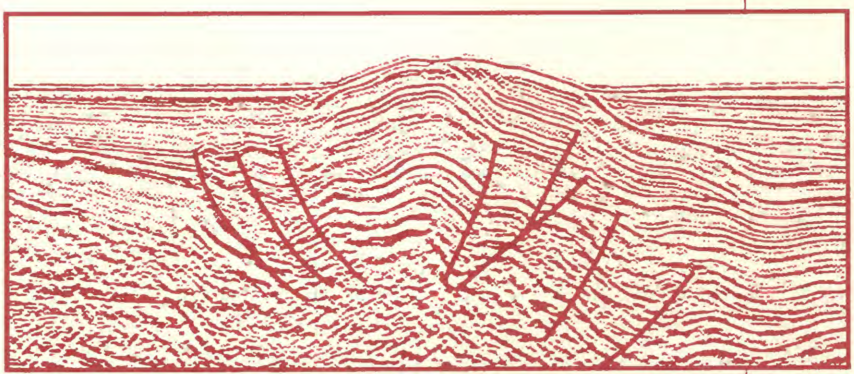
Neogene Geohistory Analysis of Santa Maria Basin, California, and Its Relationship to Transfer of Central California to the Pacific Plate

Diatom Biochronology of the Sisquoc Formation in the Santa Maria Basin, California, and Its Paleoceanographic and Tectonic Implications



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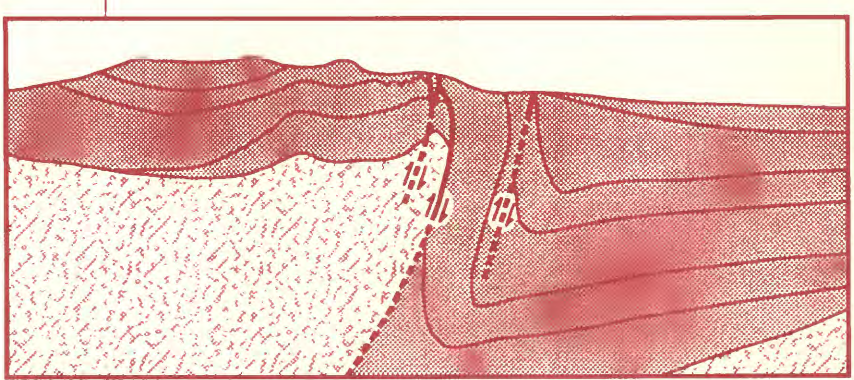

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Neogene Geohistory Analysis of Santa Maria Basin, California, and Its Relationship to Transfer of Central California to the Pacific Plate

By PATRICIA A. McCRORY, DOUGLAS S. WILSON, JAMES C. INGLE, Jr., and RICHARD G. STANLEY

Diatom Biochronology of the Sisquoc Formation in the Santa Maria Basin, California, and Its Paleoceanographic and Tectonic Implications

By MICHAEL P. DUMONT and JOHN A. BARRON

Chapters J and K are issued as a single volume and are not available separately

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SANTA MARIA PROVINCE

Edited by Margaret A. Keller

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Chapter J

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EVOLUTION OF SEDIMENTARY BASINS/ONSHORE OIL AND GAS INVESTIGATIONS—SANTA MARIA PROVINCE

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Neogene Geohistory Analysis of Santa Maria Basin, California, and Its Relationship to Transfer of Central California to the Pacific Plate

By Patricia A. McCrory, Douglas S. Wilson[1], James C. Ingle, Jr.[2], *and* Richard G. Stanley

Abstract

The central California continental margin records a complex response to changing plate motions during the Cenozoic. The record of Cenozoic tectonism preserved in Santa Maria basin strata, integrated with plate reconstructions, provides insights into the evolution of the central California continental margin during its transition from a convergent to a transform plate boundary and its transfer from the North America to the Pacific Plate. The continuation of subduction of the Monterey Microplate in the Miocene has significant implications for the evolution of the San Andreas transform boundary. In particular, this boundary originated as two separate segments. The first segment formed south of the Pioneer Fracture Zone about 30 Ma, probably near central California. The second formed between the Morro and Murray Fracture Zones about 25 Ma. The capture of the Monterey Microplate by the Pacific Plate about 19 Ma, terminating subduction, abruptly linked these transform boundaries to form a much more extensive Pacific-North America boundary.

Backstrip analyses of Santa Maria basin strata suggest that interactions between adjacent oceanic plates and the continental margin dominated the tectonic evolution of central California. The onset of late early Miocene subsidence and volcanism is likely linked to the transition from subduction to strike-slip tectonics, resulting from cessation of Monterey ridge spreading. Miocene subsidence occurred in two stages. An initial rapid phase (about 18 to 16 Ma) is attributed to extreme local extension of the continental crust, associated with the beginning of western Transverse Range rotation and triggered by Monterey Microplate capture. A subsequent slower phase (about 16 to 7 Ma) is attributed to thermal subsidence, associated with cooling of underplated young oceanic lithosphere. Transfer of the Monterey Microplate remnant to the Pacific Plate when spreading ceased would have created a wide Pacific-North America subhorizontal boundary zone at depth and perhaps allowed distributed shear between the partially subducted oceanic lithosphere and overlying relict accretionary complex, creating a mechanism for in situ rotation of overlying fault-bounded blocks. Tectonic uplift of the Point Sal and Point Arguello areas in late Miocene time may have been related to regional development of a fold and thrust belt in response to reorientation of the Pacific Plate velocity vector about 5.5 Ma, as well as rotation of the western Transverse Ranges in a constraining geometry. Since about 3 Ma, motion along the plate boundary has been partitioned between strike-slip along the San Andreas Fault system and compression along reverse faults and associated folds both west and east of the San Andreas Fault system.

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INTRODUCTION

The California continental margin records a complex response to changing plate motions in the Cenozoic. During the Cenozoic, as segments of the Pacific-Farallon spreading ridge approached the Farallon-North America subduction margin, spreading ceased and a newly formed Pacific-North America plate boundary elongated across the former subduction margin. At least two relict Farallon-derived microplates, in central California and Baja California, were stranded underneath the margin when spreading ceased on the associated ridge segments. Both microplate fragments were captured by the Pacific Plate, creating transient, broad Pacific-North America transform boundaries in each area.

The central California continental margin has been the focus of numerous geological and geophysical studies because of its crucial record of the tectonic evolution of the continental margin of North America, the petroleum accumulations within sedimentary basins along the margin, and the siting of energy facilities along the coast. However, the details of tectonic evolution are obscured by the overprinting of sequential phases of tectonic deformation, the uplift and erosion of Mesozoic and early Paleogene marine strata during the Oligocene, the lack or poor quality of surface exposures in many areas, the lack of known piercing points on major faults, and until recently, the lack of detailed geophysical imaging of deep structural features offshore and onshore.

Santa Maria province lies within central California at the southernmost end of the southern Coast Ranges and for the purposes of this report is bounded on the west by the Santa Lucia Escarpment, on the south by the Santa Ynez Fault, and on the northeast by the Sur-Nacimiento Fault Zone (fig. 1). This province contains several filled

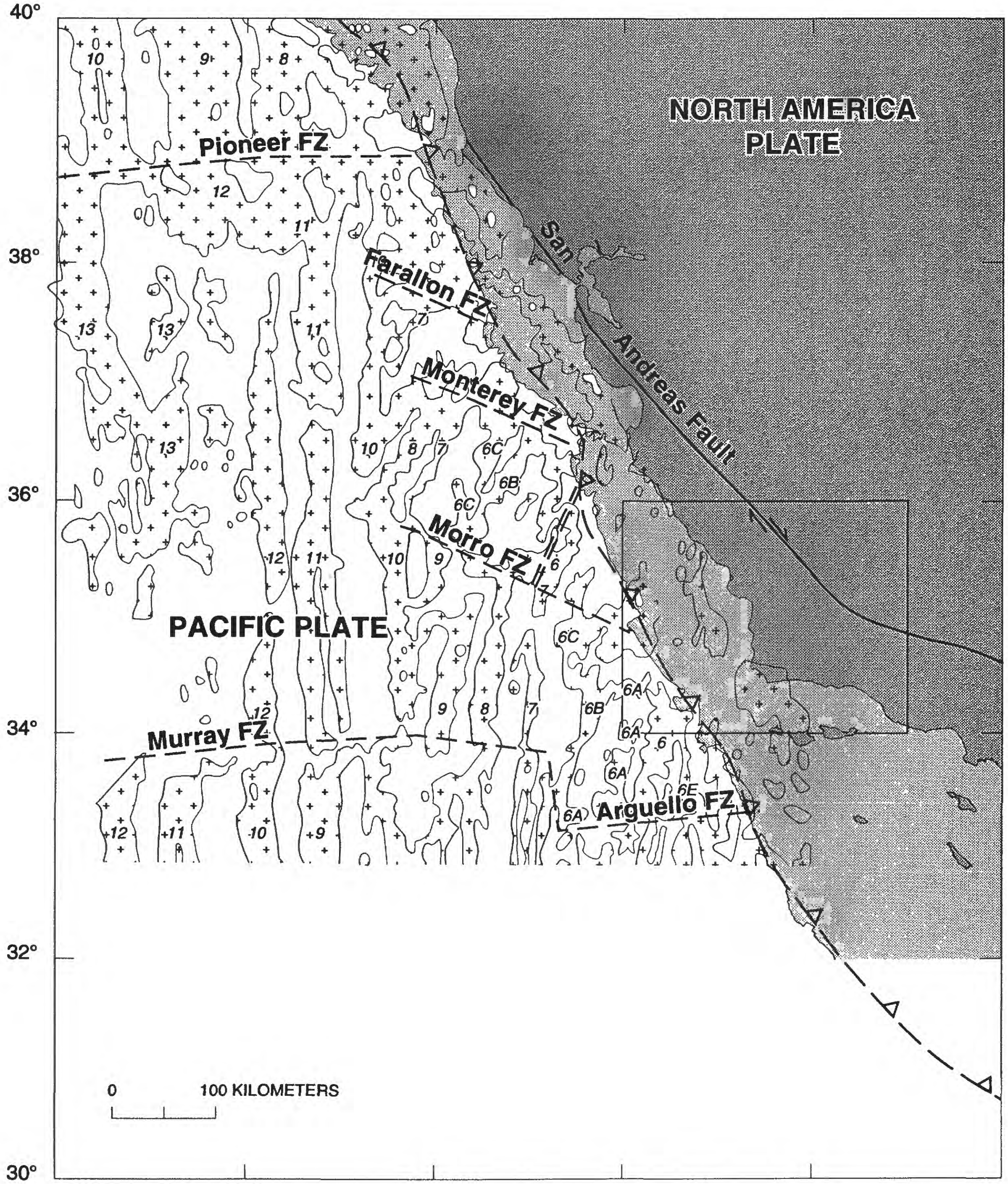

Figure 1A. Map showing present location of major tectonic features and normally magnetized magnetic anomalies (areas with patterns of crosses) on oceanic crust (see fig. 9 for age of numbered isochrons) of central California continental margin and adjacent offshore area. Solid lines are active transform faults; dashed lines are fracture zones. Paleo-spreading ridge shown by dashed double lines; paleo-subduction zone shown by barbed dashed line. Offshore continental crust has lighter shading; onshore continental crust has darker shading. FZ, fracture zone. Box indicates area of figure 1*B*. Modified from Lonsdale, 1991; Fernandez and Hey, 1991.

sedimentary basins both offshore and onshore, including the Sur, Santa Lucia, Santa Maria, and Pismo-Huasna basins. Cenozoic strata within these basins contain a record of the timing and distribution of tectonic deformation along the evolving plate boundary.

This report uses the record of vertical tectonic and isostatic movement preserved in offshore and onshore Santa Maria basin strata, coupled with both recent published accounts of regional folding and faulting histories (Namson and Davis, 1990; Sedlock and Hamilton, 1991; Clark and others, 1991) and recent plate reconstructions (Atwater, 1989; Lonsdale, 1991; Fernandez and Hey, 1991), to develop insights into the interplay between plate kinematics and continental margin deformation styles and rates. Because this complex region has several major unresolved tectonic questions, our tectonic reconstruction must be considered preliminary. More accurate reconstructions will require better constrained regional rotation histories and fault displacement histories and quantification of crustal shortening, as well as better constrained histories of microplate location along the continental margin.

