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Recent Deformation along the Offshore Malibu Coast, Dume, and Related Faults West of Point Dume, Southern California

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Abstract Offshore faults west of Point Dume, southern California, are part of an important regional fault system that extends for about 200 km, from near the city of Los Angeles westward along the south flank of the Santa Monica Mountains and through the northern Channel Islands. This boundary fault system separates the western Transverse Ranges, on the north, from the California Continental Borderland, on the south. Previous research showed that the fault system includes many active fault strands; consequently, the entire system is considered a serious potential earthquake hazard to nearby Los Angeles. We present an integrated analysis of multichannel seismic- and high-resolution seismic-reflection data and multibeam-bathymetric information to focus on the central part of the fault system that lies west of Point Dume. We show that some of the main offshore faults have cumulative displacements of 3–5 km, and many faults are currently active because they deform the seafloor or very shallow sediment layers. The main offshore fault is the Dume fault, a large north-dipping reverse fault. In the eastern part of the study area, this fault offsets the seafloor, showing Holocene displacement. Onshore, the Malibu Coast fault dips steeply north, is active, and shows left-oblique slip. The probable offshore extension of this fault is a large fault that dips steeply in its upper part but flattens at depth. High-resolution seismic data show that this fault deforms shallow sediment making up the Hueneme fan complex, indicating Holocene activity. A structure near Sycamore knoll strikes transversely to the main faults and could be important to the analysis of the regional earthquake hazard because the structure might form a boundary between earthquake-rupture segments.

Introduction

The Malibu Coast and related faults are part of a regional fault system that forms the tectonic boundary between the western Transverse Ranges, on the north, and the California Continental Borderland, on the south (e.g., Wright, 1991; Crouch and Suppe, 1993; Bohannon and Geist, 1998) (Fig. 1 and lower left inset in Fig. 2). This fault system includes numerous fault strands that collectively extend for about 200 km, from near the city of Los Angeles in the east to the far western end of the northern Channel Islands. The fault system poses a significant earthquake threat because of its length, recent activity, and proximity to the Los Angeles urban area. Dolan *et al.* (1995), for example, estimated that the Malibu Coast fault and Santa Monica fault, another member of the regional fault system, could each unleash earthquakes as large as $M_w \sim 7$. The coastal zone near our study area has but few inhabitants; even so the fault activity we describe contributes to a more complete understanding of the earthquake and tsunami hazards associated with the overall fault system.

During 2002 the U.S. Geological Survey collected medium-resolution (17 inches^3 airgun) and high-resolution (Huntec™ minisparker) seismic-reflection data west of Point Dume, across the offshore extensions of the Malibu Coast and related faults (Fig. 2). In addition, Western-Geco, Inc., recently made multichannel seismic (MCS) reflection data available to the public. We analyze seismic-reflection and multibeam-bathymetric data to determine the structure of offshore faults and how recently movement occurred along them.

Regional Geology and Seismicity

Tectonic Development

Complex tectonic events leading to the development of the Transverse Ranges included post-early Miocene clockwise rotation of the entire ranges and consequent regional extension, which was followed by late Pliocene and younger

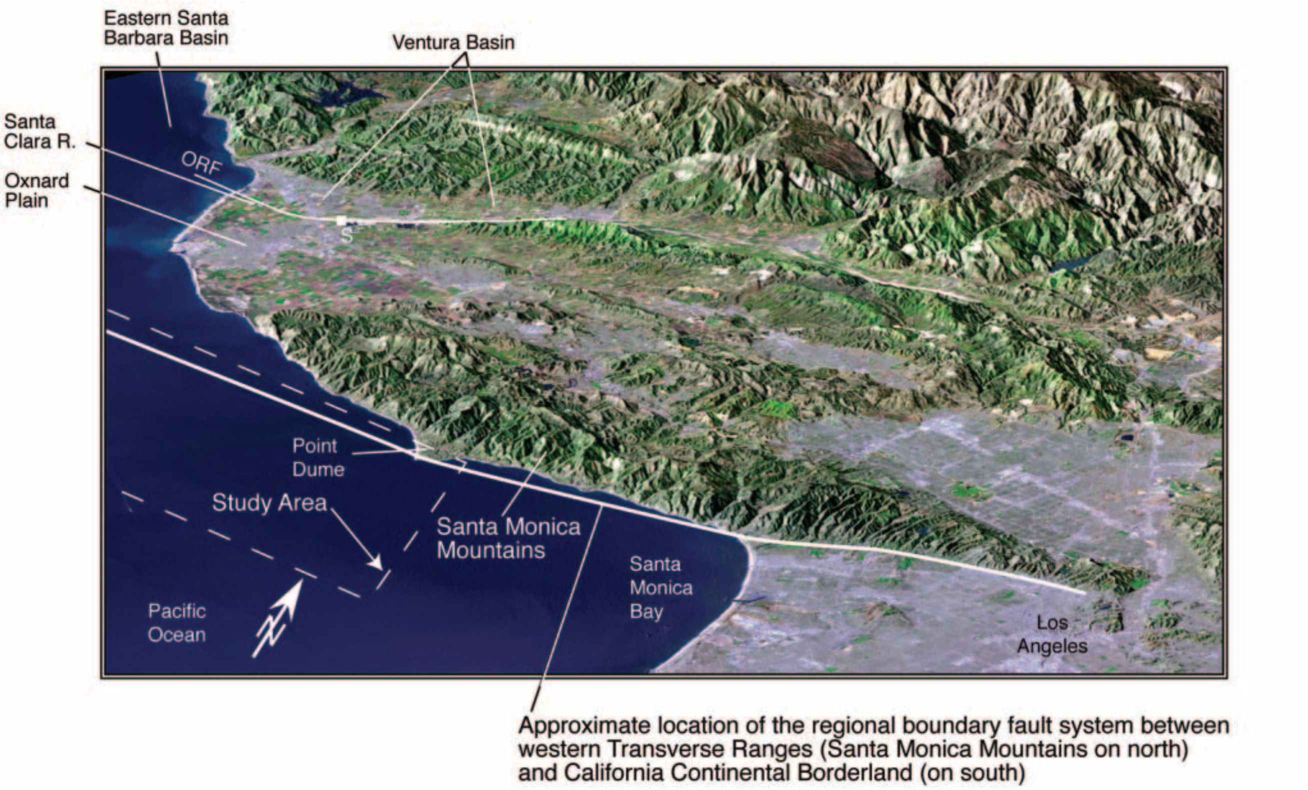

Figure 1. A view from orbit of the study area, the Santa Monica Mountains and the east-trending fault system that separates the western Transverse Ranges from the California Continental Borderland. The white box labeled "S" locates the town of Saticoy. ORF means Oak Ridge fault. View is to the west–northwest. Topography is shown with a vertical exaggeration of 1.8. The image incorporates Shuttle-radar topographic data with Landsat infrared data draped over the topography. This image is explained more fully without annotation from the website www2.jpl.nasa.gov/srtm/california.html#PIA03376.

regional transpression (Kamerling and Luyendyk, 1979; Luyendyk *et al.*, 1980; Kamerling and Luyendyk, 1985; Wright, 1991; Crouch and Suppe, 1993; Nicholson *et al.*, 1994; Bohannon and Geist, 1998; Walls *et al.*, 1998). This tectonic sequence left distinctive structural imprints on the western Transverse Ranges and the Continental Borderland—the main structures deforming the Transverse Ranges trend east, whereas Borderland structures trend northwest. The Santa Monica, Dume, and Malibu Coast faults are elements of the regional fault system that separates these structural provinces (Figs. 1 and 2).

Stratigraphy of the Santa Monica Mountains and Adjacent Offshore Area

Rocks on opposite sides of the Malibu Coast fault differ considerably in age and lithology. Basement rocks north of the Malibu Coast fault include slate of Late Jurassic protolith age that was intruded by mid-Cretaceous (102 Ma) granitic rocks (Dibblee, 1982, 1992). This basement is overlain by thick Late Cretaceous and early Tertiary, primarily marine sedimentary, rocks as well as by Oligocene and Miocene marine and terrestrial sedimentary rocks and the locally thick, middle Miocene Conejo Volcanics

In contrast to the granite and slate basement north of the Malibu Coast fault, basement rocks south of the fault are made up of Catalina Schist, interpreted to be a metamorphic core complex that was exhumed from beneath the rotating western Transverse Ranges (Crouch and Suppe, 1993; Nicholson *et al.*, 1994; Bohannon and Geist, 1998). This basement is overlain by Miocene and younger sedimentary rocks and middle Miocene volcanic rocks, which extend southward from the Malibu Coast fault to underlie the Santa Monica basin (Dibblee, 1982; Vedder *et al.*, 1987). This basin borders the continental shelf and slope on the south, under water locally as deep as 800 m (Fig. 2). Late Quaternary sediment that partly fills the Santa Monica basin makes up the Hueneme and Dume submarine fans (Normark *et al.*, 1998; Piper *et al.*, 1999, 2003; Normark *et al.*, 2004) (Fig. 2). These fans are fed by Dume Canyon, in the eastern part of the study area, and the complex of channels between and including Hueneme and Mugu canyons, in the west (Fig. 2).

