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ABSTRACT

Urban areas in Southern California are at risk from major earthquakes, not only quakes generated by long-recognized onshore faults but also ones that occur along poorly understood offshore faults. We summarize recent research findings concerning these lesser known faults. Research by the U.S. Geological Survey during the past five years indicates that these faults from the eastern Santa Barbara Channel south to Dana Point pose a potential earthquake threat. Historical seismicity in this area indicates that, in general, offshore faults can unleash earthquakes having at least moderate (M 5–6) magnitude.

Estimating the earthquake hazard in Southern California is complicated by strain partitioning and by inheritance of structures from early tectonic episodes. The three main episodes are Mesozoic through early Miocene subduction, early Miocene crustal extension coeval with rotation of the Western Transverse Ranges, and Pliocene and younger transpression related to plate-boundary motion along the San Andreas Fault. Additional complication in the analysis of earthquake hazards derives from the partitioning of tectonic strain into strike-slip and thrust components along separate but kinematically related faults.

The eastern Santa Barbara Basin is deformed by large active reverse and thrust faults, and this area appears to be underlain regionally by the north-dipping Channel Islands thrust fault. These faults could produce moderate to strong earthquakes and destructive tsunamis. On the Malibu coast, earthquakes along offshore faults could have left-lateral-oblique focal mechanisms, and the Santa Monica Mountains thrust.

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fault, which underlies the oblique faults, could give rise to large (M ~7) earthquakes. Offshore faults near Santa Monica Bay and the San Pedro shelf are likely to produce both strike-slip and thrust earthquakes along northwest-striking faults. In all areas, transverse structures, such as lateral ramps and tear faults, which crosscut the main faults, could segment earthquake rupture zones.

INTRODUCTION

Urban Southern California faces an elevated risk for societal disruption by major earthquakes because the region combines high population density and economically critical infrastructure with a vigorously deforming Earth. Recent earthquakes, notably those at Whittier Narrows (1987, M_S 5.9; Hauksson and Jones, 1989; Lin and Stein, 1989) and at Northridge (1994, Mw 6.7; Hauksson et al., 1995), underscored the hazard and the economic threat posed by the numerous faults known to crosscut the cityscape in Southern California. For example, an M ~7 earthquake along the Puente Hills blind thrust fault, which lies directly below the city of Los Angeles, could cause an economic loss of as much as $250 billion and a human toll numbering in the thousands (Field et al., 2005).

We summarize research findings, by the U.S. Geological Survey (USGS) during the years 2000–2005, concerning offshore faults that pose a potential earthquake threat to urban areas of Southern California. The area encompassed by this report extends from the eastern Santa Barbara Channel south to Dana Point (Fig. 1). A similar summary for Dana Point to San Diego is given by Ryan et al. (this volume). Compilations of Southern California seismicity (Astiz and Shearer, 2000; Richards-Dinger and Shearer, 2000; Hauksson and Shearer, 2005; Shearer et al., 2005; Kagan et al., 2006) and Quaternary fault databases (e.g., U.S. Geological Survey, 2006) show the geographic distribution of potential earthquake sources (Fisher et al., this volume, Chapter 4.2, Fig. 2). For example, earthquakes in 1979 (M_S 5.2) and 1989 (M_S 5.0) occurred ~12 km beneath Santa Monica Bay (Hauksson and Saldivar, 1989; Hauksson, 1990). The largest historic earthquake in coastal Southern California was the 1933 Long Beach event (M_S 6.4), which struck along the Newport-Inglewood Fault (Barrows, 1974; Hauksson and Gross, 1991).

Some offshore faults within ~50 km of the coast remain poorly understood and are sometimes omitted from models of tectonic evolution and estimates of seismic hazard. However, some of these faults are more than 100 km long, and according to an empirical relationship between an earthquake’s rupture length and magnitude (Wells and Coppersmith, 1994), future earthquakes in Southern California larger than the moderate ones recorded are possible. Hence, coastal and offshore faults merit close scrutiny; they are the focus of this chapter. We describe them in geographic order from the eastern Santa Barbara Channel to near Los Angeles.

