Late Cenozoic Fold and Thrust Belt of the Southern Coast Ranges and Santa Maria Basin, California

JAY NAMSON and THOM L. DAVIS

ABSTRACT

Balanced cross sections across the Santa Maria basin and southern Coast Ranges of California show the Pliocene to Quaternary convergence to be a developing basement-involved fold and thrust belt. The fold and thrust belt is seismically active as evidenced by compressive earthquakes, geodetic measurements of present shortening, and folded Quaternary deposits. The Pliocene and Quaternary structure of the southern Coast Ranges is dominated by a series of large anticlinal structures that include the Lompoc-Purisima trend, the Casmalia-Orcutt trend, the Point San Luis anticline, the Santa Lucia Range anticlinorium, and the La Panza Range anticlinorium. The anticlinal trends are interpreted to be fault-bend and fault-propagation folds resulting from thrust ramps off thrust flats and a regional detachment at 11–14 km depth. Most of the thrust faults do not reach the surface (blind thrust). The southwestern range front of the San Rafael Mountains is interpreted to be the result of uplift above a ramp in the Point San Luis thrust. The cross section across the southern Coast Ranges shows 26.8 km of shortening from the edge of the continental margin to the San Andreas fault. Region-wide shortening is interpreted to have begun between 2.0 and 4.0 Ma, which yields an average regional convergence rate of 6.7–13.4 mm/yr. The late Pliocene and Quaternary convergence across the onshore Santa Maria basin is interpreted to be 9.2 km and the average convergence rate is 2.3–4.6 mm/yr.

Compressive focal mechanisms and our structural analysis suggest that the ramp parts of the thrust system are the most likely sources for earthquakes. The historic seismic record and length of the anticlinal trends suggest that the thrust ramps probably are capable of generating moderate to large earthquakes (5.0<Mw<7.5). Major thrust ramps underlie the city of San Luis Obispo and adjacent coastal towns.

Cross section restoration reveals early formed hydrocarbon traps and accounts for the abundant hydrocarbon accumulations along the Casmalia-Orcutt anticlinal trend and under the Santa Maria Valley. The cross sections and restorations also illustrate the importance of Miocene and early Pliocene normal faults to oil maturation and trapping. Concealed normal faults along the flanks of the major anticlinal trends and the subthrust area along the north side of the Casmalia-Orcutt anticlinal trend form two relatively untested trap styles.

INTRODUCTION

The Santa Maria basin is a significant hydrocarbon-producing coastal basin in California with almost 1 billion bbl of estimated ultimate reserves onshore (California Division of Oil and Gas, 1986). The basin lies at the juncture between the northwest-trending southern Coast Range province and the east–west-trending Transverse Range province and continues westward offshore (Figure 1). The Pismo and Huasna basins are two smaller basins located north of the Santa Maria basin, along the Pismo and Huasna synclines of the southern Coast Ranges (Figure 2). All of these basins contain thick Neogene stratigraphic deposits that also include prolific source and reservoir rocks of the Monterey Formation. The Santa Maria basin and adjacent southern Coast Ranges have been subjected to considerable Pliocene and Quaternary shortening and uplift as evidenced by extensive folds, thrust faults, angular unconformities, mountain building, and synorogenic deposits (Reed and Hollister, 1936; Woodring and Bramlette, 1950; Page et al., 1979; T. W. Dibblee, 1989, personal communication) and offshore seismic reflection data (Crouch et al., 1984; McCulloch, 1987; McIntosh et al., in press). The convergence is active as indicated by numerous compressive earthquakes (Figure 3) (Eaton, 1984, 1985; Dehlinger and Bolt, 1987; Pacific Gas and Electric Company, 1988), broad bands of seismicity unrelated to surface faults (Figure 4), present crustal shortening from recent geodetic measurements (Harris and Segall, 1987; Feigl et al., 1990), and folded Quaternary deposits (Woodring and Bramlette, 1950).

Various tectonic models for the area have been proposed. (1) Miocene and Pliocene basin development has been attribut-
Late Cenozoic Fold and Thrust Belt

Figure 1—Regional location map of southern California showing the Neogene basins, Western Transverse Ranges, and Southern Coast Ranges.

The stratigraphy of the study areas is shown in Figure 5. On the regional cross sections (Figures 6, 7), some of the formations are grouped into tectostratigraphic units correlated across the different areas and indicated by letter symbols on the stratigraphic summary chart (Figure 5).

Basement Rocks and Upper Jurassic to Eocene Strata

The southern Coast Ranges and western Transverse Ranges consist of two distinct composite basement blocks separated by the Rinconada-Nacimiento fault or Sur-Nacimiento fault (Page, 1970) (Figures 1, 2, 5) (Dibblee, 1973a, 1976; Vedder et al., 1983). West of the Rinconada-Nacimiento fault, the basement is composed of melange of the Franciscan assemblage (Page, 1981) and Late Jurassic Coast Range Ophiolite (Hopson et al., 1981) (KfJ-Jop, Figures 5–7). East of the Rinconada-Nacimiento fault, the basement is composed of Precambrian (pCgn) and younger high-temperature metamorphic rocks intruded by Mesozoic plutonic rocks (Mzgr, Figures 5, 7) (Ross, 1978; Mattinson and James, 1985). In places west and east of the fault, the basement blocks are overlain unconformably by Upper Jurassic through lower Tertiary sedimentary rocks lithologically similar and coeval to the Great Valley sequence of the San Joaquin and Sacramento basins (KJu and TKu, Figures 5, 7) (Vedder et al., 1983). These rocks are mainly deep-water clastics that belong to the Knoxville Formation and various unnamed units. The Franciscan assemblage was deposited, deformed, and metamorphosed in a trench/subduc-
Explanation

- Quaternary and upper Pliocene synorogenic deposits, includes undifferentiated alluvium, and Pass Robles, Careoga, and Morales formations.
- Upper Pliocene to upper Miocene marine deposits, includes the Caso, Pismo, Salinas, and Santa Margarita formations.
- Upper and middle Miocene marine deposits, includes the Monterey and Point Sur formations.
- Middle and lower Miocene extrusive and shallow-level igneous rocks, includes the Oligocene and Transquillan formations and the Morro Bay-Taylor Hill Complex.
- Lower Miocene and Oligocene marine deposits, includes the Rincon, Vaqueria, Gustoisa, and Skene formations.
- Lower Miocene and Oligocene nonmarine synorogenic deposits, includes the Tanquary, Loa, and Steep formations.
- Undifferentiated Eocene to Upper Jurassic marine deposits.
- Franciscan Assemblage and Coast Range Ophiolite (undifferentiated Mesozoic).
- Undifferentiated granitic and gneissic rocks of the Salinian block (Mesoscopic and Precambrian).
tion zone setting (Page, 1981). Contemporaneous deposition of the Great Valley–like sequence is believed to have been in a forearc basin setting (Page, 1981). The two basement blocks and their overlying upper Mesozoic and lower Tertiary strata are interpreted to have been juxtaposed by the late Paleocene to early Eocene and shared a similar tectonic history during the Neogene (Page, 1981; Howell et al., 1987).

Throughout the western Transverse Ranges, Santa Maria basin, and southern Coast Ranges, both east and west of the Rinconada-Nacimiento and San Andreas faults, a regional unconformity separates upper Oligocene and younger rocks from older strata and the basement blocks (Davis and Lagoe, 1988). In many places, a pronounced angular discordance is found along the unconformity (Namson, 1987). The preunconformity deformation and erosion, and occurrence of upper Eocene to Oligocene coarse-grained nonmarine deposits (lower part of the Sespe Formation of the western Transverse Ranges) are interpreted to result from the Ynezian orogeny of Dibblee (1982) and uplift of the San Rafael high of Reed and Hollister (1936). The Santa Maria basin and other Neogene basins of southern California developed after the regional unconformity.

Figure 2—Geologic map showing the westernmost Transverse Ranges, southernmost Coast Ranges, and Santa Maria basin, and the locations of cross sections in this study area. CA = Casmalia anticline, EHF = East Huasna fault, HF = Hosgri fault, LP = Lompoc, LPF = La Panza fault, OA = Orcutt anticline, OF = Orcutt fault, RHF = Red Hills fault, RNF = Rinconada-Nacimiento fault, SF = Suey fault, SLO = San Luis Obispo, SLRA = Santa Lucia Range anticlinorium, SM = Santa Maria, SYF = Santa Ynez fault, WHF = West Huasna fault. Geology modified from Jennings (1958, 1959).

