Structure and kinematics along the thrust front of the Transverse Ranges: 3D digital mapping of active faults in Santa Monica Bay using reflection, well, and earthquake data: Collaborative research with University of California, Santa Barbara and Columbia University

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NEHRP Element: I Keywords: Regional Modeling, Reflection Seismology; Tectonic Structures, Fault Segmentation

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Non Technical Summary

We constructed digital 3D maps of faults beneath northern Santa Monica Bay. Mapped faults include the E-W Dume fault, a large buried fault beneath it, the Malibu Coast fault above it, and the young NW-SE surface San Pedro Basin fault. The Dume fault is probably directly connected to the Santa Monica fault and the combined system has predominantly left-horizontal slip in its ENE coastal segment. We model between 4 and 7 km of left slip in the last ~4 million years. The area of the Santa Monica-Dume fault suggests it is capable of an earthquake between 7.25 and 7.35 Magnitude.

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INVESTIGATIONS UNDERTAKEN

We used industry seismic reflection and well data to construct digital structure-contour maps of faults and a deformed horizon beneath northern Santa Monica Bay. These maps include a principal strand of the Dume fault, a blind fault beneath it, and a deformed horizon within the Pliocene Repetto Formation. Mapped NW-SE surface faults include the San Pedro basin fault and the Malibu Coast fault. Graduate student Kris Broderick has been involved in the fault mapping and stratigraphic interpretation, and this work will comprise his UCSB Master's thesis.

INTRODUCTION

Space geodesy shows about 8-12 mm/yr of N-S contraction across the western Transverse Ranges orogen, between the San Gabriel Mountains and Long Beach, or between the mountains north of Ventura basin and the average motion of several of the Channel Islands (Fig. 1 in Argus et al., 1999). Large reverse-slip earthquakes occurred both north and south of the Santa Monica Mountains (Fig. 1; e.g., USGS and SCEC, 1994; Gutenberg et al., 1932; Stierman and Ellsworth, 1973; Hauksson and Saldivar, 1986; Hauksson, 1990). There have also been large right-lateral earthquakes on NW-SE faults adjacent to Santa Monica Bay (Fig. 1; Wood, 1933; USGS and SCEC, 1994).

Surface Faults

The Santa Monica Mountains are separated from Los Angeles and Santa Monica Basins by a system of surface faults. From east-to-west, the Raymond, Hollywood, and Santa Monica fault show evidence for post-Miocene and Holocene left-lateral slip (Wright, 1991; Dolan et al., 2000, Tsutsumi et al., 2001). The Santa Monica fault continues offshore at Potrero Canyon, where it has ~0.5 mm/yr north-side-up post-~120 ka reverse separation and an unknown left-lateral component (McGill, 1989; Dolan et al., 2000). Long-term left-lateral slip is constrained by the 15 km left offset of the N-S-orientated 8 Ma Tarzana Fan system (Wright, 1991; Redin, 1991). The Santa Monica fault splits into the coastal Malibu Coast fault and offshore Dume fault (Figs. 2, 3; Vedder et al., 1974; Nardin and Henyey, 1978; Junger and Wagner, 1977).