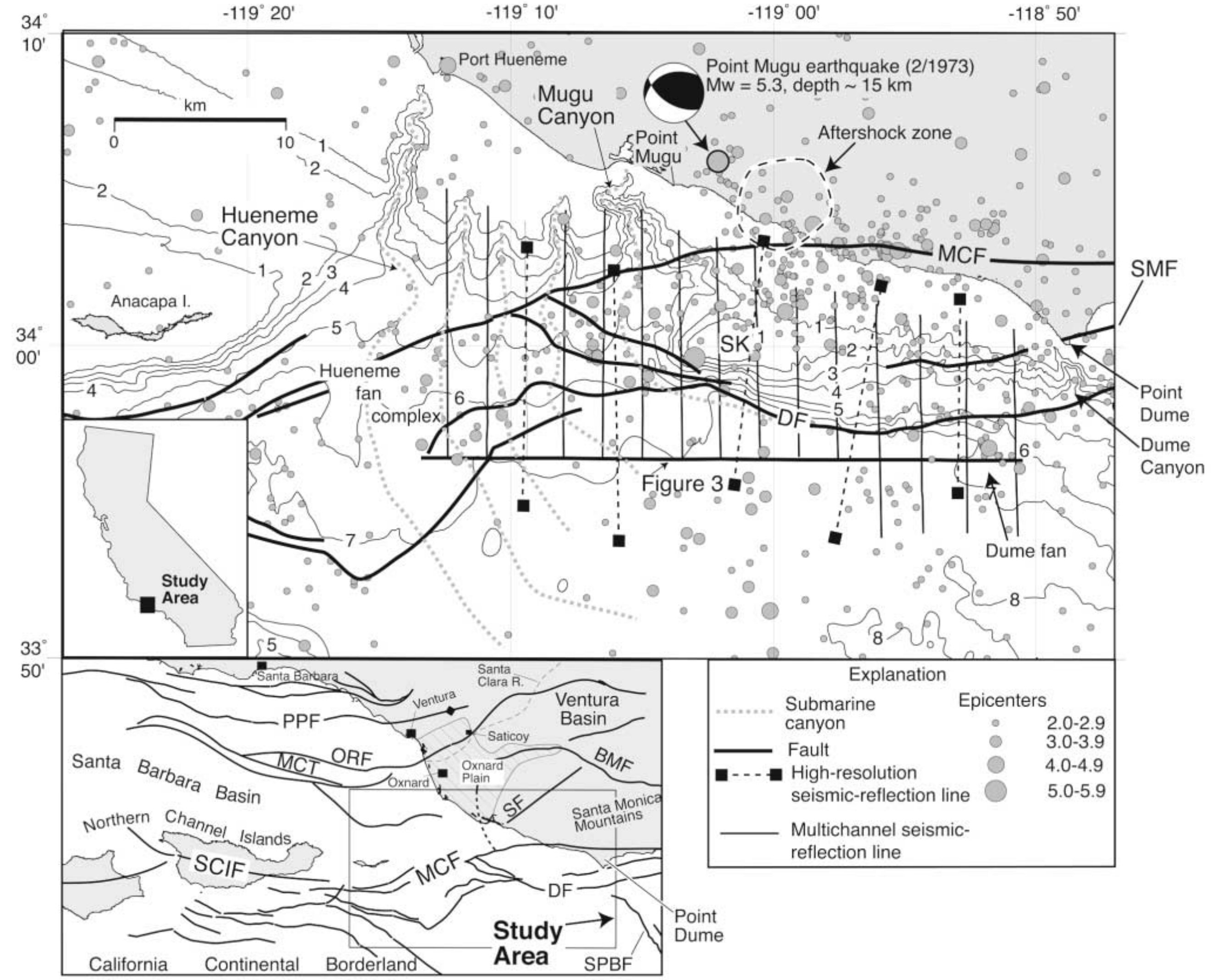

Figure 2. The study area includes faults that are part of an east-striking fault system that poses a significant seismic hazard. Epicenters are from the catalog at www.data.scec.org/catalog_search/ for the years 1970–2004. Bathymetric contours are in hundreds of meters. Dashed gray lines indicate the main submarine canyons. Offshore faults are from Sorlien *et al.* (2005). BMF, Boney Mountain fault; DF, Dume fault; MCF, Malibu Coast fault; MCT, mid-channel trend; ORF, Oak Ridge fault; PPF, Pitas Point fault; SCIF, Santa Cruz Island fault; SF, Sycamore fault; SMF, Santa Monica fault; SPBF, San Pedro basin fault. Diagonal rules in the lower-left inset indicate the Oxnard plain and adjacent onshore region. Abbreviations as in Figure 4a.

To simplify descriptions, we refer to the numerous submarine canyons and fan lobes that are associated with the Hueneme and Mugu canyons as the Hueneme fan complex.

Geologic Structure

Rocks making up the Santa Monica Mountains have been transported southward along the gently north-dipping blind Santa Monica Mountains thrust fault (Davis *et al.*, 1989; Davis and Namson, 1994; Dolan *et al.*, 2000). Another north-dipping thrust fault underlies the Santa Barbara basin to the west and is called the Channel Islands thrust fault (Shaw and Suppe, 1994; Seeber and Sorlien, 2000; Sorlien *et al.*, 2000).

From onshore evidence, the Malibu Coast and Santa Monica faults were active during the Holocene as left-lateral-reverse faults (Dibblee, 1982; Drumm, 1992; Dolan *et al.*, 2000), a probable consequence of westward movement of the western Transverse Ranges relative to the Continental Borderland during Quaternary north–south transpression (e.g., Walls *et al.*, 1998). These faults appear to have developed within the hanging wall of the underlying

Santa Monica Mountains thrust fault to accommodate crustal strain that is partitioned into left-slip and dip-slip components. Along the Malibu Coast fault, recent left-lateral strike-slip displacement is shown by the left-deflected stream channels that cross the fault and by the northwestward-plunging folds that strike obliquely away from the fault (Dibblee, 1982). Trenching across a southern splay of the Malibu Coast fault northeast of Point Dume revealed late Pleistocene and Holocene fault movement with an estimated earthquake recurrence interval of 4–5 ka (Drumm, 1992). In this location, the Malibu Coast fault zone is 300–600 m wide and includes intensely sheared rocks. The Dume fault is depicted either as a westward continuation of the Santa Monica fault (Sorlien *et al.*, 2003) or as a separate strand within the overall fault system (Dolan *et al.*, 2000).

Seismicity

Earthquakes are most common in the eastern half of the area shown in Figure 2. Many nearshore epicenters are aftershocks of the 1973 Point Mugu quake (M_l 5.3), the largest earthquake to have struck near the study area (Ellsworth *et al.*, 1973; Stierman and Ellsworth, 1976) (Fig. 2). The mainshock was caused by left-lateral-reverse slip along a north-dipping fault plane. Sorlien *et al.* (2003) show that the Dume and Malibu Coast faults converge downward and can be projected into the aftershock zone; these authors propose that the Point Mugu earthquake occurred along the faults.

Offshore Stratigraphy

MCS section WG85-395 shows the interpreted stratigraphy of the Santa Monica basin, which contains rocks at least as old as middle Miocene (Fig. 3). The rationale for the offshore stratigraphic ages is explained elsewhere (Sorlien *et al.*, 2005; M. J. Kamerling and K. Broderick, written commun., 2004), but it relies on long-distance correlation of reflections through a seismic-data grid. Acoustic basement in seismic-reflection data consists of either Catalina Schist or middle Miocene volcanic rocks. The strong smooth reflection at about 2.5 sec at the eastern end of WG85-395 (Fig. 3) is from the acoustic basement. Near the eastern end of this seismic section, the basement reflection changes in appearance, from strong and continuous to highly irregular. One interpretation is that the continuous reflection is from Catalina Schist and the irregular reflections are from middle Miocene volcanic rocks.

The stratigraphic onlap onto the interface at a travel time of about 1.7 sec (indicated in Fig. 3) is the most pronounced such interface in the Santa Monica basin. The interface may represent the top of the Pico Formation and date from the middle Pleistocene (Sorlien *et al.*, 2005). Sediment that produces the shallowest indicated horizon (yellow horizon in Fig. 3) dates from ~75 ka (Piper *et al.*, 2003; Normark *et al.*, 2004; Sorlien *et al.*, 2005).

