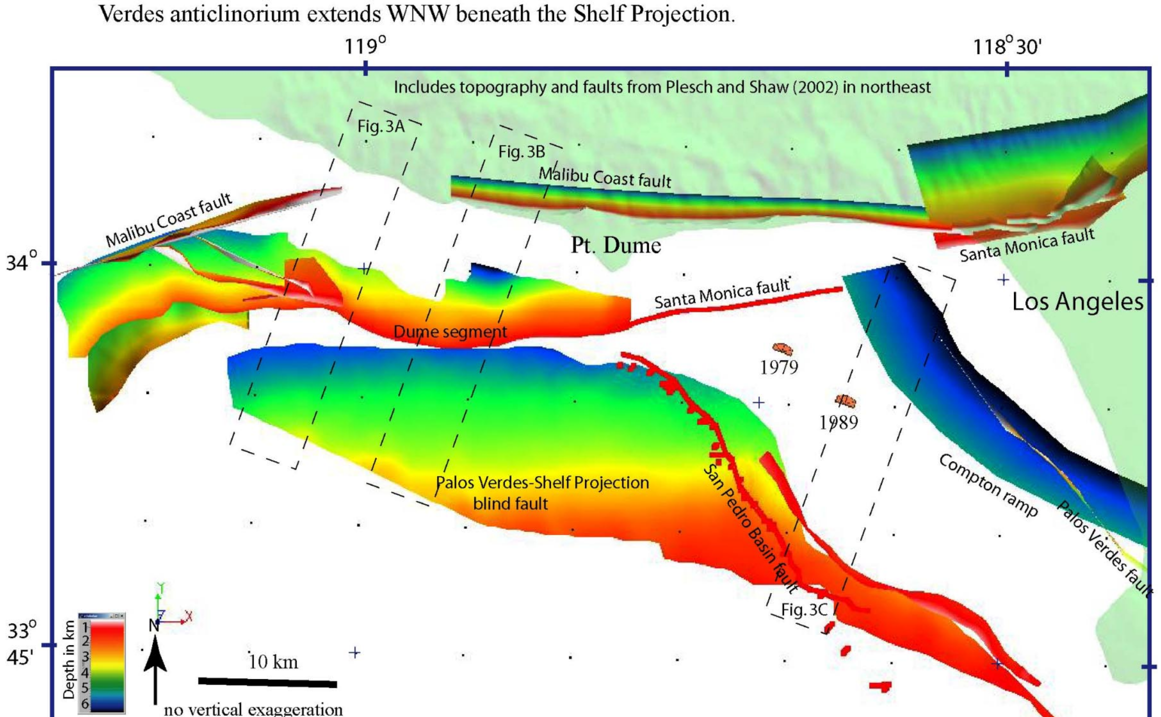
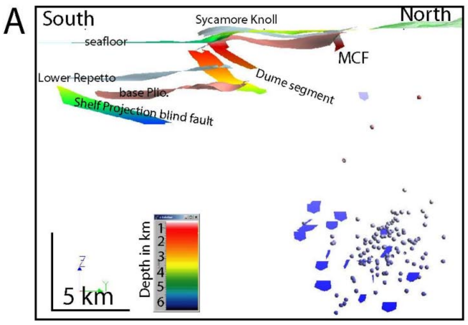


Figure 2: Representation of faults, using the software GOCAD. The onshore Malibu Coast fault, onshore Santa Monica Fault, Compton ramp, and Palos Verdes fault from Plesch and Shaw (2002) and are made transparent below 6.5 km. The rest of the faults we have supplied to the SCEC CFM. The Southeast part of our Palos Verdes-Shelf Projection blind fault is aligned in 3D with the Compton ramp and may be the same fault. The offshore Santa Monica fault east of Point Dume dips moderately north; we did not map it to the coast due to a data gap.



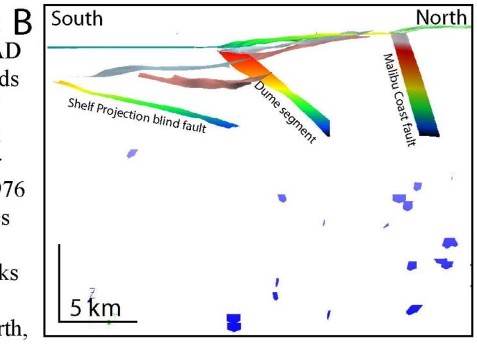


Fig. 3: Five km-thick slices through GOCAD model, viewed towards 290 deg. azimuth, of one nodal plane from Hauksson (2000), for quakes from 1975-1976 and 1981-2002. Slices located in Fig. 2. A: spheres are aftershocks of 1973 quake from Stierman and Ellsworth, (1976). Legend gives depth of faults, base Pliocene is pink, ~4 Ma horizon within Pliocene is light blue. Nodal planes are polygons with point downdip and flat edge being horizontal. B and C: Malibu Coast fault and Compton ramp from Plesch and Shaw (2002) and shown to 6.5 km depth. Compton ramp aligned in 3D with Palos Verdes-Shelf Projection blind fault, especially to SE of C.

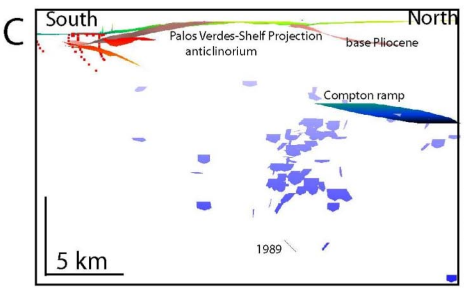


Fig. 4 (below): USGS-43, located in inset, and dashed rectangle shows area shown uninterpreted at bottom. NNW-SSE right-lateral San Pedro basin fault cuts acrossWNW-ESE blind fault in this area. Reflections immediately below the 50 ka reflection have 300 m structural relief on this fold limb, assuming they were deposited horizontally.