Santa Monica Bay revisited: Digital representations for the Community Fault Model using newly-available industry seismic reflection data

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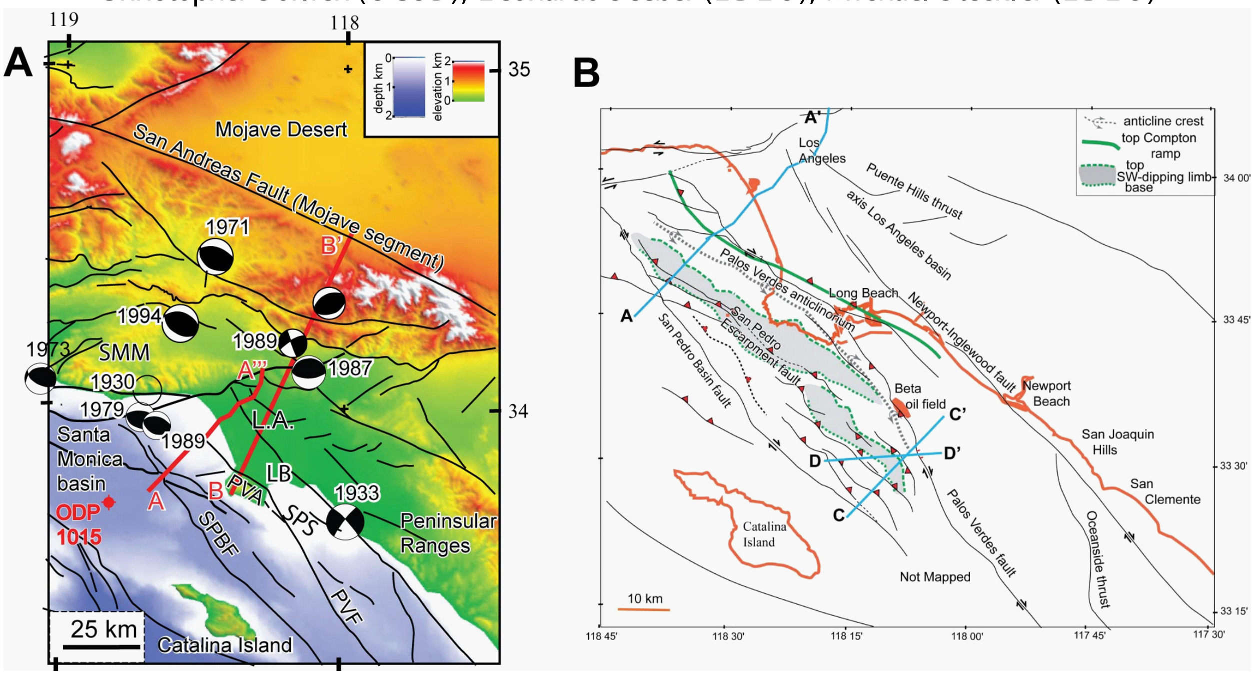

Figure 1: A: Faults, destructive earthquakes (shown as focal mechanisms in lower hemisphere projections from USGS and SCEC, 1994), and locations of cross sections. The traces or upper edges of blind faults are from the Southern California Earthquake Center Community Fault Model (Plesch et al., 2007) and from Sorlien et al. (2006, and submitted). L.A.=Los Angeles (downtown); LB=Long Beach (city and harbor); PVA=Palos Verdes anticlinorium, PVF=Palos Verdes fault; SPBF=San Pedro Basin fault; SMM=Santa Monica Mountains; SPS=San Pedro Shelf. **B:** Map showing the upper edges of faults. Gray fill is the southwest limb of Palos Verdes anticlinorium. Red triangles are on hanging-wall side of thrust-separation faults.