Findings on the Main Offshore Faults

In this section we use migrated MCS data (Plate 1, unbound insert to this issue*) to describe the main offshore faults west of Point Dume. In general, these data clearly show the main faults; for example, the Dume fault is readily evident in Figure 4 (section location on Fig. 5). This fault produced fault-plane reflections, and sedimentary rocks on the south side of the fault terminate in a footwall cutoff. The fault dips ~25° north, and the cumulative dip-slip component of displacement is between 2.5 and 4.5 km. The main uncertainty in this displacement stems from the geometry of the contact between sedimentary rocks and basement. The downlap of sedimentary rocks onto basement makes it difficult to pinpoint where basement terminates on the Dume fault's south side. We were guided primarily by the fault-plane reflection in determining the offset on basement.

The Dume fault is the southern limit of deformation associated with the Santa Monica Mountains. Deformation associated with this fault also controls the location of the continental shelf and slope. This deformation is mirrored in the bathymetry, which shows that the south dip of the continental slope increases generally westward from Point Dume toward Sycamore knoll (Fig. 2). West of the knoll, the seafloor over the Hueneme fan complex has a low south dip that contrasts with the seafloor dip near the knoll.

MCS reflection data accord with the bathymetry in the sense that the structural relief of the Dume fault increases westward from Point Dume and reaches its maximum relief at Sycamore knoll. MCS data obtained near Point Dume (line WG85-408 in Plate 1) show that the Dume fault emerges at the toe of the slope and offsets the seafloor. Where the fault emerges it has low dip, and, in its hanging wall, shallow sediments in the Santa Monica basin are gently folded (sediment body denoted by "A" in Plate 1; line WG85-408). Westward along the slope toe, this sediment body becomes increasingly deformed and incorporated into lower-slope rocks, and rocks making up the Dume fault's hanging wall are increasingly uplifted. Sesimic line WG85-400 (Plate 1) shows that sediment body A looks as if it has been deformed around the nose of the thrust front advancing southward along the Dume fault, like a pile of soil being pushed ahead of a bulldozer. Below Sycamore Knoll sediment body A is too complexly deformed to be resolved by MCS data shown here (Plate 1, line WG85-394).

The westward increase in hanging-wall deformation is spatially coincident with the thickening of late Pliocene sediment in the Santa Monica Basin (sediment between the yel-

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*Plate 1: Migrated multichannel seismic-reflection data obtained west of Point Dume show major thrust faults that dip north and deform rocks at shallow depth below the seafloor. Because of young movement, these faults potentially pose a significant earthquake hazard. Western-Geco, Inc., provided seismic-reflection data, as explained in the acknowlegments section of this report.

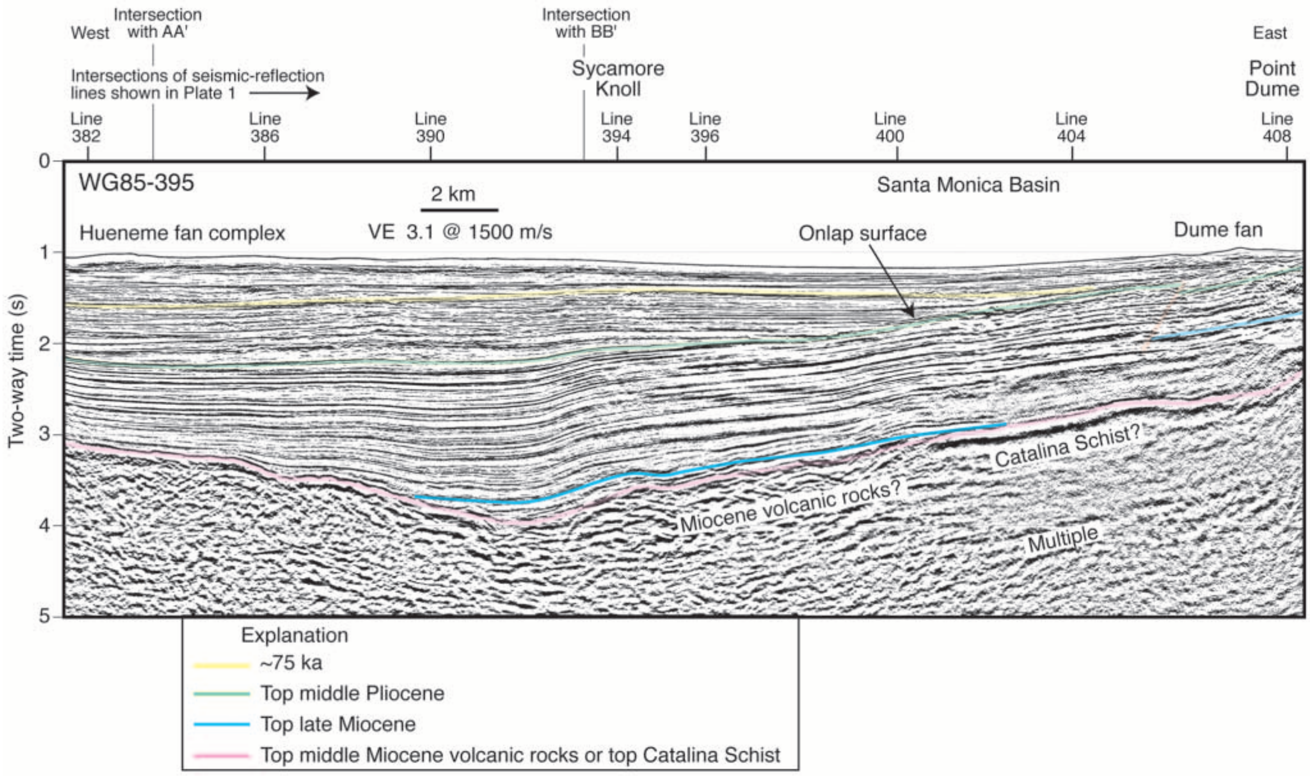


Figure 3. Regional east–west seismic line through the Santa Monica basin, in the footwall of the Dume fault, showing interpreted offshore stratigraphy. Line location is shown in Figure 2. The stratigraphy is adapted from Sorlien *et al.* (2005) and M.L. Kamerling and K. Broderick (written commun., 2004).

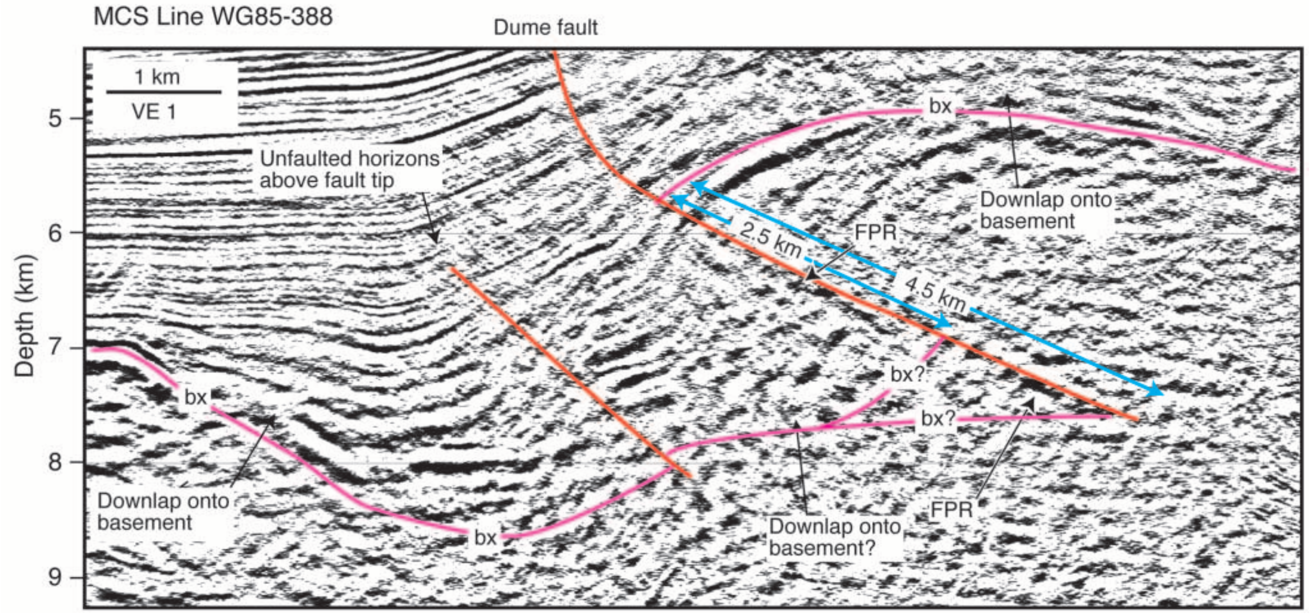


Figure 4. Part of MCS section 388 (location given in Fig. 5) showing that offset along the Dume fault west of Sycamore knoll amounts to between 2.5 and 4.5 km. Fault plane reflections (FPR) locate the fault plane, but the interpreted top of the basement complex (bx) between the two faults is uncertain. This complex is made of either Catalina Schist or middle Miocene volcanic rocks.