The Southern Coast Ranges

Basement rocks of the southern Coast Ranges include subducted and uplifted oceanic sedimentary and volcanic rocks of the Mesozoic Franciscan Complex (Page, 1981), island-arc rocks of the Jurassic Coast Range ophiolite (Hopson and Frano, 1977) and overlying Upper Jurassic to

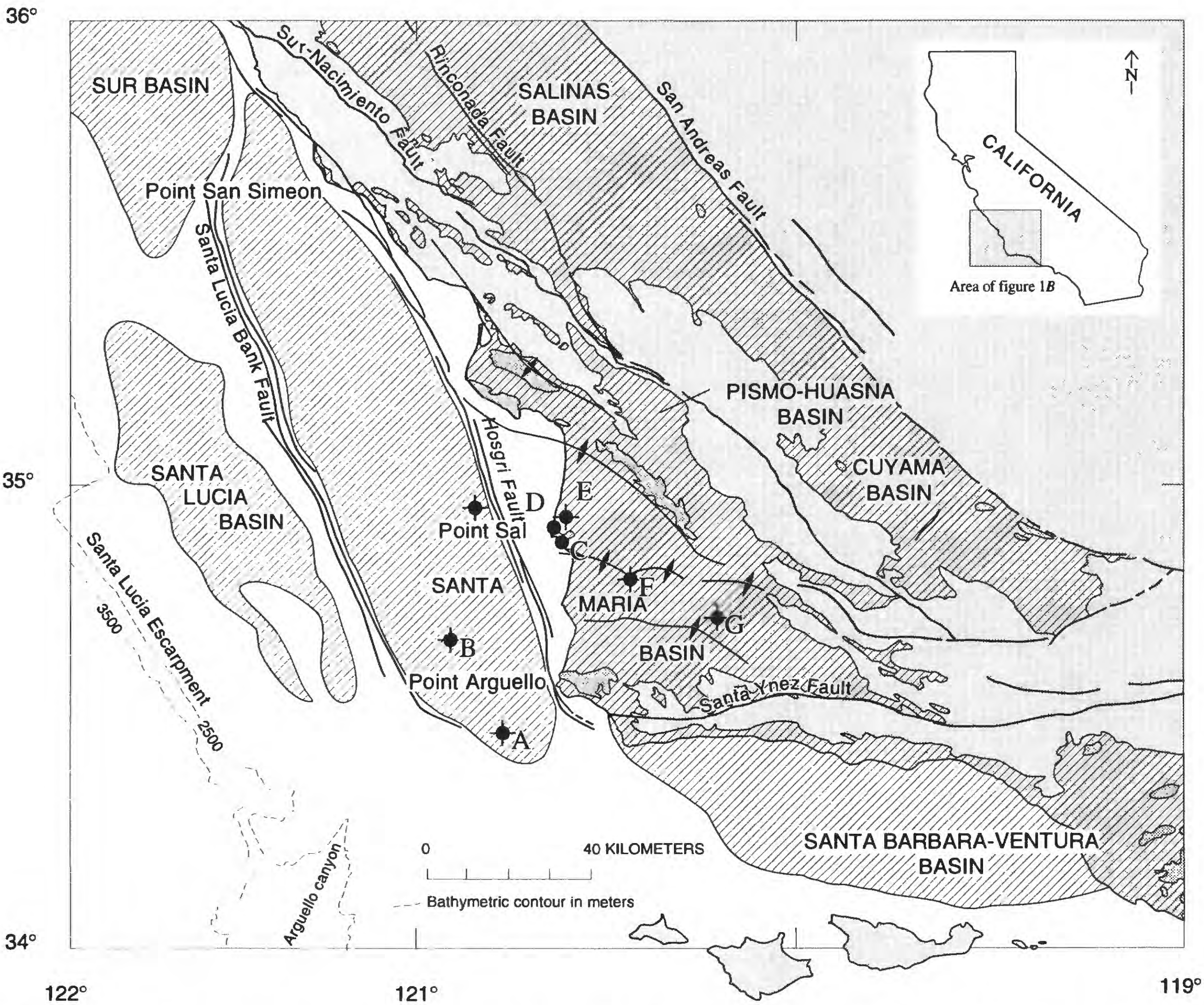

Figure 1*B*. Location map of Santa Maria province and vicinity showing distribution of Neogene sedimentary rocks, major faults, and anticlinal fold axes (modified from Jennings, 1977; Steritz, 1986). Onshore area has shading; onshore and offshore Neogene sedimentary rocks denoted by diagonal lines. A, Cost well; B, Texaco Nautilus well; C, North Beach site; D, Mussel Rock site; E, Union Los Nietos well; F, Union Newlove well; G, Tidewater Davis well.

Paleogene sedimentary rocks resembling forearc strata of the Great Valley sequence (fig. 2), and Cretaceous continental-arc plutons that intrude older metasedimentary rocks (Ross, 1984; Mattinson and James, 1985). These basement rocks are assigned to the San Simeon, Stanley Mountain, and Salinia tectonostratigraphic terranes, respectively, which were juxtaposed as early as the Late Cretaceous and accreted to North America during Paleocene or Eocene time (Vedder and others, 1983; Howell and others, 1987). Inferred late Cenozoic strike-slip displacement juxtaposed younger marine sedimentary rocks of the Patton terrane to the west of the San Simeon terrane (Page and others, 1979a, 1979b; McCulloch, 1987).

In much of the southern Coast Ranges, Mesozoic and Paleogene rocks are unconformably overlain by upper Oligocene and lower Miocene strata, including nonmarine clastic rocks, rhyodacitic and basaltic volcanic rocks (26–22 Ma; Ernst and Hall, 1974), neritic sandstone, and bathyal fine-grained clastic rocks. In early Miocene time, extension and rapid subsidence occurred in the Sur, Santa Lucia, Santa Maria, and Pismo-Huasna basins (McCulloch, 1987; Tennyson, 1989; Tennyson and others, 1991). The Santa Maria basin (for the purposes of this report, "Santa Maria basin" will denote both the offshore and onshore components of the basin) contains as much as 4.5 km of Miocene and younger strata (Woodring and Bramlette, 1950) on top of Point Sal ophiolite, Franciscan Complex, and Great Valley sequence basement rocks (McLean, 1991). Basin fill includes late early Miocene (18–16 Ma) bimodal volcanic rocks (Canfield, 1939; Dibblee, 1950, 1966; Woodring and Bramlette, 1950; McLean, 1991) with oceanic-ridge affinities (Cole and Basu, 1992).

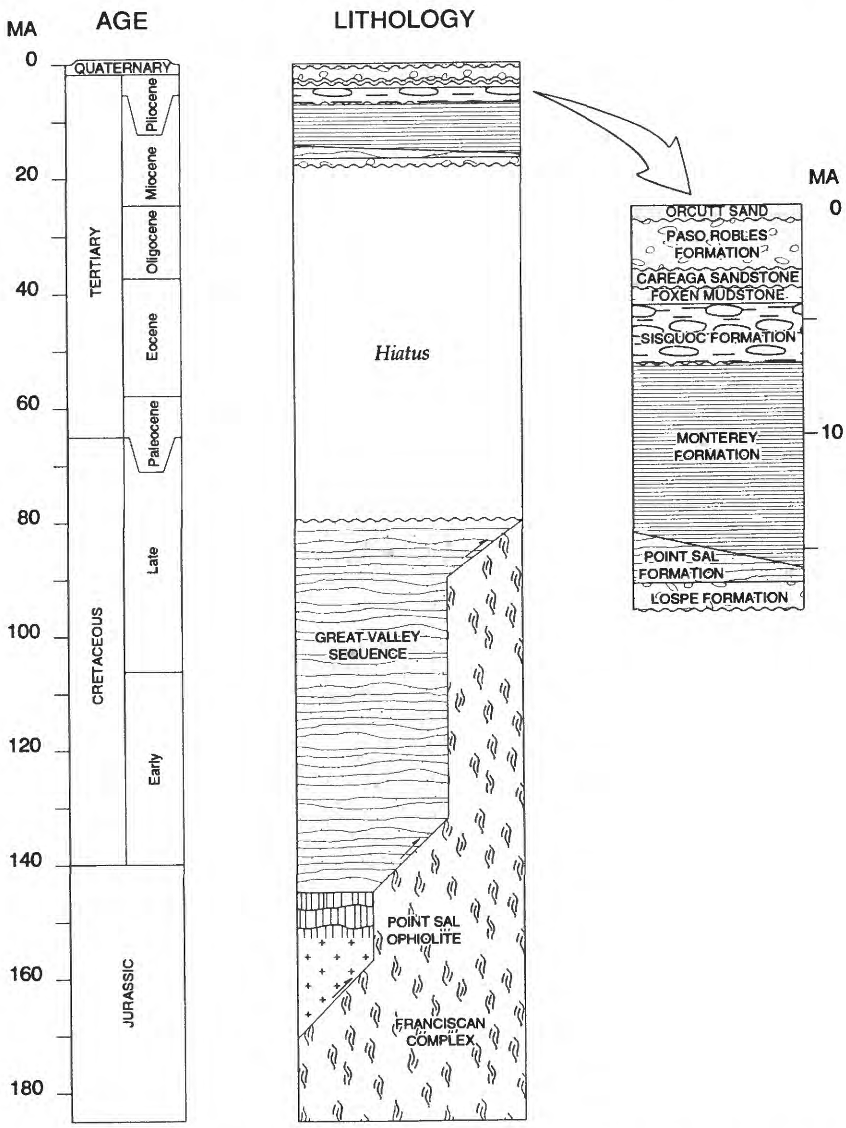

Figure 2. General lithostratigraphy for onshore Santa Maria basin (modified from Woodring and Bramlette, 1950; Stanley and others, 1991).

Santa Maria Basin Lithostratigraphy

The oldest Neogene fill within onshore Santa Maria basin consists of lower Miocene nonmarine conglomerate, sandstone, and minor tuff of the Lospe Formation (Stanley and others, 1991) (fig. 2). The lower Miocene Point Sal Formation (Stanley and others, 1990) overlies Lospe strata or basement rocks (Namson and Davis, 1990). The Point Sal Formation consists of interbedded mudstone and bathyal sandstone and records rapid subsidence and initiation of deep-marine conditions within the basin. The widespread middle and upper Miocene Monterey Formation overlies the Point Sal Formation. The Monterey Formation consists of massive to well-laminated biosiliceous rocks, dolomite, and minor bathyal sandstone. The middle Miocene to Pliocene Sisquoc Formation conformably and locally unconformably overlies the Monterey Formation (Woodring and Bramlette, 1950). The Sisquoc Formation is composed of massive to weakly laminated biosiliceous rocks, siltstone, and bathyal sandstone. The Sisquoc Formation is conformably and unconformably overlain by marine siltstone and fine-grained sandstone of the Pliocene Foxen Mudstone. The Sisquoc Formation and Foxen Mudstone are thin or absent along the basin margins and anticlinal trends but are as much as 2 km thick in the deep, central part of the Santa Maria basin (Namson and Davis, 1990).

The upper Pliocene Careaga Sandstone is a coarse-grained neritic sandstone deposited during basin shoaling. In the onshore portion of Santa Maria basin, the Careaga Sandstone commonly overlies the Foxen Mudstone in angular unconformity along anticlinal trends. Nonmarine gravel and alluvial sand of the Pliocene and Pleistocene part of the Paso Robles Formation and Pleistocene Orcutt Sand conformably and unconformably overlie the Careaga Sandstone. Widespread angular discordances, basin shoaling, and deposition of nonmarine coarse-grained units resulted from Pliocene and Quaternary uplift and erosion. This phase of uplift and erosion is attributed to a period of crustal shortening (Namson and Davis, 1990).

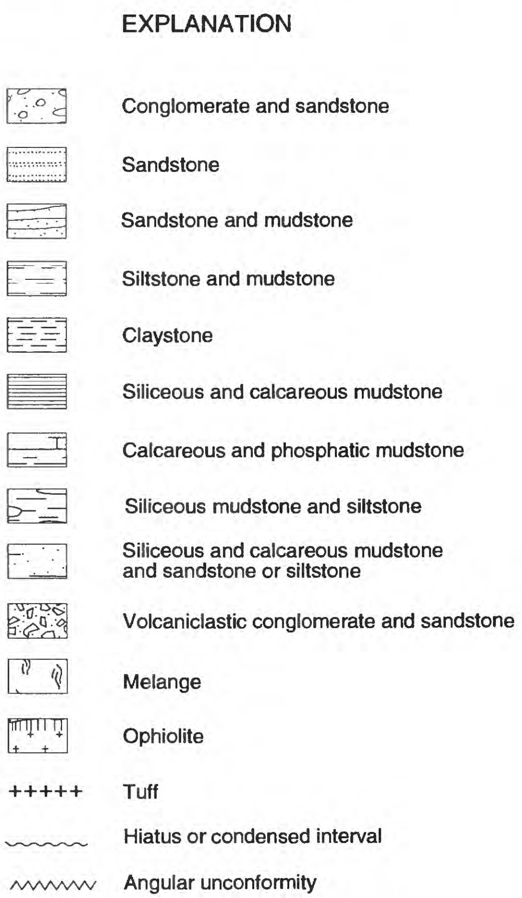

Figure 2. Continued.

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LATE CENOZOIC TECTONISM IN THE SANTA MARIA AREA

The tectonic evolution of Santa Maria province is complex, and many details of structures and timing of deformation are difficult to resolve, owing to overprinting of differing tectonic phases, reversals of bathymetric relief, lack of age control, and inability to image deep structures. The lack of Paleogene strata except for isolated remnants (Vedder and others, 1991) hampers attempts at reconstruction in Santa Maria basin. In addition, when Baja California peninsula is restored to its pre-5.5 Ma position relative to mainland Mexico (by closure of the Gulf of California by 310 km) and the western Transverse Ranges are back rotated 90°, the Point Arguello area (fig. 1) lies at the latitude of northernmost Mexico (31.5° N.).

Basins within Santa Maria province record multiple phases of tectonism: (1) An episode of late Oligocene to earliest Miocene subsidence (Tennyson, 1989; Tennyson and others, 1991), which is missing in Santa Maria basin proper, (2) a late early Miocene phase of normal faulting and rapid subsidence during inferred transtension (Stanley and others, 1992), (3) a middle Miocene phase of slow subsidence, (4) a late Miocene episode of bathymetric inversion, (5) a subsequent episode of reverse faulting and folding during inferred transpression, and (6) a poorly resolved history of strike-slip faulting during clockwise rotation of the adjacent western Transverse Ranges throughout changing stress regimes. For most of Santa Maria province, detailed fault-slip data are not available; thus, although surface and shallow subsurface fault orientations are known in many cases, the exact direction and amount of slip, amount of extension or shortening, and the fault orientations at depth are not known. Also, some faults display evidence of reactivation with differing slip directions, and some faults display evidence of merging into a midcrustal detachment zone (Crouch and others, 1984; McCulloch, 1987; Sedlock and Hamilton, 1991; McIntosh and others, 1991; Clark and others, 1991). Regional syntheses of available geological and geophysical data and more recent geochronology provide constraints summarized below.

Style, Timing, and Magnitude of Late Cenozoic Tectonism

The major faults in the southern Coast Ranges and directly offshore trend northwestward (fig. 1*B*). Regional mapping has documented few piercing points on these faults; thus, their displacement histories are poorly constrained. No displacement data are available for the Santa Lucia Bank Fault offshore, but its long, linear trace and its lateral offset of Arguello submarine canyon suggest strike-slip displacement (McCulloch, 1987).

The Hosgri Fault Zone, which separates northwest-trending basement structures in onshore Santa Maria basin from north-trending Neogene growth structures in offshore Santa Maria basin (McCulloch, 1987), consists of several northeast-dipping segments that merge with or terminate against west-trending structures near the northwestern end of the Transverse Ranges (Steritz, 1986). The northern segments of this fault system (San Gregorio and San Simeon segments) have had 150 km of dextral slip since the early Paleocene (Clark and others, 1984; James and Mattison, 1985). As much as 115 km of slip on the San Gregorio-San Simeon segments may have occurred since the early Miocene (Graham, 1978; Graham and Dickinson, 1978). However, recent reevaluation of the southern Hosgri segment suggests that it has been primarily a reverse-fault system in the late Cenozoic (Neogene and younger) with no more than 5 km post-Oligocene dextral slip (Crouch and others, 1984; Clark and others, 1991; Sedlock and Hamilton, 1991). Regardless, the Hosgri segment juxtaposes basement rocks with different Neogene structural histories (McCulloch, 1987). A mechanism for this juxtaposition needs to be resolved.

