Digital 3D mapping of active faults beneath Santa Monica Bay, basin modeling, and strain partitioning: Collaborative Research UCSB and LDEO

USDI/USGS 03HQGR0048 (UCSB)
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NEHRP Element: I Keywords: Neotectoncs, Reflection Seismology; Tectonic Structures, Fault Segmentation

Non-Technical Summary

Acoustic data were used to map faults beneath Santa Monica Bay, California. The right-horizontal San Pedro Basin fault has a local vertical component of 40 m in 50 ka. Links between the onshore Santa Monica fault, and offshore Dume segment, and Malibu Coast fault were also mapped. The fold beneath Palos Verdes Hills continues offshore and covers at least 800 square kilometers. Active folding is suggested by crestal uplift, subsidence of its flanks, and by offshore folding of 50 ka rocks. A buried fault was mapped that projects beneath this fold and into the Compton thrust ramp.

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INVESTIGATIONS UNDERTAKEN

We used industry and USGS seismic reflection data controlled by well and seafloor data to map a regional blind fault and also several other faults that reach to or close to the seafloor. This work covers northern Santa Monica Bay, California. The maps were constructed digitally, depth-converted, and provided to the SCEC Community Fault Model. In addition to these fault maps and our previously mapped lower Pliocene horizon, a digital map on base Pliocene is completed over the whole area (is top Miocene, but upper Miocene is missing in places). A map of the upper Pliocene top "Repetto" is almost complete for the area east of Pt. Dume. A ~50 ka horizon is correlated from ODP site 1015 (Normark and McGann, 2003; Shipboard Scientific Part, 1997) through part of the study area.

RESULTS

A blind N-dipping low-angle fault was mapped 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, the San Pedro escarpment thrust, or the upper Compton-Los Alamitos blind fault. Here, it is called the Palos Verdes-Shelf Projection blind fault because it projects beneath the Palos Verdes-Shelf Projection anticlinorium. 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. 3a). 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 below its mapped uppermost part (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 (Fisher et al., 2003). The NE-dipping fault segment that we mapped is aligned in 3D with the Compton thrust map from the SCEC 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, although with a slight right warp (Fig. 1). 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 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 focal mechnisms 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. In fact, the impressive area of the Palos Verdes-Shelf Projection blind fault shown in Figure 2 shows little evidence of deformation of the post-Pliocene strata above it: it is the deeper downdip part of this fault that may be active. 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.

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 proposed by others and ourselves (Sorlien et al., 2003a; 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), as the west tip of their thrust wedge is near the coastline.

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 profiles, 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 on several profiles (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.

