

# **Quaternary Tectonic Setting of South-Central Coastal California**

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[In pocket]

1. Faults and Folds in the onshore and offshore regions of south-central California (scale 1:25,000)

# QUATERNARY TECTONIC SETTING OF SOUTH-CENTRAL COASTAL CALIFORNIA

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## Abstract

Recent geodetic, geologic, and seismologic studies show that the south-central coast of California is a region of active Quaternary deformation. Northeast-directed crustal shortening is occurring in a triangular-shaped region between the Hosgri-San Simeon fault system on the west, the Southern Coast Ranges on the northeast, and the western Transverse Ranges on the south. We informally call this region the Los Osos domain. In this study, we conducted detailed geological, seismological, and geophysical investigations to characterize the nature and rates of deformation in the domain. Locations of active and potentially active faults and folds are compiled at a scale of 1:250,000 for the entire domain based primarily on onshore geologic data and offshore geophysical data. Crustal shortening in the domain is accommodated by a series of prominent north-west-trending reverse faults and localized folding. The reverse faults separate distinct structural blocks that have little or no internal deformation. Hangingwall blocks are being uplifted at rates of up to 0.2 mm/yr. Footwall blocks are either static or slowly subsiding at rates of 0.1 mm/yr or less, except for localized areas of concentrated subsidence directly adjacent to some faults. The cumulative rate of crustal shortening is about 1 to 2 mm/yr across the northern part of the domain based on observed geologic deformation. Cumulative shortening across the central and southern parts of the domain is poorly constrained by geologic data and may approach 2 to 3 mm/yr.

Historical and instrumental seismicity generally are spatially associated with the uplifted blocks and bordering reverse faults to depths of about 10 km. Together with near-surface geological data and deeper crustal geophysical imaging that show high-angle faulting, the seismicity data indicate that the reverse faults probably extend to the base of the seismogenic crust. The base of the seismogenic crust may correspond with a mid-crustal detachment or decollement surface into which the reverse faults root. We speculate that the detachment may coincide, in part, with the top of a northeast-dipping slab of oceanic crust that extends beneath the western margin of the continent or with the brittle-ductile transition above the subducted slab.

The Los Osos domain of north-northeast/south-southwest crustal shortening is structurally detached from the offshore

Santa Maria Basin by the high-angle dextral San Simeon and Hosgri Fault Zones. Both the pattern and regional extent of deformation in the Los Osos domain contrast sharply with that of the offshore Santa Maria Basin. The basin is undergoing minor east-northeast/west-southwest crustal shortening at rates of less than 0.1 mm/yr and is moving northwestward at a rate of about 1 to 3 mm/yr relative to the Los Osos domain along the San Simeon and Hosgri Fault Zones. Geodetic data and the kinematics of north-northeast-directed crustal shortening of the Los Osos domain east of the Hosgri Fault Zone show that the rate and cumulative amount of right-slip along the Hosgri Fault Zone progressively decrease southward.

Quaternary deformation within the Los Osos domain is related to distributed dextral simple shear associated with Pacific-North American plate motion. Paleomagnetic data show that clockwise rotation of the western Transverse Ranges has occurred along the southern boundary of the domain during the past 6 m.y. During this time, the Salinian crustal block, which forms the eastern boundary of the Los Osos domain, has remained relatively stable. Internal shortening of the Los Osos domain has accommodated the relative motions of these bordering crustal blocks, particularly the rotation of the western Transverse Ranges.

## Introduction

In recent years, considerable research has been conducted to assess the Quaternary tectonic setting of south-central coastal California (see for example, Cluff and others, 1994). These studies generally focused on three topics—(1) understanding the tectonic setting of the offshore and onshore Santa Maria Basin and bordering areas, including studies of specific faults and the style of regional deformation within the basin, (2) evaluating the rate and style of faulting along the Hosgri-San Simeon fault system to assess its role in accommodating strain along the Pacific-North American plate margin, and (3) evaluating the distribution and nature of seismicity in the region, including an evaluation of the location, size, and mechanism of the 1927 Lompoc, California, earthquake.

Interest in the Quaternary tectonics of south-central coastal California resulted, in part, from several concurrent activities—(1) intensive offshore exploration by the petroleum industry, (2) regional investigations of earthquake hazards performed as part of the Pacific Gas and Electric Company's (PG&E) Long Term Seismic Program for the Diablo Canyon Power Plant (see

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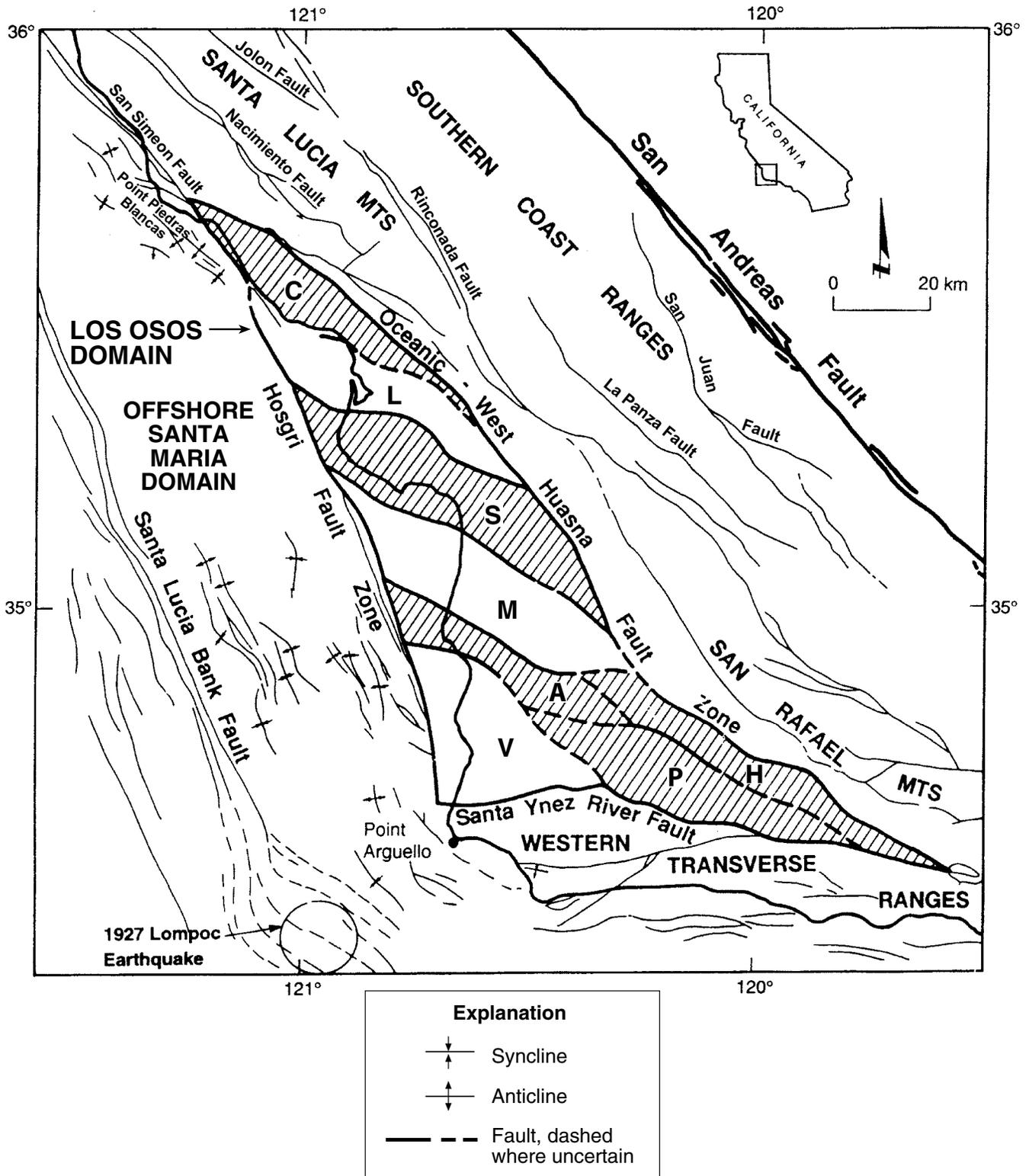


Figure 1. Map of study area showing major kinematic domains including the Los Osos domain, offshore Santa Maria Basin domain, Southern Coast Ranges domain, and western Transverse Ranges domain. The Los Osos domain is divided into distinct structural blocks, including C-Cambria, L-Los Osos Valley, S-San Luis/Pismo, M-Santa Maria Valley, A-Casmalia, H-Solomon Hills, V-Vandenberg/Lompoc, P-Purisima. Hachured areas show locations of Quaternary uplift within the Los Osos domain.

for example, PG&E, 1988), (3) the acquisition and interpretation of new geophysical data to assess deep crustal structure along the continental margin as part of the EDGE program (see for example, Trehu, 1991; Miller and others, 1992; Henrys and others, 1993; Howie and others, 1993), (4) completion of numerous graduate student theses on the geology, geophysics and tectonics of selected areas in the region (see for example, Matz, 1987; Putzig, 1988; Killeen, 1988; Clark, 1990; Howie, 1991; Miller, 1991; Steritz, 1986; Nitchman and Slemmons, 1994; Sorlien and others, 1999), and (5) study of the Santa Maria Province by the U.S. Geological Survey.

These investigations provide important data on the locations and character of late Quaternary folding and faulting in the region. In this paper, we synthesize these data to develop a comprehensive model of known and suspected Quaternary active faults and folds in the area and discuss the implications of the observed deformation for accommodating regional and local crustal strain along the Pacific-North American plate margin. Our study region is centered on the onshore Santa Maria Basin along the coast of south-central California (fig. 1). The region extends from Point Piedras Blancas on the north to Point Arguello on the south. The western and eastern margins of the study region are the Santa Lucia Bank Fault and the Oceanic-West Huasna Fault Zone, respectively. As part of this synthesis, we compiled a 1:250,000 scale map showing the distribution of all known Quaternary active faults and folds in the region (plate 1).