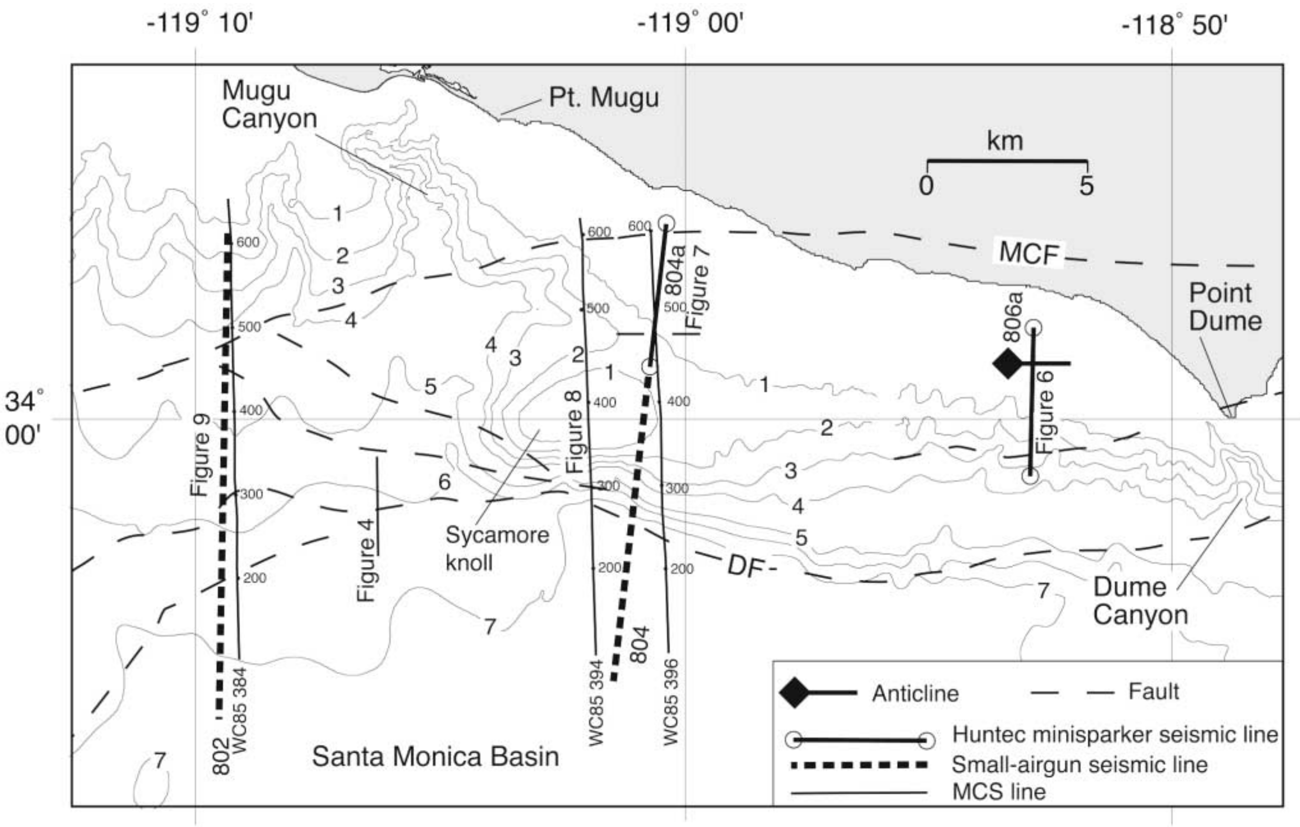


Figure 5. Locations of seismic sections in Figures 6, 7, 8, 9, 10, 11. Faults are from Sorlien *et al.* (2005) and this study.

low and green horizons in Fig. 3). South of Point Dume, this sediment is absent and the Dume fault has low structural relief, but the sediment thickens uniformly westward toward Sycamore knoll, where this fault has high relief. This spatial coincidence between the increasing sediment thickness and the thrust-fault deformation suggests a close link between basin sedimentation and tectonics.

Maximum relief along the Dume fault's tip occurs at Sycamore knoll (Plate 1, line WG85-394). Below the continental shelf, the northward dip and parallel bedding of rocks in this fault's hanging wall are unique in the study area. The entire shelf and slope appear to have been uplifted and rotated northward above the Dume fault.

The Sycamore knoll marks an anomalous structural zone because less than 2 km west of the knoll, the tip of the Dume fault loses much of its relief and is deeply buried beneath sediment of the Hueneme fan complex (Plate 1, line WG85-390). In general, the continental slope west of the knoll has undergone significantly less uplift, or has actually subsided, relative to the slope east of the knoll. This difference in uplift helps explain the location and extent of the Hueneme fan complex.

At the temporal and spatial resolution provided by MCS data shown here, the seafloor over the submarine fan and fault tip is barely arched, if at all. In fact, folding in the fault's hanging wall dies out sharply upward from the fault tip. Westward from Sycamore knoll, the Dume fault becomes progressively more deeply buried, and hanging-wall structure decreases in relief.

Thrust faults besides the Dume fault deform rocks under the shelf and upper slope. Although rock structure north of the Dume fault is poorly resolved in MCS data from near Point Dume (Plate 1, line WG85-408), west of this point a major thrust fault deforms rocks under the shelf edge (Plate 1, line WG85-400). This fault branches obliquely northwestward from the Dume fault. These oblique faults commonly produce strong fault-plane reflections in migrated MCS data.

The Malibu Coast fault cuts offshore between points Dume and Mugu (Fig. 5). MCS data shown here do not clearly reveal the connection between the onshore fault and what may be its offshore extension, because of locally strong water-bottom multiples. However, on line WG85-386 (Plate 1) what is likely to be the Malibu Coast fault dips steeply in its upper part, and deformation resulting from fault movement extends high up into the sediment of the Hueneme fan complex. Fault dip decreases with increasing depth.

Discussion

Evidence for Recent Displacement along Major Faults

In general, MCS data shown here are too limited in resolution to demonstrate Holocene faulting; however, as shown in the previous section, deep fault movement is commonly revealed in the shallow subsurface by folding. Here we merge information on the shallow and deep rock sections; MCS, high-resolution seismic, and multibeam-bathymetric data are analyzed together to investigate recent displacement along major faults.

South of Point Dume, the Dume fault offsets the seafloor, showing Holocene fault movement, especially in view of what are probably high sedimentation rates associated with the Dume submarine fan (Plate 1, line WG85-408 and detailed section 1). Also, folding extends upward to arch the seafloor.

Faults north of the Dume fault commonly involve complex structures, some of them recently active. For example, under the continental slope a zone of folds and faults appears to be truncated at the seafloor (Plate 1, line WG85-404 and detailed section 2). MCS data do not resolve whether a sediment layer blankets the truncated fold, but if a blanket exists there, it is thin (<50 m). At the resolution provided by the MCS data, we cannot determine whether the anticline deforms the seafloor.

High-resolution seismic reflection data reveal an active fault beneath the continental shelf. Seismic section 806a was collected where no companion MCS data exist to show the deep structure (Figs. 5 and 6). Despite this, the seismic section shows a fault that separates strata deformed into small folds, on the south, from steeply dipping rocks, on the north. At the base of a poorly reflective sediment layer just under the seafloor, an unconformity truncates the deformed rocks and the fault. The age of the unconformity is unconstrained, but we propose that it dates from the last glacial sea-level lowstand. If so, then the poorly reflective sediment is late Pleistocene and Holocene (younger than ~13 ka). Although the fault is truncated by the unconformity, movement along a deep blind part of this fault or along another fault occurred more recently than 13 ka because the unconformity and the overlying seafloor are broadly arched (Fig. 6).

The part of the unconformity adjacent to the fault is elevated with respect to more distant parts of the unconformity, illustrated in Figure 6, and the elevated part is bounded on the north and south by what appear to be wave-cut notches. We infer from this configuration that during the Holocene an old wave-cut terrace or island that was initially flat was arched by deep fault movement.

A possibility we favor is that the fault just described connects to the east with the Santa Monica fault. Dolan *et al.* (2000) extended the active Santa Monica fault westward from the east shore of Santa Monica Bay to connect with a supposedly active fault at the south tip of Point Dume (Fig. 2), but this fault's westward continuation beyond the point was uncertain. We propose that the subshelf fault is a strand of the Santa Monica fault west of Point Dume.