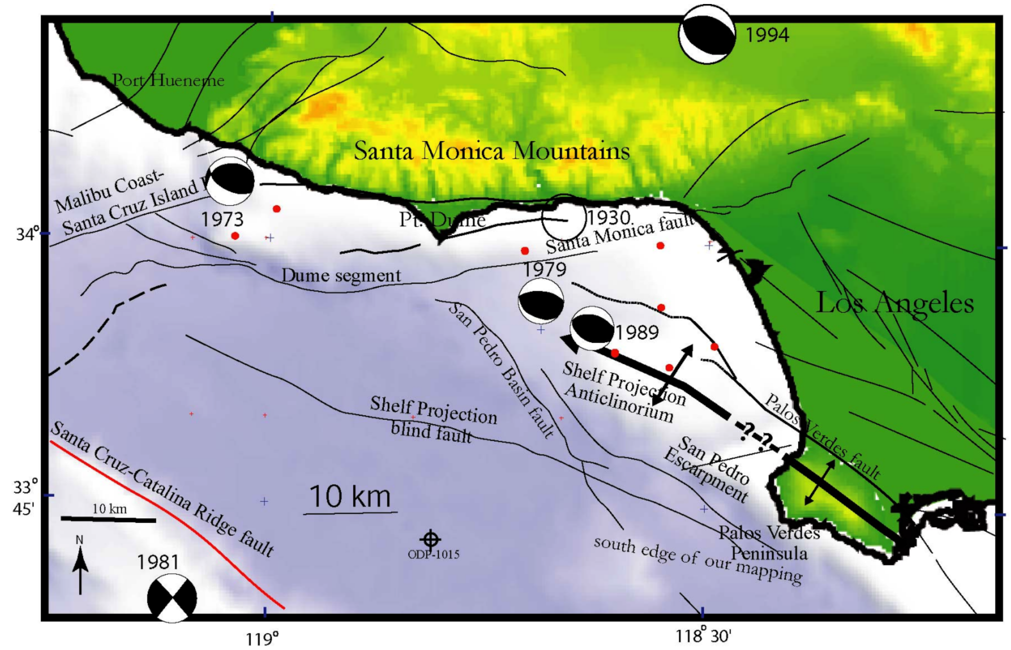


Figure 1: Fault map of Santa Monica Bay and vicinity. Focal mechanisms from USGS and SCEC (1994) and Haukkson and Saldivar (1986). Red dots are those wells used in the project (others exist). The Palos Verdes anticlinorium extends WNW beneath the Shelf Projection.

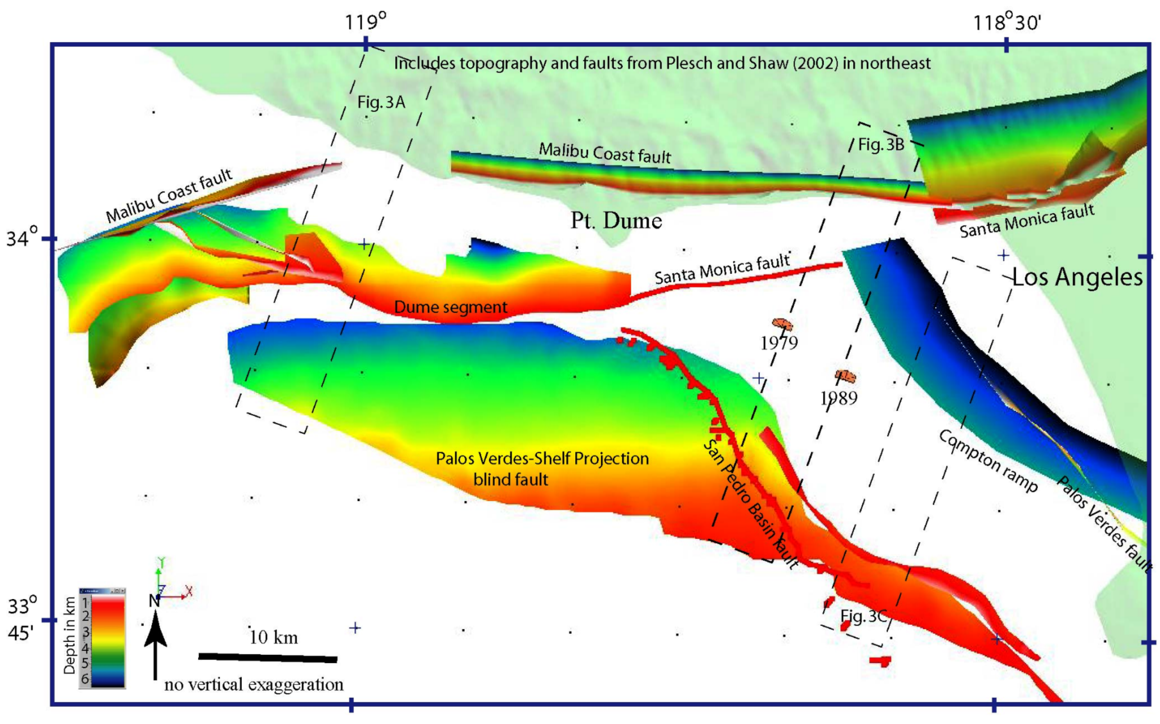
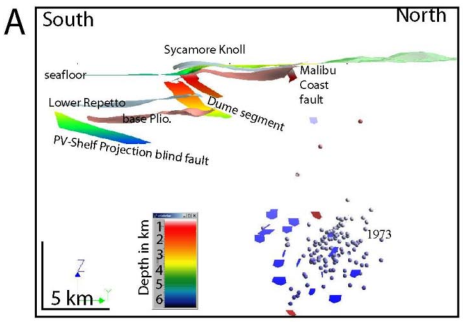


Figure 2: Representation of faults, using the software GOCAD. The onshore Malibu Coast fault, onshore Santa Monica Fault, Compton ramp, and Palos Verdes fault are from Plesch and Shaw (2002) and are made transparent below 6.5 km. The rest of the faults we have supplied to the SCEC CFM. The Southeast 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.