Post-early Miocene dextral slip of 5 to 8 km has been documented on the Oceanic-West Huasna fault using offset Miocene lavas (McLean, 1993). The Sur-Nacimiento Fault Zone has had about 90 km post-Eocene strike-slip displacement but no more than 6 km of post-Miocene displacement (Vedder and others, 1991). Post-early Miocene dextral slip on the Rinconada Fault is about 43 km in the Salinas Valley area (Graham, 1978). The Russell Fault, in the Cuyama basin area, had about 25 km of dextral slip during early Miocene time (23–19 Ma), but only a few kilometers of slip since that time (Yeats and others, 1989).

In summary, estimates of cumulative post-Oligocene dextral slip in the southern Coast Ranges and offshore (excluding the San Andreas Fault) range from as little as 85 km to as much as 195 km (Sedlock and Hamilton, 1991; Vedder and others, 1991). Namson and Davis (1990) found no evidence in the southern Coast Ranges for significant strike-slip displacement during the late Pliocene and Quaternary and suggest that lateral slip in the Santa Maria province has been minimal (<1–2 km) since early Pliocene time. However, estimating cumulative lateral displacement from sparse data has an additional uncertainty that results from extrapolating displacement rates derived from offset piercing points on one portion or segment of a fault to a complete segment or fault system (see Bilham and Bodin, 1992).

Santa Maria basin strata are cut by numerous growth faults at the surface and in the shallow subsurface that trend subparallel to folds (Namson and Davis, 1990). Because these faults are generally high angle and are commonly associated with changes in thickness of Neogene strata and are commonly buried by younger strata, they are inferred to be dip-slip faults active during Neogene deposition (Namson and Davis, 1990). A local angular unconformity (about 8 to 6 Ma; Clark and others, 1991) between the Monterey and Sisquoc Formations may result from this Neogene phase of dip-slip faulting that was widespread in central and southern California (Namson and Davis, 1990).

The lower Miocene Lospe and Point Sal Formations are thicker over the crest of the Orcutt Anticline in onshore Santa Maria basin than on its limbs, suggesting that the axial area of the present fold was a depocenter during deposition of these strata. Conversely, upper middle and upper Miocene Monterey and upper Miocene and Pliocene Sisquoc Formations thin gradually from the fold limbs to the crest, suggesting that the present crest was a structural high during the late middle and late Miocene (Namson and Davis, 1990). The bathymetric inversion indicated by these observations occurred before folding of the anticline (Namson and Davis, 1990) and may have been synchronous with the phase of Neogene dip-slip faulting discussed above.

The Santa Maria basin and vicinity have undergone considerable Pliocene and Quaternary shortening and uplift resulting in extensive folds, reverse faults, and angular unconformities (Namson and Davis, 1990). In the onshore part of Santa Maria basin, significant folding and reverse faulting began in Pliocene time (about 4 to 2 Ma) and has continued into the Quaternary (Woodring and Bramlette, 1950; Namson and Davis, 1990). In offshore Santa Maria basin, the main period of folding and reverse faulting occurred in the early Pliocene (5.3–3.4 Ma) and continued with decreased intensity into the late Pliocene and Quaternary (Crouch and others, 1984; Clark and others, 1991; Miller and others, 1992). In the Santa Lucia basin, west of the Santa Lucia Bank Fault, significant compression has continued into the Quaternary (McCulloch, 1987; McIntosh and others, 1991).

In summary, a Pliocene and younger phase of folding and reverse faulting in the southern part of Santa Maria province (Namson and Davis, 1990; Clark and others, 1991) resulted in about 30 km of cumulative northeast-directed shortening across the 200-km-wide area of the southern Coast Ranges and offshore Santa Maria basin. This estimate of shortening is based on modeling folds at the surface as thrust faults at depth. The presence of subsurface thrust faults needs to be verified by deep seismic imaging.

Paleomagnetic studies suggest that the southern Coast Ranges have undergone little or no rotation during Neogene and Quaternary time, in contrast to the western Transverse Ranges to the south (Hornafius and others, 1986; Luyendyk, 1991). However, available data are few, so this interpretation must be considered preliminary. Late Cenozoic clockwise rotations of up to 70° in the northern part of the Santa Maria province (Greenhaus and Cox, 1979) are attributed to local accommodation of distributed dextral shear (Luyendyk, 1991).

The record of Cenozoic tectonism in Santa Maria province is incomplete; data from the early Cenozoic are sparse and the overprinting of subsequent stress regimes hampers reconstruction of the central California continental margin. The locations and displacements of the major faults active during early Miocene basin formation are poorly resolved. The amount of early Miocene crustal extension is unknown. A widespread middle Miocene hiatus is attributed to both tectonic and paleoceanographic causes (Barron, 1986). Estimates of lateral offset along possible strike-slip faults vary by more than 100 percent. Nonetheless, the available estimates of crustal shortening, lateral offset, and block rotation allow the following preliminary attempt at margin reconstruction. This reconstruction can be revised as additional quantitative geologic and geophysical data are acquired.

SANTA MARIA BASIN STUDY SITES

The offshore and onshore sites chosen for this study form two transects, one that parallels the structural trend in the southern part of Santa Maria province and the other that crosses the structural trend. Lithostratigraphic and biostratigraphic data from these sites are used to estimate the timing and rate of vertical movement by using backstripping techniques (Steckler and Watts, 1978; van Hinte, 1978). Backstripping reconstructs a burial history through time by systematically calculating the diagenetic effects of sediment loading. Discrepancies between paleobathymetry estimated from microfossils and paleobathymetry calculated from decompacting and unloading the strata through time are attributed to vertical movement of the basement.

Neogene and younger strata at the sites have been decompacted using porosity-depth formulas for specific lithologies (table 1) by using a computer program developed at the University of Arizona (Dickinson and others, 1987) and modified at Stanford University (Roger Bloch, unpub. data, 1989). This computer program also calculates isostatic loading through time using a one-dimensional Airy model and lithologic densities calculated during decompaction. The isostatic loading component subtracted from the total basin uplift/subsidence curve yields a residual tectonic component of vertical movement. This tectonic component may include contributions resulting from crustal thinning, thermal decay, and flexural loading.

Backstrip modeling requires estimates of paleobathymetry through time, estimates of the age of the various stratigraphic units and duration of hiatuses, and estimates of proportions of sand, mud, biosiliceous, and micritic components in the units (see appendix). Benthic foraminifers with restricted paleoenvironmental ranges are used as proxies for paleobathymetry following the procedures and assignments of Ingle (1980). Uncertainties in water depth, deduced from microfossils, are the main source of error in backstrip analysis. Therefore, water depth is plotted within an envelope of estimated range in water depth.

Sea level has fluctuated periodically over a range of about 200 m during the time interval evaluated at sites in this study (Haq and others, 1987). However, our backstrip analyses do not attempt a correction to the modern sea level datum because the timing and magnitude of sea level variation are not well constrained at the study sites.

The principle source of age control at the sites is the benthic foraminiferal stages of Kleinpell (1938, 1980) (fig. 3), a source that is not ideal, as these organisms have restricted environmental ranges. Key indicator species may appear in a section late or disappear from a section prematurely owing to a change in environment (in other words, water-mass character), rather than true first or last appearance. For this reason, curves in the age-depth plots in this report are shown within an envelope representing each stage. Although the stages are shown as not overlapping in age, some stages may in fact overlap in age, owing to the reasons stated above. Independent age control from planktonic microfossil groups, such as diatoms, or from isotopic dating of volcanic material is needed to better constrain the ages determined from benthic foraminifers.

Table 1. Porosity-depth formulas used to decompact lithologies in backstrip program

[ϕ, porosity; Z, burial depth; NA, not applicable. Mudstone, sandstone (undifferentiated), and limestone (undifferentiated) formulas are from Dickinson and others (1987). Micrite formula is derived from Bond and Komitz (1984). Siliceous shale formula is from Ingle (1985b)]

Lithology	Formula	Burial depth
Mudstone	ϕ=0.6/(1=0.001*Z)	NA
Sandstone	ϕ=0.5/(1+0.0005*Z)	NA
Limestone	ϕ=0.5/(1.0+0.6*Z)	NA
Micrite	ϕ=0.75-(7.0*0.001*Z) ϕ=0.4/exp(0.5*(Z-500.0)/1000.0)	0-500 m >500 m
Siliceous Shale	ϕ=0.85/(1+0.003*Z) ϕ=0.10	0-2500 m >2500 m

The loss of sediment porosity with depth is strongly dependent on sediment composition (see Dickinson and others, 1987); thus, stratigraphic units are separated into five lithologies (mudstone/shale, undifferentiated sandstone, undifferentiated limestone, biosiliceous sediment, and micritic carbonate), each with a different porosity-depth function derived from empirical studies. Silica phase changes during burial diagenesis further complicate the reconstruction of the burial histories of biosiliceous sediments, such as the Monterey Formation, which have high primary porosities. We use a simple porosity-depth curve formula developed by Ingle (1985b) and Garrison (1985) from data of Isaacs and others (1983) to estimate porosity changes in biosiliceous units. However, the silica phase changes are temperature and composition dependent, and neither parameter was reconstructed for this study. Thus, refinement of these formulas (table 1) awaits empirical data from wells in the Santa Maria area.

Point Arguello Area (Offshore)

The Cost well (OCS-CAL 78–164–1) (fig. 1*B*) is located at the southernmost end of offshore Santa Maria basin, just north of the "Amberjack High" (a basement high considered to be the offshore boundary between the Coast Ranges and the Transverse Ranges) in 435 m of water. At this site, about 2,520 m of Neogene and younger strata unconformably overlie Great Valley sequence rocks (fig. 4). The basal interbedded sandstone and conglomerate mark initial subsidence from neritic (150–15 m) to middle bathyal (2,000–500 m) depths in early Miocene (?) time (Cook, 1979). The site gradually deepened during Monterey, Sisquoc, and early "Foxen" deposition and then abruptly subsided to lower bathyal (4,000–2,000 m) depths during late "Foxen" deposition. Units enclosed within quotes are here considered to be offshore biostratigraphic equivalents of named onshore units (for example, "Foxen" is the offshore equivalent of the Foxen Mudstone). This site subsequently began to shoal and had shoaled to middle bathyal depths by the end of "Foxen" deposition in late Pliocene time. No paleobathymetric data are available

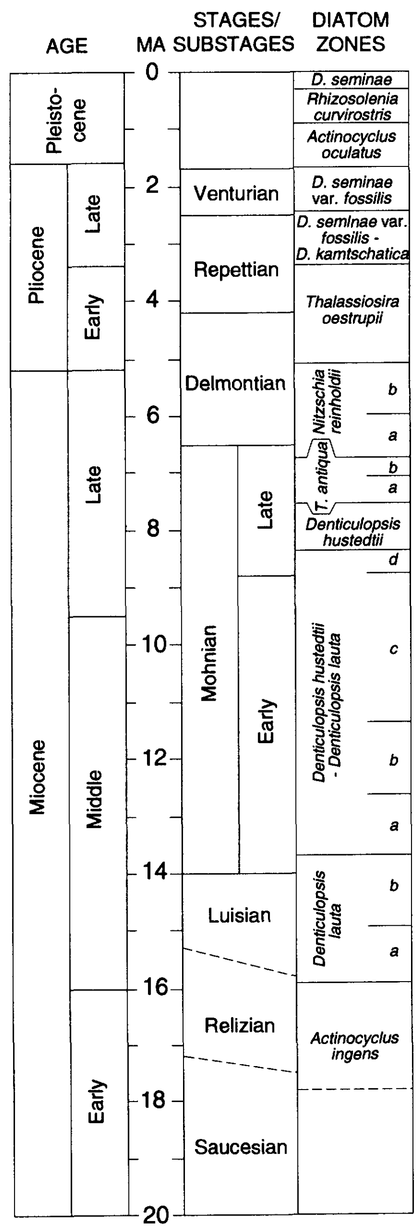

Figure 3. Late Cenozoic time scale for northeast Pacific Ocean (modified from Armentrout and others, 1984; Garrison, 1985; Barron, 1989). Stages/substages are benthic provincial foraminiferal stages of Kleinpell (1938, 1980) and are considered somewhat latitudinally diachronous, as ranges of foraminifers are restricted both by environmental and oceanographic conditions.

for the upper 172 m of the Cost well, but apparently the site continued to shoal through this interval. A hiatus or interval of extremely slow sediment accumulation (about 14 to 9 Ma) is inferred during Monterey deposition from the unusually sparse accumulation of sediment during early Mohnian time (fig. 4*A* and *B*).