EASTERN SANTA BARBARA CHANNEL

The Ventura and Santa Barbara Basins lie within the east-west Transverse Ranges Province (Fig. 1), which cuts perpendicularly across the regional, north and northwest structural grain of major faults and mountain ranges found elsewhere in Southern California. The province ends to the south along the south flank of the Santa Monica Mountains and their westward extension along the northern Channel Islands. These mountains and islands are thought to be uplifted along deep-seated, north-dipping thrust faults (e.g., Bailey and Jahns, 1954; Davis and Namson, 1994a; Shaw and Suppe, 1994; Seebirer and Sorlien, 2000). These faults extend east-west for more than 200 km and form the province boundary between the Western Transverse Ranges Province and the California Continental Borderland (Wright, 1991; Crouch and Suppe, 1993; Bohannon and Geist, 1998). Since the Miocene, the Ventura and Santa Barbara Basins have undergone strong north-south compression (Yeats et al., 1988; Yeats and Huftile, 1995; Sylvester and Brown, 1997; Sorlien et al., 2000). Global positioning system (GPS) data revealed a high rate (~6 mm/yr) of north-south shortening across the onshore Ventura Basin (Donnellan et al., 1993; Argus et al., 2005).

Despite decades of research into the geology of the Santa Barbara Basin by oil-company and academic geologists, the extent, age, and geometry of offshore faults are still controversial. Is crustal deformation thick or thin skinned (e.g., Yeats, 1998)? Do major thrust faults that appear to control the main aspects of basin structure dip north or south (e.g., Shaw and Suppe, 1994; Huftile and Yeats, 1995)?

Faults below the northern part of the Santa Barbara Channel, including the North Channel, Pitas Point, and Red Mountain, illustrate this controversy. These faults are members of a system that in aggregate extends for ~100 km east-west through the Ventura and Santa Barbara Basins (Redin et al., 1998; Kamerling et al., 2001). To the east, this south-verging fault system merges with the San Cayetano and Santa Susana Faults. In one interpretation of the structure, a balanced section through the eastern Santa Barbara Channel indicates a north-dipping décollement at 5–10 km depth, and complicated folding of rocks above the décollement occurs along north-dipping thrust faults (Novoa, 1998). Another structural section through the same general area as the one just mentioned shows reverse faults below the northern part of the channel (Redin et al., 1998) (Figs. 2 and 3). Davis and Namson (1994a) provided two north-south geologic sections, 10 km apart,
Figure 1. Regional bathymetry of the Southern California offshore. Boxes outline four areas discussed in the text. Red lines show faults (Jennings et al., 2000; Sorlien et al., 2000). Abbreviations: CCB—California Continental Borderland; LA—Los Angeles; DF—Dume Fault; NIF—Newport-Inglewood Fault; MCF—Malibu Coast Fault; ORF—Oak Ridge Fault; PVF—Palos Verdes Fault; PP-RM-NCF—Pitas Point–Red Mountain–North Channel Fault; SAF—San Andreas Fault; SB—Santa Barbara; SCIF—Santa Cruz Island Fault; SPBF—San Pedro Basin Fault; SRIF—Santa Rosa Island Fault; SMB—Santa Monica Bay; WEF—Whittier-Elsinore Fault; WTRP—Western Transverse Ranges Province.
which suggest strong along-strike structural complexity. Both sections show a flat or shallowly north-dipping décollement at ~9 km depth. In the eastern section, however, rocks above the décollement are deformed along south-dipping thrust faults, whereas the western section shows the opposite vergence along north-dipping thrust faults that are blind above ~4 km depth.

