POST-MIOCENE COMPRESSIONAL TECTONICS ALONG THE CENTRAL CALIFORNIA MARGIN

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ABSTRACT

High-resolution, 36-fold seismic reflection data from offshore Santa Maria Basin, northern Santa Barbara Channel, and off Pt. Conception reveal major post-Miocene thrust faulting in offshore central California. These thrusts can be recognized on lines both normal and parallel to the regional structural grain. On lines normal to the grain they are commonly imbricate and curve asymptotically downward to a basal sole thrust. On lines parallel to the grain they appear as a band of nearly horizontal reflectors that truncate tightly-folded strata above the thrust.

The northern Santa Barbara Channel and Pt. Conception area are part of the Transverse Ranges where reverse and thrust faults are common. The offshore Santa Maria Basin, however, is generally regarded as a wrench-style basin. The Hosgri and other major northwest-trending faults within the basin, however, appear to be predominately thrusts rather than strike-slip faults. Detailed mapping of the offshore basin indicates that the overall structural pattern is unlike typical wrench-style tectonics. Folds, for example, have a preferred asymmetry and their axes closely parallel faults rather than being en echelon to them. We conclude that whereas some strike-slip is probable, the folds and faults, as well as the present morphology of the offshore Santa Maria Basin, chiefly reflect post-Miocene northeast-southwest-directed compression. Similar conclusions can be drawn from the onshore Santa Maria Basin on the basis of field relations and well data.

Compressional structures also occur onshore throughout the Coast Ranges and are much more common and perhaps more important than modern literature on this area portrays. This is not surprising because many of the thrusts recognizable in the offshore steepen abruptly and become high-angle reverse faults near the surface. Onshore faults may have a similar character but flattening of these faults at depth is not easily determined on the basis of surface exposures.

Compressional features along the central California margin are consistent with present-day plate motion studies which require that Pacific-North American relative plate motion include (aside from strike-slip) a large component of compression that is normal to the San Andreas fault system. Vector resolution of these plate motions suggest that in central and northern California, 300 km of post-Miocene slip related to opening of the modern Gulf of California can be resolved to about: 200 km of right-slip on the San Andreas fault proper; 60 km of right-slip on northwest-trending faults east and west of the San Andreas; and 40 km of northeast-southwest shortening normal to the San Andreas.

INTRODUCTION

Published geologic mapping from offshore seismic reflection surveys along the California margin has relied heavily upon extrapolation of knowledge from onshore geologic studies. Traditionally, structural and stratigraphic trends have been extended from onshore (where they are considered to be well known) to offshore, where single-channel seismic reflection profiles and scattered well information formerly permitted only tenuous continuations of these trends. In general, the converse has not been true -- that is, offshore studies of the California margin have provided little insight into the geologic complexities onshore. Technological advances in both the collection and processing of marine seismic reflection profiles, however, have greatly improved the quality of these data in recent years. Many of these "state-of-the-art" profiles reveal subsurface structures that previously could only be dimly perceived both offshore and onshore.

The purpose of this paper is to illustrate and discuss structural interpretations of CDP seismic reflection data recently collected by Nekton Inc. in the offshore Santa Maria Basin, off Pt. Conception, and along the northern Santa Barbara Channel (Fig. 1) and to show how these offshore data may provide insight into the onshore post-Miocene structural development of the central California margin. Within these offshore areas we have concentrated on structures that are pertinent to two well-known but somewhat controversial fault systems: the northwest-trending Hosgri fault which extends from San Simeon to south of Pt. Sal off the central California coast, and the east-west North Channel Slope fault which extends along the shelf break from off Santa Barbara to Pt. Conception (Fig. 2).

The seismic reflection data collected along these structures and used in this report consist of high-resolution, deep-penetration (2.5 to 3.0 sec), 36-fold, 400 cu-in, dual-water gun profiles. The water gun source, which generates an acoustic signal by means of implosion rather than explosion, is

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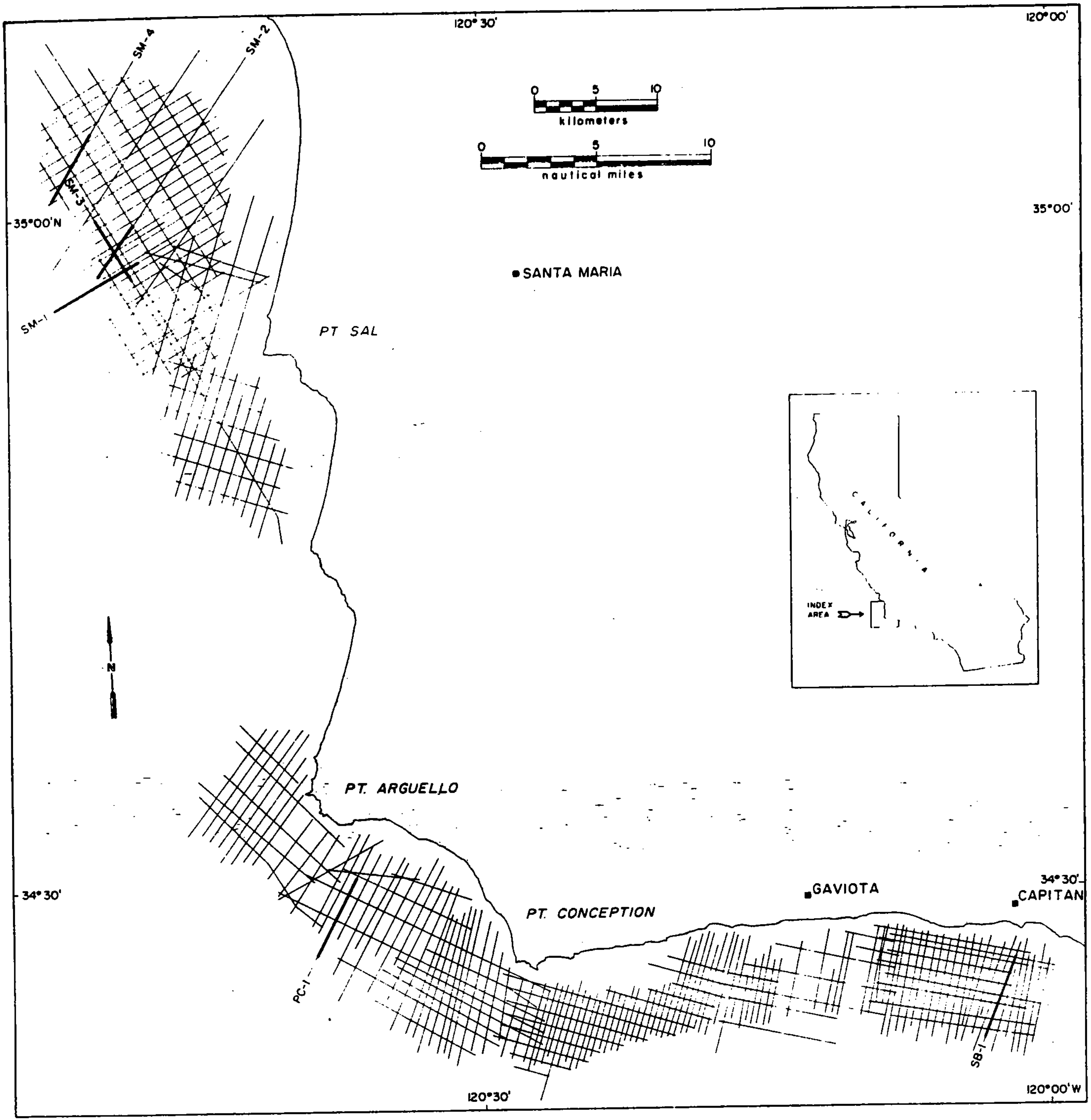


Figure 1. Track-line map of Nekton Inc. surveys across the central California margin. Heavy track lines are profiles illustrated in Figures 3-9.

especially effective in complex shallow shelf regions because 1) it does not produce a bubble pulse and 2) it produces higher frequencies than an air gun yet has an output power comparable to an air gun system.

Based on our interpretation of these reflection profiles, we believe that compressional tectonics in the form of reverse and thrust faults and associated asymmetric folds are important elements of the post-Miocene tectonic history of the central California margin. This appears to be the case not only for the east-west-trending Transverse Ranges but also for many of the major northwest-trending structures within the Southern Coast Ranges. Both the timing and the origin of these compressional structures can be related to North American-Pacific plate motions and the post-Miocene offset history of the San Andreas fault. In addition, we conclude that suggested late Cenozoic right-slip offsets on northwest-trending faults in onshore and offshore central California may be overstated and that late Cenozoic basin morphology in central California may be due largely to compression rather than exclusively to wrench-style tectonics.

SEISMIC REFLECTION DATA

Six interpretive drawings of seismic reflection profiles SB-1, PC-1, SM-1, SM-2, SM-3, and SM-4 reveal structures representative of the central California offshore (Figs. 3-8). Where noted on the sections, the near-top Miocene is based on nearby well ties. The profiles are approximately true scale, however the upper part of the profile has a slight (1:1.1) vertical exaggeration because of lower velocities in the shallower sediment.

Many of the lines indicated on Figure 1 show structures similar to those we have chosen to illustrate. Most of the illustrations and discussion are concentrated in the offshore Santa Maria Basin because the structures we recognize in the northern Santa Barbara Channel and Pt. Conception areas have, in part, already been noted by previous workers (e.g., Yerkes and others, 1980). However, very little seismic data has been available to support these earlier interpretations and, thus, the profiles we illustrate serve as strong corroborative evidence for their conclusions.

Profiles SB-1 and PC-1

Lines SB-1 and PC-1 (Figs. 3, 4) lie within the western Transverse Ranges geomorphic province (Reed, 1933) -- a region where distinctive east-west-trending compressional structures have been well-documented onshore (e.g., Dibblee, 1966; Yerkes and Lee, 1979; Savage and others, 1981; Yeats 1981, 1983). Line SB-1 extends northward across the north Santa Barbara Channel area, about 13 km west of Santa Barbara (Figs. 1, 3). Line PC-1 extends northeastward across the shelf between Pt. Arguello and Pt. Conception (Figs. 1, 4). Offshore well ties indicate that these profiles include reflectors from Oligocene and younger strata.

On both profiles, a series of major north-to-northeast-dipping, high-angle reverse or thrust faults cut the Oligocene and younger section. The most prominent fault along the north side of the Santa Barbara Channel (Fault A on Fig. 3) coincides closely with the shelf break. South of this fault, well ties from the Hondo offshore field indicate that the top of the Monterey Formation is at a depth of about 2700 to 3000 m. North of the fault, numerous well ties from within state lease tracts place the top of the Monterey between 1200 and 1800 m. This fault trends east-west and appears to be continuous from off Santa Barbara (where it coincides closely with the Pitas Point fault), to as far west as Point Conception. Similar interpretations, based chiefly on well data and fault-plane solutions, were presented by the U.S. Geological Survey (1974) and by Yerkes and others (1980). The origin of the north channel slope has been attributed to post-Pliocene uplift along this fault (Yerkes and others, 1980).