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; Fig. 1). The 700 m-high sea floor San Pedro Escarpment is the expression of the southwest limb of PVA. 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., Ward and Valensise, 1994). 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 (Davis et al, 1989; Shaw and Suppe, 1996). We have proposed a variation of the regional thrust model, where a SW-dipping roof thrust is not required and NE-dipping thrust-separation faults root beneath Los Angeles basin (Figure 2). The upper tips of these faults are imaged on seismic reflection profiles. These faults may connect with the Compton thrust ramp of Shaw and Suppe (1996), may root beneath the Compton, or both. Figure 3 shows our comparison GPS velocities, and at the same scale, of cross sections across the Nepal Himalaya (Avouac, 2003) and Los Angeles region (Argus et al., 2005). GPS shortening is seen above the transition from the deep creeping thrust beneath the high Himalaya to its shallow locked part. Earthquakes have ruptured updip100 km south of the now contracting transition. GPS-measured shortening beneath and north of downtown Los Angeles could also in part be related to a regional locked thrust system that extends into offshore San Pedro Basin.

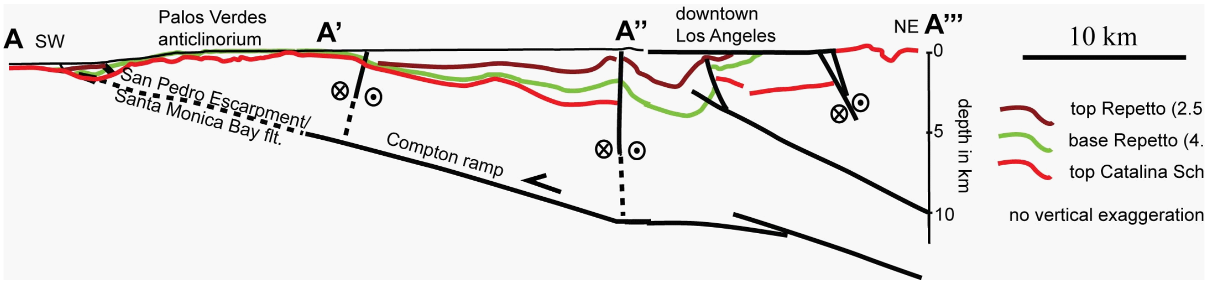

Figure 2. Cross section across the northwest plunge of Palos Verdes anticlinorium. No vertical exaggeration. It combines an offshore depth-converted seismic profile, a cross section from Wright (1991) and the SCEC Community Fault Model (Plesch, Shaw et al., 2007). Located on Figure 1.