Seismic-reflection data available to us indicate that the Pitas Point and Red Mountain Faults dip moderately (40°–60°) north (Figs. 4A and 4B). The relationship between the Pitas Point thrust fault and faults in the Red Mountain fault zone to the north is not clearly evident in these seismic-reflection data, but the faults probably merge downward to the north. Other researchers (Sorlien and Kamerling, 2000; Kamerling et al., 2001, 2003) have proposed that although the fault system includes many splays, the overall system dips 40°–50° north. Near the town of Carpinteria, the Red Mountain Fault splays into two main branches (Fig. 3), and displacement is transferred between these branches by northeast-striking cross faults (Gurrola and Kamerling, 1996; Kamerling et al., 2001, 2003). The cross faults are thought to be important to the analysis of earthquake hazards because they could delimit earthquake-rupture segments (Gurrola and Kamerling, 1996; Kamerling and Gurrola, 1997).

The Oak Ridge Fault forms the southern boundary of the Ventura Basin (e.g., Yeats, 1988; Yeats et al., 1988; Sorlien et al., 2000). This fault is thought to pose a substantial earthquake hazard, because not only does it appear to be the westward continuation of the fault system responsible for the 1994 M 6.7 Northridge earthquake (Yeats and Huftile, 1995), but also the fault

![Figure 2](specialpapers.gsapubs.org)

**Figure 2.** Location of a cross section and seismic lines through eastern Santa Barbara channel. High-resolution seismic lines in Figure 5 are shown as short lines across the Oak Ridge Fault west of Ventura. The dashed black line shows the surface trace of the Oak Ridge Fault. Bathymetry is in meters. Faults in Santa Barbara Channel are from Heck (1998); the locations are where the faults cut the top of the Monterey Formation. Faults south of the Santa Cruz Island are from Sorlien et al. (2000); locations show surface fault traces. Abbreviations: ORF—Oak Ridge Fault; PPF—Pitas Point Fault; RMF—Red Mountain Fault; SCIF—Santa Cruz Island Fault; SRIF—Santa Rosa Island Fault.
Figure 3. Geologic cross section through eastern Santa Barbara Channel showing the Pitas Point Red Mountain Faults, which merge downward to the north, as well as the Oak Ridge Fault, which dips south. Section location shown in Figure 2. Abbreviations: ORF—Oak Ridge Fault; PPF—Pitas Point Fault; RMF—Red Mountain Fault; V.E.—Vertical exaggeration; WEF—World’s End Fault.

Adapted from Redin et al. (1998)
Figure 4. (A) Migrated multichannel seismic section across the Pitas Point and related faults and the Oak Ridge Fault in eastern Santa Barbara channel. (B) Migrated seismic section showing the same faults south of Santa Barbara. Line locations shown in Figure 2.
extends along strike for ~130 km and deforms Holocene rocks. The fault extends east-west and crosses the coastline near Ventura (Fig. 2). Shaw and Suppe (1994), using offshore seismic-reflection data, proposed that this “fault” is actually an active kink band developed above a ramp in the north-dipping Channel Islands thrust fault (but see also Shaw et al., 1996; Stone, 1996). Others, however, maintain that the Oak Ridge is a major south-dipping reverse fault that has been inactive for the past 500 ka (Huf- tile and Yeats, 1995), or that this fault or splays of it have been recently active (Kamerling and Nicholson, 1996; Sorlien et al., 2000; Fisher et al., 2005a). Cumulative offset and slip-rate vary significantly along the Oak Ridge Fault. In the east, fault displacement since 500 ka ago amounts to 2.5 km and occurred at high rates (5 mm/yr; Huf tile and Yeats, 1995). In the west, how- ever, fault displacement occurred during the middle Pleistocene, but since 500 ka ago, this displacement has been only 1–2 mm/yr (Yeats et al., 1988; Hurtile and Yeats, 1995; Azor et al., 2002).