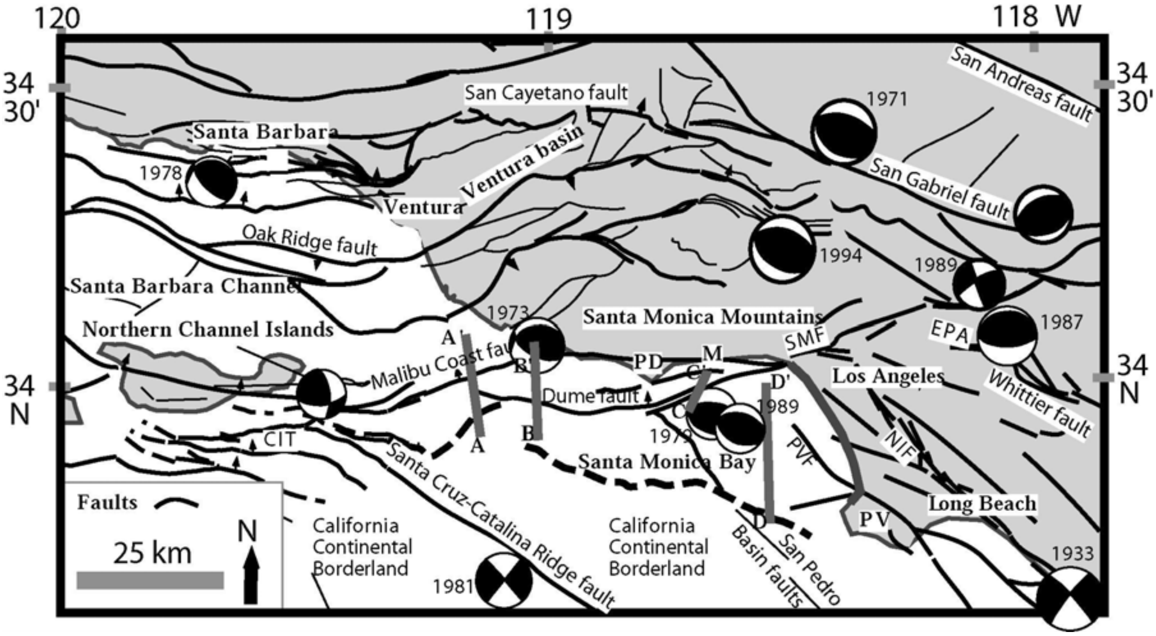

Figure 1: Faults, earthquakes, and locations. Lower hemisphere earthquake focal mechanisms from USGS and SCEC (1994). Mapping in onshore Ventura basin is from Hopps et al., 1995, and is on several subsurface horizons. Mapping in Los Angeles basin is from Wright (1991) and is on the base Repetto Formation. Offshore mapping is by Sorlien and others (2000), and is on Miocene horizons, except south and east of the Northern Channel Islands faults are mapped at the seafloor. Mapping in northern Santa Barbara Channel is by us and is projected upwards to near the sea floor. Mapping in Santa Monica Bay is from this project. Other mapping from Jennings (1994). Profiles A, B, C, and D are shown in Sorlien et al., manuscript in preparation for BSSA. CIT=zone of faults at tip of Channel Islands thrust, EPA=Elysian Park anticlinorium, NIF=Newport-Inglewood fault, PV=Palos Verdes, PVF=Palos Verdes fault, PD=Point Dume, SMF=Santa Monica fault. Dashed faults are blind.

The southern front of the E-W Transverse Range orogen interacts with NW-SE right-lateral faults that cut the Peninsular Ranges and California Continental Borderland. E-W segmentation along this front is expected to relate to this intersection. The Palos Verdes fault projects from Palos Verdes Peninsula into Santa Monica Bay (Fig. 1). A shallow paleoseismologic study of this fault on the south side of Palos Verdes Peninsula, at Long Beach Harbor, indicates 2.7-3.0 mm/yr of post-7.8-8 ka right-lateral slip (McNeilan et al, 1996); geomorphic analysis in the same general area indicates 2.5-3.8 mm/yr of post 120-80 ka right slip (Stephenson et al., 1995). A second NW-SE system of faults and folds, the San Pedro Basin fault zone, is mapped along the NE margin of deep Santa Monica bathymetric basin (Fig. 2; Junger and Wagner, 1977; Dartnell and Gardner, 1999; Fisher et al., 2001 and in revision for BSSA).

The Shelf Projection and Santa Monica Mountains blind fault

The ranges, islands, and offshore banks of the wTR and Borderland have been interpreted as anticlinoria, and most of these anticlinoria are ascribed to thrust slip on blind faults (Davis and Namson, 1994; Davis et al., 1989; Shaw and Suppe, 1994, 1996; Seeber and Sorlien, 2000). The Santa Monica Mountains and the Shelf Projection are the two main anticlinoria in and adjacent to northern Santa Monica Bay (Fig. 2). The Shelf Projection anticlinorium, located immediately west of Manhattan Beach, is expressed by a prominent 15x10 km bathymetric high (Fig. 2, Nardin and Henyey, 1978). A blind fault that accounts for this structure would have similar dimensions and thus could generate an earthquake similar in size to the M6.7 Northridge quake. Although Nardin and Henyey (1978) suggested the fold was most active before 1 Ma, our preliminary interpretation suggests that post-60 ka strata cored at ODP site 1015 (Shipboard Scientific Party, 1997) are at least locally folded along its south edge.