In preparing this paper, we draw heavily upon our personal knowledge of the region resulting from our participation in PG&E's Long-Term Seismic Program for the Diablo Canyon Power Plant. In addition, our interpretations incorporate the results from several recently published investigations, including (1) detailed mapping of marine terraces along the California coast from San Simeon Point on the north to the Casmalia Hills on the south (Hanson and others, 1992, 1994; Clark and others, 1994); (2) detailed mapping, drilling, and trenching of fluvial, marine, and colluvial deposits at selected sites along several fault zones (Lettis and Hanson, 1992; Lettis and Hall, 1994; Hall and others, 1994); (3) analysis of several hundred borehole and water well records from the Los Osos Valley, Morro Bay, and Santa Maria Valley (Hanson and others, 1994; Lettis and Hall, 1994); (4) regional reconnaissance and interpretation of aerial photography in the southern and eastern Los Osos domain; and (5) the acquisition and interpretation of seismic reflection data within the Santa Maria Valley and bordering areas (PG&E, 1988). Offshore investigations included (1) analysis of near-shore bathymetry (2) acquisition and interpretation of high-resolution shallow seismic reflection, side-scan sonar, and deep-penetration (2 to 4 second) common-depth-point seismic reflection data, and (3) offshore sea-bottom sampling (Richard Willingham, 2003, written commun.) and, in part, are summarized in Sedlock and Hamilton (1991) and Clark and others (1991). In addition, instrumental seismicity data were acquired from a dense network of seismographs in the region, including networks operated by the U.S. Geological Survey (USGS), California

Institute of Technology, and PG&E (McLaren and Savage, 2001). Information on deep crustal structure was obtained by the EDGE program, which involved the acquisition and interpretation of deep-crustal seismic reflection and refraction data by a consortium of industry and research institutions (Meltzer, 1988; 1991; Trehu, 1991; McIntosh and others, 1991; Miller and others, 1992; Henrys and others, 1993; Howie and others, 1993).

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## Regional Plate Tectonic Setting

Deformation within south-central coastal California ultimately is driven by distributed dextral shear arising from relative motion between the Pacific and North American Plates. The plate boundary is a broad, heterogeneous zone of right-lateral strike-slip faulting centered along the San Andreas Fault (see for example, Atwater, 1970; Crowell, 1962; Wilson, 1965; Dickinson and Snyder, 1979) and extending in width from the western Great Basin to the Continental Slope (McCulloch, 1987). Within this broad region of distributed deformation, movement of large crustal blocks, such as rotation of the western Transverse Ranges, has influenced the local pattern and style of deformation.

Cenozoic evolution of the plate boundary along the south-central California coast is summarized by Sedlock and Hamilton (1991). Transform motion between the Pacific and North American Plates was established sometime between 29 Ma (Atwater and Molnar, 1973) and 17 Ma (Graham, 1978), at which time it replaced orthogonal or oblique subduction along

the plate margin (Atwater, 1970; Nicholson and others, 1994). Development of the transform plate margin involved a complex break-up of the subducting slab, including the creation of several microplates at the latitude of south-central California (Lonsdale, 1991). The study region is located within the formerly overriding plate that is now coupled to the Pacific Plate as transcurrent motion became localized to the east along the San Andreas Fault.

The transform plate margin evolved from a transtensional boundary to a transpressional boundary during the late Pliocene and Quaternary. Transtensional and (or) extensional deformation during the Miocene produced large, fault-bounded basins along the Continental Shelf (McCulloch, 1987; Crouch and Suppe, 1993) and in the southern Coast Ranges (Hall, 1981a). Crouch and Suppe (1993) suggest that crustal extension at this time involved the development of low-angle detachment faults and rift basins. Structures developed during this time produced a persistent structural grain that, in part, controlled the location and pattern of later Pliocene and Quaternary deformation. Transpressional deformation along the plate boundary began during the Pliocene and produced rapid uplift of the southern Coast Ranges (Page, 1981), folding and thrust faulting along the margin of the Pacific Plate throughout the Santa Maria Basin area (see for example, Namson and Davis, 1990; Page and Brocher, 1993), and tectonic inversion of Miocene basins by reactivation of earlier normal- or oblique-slip faults as reverse faults (PG&E, 1988; Smith and Angell, 1990; Clark and others, 1991; Meltzer and Levander, 1991). The “Queenie structure” in the interior of the offshore Santa Maria Basin and the Pismo Syncline in the interior of the San Luis Range are examples of Miocene basins that were uplifted and folded following the change to transpressional deformation along the plate boundary (see for example, Clark and others, 1991).

The onset of transpression during the Pliocene probably resulted from (1) a change in the azimuth of Pacific Plate motion to a more northerly direction relative to the North American Plate (Cox and Engebretson, 1985; Page and Engebretson, 1985; Zoback and others, 1987) from approximately 3.9 to 3.4 Ma (Harbert and Cox, 1989), (2) development of the independent Sierra Nevada Central-Valley (Sierran) microplate during the Pliocene (Argus and Gordon, 1991), (3) westward displacement of the Sierran microplate as a result of Basin and Range extension (Wright, 1976), and (or) (4) opening of the Gulf of California around 5 Ma and the resultant change in the rate and distribution of slip along faults of the San Andreas Fault system (Crowell, 1987).

## Rates of Tectonic Deformation

Rates of deformation in south-central California generally are deduced from three types of information—(1) plate motion data, (2) geologic data (observed and modeled), and (3) geodetic data. The modern motion between the Pacific and North American (Sierran) Plates is estimated by the NUVEL-1 plate-motion model to be  $48 \pm 2$  mm/yr, directed towards an azimuth of  $N35^\circ W \pm 2^\circ$ , at latitude  $36^\circ$  (DeMets and others,

1987, 1990; Gordon and others, 1987). This predicted motion is approximately 6 to 8 mm/yr slower than, but in the same general direction as, that predicted by the RM2 model of Minster and Jordan (1978). More recently, Harbert (1991) suggested that since 2.7 Ma the azimuth of plate motion is  $N28.5^\circ W$ . The NUVEL-1 plate motion rate has been further reduced by an additional 2 mm/yr using recent revisions to the paleomagnetic time scale (Feigl and others, 1990).

Estimates of relative motion between the Pacific and North American (Sierran) Plates based on geologic observations typically are less than those calculated by these plate motion models. Geologic and geodetic studies show that the San Andreas Fault accommodates 32 to 35 mm/yr of the motion between the North American (Sierran) and Pacific Plates, in a direction  $N41^\circ W$  (Sieh and Jahns, 1984; Kroger and others, 1987; Jordan and Minster, 1988; Shen and Jackson, 1993). The difference in velocity between the plate motion rate and San Andreas Fault rate has been called the “San Andreas discrepancy” (Minster and Jordan, 1984). This discrepancy is accommodated, in part, by extension and right shear in the Basin and Range province. Very long baseline interferometry (VLBI) data and Global Positioning System (GPS) data show that the Sierra Nevada-Central Valley microplate is moving about 12 to 14 mm/yr toward the northwest relative to stable North America (Argus and Gordon, 1991; Dixon and others, 2000; Argus and Gordon, 2001). The combined displacement of the San Andreas Fault and extension of the Basin and Range, however, do not accommodate the total amount of relative plate motion predicted by some of the plate motion models described above. This difference is referred to as the “modified San Andreas discrepancy” (Argus and Gordon, 1991; Feigl and others, 1990).

Estimates of the magnitude of the modified San Andreas discrepancy, which can be decomposed into a component of translation parallel to the Pacific-North American (Sierran) plate margin and a component of shortening normal to the plate margin, have changed with the improvement in GPS and VLBI geodetic data. A summary of these recent geodetic studies is provided by Gordon (1991) and Feigl and others (1990). As shown on table 1, estimated rates of the decomposed modified San Andreas discrepancy parallel to and normal to the plate margin in the region west of the San Andreas Fault have been considerably reduced from initial estimates in the late 1970's. Ward (1990), Argus and Gordon (1991), Feigl and others (1990), and Shen and Jackson (1993), for example, conclude that the component of deformation perpendicular to the San Andreas Fault is several times smaller than previously thought. These studies show that the rate of deformation occurring west of the San Andreas Fault in south-central California is about 4-5 mm/yr dextral shear parallel to the fault and about 2 mm/yr shortening perpendicular to the fault.

The fault-parallel component of the modified San Andreas discrepancy is reduced significantly if dextral slip on the Hosgri-San Simeon fault system is 1 to 3 mm/yr (Hanson and others, this volume; Hanson and Lettis, 1994). The remaining 1 to 4 mm/yr may be distributed among other major north-west-trending strike-slip and oblique-slip faults within the

Table 1. Modified San Andreas discrepancy estimates

Reference	NW-directed dextral component	NE-directed contractional component
Minster and Jordan (1978; 1984)	6 – 25 mm/yr	4 – 13 mm/yr
Minster and Jordan (1987; RM2 Model)	13 ± 5 mm/yr	9 ± 3 mm/yr
Jordan and Minster (1988)	~ 6 mm/yr	~ 8 mm/yr
DeMets and others (1990)	4 mm/yr	7 mm/yr
Feigl and others (1990)	3 ± 1 mm/yr	6 ± 2 mm/yr
Ward (1990, $V_m^2$ model)	~0	~0
Argus and Gordon (1991)	5 ± 5 mm/yr	2 ± 3 mm/yr
Feigl and others (1993)	4 ± 2 mm/yr	2 ± 1 mm/yr
Shen and Jackson (1993)	0 - 4 mm/yr	~0

California continental margin, including the Santa Lucia Bank, West Huasna, Nacimiento, and Rinconada Faults. The more recent analysis of VLBI and GPS data by Argus and Gordon (1990; 1991) and Feigl and others (1990) allow for, but do not require, up to 3 mm/yr of dextral slip on faults in offshore coastal central California such as the Hosgri-San Simeon Fault Zone. Alternatively, Ward (1990) concludes, on the basis of analysis of VLBI data, that there is no San Andreas discrepancy west of a point at 36°N, 120.6°W, although a few mm/yr of dextral strike-slip on offshore faults cannot be precluded. Sedlock and Hamilton (1991) also show that the displacement vector based on an integrated geologic deformation rate along a path that crosses the plate margin at approximately the same latitude and assumes a slip rate of 1 mm/yr on the Hosgri Fault is not significantly different than the relative plate motion determined using the NUVEL-1 model.