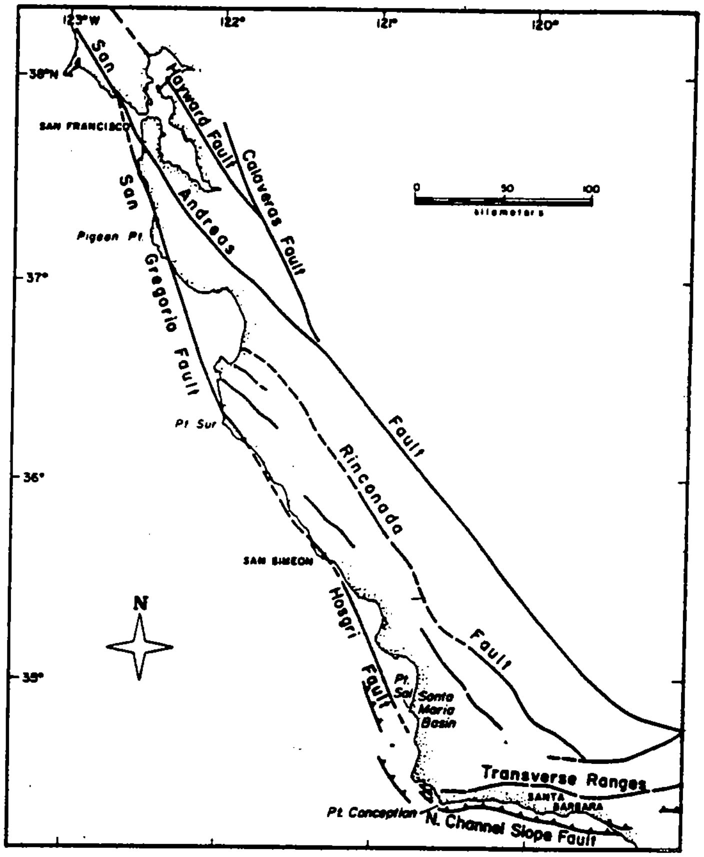


Figure 2. Map of central California showing geographic locations and major faults.

It is noteworthy that numerous thrust and reverse faults, similar to those in the channel, occur between Pt. Arguello and Pt. Conception (Figs. 1, 4). Here faults and folds trend roughly N55°W (e.g., McCulloch and others, 1980; Yerkes and others, 1980). Hence, they are oblique to the east-west trends in the Santa Barbara Channel. Most of the fault-plane solutions within the channel indicate either reverse or combinations of reverse and left-lateral strike-slip faulting (e.g., Yerkes and others, 1980). In the Pt. Conception - Pt. Arguello area, seismograph networks have been too sparse to give well-constrained locations and fault-plane solutions (Gawthrop, 1975; Yerkes and others, 1980). However, because of the consistent northwest trend of faults and folds off Pt. Conception, we suspect that the left-lateral component in the channel produces northeast-southwest-directed compression in the Pt. Conception to Pt. Arguello area.

Many of the low-angle reverse and thrust faults along the north side of the channel and off Pt. Conception steepen abruptly toward the surface and appear to die out in the younger part of the section. However, earthquake seismicity data (Yerkes and Lee, 1979; Yerkes and others, 1980), high uplift rates of coastal marine terraces (Lajoie and others, 1979), and geodetic data (Buchanan-Banks and others, 1978) suggest that movement along many of the east-west faults in the channel is still occurring. Perhaps the offshore faults are active, and the younger more, ductile sediments are being folded and flexed as the deeper sediments are being faulted. Many of the onshore thrust faults are similar in style (e.g. Yeats, 1982). Interestingly, in the offshore most of the faults that reach the seafloor are minor, steeply-dipping normal and reverse faults that appear to be caused by uplift and subsequent instability of the overthrust block. Thus, it is not surprising that investigations that have concentrated on the younger, shallower part of the section either do not support the existence of

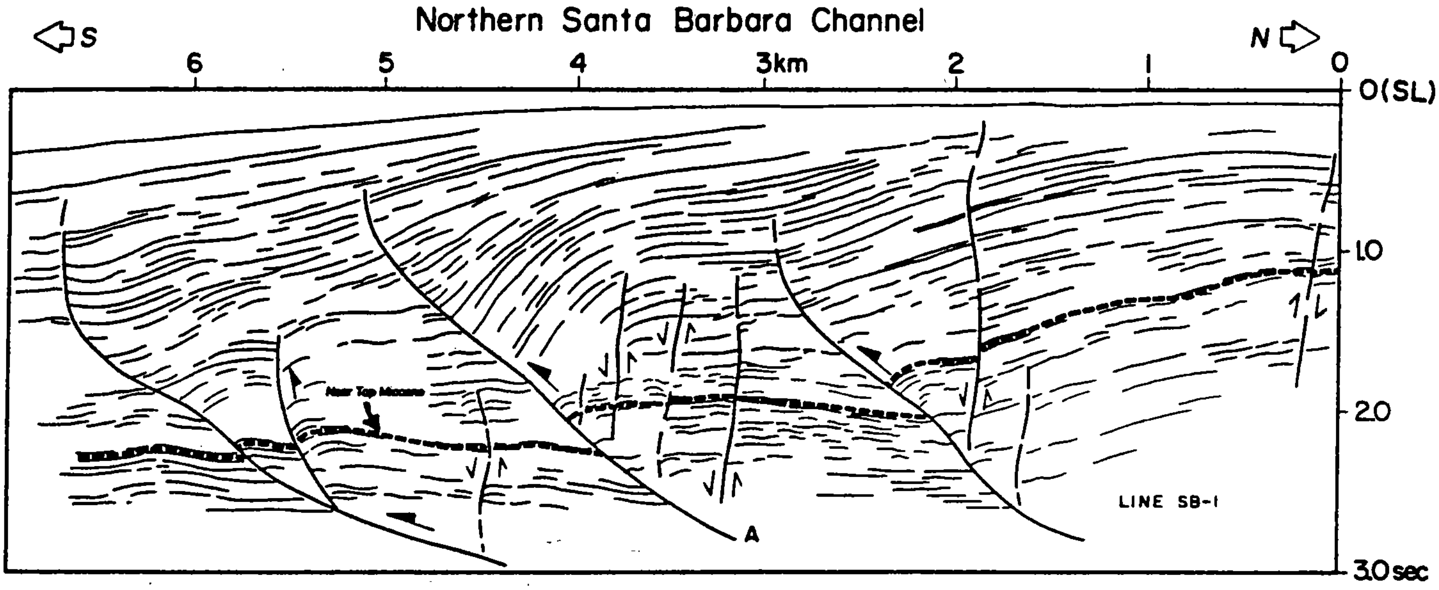


Figure 3. Interpretive line drawing of seismic reflection profile SB-1 across northern Santa Barbara Channel. For location of profile see Figure 1. Fault labeled "A" coincides with North Channel Slope fault of Yerkes and others (1980). Vertical exaggeration negligible.

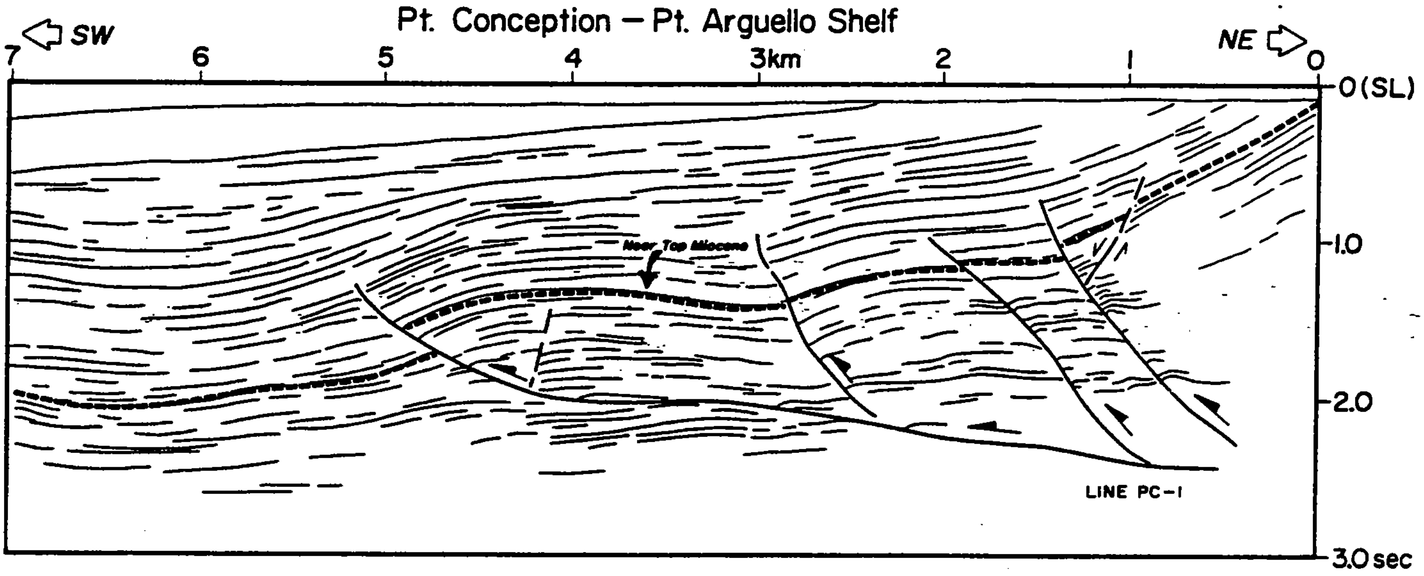


Figure 4. Interpretive line drawing of seismic reflection profile PC-1 across Point Conception - Point Arguello shelf. For location of profile see Figure 1. Vertical exaggeration negligible.

continuous east-west-trending thrust or reverse faults along the north channel slope (Fischer and Simila, 1983) or show a number of steeply dipping near-surface faults above the zone of thrusting (e.g., Luyendyk and others, 1983).

Profiles SM-1, SM-2, SM-3, and SM-4

Lines SM-1 through SM-4 (Figs. 5-8) were selected in order to illustrate structural features along the Hosgri fault zone that bounds the northeastern margin of the offshore Santa Maria Basin (Hoskins and Griffiths, 1971; Wagner, 1974). It is now believed that the Hosgri and the San Gregorio fault to the north (Fig. 2) forms a major (380 km-long) late Cenozoic right-slip fault zone (Silver, 1978). Hall (1975) postulated 80 km of right slip since the late Miocene or early Pliocene on the Hosgri segment; Graham and Dickinson (1978) suggested that the Hosgri is continuous with the San Gregorio and that the entire zone has undergone about 115 km of "probable post-early Miocene right slip". Hamilton and Willingham (1977, 1979) argue that geological and geophysical data limit the amount of offset along the fault zone to less than 20 km since the Miocene.