Figure 3—Focal mechanism (circles) of magnitude 3.0 and larger earthquakes of the southern Coast Ranges west of the San Andreas fault and the Santa Maria basin. Most of the fault-plane solutions indicate thrust or reverse-fault earthquakes showing the seismically active compression of the region (modified from Pacific Gas and Electric Company, 1988).

Figure 4—Earthquake distribution map for January 1981 to January 1988 showing the location of magnitude 2 and larger earthquakes. Seismicity occurs in broad bands throughout the region except for the concentration of seismicity along the San Andreas fault (L. Jones, 1989, personal communication).
Middle and Upper Cenozoic Stratigraphy of the Santa Maria Basin

The Santa Maria basin is composed of up to 4.5 km of lower Miocene through Quaternary volcanic and sedimentary rocks that lie unconformably on the Franciscan assemblage and Knoxville Formation (McLean, 1989) (Figure 5). Paleocene and Eocene strata are absent within the basin, and middle and upper Cenozoic units lie above the regional unconformity associated with the late Eocene to early Oligocene Ynezian orogeny. The oldest rocks above the unconformity are lower Miocene, nonmarine, coarse-grained red beds of the Lospe Formation, which is overlain in places by volcanic and volcanioclastic rocks of the Obispo Formation. These two units have
Figure 6—(A) Regional cross section and (B) restoration across the Santa Maria basin. Well log correlations across the crest of the Orcutt anticline are from AAPG (1959). The interpretation shows the Point San Luis anticline to be a fault-bend fold associated with the Point San Luis thrust. Slip on the Point San Luis thrust reverses northward on the Purisima-Solomon thrust to form the Lompoc-Purisima anticline and the Orcutt anticline. The restoration suggests 9.2 km of convergence across the Santa Maria basin. The convergence includes 2.8 km of slip transferred southward to form the Santa Ynez Mountains. The dashed line within the KJF-Jop is an arbitrary structural reference horizon that illustrates late Cenozoic convergent deformation. Stratigraphic nomenclature abbreviations are as in Figure 5.
Figure 7—(A) Regional cross section AA' and (B) interpretation across the southern Coast Ranges from the offshore Santa Maria basin to the San Andreas fault. The anticlinoriums are interpreted to be caused by thrust fault ramps off a regional detachment. Only late Cenozoic convergence is restored in the restoration-preserving preconvergence structures and the trajectories are shown of the late Cenozoic thrusts. The restoration shows 26.8 km of late Cenozoic shortening on the regional detachment and 21.8 km on the middle Cenozoic unconformity. The shortening discrepancy yields a 4% error in the interpretation. Abbreviations as shown in Figure 5, and Tu = undifferentiated Tertiary. The dashed line within the KJf-Jop is an arbitrary structural reference horizon that illustrates late Cenozoic convergent deformation. Stratigraphic nomenclature abbreviations as in Figure 5.
a limited distribution and are grouped together in the Santa Maria basin (Tom, Figures 5, 6).

The middle Miocene Point Sal Formation overlies the Lospe and Obispo Formations or Franciscan assemblage and is present throughout much of the basin. The Point Sal Formation consists of deep-water sandstone and silty shale and records increased subsidence and the initiation of deep-marine conditions within the basin. The middle and upper Miocene Monterey Formation overlies the Point Sal Formation. The Monterey Formation consists of well-laminated, fine-grained siliceous rocks, deep-water sandstone, and dolomite. The Point Sal and Monterey Formations are grouped together in the Santa Maria basin (Tom, Figures 5, 6).

The upper Miocene and lower Pliocene Sisquoc Formation conformably and locally unconformably overlies the Monterey Formation (Woodring and Bramlette, 1950). The Sisquoc Formation is composed of un laminated to poorly laminated, fine-grained siliceous rocks and deep-water siltstone and sandstone. The Sisquoc Formation is conformably and unconformably overlain by marine siltstone and fine-grained sandstone of the lower Pliocene Foxen Mudstone. The Sisquoc Formation and Foxen Mudstone are grouped together in the Santa Maria basin (Tmp, Figures 5, 6). These two units are thin or absent along the basin margins but are up to 2 km thick in the deep central part of the Santa Maria basin (Figure 6).

Along the anticlinal trends of the basin, the upper Pliocene Careaga Sandstone commonly overlies the Foxen Mudstone with angular discordance. The Careaga Sandstone is a shallow-water, coarse-grained sandstone deposited during basin shoaling. Nonmarine gravel and alluvial sand of the Pliocene–Pleistocene Paso Robles Formation and Orcutt Sand conformably and unconformably overlie the Careaga Sandstone. The Careaga, Paso Robles, and Orcutt formations are grouped together in the Santa Maria basin (QTu, Figures 5, 6). Widespread angular discordances, Pliocene basin shoaling, and the deposition of nonmarine, coarse-grained upper Pliocene and Quaternary units are interpreted by us to be the result of uplift and erosion of the Pliocene and Quaternary fold and thrust belt.

**Middle and Upper Cenozoic Stratigraphy of the Pismo and Huasna Basins**

The Pismo and Huasna basins occur within two regional synclines of the same names. These small basins contain approximately 3 km of upper Oligocene through Pliocene strata (Figures 2, 7). These strata rest unconformably on the Franciscan assemblage and Cretaceous strata (Figure 5) (Hall and Corbato, 1967; Hall, 1973a). The oldest rocks above the unconformity are red beds of the upper Oligocene Sespe Formation. The Sespe Formation is overlain by upper Oligocene to lower Miocene shallow-marine sandstone of the Vaqueros Formation, which is overlain by deep-marine siltstone, sandstone, and fine-grained sandstone of the lower Miocene Rincon Formation. As in the Santa Maria basin, these deposits record increased subsidence of the basin during the early Miocene. Along the basin margins, the Rincon Formation is conformably overlain by lower and middle Miocene tuff and volcanic breccia of the Obispo Formation. The Sespe, Vaqueros, Rincon, and Obispo formations are grouped in the Pismo and Huasna basins (Tom, Figures 5–7).

The Obispo and Rincon formations are conformably overlain by the Point Sal and Monterey formations (Tm, Figures 5–7). In the Pismo syncline, the upper Miocene and lower Pliocene shale, sandstone, and siltstone of the Pismo Formation (Tmp, Figures 5, 7) conformably and unconformably overlie the Monterey Formation. The Pismo Formation is age equivalent to the Sisquoc, Foxen, and possibly Careaga formations of the Santa Maria basin (Stanley and Surdam, 1984). In the Huasna basin, the upper Monterey intertongues with and is overlain by the distinctive white-weathering sandstone and siltstone of the Santa Margarita Formation, which ranges in age from late Miocene through early Pliocene (Tmp, Figures 5–7) (Hall and Corbato, 1967).

**Middle and Upper Cenozoic Stratigraphy of the La Panza Range and Northern Carrizo Plain**

Within the La Panza Range and northern Carrizo Plain (Figure 2) is a middle and upper Cenozoic stratigraphic section that is part of the northern Cuyama basin. The section rests unconformably on crystalline basement rocks of the Salinian block (i.e., the fault block between the Riconda-Nacimiento fault and the San Andreas fault containing P-Cgn and Mzgr) and Upper Cretaceous to Eocene forearc strata (TKu, Figures 5, 7) (Dibblee, 1973a, b). This unconformity, which is due to the Ynezian orogeny, has an angular discordance of up to 90° within the La Panza Range and adjacent Sierra Madre Range (Vedder and Brown, 1968; Dibblee, 1973a; Vedder et al., 1988). Above the unconformity are Oligocene Simmler Formation red beds, which are overlain by shallow-marine sandstone and deep-water shale of the Vaqueros Formation (Tom, Figures 5, 7). The Vaqueros Formation is overlain by deep-water, clay-rich and siliceous shale and sandstone of the Monterey Formation. The Monterey Formation interfingers eastward with the shallow-marine Branch Canyon Sandstone, which interfingers with the nonmarine Caliente Formation (Dibblee, 1973a). The Monterey, Branch Canyon, and Caliente formations are grouped in the northern Carrizo Plain (Tmp, Figures 5, 7). All of these units are overlain by the shallow-marine sandstone of the upper Miocene Santa Margarita Formation (Tmp, Figures 5, 7). The Santa Margarita Formation is overlain conformably and unconformably by the Pliocene nonmarine strata of the Morales Formation, which is overlain along a significant angular discordance by the Pliocene–Pleistocene Paso Robles Formation. The Morales and Paso Robles formations are grouped together (QTu, Figures 5, 7). The coarsening-upward sequence and angular discordance are the result of uplift and erosion associated with folding and thrusting during the Pliocene and Quaternary (Davis et al., 1988).