High-resolution, seismic-reflection data show that offshore near Ventura, the main strand of the Oak Ridge reverse fault extends upward to within ~80 m of the seafloor (Figs. 5A and 5B). Consequently, movement along the nearshore part of this fault continued until sometime during the late Pleistocene or early Holocene (Fisher et al., 2005a). Fisher et al. (2005a) posit two generations of the Oak Ridge Fault—the older is the main basin- bounding reverse fault, which is beveled by an unconformity possibly at the base of late Pleistocene and Holocene sediment (Fig. 5B). This fault shows no evidence for Holocene movement. The younger fault generation includes possible left-slip along a vertical fault that is indicated in seismic-reflection data by vertically aligned inflections (Figs. 5B and 5C). This possible fault may be related to ones involved in the formation of the Montalvo mounds, which are pressure ridges, located over the Oak Ridge Fault, that indicate recent left or oblique slip on one or more shallow faults (Hall, 1982).

**THE NORTHERN CHANNEL ISLANDS AND MALIBU COAST**

The Dume, Santa Monica, Malibu Coast, and related faults are part of the regional fault system that forms the tectonic boundary between the Western Transverse Ranges Province, on the north, and the California Continental Borderland, on the south (e.g., Wright, 1991; Crouch and Suppe, 1993; Dolan et al., 1995) (Fig. 1). This fault system extends for ~200 km, from near the city of Los Angeles in the east to the far western end of the northern Channel Islands. The province-bounding fault system poses a significant earthquake threat because of its length, recent activity, and the proximity of the fault’s eastern end to the city of Los Angeles. For example, Dolan et al. (2000) estimated that the Malibu Coast and the Santa Monica Faults, members of the regional fault system, could each unleash earthquakes as large as Mw ~7. To date, the Point Mugu earthquake (Mw = 5.3; Ells- worth et al., 1973; Stierman and Ellsworth, 1976) is the largest one to have struck near the fault system west of Point Dume (Fig. 1). The main shock was caused by left-lateral-reverse slip along a north-dipping fault plane.

The main uncertainties in understanding fault deformation along the regional fault system concern the Channel Islands thrust fault (Shaw and Suppe, 1994; Seeber and Sorlien, 2000), which is proposed to dip north below Anacapa Island and the other islands farther west as well as below the Santa Barbara Basin. This thrust fault is similar in structural position to the Santa Monica Moun- tains thrust fault, east of Point Dume, which dips north beneath the Santa Monica Mountains (Bailey and Jahns, 1954; Davis et al., 1989; Davis and Namson, 1994b). Whether the Channel Islands and Santa Monica Mountains thrust faults link along strike is uncertain. If they do, the throughgoing thrust fault could unleash a larger earthquake than would the two separate faults. However, Shaw and Suppe (1994) propose that the faults do not connect, that east of Anacapa Island the Channel Islands thrust fault strikes northeastward across the Ventura Basin.

Rocks exposed on the northern Channel Islands are deformed by the left-lateral, strike-slip Santa Cruz Island and Santa Rosa Island Faults (Pinter et al., 1998a, 1998b, 2001). These faults were active during the late Quaternary, as shown by deflected stream channels and offset terraces (Pinter and Sorlien, 1991). One structural interpretation is that the strike-slip faults are confined to the hanging wall of the underlying Channel Islands thrust fault and that they terminate downward into this thrust fault (Pinter et al., 2003). Together the thrust and strike- slip faults accommodate partitioned crustal strain (e.g., Pinter et al., 1998a), so both thrust and strike-slip earthquake are possible. A major thrust earthquake could generate a tsunami that threatens the populated coast along the north side of the Santa Barbara Channel (Borrero et al., 2001).

East of the Channel Islands, in the Santa Monica Moun- tains, the Malibu Coast and Santa Monica Faults are members of the province-bounding fault system and were active during the Holocene as left-lateral-reverse faults (Dibblee, 1982; Drumm, 1992; Dolan et al., 2000). The probable offshore extension of the Malibu Coast Fault dips steeply in its upper part, but at depth, it flattens and dips shallowly north (Fisher et al., 2005b; Sorlien et al., 2006).

The Dume Fault dips north and is the main fault along this part of the coast, in the sense that other faults merge downward into it. Sorlien et al. (2006) propose that the Santa Monica basin, located south of these faults, subsided by 4 km since 5 Ma ago and that this rate of subsidence might continue today. Combining this subsidence with the rate of uplift of the Santa Monica Moun- tains indicates that substantial slip occurs along a blind thrust fault under the mountains.