Lines SM-1, SM-2, and SM-4 extend northeast across the northwest-trending Hosgri fault, whereas line line SM-3 subparallels the Hosgri on the east (Fig. 1; see also Fig. 10). Both the top Sisquoc and near-top Miocene horizons are based on ties to the nearby Oceano well. Vertical offsets of these horizons are based on line ties, reflector correlations, and recognizable unconformities within the section. As noted by Wagner (1974) and as seen on our profiles, the Hosgri fault is a zone of deformation roughly 3 to 5 km wide. The most commonly mapped main trace of the fault in many instances corresponds to a linear zone of disturbed, gas-charged sediment which may be faulted close to the seafloor along some segments of the fault. We have labeled this main trace the "Hosgri Fault" on lines SM-1, SM-2, and SM-4 (Fig. 5, 6 and 8).

A series of imbricate, northeast-dipping thrust and reverse faults make up the 3- to 5-km-wide zone along this segment of the Hosgri fault (Figs. 5, 6 and 8). On a number of these faults, the low-angle fault surfaces are detected directly as a zone of shallow, northeast-dipping reflectors which cross cut the stratigraphic section (e.g., above and below the surface of the seaward-most fault on line SM-2, Fig. 6). Similar, anomalously oriented reflectors are also evident on strike lines, such as SM-3 (Fig. 7), that subparallel the east side of the Hosgri fault. Note that both the upper and lower thrust surfaces depicted on line SM-2 (Fig. 6) match the upper and lower fault surfaces (circled areas) where they cross line SM-3 (Fig. 7). The continuity of reflectors beneath the shallower portions of the thrusts (e.g., at 3-5 km on line SM-2, Fig. 6) indicate that none of the faults that make up this segment of the Hosgri fault zone is vertical at depth as might be expected along a wrench fault.

Folds are often developed above the thrusts. Some are markedly asymmetric and are thrust over relatively flat underlying strata (e.g., at 5-6 km on line SM-1, Figs. 5, 9). The genetic relationship of folds to faulting and strong evidence for the compressive nature of the faults are exemplified by the parallelism of these structures (Fig. 10). Moreover, we have mapped structures throughout the offshore Santa Maria Basin and find that virtually all of the major faults and folds west of the main trace of the Hosgri Fault are parallel or subparallel to one another (see maps by Hoskins and Griffiths, 1971, and McCulloch and others, 1980, for similar interpretations). Major en echelon structures that might be expected from simple shear modeling of wrench faults (e.g., Wilcox and others, 1973) are not present within the offshore Santa Maria Basin west of the main Hosgri fault trace.

Thrust faulting occurs not only along the Hosgri fault zone but throughout the offshore Santa Maria Basin. Payne and others (1979) classified the offshore Lompoc fault as an "eastward-dipping reverse fault which parallels the western flank of a large anticline". On the basis of our seismic data (which has negligible vertical exaggeration), we interpret the offshore Lompoc fault to be a thrust. Other, well-defined northwest-trending thrust faults occur beneath asymmetric folds along the seaward edges of the basin -- as much as 28 km west of the Hosgri trend. Farther west, the Santa Lucia Bank, which bounds the western flank of the Santa Maria Basin, is cut by a number of faults that are between 40 and 60 km west of and roughly parallel to the Hosgri fault zone (McCulloch and others, 1980). Nearly pure thrust motion solutions were determined from two mainshocks of a 1969 series of earthquakes located along the Santa Lucia Bank (Gawthrop. 1977, 1978). Page and others (1979) noted eastward-dipping low-angle faulting in strata as young as Quaternary within the abandoned trench at the base of the continental slope. This paleotrench lies parallel to and 100 km west of the Hosgri fault zone.

Age of Faulting

Initial, mild deformation along the segment of the Hosgri fault zone we have mapped occurred at about the near-top Miocene horizon indicated on Figures 5 and 8. On the basis of ties to the P-060 "Oceano" well (Fig. 10) and paleontologically dated bottom samples along seismic reflection profiles, this horizon is interpreted to occur within the lower part of the Sisquoc Formation. In terms of age, it closely corresponds to the Miocene-Pliocene boundary of the international time scale. It marks a slight angular discordance that can be mapped throughout the offshore Santa Maria Basin. This estimate is in agreement with Hall's (1978, 1981) estimate of initial deformation (post-5 m.y.) along the Hosgri.

Obispo and Tranquillion Volcanics onshore (Turner, 1970) may signal earlier extensional or wrench-faulting along the Hosgri fault zone. However, faulting along the zone cannot have been continuous since emplacement of these volcanics because from the base of the Monterey up to and including the lower part of the Sisquoc (near-top Miocene horizon) the strata are remarkably conformable and show no signs of major deformation during deposition.

Determining the youngest movement along the zone is problematic. A number of studies have cited evidence for Quaternary movement along the zone (e.g., Wagner, 1974; Payne and others, 1979) and seismicity studies (e.g., Gawthrop, 1978) suggest that the zone is still active. On our profiles (Figs. 5 - 8), however, most of the faulting and folding appear to have ceased near the top of the Sisquoc (or by the mid to late Pliocene). Minor faulting may be continuing and may offset the seafloor along the main trace of the zone ("Hosgri Fault" noted on Figs. 5, 6 and 8) but on our profiles we can detect only a disturbed gas zone in the sediment that unconformably overlie the top of the Sisquoc. This gas zone, which at the seafloor forms a narrow band along most of the fault, could easily be interpreted to indicate faulting on shallow-penetration seismic reflection profiles.

COMPRESSIONAL ASPECTS OF THE SAN GREGORIO-HOSGRI FAULT ZONE

We have mapped thrust and reverse faults and associated subparallel fold trends for more than 40 km along the southern segment of the Hosgri fault zone (Fig. 10). Similar compressional structures have been noted off Purisima Pt. at the southern end of the Hosgri (Hamilton and Willingham, 1979), and along the San Gregorio fault, south of Pt. Sur (McCulloch and others, 1980).

As reported by Graham and Dickinson (1978), 85 percent of the 380-km-long San Gregorio - Hosgri fault lies offshore. The remaining 15 percent (60 km) of the zone transects the coastline protuberances near Pigeon Pt., Pt. Sur, and San Simeon (Fig. 2). Marked differences in stratigraphic sequences occur across the fault zones that cut these onshore

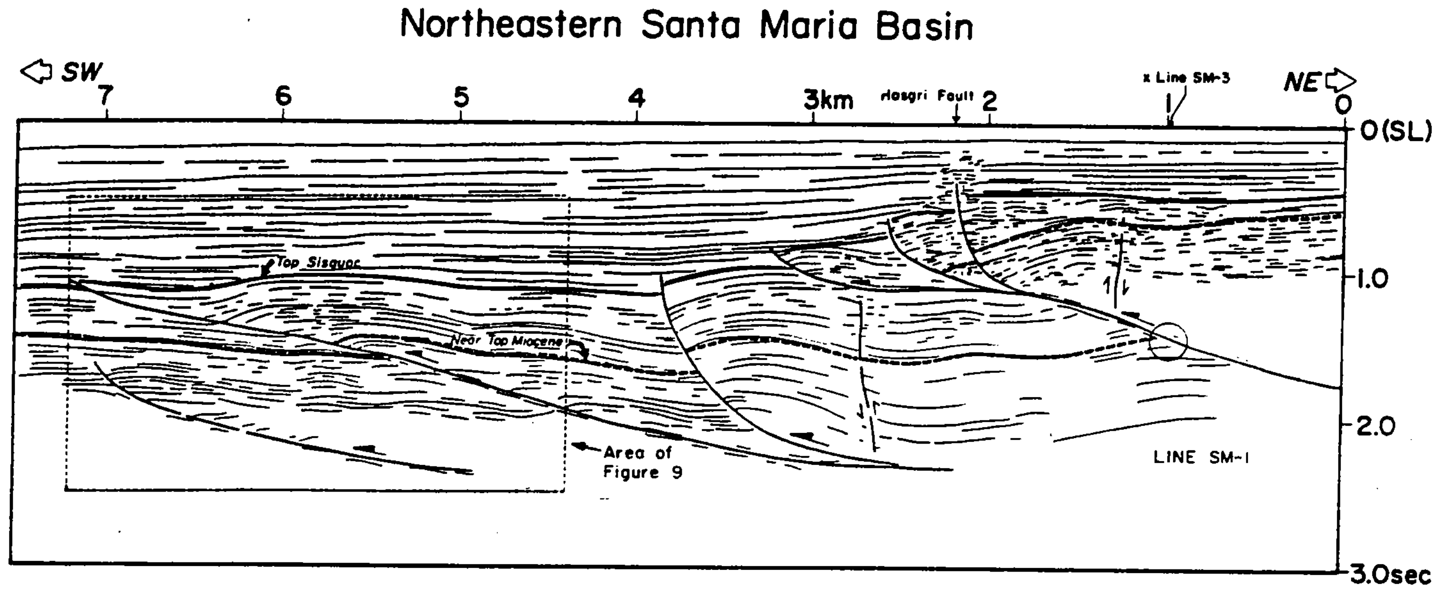


Figure 5. Interpretive line drawing of seismic reflection profile SM-1 across northeastern offshore Santa Maria Basin. For location of profile see Figure 1. "Hosgri Fault" indicates most commonly depicted trace of Hosgri fault zone. Circle indicates structure also exhibited by cross line SM-3 on Figure 7. Vertical exaggeration negligible.