**STRUCTURAL FEATURES**

**Shallow Structure of the Santa Maria Basin**

The Santa Maria basin is a triangular basin bounded on the north and northeast by the Santa Lucia Range and San Rafael Mountains of the southern Coast Ranges and on the south by...
Figure 8—Seismic reflection profile across the Hosgri fault zone and the southwest limb of the Point San Luis anticline (seismic reflection interpretation from Pacific Gas and Electric Company, 1988). Dashed lines indicate the front limb of the anticline. The Hosgri fault zone is shown as a high-angle fault that separates thick Neogene deposits in the offshore Santa Maria basin from a thinner section to the northeast. The reflections document the continuation of the Point San Luis anticline into the offshore. Note that the anticline has far more structural relief than can be attributed to the Hosgri fault. Our interpretation of the Point San Luis thrust in Figure 7 would occur below 3.0 sec twoway traveltime on this seismic reflection profile. A = Pliocene–Holocene deposits, B = Miocene deposits, C = undifferentiated basement complex.

the Santa Ynez Mountains of the western Transverse Ranges (Figures 1, 2). The basin extends westward and northward offshore. Along the northern margin of the Santa Maria basin, the structural grain is parallel to the northwest-trending southern Coast Ranges and the grain trends increasingly eastward across the basin where it is parallel to the Transverse Ranges (Figure 2). The Santa Maria basin is deformed by three major anticlinal trends. Along the northern margin of the Santa Maria basin is a major anticline named the Point San Luis anticline by Davis and McIntosh (1987) (Figures 2, 6, 7). Reed and Hollister (1936) showed this anticline as a through-going structure along the entire northern margin of the basin and extending offshore. The north limb of the anticline forms the southwestern range front of the San Rafael Mountains and the southwestern limb of the Pismo and Huasna synclines (Figures 2, 6, 7). The south limb of the Point San Luis anticline forms much of the south dip under the northern portion of the Santa Maria Valley and is documented by onshore well data (Figure 6) and offshore seismic reflection data (Figure 8). South of the Point San Luis anticline is the north-vergent Casmalia and Orcutt anticlines, and other en echelon folds that underlie the Casmalia and Solomon hills and form the traps of the Casmalia, Orcutt, and Cat Canyon oil fields. To the south, the San Antonio–Los Alamos syncline separates the Casmalia-Orcutt anticlinal trend from the symmetric to north-vergent Lompoc-Purisma anticlinal trend that underlies the Purisima Hills. The region between the Santa Ynez Range and the southern margin of the basin is underlain by a structural shelf deformed by numerous low-amplitude, short wavelength folds (AAPG, 1959).

The Santa Maria basin and its margins are cut by numerous faults of middle and late Cenozoic age that trend subparallel to the folds (Figure 6). Faults at the surface and in the shallow subsurface generally have a high-angle dip and commonly are associated with middle and late Cenozoic stratigraphic thickness changes. The most common and significant changes are stratal thickening in the downthrown side of the faults. These changes are valuable for determining age and type of fault motion. Most commonly these faults control stratigraphic thicknesses of Miocene and/or Pliocene sections and commonly are overlapped by younger strata (Figure 6). These relationships suggest to us that the faults were active normal or strike-normal-slip growth faults during the Miocene and Pliocene.

**Shallow Structure of the Southern Coast Ranges and Offshore**

The part of the southern Coast Ranges discussed herein is composed of several large anticlinal trends separated by syn-
clinal trends containing the Neogene basins (Figures 2, 7). From southwest to northeast, these regional folds are the Point San Luis anticline, the Pismo syncline, the Santa Lucia Range anticlinorium, the Huasna syncline, the La Panza Range anticlinorium, and the Carrizo Plain area. The age and geometry of the folds are best recorded in the synclinal trends because of the relatively complete Neogene sections. The crests of the anticlinoriums are composed of lower Tertiary and upper Mesozoic strata, crystalline basement of the Salinian block, the Franciscan assemblage, and Coast Range Ophiolite.

A number of high-angle faults occur along the borders of the synclinal trends. Offshore, the northern part of the Hosgri fault is along the northeastern margin of the offshore Santa Maria basin. Seismic reflection data have documented the trend of the fault to be parallel to the coast line (Pacific Gas and Electric Company, 1988). Generally, across its northern part, the fault separates a thick Neogene section on the west from a thinner section on the east (McCulloch, 1987) and late Cenozoic folding has occurred along the fault trace (Crouch et al., 1984).

Interpretations of Cenozoic movement on the Hosgri fault zone are numerous. Large slip interpretations include 115 km of right slip since the early Tertiary (Graham and Dickinson, 1978) and 90 km of right slip since the Cretaceous (Hall, 1975). Hamilton and Willingham (1978) proposed a maximum of 20 km of right slip during the Neogene. Hamilton (1984) concluded that post-Miocene right slip is no more than 5 km and that most of the large slip estimates of other workers occurred prior to the Miocene. McCulloch (1987), using seismic reflection data, interpreted the Hosgri fault to be a Miocene transensional fault zone. Alternatively, Crouch et al. (1984), using a different set of seismic reflection data, interpreted the Hosgri fault as a large post-Miocene thrust. In a regional cross section across the southern Coast Ranges, Namsen and Davis (1988a) followed the interpretation of Crouch et al. (1984) and show the Hosgri fault as a major thrust uplifting the southwest flank of the Coast Ranges. Our previous interpretation is modified in this structural analysis as is discussed in a following section.

The San Miguelito fault occurs along the southwestern side of the Pismo syncline and was apparently active during the Miocene and early Pliocene as a down-to-the-basin right-normal-slip fault (Hall, 1973a). The Edna fault bounds the northern side of the Pismo syncline where middle Cenozoic strata are faulted against the Franciscan assemblage. The Edna fault also appears to be a down-to-the-basin, normal or right-normal-slip fault (Hall, 1973a; Hall et al., 1979). Both faults are discontinuous along the margins of the Pismo basin and are overlapped by Pliocene strata to the northwest and southeast. These relationships suggest that the faults may have had strike-slip motion during the Miocene or early Pliocene, but cannot have moved much during the late Pliocene and Quaternary.

The West Huasna fault zone is located near the west side of the Huasna basin (Figures 2, 6), and Hall and Corbato (1967) discussed the detailed relationships along the fault. The fault zone is composed of a series of discontinuous high-angle faults that includes the Suey fault. The most distinctive relationship across the West Huasna fault is the presence of a thick accumulation of volcanic and volcaniclastic rocks of the Obispo Formation west of the fault zone, and a thin and limited presence of volcanic rocks east of the fault zone (Hall and Corbato, 1967). Hall and Corbato (1967) favored right-lateral offset for the fault zone but suggested that evidence for such offset is inconclusive. This relationship could also be explained by having dip-slip fault motion that controlled deposition of volcanic rocks of the Obispo Formation west of the fault zone.

The East Huasna fault zone occurs along the east side of the central part of the Huasna basin and generally separates Upper Cretaceous strata and Franciscan assemblage on the east from Miocene strata on the west (Figure 2) (Vedder et al., 1986b, 1988, 1989). To the north and south, the fault separates Miocene strata and the total strike-slip offset would have to be small because the middle Tertiary units are only slightly offset. Hall and Corbato (1967) showed a down-to-the-basin, dip-slip component for the fault, but suggested a strike-slip component to explain a cross fault facies change in the Santa Margarita Formation. However, dip-slip motion also could have controlled the facies changes in the Santa Margarita Formation.

The Rinconada-Nacimiento fault is crossed in our regional Coast Range transect (Figure 7). The early Tertiary history of the fault is controversial and both strike slip and thrusting or some combination of slips have been proposed for the juxtaposition of the Salinian and Franciscan basement blocks. Hill (1954) was the first to suggest large strike slip on the fault and Dickinson (1983) proposed up to 560 km of left slip on the fault during the Late Cretaceous. Hall and Corbato (1967) and Vedder and Brown (1968) indicated that if large strike slip occurred on the fault, then it must have been prior to the Miocene. However, Dibblee (1976) proposed 23–56 km of right-lateral strike-slip offset along the Rinconada-Nacimiento fault since the early Miocene with as much as 18 km of offset since the early Pliocene. The basis of these offsets are en echelon fold trends and facies and thickness changes across the fault north of the area in Figure 2. There are no conclusive piercing points to document these offsets in the area of Figure 2. Evidence in the Nipomo area (east of the Huasna syncline) (Hall and Corbato, 1967) suggests that post-Miocene movement on the fault is only dip slip and inconclusive during the preceding time period. Along the northeastern San Rafael Mountains (southeast of Figure 2) stratigraphic facies correlations of a lower and middle Miocene fan deposit across the fault suggest post–middle Miocene dip slip of 800 m and strike slip of 0–6 km (Yaldezian et al., 1983). All workers agree that offset Miocene deposits across the fault indicate some amount of reverse slip motion, with the northeast side up, during the late Cenozoic.