The northeast-directed contractional component of the modified San Andreas discrepancy is more difficult to resolve. Some workers have proposed that the southern Coast Ranges and Santa Maria Basin are contracting at a rate of  $6 \pm 2$  mm/yr (Feigl and others, 1990) and that the shortening is accommodated by a detached fold-and-thrust belt (Namson and Davis, 1990). More recent GPS and VLBI data show that the rate of shortening normal to the San Andreas Fault in the Santa Maria Basin region is about 2 mm/yr or less (Ward, 1990; Argus and Gordon, 1991; Feigl and others, 1993) (table 1). Using available data on fault slip rates from this study, the cumulative rate of convergence across the Santa Maria Basin is about  $2 \pm 1$  mm/yr.

## Kinematic Domains of South-Central Coastal California

The south-central coastal region of California can be divided into several distinct kinematic domains based on differing patterns and styles of Quaternary deformation (see for example, Sedlock and Hamilton, 1991; Clark and others, 1994). In this paper, we define these domains as the Los Osos, offshore Santa Maria Basin, western Transverse Ranges, and southern Coast Ranges domains (fig. 1). The domains are separated by active strike-slip or reverse-slip faults: the Hosgri-San Simeon fault system separates the Los Osos and offshore Santa Maria Basin domains (Hanson and others, this volume), the Santa Ynez and inferred Santa Ynez River Faults separate the Los Osos and western Transverse Ranges domains, and the Oceanic-West Huasna fault system separates the Los Osos and southern Coast Ranges domains (fig. 1; plate 1).

The Los Osos domain is a triangular region that lies between the offshore Santa Maria Basin on the west, the western Transverse Ranges domain on the south, and the Santa Lucia and San Rafael Ranges of the southern Coast Ranges domain on the northeast (fig. 1; plate 1). The domain consists of a series of west-northwest-trending topographic lowlands and uplands, the most prominent of which are the Los Osos, Santa Maria, and Vandenberg-Lompoc Valleys and the Cambria, San Luis/Pismo, Casmalia, Solomon, and Purisima Hills. Near-surface bedrock platforms occur offshore along the

projections of the San Luis Range and Casmalia Hills, and sediment-filled basins occur along the projections of the Santa Maria and Los Osos Valleys (plate 1). In general, topographic uplands within the domain coincide with uplifting structural blocks, and the lowlands coincide with subsiding, tilting, or static structural blocks (Lettis and Hanson, 1992). In the offshore region to the west, geophysical data indicate that the geomorphic character of the province continues out to, but not across, the Hosgri Fault Zone (Miller, 1991; Richard Willingham, 2003, written commun.).

The offshore Santa Maria Basin is characterized by regional subsidence, scattered faults, and broad, long-wavelength late Cenozoic folds that trend north-northwest, sub-parallel to the Hosgri and San Simeon Fault Zones (plate 1; McCulloch, 1987; Clark and others, 1991). These faults and associated folds are most prevalent in the southern portion of the basin (south of Point Sal) and include the Queenie, Lompoc, and Purisima structures. For convenience, we refer to this part of the offshore Santa Maria Basin as the southern sub-basin. In addition, a wide zone of folding and faulting locally deforms the northeastern margin of the basin. We refer to this zone as the Piedras Blancas anticlinorium (fig. 1, plate 1).

The western Transverse Ranges form the southern boundary of the study region. The ranges generally trend east-west and include the Santa Ynez and Topotopa Mountains. Quaternary north-directed crustal shortening is accommodated by folding and thrust faulting (Yeats, 1981, 1983; Rockwell and others, 1984, 1988; Rockwell, 1988; Namson and Davis, 1990). Paleomagnetic studies of Miocene volcanic and sedimentary rocks show that the western Transverse Ranges have rotated clockwise a total of approximately 90° as a rigid block (Luyendyk and others, 1985; Hornafius, 1985; Hornafius and others, 1986; Liddicoat, 1990; Luyendyk, 1991). Approximately 55° of this rotation occurred between 17 and 11 Ma, and the remainder has occurred since 6 Ma (Hornafius, 1985; Hornafius and others, 1986).

The southern Coast Ranges domain forms the eastern boundary of the study region. Major faults in this domain include the West Huasna and Oceanic Faults along the southwestern margin of the ranges and the Nacimiento, Rinconada, East Huasna, La Panza, and Jolon Faults within the ranges (plate 1). Aside from regional late Cenozoic uplift accommodated primarily by reverse displacement on the Oceanic-West Huasna fault system, the southern Coast Ranges appear to have acted largely as a rigid, relatively undeformed block since approximately 50 Ma (Sedlock and Hamilton, 1991). The Nacimiento Fault appears to be an inactive fault that juxtaposes the Cretaceous Great Valley sequence against the Franciscan Complex. Cumulative dextral shear within this domain since the early Miocene appears to have been 50 km or less, and the majority of strike slip appears to have been accommodated by the Rinconada Fault along the eastern margin of the domain (Sedlock and Hamilton, 1991). Geomorphic and geologic evidence for Pliocene and younger slip on the Rinconada Fault is cited by Dibblee (1976) and PG&E (1988), with geomorphic evidence of late Quaternary slip decreasing northward along the fault.

Shen and Jackson (1993) summarize available geodetic data across the Rinconada Fault (Sauber and others, 1989; Harris and Segall, 1987; Sung and Jackson, 1988) and conclude that contemporary slip on the fault probably is insignificant. Scattered microseismicity occurs between the Nacimiento and Oceanic Faults (fig. 2). These events have primarily reverse focal mechanisms on northwest-striking nodal planes (fig. 3), showing that the area is undergoing northeast-southwest oriented crustal shortening. We infer that this crustal shortening is produced by (1) a left-restraining transfer of dextral shear between the Rinconada and (or) San Andreas Faults to the south and the San Simeon-San Gregorio fault system to the north, (2) a left restraining bend along the Hosgri-San Simeon-San Gregorio fault system centered on the San Simeon Fault, and (or) (3) northeast-directed convergence of the Los Osos domain against the relatively stationary Salinian block to the northeast.

The Los Osos and offshore Santa Maria Basin domains are structurally and physiographically separated by the Hosgri-San Simeon fault system. This fault system includes the San Simeon Fault Zone north of the latitude of Point Estero and the Hosgri Fault Zone south of Point Estero (fig. 1; plate 1). The two fault zones are kinematically and structurally linked by the Hosgri-San Simeon pull-apart basin, a subsiding Quaternary basin located within a right en-echelon stepover between the two faults (DiSilvestro and others, 1990; Hanson and others, this volume).

## **Quaternary Deformation of the Los Osos and Offshore Santa Maria Basin Domains**

The principal focus of this paper is to define and document the style of Quaternary deformation within and between the Los Osos and offshore Santa Maria Basin domains. The major Quaternary faults and folds in these domains are compiled at a scale of 1:250,000 on plate 1. The following sections describe the fault compilation shown on plate 1 and summarize evidence for the style and kinematics of deformation within the Los Osos and offshore Santa Maria Basin domains.

### **Quaternary Faults and Folds of South-Central Coastal California**

Plate 1 presents a compilation of known late Cenozoic faults and folds in south-central coastal California. The compilation is based on a review of available literature and original geological and geophysical mapping. Sources used in preparing the compilation are listed on plate 1.

Different techniques and age criteria were used to identify and map structures in the onshore and offshore regions. Onshore, faults and folds were identified primarily on the

basis of geologic mapping at scales of 1:24,000, 1:12,000 and 1:6,000, supplemented by seismic reflection and borehole data. Faults are shown as active or inactive if they deform or do not deform, respectively, surficial deposits or geomorphic surfaces that are 500,000 years old or younger. Late Qua-

ternary marine terraces, fluvial terraces, and alluvial fans were the primary units used to assess fault activity. Faults that deform Pliocene or early Quaternary strata, but do not demonstrably deform late Quaternary deposits, are shown as potentially active. For faults compiled from other sources, we