MCS data reveal a deep thrust fault below the continental shelf north of Sycamore knoll, and high-resolution data indicate that this fault was recently active (Figs. 5, 7A and B). Movement along the deep (~1.5 sec) thrust fault deformed superjacent rocks into a parasitic anticline and a small fault that dips south (Fig. 7A). The rock section at ~1.0 sec thins sharply north near the deep thrust fault. This thinning indicates that the main fault movement occurred sometime during the Pliocene.

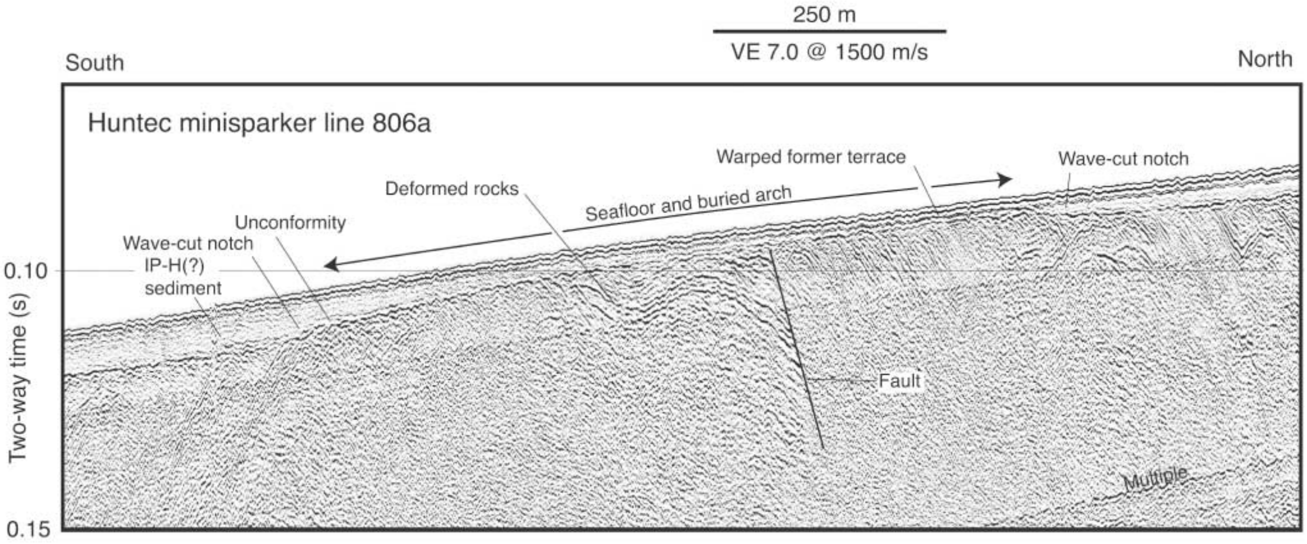


Figure 6. Unmigrated seismic-reflection section 806a across the continental shelf west of Point Dume. Location shown in Figure 5. A broad seafloor arch and underlying arch in the unconformity indicates recent structural activity. LP-H(?) means late Pleistocene and Holocene(?) age.

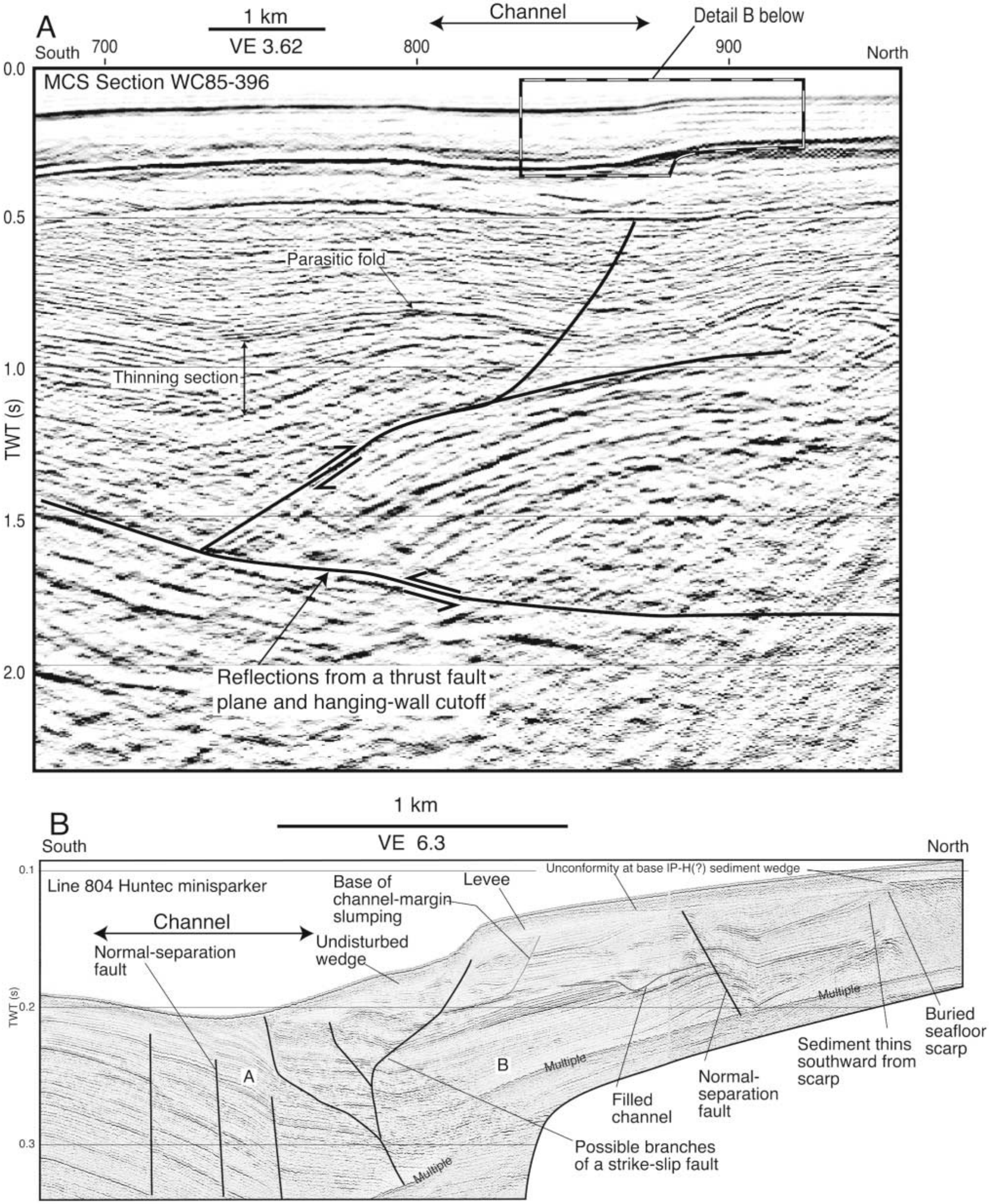


Figure 7. (A) Migrated MCS section WG85-396 across the crest of Sycamore knoll. Section location shown in Figure 5. (B) Unmigrated high-resolution seismic section 804a across the channel that bounds the knoll on the north. Section location shown in Figure 5. The channel is structurally controlled, at least in part, as shown by normal-separation faults that step downward toward the channel axis. Complicated stratigraphy below the channel, compare reflections at locations A and B, may be due to offset along a strike slip fault. "1P-H(?)" means late Pleistocene and Holocene(?) age.

The subsidiary south-dipping fault extends upward toward a broad seafloor channel (Figs. 7A and B), and evidence from the shallow subsurface supports the possibility of strike-slip displacement along this fault. Specifically, the difference in reflection appearance near the letters "A" and "B" annotated on the high-resolution seismic section in Figure 7B suggests that rocks across the seafloor channel differ considerably in acoustic properties. The combined evidence from the shallow and deep parts of these faults indicates that movement along the deep fault is ongoing and most likely is oblique. Strain appears to be partitioned into deep thrust and shallow strike-slip components.

The high-resolution seismic section in Figure 7B shows the complicated structure of shallow sedimentary rocks below the seafloor channel. Where the deep south-dipping fault emerges, rocks below the channel's south flank are deformed by small normal-separation faults. These faults are positioned over the parasitic anticline evident in MCS data, so they may reveal flexure of shallow rocks over the deep fold or bending related to uplift of the Sycamore knoll. The shallow deformation suggests ongoing displacement on the underlying faults.

Seismic-reflection data across Sycamore knoll show the Dume fault at the base of a thick parallel-bedded rock section ranging in age from middle Miocene to Pliocene (Figs. 5, 8A–C). These hanging-wall strata do not thin southward toward the fault tip; the deformation that uplifted and rotated the hanging wall is younger than the tilted rocks.