Northeast of the Rinconada-Nacimiento fault is the La Panza fault. Map relations show the fault to be an eastward-dipping reverse fault (Vedder et al., 1986a) that uplifted the La Panza Range during the Pliocene and Quaternary (Dibblee, 1976). At the northern end of the Carrizo Plain, near Red Hills, is the poorly exposed Red Hills fault (Dibblee, 1973a). This fault has a high-angle dip and separates a thick Neogene section of mostly nonmarine rock on the west from a thin coeval section on the east (Figures 2, 7). This fault may connect southeastward with the San Juan fault (Dibblee, 1973a). Smith (1977) and Yeats et al. (1988) proposed that the San Juan fault is one segment of a large displacement right-lateral strike-slip fault active during the middle Cenozoic. In the northern Carrizo Plain, the San Juan fault is covered in places by unbroken Santa Margarita Formation, which indicates no significant strike-slip offsets since the late Miocene (T. Davis and T. Nel-
Orcutt Anticline

Figure 9—Geologic cross section and interpretation of the Orcutt anticline as a fault-propagation fold resulting from 5.7 km of slip on the Purisima-Solomon thrust. The Orcutt fault is interpreted to be a late Miocene and early Pliocene normal fault controlling Sisquoc Formation deposition and block rotation of south dipping homocline under the southern portion of the Santa Maria Valley. The dashed line within the KJf-Jop and Mzgr-p€gn is an arbitrary structural reference horizon that illustrates late Cenozoic convergent deformation. Qpr = Paso Robles Formation, Tca = Careaga Sandstone, Tf = Foxen Mudstone, Tsq = Sisquoc Formation, Tm = Monterey Formation, Tps = Point Sal Formation, Tls = Lospe Formation, KJf-Jop = undifferentiated Franciscan assemblage, 1989, personal communication). The study area is bounded on the east by the San Andreas fault (Figure 2).

STRUCTURAL INTERPRETATION

Our approach to understanding the origin and evolution of Pliocene and Quaternary convergence of the region is to construct balanced cross sections. One of the assumptions of constructing two-dimensional balanced cross sections is that there has been minimal motion in or out of the section plane during convergent deformation (i.e., no significant strike-slip motion). We conclude that there is no evidence in the Santa Maria basin or southern Coast Ranges for significant strike-slip motion (<1–2 km) during the late Pliocene and Quaternary, except on the San Andreas fault. Our focus is the origin and evolution of structures formed during Pliocene and Quaternary convergence. In constructing and restoring the cross sections, we use the unconformity caused by the middle Cenozoic Ynezian orogeny as a structural reference. The complex structures that predate the unconformity do not affect our restoration and are not considered in our analysis. The following discussion includes interpretations of structures within the Santa Maria basin (Figures 9, 10), regionally across the Santa Maria basin (Figure 6), and regionally across the offshore Santa Maria basin and southern Coast Ranges (Figure 7).

Orcutt Anticline

The Orcutt anticline (cross section XX', Figure 9) is part of the Casmalia-Orcutt anticlinal trend (Figure 2). The structural and stratigraphic relationships of the fold are well known from extensive drilling, detailed surface maps (Woodring and Bramlette, 1950; T. W. Dibblee, 1989, personal communication), and structural cross sections (Woodring and Bramlette, 1950; AAPG, 1959). The fold is asymmetric with a broad flat crest, gently dipping south limb, and steeply dipping or overturned north limb. Deep drilling shows the fold is cored by the Franciscan assemblage.

The Purisima-Solomon thrust has been encountered along the northern limb of the fold at about 2.5 km depth in well 23.
Late Cenozoic Fold and Thrust Belt

Figure 10—Geologic cross section across the Lompoc-Purisima anticline showing a fault-bend fold origin for the structure with 5.8 km of slip on the Purisima-Solomon thrust. High-angle faults are interpreted to be late Miocene to early Pliocene normal faults that controlled Sisquoc Formation deposition. The dashed line within the KJf-Jop is an arbitrary structural reference horizon that illustrates late Cenozoic convergent deformation. Qpr = Paso Robles Formation, Tca = Careaga Sandstone, TF = Foxen Mudstone, Tsq = Sisquoc Formation, Tm = Monterey Formation, KJf-Jop = undifferentiated Franciscan assemblage, Coast Range Ophiolite, and Knoxville Formation.

(Figure 9), where it places the Franciscan assemblage over the Sisquoc Formation. The Purisima-Solomon thrust is interpreted to be the causative fault in forming the Orcutt anticline because the fold is not present below the thrust. The thrust is not found in wells north of well 23, so the thrust apparently dies out in the syncline that bounds the steep north fold limb. Below the thrust, dipmeter data show that the Sisquoc and Monterey Formations dip 15–20° south. In the footwall of the thrust, stratigraphic correlation and dip information show a small fold to be present, which is interpreted to be a fault-bend fold because of the gentle limb dips. The Purisima-Solomon thrust is interpreted to dip about 40° south, for a short distance, as it cuts across strata of the south limb of the small fault-bend fold. Farther south, the thrust is interpreted to dip 25°, parallel to the south limb of the Orcutt anticline. The position of the lower detachment is fairly well constrained by the intersection of the northern hinge of the San Antonio–Los Alamos syncline and the thrust ramp, and the hanging wall cutoff thickness above the Purisima-Solomon thrust. In this solution, the total slip on the thrust is 4.8 km, which is the length of the south limb of the anticline. The thrust responsible for the small fault-bend fold north of the Orcutt anticline is interpreted to root in the same detachment as the Purisima-Solomon thrust.

The Orcutt anticline is cut by numerous west-northwest-trending, high-angle faults that are discontinuous along strike. Some of these faults are interpreted to account for discontinuities in stratigraphic correlation and Miocene and Pliocene thickness changes. Stratal thickness changes suggest the faults are growth faults active during the Miocene and early Pliocene. The best-documented example of these faults is the Orcutt fault, which dips steeply south and trends along the north limb of the fold. The Sisquoc Formation is much thicker in the syncline north of the Orcutt fault than on the fold crest south of the fault. The Orcutt fault is interpreted to have been a late Miocene and early Pliocene north-dipping normal fault that controlled Sisquoc Formation depositional thickening in the downthrown block. The fault is shown to be translated in the upper plate of the Purisima-Solomon thrust and folded to a south dip during the formation of the Orcutt anticline. The gentle south dip of middle and upper Miocene units under the Santa Maria Valley may be the result of downdropping and rotation of the hanging wall of the Orcutt normal fault (see restoration, Figure 6). Slight reactivation of the Orcutt fault as a high-angle reverse fault during late Cenozoic shortening is suggested by the minor displacement of upper Pliocene and Pleistocene units at or near the surface.

Thrust fault termination in a syncline and the steep north limb of the Orcutt anticline indicates fault-propagation folding
The Lompoc-Purisima anticline (cross section CC', Figure 10) is the major anticlinal trend along the southern margin of the Santa Maria basin (Figures 2, 6). The fold trend is at least 45 km in length from the coastline eastward. The fold is late Pliocene to Quaternary because stratigraphic units of this age are deformed almost as much as the older units and the fold trend is expressed as uplift of the Purisima Hills (Figure 10). Surface maps, electric log correlations, and dipmeter data from wells show the anticline is asymmetric with a steep north limb that ranges from vertical to 40° and a moderately dipping south limb (Woodring and Bramlette, 1950; Dibblee, 1988; T. W. Dibblee, 1989, personal communication). At its western end, near Lompoc, the anticline has a broad, nearly flat crest (Figure 6), whereas to the east, the crest of the anticline is narrower and deformed by low-amplitude, short-wavelength, shallow-level folds (Figure 10).

Cross section CC' (Figure 10) crosses the culmination of the Lompoc-Purisima anticline, where the late Cenozoic structural relief is greater than 2 km. Surface data and several deep wells constrain the shallow subsurface fold geometry. The south limb of the anticline dips 20° and along the north limb is a smaller, second-order anticline with a steeply dipping (70–90°) north limb that extends only a few kilometers along strike and 2–3 km in depth. In the subsurface, the McCulloch 1-1 Ferrero et al. well and the White Shield 1 Alamo well show that the steep dips do not continue below the Monterey Formation and the more representative deeper north limb dip is about 30°.