West of Point Dume, the flat-topped Sycamore knoll marks an abrupt along-strike discontinuity in the structure of the regional fault zone that encompasses the Dume and Malibu Coast Faults (Fig. 6). Just 2 km west of the knoll, the structural relief near the tip of the Dume Fault decreases abruptly. Compare seismic sections WG85-394 and WG85-390 (Figs. 7A and 7B). Sorlien et al. (2006) explain the anomalous fault structure near the knoll
Figure 5. Stacked high-resolution seismic sections across the Oak Ridge Fault west of Ventura. Section locations shown in Figure 2. V.E.—Vertical exaggeration.
Figure 6. Bathymetry and seismic section locations for the area of the Malibu coast. Area located in Figure 1. Faults are from Sorlien et al. (2000), and the earthquake focal mechanism is from Ellsworth et al. (1973).
Figure 7. (A) Migrated multichannel seismic section shows high structural relief in the hanging wall of the Dume Fault. (B) shows much lower relief. The loss of structural relief along the Dume Fault over a short along-strike distance may signify that a transverse structure extends west of the knoll. This structure may form a boundary to earthquake rupture. Section locations shown in Figure 6. V.E.—Vertical exaggeration.
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as resulting from deformation within a restraining double bend formed within a broad left-oblique fault zone.

Another possibility to explain the structural differences evident in these seismic sections (Figs. 7A and 7B) is that near Sycamore knoll, a transverse structural zone strikes north across the province-bounding fault system (Fisher et al., 2005b). Transverse structures are fundamental to the development of many foreland fold-and-thrust belts (e.g., Wheeler et al., 1979; Thomas, 1990). Typically, such structures include lateral ramps, transverse faults, and displacement-transfer zones. 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 because of the constrained rupture-zone length (e.g., Wells and Coppersmith, 1994). A local example of this effect is the two lateral ramps in the Santa Susana Fault that constrained the rupture zone of the 1994 Northridge earthquake (Hauksson et al., 1995). Similar fault segmentation has been described for faults in the eastern Santa Barbara Channel (Gurrola and Kamerling, 1996; Kamerling and Gurrola, 1997).

South of Point Dume, the Dume Fault offsets the seafloor, and fault-related folding extends upward to arch the seafloor (Fig. 8). This shows very recent fault movement, especially in view of the probable high sedimentation rates associated with the Dume submarine fan.

SANTA MONICA BAY

The area of concern in this section includes the continental shelf under Santa Monica Bay as well as the eastern part of the deep-water Santa Monica and San Pedro Basins to the southwest (Figs. 1 and 9). This area is bounded on the north by
the Santa Monica Mountains and the active faults that make up the province-bounding fault system, namely the Santa Monica, Dume, and Malibu Coast Faults (see the previous section). The Los Angeles Basin borders the east side of the shelf, and along the southeast side, the Palos Verdes Hills jut above the otherwise low-lying coastal plain. The main faults below and bordering Santa Monica Bay include the Santa Monica and San Pedro Basin Faults as well as the closely related Palos Verdes Fault and Compton thrust ramp.

The northwest-striking San Pedro Basin and Palos Verdes Faults abut to the northwest against the west-striking Santa Monica and related faults, which are associated with the Western Transverse Ranges (Fig. 1). In 1979 and 1989, the two largest (ML > 5.5) historic earthquakes under Santa Monica Bay nucleated at a depth of ~12 km and show west-vergent, thrust-fault focal mechanisms (Hauksson and Saldivar, 1986, 1989; Hauksson, 1990).