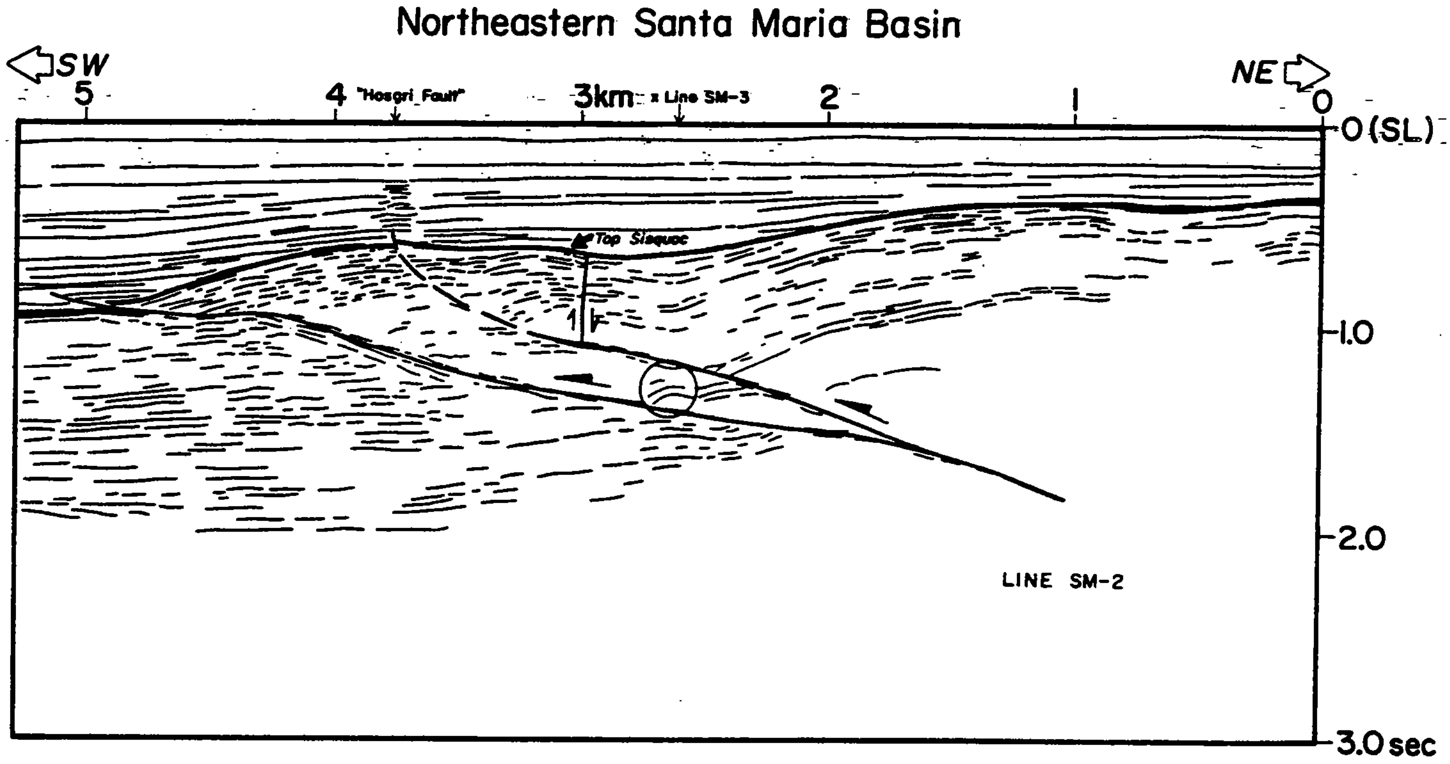


Figure 6. Interpretive line drawing of seismic reflection profile SM-2 across northeastern offshore Santa Maria Basin. For location of profile see Figure 1 and for explanation see Figure 5.

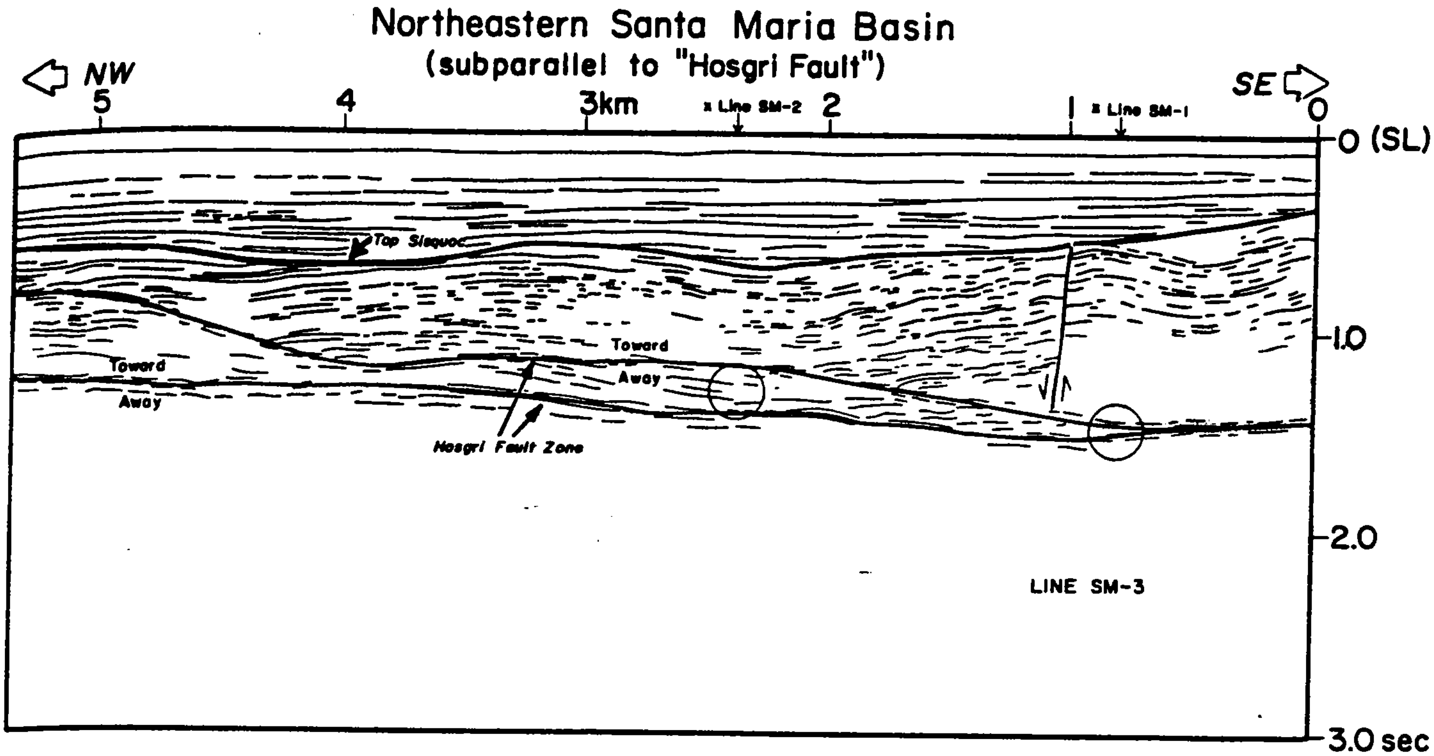


Figure 7. Interpretive line drawing of seismic reflection profile SM-3 east of and subparallel to "Hosgri Fault". For location of profile see Figure 1. Circles indicate cross line structures depicted on profiles SM-1 (Fig. 5) and SM-2 (Fig. 6). Vertical exaggeration negligible.

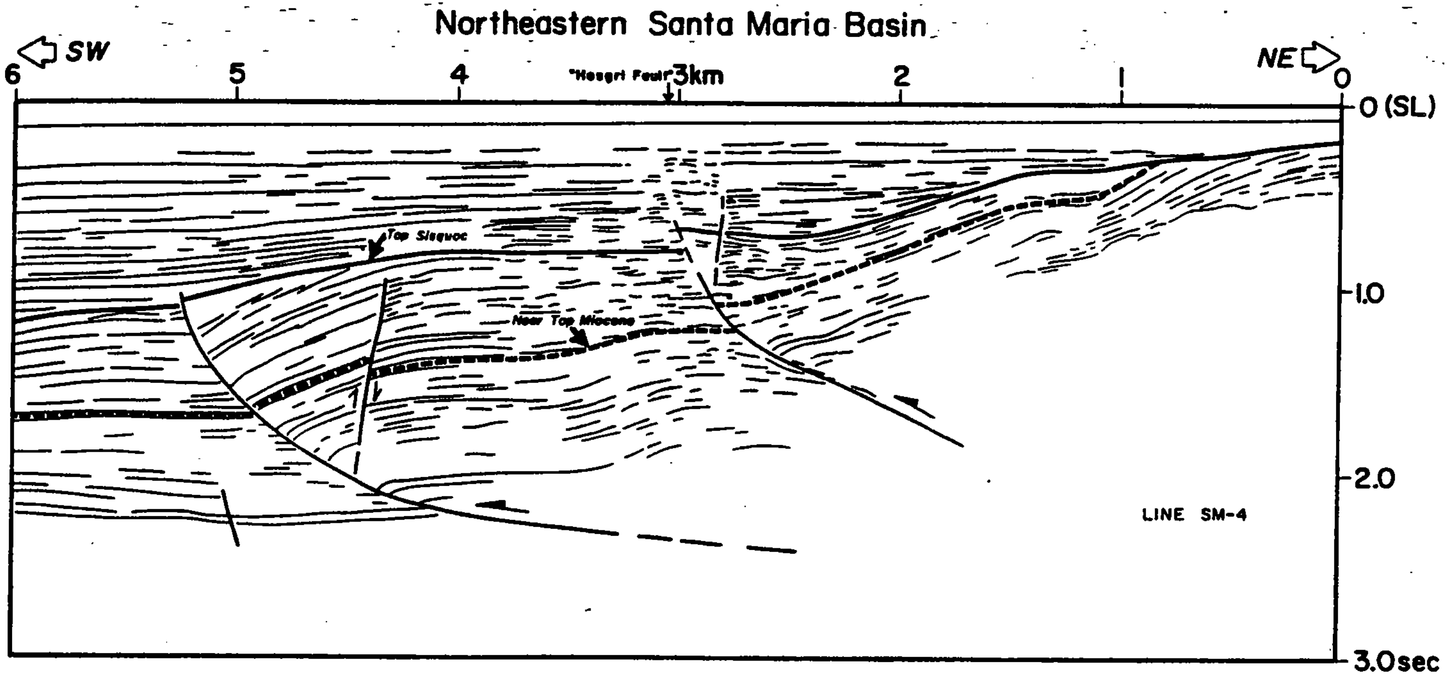


Figure 8. Interpretive line drawing of seismic reflection profile SM-4 across northeastern Santa Maria Basin. For location of profile see Figure 1. Vertical exaggeration negligible.