The thick accumulation of Sisquoc Formation on the north limb of the Lompoc-Purisima anticline is interpreted to result from development of a late Miocene graben. These faults are not observed at the surface and have not been intersected by drilling to our knowledge. Onlap of the Sisquoc Formation is another possibility to explain these rapid thickness changes. We favor normal faulting because of the large thickness changes (1–2.5 km) that occur over a short distance and normal faults of this age are common in other parts of the Santa Maria basin and in other Neogene basins of southern California (Davis and Lagoe, 1988; Namson and Davis, 1988b; Davis et al., 1989). In this interpretation, Pliocene and Quaternary folding has deformed and rotated the older normal faults.

The slight asymmetry of the deeper Purisima anticline and its moderate limb dip suggest to us that the fold is a north-vergent, fault-bend fold associated with a ramp in the Purisima-Solomon thrust (Figure 10). The specific level of the detachments is not well constrained. The upper detachment is deeper than 3.5 km because no thrusts large enough to generate the fold or structural relief have been encountered by drilling. We interpret the upper detachment level to be in the 6 km range by connecting the detachment level of the Purisima-Solomon thrust previously determined under the Orcutt anticline (Figure 9). In this solution, the Lompoc-Purisima anticline is related to a thrust ramp connecting a detachment at about 8 km depth to the 6 km depth detachment level. The geometry and slip of the Purisima-Solomon thrust under the Lompoc Purisima anticline is determined by using the observed fold geometry in conjunction with the fault-bend fold model. The ramp height is interpreted to be 2 km and is determined by measuring the stratigraphic thickness of the hanging-wall cutoff, which is the...
stratal thickness between the intersection of the main anticlinal axis with the upper detachment and the synclinal axis with the upper detachment. The top of the ramp occurs at the intersection of the main anticlinal axis and the upper detachment. The ramp is constructed parallel to the south limb dip of the Lompoc-Purisima anticline. This solution yields 5.8 km of slip in the ramp region of the Purisima-Solomon thrust with approximately 5.3 km of slip transferred northward on the upper detachment to form the Casmalia-Orcutt anticlinal trend to the north (Figures 2, 6).

Structure of the Western Santa Maria Basin

A regional structural interpretation across the western part of the Santa Maria basin (cross section BB', Figure 6) from the west end of the Santa Ynez Mountains to the San Rafael Mountains shows the major geologic structures include the western end of the Lompoc-Purisima anticline, San Antonio–Los Alamos syncline, Orcutt anticline, syncline under the Santa Maria Valley, Point San Luis anticline, and Huasna syncline. The interpretation links the origin of these structures into an internally consistent model that explains their late Cenozoic structural evolution (Figure 12).

The largest fold is the Point San Luis anticline, which trends along the northern margin of the Santa Maria basin (Figure 2). This fold has Franciscan rocks exposed along the fold crest and Miocene and Pliocene rocks of the Huasna syncline on the north limb. The south limb of the Point San Luis anticline is documented by the southward dip of Miocene and Pliocene strata under the northern half of the Santa Maria Valley. The south dip under the south half of the valley is interpreted to be related to Pliocene and Miocene block rotation along the Orcutt normal fault (see restoration, Figure 6) and/or onlap of Miocene and lower Pliocene strata onto an Oligocene fold resulting from the Ynezian orogeny. These relationships extend along strike for at least 70 km northwest of cross section BB' under the Santa Maria Valley and offshore (Figures 2, 7), and 30 km southeast along the northeast edge of the Santa Maria basin for a total length of 100 km.

We interpret the Point San Luis anticline to be a fault-bounded fold on the basis of its symmetrical profile and moderate limb dip. In our solution, the fold is caused by the south vergent Point San Luis thrust that ramps from a lower detachment at 13 km to an upper detachment at 9 km depth. Approximately 9.2 km of slip is transferred southward on the 9 km depth detachment under the Lompoc-Purisima anticline. The Lompoc-Purisima and Casmalia-Orcutt anticlinal trends take up 6.4 km of this slip. The additional 2.8 km of slip (9.2–6.4 km) is shown to be transferred southward to form the uplift and late Cenozoic convergence present in the western Santa Ynez Mountains. This structural solution of the western Santa Maria basin is a restorable minimum slip solution consistent with the observed fold geometry and position of the Purisima-Solomon thrust determined from drilling.

A general model of the sequential development of the western Santa Maria basin structures is illustrated in Figure 12. As previously discussed, some of the slip on the upper detachment of the Point San Luis thrust is transferred to the Purisima-Solomon thrust forming the Lompoc-Purisima and Casmalia-Orcutt anticlinal trends and the remainder of slip is consumed in uplifting and folding of the western Santa Ynez Mountains.

The model explains the observed relationship between uplift of the range front of the San Rafael Mountains and the structural kinematics of the Point San Luis anticline and Pismo and Huasna synclines. The southwest range front of the San Rafael Mountains is a sharp and regionally continuous topographic break, which coincides with the northeast limb (back limb) of the Point San Luis anticline (south limbs of the Pismo and Huasna synclines) (Figures 2, 13). The crest and south limb of the anticline are submerged offshore near Point San Luis and underlie the Santa Maria Valley eastward (Figures 6, 7). Arrows on the structural model of the Point San Luis anticline indicate the motion of material points in the fold as the structure grows (Figure 12). In the early stages of fold development, prior to the base of the hanging-wall cutoff reaching the top of the ramp, uplift occurs over the crest and back limb of the Point San Luis anticline (Figure 12A). As material points are translated over the ramp they have only a horizontal component of motion (i.e., no uplift). After the entire hanging-wall cutoff has been translated over the ramp, only the back limb (north limb) has a vertical component of motion and the fold crest moves horizontally (Figure 12B, C). The latter stage of fold growth (Figure 12C) is similar to our interpretations of the Point San Luis anticline (Figures 6, 7) and gives a structural explanation for uplift of the San Rafael Mountains range front being confined to the north limb of the anticline (Figure 13).

Structure of the Southern Coast Ranges

Cross section AA' (Figure 7) extends from offshore near San Luis Obispo across the Santa Lucia and La Panza ranges to the San Andreas fault (Figure 2). The major geologic structures intersected by this cross section line include the Hosgri fault zone, Point San Luis anticline, Pismo syncline, Santa Lucia Range anticlinorium, Huasna syncline, La Panza Range anticlinorium, and northern Carrizo Plain. This interpretation explains only the Pliocene through Quaternary structural development of the region and no attempt is made to resolve earlier deformation. The section crosses the Rinconada-Nacimiento fault that separates the Franciscan and Salinian basement blocks of the Coast Ranges. As previously discussed, these two basement blocks were juxtaposed by the early Tertiary, so the middle Cenozoic unconformity of the Ynezian orogeny extends across the area and can be used to define the late Cenozoic map-scale fold geometry.

The major folds are interpreted to be related to thrust ramps stepping up from a regional detachment that ranges from 14 km depth at the eastern end of the section to 11 km depth at the western end. This depth of the regional detachment corresponds roughly to the maximum depth of seismicity in the southern Coast Ranges (Wesson et al., 1977; Eaton, 1985) and probably to the brittle-to-ductile transition (Eaton and Rymer, in press), but is only poorly constrained from the surface and limited subsurface data used in constructing this cross section. The detachments and ramps could be moved up or down several kilometers and still be used to resolve the structural geometries with only minor changes in the fault slip or regional shortening.

Cross section AA' (Figure 7) begins along the margin of the offshore Santa Maria basin and crosses the Hosgri fault zone.
Figure 12—Kinematic model illustrating the structural evolution of compressional structures of the western Santa Maria basin. Arrows on the Point San Luis anticline indicate the motion of material points within the fault-bend fold. Only material above the ramp has a vertical component of motion during fold growth. During the early stage of fold growth (A), both the anticlinal crest and back limb have a vertical component of motion. The intermediate stage is shown by (B). In the later stage of fold growth (C), only the back limb above the ramp has a vertical component of motion and a significant amount of thrusting can occur without uplift of the fold crest and front limb. The later stage corresponds to the uplifted topographic mountain front of the San Rafael Mountains, which is underlain by the back limb of the Point San Luis anticline (Figure 13).