Mass-wasting deposits near the tip of the Dume fault, revealed by high-resolution seismic data (Fig. 8B), can be interpreted as evidence that this fault was recently active. Tongues of mass-wasting deposits interfinger with the shallow basin fill, and the shallowest basin deposit adjacent to the fault tip is a small debris cone or wedge. This cone might have been emplaced when upslope areas were oversteepened, as the hanging wall of the Dume fault rose. Other possibilities, however, are that the mass-wasting deposits result from sediment either destabilized by changes in sea level or dislodged by local earthquakes not generated along the Dume fault.

High-resolution seismic-reflection data obtained across the crest of Sycamore knoll help resolve this ambiguity. These data reveal two marine terraces (Fig. 8C), the older of which underlies the north half of the knoll, dips north, and truncates underlying Pliocene rocks. The younger terrace dips gently north and coincides with the present seafloor. Both terraces are undated; however, the deeper one must be post-Pliocene because it truncates rocks of this age, and we propose that the shallow terrace formed during the last glacial sea-level lowstand. If so, then the shallow terrace indicates Holocene northward tilting of the knoll. Taken together, the mass-wasting deposits at the seafloor in the Santa Monica basin and the terraces are consistent with an ongoing component of thrusting along the Dume fault.

Sycamore knoll marks an abrupt along-strike discontinuity in the structure of the regional fault zone that encompasses the Dume and Malibu Coast faults. Just 2 km west of the knoll, the structural relief near the tip of the Dume fault decreases abruptly (compare sections WG85 394 and 390 on Plate 1). West of Sycamore knoll, the Malibu Coast fault deforms shallow deposits making up the Hueneme fan complex (Figs. 5, 9A–C). MCS data show deformation along this fault extending upward to affect sediment that is as shallow as these data can resolve (Fig. 9A). Furthermore, high-resolution seismic data from the same area show that a band of reflective fan sediment was truncated at very shallow depth above the fault's location (Fig. 9B), and sediment just under the seafloor shows marked differences in reflectivity across this location (Fig. 9C).

These indications of shallow faulting in seismic-reflection data suggest that seafloor morphology might provide additional evidence for Holocene fault offset; in general, however, this morphology, as revealed in multibeam-bathymetric data (Fig. 10A), shows scant evidence for Holocene fault movement. Multibeam data might reveal such fault-related features as deflected channels, uplifted terraces, truncated folds, or local widening along canyon bottoms where sediment transport was impeded by fault uplift. However, highly active sedimentary processes produced features, such as slumps, subsidiary fan lobes, and abandoned channel meanders, that have sufficient topographic relief to obscure fault scarps. For example, the interchannel area A, over the tip of the Malibu Coast fault (Figs. 10A and 10B, bathymetric profile 1) has relief and steepness that are similar to slopes produced by canyon cutting (Figs. 10A and 10B, bathymetric profile 2).

Multibeam bathymetric data show that all canyons across the Hueneme fan complex are incised and sinuous, so it is difficult to relate any particular channel deflection to fault movement. However, in the lower reaches of Mugu Canyon near the west flank of Sycamore knoll, the channel is deflected through two right-angle bends (labeled "B" in Fig. 10A). These deflections are directly above an anticline that is associated with a thrust fault (Plate 1, line 390 and detailed section 4). The anticline is truncated at shallow depth along a horizon interpreted to be ~75 ka old. This horizon itself is arched, indicating that fault movement occurred after the fold was truncated. The seafloor over the anticline is not arched at the resolution provided by MCS data, but it would be difficult to separate a seafloor arch caused by deep faulting from the relief of the channel's levee. Even so, the deflected Mugu Canyon and underlying fold indicate late Quaternary movement along this stretch of the Dume fault.

A Proposed Transverse Structural Boundary

Structural variation along the Dume fault near Sycamore knoll appears similar to structural changes along the Oak Ridge fault near the town of Saticoy. The Oak Ridge fault forms the Ventura Basin's south boundary, and eastern and western segments of this fault connect near the town of

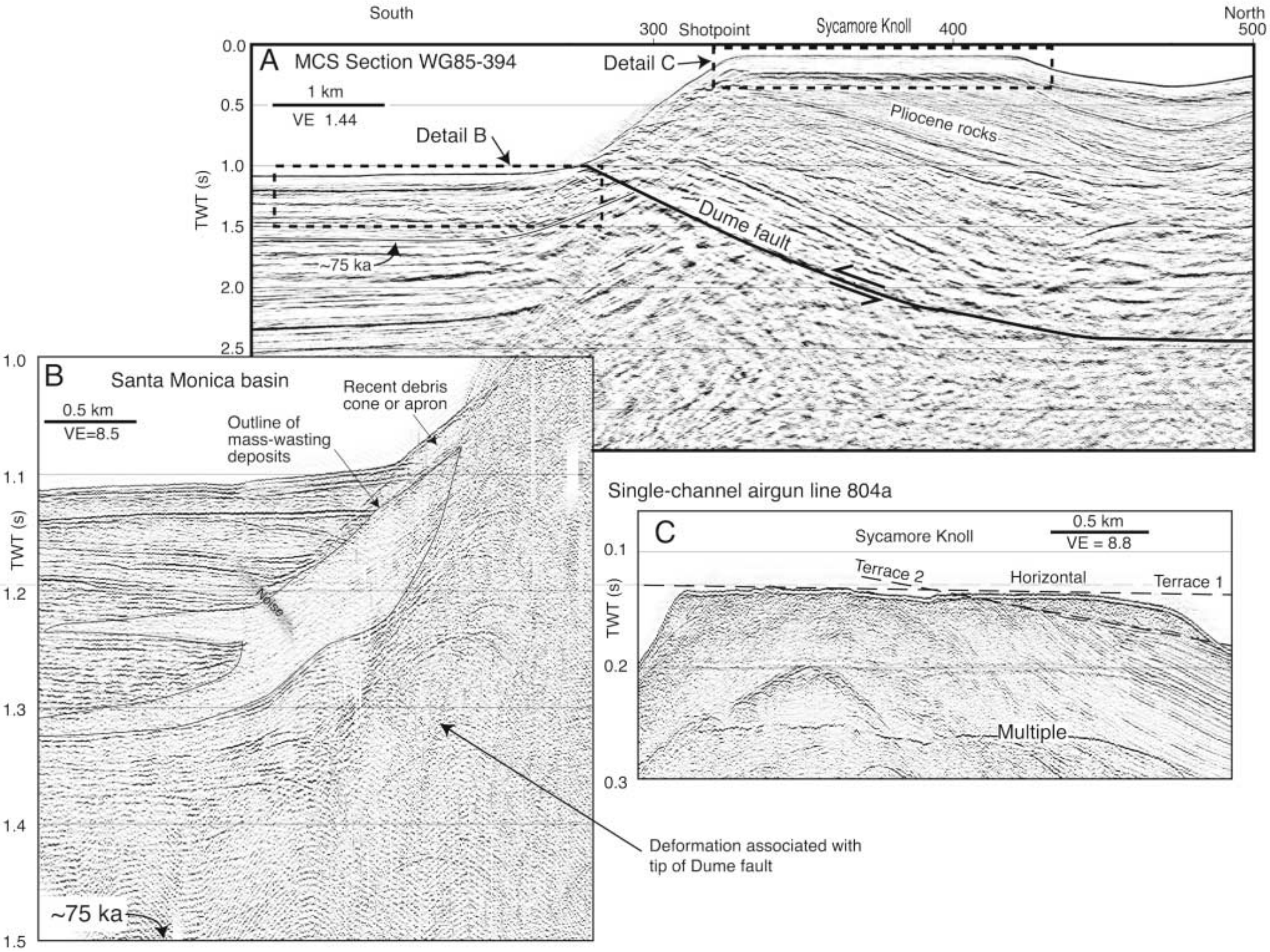


Figure 8. (A) Migrated MCS section 394 across the Sycamore knoll. Section location shown in Figure 5. Pliocene and older rocks were tilted north during movement along the underlying Dume fault. (B) Detail of unmigrated high-resolution seismic section 804a showing mass-wasting deposits in the basin fill near the tip of the Dume fault. Section location shown in Figure 5. (C) Unmigrated high-resolution seismic section 804a showing two wave-cut terraces that truncated the upturned ends of Pliocene and older rocks. The shallowest terrace may date from the last glacial sea-level lowstand. Section location shown in Figure 5.