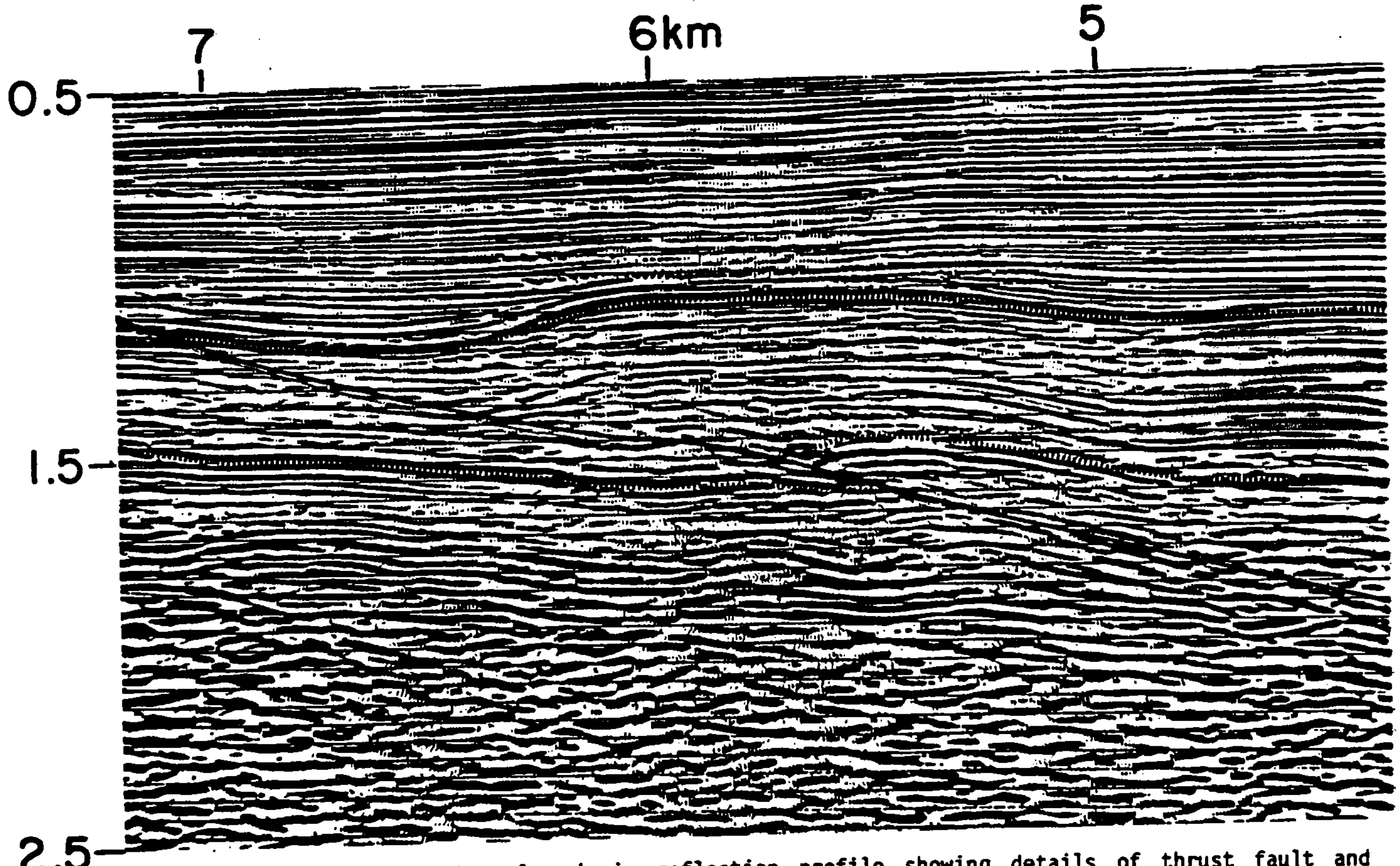
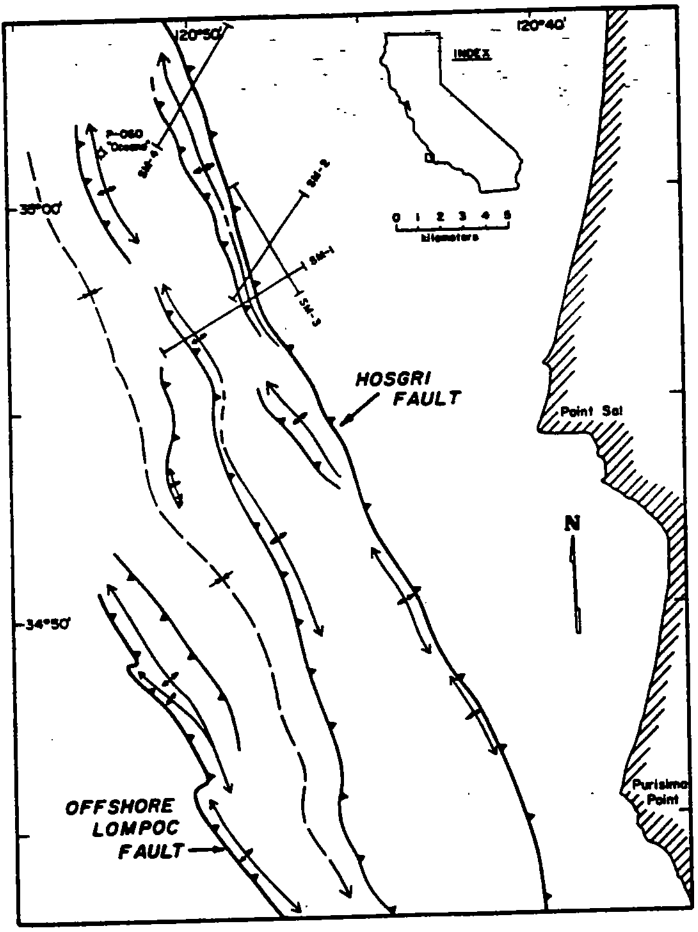


Figure 9. Thirty-six-channel seismic reflection profile showing details of thrust fault and overlying asymmetric fold interpreted on profile SM-1. See Figures 1 and 5 for location. Vertical exaggeration negligible.



localities and, for the most part, these differences form the basis for establishing major right-lateral offsets along the San Gregorio - Hosgri fault zone (Hall, 1975; Graham and Dickinson, 1978; Clark and Brabb, 1978; and Clark and others, this volume). However, in view of our findings and the fact that stratigraphic contrasts are also common along thrust and reverse faults, the following lines of evidence seem worthy of consideration:

1. At Pt. Ano Nuevo (just south of Pigeon Pt. on Fig. 2) an onshore seacliff exposure of a fault trace within the San Gregorio fault zone exhibits a northeast-dipping thrust that juxtaposes Miocene Monterey strata over Pleistocene marine terrace and fluvial deposits (see Fig. 2 of Coppersmith and Griggs, 1978). First-motion solutions for earthquakes near Ano Nuevo Point are compatible with thrusting --other analyses along the San Gregorio zone indicate a combination of right shear and compressional stress (Coppersmith and Griggs, 1978).

2. Farther south near Pt. Sur, the Sur fault zone is believed to represent an onshore segment of the San Gregorio fault. Faults within this zone, such as the Sur, Sur Hill, Serra Hill,

Figure 10. Top Sisquoc structure map of northeastern offshore Santa Maria Basin showing fault and fold axes trends along and west of the main trace of the "Hosgri Fault". Barbs (on upthrown side) indicate reverse or thrust character.

and McWay, however, have long been recognized as major thrust or reverse faults (e.g., Trask, 1926; Reiche, 1936; Taliaferro, 1943a; and Gilbert, 1973). In summarizing the structure of the Sur fault zone, Trask (1926) points out the following: six parallel northwest-trending thrusts a) outcrop over a ten-mile span, b) dip 40° to 70° northeast except the Sur fault which dips less than 30° along most of its course, and c) are all Pliocene in age.

3. Near San Simeon, where the San Gregorio and Hosgri reportedly join, a series of onshore faults that include the San Simeon, Arroyo Laguna, Oceanic, and Arroyo Del Oso make up the San Simeon fault zone. The Arroyo Laguna was interpreted by Taliaferro (1943a) to be a thrust fault and the Arroyo Del Oso is depicted by Hall (1976) as a thrust. Uplifted and faulted Pleistocene terraces are common along the zone (Hall, 1975; Weber, 1983). Earthquake solutions from recent seismicity in the area indicate large thrust components along faults coincident with the northwest-trending Hosgri fault zone (Gawthrop, 1978, Lindh and others, 1980; J. Eaton personal communication, 1984).

4. Onshore in the Pt. Sal area, major thrust faults such as the Pezzoni, Casmalia, and Orcutt exhibit Pliocene or younger activity (Sylvester and Darrow, 1979). Several solutions from recent seismicity studies of earthquakes located approximately along the Hosgri zone just west of Pt. Sal have well-constrained pure-thrust focal mechanisms (Lindh and others, 1980).

COMPRESSION IN THE SOUTHERN COAST RANGES

From San Francisco south to the Transverse Ranges, the Southern Coast Ranges consist of a number of northwest-trending ranges (e.g., the Santa Cruz, Diablo, Santa Lucia, Gabilan, La Panza, Caliente, Temblor, San Rafael, and Sierra Madre ranges) and intervening or adjacent basins (e.g., Santa Clara, Salinas, Lockwood, Huasna, Santa Maria, and Cuyama). For more than half a century, California geologists have been impressed by the amount and recency of deformation that has formed these major uplifts and depressions (e.g., Reed, 1933; Reed and Hollister, 1936; Taliaferro, 1943a; Christensen, 1965; Page, 1966, 1977, 1981; Dibblee, 1976). Although their interpretations concerning tectonic development differ broadly, many of the observations of these and other notable geologists who have studied the Southern Coast Ranges are similar. These observations are that: 1) marked regional tectonism that formed these individual ranges originated in the Pliocene or early Pleistocene and culminated in the Quaternary; 2) the trends of the ranges and basins, as well as the majority of fault traces and fold axes, approximately parallel (within 10° or less) the strike of the San Andreas fault (see Page, 1966, Fig. 10, 1981, Fig. 13-16; Dibblee, 1976, Fig. 20); and 3) on a regional scale many of these structures reflect severe compression and crustal shortening in a direction normal to their trends and to the strike of the San Andreas fault.

There is general agreement that several major faults in the Southern Coast Ranges have a significant strike-slip component; we also believe there is evidence that many of the northwest-trending faults in the Southern Coast Ranges are reverse or thrust faults (Fig. 11, Table 1). In the following paragraphs we summarize some of the evidence that has been presented for compression and crustal shortening along these and other prominent structures within the Southern Coast Ranges.

Region I

The majority of faults in the northern Santa Lucia Range (Region I, Fig. 11) are post-early Pliocene, northeast-dipping reverse faults (Trask, 1926; Reiche, 1936; Taliaferro, 1943a; Compton, 1966; Dibblee, 1976, 1979). Several, such as the Tularcitos and Chucagua, dip to the southwest (Dibblee, 1976) and some, such as the Sur fault, are shallow-dipping thrust faults (Trask, 1926). In perhaps the most detailed structural study ever made in the northern Santa Lucia Range, Compton (1966) concluded that 1) the numerous, predominately northeast-dipping reverse faults in the range are a result of Pliocene-Pleistocene deformation; 2) maximum compressive stress as well as crustal shortening of about 12 percent occurred in a direction roughly normal to the N40°W-trend of the ranges; 3) faults tend to parallel folds, indicating that they are genetically related; and 4) crustal shortening and compressive uplift of the range may have been accomplished by northeast-to-southwest flowage under the crust.