Microfossil data do not allow quantification of initial site subsidence; however, backstrip analysis indicates slow

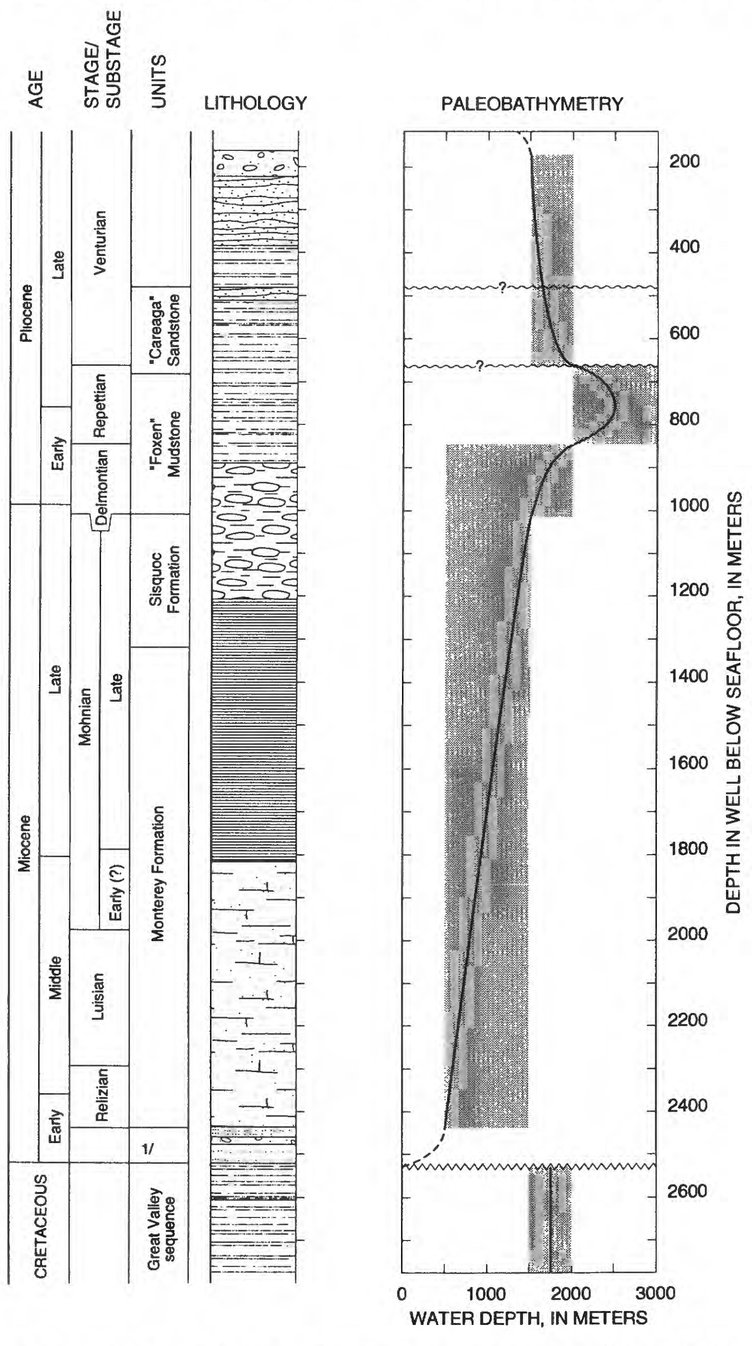

Figure 4*A*. Lithostratigraphy and paleobathymetry for Cost Well (OCS-CAL 78–164–1). Shaded areas represent range in paleobathymetric estimates inferred from benthic foraminifers. Lithostratigraphic data modified from (Cook, 1979) and Isaacs and others (1989). Determination of stage/substage boundaries (see fig. 3) is based on biostratigraphic data from Unocal (unpub. report, 1990). Paleobathymetric estimates are from Unocal (unpub. report, 1990). Units enclosed within quotes are considered to be offshore stratigraphic equivalents of named onshore units. See figure 2 for explanation of patterns and symbols; 1/, unnamed rocks.

subsidence from about 18? to 6.5 Ma (fig. 4*C*). At 6.5 Ma, a short, rapid subsidence event is inferred from a change in paleobathymetry (at 846 m depth in the well) from middle bathyal to lower bathyal water depths, followed by slow subsidence until about 2.5 Ma. At 2.5 Ma, the site began to shoal owing both to sediment fill and tectonic uplift. Uplift continued into the Pleistocene and is probably still occurring as the upper 172 m of Quaternary sediment (compacted thickness) at the top of the well spans a 1,000-m decrease in water depth (from 1,500 to 500 m), suggesting the possibility of missing section, as well as tectonic uplift.

The Texaco Nautilus well (OCS-P 0496–1), 27 km to the northwest of the Cost well, is also located in offshore Santa Maria basin (fig. 1) but in a different subbasin north of a basement high. This well is in 375 m of water and penetrates about 1,120 m of Neogene and younger strata unconformably overlying early Cretaceous sedimentary rocks (fig. 5). The basal sandstone and conglomerate are overlain by volcanic and volcaniclastic rocks. At this site, the initial deepening from neritic to lower bathyal depths is obscured by a hiatus separating volcaniclastic rocks and Monterey strata (fig. 5*A* and *B*) This hiatus or interval of extremely slow sediment accumulation is estimated to

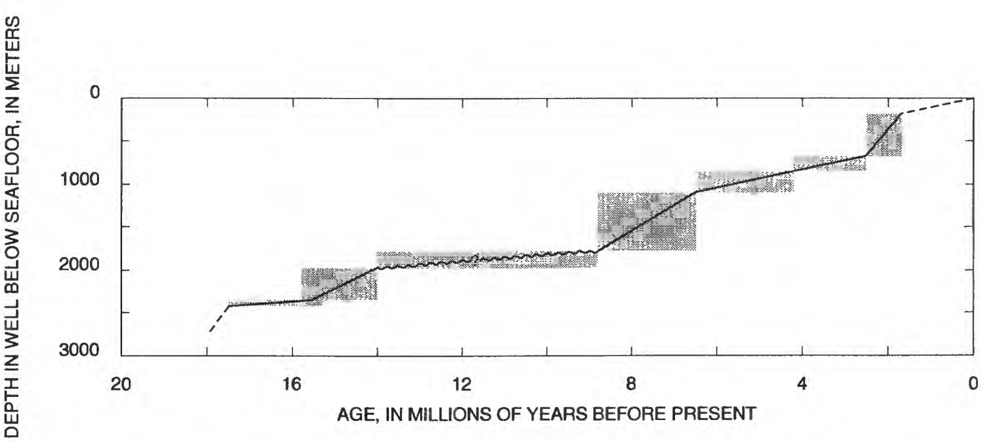

Figure 4*B*. Age-depth plot for Cost well (OCS-CAL 78–164–1) showing inflection points indicating changes in rate of sediment accumulation. Steeper slopes indicate rapid rates of sediment accumulation; flatter slopes indicate slow rates of sediment accumulation. Solid line, interpolated rate of sediment accumulation; dashed line, extrapolated rate; wavy line, hiatus or condensed interval. Shaded areas represent benthic foraminiferal stages (see fig. 3).

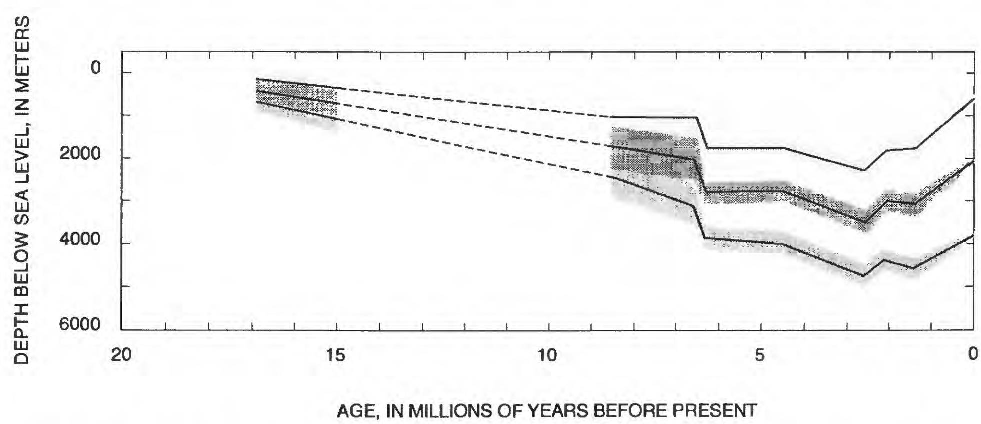

Figure 4*C*. Backstrip plot of Cost well (OCS-CAL 78–164–1) showing isostatic loading and tectonic components of vertical movement. Upper curve represents paleobathymetry inferred from benthic foraminifers (Unocal, unpub. report, 1990). Lower curve represents total (decompacted) movement of Great Valley sequence rocks. Middle curve represents residual tectonic movement after sediment and water loading are removed from lower curve. Shaded area on each curve represents range in paleobathymetric estimates. Positive slope indicates uplift; negative slope indicates subsidence; cumulative sediment thickness represented by vertical distance between basement (lower) and paleobathymetry (upper) curves.

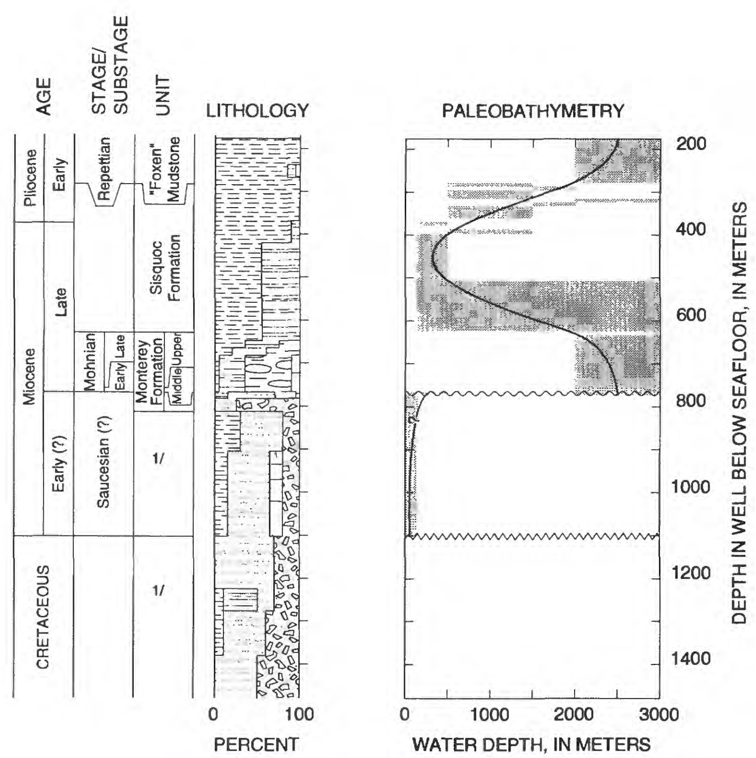

Figure 5*A*. Lithostratigraphy and paleobathymetry for Texaco Nautilus well (OCS-P 0496–1). Shaded areas represent range in paleobathymetric estimates inferred from benthic foraminifers. Lithostratigraphic data from Texaco (unpub. mudlog and report, 1986). Determination of stage/substage boundaries (see fig. 3) is based on biostratigraphic data from Unocal (unpub. mudlog and report, 1986). Paleobathymetric estimates are from this report using faunal data from Texaco (unpub. report, 1986). Units enclosed within quotes are considered to be offshore stratigraphic equivalents of named onshore units. See figure 2 for explanation of patterns and symbols; 1/, unnamed rocks.

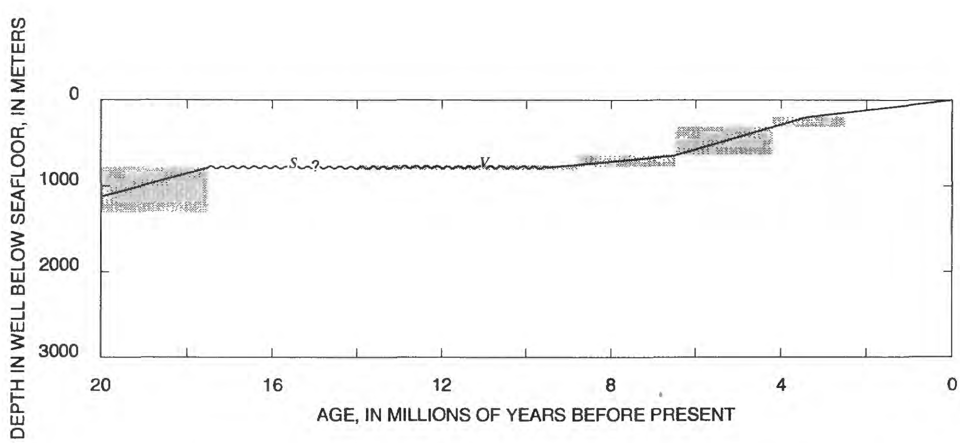

Figure 5*B*. Age-depth plot for Texaco Nautilus well (OCS-P 0496–1) showing inflection points indicating changes in rate of sediment accumulation. Steeper slopes indicate rapid rates of sediment accumulation; flatter slopes indicate slow rates of sediment accumulation. Solid line, interpolated rate of sediment accumulation; dashed line, extrapolated rate; wavy line, hiatus or condensed interval. S, strontium-isotope datum; V, K/Ar datum. Shaded areas represent ranges in benthic foraminiferal stages (see fig. 3).

have spanned 17.5 to 9.5 Ma, using age control from benthic foraminifers (indicating a lack of Relizian or Luisan (fig. 3) fauna) and siliceous microfossils, as well as strontium isotopic dating of dolomitic cement and K/Ar dating of volcanic rocks (Texaco, unpub. report, 1986).

Monterey and lower Sisquoc strata record a rapid shoaling to upper bathyal water depths. The site then deepened abruptly to lower bathyal water depths during late Sisquoc and "Foxen" time. The upper 200 m of post-"Foxen" strata were not logged at this site. These post-"Foxen" strata likely record shoaling from lower bathyal to present upper bathyal water depths. However, the details of this shoaling are not known.

Initial subsidence to marine bathyal conditions occurred during a middle Miocene hiatus; therefore, the details of subsidence are unknown. The site remained at lower bathyal depths during Monterey deposition (8.8–6.5 Ma) but underwent rapid tectonic uplift to upper bathyal depths during Sisquoc deposition (6.5–5.0 Ma). A subsequent phase of rapid bathymetric deepening followed (5–4 Ma). The site shoaled from 3 Ma to present. The more than 1,500-m decrease in water depth across the upper 200 m of strata (compacted thickness) seems extreme, suggesting the possibility of missing upper Pliocene and Pleistocene section as well as tectonic uplift. Low apparent sediment accumulation rates (fig. 5*B*) from 3 Ma to present support this possibility.

The late Pliocene uplift was synchronous at the Cost and Nautilus well sites. However, during the late Miocene uplift event at the Nautilus site, the Cost site was undergoing renewed subsidence. If the timing of both tectonic events (about 6 Ma) is indeed synchronous, the stress regime in the latest Miocene must allow adjacent uplift and subsidence. A possible explanation for this pattern of deformation is presented below.

Point Sal Area (Onshore)

The Point Sal site is a composite of two adjacent surface sections and a subsurface well section (the North Beach section, the Mussel Rock section, and Union Los Nietos (Leroy A-2) well 9 (fig. 1*B*) section), which together represent about 2,800 m of Neogene and younger strata (fig. 6*A*). The quality of this composite section is affected by the need to extrapolate the ages of the tops and bottoms of each subsection; nonetheless, this data set has the best age control and paleobathymetry of the sites studied and thus represents the best constrained site. In particular, the timing of initial subsidence from neritic to marine bathyal depths is well constrained by isotopically dated tuff units in the Lospe Formation (Stanley and others, 1991) and by benthic foraminifers in the Point Sal Formation.