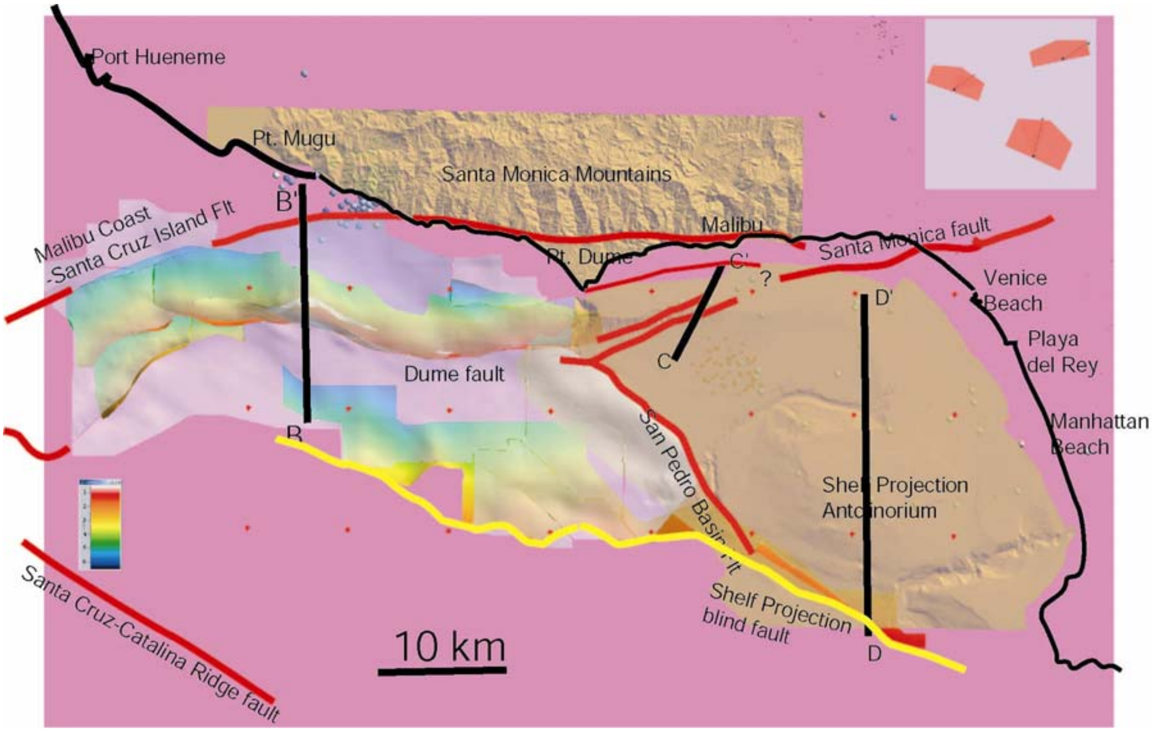

Figure 2*:* Vertical view of structure, bathymetry, and topography in and around Santa Monica Bay. This image was captured from our 3D model in GOCAD. USGS multibeam bathymetry is shown east of Pt. Dume, and the lower Repetto horizon is shown as semi-transparent west of Pt. Dume. The Dume segment of the Santa Monica fault and the underlying Tuscan Red-Shelf Projection blind fault are shown as opaque in rainbow color scheme (0-6 km). Profiles B, C, D are shown in Sorlien et al. manuscript in preparation. Not all faults are shown. Earthquakes are seen dimly through semi-transparent layers as spheres and small dots; the small dots are selected preferred slip planes. The inset shows our representation of earthquake slip planes in 3D-view is straight down. The long straight edge is horizontal and the point is downdip. Thin lines with arrowheads give slip of the hanging-wall. The bottom slip plane is reverse and the other two are oblique-reverse left-lateral.

Methods

We used three different overlapping grids of industry multichannel seismic reflection data, and a few profiles from two other data sets, and an additional 800 m x 2500 m grid of single channel sparker data to map structure and correlate stratigraphy through northern Santa Monica Bay. Stratigraphic control was provided by logs from several wells drilled in the hanging-wall of the Dume fault, including 2 with sonic logs, and by other wells in the footwall farther east. The well information was converted to travel time and then correlated through the grids of reflection data, and around the east and west plunge of the Dume fault into the footwall basin to the south. This correlation was supplemented by published information on seafloor outcrop (Vedder, 1990; Nardin and Henyey, 1978), and by stratigraphic and velocity information from coastal and offshore oil fields at Playa del Rey and Venice Beach (Cal Div. Oil and Gas, 1992).

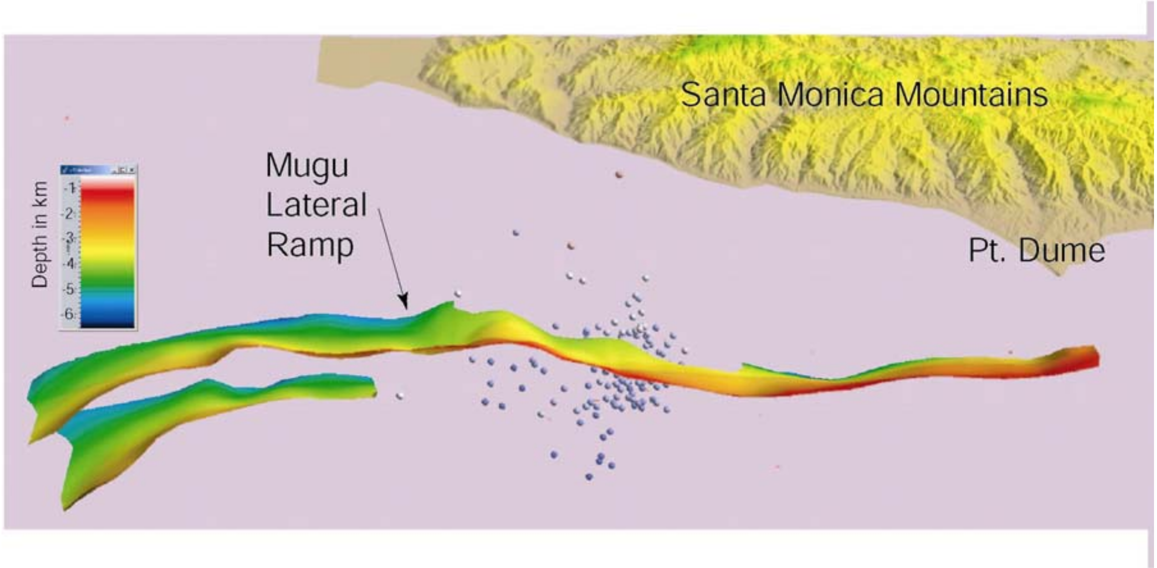

Figure 3: Oblique view of Dume segment of Santa Monica fault, inclined 45 deg. down to the north. In the west the fault dips a little less than 45 deg, in the east it is close to 45 deg. Blue spheres are aftershocks to the 1973 Point Mugu earthquake from Stierman and Ellsworth (1976). Although the Dume segment projects near the aftershocks, so do the steeper Malibu Coast fault to the north, and the flatter Tuscan Red fault to the south.

RESULTS

Mapping and Map Restoration

We mapped a horizon within the lower part of the Repetto Formation (Fig. 2). The unconformable base of Repetto Siltstone is between 4.42 +/- 0.57 m.y. and 3.4 +/- 0.3 m.y. (Blake, 1991), with the lower part missing where it onlaps growing folds. Because this horizon locally onlaps structure beneath, its age probably falls within the range for the base Repetto unconformity, or about 4 Ma. Reflections just below this horizon are parallel to it in both the hanging-wall and footwall of the Dume segment, indicating little seafloor relief at the time of deposition.

We used unfolding and map restoration to quantify strain due to faulting and folding of the ~4 Ma horizon. UNFOLD organizes grid points of the digital maps into adjoining triangles, lays each triangle flat, and then minimizes gaps and overlaps between triangles in an iterative process (Gratier et al, 1991, 1999). The flattened maps of each fault block are then manually fit together using a graphics software. Comparison between the restored and present state defines the finite displacement field with respect to a fixed reference line (Fig. 4). The details of the computer program UNFOLD and the technique of map restoration have been published (Gratier *et al*., 1991, 1999).