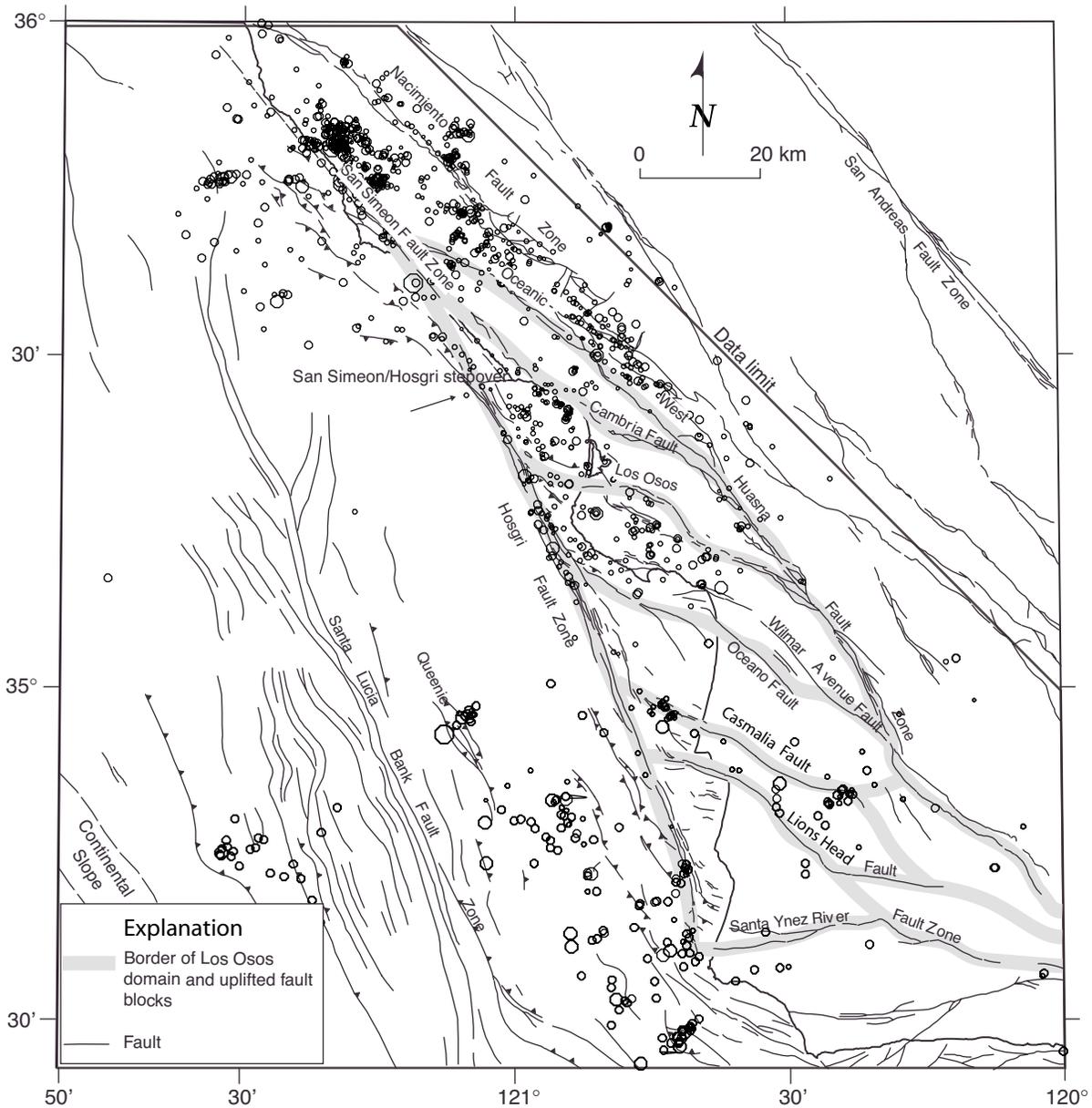


Figure 2. Map showing Quaternary faults, the boundaries of the Los Osos domain from figure 1, and seismicity recorded by the PG&E Central Coast Seismic Network and the U.S. Geological Survey from October 1987 through January 1997 (from McLaren and Savage, 2001). The magnitude threshold for onshore and near offshore events (to about 10 km offshore) is about 1.0, whereas for farther offshore areas and near the north and south ends of the network coverage, it is about magnitude 1.8. Horizontal and depth uncertainties for onshore and near offshore events is generally less than one kilometer and 1 to about 5 km for far offshore events. Seismicity patterns show that most of the earthquakes are occurring in three areas— (1) north of Point San Luis between the northwest-trending faults of the Nacimiento and West Huasna Faults to the northeast and the San Simeon and the Hosgri Fault Zones to the southwest (2) near Point Sal within the Casmalia block bounded by the Casmalia and Lions Head Faults east of the Hosgri Fault Zone and (3) the southern offshore Santa Maria Basin area west of the Hosgri Fault Zone. A small cluster of seismicity also occurs offshore north of Point Piedras Blancas associated with the Piedras Blancas anticlinorium. Notable quiescent areas are the central and northern offshore Santa Maria Basin, and the onshore Santa Maria Valley.

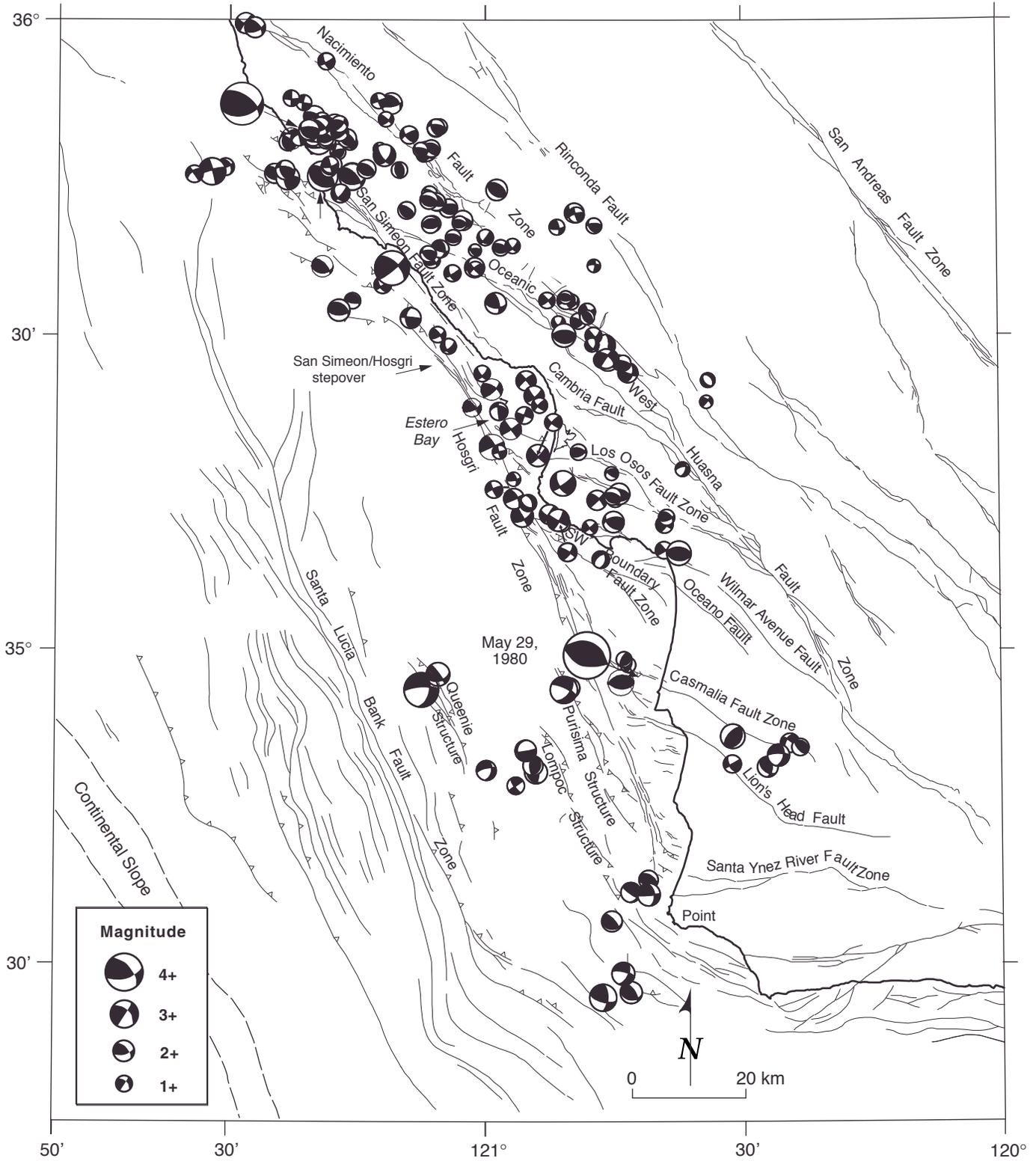


Figure 3. Map showing Quaternary faults and P-wave first-motion focal mechanisms from McLaren and Savage, 2001, (minimum, 20 first motions) from earthquakes along the south central coastal region from Point Piedras Blancas to Point Arguello. Focal mechanisms show (1) predominantly reverse and oblique-reverse motion between the Nacimiento and the San Simeon Fault Zones, (2) a mixture of strike slip, reverse, and oblique motion between the West Huasna-Oceanic and Hosgri Fault Zones, (3) strike slip motion along the northern Hosgri Fault Zone, and (4) reverse motion near the Casmalia Fault Zone and southwest of the Hosgri Fault Zone in the offshore Santa Maria Basin region.

adopted the interpretation of fault activity from that source using the 500,000 year criteria above or, if fault activity was not specified in the source, we judged faults to be potentially active if they deform Quaternary strata. Although abundant microseismicity occurs within the region (fig. 2), a confident association of seismicity to a specific onshore fault is not possible. The Nacimiento Fault, for example, appears to be an abrupt boundary to seismicity in the northeastern part of the study area, but the seismicity is not localized along the fault and geologic data do not show evidence of late Quaternary activity; hence, the fault is shown as inactive.

The activity of onshore folds is more difficult to assess based on existing map information. Folds are shown as active or potentially active where they deform late Miocene or younger strata. Miocene and younger folds are shown as inactive where they are overlain by undeformed deposits or geomorphic surfaces 500,000 years old or younger. Detailed information on the absence of fold deformation, however, is available only in local areas along the coast where well-preserved late Quaternary marine terraces provide strain datums to document the absence of deformation (Clark and others, 1990; Hanson and others, 1994).

Offshore faults and folds were identified primarily from interpretation of seismic reflection data (Richard Willingham, 2003, written commun.) and geomorphic features on the sea floor. Geomorphic features primarily include sea-floor scarps and anomalous bathymetric "highs." Faults and folds are shown as active or inactive if they deform or do not deform, respectively, the early/late Pliocene unconformity (Clark and others, 1991). The unconformity represents a hiatus in time. It is underlain by deposits as young as 3.4 Ma and overlain by deposits as old as 2.8 Ma (Barron, 1986; Richard Willingham, 2003 written commun.). To provide conservative estimates of the locations and maximum rates of deformation, we assume that the unconformity is a datum that is as young as 2.8 Ma. On seismic-reflection profiles, the unconformity is a prominent reflector that separates the Foxen Mudstone and Sisquoc Formations in the offshore region. However, in many areas the early/late Pliocene unconformity is not preserved and younger Quaternary deposits rest unconformably on Miocene and older rocks. In these areas, geomorphic features were used to identify active faults and folds. In the absence of geomorphic features in these areas, faults and folds were classified as potentially active.

As shown on plate 1, numerous active and potentially active faults are present in the Los Osos and offshore Santa Maria Basin domains. Faults and folds in the Los Osos domain generally trend west-northwest to north-northwest. Faults in the offshore Santa Maria Basin domain generally trend north-northwest to north-south. These two domains appear to be structurally and kinematically detached by the San Simeon and Hosgri Fault Zones. The San Simeon Fault Zone is a prominent strike slip fault with well-preserved geomorphic expression and a late Pleistocene slip rate of 1 to 3 mm/yr (Hall and others, 1994; Hanson and Lettis, 1994). The Hosgri Fault Zone is a high-angle fault

that locally deforms the sea floor (PG&E, 1988) and is well imaged on seismic-reflection data in the upper 1 to 2 km of the crust (Richard Willingham, 2003, written commun.). Other prominent faults in the study region include the Los Osos Fault with a slip rate of 0.2 to 0.8 mm/yr (Lettis and Hall, 1994) and the Oceanic-West Huasna Fault Zone that lies along the southwestern margin of the Santa Lucia Range. Prominent active folds in the region include the offshore Queenie structure (Clark and others, 1991) and the Purisima and Lompoc folds in the southern part of the basin. The activity of onshore folds within the Los Osos domain is much less well expressed.