The basal part of the Lospe Formation unconformably overlies an isolated block of Point Sal ophiolite (Hopson and Frano, 1977), just southeast of Point Sal. Upper Lospe and lower Point Sal strata, exposed at North Beach, record abrupt deepening from neritic to upper bathyal depths about 17.0 Ma. Upper Point Sal and lower Monterey strata, exposed at the Mussel Rock section, recorded gradual deepening to middle bathyal depths recorded (fig. 6). The lower part of the Monterey Formation contains a well-constrained hiatus or condensed interval (from 15.5 to 14 Ma; Ingle, 1985a), which occurred 2 m.y. after the Mussel Rock section reached its maximum water depth. This relationship contrasts with the Nautilus well site to

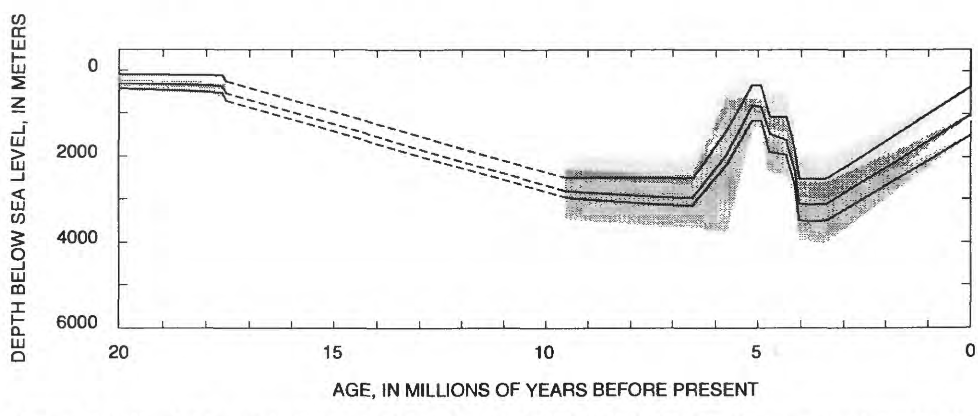

Figure 5*C*. Backstrip plot of Texaco Nautilus well (OCS-P 0496–1) showing isostatic loading and tectonic components of vertical movement. Upper curve represents paleobathymetry inferred from benthic foraminifers (this report using faunal data from Texaco unpub. report, 1986). Lower curve represents total (decompacted) movement of Franciscan Complex rocks. Middle curve represents residual tectonic movement after sediment and water loading are removed from lower curve. Shaded area on each curve represents range in paleobathymetric estimates. Positive slope indicates uplift; negative slope indicates subsidence; cumulative sediment thickness represented by vertical distance between basement (lower) and paleobathymetry (upper) curves.

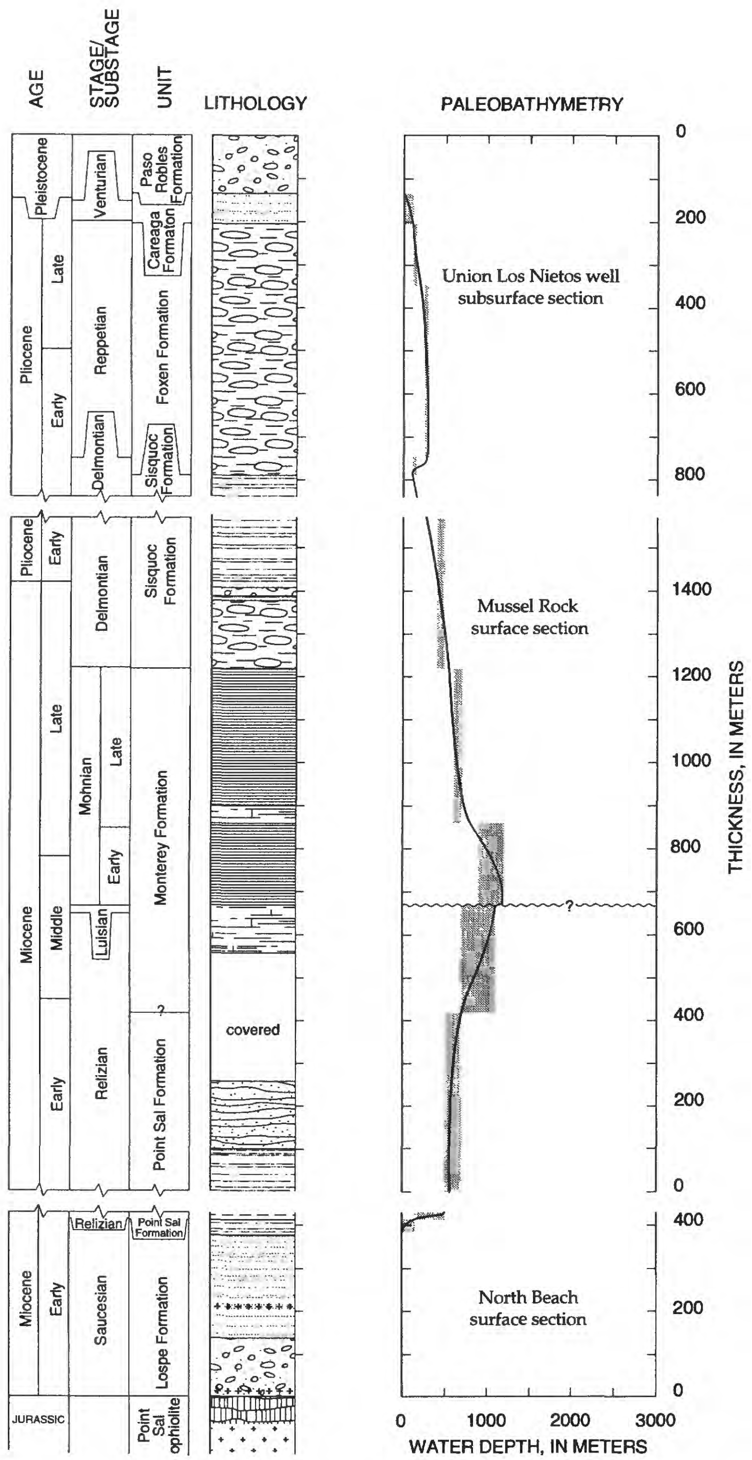

Figure 6A. Lithostratigraphy and paleobathymetry for Point Sal composite section. Shaded areas represent range in paleobathymetric estimates inferred from benthic foraminifers. Determination of stage/substage boundaries (see fig. 3) is based on biostratigraphic data from Ingle (1985a), Garrison (1985), and Stanley and others (1990). Lithostratigraphic data and paleobathymetric estimates for North Beach surface section are from Stanley and others (1990). Biostratigraphic data for North Beach surface section is from Stanley and others (1990). Lithostratigraphic and biostratigraphic data, and paleobathymetric estimates for Mussel Rock surface section and Union Los Nietos well subsurface section are from Ingle (1985a) and Garrison (1985). See figure 2 for explanation of patterns and symbols.

the southwest, where subsidence occurred within the missing interval. The composite site shoaled gradually during deposition of the Monterey and Sisquoc Formations, and Foxen Mudstone, except for a minor deepening in earliest Foxen time marked in the Los Nietos well by a biosiliceous unit in the otherwise clastic Foxen Mudstone (Behl and Ingle, unpub. data, 1993). Deposition of the upper Pliocene Careaga Sandstone marked the end of marine conditions.

Backstrip analysis indicates rapid subsidence from nonmarine to middle bathyal depths between 17.7 and 15.5 Ma, a 1.5-m.y. hiatus from 15.5 to 14 Ma during slow net subsidence, continued slow subsidence until about 7 Ma. The Point Sal site underwent rapid tectonic uplift from 7 to 6 Ma, followed by tectonic quiescence from 6 to 4 Ma. A pulse of rapid subsidence occurred about 4 to 3 Ma, followed by gradual shoaling (in part due to uplift) that led to nonmarine conditions. In summary, this site records a rapid subsidence event about 17 Ma, a long period of quiescence, an uplift event about 6.5 Ma, and another quiescent period interrupted by a subsidence event about 3.5 Ma.

Central Basin Area (Onshore)

Our central onshore Santa Maria basin site, Union Newlove No. 51 well, is located 23 km southeast of the Point Sal site (fig. 1*B*). This site is on the south flank of the Casmalia-Orcutt anticlinal trend and thus was located in a different subbasin than the Point Sal site during late Neogene crustal shortening. The well did not penetrate

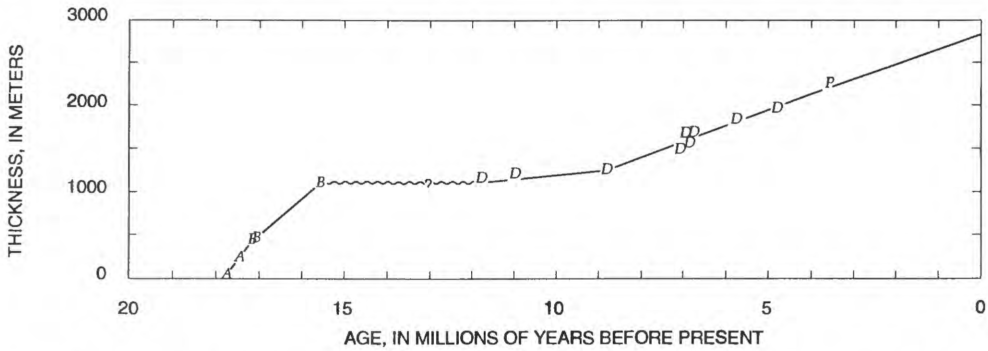

Figure 6*B*. Age-thickness plot for Point Sal composite section showing inflection points indicating changes in rate of sediment accumulation. Steeper slopes indicate rapid rates of sediment accumulation; flatter slopes indicate slow rates of sediment accumulation. Solid line, interpolated rate of sediment accumulation; wavy line, hiatus or condensed interval. A, Ar^{40}/Ar^{39} datum; B, benthic foraminiferal datum; D, diatom datum; P, planktonic foraminiferal datum.

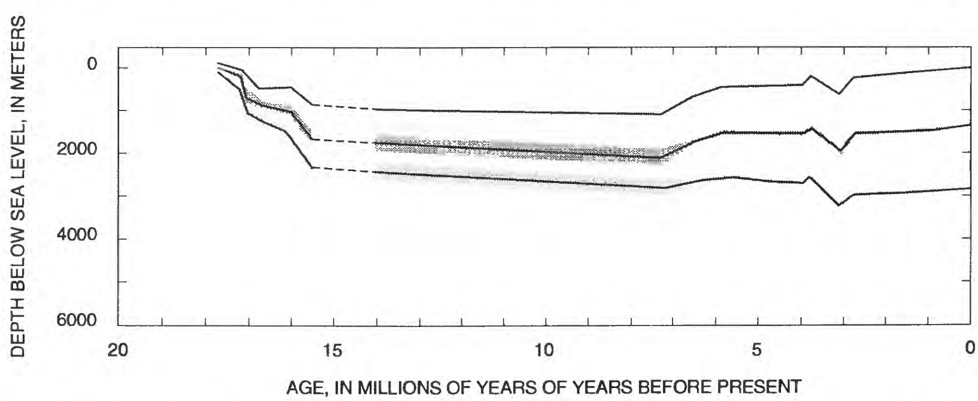

Figure 6*C*. Backstrip plot for Point Sal composite section showing isostatic loading and tectonic components of vertical movement. Upper curve represents paleobathymetry inferred from benthic foraminifers (Ingle, 1985a; Garrison, 1985; Stanley and others, 1990). Lower curve represents total (decompacted) movement of Point Sal ophiolite (basement). Middle curve represents residual tectonic movement after sediment and water loading are removed from lower curve. Shaded area on each curve represents range in paleobathymetric estimates. Positive slope indicates uplift; negative slope indicates subsidence; cumulative sediment thickness represented by vertical distance between basement (lower) and paleobathymetry (upper) curves.

basement rocks, so the basement type is unknown. The Miocene strata at this site are quite thin as compared with the Point Sal site (approximately 1,200 m of Point Sal and Monterey Formations at the Point Sal site compared with 650 m at this site). The Newlove site may have been isolated from the main loci of deposition during early and middle Miocene deposition.

This central Santa Maria basin site abruptly deepened in the early Miocene, as marked by the shift from nonmarine deposition of the Lospe Formation to middle bathyal deposition of the Point Sal Formation (fig. 7*A*). Water depths shoaled gradually during deposition of the upper part of the Point Sal and Monterey Formations, with an apparent hiatus or condensed section of weakly constrained duration marking the boundary between deposition of the Monterey and Sisquoc Formations. A decrease from middle to upper bathyal (500–150 m) water depths accompanied the hiatus or interval of slow sediment accumulation. The basin continued to shoal gradually during Sisquoc time. An angular unconformity and an abrupt change from upper bathyal to inner neritic water depths mark the boundary between the Sisquoc Formation and the overlying Careaga Sandstone. The time interval represented by this unconformity is unknown.

Age control from benthic foraminifers roughly constrains the period of apparent slow sediment accumulation (fig. 7*B*) from 14 to 9 Ma. Backstrip analysis (fig. 7*C*) indicates rapid subsidence from about 17.5 to 16 Ma, followed by tectonic quiescence from about 16 to 6 Ma. From 6 Ma to present this site shoaled tectonically as it filled with a prograded sequence of nearshore and paralic sediment. Age control is somewhat poor at this site, resulting in a smoothed backstrip curve, which may hide detail, such as shorter duration hiatuses and abrupt bathymetric changes documented elsewhere. For example, the Standard Los Flores No. 1 well, 8 km east of this site, records a short time interval of significant deepening between deposition of the upper part of the Sisquoc Formation and lower part of the Foxen Mudstone, marked by biosiliceous strata (Behl and Ingle, unpub. data, 1993). This subsurface biosiliceous unit is found along synclinal trends elsewhere in Santa Maria basin. Behl and Ingle (unpub. data, 1993) attribute this regional deepening to early Pliocene subsidence in synclinal axes resulting from folding and regional tectonic compression.