Interpretations

The overall strike of the offshore Santa Monica-Dume fault system is east-west, but it is arcuate, being north-concave between Pt. Mugu and Pt. Dume, and being north-convex west of Point Mugu. It can be divided into three segments based on strike: 1) the ENE-striking Santa Monica segment between Pt. Dume and its onshore intersection with the Newport-Inglewood trend; 2) the WNW-striking Dume segment; and 3) the partially blind set of NE-SW faults beneath the Hueneme submarine fan (Fig. 5). The Dume segment may link westward to the Malibu Coast fault via distributed high-angle strands with small vertical separation (tens of meters or less). We extended the structure contour map of the Dume segment an additional 10 km east as a fault trace map (Figs. 2, 5). The mapped Dume segment steps right about 1 km, not left, to the Santa Monica segment in the area southeast of Pt Dume (Fig. 2). The dominant N-dipping strand at C-C' (located on Fig. 2) aligns with the onshore Santa Monica fault at Potrero Canyon (also Vedder et al., 1974; and Nardin and Henyey, 1978). It cuts across an E-W elongate anticline that extends between Pt. Dume and Venice Beach.

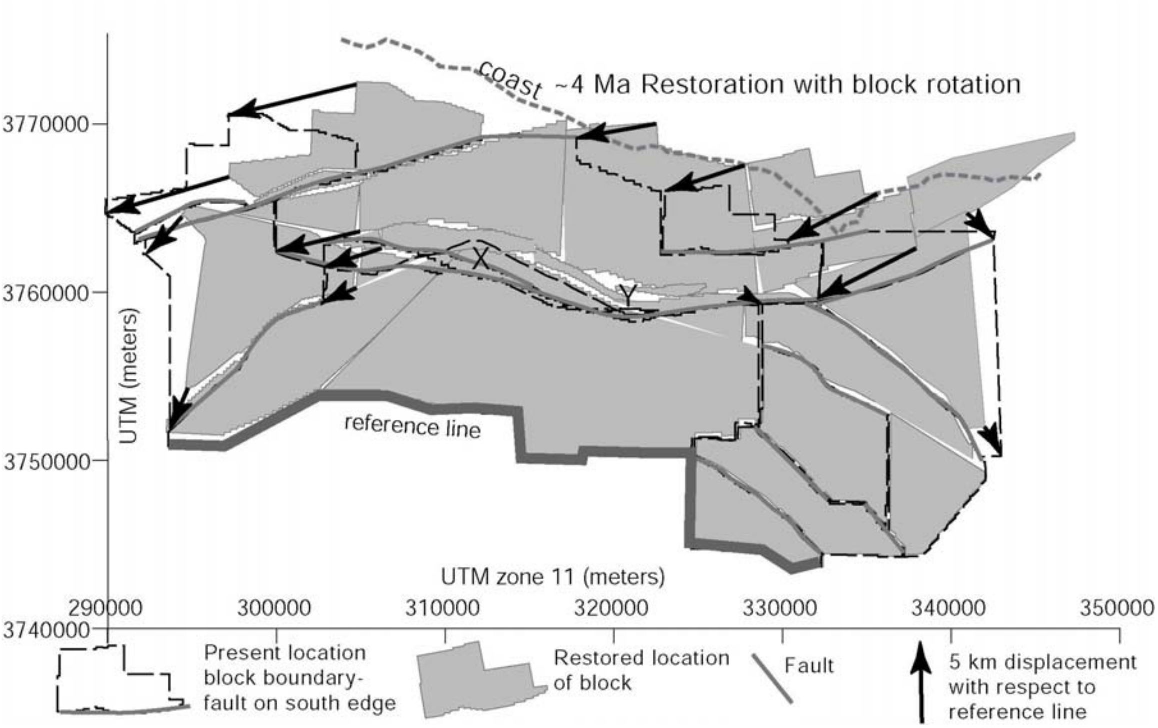

Figure 4: Preferred map restoration. The labeled dashed gray line is the coastline in its present position. The arrows connect the restored positions of corners of blocks to their present positions and represent finite displacement with respect to the reference line. Overlap of restored blocks at "X" suggests we overestimated contraction there, and gaps at "Y" suggest we underestimated contraction there. The deformed state of this map is shown in Figure 2, and faults are labeled there. Displacement across the Santa Monica-Dume fault (through X and Y) is 7 km in the east and 4 km in the west; the variation is related to clockwise rotation in the east and counterclockwise rotation in the west.

The Dume segment dips moderately (40-50 deg) north in its upper 4-6 km (Fig. 3). The Malibu Coast fault strikes WSW in the offshore area south and west of Point Mugu, cutting the hanging-wall of the Dume fault. It is vertical above the Miocene volcanics (or equivalent) reflection. Within a few kilometers of A-A' (located in Fig. 2) the Miocene volcanics reflector has about 400 m N-side-up separation across the Malibu Coast fault, and the lower Repetto Formation map horizon has about 200 m vertical separation across that fault. We trace the Malibu Coast fault directly to the Santa Cruz Island fault (Fig. 1).

South of and beneath the Dume fault, we interpret a blind, gently N-dipping fault that may be linked with or continuous with a NNE-dipping blind fault along the southern edge of the Shelf Projection anticlinorium (Fig. 2). Here, it is informally called the "Tuscan Red fault" after the color pencil we used to interpret it. The N-dipping segment of the fault preserves normal-separation in Miocene strata, and is interpreted as a Miocene low-angle normal fault. The Shelf Projection segment of the Tuscan Red fault has been thrust-reactivated and is responsible for the post-Miocene folding.