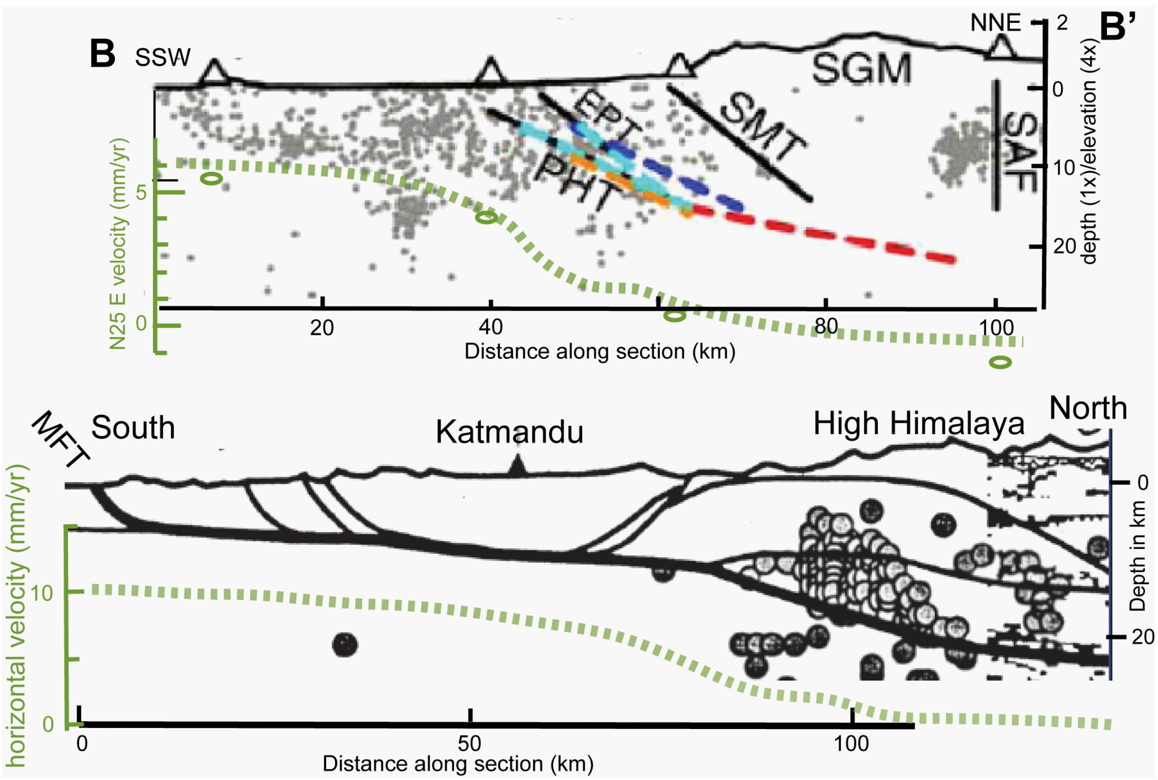

Figure 3: GPS velocity profile (dotted green; best-fit model) and hypocenters across LA basin (**A**; modified from Argus et al., 2005). In order to fit the profile by thrust faulting, the long-term horizontal slip component needs to be 8mm/y. Seismicity is as deep as 15-20km and best-fit fault (blue) has unrealistically shallow locking depth of 6km, which Argus et al. (2005) ascribe to the un-modeled lower stiffness of the basin relative to the uplifted basement to the north. Furthermore, known thrust faults in the LA Basin can only account for about half the observed shortening. Could the missing slip be taken up by a shallower-dipping fault surfacing far to the SSW?. Such a fault would be analogous to the basal Himalayan detachment (" MFT"), which has ruptured in great historic earthquakes and is associated with A GPS velocity profile that resembles the LA Basin profile (**B**; combined from Avouac, 2003).

Our data and approach
We had previously completed stratigraphic interpretations of the northwest part of the PVA beneath Santa Monica Bay (Broderick, 2006), and of the southeast plunge of PVA beneath San Pedro Shelf and adjoining slope. However, stratigraphic correlation between the two areas had not been done and the preliminary fault interpretation of the central and southern San Pedro Escarpment was based on limited data then available. We have now completed the interpretation, correlating a Miocene-Pliocene unconformity and top Repetto through several grids of industry and USGS seismic reflection profiles, and remapped the faults in San Pedro Basin and along San Pedro Escarpment (Fig. 1b). As part of this, we incorporated several additional wells on San Pedro Shelf on either side of the Palos Verdes fault, using paleontology and well logs provided by the Minerals Management Service (MMS) (Fig. 4).

Discussion
Multibeam bathymetric data image a field of latest Pleistocene-Holocene short-wavelength folds centered midway between Catalina Island and Long Beach (Dartnell and Gardner, 1999; Fisher et al., 2004). We mapped mostly NE-dipping blind (oblique?) thrusts beneath them (Figs 1b, 4, 5). Late Pliocene strata do not thin onto the southern San Pedro Escarpment, which is nearly a dip slope, indicating that this fold limb initiated at the beginning of Quaternary time. These faults reactivate some of the numerous strands of Miocene extensional faults, which in turn logically reactivated early Miocene and older subduction-related thrust faults. The critical question is whether the Quaternary reactivation is being driven by local strike-slip tectonics, or whether this folding represents the tip of a regional thrust system rooted beneath Los Angeles.