The nature and history of major faults that bound the eastern flank of the ranges (e.g., King City and Reliz faults) are imprecisely known because they are extensively buried by alluvial fan deposits. Nevertheless, major vertical uplift along these faults is clearly evident and may be as great as 3000 m or more (Dibblee, 1976). Although Dibblee (1976) has suggested that the King City and Reliz faults are part of the Rinconada fault (which he interprets to be a major right-lateral system), others (e.g., Schombel, 1943; Taliaferro, 1943a; Kilkenny, 1948; and Gribi, 1979) interpret the King City - Reliz fault to be a southwest-dipping thrust or reverse fault. Where it is well exposed on the west flank of Reliz Canyon and on the north bank of the Arroyo Seco, the Reliz fault dips 70° southwest (Dibblee, 1976). As noted by Gribi (1963, 1979) and Durham (1965), the well-known Los Lobos thrust (LL in Region II on Fig. 11) may be a more easterly expression of the northeast-southwest compression that has occurred within the Santa Lucias and along the King City - Reliz fault zone.

Region II

In the Lockwood Valley, just southeast of the Junipero Serra uplift studied by Compton (1966), several local thrusts bound the San Antonio hills (SA on Fig. 11) and show evidence of late Quaternary movement (Dibblee, 1979). Within the valley, the Jolon fault may be a northeast-dipping thrust (Dibblee, 1979), and along the southwestern margin of the valley, the Bee Rock fault (BR on Fig. 11) is a well-documented northeast-dipping thrust (Durham, 1974; Dibblee, 1976). It is noteworthy that Durham (1974) argues that these structures have resulted from right-lateral offset along the Jolon-Rinconada fault zone, yet he concedes that the structures are more compatible with northeast-

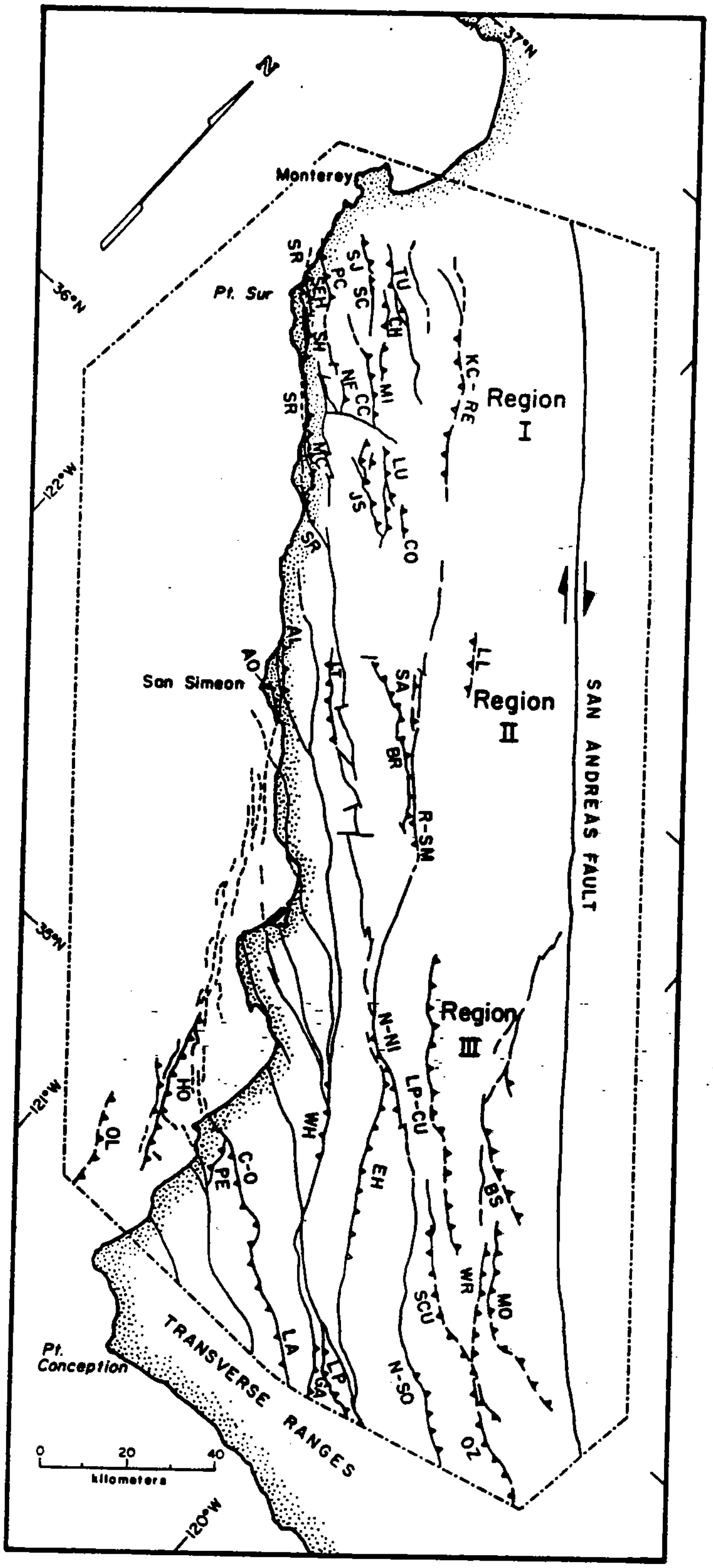


Figure 11. Map of Southern Coast Ranges extending from Monterey south to the Transverse Ranges, showing major northwest-trending faults west of the San Andreas fault that have undergone Pliocene and younger movement (see text). Barbs (upthrown side of faults) indicate reverse or thrust type faulting. Open barbs indicate lower degree of certainty.

southwest crustal shortening than with right-lateral shear. Other Pliocene-Pleistocene thrust or reverse faults in the area include the San Marcos segment of Dibblee's (1976) Rinconada fault zone (R-SM on Fig. 11) and possibly the Espinosa fault. Taliaferro (1943a) referred to the San Marcos fault as a thrust zone and Dibblee (1976) noted that the fault dips 50° southwest where it is well exposed along San Marcos Creek.

West of the Lockwood Valley in the southern Santa Lucias, the Las Tablas fault is believed to be a Pliocene-Pleistocene thrust (Taliaferro, 1943a). Within the same region, a number of faults with possible reverse movement (Taliaferro, 1943a) make up the Nacimiento fault zone. Page (1970) speculated that the Nacimiento fault zone may have undergone reactivated reverse movement in Pliocene or Pleistocene time.

As previously mentioned, the Arroyo Laguna and Arroyo Del Oso faults along the coast near San Simeon (AL and AO on Fig. 11) are considered to be young thrusts.

Region III

Further south, in Region III (Fig. 11), major northeast- and southwest-dipping thrust fault are well documented from both surface and subsurface data. These include the La Panza faults that bounds the western flank of the La Panza Range (Reed and Hollister, 1936; Dibblee, 1976), the well-known Morales, Whiterock, and South Cuyama faults that bound the Cuyama Basin (e.g., Reed and Hollister, 1936; Baldwin, 1971; Vedder, 1973), and the Ozena thrust fault that bounds the southeast flank of the Sierra Madre range (Fritsche, 1972; Dibblee, 1976). All of these faults exhibit substantial post-Miocene horizontal displacement.

West of the San Rafael Range, the East and West Huasna faults (EH & WH on Fig. 11) that bound the respective flanks of the Huasna Basin were considered by Taliaferro (1943b) to be high-angle reverse faults developed in the late Pliocene. Hill (1954) and Hall (1981) favor strike-slip along these faults, but in a detailed study of the area Johnson and Page (1976) conclude that the regional stress that created the Huasna syncline was one of maximum compression in a southwest-northeast direction and that this compression was approximately normal to the traces of the large faults in the area. The Little Pine fault (LP on Fig. 11), which is on trend with the Huasna Basin, is clearly a northeast-dipping thrust (Dibblee, 1966; Hall, 1981).

Within the onshore Santa Maria Basin, several southwest-dipping thrusts, such as the Pezzoni, Casmalia-Orcutt, and Los Alamos (PE, C-O and LA on Fig. 11), are well known (e.g., Woodring and Bramlette, 1950; Krammes and others, 1959; Sylvester and Darrow, 1979). It is not widely known, however, that detailed subsurface studies within the basin indicate that northwest-trending thrust faults are prevalent throughout the basin. With the possible exception of Guadalupe, nearly every field in the onshore Santa Maria Basin is underlain or cut by thrust faults. Folds, such as those that form Casmalia, Orcutt, Four Deer, Los Alamos, and Zaca fields, are all genetically related to and underlain

Region	Fault Symbol	Fault Name	Reference
I	SR	Sur	Trask, 1926; Reiche, 1936; Taliaferro, 1943a; Compton, 1966; Gilbert, 1973; Dibblee, 1976
	SH	Sur Hill	Trask, 1926; Gilbert 1973
	SEH	Serra Hill	Trask, 1926; Gilbert 1973
	MC	Mcway	Reiche, 1936
	PC	Palo Colorado	Trask, 1926
	NF	North Fork	Trask, 1926; Reiche, 1936
	CC	Church Creek	Reiche, 1936; Dickinson, 1959; Graham, 1976, 1978
	SJ	San Jose	Trask, 1926
	SC	San Clemente	Trask, 1926
	CH	Chucagua	Dibblee, 1976
	MI	Miller Creek	Dibblee, 1976; Graham, 1976, 1978
	TU	Tularicitos	Dibblee, 1976
	JS	Junipero Serra	Compton, 1966; Dibblee, 1976, 1979
	LU	Lucia	Compton, 1966; Dibblee, 1976, 1979
	CO	Coleman	Compton, 1966; Dibblee, 1976, 1979
	KC-RE	King City-Reliz	Schombel, 1943; Taliaferro, 1943a; Kilkenny, 1948; Dibblee, 1976
II	AO	Arroyo del Oso	Hall, 1975*, 1976
	AL	Arroyo Laguna	Taliaferro, 1943a; Hall, 1975*
	LT	Las Tablas	Taliaferro, 1943a, 1944
	BR	Bee Rock	Durham, 1974; Dibblee, 1976
	SA	San Antonio	Compton, 1966; Durham, 1974; Dibblee, 1976, 1979
	LL	Los Lobos	Colvin, 1963; Gribi, 1963, 1979; Durham, 1974; Dibblee, 1976
III	R-SM	Rinconada-San Marcos Segment	Taliaferro, 1943a; Kilkenny, 1948; Dibblee, 1976
	OL	Offshore Lompoc	Payne and others, 1979; this report
	HO	Hosgri	This report
	PE	Pezzoni	Woodring and Bramlette, 1950; Sylvester and Darrow, 1979; Hall, 1981, 1982
	C-O	Casmalia-Orcutt	Woodring and Bramlette, 1950; Sylvester and Darrow, 1979; Krammes and others, 1959; Hall, 1981, 1982
	LA	Los Alamos	Woodring and Bramlette, 1950; Sylvester and Darrow, 1979; Guptill, 1982
	WH	West Huasna	Taliaferro, 1943b; Hall and Corbato, 1967*; Hall, 1975*
	EH	East Huasna	Taliaferro, 1943b; Hall and Corbato, 1967*
	GA	Garey	Hall, 1981
	LP	Little Pine	Hill, 1954; Dibblee, 1966, 1976; Hall, 1981
	N-NI	Nacimiento-Nipomo Segment	Hall and Corbato, 1967; Page, 1970
	N-SO	Nacimiento-Southern Segment	Vedder and Brown, 1968; Dibblee, 1976
	LP-CU	La Panza - Cuyama	Reed and Hollister, 1936; Dibblee, 1976
	SCU	South Cuyama	Reed and Hollister, 1936; Zulberti, 1954; Hill and others, 1958; Baldwin, 1971; Vedder, 1973; Dibblee, 1976
	BS	Big Spring	Dibblee, 1976
	WR	White Rock	Reed and Hollister, 1936; Eaton, 1943; Eckis, 1952; Hill and others, 1958; Baldwin, 1971; Vedder, 1973
	OZ	Ozena	Fritsche, 1972; Vedder, 1973; Dibblee, 1976
	MO	Morales	Eaton, 1943; Hill and others, 1958; Vedder, 1973; Baldwin, 1971; Dibblee, 1976