## Los Osos Domain

The Los Osos domain is characterized by a series of west-northwest-striking reverse faults that bound similar-trending structural blocks (Lettis and others, 1989, 1994). From northeast to southwest, these blocks are the Cambria, Los Osos Valley, San Luis/Pismo, Santa Maria Valley, Casmalia, Solomon Hills, Purisima Hills, and the Vandenberg/Lompoc blocks (fig. 1). Many of these structural blocks are coincident with west-northwest-trending Cenozoic synformal and antiformal folds that deform Miocene and Pliocene strata and with areas of uplifting hills or subsiding valleys.

Cenozoic strata of the Los Osos domain are underlain by accretionary prism rocks of the Franciscan complex (Dibblee, 1950; Page, 1981; Hall 1973a,b; 1974, 1976, 1978; Hall and Corbato, 1967; Hall and Prior, 1975; Hall and others, 1979; McCulloch, 1987), as well as fragments of Coast Range ophiolite and Great Valley sequence strata (Hopson and others, 1981; Hall, 1991; McLean, 1991). Seismic reflection and refraction data suggest that the Franciscan complex of the Los Osos domain is underlain by an east-dipping slab of oceanic crust that is locally imbricated along east-dipping reverse or thrust faults (Meltzer, 1988; Meltzer and Levander, 1991; Howie and others, 1993; Miller and others, 1992; Henrys and others, 1993). Basement of the western Transverse Range is, for the most part, unknown; however, Dibblee (1950) maps the Franciscan complex structurally overlain by strata similar to the Mesozoic Great Valley sequence (Vedder, 1987) at the westernmost end of the range and locally along the Santa Ynez Fault. These Mesozoic strata probably were deposited in a forearc basin east of the Franciscan trench along the southern California border (Keller and Prothero, 1987; Up de Graff and Luyendyk, 1989). Northeast of the Los Osos domain, Franciscan basement is tectonically juxtaposed against Salinian granitic basement along the Nacimiento and Rinconada Faults within the Santa Lucia and San Rafael Ranges.

Detailed studies were conducted to characterize the style and rate of Quaternary deformation in the San Luis/Pismo block, Casmalia Hills block, and adjacent blocks. In the following sections, we summarize the evidence for this deformation and present a kinematic model to explain the style and pattern of deformation in the Los Osos.

### The San Luis/Pismo Block

The San Luis/Pismo block (fig. 1) is topographically the most prominent uplifted block in the Los Osos domain. The block is separated from the Los Osos Valley block to the northeast by the southwest-dipping Los Osos Fault Zone (Lettis and Hall, 1994) and from the Santa Maria Valley block to the southwest by a diffuse zone of northeast-dipping faults and southwest-facing monoclines (Lettis and others, 1994; Nitchman and Slemmons, 1994) (plate 1). The block is truncated to the northwest by the Hosgri-San Simeon Fault Zone and extends approximately 70 km southeast to a juncture with the southeastern West Huasna Fault Zone. The San Luis/Pismo block underlies the San Luis Range and Irish Hills, and has a maximum surface width of approximately 18 km.

Deformation within and along the margins of the San Luis/Pismo block has been investigated by a variety of techniques, including detailed mapping of marine and fluvial terraces (Hanson and others, 1992; Lettis and Hanson, 1992; Killeen, 1989), mapping of pre-Quaternary bedrock (Hall, 1973a,b; Clark and others, 1988), and site-specific paleoseismic studies of faults that included geomorphic mapping, drilling, and trenching (Lettis and Hall, 1994; Lettis and others, 1994). These studies define an elevated flight of marine terraces along the coastal perimeter of the block. The presence of the terraces shows that the block has been uplifted in the late Quaternary (past 500,000 years). Elevations of dated marine terraces show that the northwestern part of the block has undergone rigid uplift at a relatively constant rate (both spatially and temporarily) of 0.1 to 0.2 mm/yr during the late Quaternary (Hanson and others, 1992). The terraces do not show detectable internal fold or fault deformation associated with the northwest-trending Neogene Pismo Syncline or the Edna, San Miguelito, Indian Knob, and Pismo Faults (Lettis and others, 1994) (plate 1). Longitudinal profiles of Pleistocene stream terraces along San Luis Obispo Creek also confirm the absence of deformation within the block (Killeen, 1989). The creek is antecedent to uplift of the block and flows from northeast to southwest, orthogonal to the structural grain. Detailed Quaternary mapping and paleoseismic trench studies also show the absence of deformation during the late Quaternary along the Edna and San Miguelito Faults.

Uplift of the San Luis/Pismo block is accommodated by reverse displacement along the bordering fault systems. Lettis and Hall (1994), for example, present geologic and geomorphic mapping and paleoseismic trench data showing that the Los Osos Fault Zone is a southwest-dipping reverse fault with a late Quaternary slip rate of 0.2 to 0.5 mm/yr. The fault is segmented, and at least one segment exhibits Holocene activity. Hanson and others (1992) and Nitchman and Slemmons (1994) provide marine terrace mapping, geophysical data, and paleoseismic trench evidence for late Quaternary slip on faults along the southwestern margin of the block, which are informally named the Olson, San Luis Bay, Wilmar Avenue, Oceano and Pecho faults. These faults are moderately to steeply northeast-dipping reverse faults with late Quaternary slip rates of 0.01 to 0.1 mm/yr. To the southeast, the Santa Maria, Foxen Canyon,

and Little Pine Faults occur along trend and may have been active in the Quaternary (Dibblee, 1966; Schweickert, 1989).

### Casmalia Hills Block

The Casmalia Hills block is bordered by the Casmalia Fault (Gray, 1980) (also called Orcutt Frontal Fault; see for example, Krammes and Curran, 1959) on the northeast, the Hosgri Fault Zone on the west, the Lions Head Fault on the southwest (Sylvester and Darrow, 1979), and the Purisima Hills on the southeast (plate 1). The block underlies the Casmalia Hills and is approximately 55 km long and 7-9 km wide at the surface. Seismicity data (McLaren and Savage, 2001; Hanson and others, this volume), offshore seismic reflection data (Richard Willingham, 2003, written commun.), oil well data (Krammes and Curran, 1959), and onshore geologic mapping (Woodring and Bramlette, 1950; Dibblee, 1950, 1966; Clark, 1990) show that the Casmalia and Lions Head Faults are reverse faults that dip steeply beneath the Casmalia block.

Similar to the San Luis/Pismo block, an elevated flight of marine terraces is present along the coastal perimeter of the Casmalia block (Clark, 1990; Clark and others, 1994). The presence of the terraces shows that the block has been uplifted in the late Quaternary. On the basis of estimated ages for these terraces, Clark (1990) reports an uplift rate of about 0.15 mm/yr. Although the Pleistocene part of the Paso Robles Formation and the Orcutt Sand are locally folded along the Casmalia Fault (Dibblee, 1966), field mapping of marine and fluvial terraces and surfaces within the block shows uniform late Quaternary block uplift with no significant internal faulting, tilting, or folding (Clark, 1990). Clark (1990) presents two models to explain the uniform, block-style uplift with observed localized folding along the Casmalia fault and minor reverse and normal displacements on the Lions Head Fault—(1) continued anticlinal folding of the Casmalia Range above a listric blind thrust or reverse fault (similar to the model presented by Namson and Davis, 1990), and (2) uplift of a rigid structural block along high-angle reverse faults with localized drag folding at the surface along the Casmalia Fault. We favor the block uplift model for several reasons—(1) the Namson and Davis (1990) model of anticlinal folding above a blind thrust fault predicts rates of shortening (2-5 mm/yr) and uplift (~1 mm/yr) that far exceed observed rates of geologic deformation (0.15 mm/yr uplift), (2) uniform block uplift rather than anticlinal folding is documented by the marine and fluvial terrace record, and (3) the nature and pattern of seismicity indicates high-angle reverse faulting beneath the block. We conclude, therefore, that uplift of the block is occurring via reverse displacement on the block-bounding Casmalia and Lions Head Faults.

### Seismicity in the Los Osos Domain

Within the Los Osos domain, seismicity generally is concentrated within the uplifting San Luis/Pismo and Casmalia

Hills structural blocks, and the western half of the down-dropped Los Osos Valley near the San Simeon/Hosgri stepover (fig. 2). The pattern of seismicity in the domain is abruptly truncated along the Hosgri Fault Zone; no modern instrumental seismicity occurs in the northern and central offshore Santa Maria Basin west of the Hosgri Fault Zone, except events associated with the Piedras Blancas antiform. In the southern offshore Santa Maria Basin, seismicity occurs in the areas of active folding, including the Lompoc-Purisima fold trend and the Queenie structure.

Analysis of the instrumental seismicity provides important constraints on the nature and style of deformation in the Los Osos domain. The occurrence of seismicity associated with uplifting structural blocks shows that these blocks are active structures and supports the geologic evidence that uplift of the blocks is occurring by active faulting along the block margins. Hypocentral data show that the seismicity extends to depths of approximately 12 km, below which seismogenic deformation dies out. This observation indicates that the uplifting blocks are not detached by low-angle faults within the seismogenic crust but appear to extend at least to the base of the seismogenic crust. Focal mechanism solutions within the Los Osos domain show predominantly reverse and right-oblique reverse displacement on planes that trend northwest to west-northwest (fig. 3). These are consistent with geologic observations of northwest- to west-northwest-striking active reverse faults along the block boundaries. The 1980 moment magnitude (M) 5.1 Point Sal earthquake, for example, occurred at a depth of between 6 and 9 km beneath the northwestern margin of the Casmalia Hills block (Hanson and others, this volume, fig. 7B). Focal mechanism solutions for the 1980 Point Sal event and the 1984 M3.4 aftershock show reverse displacement on a west-northwest-trending plane consistent with the trend of the Casmalia Fault along the northern margin of the block (Eaton, 1984; McLaren and Savage, 1987, 2001; Hanson and others, this volume, fig. 7) (fig. 3).