The location and geometry of the Hosgri fault zone and the south limb of the Point San Luis anticline are defined from offshore seismic reflection data (Figure 8). The Hosgri fault zone is shown as a series of high-angle faults probably responsible for Miocene and Pliocene stratal thickening in the downthrown blocks. This interpretation is consistent with the Hosgri being a transtensional wrench zone (McCulloch, 1987) or normal fault during the Miocene and early Pliocene. The Hosgri fault...
Figure 13—Black and white Thematic Mapper Landsat image of the westernmost Transverse Ranges and southernmost Coast Ranges illustrating the major fold trends of the area. The front of the San Rafael Mountains is fairly straight and coincides with the back limb of the Point San Luis anticline (southwest limbs of the Pismo and Huasna synclines). Topographic uplift is confined to the back limb of the Point San Luis anticline and is interpreted to be related to the advanced stages of fault-bend fold growth above a ramp in the Point San Luis thrust (Figures 6, 7, and 12).
has been deformed into its present eastward-dipping geometry and has undergone minor reactivation as a reverse fault during growth of the Point San Luis anticline in the late Pliocene and Quaternary. The Hosgri fault cannot have played a major role as a compressional structure in forming the Point San Luis anticline because (1) the amount of Quaternary reverse slip is too small compared with the size of the anticline (Figure 8), (2) the dip-slip component is Miocene and early Pliocene as indicated by stratal thickening and, thus, was prior to major fold growth, and (3) the Hosgri fault geometry does not explain the structural relief or geometry of the Point San Luis anticline.

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).

The Point San Luis anticline is interpreted to be a fault-bend fold because of the symmetric shape and moderate limb dips of the anticline. In our solution, the anticline is associated with a ramp on the Point San Luis thrust that steps up from a lower detachment at 13 km to a higher detachment at 8 km. The 7.2 km of slip transferred southeastward on the higher detachment of the Point San Luis thrust is interpreted to cause the numerous convergent structures observed in the offshore Santa Maria basin and offshore continental margin (McCulloch, 1987; McIntosh et al., in press).
fore, we estimate the base of the Careaga Sandstone to be approximately 2.0 Ma. Although more stratigraphic work and age dating are needed, we believe the available data indicate the Orcutt anticline started to grow sometime between 4.0–2.0 Ma.

The stratigraphic sections in the Pismo and Huasna basins do not provide as complete a record of the initiation of convergence as in the Santa Maria basin. Within the Pismo basin, the upper Pliocene part of the Pismo Formation is folded less than the underlying Miocene–Pliocene part of the Pismo and the Miocene Monterey formations. Within the Huasna basin, the lower Pliocene Saucelito Member of the Santa Margarita Formation is the youngest Neogene unit preserved and is folded concordantly with the underlying units (Hall and Corbato, 1967), suggesting that the onset of folding is no older than the end of the early Pliocene. These relationships show that convergence in the southernmost Coast Ranges began sometime during the late early Pliocene or late Pliocene, which is contemporaneous with initiation of the Orcutt anticline of the Santa Maria basin.

The geologic relationships of the Pliocene–Pleistocene Paso Robles Formation indicate that convergence has continued through the Quaternary. In the Santa Maria basin, the Paso Robles Formation is gently to steeply folded along the limbs of the Orcutt and Lompoc-Purisima anticlines (Woodring and Bramlette, 1950). Along the outer limbs of the Pismo syncline, the Paso Robles Formation is gently folded (Hall, 1973a). On the north limb of the Santa Lucia Range, anticlinorium the Paso Robles Formation is folded up to 45° (Hall et al., 1979). Similarly, Dibblee (1973a) has mapped gently to moderately folded Paso Robles Formation in many parts of the southern Coast Ranges and Carrizo Plain. Generally, the Paso Robles is coarse grained, locally derived, and nonmarine. We interpret the Paso Robles Formation to be a synorogenic deposit that is the result of erosion of the late Pliocene and Quaternary fold and thrust belt. In the offshore Santa Maria basin, seismic reflection data show folding and related thrust faulting occurred during the Pliocene with decreasing intensity during the Quaternary (McIntosh et al., in press).

A similar age for the onset of convergence and its continuation through the Quaternary is derived from plate tectonic studies. Cox and Engebretson (1985) proposed that a change in plate motion at 5.0 Ma initiated convergence, and Harbert and Cox (1989) revised this age to 2.4–3.9 Ma. Based on the geologic relationships and plate tectonic studies, we assume that convergence initiated in the southern Coast Ranges and Santa Maria basin between 4.0 and 2.0 Ma, and continued through the Quaternary. We use this age range to calculate average regional convergence rates and slip rates on individual thrust faults (Table 1).

The regional cross section AA' (Figure 7) can be used to calculate the total late Cenozoic convergence across the southern Coast Ranges west of the San Andreas fault and estimate the convergence that must be accommodated in the development of structures in the offshore northern Santa Maria basin. The restoration of cross section AA' removes the late Cenozoic convergence. The cross section documents 26.8 km of convergence between the present deformed length of the cross section (95.8 km) and the restored regional detachment (122.6 km), which yields a regional convergence rate of 6.7–13.4 mm/yr between the San Andreas fault and offshore continental margin. The restoration also shows the geometry of preconvergence structures and the undeformed geometry of the late Cenozoic thrusts. The hachured area in Figure 7 indicates a 5.0 km discrepancy in shortening between the regional detachment on the middle Cenozoic unconformity, which amounts to a 4% error in the interpretation. The slip rate on individual thrusts also can be determined from the displacement on faults that root into the basal detachment and range from 0.3–4.9 mm/yr (Table 1). Approximately 7.2 km of slip is transferred into the northern part of the offshore Santa Maria basin on the upper detachment of the Point San Luis thrust, which is consumed in forming the offshore structures between the Point San Luis anticline and the Santa Lucia Bank (continental margin). The predicted time-averaged convergence rate offshore is 1.8–3.6 mm/yr, which would be divided among the offshore structures.

Restoration of cross section BB' (Figure 6) is made from the syncline axis in Santa Rita Valley to the Huasna syncline axis. The present deformed length is 54.7 km and the restored length is 63.9 km, which yields 9.2 km of convergence. The
average convergence rate across the onshore Santa Maria basin is 2.3–4.6 mm/yr. This convergence includes 2.8 km of slip transferred southward, which is inferred to form the Santa Ynez Mountains. The maximum line length restoration discrepancy is 1.3 km (hachured area, Figure 6), which is a 2% balancing error in the interpretation. Slip rates for the ramp regions of the thrusts in cross section BB' range from 1.4–4.6 mm/yr (Table 1).

Regional convergence rates across the southern Coast Ranges and Santa Maria basin have been determined independently by plate tectonic studies and geodetic measurements. Plate tectonic studies of the North American and Pacific plates indicate a convergent component of plate motion of 7.0 mm/yr (DeMets et al., 1987) or a range of 3.7–15.0 mm/yr (Minster and Jordan, 1984). The regional convergence rates from plate tectonic studies apply to shortening of the Coast Ranges on both sides of the San Andreas fault. Results from a geodetic triangulation network from the San Andreas fault to the Pismo syncline near San Luis Obispo indicate active shortening of 6.1 ± 1.7 mm/yr (Harris and Segall, 1987). The triangulation network is in the same location as cross section AA' (Figure 7) and the active shortening rate compares quite well with the low end of our time-averaged rate of 6.7 mm/yr (Table 1). In comparing the two rates, note that our rate also includes shortening offshore to the continental margin. A geodetic survey across the onshore Santa Maria basin indicates 7 ± 2 mm/yr of active shortening (Feigl et al., 1990). This convergence rate is higher than the convergence rate of 2.3–4.6 mm/yr determined from cross section BB' (Figure 6), which may indicate that shortening is nonuniform over geologic time.

DETACHMENT AND SAN ANDREAS FAULT INTERACTION

Cross section AA' (Figure 7) shows the thrust detachment intersecting the San Andreas fault. As previously discussed, 26.8 km of west-vergent displacement is interpreted on the detachment, creating a significant kinematic interaction between the San Andreas fault and the detachment. Namson and Davis (1988a,b) have proposed a model where transpression (convergent strike-slip motion) between the Pacific and North American plates over the last 2–4 m.y. is resolved into tangential and normal components of strain with respect to the plate boundary. In the shallow crust (above the principal detachment), the tangential strain component is recorded as strike-slip offset along the San Andreas fault, whereas the normal strain component is recorded in upper Pliocene and Quaternary thrust faults and folds that generally strike parallel to the San Andreas fault and root in the principal detachment. The lower crust and mantle lithosphere must also be shortened an amount equivalent to that in the shallow crust by using either tectonic thickening or subduction into the asthenosphere. This model is consistent with the geologic observation that Quaternary folds, both east and west of the San Andreas fault, have developed parallel to the San Andreas fault (Page and Engbretson, 1984) and that a substantial number of earthquakes in the Coast Ranges are not on the San Andreas fault and have thrust or reverse fault focal mechanisms (Eaton, 1985). The model is also consistent with central California current stress fields, which show the principal compressive stress to be oriented normal to the San Andreas fault (Mount and Suppe, 1987).