Like Fisher et al. (2001), we interpret that the Palos Verdes fault does not intersect the Santa Monica-Dume fault, at least in Pliocene or younger strata. We map it to either bend to the west-northwest as a minor fault or to terminate against minor WNW faults (Fig. 2). In contrast, two strands of the San Pedro basin fault zone do intersect the Santa Monica-Dume fault. We interpret the 10x15 km Shelf Projection anticlinorium, located in eastern Santa Monica Bay, to be a blind thrust-fold structure forming a restraining stepover between the Palos Verdes and San Pedro Basin faults. Co-located active thrust faulting is manifested by M5 earthquakes (1979, 1989; Fig. 1).

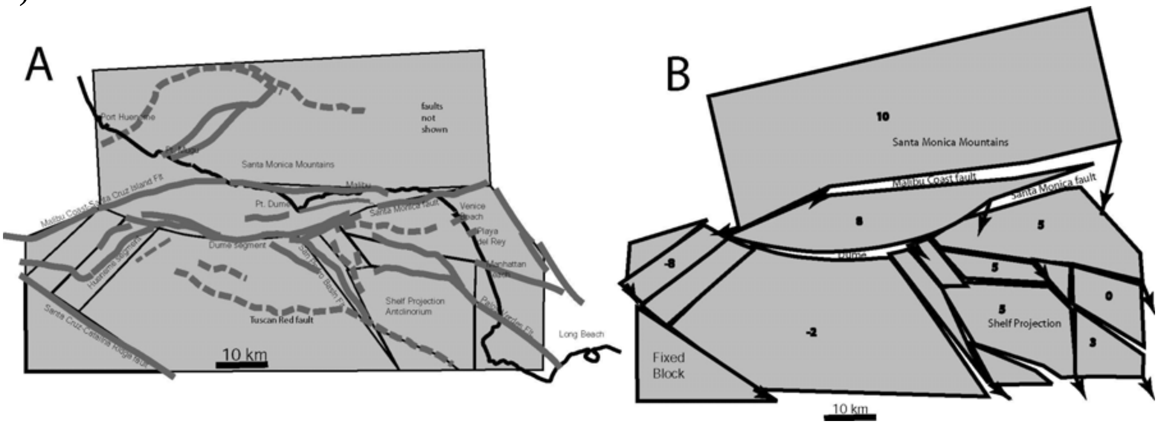

Figure 5: Simplified block model for Santa Monica Bay and vicinity. “A” shows the mapped fault pattern, dashed faults being blind, and the simplified block boundaries derived from that. “B” shows restored positions, roughly similar to the 4 Ma restoration in Figure 4. Positive numbers are amount of clockwise rotation and negative numbers are amount of counterclockwise rotation. Gaps represent shortening, and arrows represent displacement with respect to the fixed block. Variations of the simplified block model from the actual geometry, internal deformation of blocks, and the fact that thrust overlaps across faults are not included and unfolding was not done, all change the modeled contraction and displacements. But, large-scale patterns such as the relation of left slip on the Santa Monica-Dume fault to rotation of the Santa Monica Mountains are revealed.

Deformation Models

Contraction across the Santa Monica-Dume fault varies depending on its strike: it is large across the WNW-striking segment and low across the eastern, ENE striking segment. These variations can be accounted for by uniform slip on the fault, provided the slip is nearly parallel to the eastern segment. Thus, predominantly left-lateral slip along the ENE-striking segment is responsible for transpression in its WNW-striking section. Thus, the WNW-striking Dume segment is a restraining segment in the Santa Monica fault. Similarly, there is little structural relief across the subvertical ENE-striking part of the Malibu Coast fault across Hueneme Fan, while its E-W segment along the Malibu Coast of the Santa Monica Mountains displays a north dip and subvertical and overturned Monterey Formation (Dibblee and Ehrenspeck, 1993).

These qualitative kinematic interpretations were tested and quantified using a map restoration technique. Maps of fault-bounded pieces of the Pliocene horizon were restored to a horizontal state with UNFOLD. The flattened pieces were then assembled with respect to a southern reference line. Vertical-axis rotation is allowed along with limited internal deformation of blocks. The trace of the Santa Monica-Dume fault (map view) is concave-north along ~40 km

(Figs. 4, 5). If slip was pure left-lateral along this entire length, the Santa Monica Mountains block to the north would rotate clockwise relative to the Borderlands block to its south. In support of this model, paleomagnetic data indicate at least 75 deg of clockwise rotation of the Santa Monica Mountains since eruption of the middle Miocene Conejo Volcanics there (Kamerling and Luyendyk, 1979). GPS data indicate current clockwise rotation of the Santa Monica Mountains block at 7 +/-1 deg/m.y. (Donnellan et al., 1993). We thus restore deformation assuming a clockwise rotation in the hanging-wall block of the Santa Monica-Dume fault.

The Santa Monica-Dume fault has a greater left-lateral slip component adjacent to clockwise rotating blocks than adjacent to counter-clockwise rotating blocks. The restoration in Figure 4 shows about 7 km of left-lateral slip in the east and about 4 km in the west. About 0.5 km of the slip is absorbed in the west plunge of the Sycamore Knoll anticline and does not reach the Hueneme Fan area. Right-lateral slip on two strands of the San Pedro Basin fault is 1.9 km in this fitting, as opposed to zero in a fitting with no rotations (not shown).