## Quaternary Offshore Santa Maria Basin

The Quaternary offshore Santa Maria basin domain is bounded on the east by the Hosgri-San Simeon Fault Zone (discussed below) and on the west by the Santa Lucia Bank Fault, which separates the domain from the Santa Lucia Basin to the west (plate 1). This western boundary fault may have accommodated both dextral strike-slip and normal dip-slip displacements during the Neogene (McIntosh and others, 1991). Seismic reflection and drill-hole data show that during the Miocene the offshore Santa Maria Basin domain was either an actively subsiding, transtensional basin (McCulloch, 1987; Clark and others, 1991; McIntosh and others, 1991; Meltzer and Levander, 1991) or a region of highly extended crust or rifting (Crouch and Suppe, 1993).

Quaternary deformation of the offshore Santa Maria Basin domain, in contrast, is characterized by west-southwest-directed crustal shortening and reactivation of the north-north-

west-striking transtensional normal faults as thrust or reverse faults (Clark and others, 1991; McIntosh and others, 1991; Meltzer and Levander, 1991). Pliocene (and Quaternary) reactivation of the earlier-formed Miocene structures did not occur throughout the entire offshore Santa Maria Basin domain. Deformation was concentrated in the southern part of the basin, where the Lompoc, Purisima, and Queenie structures form prominent antiformal uplifts, and near Piedras Blancas in the northeastern part of the domain within the Piedras Blancas antiform (plate 1). Similar Quaternary structures are not present in the central and northern parts of the offshore Santa Maria Basin domain between these two areas. The antiformal uplifts in the southern part of the basin are bounded on one or both sides by Miocene normal faults that were reactivated in the Pliocene and Quaternary as moderately to steeply dipping thrust or reverse faults (Clark and others, 1991; McIntosh and others, 1991; Meltzer and Levander, 1991). On the basis of stratigraphic and structural relationships interpreted from seismic reflection profiles and oil industry well data, Clark and others (1991) concluded that principal growth of the Queenie structure occurred between 5.3 and 3.4 Ma because the early/late Pliocene unconformity is not significantly deformed across the fold. Minor late Quaternary folds in the sea floor adjacent to the Queenie structure, visible on seismic reflection profiles, are evidence for continued post-3.4 Ma shortening at a rate of 0.005 mm/yr. Clark and others (1991) further conclude that the reverse fault beneath the Queenie structure extends to the base of the seismogenic crust at a depth of 10 to 12 km. Seismic reflection profiles across the Purisima and Lompoc structures show strong evidence of post-early Pliocene folding and, locally, evidence of warping or folding of the sea floor (Lettis and Hanson, 1991; Richard Willingham, 2003, written commun.). This deformation of the sea floor indicates that the Queenie, Lompoc, and Purisima structures are all active Quaternary features. Similarly, seismic reflection data across the Piedras Blancas antiform show evidence of post-early Pliocene deformation on individual folds (PG&E, 1988). Between the Piedras Blancas antiform and the southern part of the basin, however, geophysical and geologic data show that only a few scattered folds are present (plate 1; McCulloch, 1987; PG&E, 1988).

## Seismicity in the Offshore Santa Maria Basin

Microseismicity within the offshore Santa Maria Basin is concentrated in the southern part of the basin west and northwest of Point Arguello and within the Piedras Blancas antiform (fig. 2). There is no seismicity in the northern and central parts of the basin between these two areas, supporting the geologic evidence that there is no Quaternary deformation in this area. Seismicity in the southern part of the basin is evenly distributed along the Lompoc, Purisima, and Queenie structural trends. Focal mechanism solutions for these earthquakes show primarily reverse and oblique displacements on moderately to steeply dipping north-northwest-striking planes coincident

with the surface trends of the antiformal structures (fig. 3). These data indicate that the Purisima, Lompoc, and Queenie structures are underlain by seismically active, moderately dipping reverse or thrust faults.

Microseismicity also occurs approximately 25 km southwest of Point Arguello, near the epicentral area of the 1927 M6.6 Lompoc earthquake (Helmberger and others, 1992). On the basis of analysis of teleseismic seismograms, and modeling of regional seismograms and tsunami data, the Lompoc earthquake occurred approximately 25 km southwest of Point Arguello and was produced by nearly pure reverse slip on a plane striking N20°W and dipping 66° to the northeast (PG&E, 1988; Helmberger and others, 1992; Sataki and Somerville, 1992). There is no clear association of the 1927 earthquake with any specific fault, although its epicenter is located near the southern end of the Santa Lucia Bank Fault, where it splays into several north-northwest-trending traces. The earthquake could be associated with one of these traces.

## Hosgri-San Simeon Fault Zone

The northwest-striking Hosgri-San Simeon Fault Zone forms the structural boundary between the Los Osos and offshore Santa Maria Basin domains and accommodates the contrasting styles, orientations, and rates of crustal shortening between these two domains (plate 1). The west-northwest-striking reverse faults and structural blocks of the Los Osos domain terminate abruptly against the north-northwest-trending Hosgri-San Simeon Fault Zone and contrast with the more northerly trending contractional structures in the offshore Santa Maria Basin domain west of the Hosgri-San Simeon Fault Zone.

Numerous tectonic models have been proposed to explain the role of the Hosgri-San Simeon Fault Zone in Cenozoic tectonics of the south-central coast region. The fault zone has been interpreted as a strike-slip fault that, together with the San Gregorio Fault, accommodated large right-lateral displacements (80-150 km) during the Cenozoic (see for example, Hall, 1975; Silver, 1978; Graham and Dickinson, 1978). Alternatively, the Hosgri Fault Zone is interpreted by some workers to be a former detachment fault that has been reactivated by Pliocene and younger northeast-southwest shortening (Crouch and others, 1984) or as a west-dipping Neogene normal fault rotated and reactivated as an east-dipping, high-angle reverse fault in the forelimb of a large, southwest-vergent fault-bend fold (Namson and Davis, 1990).

Numerous recent studies have been conducted to assess the style and rate of Quaternary deformation along the Hosgri-San Simeon Fault Zone. These studies are described by Hanson and others (this volume) and include (1) detailed mapping of offset marine terraces along the onshore reach of the San Simeon Fault Zone (Weber, 1983; Hanson and others, 1992; Hanson and Lettis, 1994), (2) paleoseismic trench investigations at several locations along the San Simeon Fault Zone (Hall and others, 1994), (3) interpretation of an extensive

suite of shallow high-resolution and CDP seismic reflection data across the Hosgri Fault Zone and the area of interaction between the San Simeon and Hosgri Fault Zones (Richard Willingham, 2003, written commun.), (4) analyses of components of slip along the Hosgri-San Simeon Fault Zone between Piedras Blancas and Point Arguello (Hanson and others, this volume) and (5) analysis of seismicity along the Hosgri-San Simeon Fault Zone (PG&E, 1988; McLaren and Savage, 2001; Hanson and others, this volume).

These studies provide direct evidence that the San Simeon and Hosgri Fault Zones form an integrated system of active right-lateral strike-slip faults, as well as evidence that the fault zone is not a listric southwest-verging thrust fault. Offset late Pleistocene marine terraces and Holocene fluvial deposits yield a right-lateral slip rate of 1-3 mm/yr on the San Simeon Fault Zone (Hanson and Lettis, 1994; Hall and others, 1994). Rates of vertical offset are less than 0.1 mm/yr. The San Simeon and Hosgri Fault Zones are mechanically linked across a right echelon stepover in the offshore Estero Bay area, which has produced a 3- to 5-km-wide pull-apart basin (DiSilvestro and others, 1990; Hanson and others, this volume). Active subsidence of this basin implies that dextral slip is transferred across the basin between the southern San Simeon Fault Zone and the northern Hosgri Fault Zone. Hanson and others (this volume) conclude that as much as 3 mm/yr of dextral slip is transferred southward across this pullapart basin from the San Simeon Fault Zone to the northern Hosgri Fault Zone. They conclude that dextral slip on the fault progressively decreases southward as slip is consumed by crustal shortening within the Los Osos domain (fig. 4). The component of vertical slip across the Hosgri Fault Zone is estimated from rates of coastal uplift deduced from elevated marine terraces east of the fault zone and from approximate rates of subsidence west of the fault zone. Rates of vertical slip range from 0.1 to 0.4 mm/yr. As reported by Hanson and others (this volume), the proportion between horizontal and vertical slip rate confirms that the Hosgri Fault Zone is a right-lateral strike-slip fault over most or all of its length. The ratio of horizontal to vertical slip is not consistent with southwest-vergent thrust or reverse movement during the Quaternary on the Hosgri Fault Zone.

In addition to these slip-rate data, constraints on the down-dip geometry of the Hosgri Fault Zone provided by seismic reflection data and patterns of seismicity support the interpretation that the Hosgri Fault Zone primarily accommodates strike-slip displacement. Analysis of deep seismic reflection lines shows that the fault zone appears to be vertical or steeply dipping (Shih and Levander, 1989; Richard Willingham, 2003, written commun.). On deep seismic lines opposite northern Estero Bay, the fault appears to dip steeply to the west; south of Point Buchon, the fault zone appears to be vertical or to dip steeply to the east. The steep to vertical dip, and apparent changes in dip direction along strike, are consistent with strike-slip faulting. The seismic reflection data also show evidence for local pull-apart grabens and contractional flower structures along the Hosgri fault zone, structures that are characteristic of strike-slip deformation.