Saticoy (Yeats, 1983, 1988; Yeats *et al.*, 1988; Huftile and Yeats, 1995) (Fig. 1 and lower left inset in Fig. 2). East of the town, the fault has strong topographic expression, and late Quaternary fault displacement amounts to about 2.5 km (Yeats, 1988). West of the town, however, the fault curves to strike east–northeast, and during the late Quaternary, fault displacement apparently ceased (Yeats *et al.*, 1988; Huftile and Yeats, 1995; Azor *et al.*, 2002; Fisher *et al.*, 2005). A north-striking displacement-transfer zone was proposed to account for the different structure and activity of the fault segments near Saticoy (Yeats, 1983, 1988; Yeats *et al.*, 1988; Huftile and Yeats, 1995).

The similarity between the Oak Ridge and Dume faults is greatest near Sycamore knoll, where the Dume fault curves southward, and within a short distance (~2 km) west of this knoll, topographic expression and structural relief of the fault decrease sharply. Sorlien *et al.* (2005) explain the anomalous fault structure near the knoll as resulting from deformation within a restraining bend formed within the left-oblique fault zone that includes the Dume and Malibu Coast faults.

Another possibility is that a displacement-transfer zone, like the one affecting the Oak Ridge fault, strikes north, transverse to the main faults near Sycamore knoll. In general, transverse structures are fundamental to the development of many foreland fold-and-thrust belts (Wheeler *et al.*, 1979; Thomas, 1990; Thomas and Bayona, 2002; Wilkerson *et al.*, 2002; Bayona *et al.*, 2003). Typically, such structures include lateral ramps, transverse faults, and displacement-transfer zones.

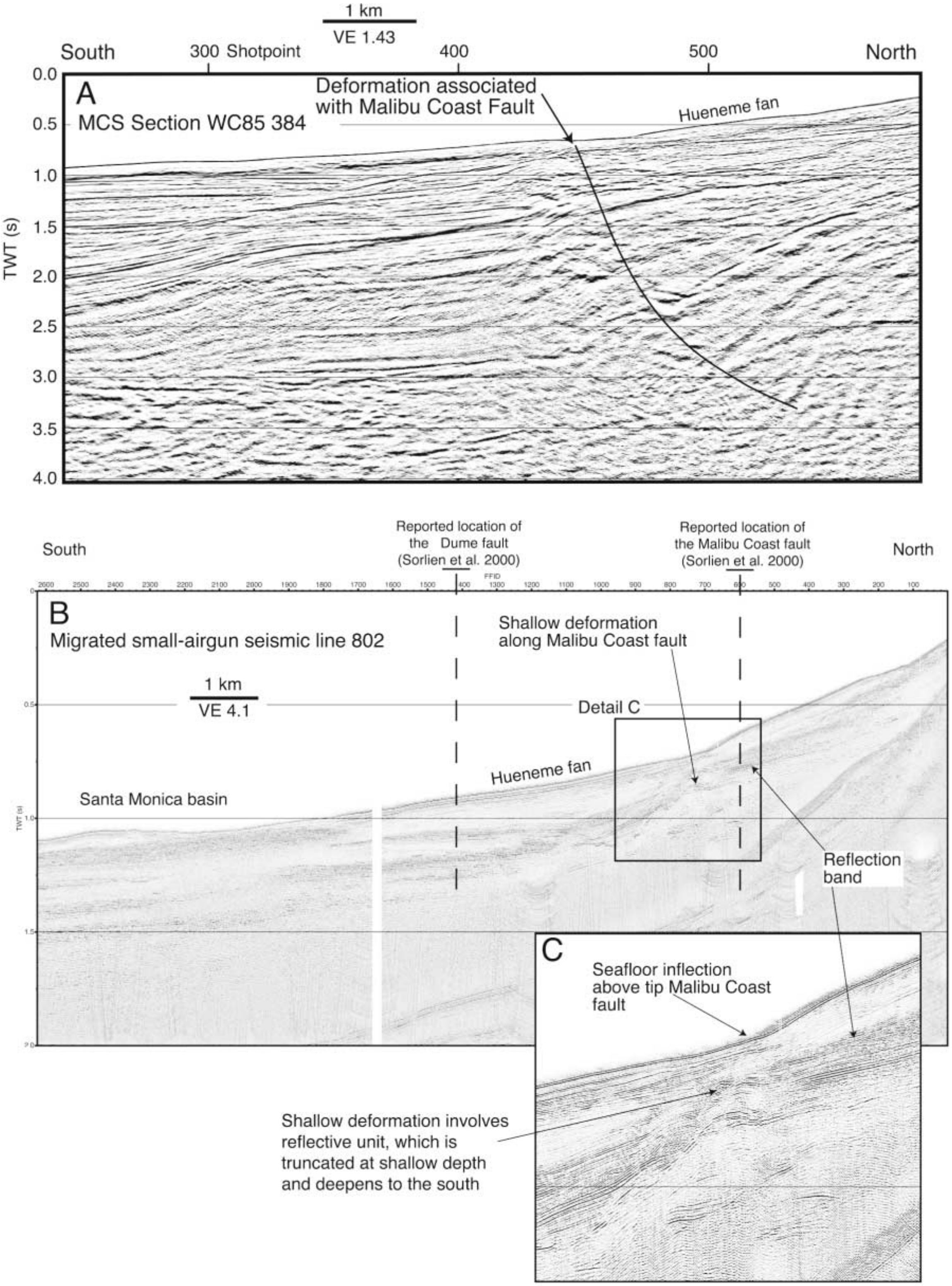
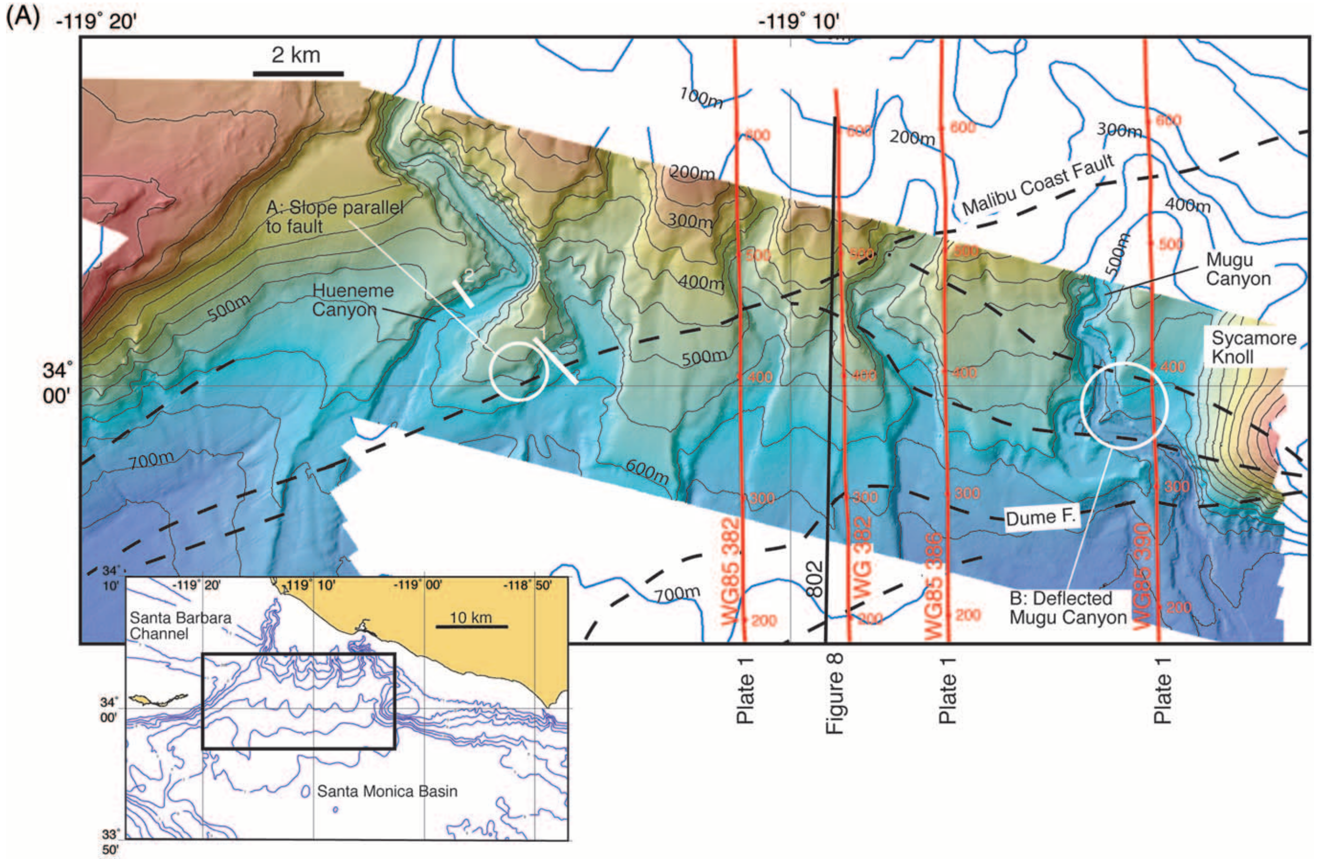


Figure 9. (A) Migrated MCS section 384 shows that deformation along the Malibu Coast fault extends upward to shallow depth within late Quaternary Hueneme fan complex deposits. Section location shown in Figure 5. (B) Migrated high-resolution seismic section 802 showing the detailed shallow fan stratigraphy. Section location shown in Figure 5. (C) Detail of migrated high-resolution seismic section 802 showing shallow deformation associated with the Malibu Coast fault. The reflection band is truncated within shallow fan deposits. Section location shown in Figure 5.