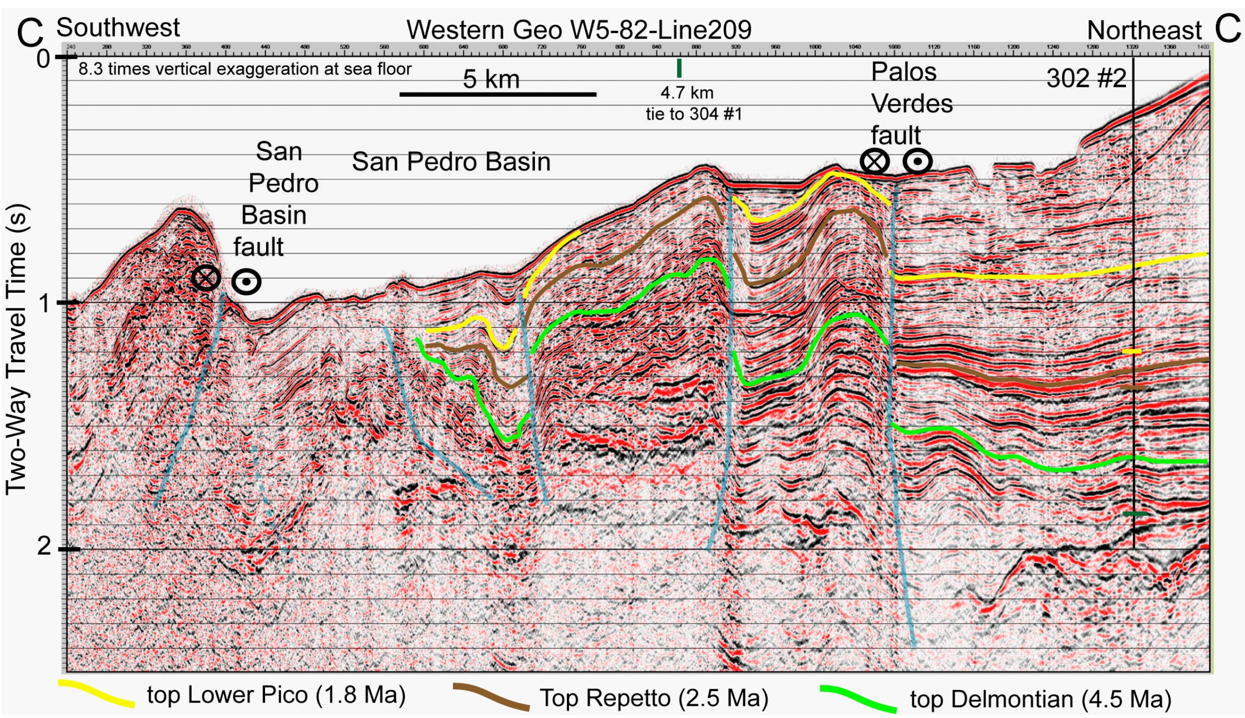

Figure 4: Multichannel industry profile from the USGS NAMSS web site (Hart and Childs, 2005). Minerals Management (MMS) paleontology and velocity surveys from wells on either side of the Palos Verdes fault, along with dated sea floor outcrop (Nardin and Henyey, 1978) constrain the stratigraphy. Northeast of the Palos Verdes fault the top Lower Pico of Wright (1991) and Rigor (2003) is used rather than the deeper MMS picks.

Our new mapping illustrates a restraining segment in the right-lateral San Pedro Basin fault adjacent to the zone of basin-floor folding. Catalina Island represents an uplift associated with a restraining segment on a fault to its south (Legg et al., 2007), and it may be impinging on San Pedro Basin (Fig. 1). Such transpression may be enhancing contraction associated with regional SW-verging thrusting rooted beneath Los Angeles. Subduction resulted in a preferential landwards dip on large gently to moderately-dipping offshore faults. NE-dipping faults that extended during the Miocene are imaged beneath San Pedro Basin (Sorlien et al., in revision). However, it is the PVA, which extends beyond restraining segments of local strike-slip faults, which may be most convincing for the existence of a regional thrust system rooted beneath Los Angeles. Our recent completion of the near top Miocene stratigraphic interpretation will allow us to produce an improved digital representation of the PVA.