Hypocentral and focal mechanism data also shed light on the down-dip geometry and sense of offset on the Hosgri Fault Zone along the western margin of the Los Osos domain (McLaren and Savage, 2001; Hanson and others, this volume). Hypocentral depths show that the abrupt westward termination of seismicity at the Hosgri Fault Zone occurs along a sub-

vertical zone coincident with the surface trace of the Hosgri Fault Zone to a depth of about 12 km (Hanson and others, this volume). Little or no seismicity occurs west of the fault zone in the northern and central offshore Santa Maria Basin domain (fig. 3). We interpret this relation to show that the Hosgri Fault Zone forms a subvertical boundary along the western margin

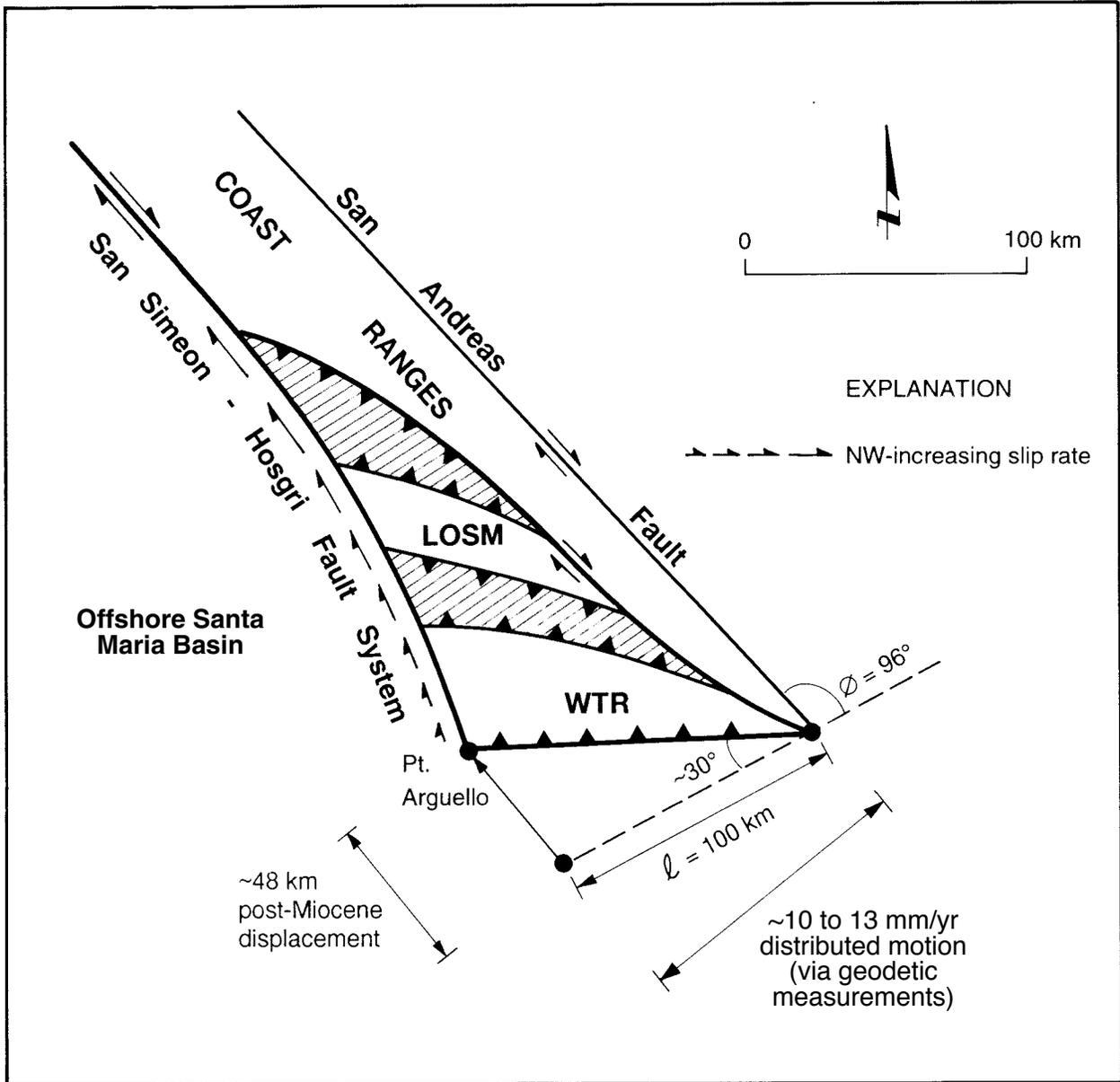


Figure 4. Kinematic model (modified from Hornafius, 1985) showing combined late Cenozoic clockwise rotation of the western Transverse Ranges domain and distributed deformation within the Los Osos domain. Hachured areas represent uplifted crustal blocks bounded by reverse faults. The model predicts approximately 48 km of post-Miocene northwestward displacement of Point Arguello relative to a fixed point on the San Andreas Fault due to clockwise rotation of the western Transverse Ranges. Depending on when rotation of the western Transverse Ranges began, the model predicts that Point Arguello has moved northwest relative to the San Andreas Fault at a rate of 8 to 14 mm/yr (see text for discussion). We interpret that rotation of the western Transverse Ranges is accommodated by distributed deformation within the Los Osos domain. The rate of northwest movement of the Transverse Ranges implicit in this model is comparable to the rate of distributed motion across the region determined by satellite geodetic measurements (10-13 mm/yr; see text for discussion).

of the Los Osos domain to at least a depth of 10 to 12 km at the brittle-ductile transition zone. Focal mechanisms from earthquakes occurring along the northern part of the Hosgri Fault Zone generally show right-lateral slip on vertical north-northwest-striking planes coincident with the surface trace of the Hosgri Fault Zone (fig. 3). On the basis of the seismic reflection data and seismicity data, we conclude that north-northeast-directed crustal shortening within the Los Osos domain is separated from the seismically quiescent offshore Santa Maria Basin domain by right-lateral shear along a near-vertical, north-northwest-trending Hosgri Fault Zone.

## Kinematic Model for Quaternary Deformation of South-Central Coastal California

Quaternary deformation of the south-central coastal region of California appears to result from relative dextral motion between the Pacific Plate and the Sierra Nevada-Central Valley microplate. In this section, we present a kinematic model for late Cenozoic deformation of the Los Osos and the western Transverse Ranges domains based on a synthesis of geologic, geodetic, and seismologic data. We adopt the interpretation of Hornafius (1985) that clockwise rotation of the western Transverse Ranges has deformed the Los Osos domain against the relatively stationary southern Coast Ranges to the northeast. We use the kinematic model to estimate the velocity of northward movement of the western Transverse Ranges and shortening within the Los Osos domain, and interpret this velocity in the context of regional simple shear associated with plate motions.

Pliocene and Quaternary crustal shortening in the Los Osos domain is coeval with post-Miocene clockwise rotation of the western Transverse Ranges. As shown on plate 1, crustal shortening is oriented northeast-southwest, orthogonal to the trend of the uplifted crustal blocks and bounding reverse faults. In our model, we assume that the crustal shortening resulted, in part, from rotation of the western Transverse Ranges as a rigid body about a "pivot" attached to the San Andreas Fault (fig. 4). Using this model, Hornafius (1985) showed that the component of northwest motion parallel to the San Andreas Fault ( $d$ ) at the western end of the Transverse Ranges is given by

$$d = l [\cos \theta - \cos (\theta + r)] \quad (1)$$

where  $l$  is the distance along the western Transverse Ranges from the San Andreas Fault,  $\theta$  is the initial angle between the western Transverse Ranges and the San Andreas Fault prior to rotation, and  $r$  is the amount of rotation in degrees.

Following Hornafius (1985), we assume an approximately 100 km length for the western Transverse Ranges ( $l$ ), an initial angle of  $96^\circ$  between the western Transverse Ranges and the

San Andreas Fault ( $\theta$ ), and  $30^\circ$  of post-Miocene rotation ( $r$ ). The kinematic model thus predicts approximately 48 km of northwest displacement of the western end of the Transverse Ranges parallel to the San Andreas Fault since the onset of late Cenozoic clockwise rotation. If this rotation occurred primarily during the past 6 m.y. (the age of the youngest rocks from which paleomagnetic data were obtained), the resulting northwestward displacement rate of Point Arguello relative to a fixed point on the San Andreas Fault is approximately 8 mm/yr. If the deformation began approximately 3.5 Ma, as suggested by Namson and Davis (1988) based on regional stratigraphic and structural relationships, the resulting average displacement rate of Point Arguello is approximately 14 mm/yr. On the basis of this kinematic model and these assumptions, we conclude that the average post-Miocene rate of northwestward motion of Point Arguello due to clockwise rotation of the western Transverse Ranges is 8 to 14 mm/yr.

If the western Transverse Ranges have rotated as a rigid body, then the rate of northwestward motion parallel to the San Andreas Fault along the length of the domain decreases from west to east. The clockwise rotation thus produces a velocity gradient of 8 to 14 mm/yr per 100 km perpendicular to the San Andreas Fault. For comparison, geodetic data presented by Shen and Jackson (1993) show that the average velocity of reference stations near the western edge of the Los Osos domain in a direction subparallel to the San Andreas Fault is approximately 10 to 13 mm/yr faster than stations located a few km west of the San Andreas Fault.

At least some of the geodetically determined velocity gradient across the Los Osos domain may be attributed to elastic deformation associated with the San Andreas Fault. Shen and Jackson (1993), for example, attribute the bulk of the velocity gradient to elastic strain associated with locking of the San Andreas Fault to a depth of 20 km. However, there are two problems with this model—(1) the assumed locking depth of 20 km is approximately 5 km deeper than most, but not all, of the seismicity associated with the San Andreas Fault (Hill and others, 1990) and thus may predict greater elastic strain than is presently accumulating, and (2) all of the elastic strain is presumably released by earthquakes on the San Andreas Fault. If the velocity gradient perpendicular to the fault is an exclusively elastic phenomenon, then the observed finite clockwise rotations, such as those associated with the western Transverse Ranges, must occur by other tectonic processes that produce distributed plastic deformation.

Feigl and others (1990) derived the velocities of stations in the western Transverse Ranges and Los Osos domains and observed that the rates of northwest-directed motion decrease between the western part of the domain and the San Andreas Fault. They subtracted a predicted deformation field associated with accumulation of elastic strain on the San Andreas Fault from the observed velocity field to derive a residual velocity field that presumably reflects plastic deformation independent of elastic strain on the San Andreas Fault. Assuming a locking depth of 25 km, Feigl and others (1990) observed that the residual velocity of stations POZO and

MADC near the eastern boundary of the Los Osos domain are 4 to 5 mm/yr slower than station VNDN at Point Arguello, thus suggesting the presence of a 4 to 5 mm/yr velocity gradient across the Los Osos domain that is independent of elastic strain associated with a locked San Andreas Fault.