Slip partitioning between right-lateral Borderlands faults and vertical axis block rotation
We constructed a simplified block model in order to examine the kinematics of block rotations and fault terminations beyond the area of our lower Repetto Formation mapping (Fig. 5). This block model incorporates our fault mapping as well as published fault mapping, but blocks are simplified to polygons. We qualitatively retrodeform this block model to investigate regional patterns of deformation (Fig. 5). Right-lateral slip is transferred between the Palos Verdes fault and the northern San Pedro Basin fault by contraction in the Shelf Projection restraining step. The block model includes clockwise rotation of Shelf Projection block and of the basin blocks between it and the Santa Monica Mountains. Part of the right-lateral slip on the Palos Verdes fault is dissipated into clockwise rotation and part is transferred to the northern San Pedro Basin fault.

Hazard from distributed faulting in rotating system
If the ~3 mm/yr of post-~8 ka right-lateral slip on the Palos Verdes fault (McNeilan et al., 1996) were absorbed by contraction across the Shelf Projection anticlinorium with no block rotation, the blind fault(s) beneath it would accumulate about 1 m of contraction (1.15 m of slip on 30 deg dipping fault) every ~330 years. The pattern of thrust loading would be different if blocks rotate. Our simplified block model includes 5 deg clockwise rotation of the Shelf Projection and of blocks to its north. A system of clockwise rotating elongate blocks includes left-lateral oblique slip between the blocks, and can include both extension and contraction where space problems manifest (Luyendyk, 1991). In such a system, you may have many faults active at lower slip rates. The hazard from such a system for damaging earthquakes is large because earthquakes will be common (as has been observed historically), but they will also be spatially distributed and the maximum Magnitude not as large. On the other hand, if right-lateral slip is transformed into clockwise rotation or distributed shear, the right-lateral system can end or become blind, and need not segment the Santa Monica-Dume fault. In this case, a large onshore-offshore rupture on the Santa Monica-Dume fault, although rare (e.g., Dolan et al., 2000), is probable.

Fault area and Maximum Magnitude
The only major segment boundary of the Santa Monica-Dume fault is 55 km west of Potrero Canyon, where the Dume fault segment becomes blind near the Hueneme segment. We suggest

that intersections with the San Pedro Basin fault system near Point Dume and a <1 km right step in the shallow Santa Monica-Dume fault in that area need not stop a rupture. Thus, the Santa Monica-Dume fault is 65 km-long between the Hueneme segment and the left step at the West Beverly Hills lineament (aligned with Newport-Inglewood fault, Dolan et al., 2000). One caution is that we do not now have data that cross the fault in the 14 km west of the coast, and rely there on earlier mapping (Dolan et al., 2000; Nardin and Henyey, 1978, Osborne et al., 1980). We use a dip of 45 deg and a depth of 20 km to project Santa Monica fault beneath the Northridge hypocenter (as was done by Tsutsumi et al., 2001). The fault downdip width is 28 km and its area is 1840 sq km. Using the rupture area-Magnitude relation for California earthquakes of Dolan et al. (1995), the maximum Magnitude for the Santa Monica-Dume fault is 7.35. Using the rupture area-Magnitude relation of Wells and Coppersmith (1994) for global earthquakes results in a maximum Magnitude of 7.25.

We cannot model a late Quaternary blind thrust component of slip without more information on late Quaternary folding of the Santa Monica Mountains. We also choose not to calculate a maximum magnitude for the Tuscan Red fault because we do not know how much of it has been reactivated and remains active, and have only been able to map its uppermost part along the Shelf Projection anticlinorium. We did calculate above that if 3 mm/yr of Palos Verdes fault-right slip were absorbed by thrusting without block rotation, a Northridge-sized earthquake would occur every 330 years. Alternatively, smaller, much more frequent earthquakes are associated with distributed deformation.

Data efforts, sound levels, and siting USGS reflection profiles

We also have been working on three related projects. The first is working with Chevron-Texaco and with SCEC to find a way to preserve and make public their offshore west coast seismic reflection data. The second is working with Mike Fisher and Bill Normark of USGS to carefully site profiles for their June 2002 field program. The third was investigating sound levels and permitting to acquire seismic reflection data and multibeam bathymetry in a cruise of opportunity. This was time-consuming for one of us (C.C.S.), and data acquisition in that area will not occur because of equipment problems (the cruise was always intended as a test of equipment). However, the investigations on sound levels and permitting are not wasted as we have submitted proposals to use acoustic sources in the California Borderland.

Conclusions

The Santa Monica and Dume faults are part of the same fault system, and are probably directly connected. The interval between the mapped Pliocene horizon and the top Miocene volcanics is thicker on the upthrown hanging-wall side of both onshore and offshore segments of the fault, which is consistent with basin inversion. The folding along the Dume segment initiated during the Pliocene Repettian Stage and accelerated towards the end of this stage. Left-lateral slip on the ENE-striking Santa Monica segment resulting in contraction across the offshore Dume restraining segment. Incorporating reasonable rates of clockwise rotation of the Santa Monica Mountains, in a map restoration results in an estimate of 4-7 km of left slip on the Santa Monica-Dume fault system and 1.8 km of right slip on the San Pedro Basin fault zone in the last ~4 m.y.. Alternatively, but less probably, a restoration with no vertical axis rotation and no distortion of fault blocks produces an estimate of 3 km of left slip, and no right slip on the San Pedro Basin fault zone. The Palos Verdes fault does not have any obvious affect on the continuity of the Santa Monica Dume fault, and the two systems do not intersect at or above the Pliocene map horizon. Strands of the San Pedro Basin fault zone do intersect the Dume fault, but do not appear to offset it. There is, however, a <1 km right step and a small increase to the west in vertical separation across the Santa Monica-Dume fault in the general area of this intersection. Maximum magnitude for an earthquake on the Santa Monica-Dume fault is 7.35 based on a rupture area-Magnitude relationship for California. A blind fault that dips north beneath the Shelf Projection anticlinorium extends at least 50 km beneath Santa Monica Bay, and is a Miocene low-angle normal fault partially reactivated as a thrust fault.