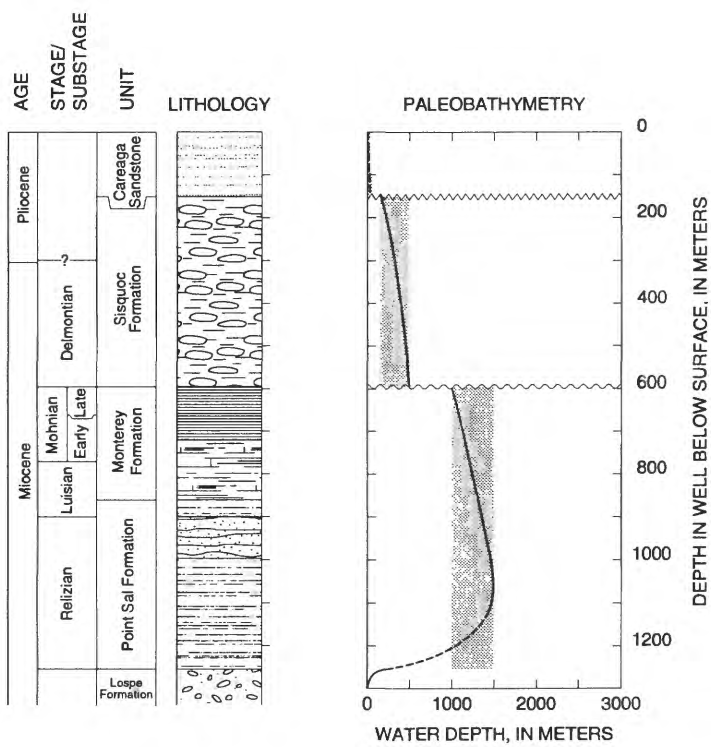

Figure 7*A*. Lithostratigraphy and paleobathymetry for Union Newlove No. 51 well (Orcutt Field). Shaded areas represent range in paleobathymetric estimates inferred from benthic foraminifers. Data and stage/substage boundary (see fig. 3) determinations from Ingle (1985a), Garrison (1985), and Lagoe (1987). See figure 2 for explanation of patterns and symbols.

Eastern Basin Area (Onshore)

Our easternmost site, the Tidewater Davis No. 1 well, is located 25 km southeast of the Newlove site, in the same late Neogene subbasin, on top of Franciscan basement. The Tidewater site has 2,750 m of Neogene and younger strata; however, this stratigraphic sequence does not contain the Lospe Formation at its base. Thus, this site is missing a record of early nonmarine conditions and subsequent subsidence to marine bathyal conditions. Nonetheless, Neogene strata at the Tidewater site record a shoaling history similar to the Newlove shoaling history (fig. 8*A*)—stable middle bathyal conditions during deposition of the Point Sal and Monterey Formations from about 17 (?) to 6.5 Ma, followed by gradual shoaling to the present. A condensed interval from about 14 to 8 Ma and formation of an angular unconformity about 3 Ma interrupt this sequence.

Age control at the Tidewater site is poor; thus it is premature to attempt to extract tectonic details from the backstrip analysis. However, it appears that this and perhaps other sites more distant from the continental margin (and inferred major basin-defining faults) had a more subdued response to regional tectonic events than sites to the west, even though the timing appears synchronous.

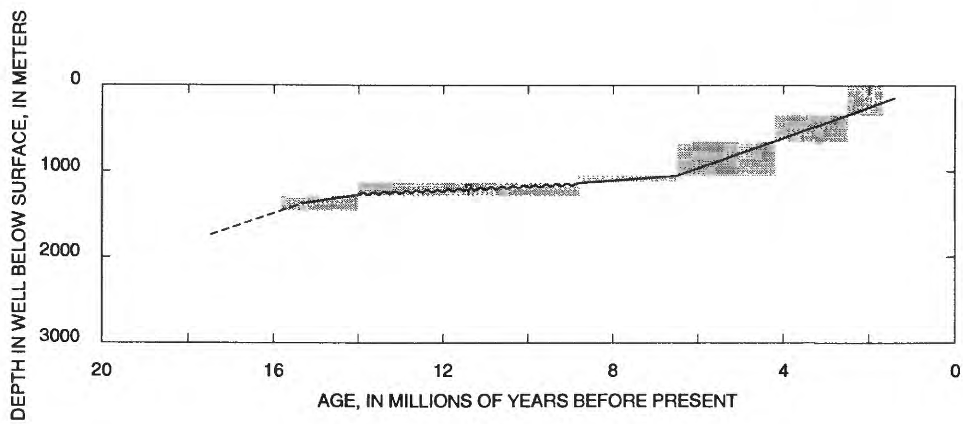

Figure 7*B*. Age-depth plot for Union Newlove No. 51 well (Orcutt Field) showing inflection points indicating changes in rate of sediment accumulation. Steeper slopes indicate rapid rates of sediment accumulation; flatter slopes indicate slow rates of sediment accumulation. Solid line, interpolated rate of sediment accumulation; dashed line, extrapolated rate; wavy line, hiatus or condensed interval. Shaded areas represent benthic foraminiferal stages (see fig. 3).

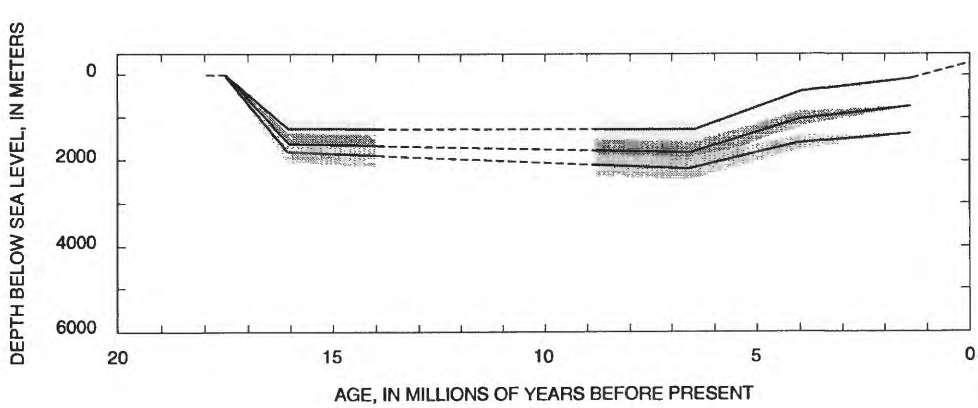

Figure 7*C*. Backstrip plot for Union Newlove No. 51 well (Orcutt Field) showing isostatic loading and tectonic components of vertical movement. Upper curve represents paleobathymetry inferred from benthic foraminifers (Ingle, 1985a; Garrison, 1985; Lagoe, 1987). Lower curve represents total (decompacted) movement of Franciscan Complex rocks. Middle curve represents residual tectonic movement after sediment and water loading are removed from lower curve. Shaded area on each curve represents range in paleobathymetric estimates. Positive slope indicates uplift; negative slope indicates subsidence; cumulative sediment thickness represented by vertical distance between basement (lower) and paleobathymetry (upper) curves.

Tectonic Events Recorded at Study Sites

The sequence of tectonic events documented in the Santa Maria area by others (see Namson and Davis, 1990; Sedlock and Hamilton, 1991; Clark and others, 1991) is reflected in vertical tectonic movement that is recorded at our study sites. In particular, all sites record an early Miocene subsidence event during inferred transtension and a middle Miocene interruption in sediment accumulation or a condensed interval. The sites with more detailed geohistories also record a complicated and disparate late Miocene episode (about 6.5 Ma) of tectonic deepening or shoaling depending on location and an early Pliocene (about 3.5 Ma) deepening during inferred transpression. All sites record late Pliocene to Holocene uplift.

Two sites document initially abrupt early Miocene subsidence that later slowed. Rapid initial subsidence may have also occurred at the other sites, but the data are inadequate to resolve this possibility. It is also difficult to resolve whether late Miocene compression began throughout the province at the same time because of the limited availability of biostratigraphic data.

In summary, backstrip techniques are useful in constraining rates, timing, and magnitude of vertical movement.

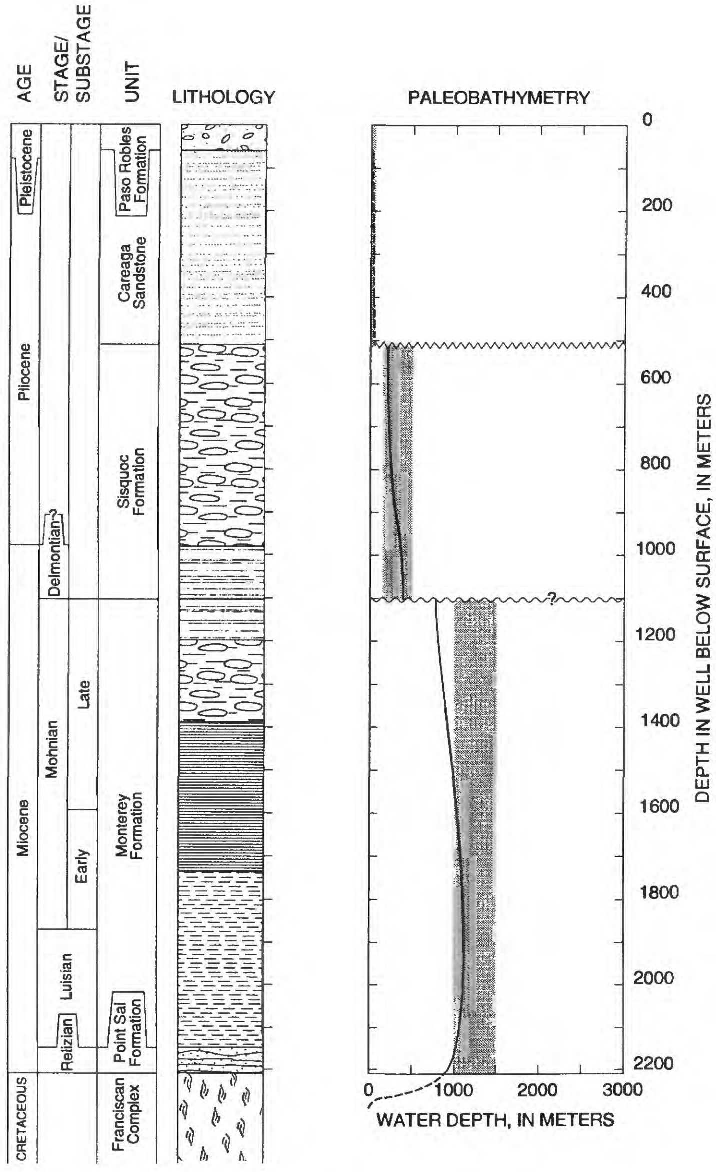

Figure 8A. Lithostratigraphy and paleobathymetry for Tidewater Davis No. 1 well (Zaca Field). Shaded areas represent range in paleobathymetric estimates inferred from benthic foraminifers. Data and stage/substage boundary (see fig. 3) determinations from Ingle (1985a) and Garrison (1985). See figure 2 for explanation of patterns and symbols.

To yield a complete model of past tectonism, these results need to be integrated with regional faulting and folding histories. Furthermore, additional study sites are needed to detail the spatial and temporal evolution of the structurally complex Santa Maria basin region.

LATE CENOZOIC PLATE TECTONIC SETTING OF CENTRAL CALIFORNIA

The history of plate interactions along the central California margin appears to be reflected in the timing and nature of tectonism within Santa Maria province. During early Cenozoic time, the central California continental margin was part of the North America Plate, and the Farallon Plate was being subducted eastward underneath the margin. About 30 Ma, two microplates detached from the Farallon Plate between the Pioneer and Murray Fracture Zones (Atwater, 1989; Lonsdale, 1991; Fernandez and Hey, 1991). The Pacific Plate, just south of the Pioneer Fracture Zone (Wilson, 1988), interacted directly with North America sometime after 30 Ma (Atwater, 1970) at a latitude north of Point Arguello (Atwater and Molnar, 1973; Stock and Molnar, 1988), with the Gulf of California closed by 310 km of back slip along the San

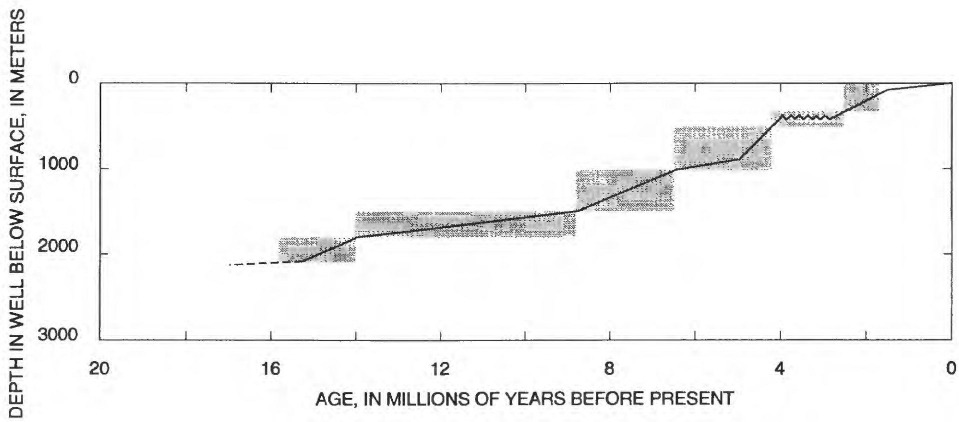

Figure 8*B*. Age-depth plot for Tidewater Davis No. 1 well (Zaca Field) showing inflection points indicating changes in rate of sediment accumulation. Steeper slopes indicate rapid rates of sediment accumulation; flatter slopes indicate slow rates of sediment accumulation. Solid line, interpolated rate of sediment accumulation; dashed line, extrapolated rate; wavy line, hiatus or condensed interval. Shaded areas represent benthic foraminiferal stages (see fig. 3).