The Palos Verdes Fault is not evident in high-resolution, seismic-reflection data collected in Santa Monica Bay (Nardin and Henyey, 1978; Fisher et al., 2003); however this fault apparently is evident in proprietary multichannel seismic data acquired there (Sorlien et al., 2004). In small-airgun, seismic-reflection data, a northeast-dipping reflection, likely from the top of the Catalina Schist, ends in the northeast near but not at the reported location of this fault (Fisher et al., 2003) (Fig. 10A). This reflection end might show the fault’s location, but taken alone, the evidence is equivocal. The Palos Verdes Fault passes northeast of the Palos Verdes Peninsula, sharing the regional northwest strike of most major structures south of the Transverse Ranges (Woodring et al., 1946; Yerkes et al., 1965; Wright, 1991; Legg, 1992; Shaw and Suppe, 1996). This fault apparently extends for more than 200 km southeastward from below Santa Monica Bay to near Lasuen Knoll (Clarke et al., 1983, 1985; Greene and Kennedy, 1987; McNally et al., 1996; Marlow et al., 2000; Fisher et al., 2004a) (Fig. 1).

The main question concerning potential earthquake faults under Santa Monica Bay is: Do large faults and folds there result from thrust or strike-slip faults? Unfortunately, the structural geometry of the Palos Verdes Fault below Santa Monica Bay remains unclear. In one interpretation, this fault splays upward to the east from the underlying blind Compton thrust ramp, on the basis of an analysis of fault-bend folding of rocks associated with the fault (Shaw and Suppe, 1996). Below the east shore of Santa Monica Bay, the thrust ramp is proposed to be at a depth of ~5 km, and its hanging wall verges westward from and is rooted within the Los Angeles Basin (Shaw and Suppe, 1996). This vergence direction agrees with the results of modeling of GPS data, which suggests west-directed thrusting from within the basin (Argus et al., 2005). Whether or not this thrust ramp exists is an important issue for earthquake-hazards analysis because the ramp would partly underlie coastal urban areas and could cause an earthquake estimated to be as large as M 6.6 (Shaw and Suppe, 1996).

An alternative interpretation to explain the development of the offshore structure involves strike-slip faulting. Three large anticlinoria underlie Santa Monica Bay, the Palos Verdes Peninsula, and the San Pedro shelf (Nardin and Henyey, 1978; Ward and Valensise, 1994; Fisher et al., 2003, 2004a; Legg et al., 2004). These structures could have developed within restraining bends along a strike-slip fault. Explanations for the discontinuities between anticlinoria include: (1) these structures may be separated by lateral ramps along a deep thrust fault (Shaw and Suppe, 1996); (2) they could have developed during convergent dextral shear along the Palos Verdes Fault (Nardin and Henyey, 1978); or (3) they may have formed along restraining bends in this fault (Ward and Valensise, 1994; Legg and Borrero, 2001; Fisher et al., 2003; Legg et al., 2004).

The San Pedro Escarpment marks an important geologic boundary between the Santa Monica shelf and the deep-water (~800 m) Santa Monica and San Pedro Basins (Figs. 9, 10B, and 11). This escarpment is the steep section of seafloor that extends nearly 60 km southeastward from Santa Monica Canyon to southeast of the Palos Verdes Peninsula (Fig. 9). Along much of the escarpment’s length, active folds and faults cut the seafloor and form the escarpment’s foot. Southwest-dipping rocks under the escarpment indicate the presence of a fault at depth, possibly one that dips southwest (e.g., Davis and Namson, 1994a), but the dip and mode of offset along this fault are controversial.

The San Pedro Basin fault zone dips steeply and is probably strike slip, as indicated by the flower structures developed along it (Fisher et al., 2003). Where this fault and the San Pedro Escarpment converge near the mouth of Santa Monica Canyon (Fig. 9), the escarpment ends abruptly and a low-relief continental slope extends farther north and northwest. Anticlines that deform rock below this low-relief slope show that the fault continues northwest nearly to intersect with the Dume Fault.

The Redondo Canyon Fault has been proposed (e.g., Nardin and Henyey, 1978; Wright, 1991; Bohannon et al., 2004) to follow Redondo Canyon southwestward across the continental shelf (Fig. 9). However, high-resolution, seismic-reflection sections across this proposed fault do not show fault-plane reflections or other clear evidence for faulting (Fisher et al., 2003).