SEISMICITY AND HAZARDS IMPLICATIONS

The active fold and thrust belt interpretation of the southern Coast Ranges and Santa Maria basin is consistent with other parts of the Coast Ranges and southern California subjected to late Cenozoic convergence (Namson and Davis, 1988a, b; Davis et al., 1988; Davis et al., 1989). Locally, the interpretation is supported by the presence of blind thrusts encountered by drilling beneath the anticlinal trends (Purisima-Solomon thrust under Orcutt anticline) (Figures 6, 9) and the common occurrence of earthquakes with compressive focal mechanisms (Figure 3) (Gawthorpe, 1978; Eaton, 1984, 1985; Dehlinger and Bolt, 1987; Pacific Gas and Electric Company, 1988). Other data supportive of the interpretation include broad bands of seismicity not associated with surface faults (Figure 4), geodetic measurements showing present crustal shortening (Feigl et al., 1990), and folded upper Pliocene and Quaternary deposits. The distribution of broad bands of seismicity in the Santa Maria basin and southern Coast Ranges is also consistent with the fault-bend and fault-propagation origin of the folds.

Our structural interpretation has several important implications with regard to seismicity and hazards evaluation of the area. The major anteclines and anticlinoria of the Santa Maria basin and southern Coast Ranges are postulated to be the result of thrust ramps in an upper Pliocene and Quaternary fold and thrust belt dominated by blind thrusts (Figures 6, 7).

Our structural interpretation is consistent with the seismic character of the region and suggests that moderate to large earthquakes will occur along the thrust ramps of the system. Compressive focal mechanisms show fault dips between 10–45°, indicating earthquakes most commonly occur along the ramp parts rather than the detachment parts of the system. This location is consistent with other areas of southern California, where Namson and Davis (1988b) and Davis et al. (1989) noted a correspondence between gentle- to moderately-dipping compressive earthquakes and regional anticlinal trends of the western Transverse Ranges and Los Angeles basin, and proposed that thrust ramps are the most likely source for these earthquakes. No focal mechanisms from the Santa Maria basin or southern Coast Ranges can be associated with the principal detachments (Figure 3). Similarly, detachment events in other parts of southern California are uncommon (Webb and Kanamori, 1985). The nearly flat focal mechanism of the 1978 Santa Barbara earthquake (M = 6.7, Corbett and Johnson, 1982) is probably the major exception to this observation. Although the focal mechanism record is short and incomplete, the available record suggests the principal detachments generally are aseismic.

The largest historic earthquake to have occurred in the study area was the 1927 Lompoc event (moment magnitude or Mw = 7.3) (Figure 2), interpreted to have occurred on a thrust fault (Savage and Helmberger, 1987). Moderate-size earthquakes also occurred in the Los Alamos area in 1902, Mw = 5.4, and 1915, Mw = 5.8 (Yerkes, 1985). Other moderate to large compressive earthquakes in southern and central California include the 1952 Arvin-Tehachapi, Mw = 7.5, the 1971 San Fernando,
determine the areal extent of the thrust ramps. The fold length trend to 80 km for the Point San Luis anticline and La Panza basin and southern Coast Ranges the ramp lengths range from 15 km for the individual folds of the Casmalia-Orcutt anticlinal trend to 80 km for the Point San Luis anticline and La Panza Range anticlinorium. The seismic moment ($M_o$) can be calculated from Aki (1966):

$$M_o = \mu AD,$$

(1)

where $\mu$ (3x10$^{11}$ dyne/cm$^2$) is the rigidity constant, A is the rupture surface area, and D is the average displacement during an earthquake. The moment magnitude $M_W$ can be estimated from Kanamori (1978):

$$M_W = (\log M_o)/1.5 - 10.7.$$  

(2)

Using these relationships, the moment magnitude can be calculated for representative structures in the study area. For example, a 1-m slip event along a 10-km-wide, 15-km-long thrust ramp would produce a 6.4 $M_W$ earthquake, whereas a 2-m slip event along a 10-km-wide, 80-km-long thrust ramp would produce a 7.1 $M_W$ earthquake.

The overall convergence rates and individual fault slip rates determined from the cross sections can be used to estimate repeat times for moderate to large earthquakes with characteristic slip events of 1 and 2 m if we assume the convergence is completely consumed in seismic events along the thrust ramps (Table 1). The repeat times for moderate to large slip earthquakes could be expected somewhere along cross section AA' (Figure 7) in the southern Coast Ranges every 75–299 yr, and along cross section BB' (Figure 6) in the onshore Santa Maria basin every 217–870 years. Repeat time estimates apply only to segments adjacent to the cross section (within ~40 km). Repeat times for entire fold trends will depend on fold length, fault segment length, and variations in slip rate along trend. Such estimates will require additional structural analysis.

The structural interpretation presented here suggests the region is dominated by a number of seismically active blind thrusts that are largely unknown to the geological community. The city of San Luis Obispo and adjacent coastal towns are situated above major thrust ramps of the Point San Luis and Santa Lucia thrusts. These ramps are potential seismic sources, and given their 50–80 km length and the historic seismic record of compressive earthquakes, could be capable of generating moderate to large earthquakes ($5.0 < M_W < 7.5$).

Previous geologic evaluations of the seismic potential of the area have concentrated on surface faults and have not attempted to explain the origin of the large young anticlinal trends of the area. Our analysis suggests these surface faults may be relatively unimportant seismogenic features of the area and are due to previous deformational episodes or flexural slip associated with fold growth. Surface studies alone cannot evaluate the seismic potential of active convergence and such studies are subject to numerous pitfalls that may provide an abbreviated and/or misleading evaluation of seismic hazards (Namson and Davis, 1988a; Davis et al., 1989).

**HYDROCARBON IMPLICATIONS**

The onshore Santa Maria basin is a major hydrocarbon producing area of California with 938 million bbl of estimated ultimate oil reserves and 875 bcf of associated gas in the onshore part of the basin (California Division of Oil and Gas, 1986). Oil fields occur along three major trends (Figure 14): (1) Santa Maria Valley (296 million bbl) (Figure 15), (2) Casmalia-Orcutt anticlinal trend (595 million bbl) (Figures 16, 17), and (3) Lompoc-Purisima anticlinal trend (50 million bbl). Most of the hydrocarbon production is from sandstones of the Point Sal Formation, Monterey Formation, or lower portion of the Sisquoc Formation, and fractured cherts within the Monterey Formation. The trends include a variety of trap styles: surface anticlines, normal faults, subthrust anticlines, stratigraphic pinch-outs, or some combination of these trap styles. The trap styles of the most prolific oil trends (Santa Maria Valley and Casmalia-Orcutt trend) are partly the result of Miocene and Pliocene interaction between deep-water sedimentation, extensional faulting, and/or paleohighs. These trap styles are overprinted by late Pliocene and Quaternary folding and thrust faulting, which accentuated their structural closure. Oil traps along the Lompoc-Purisima trend largely are the result of late Pliocene and Quaternary folding and thrusting. Review of the trap styles of the basin in conjunction with our structural interpretation provides new exploration insights and concepts for the basin. Figure 18 illustrates the relationship between structural trap styles of the Santa Maria basin and our structural interpretation.
The Santa Maria Valley contains the Santa Maria oil field (238.5 million bbl) and the Guadalupe oil field (57.3 million bbl). Both fields are similar and hydrocarbons are trapped along updip pinch-outs in sandstones in the Point Sal and Monterey formations (Figure 15). Some of the dip is due to the south limb of the Point San Luis anticline (Figure 6). Undeforming the late Pliocene and Quaternary anticline shows the presence of a paleohigh during the Miocene and early Pliocene (restoration, Figure 6). As previously discussed, the paleohigh could be the result of hanging-wall folding along the Orcutt normal fault and/or middle Cenozoic uplift associated with the Ynezian orogeny. Onlap of westward directed deep-water sandstone systems onto this paleohigh probably accounts for the pinch-out, and late Pliocene and Quaternary growth of the

Figure 15—Structure contour map and cross section on the top of the Monterey Formation of the Santa Maria Valley oil field (modified from California Division of Oil and Gas, 1984). The oil is trapped in the Monterey Formation below the Sisquoc Formation unconformity and by faults. The trap is interpreted to be related to a paleohigh associated with the Ynezian orogeny or block rotation by movement on the Orcutt normal fault. Contour interval 400 ft. Stratigraphic nomenclature abbreviations as in Figure 9.
Figure 16—Structure contour map and cross section on the top of the Monterey Formation of the Orcutt oil field (modified from California Division of Oil and Gas, 1984). The trap is an anticlinal closure and bounded on the north by the late Miocene and early Pliocene Orcutt normal fault. Oil fields along the Casmalia-Orcutt anticlinal trend are interpreted to be within a paleohigh that preceded late Cenozoic folding and thrusting. Contour interval 500 ft. Stratigraphic nomenclature abbreviations as in Figure 9. Point San Luis anticline accentuated the trap dip. Additional strike closure and intrafiel closure is provided by small north–south-trending Miocene and early Pliocene Orcutt normal faults (Figure 15). Undiscovered oil fields with a similar trap style may be present along the south limb of the offshore continuation of the Point San Luis anticline.