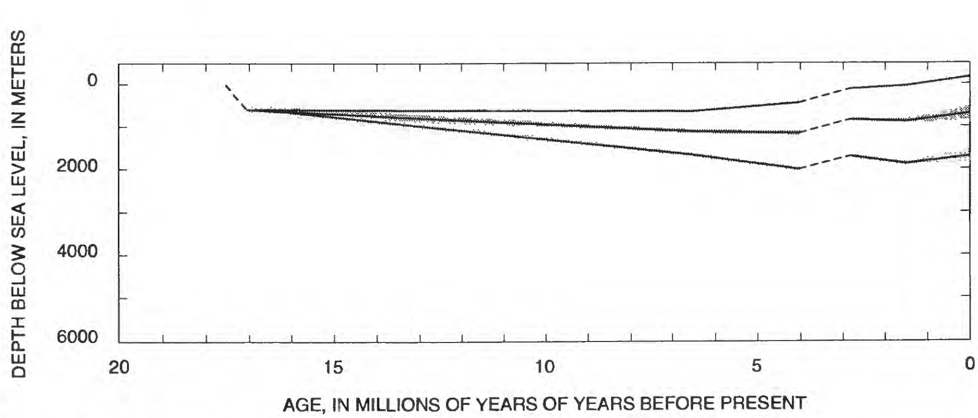

Figure 8*C*. Backstrip plot for Tidewater Davis No. 1 well (Zaca Field) showing isostatic loading and components of vertical movement. Upper curve represents paleobathymetry inferred from benthic foraminifers (Ingle, 1985a; Garrison, 1985). Lower curve represents total (decompacted) movement of Franciscan Complex rocks. Middle curve represents residual tectonic movement after sediment and water loading are removed from lower curve. Shaded area on each curve represents range in paleobathymetric estimates inferred from benthic foraminifers (Ingle, 1985a; Garrison, 1985). Positive slope indicates uplift; negative slope indicates subsidence; cumulative sediment thickness represented by vertical distance between basement (lower) and paleobathymetry (upper) curves.

Andreas transform. The newly formed Pacific-North America transform boundary separated the Farallon Plate into northern and southern remnants (see Dickinson and Snyder, 1979a); however, subduction of Farallon-derived microplates, between these Farallon remnants, continued into the early Miocene.

Thus, the initial segment of the Pacific-North America transform boundary formed along the margin between the Mendocino and Pioneer Fracture Zones when this ridge segment stopped spreading, with Juan de Fuca-North America subduction occurring to the north and microplate-North America subduction occurring to the south of the initial transform boundary (Lonsdale, 1991; Fernandez and Hey, 1991). The length of the central California transform boundary increased during the early Miocene by northward migration of the Mendocino Triple Junction, episodic ridge-segment deaths, and transfer of microplates to the Pacific Plate (Lonsdale, 1991; Fernandez and Hey, 1991).

The composites of Oligocene and younger plate configurations in the central California region (figs. 9 and 10)

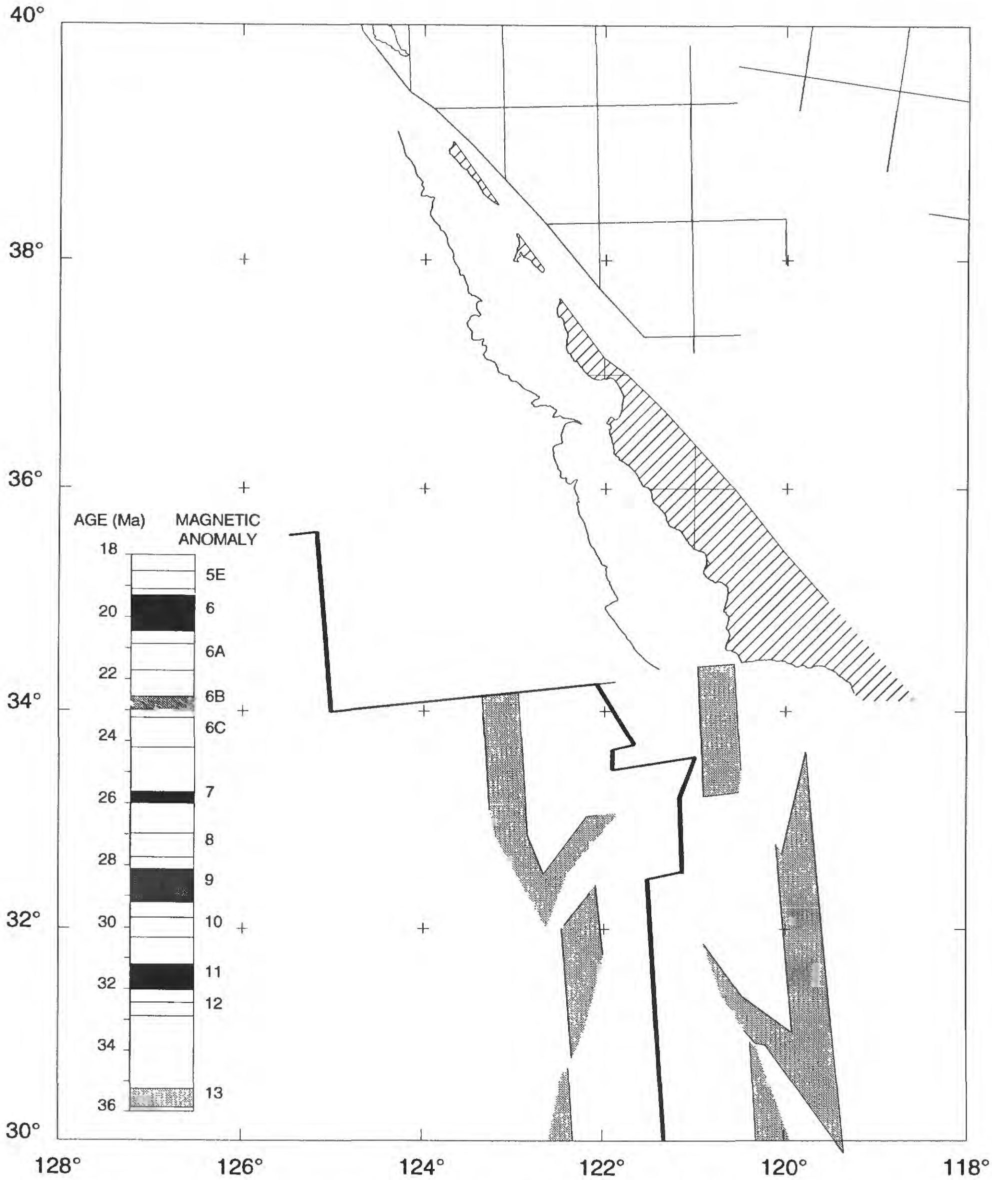

Figure 9*A*. Reconstruction of Pacific, Farallon, and North America Plates with coastal California block fixed, 33.0 Ma. Age scale (Kent and Gradstein; 1985) at lower left shows age in Ma of selected isochrons. In figures 9*A* through *J*, spreading ridges are thick black lines, transform faults are medium black lines, and fracture zones are thin black lines; isochrons east of California coastline are shown in gray; coastal California block has diagonal lines; grid shows extension between interior California block and North America through time. See fig. 10 for names of plates and fracture zones.

are based on global plate-circuit reconstructions of the Pacific Plate to a rigid North America Plate (Stock and Molnar, 1988) and forward-modeling reconstructions of microplates relative to the Pacific Plate (Fernandez and Hey, 1991; see same for explanation of forward-modeling technique). In a few aspects, the magnetic anomaly interpretations of Fernandez and Hey (1991) differ from those of Lonsdale (1991). We agree with Lonsdale that there is only evidence for one microplate, the Monterey Microplate, between the Pioneer and Morro Fracture Zones (fig. 10) and that the anomaly sequence on the Pacific Plate recording Monterey Microplate spreading has no significant gaps or duplications. Therefore, we have made the following modifications to the Fernandez and Hey (1991) reconstructions of plate configurations younger than 30 Ma. We removed the Reyes Microplate north of the Monterey Microplate and, in part, replaced it by a northward extension of the Monterey Microplate to what Lonsdale terms the Farallon Fracture Zone (aligning approximately with the Farallon Islands). We changed the details of the reorientation from a north-south to a northeast-southwest oceanic ridge orientation to conform to Lonsdale's (1991) age identifications, and we slowed the Pacific-Monterey ridge spreading rate slightly to yield the same spreading distance as Lonsdale (1991) without assuming that anomaly 7 (fig. 9A) is missing from the Pacific Plate.

Our reconstructions differ from previous ones (for example, Atwater, 1989; Lonsdale, 1991) because of the

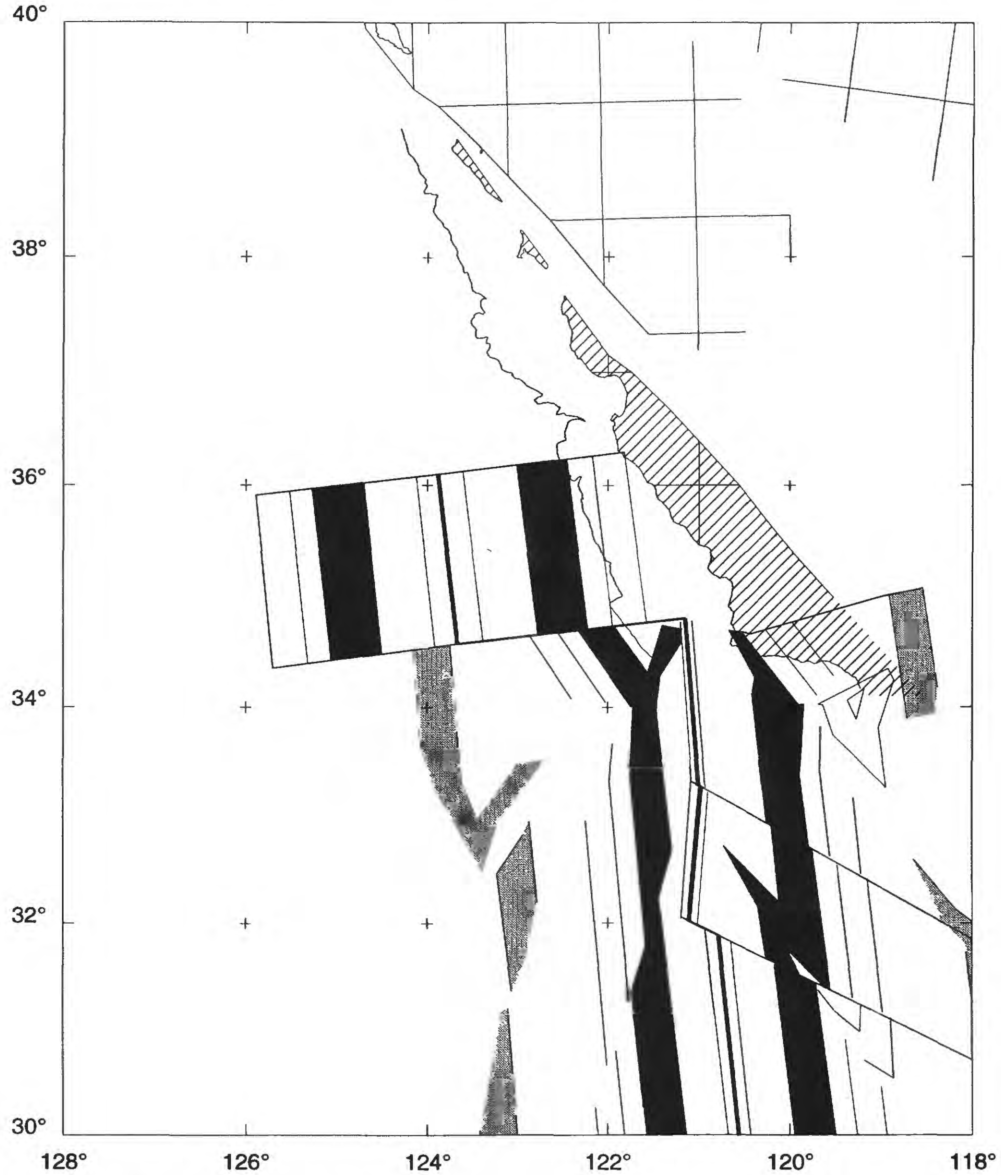

Figure 9*B*. Reconstruction of Pacific Plate, Monterey Microplate, Arguello Microplate, and North America Plate with coastal California block fixed, 30.0 Ma. See fig. 9*A* for explanation of patterns.

additional attempt to model shortening of coastal California, its lateral movement along the California continental margin by way of the San Andreas Fault, and extension in the Basin and Range Province. Because each composite (fig. 9*A–I*) represents a specific time in the past, the difference between two reconstructions indicates the net displacement, not the actual displacement path, for plate motion between specific times. Also, plate circuits have only been completed for 35, 20, and 10 Ma (Stock and Molnar, 1988); therefore, any other reconstructions represent interpolations between 35 and 20 Ma, 20 and 10 Ma, or 10 and 0 Ma. These interpolations result in artifacts, such as the large apparent change in plate-velocity vectors at 20 Ma (fig. 11), which could have occurred anytime between 30 and 15 Ma, although most likely they occurred about 26 Ma (Cande and others, 1992). More tightly constrained displacement histories will require shorter time intervals between global plate-circuit reconstructions and more detailed chronologies of late Cenozoic tectonism and volcanism along the California continental margin.