SAN PEDRO SHELF

The San Pedro shelf extends southeastward from the Palos Verdes Peninsula to where the continental shelf narrows abruptly about halfway between Huntington Beach and Dana Point (Fig. 11). The Los Angeles Basin borders this shelf on the east, and the deep-water San Pedro Basin delimits the shelf’s western flank. The major faults under this shelf are the Newport-Inglewood, Thums–Huntington Beach, and Palos Verdes. Near the San Pedro shelf, the Newport-Inglewood right-lateral, strike-slip fault is known primarily where the fault cuts onshore (Yeats, 1973; Barrows, 1974; Hauksson, 1987; Wright, 1991, Fischer, 1992; Freeman et al., 1992; Grant et al., 1997; Grant and Shearer, 2004). The Newport-Inglewood Fault either forms the contact between different basement types, or the Fault closely follows this contact. North and east of the fault, basement rocks consist of Jurassic and Cretaceous crystalline continental crust, whereas...
Figure 10. Migrated small-airgun (80 in³) seismic sections across the continental shelf and slope in Santa Monica Bay. Section locations shown in Figure 9. V.E.—Vertical exaggeration.
south and west of the fault the basement is composed of highly extended and metamorphosed subduction-zone rocks.

Below the Long Beach area, the Thums–Huntington Beach Fault diverges southeastward away from the Palos Verdes Fault (Wright, 1991). Unpublished oil-company, seismic-reflection data indicate that this fault has been inactive since during the Pliocene (T.L. Wright, 2005, written commun.) because an anticline in the fault’s hanging wall is overlain by undeformed Pliocene and Quaternary strata. Interpretive cross sections by different authors disagree on fundamental issues about this fault—one section shows the fault to be a normal fault that dips east and is downthrown on the east (Wright, 1991); another interpretation shows that it dips west and is downthrown on the west and merges downward with the Palos Verdes Fault (Davis and Namson, 1994a).

The Palos Verdes Fault strikes southwestward from the Palos Verdes Peninsula to underlie the San Pedro shelf and the area near Lasuen Knoll (Greene and Kennedy, 1987; Wright, 1991; Petersen and Wesnousky, 1994; Clarke et al., 1997; Marlow et al., 2000; Bohannon et al., 2004; Fisher et al., 2004a, 2004b; Baher et al., 2005) (Fig. 11). The slip rate along the Palos Verdes Fault is ~3 mm/yr, based on analysis of wave-cut terraces and offset stream courses (Ward and Valensise, 1994). McNeilan et al. (1996) proposed that recently the main style of movement along the Palos Verdes Fault was strike slip. Stephenson et al. (1995) interpreted high-resolution, seismic-reflection data collected onshore and proposed that five strands make up the shallow part of this fault zone. These strands dip steeply southwest and are downthrown on the northeast. Multibeam bathymetric data show recent scarps along this fault near Lasuen Knoll (Marlow et al., 2000).

The earthquake and tsunami hazards from faults below the San Pedro shelf appear to be high (Legg, 1992; Legg and Borrero, 2001; Fisher et al., 2004b), as has been deduced, in part, from the rapid Quaternary uplift of rocks on the Palos Verdes Peninsula (Woodring et al., 1946; Bryan, 1987; Ward and Valensise, 1994).

Figure 11. Location of seismic sections over San Pedro shelf. Area located in Figure 1. Faults are from Wright (1991).
However, the geometry of the Palos Verdes Fault at depth and whether it splays upward from a thrust fault that extends westward from within the Los Angeles Basin are unknown. One possibility is that this uplift resulted from right-oblique reverse slip along faults making up a restraining bend in the Palos Verdes Fault (Ward and Valensise, 1994). This style of deformation may extend south from the peninsula to involve faults under the San Pedro shelf, thereby heightening the regional earthquake hazard.