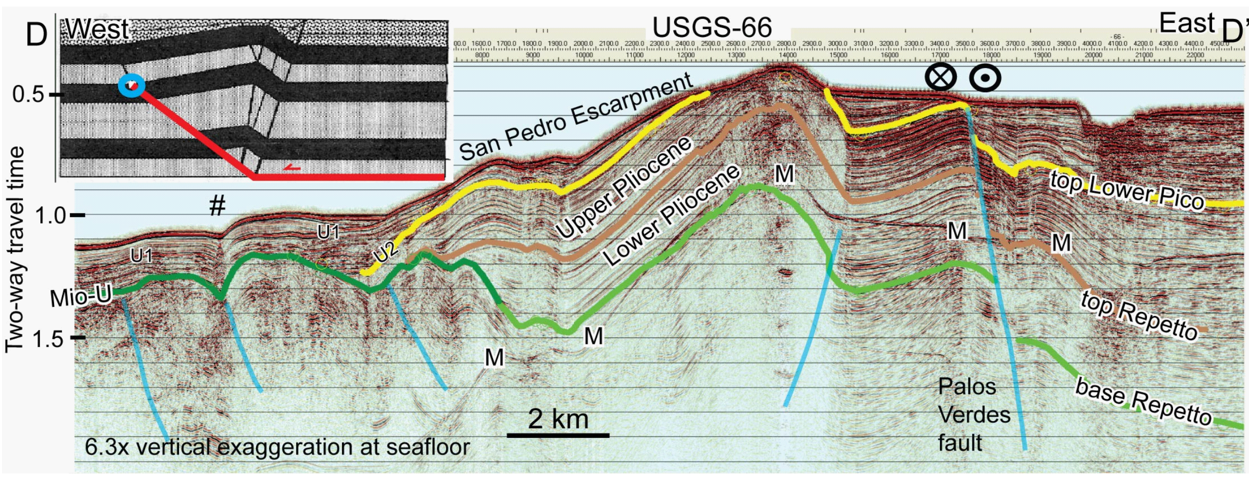

Figure 5: Migrated USGS multichannel seismic reflection profile D-D', located on Figure 1. Data from Sliter et al., (2005). The thickness between top Repetto (~2.5 Ma, brown) and top Lower Pico (~1.8 Ma, yellow) does not change on the southwest limb of the PVA. Quaternary strata onlap of the lower part of the limb and probably mark the initiation of folding in this part of the structure. The entire Pliocene section pinches out beneath the modern bathymetric basin at the west end of profile, which is interpreted as the footwall of NE-dipping Miocene normal-separation faults. This area remained relatively high-standing through Pliocene time. 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. The inset shows a figure from Wickham (1995), where the progressively-tilting forelimb is wider than the backlimb, and thus anticline asymmetry does not indicate the dip direction of the underlying fault.

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References.

Argus, D. F., M. B. Heflin, G. Peltzer, F. Crampe, and F. H. Webb (2005), Interseismic strain accumulation and anthropogenic motion in metropolitan Los Angeles, Journal of Geophysical Research v. 100, B04401, doi:10.1029/2003JB002934.

Avouac, J.P., Mountain Building, Erosion, and the Seismic Cycle in the Nepal Himalaya, *Advances in Geophysics*, Vol. 46, 10.1016/S0065-2687(03)46001-9, December 2003.

Broderick, K.G., (2006), Giant blind thrust faults beneath the Palos Verdes Hills and western Los Angeles Basin, California: Mapping with seismic reflection and deep drilling data, unpublished M.S. thesis, 68 pp., University of California, Santa Barbara, Santa Barbara, California.