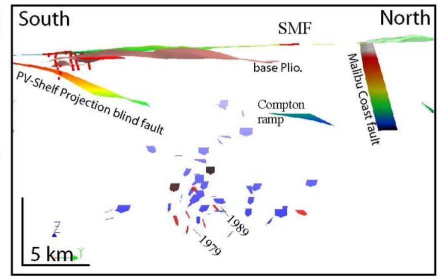


Fig. 3: Five km-thick slices through GOCAD model, viewed towards 290 deg. azimuth, of one nodal plane from quakes from 1975-1976 and 1981-2002 (blue; Hauksson, 2000). Selected slip planes (red) from 1971 and 1977-1980 (Armbruster and Seeber). Slices located in Fig. 2. A: spheres are aftershocks of 1973 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 horizontal. B and C: Malibu Coast fault and Compton ramp from Plesch and Shaw (2002), shown to 6.5 km depth. Compton ramp aligned in 3D with Palos Verdes-Shelf Projection blind fault. SMF=trace Santa Monica fault.

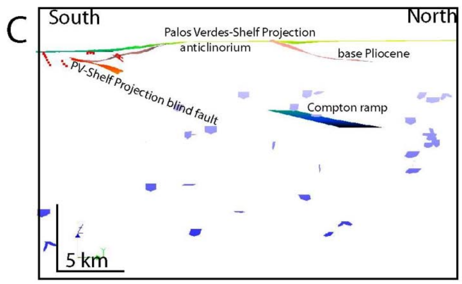
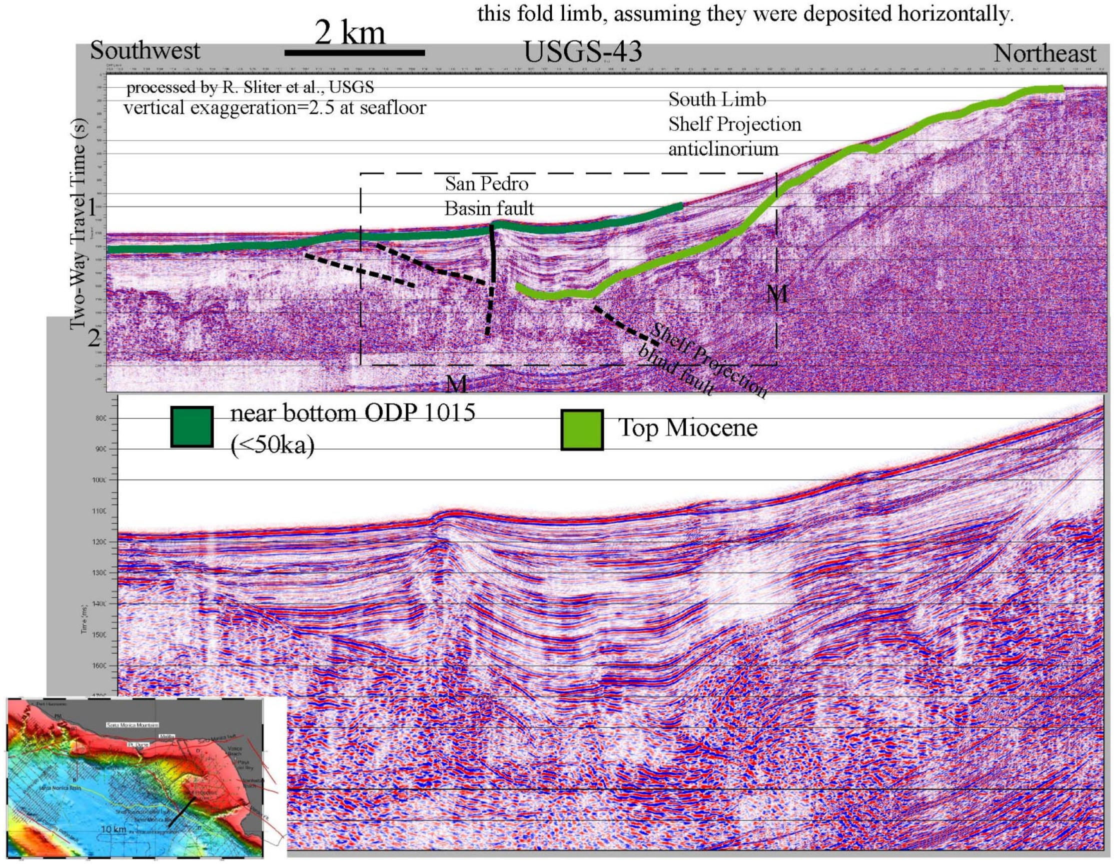