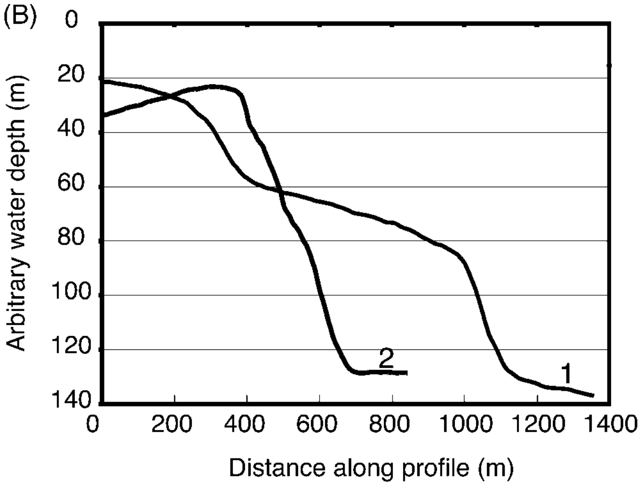


Figure 10. (A) Multibeam bathymetric data obtained over the lower reaches of the Hueneme–Mugu Canyon system. The numbered white line segments show the locations of bathymetric profiles shown in B. Circled features are discussed in the text. West of Sycamore knoll, Mugu Canyon deflects through two right-angle bends, and MCS section WG85-390 (Plate 1) shows the thrust fault and fold that underlie these deflections. (B) Bathymetric profiles across selected features of the Hueneme fan complex. Profile locations are shown as numbered white lines in A. Profile 1 shows the height and steepness of a bathymetric slope that results solely from canyon-cutting processes. Profile 2 shows a bathymetric slope that parallels the Malibu Coast fault. This slope might result from movement along this fault, but it is comparable in height and steepness to the nonstructural slope shown in profile 1. Profile locations are shown in A.

A transverse structure would be important to the analysis of earthquake hazards because the structure could bound earthquake-rupture zones along a fault, thereby limiting the maximum earthquake magnitude (Wells and Coppersmith, 1994). A local example of this effect is the two lateral ramps in the Santa Susana fault (Yeats, 1988), which constrained the rupture zone of the 1994 Northridge earthquake (Hauksson *et al.*, 1995).

Some evidence suggests that the transverse structure we propose affects regional seismicity. Although in map view, epicenters do not cluster along a transverse structure near Sycamore knoll (Fig. 2), we note that epicenters are distributed unevenly across the proposed structure—they are more common in the east than in the west (Fig. 11). The spatial coincidence between our proposed transverse structure and the westward decrease in seismicity does not prove a cause-and-effect relationship, but the coincidence is at least provocative.

Conclusion

We identified major thrust faults that strike west through the offshore area west of Point Dume and fall within the

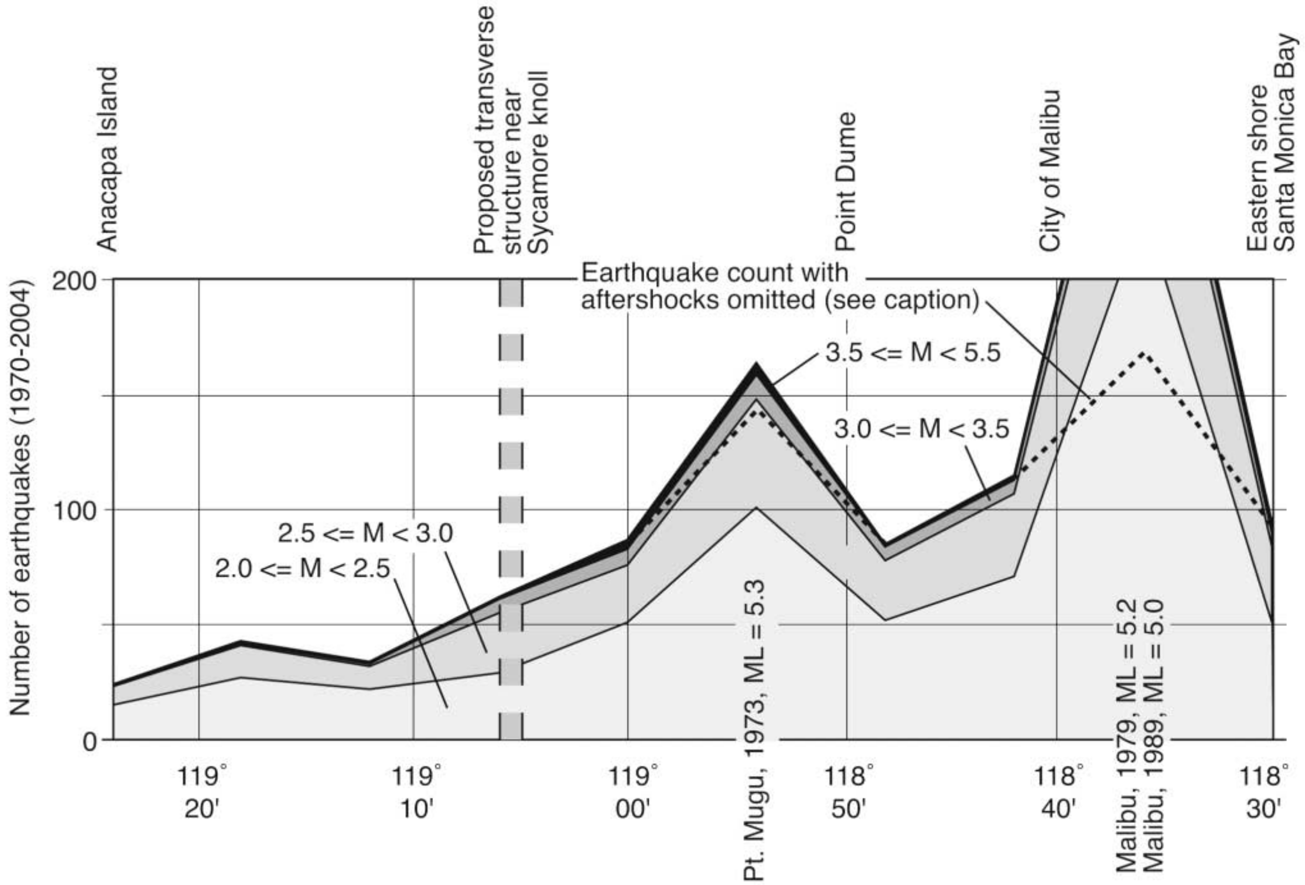


Figure 11. The number of earthquakes that occurred near the proposed transverse structural zone decreases westward across the zone. The number of earthquakes are totaled for bins that are 0.1° of longitude wide; the bins extend west from the eastern shore of Santa Monica Bay (118°30′W longitude) to Anacapa Island (119°25′W longitude) and are bounded by the latitudes 33°50′N and 34°10′N (the same latitudes delimit Fig. 2). Earthquakes occurring between 1970 and 2004 (excluding the years 1977–1980) were obtained from the catalog at www.data.scec.org/catalog_search/. The thin black dashed line shows the approximate earthquake totals that result when aftershocks of the three main events (Point Mugu 1973, Malibu 1979, and Malibu 1989) are excluded from the count. We attempted to exclude aftershocks by omitting all events, in the bin where each mainshock occurred, that struck within 1 year of each mainshock.

boundary fault zone between the western Transverse Ranges and the California Continental Borderland. These faults pose a significant potential earthquake and tsunami threat because cumulative displacement along some of the main thrust faults is measured in kilometers, and many of these faults moved during the Holocene. The Dume fault is the main active offshore fault; we presume but cannot demonstrate that other offshore faults merge downward into the Dume fault. The structure of the boundary fault zone is complicated by a transverse structural zone near Sycamore knoll. This zone could play a significant role in the analysis of offshore structure and earthquake hazards because the transverse structure appears to separate areas of the continental margin that differ in seismicity, and east–west offshore faults might not continue uninterrupted across the zone, so the zone forms a boundary between earthquake-rupture segments.

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