Table 1. References to interpretations of faults shown on Figure 11. Asterisk indicates age documentation only.

by southwest-dipping thrust faults, whereas those that form the Lompoc, Barnham Ranch, and parts of Clark Avenue fields are underlain by northeast-dipping thrusts (J.K. Crouch, unpublished data; Katherman, 1983). In a manner somewhat similar to Sylvester and Darrow (1979), we interpret the southwest-dipping thrusts that bound the Casmalia, Orcutt, and Los Alamos fields to be one continuous fault (C-O and LA on Fig. 11).

Other Evidence

Other lines of evidence also suggest that northeast-southwest compression and crustal shortening are major elements of the post-late Miocene structural development of the Southern Coast Ranges. Foremost is the predominant N40°-50°W trend of Plio-Pleistocene fold axes, basins, and uplifted ranges (e.g., Page, 1966, 1981; Burford, 1967; and Gawthrop, 1978). As Page (1966, 1981) aptly points out, these trends are in agreement with the direction of maximum shortening indicated by Pliocene and younger reverse and thrust faults throughout the ranges. These trends also agree with Burford's (1965, 1967) analyses of present-day strain across two transects of the Southern Coast Ranges in which he concludes that maximum crustal shortening in approximately a N35°E direction has dominated the pattern of crustal movement over the 20-year period from 1932-1951.

Studies of both historic and modern earthquakes in the Southern Coast Ranges commonly indicate thrust and reverse type faulting as well as strike slip (Gawthrop, 1977, 1978; Coppersmith and Griggs, 1978; Savage and Prescott, 1978; Lindh and others, 1980). In fact, Gawthrop (1977, 1978) found that out of 31 events in the central California coastal region, there were approximately an equal number of strike-slip and thrust events. On the basis of his studies, he concluded that "focal mechanisms throughout the region suggest that the driving motion is not parallel to the San Andreas fault or the strike of the faults to the west, but has a component normal to these faults, resulting in some thrust faulting and folding."

Tectonic Framework and Relative Plate Motions

In the context of modern-day tectonics, several aspects of the compressional structures we have summarized are especially noteworthy. First, with regard to the plate reconstructions deduced by Atwater (1970) and Atwater and Molnar (1973), the compressional features of the Southern Coast Ranges developed after the cessation of subduction of the Farallon plate and after the northwestward passage of the Mendocino triple junction. With respect to the Southern Coast Ranges, passage of the Mendocino triple junction and cessation of subduction occurred at approximately 28 m.y. B.P. off Pt. Sal, 24 m.y. B.P. off Point Sur, and 20 m.y. B.P. off San Francisco (see Graham, 1978, Fig. 1; Dickinson and Snyder, 1979, Fig. 8). Thus, post-Miocene compressional structures within the Southern Coast Ranges could not have been the result of subduction of oceanic lithosphere beneath the margin.

Secondly, the development of the Southern Coast Ranges occurred after the opening of the modern Gulf of California (now set by Curray and Moore, this volume at 5.5 m.y. B.P.), and contemporaneously with right-lateral motion along the San Andreas fault. Thus, northeast-southwest-directed compression within the Southern Coast Ranges has been occurring during a transform tectonic regime.

Finally, the trends of many of the reverse and thrust faults as well as the folds, ranges, and basins within the Southern Coast Ranges are not in harmony with the popular notion of a broad transform regime (Atwater, 1970). Simple shear models (e.g., Wilcox and others, 1973) indicate that these compressional structures should lie at an angle of approximately 30° to the wrench trend; instead many are generally parallel to the trend of the San Andreas fault.

In order to resolve these apparent discrepencies between expected trends of transform structures and actual trends of compressional structures, we combined plate-motion studies and outcrop geology to better understand the tectonics responsible for central California structures. Post-late Miocene relative motion between the North American and Pacific plates can be determined from instantaneous plate motions over the last few million years and from the amount of opening of the Gulf of California. The relative NA-PAC plate motions of 56±3 mm/yr in a N35°W±2° direction (Minster and Jordan, 1978; Jordan and Minster, this volume) yield a total right-lateral offset of about 308 km in the last 5.5 m.y. This agrees closely with the 300 km estimate of opening of the Gulf of California (Curray and others, 1982; Moore and Curray, 1982; Curray and Moore, this volume). Because this relative plate motion is not parallel to the San Andreas fault (Jordan and Minster, this volume) and exceeds the motion along the San Andreas fault, contributions from additional structures are required in order to resolve the overall plate motion. These contributions include opening of the Basin and Range, motion along faults subparallel to the San Andreas fault, and convergence along the California margin.

The motion along the San Andreas fault has been calculated from several data bases. Thatcher (1979) and Hall and Sieh (1977) have determined post-Miocene rates of 33-45 mm/yr and 37±4 mm/yr, respectively. Huffman (1972) demonstrated 234±8 km of displacement of upper Miocene rocks in central California and Dickinson and others (1972) estimated that lower Pliocene rocks were offset by 160 to 200 km. In Figure 12, we have used 37 mm/yr (yielding 204 km of displacement in the last 5.5 m.y.) of post-Miocene slip on the San Andreas as a number compatible to all the measurements. The greatest variability in motion vectors occurs with the uncertainty involved in the opening of the Basin and Range. This motion (Fig. 12) has been estimated to be 6±4 mm/yr (Thompson and Burke, 1973) with an azimuth of N60°W±25° (Zoback and Zoback, 1980).

As shown on Figure 12, the combined motion of Basin and Range opening and slip on the San Andreas fault does not resolve all of the motion between the Pacific and North American plates; there remains significant motion in a northern or northeastern direction that needs to be taken into account. We have split this residual motion into vectors that are parallel to (strike-slip of Fig. 12) and normal to (convergence of Fig. 12) the trend of the San Andreas fault. We then calculated a range of values for these vectors required by the variability in Basin and Range measurements. The amount of post-Miocene (0-5.5 m.y.) convergence ranges from 28 to

72 km, with companion strike-slip motion of 45 to 68 km. Slightly larger strike-slip offset can be calculated by optimizing the choice of vector solutions in Figure 12.

Determinations of the amount of apparent post-Miocene shortening along the central California margin provides a rough check on our convergence calculation. Compton (1966) determined that basement rocks in the Santa Lucia Range have undergone an average shortening of 12 percent in a direction approximately normal to the range. Fritsche (1972) calculated an average shortening of 22 percent in Miocene rocks along the Ozena and related faults in the Sierra Madre Range. From preliminary studies we have estimated the amount of shortening across the offshore Santa Maria Basin to be roughly 15 to 20 percent. The average of these three estimates of shortening is about 17 percent in a N45° E direction, or roughly normal to the trend of the San Andreas fault. The width of the central California margin over which we infer shortening is taking place (from the base of the continental slope to the east side of the Temblor Range) is about 200 km. An estimate of northeast-southwest shortening is then 200 km x 17% or 34 km. This estimate should be considered a minimum because the amount of shortening is most likely greatest along major northwest-trending fault zones rather than within intervening basins and ranges. Note that this estimate agrees closely with our minimum estimate of shortening based on residual plate motions (Fig. 12).

TECTONIC IMPLICATIONS

Our seismic reflection data along the central California margin reveal a number of major offshore faults that change from high-angle reverse faults in the upper part of the section to low-angle thrust faults at depth. On the basis of these data and the evidence summarized in the previous sections, we infer that many of the post-Miocene high-angle reverse faults within the Southern Coast Ranges (Fig. 11) also flatten at depth and that northeast-southwest crustal shortening along this part of the California margin is far greater than is generally believed. If this is true, then it is plausible that the Southern Coast Ranges and the adjacent offshore continental margin may rest on a horizontal detachment surface or decollement.

Decollement Model

The detachment surface we envision is diagramatically portrayed on Figure 13. In general, it coincides with the focal depth limit of earthquakes (including those on the San Andreas) and the top of a high-velocity layer (6.8 km/sec) in the Coast Ranges, both of which range from about 12 to 15 km in depth (Hill, 1978, and references therein). We also infer that this zone represents the top of an intermediate crustal layer of oceanic character that extends down to the Moho. Depth to the Moho (23 km) is generalized from Healy (1963) and the thickness of the oceanic? layer is based on typical oceanic crustal thickness of 10 km. The top of this oceanic crustal layer may, in part, be serpentinized and would provide a well-suited aseismic glide surface at the zone of detachment. The model we suggest is similar to Yeats' (1981) flake-tectonic hypothesis for the Transverse Ranges and the model

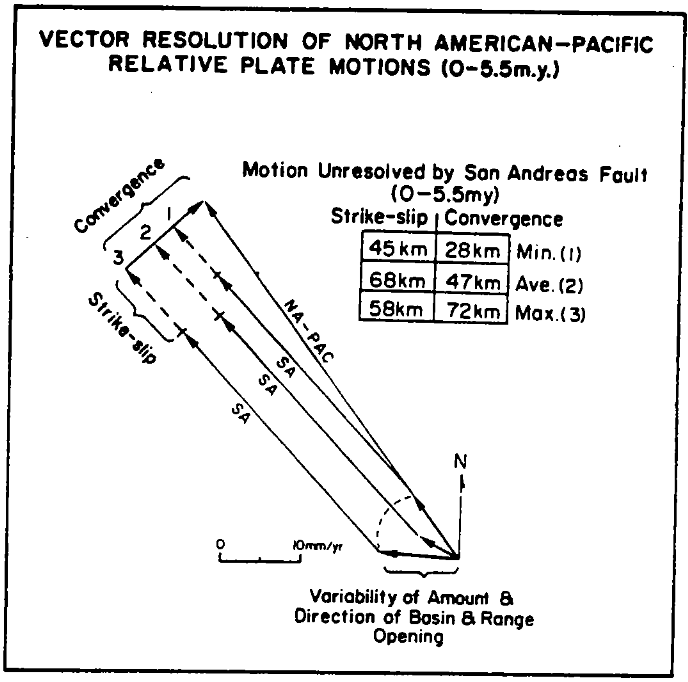


Figure 12. Vector resolution of North American-Pacific relative plate motions from 5.5 m.y. to present, showing estimates of residual strike slip and convergence not accounted for by Basin and Range opening and slip on the San Andreas fault. Assumptions: 1) 308-km opening in the Gulf of California (5.5 m.y. @ 56 mm/yr); 2) 204-km right slip on San Andreas (5.5 m.y. @ 37 mm/yr). See text for discussion.

envisioned by Compton (1966), who argued that the structural relationships in the Santa Lucia Range suggest northeast-to-southwest flowage under the crust.