Fig. 4 (below): USGS-43, located in inset, and dashed rectangle shows area shown uninterpreted at bottom. NNW-SSE right-lateral San Pedro basin fault cuts acrossWNW-ESE blind fault in this area. Reflections immediately below the 50 ka reflection have 300 m structural relief on this fold limb, assuming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



Notes: Related but distinct work has been funded by NEHRP and SCEC. This report is similar to Sorlien et al., 2003b. For more information, figures, and estimates of deformation see our NEHRP final report, due January 31, 2004. The coauthors will not review this report (they will review the Final Technical Report), but Broderick, Seeber, Sliter, and Fisher have approved Sorlien et al., 2003b. See Sorlien et al., 2003c for more information on the Santa Monica-Dume fault system, including long-term slip estimates. What we now call the Palos Verdes-Shelf Projection blind fault we had previously called the "Tuscan Red" fault after the color pencil, then the Shelf Projection blind fault. We now interpret the Shelf Projection anticlinorium to be the same fold as the Palos Verdes anticlinorium. If future work shows that this fault indeed extends downdip into the Compton-Los Alamitos ramp, an additional name change may be required. NEHRP funding supported a large part of the Master's thesis of Kris Broderick.

Reports published

See the reference list for Sorlien et al. 2003a and b. An unpublished manuscript will be rewritten as two separate papers, one on the Santa Monica-Dume fault and another on the Palos Verdes-Shelf Projection anticlinorium and blind fault, and associated high-angle faults. This latter manuscript will be developed by Kris Broderick (and others) from his thesis (in progress).

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Drew Mayerson and others at the U.S. Minerals Management Service provided access to the Digicon data, Tom Wright's and David Okaya's efforts made Exxon data available to SCEC researchers, other industry sources provided additional data. John Armbruster did one set of the earthquake relocations. Egill Hauksson provided a more up-to-date version of the relocated hypocenters referenced as Hauksson (2000). Bruce Luyendyk is supervising Kris Broderick's thesis. Information on petroleum wells along the Los Angeles area coast was found in the repository at Long Beach State operated by Dan Francis. Discussions with Bob Bohannon and Shirley Baher of USGS are appreciated.

Data Availability

Well data, including sonic surveys, are public and available from the California Division of Oil and Gas in Long Beach, Dan Francis' data repository at Long Beach, or from us. Wells in Federal waters (more than 5 km from the coast) are usually available from the US Minerals Management Service in Camarillo, but the wells in Santa Monica Bay all predate 1970 and the MMS does not seem to have information on them. The 800x2500 m grids of single channel sparker data, minisparker, and 3.5 kHz data are described in Burdick and Richmond (1982), but are apparently are missing from the sets of microfilm available from the NGDC. The originals can be found with difficulty from the US Minerals Management Service, but it is probably simpler to contact us. A 2.5 km by 2.5 km grid of non-migrated mid-1970s-vintage multichannel seismic reflection data from Digicon has been released by the U.S. Minerals Management Service and the films are in Camarillo. A grid of migrated seismic reflection data from Exxon is available from the Southern California Earthquake Center (contact David Okaya). Other industry seismic reflection data used in this project are not available, but may become available as part of the ongoing effort to transcribe and make public industry data. Our digital structure-contour maps of faults have been provided to the SCEC Community Fault Model (http://structure.harvard.edu/cfma/), although some of our faults are not in version CFM-1.01beta. BASIC programs and awk scripts were written to convert focal mechanism data (e.g., Hauksson, 2000) into our GOCAD format. These are available from C. Sorlien, but are in an old version of Omikron BASIC and would have to be reprogrammed for other languages. Contact Christopher Sorlien at chris@crustal.ucsb.edu for additional information on data.

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