The restoration (Figure 6) also shows the organic-rich Monterey and Point Sal formations buried 2–3 km by the beginning of the late Pliocene under the deepest part of the Santa Maria Valley. Thus, a substantial part of the Monterey and Point Sal formations entered oil maturation depths before significant development of the prominent late Pliocene and Quaternary anticlinal trends. Pliocene initiation of oil migration would explain the greater oil accumulations along trends that include pre-late Pliocene trap styles. Figure 6 shows that an additional 1 km of burial was provided under the Santa Maria Valley by synorogenic deposits derived from the uplift and erosion of the fold and thrust belt. This increased burial placed additional parts of the Monterey and Point Sal formations and marine shales of the Sisquoc Formation into the oil window.

The Casmalia (49.5 million bbl), Orcutt (176.1 million bbl), Four Deer (2.3 million bbl), Cat Canyon (335.0 million bbl), and Zaca (32.5 million bbl) oil fields lie along the Casmalia-Orcutt anticlinal trend. Although the fields lie along the crestal region of the anticlinal trend, none of the fields are simple anticlinal traps. As with the Santa Maria Valley oil fields, cross-cutting Miocene and early Pliocene age normal faults and coeval stratigraphic pinch-outs provide some of the updip and upplunge closure (Figure 16). Unfolding of the late Pliocene and Quaternary anticlinal trend (restoration, Figure 6) shows...
the trend was preceded by a paleohigh that we interpret to be bounded by Miocene and early Pliocene normal faults. The paleohigh was favorably located for the accumulation of migrating hydrocarbons from the adjacent portions of the Santa Maria basin that underwent accelerated subsidence and burial during the late Miocene and early Pliocene (restoration, Figure 6). This favorable trapping situation is supported by the Casmalia-Orcutt anticlinal trend having larger total reserves than the other two oil trends combined; folding of the anticlinal trend accentuated trap closure.

The Zaca oil field (Figure 17) illustrates a trap style that may be important to future exploration efforts in the basin. The field lies along the south limb of the Casmalia-Orcutt anticlinal trend. The trap consists of updip closure by a Miocene and early Pliocene normal fault parallel to the anticlinal trend. The normal fault is down to the south and clearly a barrier to northerward migrating hydrocarbons. As previously discussed, our structural interpretations and detailed mapping of other oil fields (Figures 15–17) (California Division of Oil and Gas, 1984) suggest that much of the thickness changes in the Monterey and Sisquoc formations in the Santa Maria basin are associated with normal faults that predate convergence. Oil fields such as Zaca and intrafield traps in other oil fields show that such normal faults are important early formed hydrocarbon trapping structures. These normal faults now occur in a variety of structural positions along the anticlinal limbs. At Zaca oil field, the original normal fault geometry is preserved through anticlinal growth, but at Orcutt oil field (Figures 9, 16), the Orcutt normal fault has been rotated into a reverse fault geometry by subsequent anticlinal growth. Because these faults can occur in a variety of locations with differing geometry and are mostly concealed by upper Pliocene through Quaternary strata, they probably represent an only partly tested exploration trap style (Figure 18). In addition, the normal faults are early formed traps present throughout much of the migration history, and may lie adjacent to deeper, more generative parts of the Santa Maria basin.

Along the Lompoc-Purisima anticlinal trend are the Lompoc (48.3 million bbl), Jesus Maria (0.5 million bbl), Los Alamos (0.5 million bbl), and Barham Ranch (0.6 million bbl) oil fields (Figure 14). The Lompoc and Barham Ranch oil fields occur along smaller subsidiary folds in the crestal region of the Lompoc-Purisima anticlinal trend. Our structural interpretation suggests these small folds are probably the result of shallow thrust faults unrelated to the deeper, more fundamental Purisima-Solomon thrust. The Los Alamos oil field is a small
structures such as in the Los Alamos oil field.

In our structural interpretation, the only subthrust trend capable of containing significant undiscovered reserves (> 5 million bbl) is in the footwall of the Purisima-Solomon thrust along the north side of the Casimilla-Orcutt anticlinal trend. Along this trend, the Purisima-Solomon thrust steps up across the known reservoir units and there is a sizeable unexplored subthrust area. Potential subthrust traps include folds or fault-trapped homoclines (Figure 18). A partly explored anticlinal trap is indicated from well data in the footwall of the Purisima-Solomon thrust in Figure 9. Exploration of this trend will require deep drilling (> 10000 ft or 3048 m) in an area of complex structure that will be difficult to define with seismic reflection data. In other areas the principal thrusts, Purisima–Solomon and Point San Luis, are too deep to have any subthrust exploration potential. Additional subthrust potential may exist under shallow thrusts unrelated to the principal thrusts of the area; however, trap size probably is small (< 1 million bbl) and may require moderate to deep drilling in complex structures such as in the Los Alamos oil field.

**CONCLUSIONS**

* The fold structures of the Santa Maria, Pismo, and Huasca basins, and southern Coast Ranges are interpreted to be the result of a seismically active, basement-involved, fault and thrust belt. The anticlines are fault-bend and fault-propagation folds associated with thrust ramps that step up from thrust flats and a regional detachment at 11–14 km depth.

* The range front of the San Rafael Mountains is interpreted to be uplifted above a ramp in the Point San Luis blind thrust. The length and continuity of the range front across the northern margin of the Santa Maria basin suggests it is underlain by an important regional fault.

* Total convergence across the southern Coast Ranges from the San Andreas fault to the Santa Lucia Bank is 26.8 km. The convergent structures probably began to develop between 2.0–4.0 Ma and the convergence rate is 6.7–13.4 mm/yr. The total convergence across the onshore western Santa Maria basin is 9.2 km, yielding a convergence rate of 2.3–4.6 mm/yr.

* Abundant compressive earthquakes, a map pattern of broad bands of seismicity, geodetic measurements of present shortening, and folded Quaternary deposits indicate the fold and thrust belt is undergoing active convergence. The ramp parts of these thrusts are the most likely seismogenic sources as evidenced by compressive focal mechanisms and our structural analysis. Most of the thrust faults are blind, presenting a major problem with existing seismic evaluations of the region, which generally have considered only strike-slip and reverse faults with surface expression.

* The historic seismic record of compressive earthquakes in central and southern California and the 15–80 km length of the thrust ramps suggest the faults are capable of generating moderate to large earthquakes (5.0 < MW < 7.5). If the convergence is relatively uniform over the last 2.0–4.0 m.y. and is taken up seismically along the thrust ramps, then our slip rates indicate that moderate to large earthquakes can be expected every 75–299 yr on or near the southern Coast Range cross section (Figure 7) and every 217–870 yr on or near the onshore Santa Maria cross section (Figure 6). These recurrence intervals do not account for areas away from section lines and the regional recurrence interval for moderate to large compressive earthquakes of the entire area is probably more frequent. Additional structural analysis will be required to evaluate the recurrence interval of moderate to large earthquakes for the entire region.

* Cross section restoration shows early formed hydrocarbon trap settings along the Casimilla-Orcutt anticlinal trend and under the Santa Maria Valley and accounts for the major hydrocarbon accumulations along these trends. This analysis also shows that Miocene and early Pliocene normal faults have played an important role in oil maturation and trapping. Two relatively untested hydrocarbon trap styles are present in the Santa Maria basin: concealed normal faults along flanks of major anticlines and the subthrust structures along the north flank of the Casimilla-Orcutt anticlinal trend.

**REFERENCES CITED**


AAPG, 1959, Correlation section across Santa Maria basin from outcrop in Santa Ynez Mountains north to onshore north of Santa Maria River, California: Pacific Section AAPG Published Correlation Sections 12, scales 1:4000 and 1:1000.


California Division of Oil and Gas, 1984, California oil and gas fields, volume II, south, central coastal and offshore California: California Division of Oil and Gas, TR 12, no page numbers listed.

California Division of Oil and Gas, 1986, 72nd annual report of the state oil and gas supervisor: California Department of Conservation Division of Oil and Gas, PR 06, 167 p.


Late Cenozoic Fold and Thrust Belt