Feigl and others (1990) noted that increasing the locking depth (>25 km) on the San Andreas Fault is an implausible explanation for the residual velocity gradient across the Los Osos domain. Given the depth of seismicity associated with the San Andreas Fault (approximately 15 km; Hill and others, 1990), and the results of numerous studies showing that the San Andreas Fault is weak and supports very little shear stress (Zoback and others, 1987; Mount and Suppe, 1987), we believe that the locking depth of 25 km assumed by Feigl and others (1990) also is probably too deep. Thus, we conclude that the residual velocity gradient of 4 to 5 mm/yr across the Los Osos domain calculated by Feigl and others (1990) with an assumed 25 km locking depth is probably a minimum estimate of the non-elastic deformation. For comparison, this residual velocity gradient is similar to the 6 to 8 mm/yr absolute gradient across the domain determined by Shen and Jackson (1993), which they interpreted as distributed elastic strain accumulation on the San Andreas Fault.

Because the Los Osos domain and western Transverse Range domain share a common boundary, rigid rotation of the western Transverse Ranges necessarily produces rotation of the southern boundary of the domain. If the eastern and western boundaries of the domain (the Coast Ranges and the offshore Santa Maria Basin, respectively) do not rotate and if the northeastern boundary of the Los Osos domain does not move northward at the same velocity as the western Transverse Ranges, then the Los Osos domain must absorb a large component of the distributed shear associated with rotation of the western Transverse Ranges. We therefore conclude that the 4 to 5 mm/yr or greater velocity gradient across the Los Osos domain represents distributed plate motion that is accommodated by internal deformation of the domain. The deformation is characterized by oblique reverse slip on west-northwest-striking faults that bound the structural blocks of the domain.

This kinematic interpretation does not require a large component of shortening perpendicular to the plate boundary to explain the crustal shortening of the Los Osos domain. Shen and Jackson (1993) determined the displacement rate vectors for five stations in the domain and observed that the motions of the stations are generally parallel, rather than oblique, to the San Andreas Fault. The stations do not consistently display a significant component of north-northeast-directed motion, suggesting that the Los Osos domain is not accommodating a large component of shortening perpendicular to the plate boundary. Shen and Jackson (1993) determined the orientations and magnitudes of the principal components of the mean strain rate field for the central Los Osos domain and concluded that the rate of northwest-directed extension is not significantly different from the rate of northeast-directed shortening, consistent with a pure shear

strain component within an overall simple shear deformation field. Although the uncertainties in the data are large relative to the measured strain rates, the results of Shen and Jackson (1993) suggest that the observed northeast-directed crustal shortening may be primarily accommodating northwest dextral simple shear.

As stated earlier, the onshore Los Osos domain is structurally separated from the offshore Santa Maria Basin domain by the Hosgri-San Simeon Fault Zone (plate 1). Dextral slip on the fault zone progressively decreases southward from about 1 to 3 mm/yr to 0.5-2 mm/yr (Hanson and others, this volume). The northern and central parts of the offshore Santa Maria Basin domain are not deforming internally, but rather are moving northwest at a rate equal to or slightly less than the full "rescaled" NUVEL-1 velocity (Feigl and others, 1990) for the Pacific Plate relative to stable North America (46 mm/yr). The geodetic data described by Shen and Jackson (1993) show that the absolute velocities of points within the Los Osos domain decrease northeastward, and thus the Los Osos domain is moving northward at somewhat lower velocities than the offshore Santa Maria Basin. Because the Hosgri-San Simeon Fault Zone accommodates this differential motion, or velocity contrast, between the two domains, the kinematic model predicts a progressive southward decrease in the rate of relative right-lateral displacement on the fault zone, and the fault should terminate near the southern margin of the Los Osos domain where the velocity contrast diminishes to near zero. The southward decrease in slip rate on the Hosgri Fault Zone agrees well with the analysis of slip rates based on geological and geophysical data presented by Hanson and others (this volume) that also shows progressive southward decay of slip on the Hosgri Fault Zone.

Geologic estimates of crustal shortening in the Los Osos domain can be estimated by summing the rate of slip on reverse and thrust faults in the domain. The resolved component of slip parallel to the Hosgri Fault Zone is a maximum of about 0.1 to 0.2 mm/yr for each of the Los Osos, Olson, San Luis Bay, Wilmar Avenue, Casmalia, and Lions Head Faults. As depicted on figure 4, if a horizontal slip rate of 1 mm/yr for the northern end of the Hosgri Fault Zone (the lower value of our preferred range) is used for the integrated model of slip distribution, then the southward decay of horizontal slip by crustal shortening in the Los Osos domain brings the rate of lateral slip on the Hosgri Fault Zone to less than 0.5 mm/yr south of Point Sal. Slip on the fault ultimately must decrease to zero where it dies out near Point Arguello. At this southern end of the fault, the Hosgri Fault Zone may be either an oblique-slip, strike-slip or reverse fault depending on the relative rate of vertical movement on the fault which also must ultimately die out at the southern end of the fault.

Regional stress data show an apparent change in the direction of the maximum horizontal stress from northeast to east-west across a very narrow corridor coincident with the trace of the Hosgri Fault Zone (Mount and Suppe, 1992). This change can be readily explained if the Hosgri Fault Zone is a weak, near-vertical, strike-slip fault with mechanical charac-

teristics similar to the San Andreas Fault Zone (Zoback and others, 1987).

We interpret the relationship between stress and strain in the vicinity of the Hosgri Fault Zone to be an expression of strain partitioning. Recently proposed models of strain partitioning suggest that oblique strain in the lithospheric mantle and lower crust partitions into tangential and normal strain components in the upper crust, producing concurrently active, subparallel strike-slip and dip-slip faults with associated fold belts (Zoback and others, 1987; Mount and Suppe, 1987, 1992; Michael, 1990; Lettis and Hanson, 1991). The strain partitioning model predicts the development of subparallel strike-slip and reverse/thrust faults and folds, as is observed between the Hosgri Fault Zone and folds and thrust faults in the offshore Santa Maria Basin. East of the Hosgri Fault Zone, however, contractional structures in the Los Osos domain trend oblique to the Hosgri Fault Zone. We explain this deviation from the expected pattern required by strain partitioning by the influence of three tectonic mechanisms—noncoaxial strain due to the influence of preexisting basement structures, local distortion of the regional stress field by elastic strain at the southern tip of the Hosgri Fault Zone, and post-Miocene clockwise rotation of the western Transverse Ranges as described above.

The contrasting styles and orientations of crustal shortening across the Hosgri Fault Zone, as well as the near vertical boundary defined by the distribution of microseismicity (McLaren and Savage, 2001; Hanson and others, this volume), are not explained by the listric thrust model proposed by Crouch and others (1984) or the reactivated reverse fault model proposed by Namson and Davis (1990). The west-northwest-trending orientation of faults east of the fault zone is not compatible with active west-directed thrust or reverse faulting on the Hosgri Fault Zone. If the Hosgri Fault Zone were a southwest-verging listric thrust fault above a detachment, faults and folds east of the fault (in the hanging wall) should be subparallel to and not oblique to the fault. The Los Osos, Pecho, San Luis Bay, Casmalia, and Lions Head Faults, however, intersect the Hosgri Fault Zone from the east at oblique angles. Attributing all deformation in the region to contraction on thrust faults, therefore, is not correct. The east-northeast/west-southwest crustal shortening represented by these faults is mechanically more compatible with lateral slip along the more northerly trending Hosgri Fault Zone. Sorlien and others (1999) also note that structure-contour maps of deformed horizons show a spatial relationship between faulting and folding along the southern Hosgri Fault Zone that is consistent with right-lateral slip.

## Conclusions

This paper provides a synthesis of the Quaternary tectonic setting of south-central coastal California. Plate 1 illustrates the distribution of all known and potentially active late Quaternary faults and folds in the region based on a review of recently published and unpublished data. Our interpretation of

the tectonic setting incorporates the data and conclusions presented by Hanson and others (this volume).

South-central coastal California can be divided into several distinct tectonic domains characterized by unique patterns and styles of Quaternary deformation and seismicity. In particular, we define and describe the Los Osos and offshore Santa Maria Basin domains. These domains are separated by the dextral-slip Hosgri-San Simeon fault system, which has a late Quaternary slip rate of 1 to 3 mm/yr.

The offshore Santa Maria Basin domain is characterized by localized anticlinal deformation underlain in places by active southwest-verging reverse thrust faults. These faults are subparallel to the Hosgri Fault Zone, have associated microseismicity, and occur primarily in the southern part of the offshore Santa Maria Basin domain. The northern and central parts of the domain, south of the Piedras Blancas anticlinorium are characterized by the general absence of late Quaternary deformation and lack of instrumental seismicity.

The Los Osos domain is characterized by west-northwest-striking reverse faults along the margins of distinct uplifting and subsiding structural blocks. Detailed mapping of Quaternary deposits and surfaces shows that deformation is concentrated along the block-bounding faults and little or no deformation is occurring within the blocks. Sparse seismicity is concentrated primarily within the uplifting blocks. The depth distribution of the seismicity shows that the blocks extend to the base of the seismogenic crust (10-12 km) and are not structurally detached by one or more decollements higher in the seismogenic crust as postulated by others (see for example, Crouch and others, 1984; Namson and Davis, 1990). The orientation and style of deformation within the domain clearly reflects north-northeast/south-southwest crustal shortening. This orientation of crustal shortening is oblique to the trend of the Hosgri Fault Zone and strongly supports the interpretation that the Hosgri Fault Zone is a strike slip fault that, in part, accommodates the contrasting orientations of crustal shortening between the Los Osos and offshore Santa Maria Basin domains.

Deformation within the Los Osos domain results from distributed dextral simple shear associated with the Pacific-North American plate motion, modified by clockwise rotation of the western Transverse Ranges. The cumulative rate of shortening across the domain based on observed fault slip rate (excluding the domain-bounding Santa Ynez and Oceanic-west Huasna Faults) is about 1 to 2 mm/yr. These observed rates are consistent with geodetic and plate motion rates of northeast-directed contraction of less than  $2 \pm 1$  mm/yr.

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