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References

Argus, D. F., Heflin, M. B., Donnellan, A., Webb, F. H., Dong, D., Hurst, K. J., Jefferson, D. C., Lyzenga, G. A., Watkins, M. M., and Zumberge, J. F., 1999, Shortening and thickening of metropolitan Los Angeles measured and inferred by using geodesy, Geology, v. 27, p. 703-706

Blake, G. H., 1991, Review of the Neogene biostratigraphy and stratigraphy of the Los Angeles Basin and implications for basin evolution, in K.T. Biddle, ed., Active Margin Basins, AAPG Memoir 52, American Association of Petroleum Geologists, Tulsa, p. 135-184

Burdick, D. J., and Richmond, W. C., 1982, A summary of geologic hazards for proposed OCS oil and gas lease sale 68, Southern California, MMS and USGS Open-File Report 82-33

California Division Oil, Gas, and Geothermal Resources, 1992, California Oil & Gas Fields, Volume II: Southern, Central Coastal, and Offshore California, Pub. TR11

Dartnell, P., and Gardner, J. V., 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, Digital Data Series DDS-55 Version 1.0

Davis, T. L., and Namson, J. S., 1994, A balanced cross-section of the 1994 Northridge earthquake, southern California, Nature, vol. 372 p. 167-169

Davis, T. L., Namson, J., and Yerkes, R. F., 1989, A cross section of the Los Angeles Area: Seismically active fold and thrust belt, the 1987 Whittier Narrows earthquake, and earthquake hazard, Journal of Geophysical Research, vol. 94, no. B7, p. 9644-9664

Dibblee, T. W. Jr, and Ehrenspeck, H. E., 1993, Geologic Map of the Point Dume quadrangle, Los Angeles and Ventura Counties, California, H. E. Ehrenspeck, ed., Dibblee Geological Foundation, Santa Barbara, California, scale 1:24,000

Dolan, J. F., Sieh, K. E., and Rockwell, T. K, 2000, Late Quaternary activity and seismic potential of the Santa Monica fault system, Los Angeles, California, Geological Society of America, v. 112, p. 1559-1581

Dolan, J. F., Sieh, K. E., Rockwell, T. K., Yeats, R. S., Shaw, J., Suppe, J., Huftile, G. J., and Gath, E. M., 1995, Prospects for larger or more frequent earthquakes in the Los Angeles metropolitan region, Science, vol. 267, p. 199-205

Donnellan, A., Hager, B. H., King, R. W., and Herring, T. A., 1993a, Geodetic measurement of deformation in the Ventura Basin region, southern California, Journal of Geophysical Research, vol. 98, no. B12, p. 21,727-21,739

Fisher, M. A., Normark, W. R., Bohannon, R. G., Sliter, R. W., Calvert, A. J., 2001, Geology of the continental margin beneath Santa Monica Bay, southern California, from small-airgun, seismic-reflection data, Eos. Trans. AGU, 82(47), Fall Meet. Suppl., Abstract S11A-0544, p. F804

Fisher, M. A., Normark, W. R., Bohannon, R. G., and Sliter, R. W., Geology of the continental margin beneath Santa Monica Bay, southern California, from seismic reflection data, in revision for Bulletin of the Seismological Society of America

Gratier, J.-P., Guillier, B., Delorme, A., and Odonne, F., 1991, Restoration and balance of a folded and faulted surface by best-fitting of finite elements: principle and applications, Structural Geology, vol. 13, no. 1, p.111-115

Gratier, J.-P., Hopps, T., Sorlien, C. C., and Wright, T., 1999, Recent crustal deformation in southern California deduced from the restoration of folded and faulted strata, Journal of Geophysical Research, v. 104, p. 4887-4899

Gutenberg, B., Richter, C. F., and Wood, H. O., 1932, The earthquake in Santa Monica Bay, California, on August 30, 1930, Bulletin Seismological Society of America, V. 22, p. 138-154

Hauksson, E. and Saldivar, G. V., 1986, The 1930 Santa Monica and the 1979 Malibu, California, earthquakes, Seismological Society of America Bulletin, v. 76, p. 1542-1559

Hauksson, E., 1990, Earthquakes, faulting, and stress in the Los Angeles Basin, Journal of Geophysical Research, vol. 95, no. B10, p. 15365-15394

Hopps, T.E., H.E. Stark and R.J. Hindle, 1995, Subsurface data in basin analysis: An example from Ventura Basin, California, SCEC Workshop: Thrust Ramps and Detachment Faults in the Western Transverse Ranges, UC Santa Barbara, p. 10.

Jennings, C. W., 1994, Fault activity map of California and adjacent areas with locations and ages of recent volcanic eruptions, California Division of Mines and Geology, Geologic Data Map no. 6 scale 1:750,000

Junger, A., and Wagner, H. C., 1977, Geology of the Santa Monica and San Pedro Basins, California continental borderland: U. S. Geological Survey Misc. Field Studies Map MF-820, 10 p. 5 pls., map scale 1:250,000.

Kamerling, M. J., and Luyendyk, B.P., 1979, Tectonic rotations of the Santa Monica Mountains region western Transverse Ranges, California, suggested by paleomagnetic vectors, Geological Society of America Bulletin, Part 1, vol. 90, p. 331-337

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California, Geological Society of America Bulletin, v. 103, p. 1528-1536.