No large historical earthquakes have occurred along the Palos Verdes Fault; even so, McNeilan et al. (1996) estimate that this fault could produce an earthquake as large as M 7. Earthquakes in Hauksson (1990) revealed shallow strike-slip focal mechanisms along this fault. Deep focal mechanisms in the same area show thrust-fault first motions. These results are in apparent agreement with proposals by Brankman and Shaw (2004) that displacement along the Palos Verdes Fault is partitioned into right-lateral, strike-slip motion on shallow, nearly vertical faults and thrust motion along deep, gently to moderately dipping blind thrust faults.

Using high-resolution, seismic-reflection data obtained south of the Palos Verdes Peninsula, the offshore part of the Palos Verdes Fault can be divided into three segments, on the basis of the fault’s structure in the upper 2 km of the crust (Fisher et al., 2004a, 2004b). The northwestern segment underlies the San Pedro shelf; the middle fault segment underlies the bathymetric saddle that separates the San Pedro shelf from Lasuen Knoll; and the southeastern segment offsets the seafloor near Lasuen Knoll (Fig. 11).

Close to the Palos Verdes Peninsula, the northwest segment of the Palos Verdes Fault zone deforms young rocks and the seafloor (McNeilan et al., 1996; Clarke et al., 1998). Along this part of the fault zone, high-resolution, seismic-reflection data (Francis et al., 1996) reveal a restraining bend and attendant flower structure that coincides with a low seafloor swale ~1–4 m high. This deformation apparently accumulated during the past 10 ka, as sea level rose after the last glacial lowstand. The middle segment of the Palos Verdes Fault underlies the part of the seafloor that deepens southeastward from within the San Pedro shelf. This fault segment includes numerous normal-separation faults that probably formed within a releasing bend along the right-lateral, strike-slip fault (Fisher et al., 2004a, 2004b). Along the southeast segment of the Palos Verdes fault zone, sharp seafloor scarps bordering Lasuen Knoll, possible tilted wave-cut terraces, and disrupted shallow sediment all attest to recent fault movement (Marlow et al., 2000; Fisher et al., 2004a, 2004b). Lasuen Knoll appears to be underlain by a popup structure, like those that develop along a restraining bend or stepover in a strike-slip fault system.

Multichannel seismic-reflection data show the structural variability along the Palos Verdes Fault (Figs. 12A, 12B, and 12C). Near the Palos Verdes Peninsula, this fault dips at a low angle southwest, and the basement complex, made up of Catan- lina Schist, rises to shallow depth and is arched in a fault-related fold. Southeast from the peninsula, the Palos Verdes Fault dips at increasingly steeper angles, at least in the upper reflective part of the crust, and deformation of the top of basement becomes corre-
Figure 12. Northeast-southwest migrated, multichannel seismic sections across the San Pedro shelf and slope show that the Palos Verdes Fault gains structural relief northwestward below the San Pedro shelf. Line locations shown in Figure 11. bx—basement complex.
A main source for uncertainty in analyzing offshore faults is the complicated geologic history of the offshore area. This history developed during three tectonic episodes: Mesozoic through early Miocene subduction, early Miocene extension, and Pliocene and later transpression (Kamerling and Luyendyk, 1979; Luyendyk et al., 1980; Kamerling and Luyendyk, 1985; Hornafius et al., 1986; Atwater, 1989; Wright, 1991; Crouch and Suppe, 1993; Nicholson et al., 1994; Bohannon and Geist, 1998). Each episode left its mark on offshore structures, and early-formed structures controlled or at least influenced the location and development of later ones. Unraveling the sequence of structural inheritance will shed more light on how strain currently is distributed throughout the crust and on the geometry of faults at seismogenic depths. For example, since the Miocene, rocks once deformed under extension have undergone transpression. In general as rifts form, faults commonly develop that are transverse to and bridge across the opening rift (e.g., Acocella et al., 2005), and under subsequently reoriented contraction, these transverse structures could form structural discontinuities that segment earthquake rupture zones. Furthermore, the reoriented contraction since the Miocene could have transformed major rift-bounding extensional faults into thrust, reverse, strike- and oblique-slip faults. Clearly, continued research is necessary to understand the hazard to urban areas from offshore and coastal faults having such a complicated development history.

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