Within the framework of this model, northeast-southwest crustal shortening is taken up by southwest- and northeast-dipping reverse and thrust faults that extend upward from the zone of detachment. Note that on Figure 13 we also show the zone of detachment east of the San Andreas proper. This is to account for reverse and thrust faults that subparallel the San Andreas on the east (Hudson and White, 1941; Wentworth and others, 1983) and the possibility that the detachment zone as well as the Pacific-North American plate boundary continues east of the San Andreas fault (Hadley and Kanamori, 1977, Yeats, 1981).

Some of the east-west-trending sinistral faults that cut across the Transverse Ranges may connect with northwest-trending faults in the Southern Coast Ranges. For example, the southern end of the Hosgri fault may join with the sinistral Santa Ynez River fault of Sylvester and Darrow (1979). Left-lateral offset along this fault would be accommodated by the thrust faulting and folding we recognize along the Hosgri fault zone. A similar example is the western end of the Big Pine fault where it becomes oblique-left-slip and merges with the northwest-trending Hildreth-Camuesa fault system (Vedder and others, 1967). These examples may explain why major northwest-trending fault zones such as the Hosgri and Nacimiento do not cut the east-west trend of the Transverse Ranges. They also offer an alternative to the rotational block model of Luyendyk and others

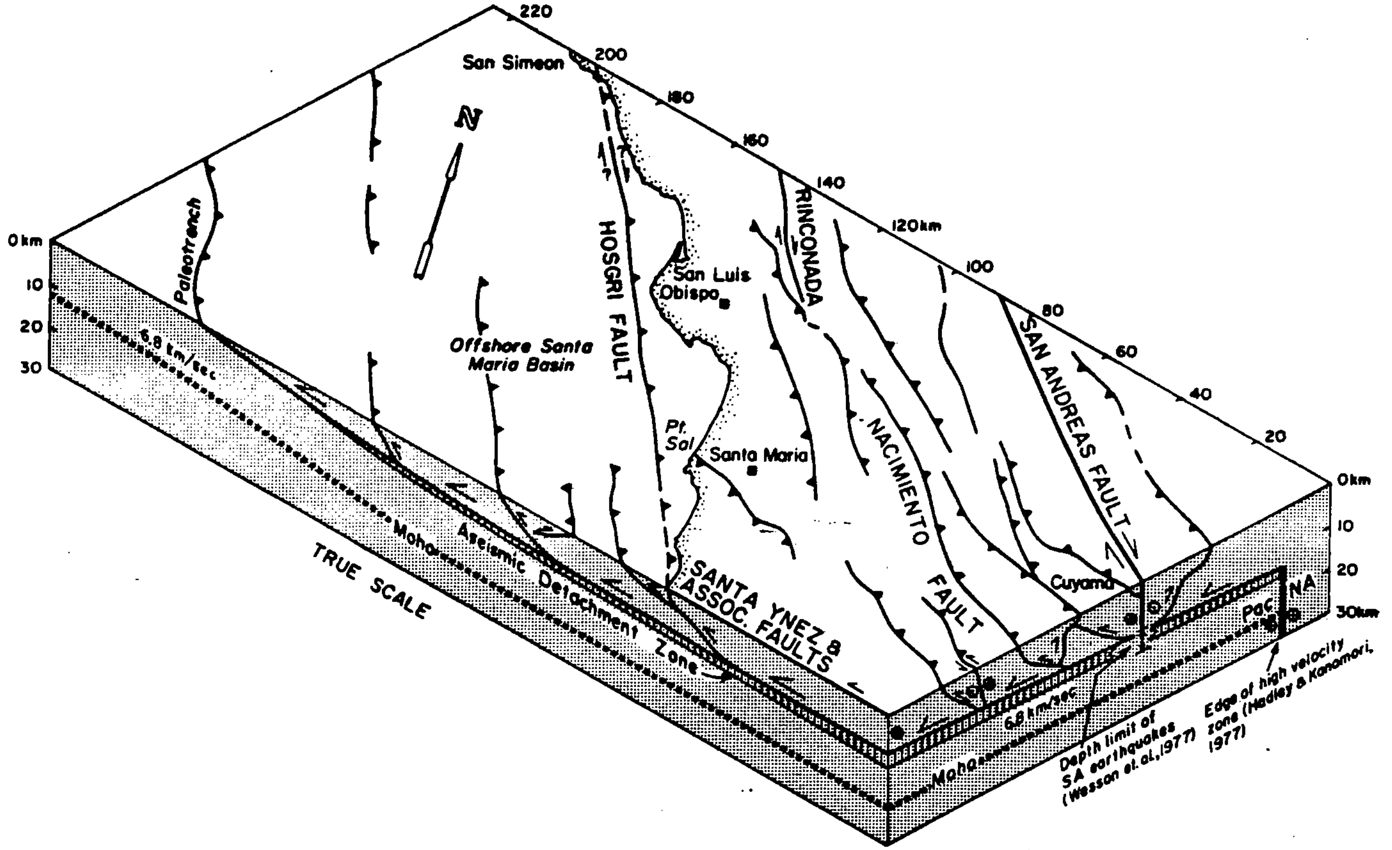


Figure 13. Block diagram illustrating inferred upper crust detachment of the central California margin due to northeast-southwest compression. Santa Ynez and associated faults are left-lateral and follow the westerward front edge of the block. The San Andreas fault is interpreted to be west of the Pacific-North American plate boundary. See text for discussion.

(1980) which requires that terminated, northwest-trending faults such as the Hosgri and Nacimiento undergo major right-slip displacement.

Post-Miocene Basin Development

It is now generally believed that the initiation and continuing development of Neogene basins that lie west of the San Andreas fault in California are directly related to right-lateral shear (e.g., Crowell, 1974; Dibblee, 1976; Blake and others, 1978; Hall, 1978, 1981; Dickinson, 1981; and many others). While we agree that right-lateral motion has probably played an important part in the history of these Neogene basins, we question whether or not it is the only mechanism responsible for basin development. For example, we interpret the post-Miocene development of the offshore Santa Maria Basin to be largely compressional. If ongoing right-lateral shear has played a dominant role, why are the pliant strata within this basin not arranged in a pattern of en echelon folds? The same question applies to the onshore Santa Maria, Huasna, and southwestern Cuyama Basins and, perhaps, to many of the other onshore and offshore basins along the central California margin.

Petroleum Traps Associated with Convergence

Substantial post-Miocene crustal shortening along the central California margin may have developed a number of subtle petroleum traps above and below thrust and reverse faults. A good example is the Orcutt field in the onshore Santa Maria Basin. This field, which is formed by an asymmetric anticline developed above the Orcutt thrust fault, was discovered in the early 1900s. Production is mainly from the Monterey Formation and oil gravities generally range from 15° to 20° API. In just the past few years several new Monterey oil discoveries have been made in deeply buried folds developed beneath the thrust. Oil gravities from these subthrust traps are generally at least twice the gravity of oil normally found in the Santa Maria Basin. We suspect that a significant number of other subthrust traps and structurally complicated overthrust traps still remain to be discovered in offshore and onshore California.

CONCLUSIONS

1. Many of the major faults along the offshore central California margin are either thrust faults or high-angle reverse faults that flatten and become thrust faults at depth. Along the northern Santa Barbara Channel these faults generally trend east-west, dip to the north, and probably have left-lateral as well as dip-slip motion (e.g., Yerkes and others, 1980). Along the Pt. Conception - Pt. Arguello shelf, thrust and reverse faults trend roughly N55°W and dip north-northeast. In the offshore Santa Maria Basin, thrust and reverse faults trend about N35°W and dip predominately to the

northeast. Right-lateral slip has probably occurred on some of these faults, however folds associated with the faults are usually asymmetric and their axes closely parallel the fault traces indicating that compression is playing a dominant role in structural development.

2. Similar fault and fold relationships have been reported in adjacent onshore regions. Within the western Transverse Ranges compressional structures are well known. However, the northwest-trending structural features in the Southern Coast Ranges are generally regarded as being related to right-lateral wrench tectonics. Because many of the faults in this region are steeply-dipping, high-angle reverse faults at the surface, the role of compressional tectonics in the Southern Coast Ranges may not be fully appreciated. We conclude that many of these high-angle reverse faults, like those in the offshore, flatten and become thrust faults at depth.

3. Resolution of present-day plate motions coupled with estimates of the amount of crustal shortening from offshore and onshore structural studies suggest that in the past 5.5 m.y. at least 30 km and perhaps as much as 70 km of northeast-southwest crustal shortening has occurred across the central California margin. These estimates are comparable to estimates for right-slip offsets along northwest-trending faults west of the San Andreas.

4. In order to accommodate major crustal shortening in the past 5.5 m.y., we propose that the upper crust (<12 km depth) along the central California margin is separated from a lower, possibly oceanic crustal layer along an aseismic zone of detachment or decollement. Thrust faults extending upward from the zone of detachment are compressed into high-angle reverse faults at shallow crustal depths.

5. Compressional tectonics may be an important element of basin development along the central California margin. Prominent basins, such as the offshore and onshore Santa Maria, Huasna, and Cuyama Basins, all appear to have undergone northeast-southwest-directed compression in post-Miocene time. The predominance of thrust faults and parallelism of folds within these basins suggest that compression rather than right-slip has dominated the late stages of basin development.

6. New petroleum field discoveries along the central California margin may come from subtle traps associated with compressional folding and faulting. Exploration concepts that have been used to discover petroleum in the Rocky Mountain Overthrust belt may also apply (perhaps on a smaller scale) to major zones of crustal shortening along the California margin.

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