McGill, J. T., 1989, Geologic maps of the Pacific Palisades area, Los Angeles, California, U. S. Geological Survey Map I-1828, scale 1:4,800

McNeilan, T. W., Rockwell, T. K., Resnick, G. S., 1996, Style and rate of Holocene slip, Palos Verdes fault, southern California: Journal of Geophysical Research, v. 101, p. 8317-8334.

Nardin, T. R., and Henyey, T. L., 1978, Pliocene-Pleistocene diastrophism of Santa Monica and San Pedro shelves, California Continental Borderland, American Association of Petroleum Geologists Bulletin, v. 62, p. 247-272

Osborne, R. H., Scheidemann, R. C. Jr., Nardin, T. R., and Harper, A. S., 1980, Quaternary stratigraphy and depositional environments, Santa Monica Bay, Southern California, *in* Field, M. E., et. al., eds., Quaternary Depositional Environments of the Pacific Coast: Pacific Coast Paleogeography Symposium 4: Los Angeles, California, The Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 143-156.

Redin, T., 1991, Oil and gas production from submarine fans of the Los Angeles basin, in K.T. Biddle, ed., Active Margin Basins, AAPG Memoir 52, American Association of Petroleum Geologists. P. 239-259

Seeber, L, and Sorlien, C. C., 2000 Listric thrusts in the western Transverse Ranges, California, Geological Society of America Bulletin, v. 112, p. 1067-1079.

Shaw, J. H., and Suppe, J., 1994, Active faulting and growth folding in the eastern Santa Barbara Channel, California, Geological Society of America Bulletin, vol. 106, p. 607-626

Shaw, J. H., and Suppe, J., 1996, Earthquake hazards of active blind-thrust faults under the central Los Angeles basin, California, Journal of Geophysical Research, vol. 101, no. B4, p. 8623-8642

Shipboard Scientific Party, 1997, 9. Site 1015, in Proceedings of the Ocean Drilling Program, Initial Reports, v. 167, Lyle, M., Koizumi, I., and Richter, C., eds., p. 223-237

Sorlien, C. C., Gratier, J. P., Luyendyk, B.P.,Hornafius, J. S., and Hopps, T. E, 2000, Map restoration of folded and faulted late Cenozoic strata across the Oak Ridge fault, onshore and offshore Ventura basin, California, Geological Society of America Bulletin, v. 112, p. 1080-1090.

Stephenson, W. J., Rockwell, T. K., Odum, J. K., Shedlock, K. M. and Okaya, D. A.,1995, Seismic reflection and geomorphic characterization of the onshore Palos Verdes fault zone, Los Angeles California: Bulletin of the Seismological Society of America, v. 85, p. 943-950.

Stierman, D. J., and Ellsworth, W. L., 1976, Aftershocks of the February 21, 1973 Point Mugu, California earthquake, Bulletin of the Seismological Society of America, vol. 66, no. 6, p. 1931-1952

Tsutsumi, H., Yeats, R. S., and Huftile, G. J., 2001, Late Cenozoic tectonics of the northern Los Angeles fault system, California, Geological Society of America Bulletin, v. 113, p. 454-468

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, p. 389-397

Vedder, J. G., Beyer, L. A., Junger, A., Moore, G. W., Roberts, A. E., Taylor, J. C., and Wagner, H. C., 1974, Preliminary report on the geology of the Continental Borderland of southern California, U. S. Geological Survey Misc. Field Studies Map MF-624, 34 pages and 9 plates

Vedder, J. G., 1990, Maps of California Continental Borderland showing compositions and ages of samples acquired between 1968 and 1979, U. S. Geological survey Miscellaneous Field studies Map, Map MF-2122

Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among Magnitude, rupture length, rupture width, rupture area, and surface displacement, Bulletin of the Seismological Society of America, v. 84, p. 974-1002

Wood, H. O., 1933, Preliminary report on the Long Beach earthquake, Bulletin of the Seismological Society of America, v. 23, p. 43-56

Wright, T. L., 1991, Structural geology and tectonic evolution of the Los Angeles Basin, California: *in* K. T. Biddle, ed., Active margin basins; AAPG, Memoir 52, p. 35-134.

Abstracts from this project:

Sorlien, C. C., Kamerling, M. J., and Seeber, L., 2001, The Dume fault, northern Santa Monica Bay, California, EOS Trans. AGU, Fall Meet. Suppl., v. 82, p. F802

Broderick, K., Sorlien, C. C., Kamerling, M. J., Seeber, L., and Luyendyk, B. P., 2002, Post-Miocene Faulting and Folding in the Southwestern Transverse Ranges, Santa Monica Bay, California, Eos. Trans. AGU, v. 83, Fall Meet. Suppl., Abstract

Sorlien, C. C., Broderick, K., Kamerling, M. J., Fisher, M., and Seeber, L., 2002, A blind fault beneath Santa Monica Bay, Proceedings and Abstracts, Southern California Earthquake Center Annual Meeting, p. 132

Nearly completed manuscript

Sorlien, C. C., Pinter, N, Kamerling, M. J., Seeber, L., and Broderick, K., The Santa Monica-Dume fault system in northern Santa Monica Bay, California
To be submitted to Bulletin of the Seismological Society of America.

Data Availability

Well data, including sonic surveys, are public and available from Industry sources such as Rileys, or from the California Division of Oil and Gas in 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 may not have information on them. The 800x2500 m grids of single channel sparker 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. Our digital structure-contour maps of faults have been, and are being provided to the SCEC Community Fault Model. This model is being produced by Andreas Plesch and John Shaw and others at Harvard, and will be released in early 2003. It will be likely linked to www.scec.org. Contact Christopher Sorlien at chris@crustal.ucsb.edu for additional information on data.