Dartnell, P., and J. V. Gardner (1999), Sea-Floor Images and Data from Multibeam Surveys in S.an Francisco Bay, Southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada, *U.S. Geol. Surv. Digital Data Series* DDS-55 Version 1.0.

Davis, T. L., J. Namson, and R. F. Yerkes (1989), A cross section of the Los Angeles Area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard, *J. Geophys. Res.* 94, 9644-9664. (and **http://www.davisnamson.com/downloads/index.htm**).

Fisher, M. A., W. R. Normark, V. E. Langenheim, A. J. Calvert , and R. W. Sliter, (2004), The offshore Palos Verdes fault zone near San Pedro, southern California, *Bull. Seism. Soc. Amer.,* v. 93 p. 1955-1983.

Hart, P. E. and J. R. Childs, 2005, National archive of marine seismic surveys (NAMSS): Status report on U. S. Geological Survey program providing access to proprietary data, *Eos Trans. AGU, 86*(18), Jt. Assem. Suppl., Abstract S41A-10, http://walrus.wr.usgs.gov/NAMSS/.

Legg, M. R., C. Goldfinger, M. J. Kamerling, J. D. Chaytor, and D. E. Einstein, 2007, Morphology, structu evolution of California Continental Borderland restraining bends, Geological Society, London, Specia Publications, v, 290, p. 143-168, DOI: 10.1144/SP290.3

Nardin, T. R., and T. L. Henyey (1978). Pliocene-Pleistocene diastrophism of Santa Monica and San Pedro shelves, California Continental Borderland, *Amer. Assoc. Petroleum Geol. Bull.* 62, 247-272.

Plesch, A, J. H. Shaw, C. Benson, W. A. Bryant, S. Carena, M. Cooke, J. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N. Niemi, M. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. Suss, J. Suppe, J. Treiman, and R. Yeats, Community Fault Model (CFM) for southern California, Bulletin of the Seismological Society of America, V. 97, p. 1793-1802, DOI: 10.1785/0120050211

Rigor, A. W., 2003, Structure and deformation of the Palos Verdes fault in San Pedro Bay, California, Masters thesis, San Diego State University, 85 pages.

Shaw, J. H., and J. Suppe (1996), Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California, *J. Geophys. Res.* **101**, 8623-8642.

Sliter, R. W., W. R. Normark, and C. E. Gutmacher (2005), Multichannel seismic-reflection data acquired off the coast of southern California-Part A 1997, 1998, 1999, and 2000, *U. S. Geological Survey Open-File Report 2005-1084*,

Sorlien, C. C., M. J. Kamerling, L. Seeber, and K. G. Broderick (2006), Restraining segments and reactivation of the Santa Monica–Dume–Malibu Coast fault system, offshore Los Angeles, California, J. Geophys. Res., 111, B11402, doi:10.1029/2005JB003632.

Sorlien, C. C., Seeber, L., and Broderick, K. G., Luyendyk, B. P., Fisher, M. A., Sliter, R.W., and Normark, W. R., Offshore Los Angeles Thrust-folding: Pliocene-Quaternary Evolution of Palos Verdes Anticlinorium, California, submitted to J. Geophys. Res.

U. S. Geological Survey and Southern California Earthquake Center, Scientists of, (1994), The magnitude 6.7 Northridge, California earthquake of 17 January, 1994, *Science,* 266, 389-397.

Ward, S. N., and G. Valensise, (1994), The Palos Verdes terraces, California: Bathtub rings from a buried reverse fault, *J. Geophys. Res*., v. 99, p. 4485-4494.

Wickham, J., 1995, Fault displacement-gradient folds and the structure at Lost Hills, California (U.S.A.), Journal of Structural Geology, v. 191, p. 1293-1302.

Wright, T. L. (1991), Structural geology and tectonic evolution of the Los Angeles Basin, California, in *Active Margin Basins*, edited by K.T. Biddle, AAPG Memoir **52**, 35-134.