Reconstructed Positions of Central California

During the Cenozoic, the plate tectonic setting of the central California continental margin shifted from an accretionary North America continental margin overlying Farallon Plate subduction to oblique subduction between

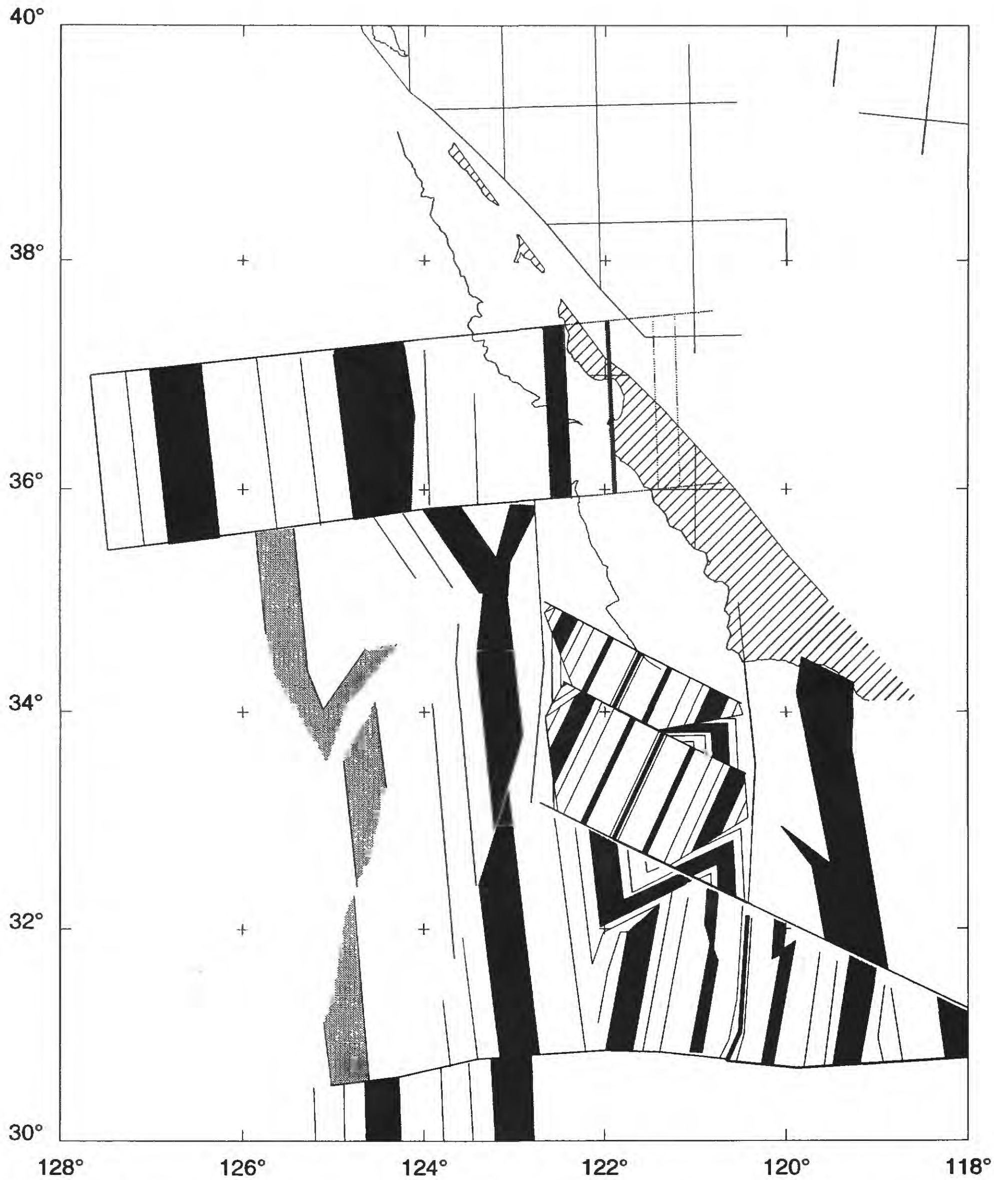

Figure 9*C*. Reconstruction of Pacific Plate, Monterey Microplate, Arguello Microplate, and North America Plate with coastal California block fixed, 24.0 Ma. See fig. 9*A* for explanation of patterns.

the microplates and North America and then to transform motion with modest amounts of divergence or convergence between the Pacific and North America Plates. Currently, the central California continental margin appears to be almost completely coupled to the Pacific Plate, with the major portion of transform motion between the Pacific and North America Plates occurring along the San Andreas Fault to the east. Plate motion estimates for the last 3 m.y. and geodetic measurements for the last 50 years require little or no strike-slip displacement west of the San Andreas Fault Zone (DeMets and others, 1990; Feigl and others, 1990; McWilliams, 1991; Baksi and others, 1992; Feigl and others, 1993). Minor amounts of modern north-east-directed shortening (4–6 mm/yr) have been documented in the Santa Maria province (Harris and Segall, 1987; Feigl and others, 1990; Feigl and others, 1993), indicating that this area is still part of the Pacific-North America plate boundary, at least for the normal component of relative motion.

For our reconstructions, several simplifying assumptions were made: (1) The reconstructions are fixed in the frame of a California central coast microplate, defined as the continental material west of the San Andreas Fault and north of the Transverse Ranges; (2) the motion of this microplate relative to an interior California microplate across the San Andreas Fault was specified to produce

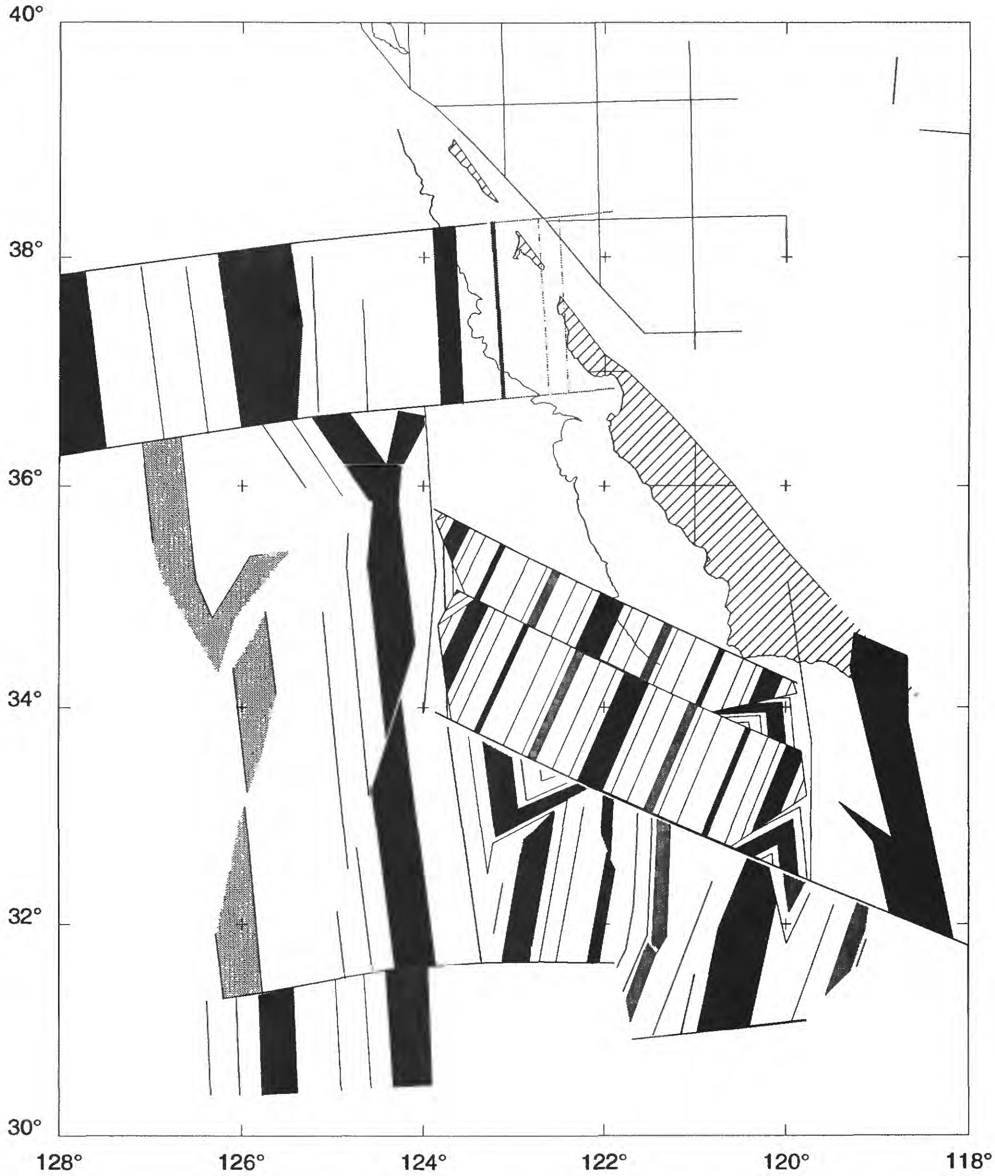

Figure 9*D*. Reconstruction of Pacific Plate, Monterey Microplate, Arguello Microplate, and North America Plate with coastal California block fixed, 19.7 Ma. See fig. 9*A* for explanation of patterns.

310 km of right-lateral displacement and several kilometers of convergence since 10 Ma; (3) the interior California microplate is defined as bounded by the San Andreas and Garlock faults, and the frontal faults of the Eastern Sierra Nevada; (4) for simplicity, we assumed these microplates had no internal deformation, and their motion rates were constant; and (5) the motion of the California microplates relative to North America was specified such that at 30 Ma interior California did not overlap with the Colorado Plateau and that coastal California did not overlap with the Pacific Plate, as reconstructed relative to North America by Stock and Molnar (1988). Avoiding both of those overlaps requires either a larger translation or a larger clockwise rotation relative to geographic north than most workers would expect. The motion specified in table 2 corresponds to a motion of the southern Sierra Nevada of 15 mm/yr in the direction of N. 65° W., rotating with respect to local North American north at about 0.3°/m.y. The motion for 30 to 0 Ma exceeds the maximum estimate of Wernicke and others (1988) for Sierra Nevada-Colorado Plateau motion by a factor of about 1.5. Several potential sources of this discrepancy (for example, internal deformation of the California microplates or errors in estimating either the Basin and Range motion or the global circuit motion) could be resolved with little effect on the relative positions of the Santa Maria province and the offshore plates.

The assumption of rigid block behavior is clearly in error, and as better constrained displacement histories are

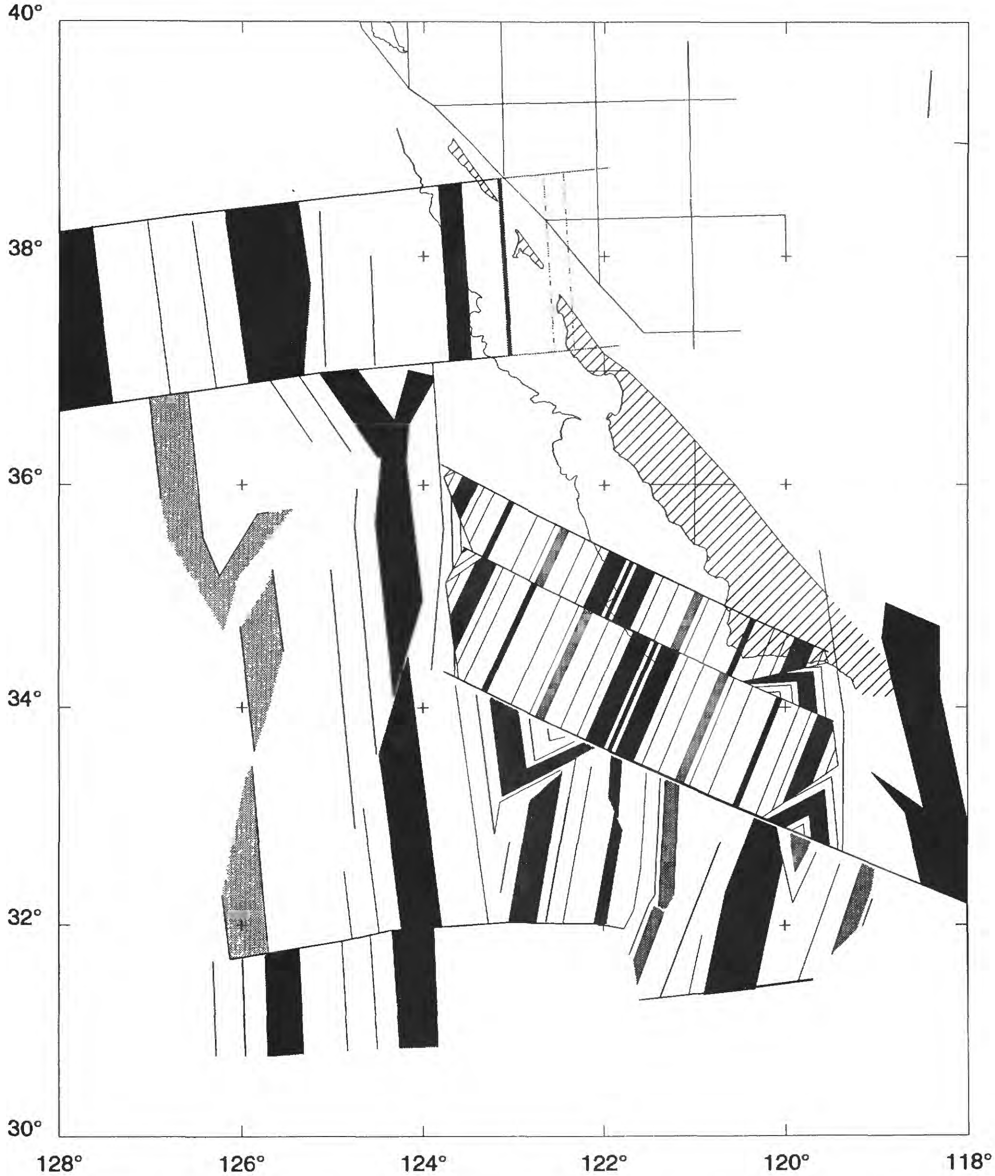

Figure 9*E*. Reconstruction of Pacific Plate, Arguello Microplate, and North America Plate with coastal California block fixed, 17.0 Ma. See fig. 9*A* for explanation of patterns.

developed, this oversimplification can be remedied. The residual component of lateral displacement between the Pacific and North America Plates (not accommodated along the San Andreas Fault) is placed at the base of the continental margin in our reconstructions (2,500-m isobath), as can be seen in the sequential northward progression of the magnetic isochrons shown in figure 9.

Reconstructed Positions of the Farallon Microplates

Reconstructions of the Pacific and Farallon Plates, Farallon remnants and microplates, the interior and coastal California blocks, and the Basin and Range Province to a rigid North America (fig. 9) from 35.6 to 10.6 Ma (magnetic anomalies 13–5; fig. 9*A*) were interpolated from Stock and Molnar (1988) poles assuming constant relative motion between the Pacific and North America Plates between poles. Reconstructions from 5.5 Ma to present (magnetic anomalies 3–0; fig. 9*A*) were extrapolated from DeMets and others (1990) poles. Uncertainties in these reconstructions are at least ±50 km in latitude and ±70 km in longitude (Stock and Hodges, 1989).

In the Stock and Hodges (1989) reconstructions, the plates in the global plate circuit (Pacific, Antarctica, Africa, and North America) are assumed to have been rigid since 20 Ma. For some of their reconstructions, the

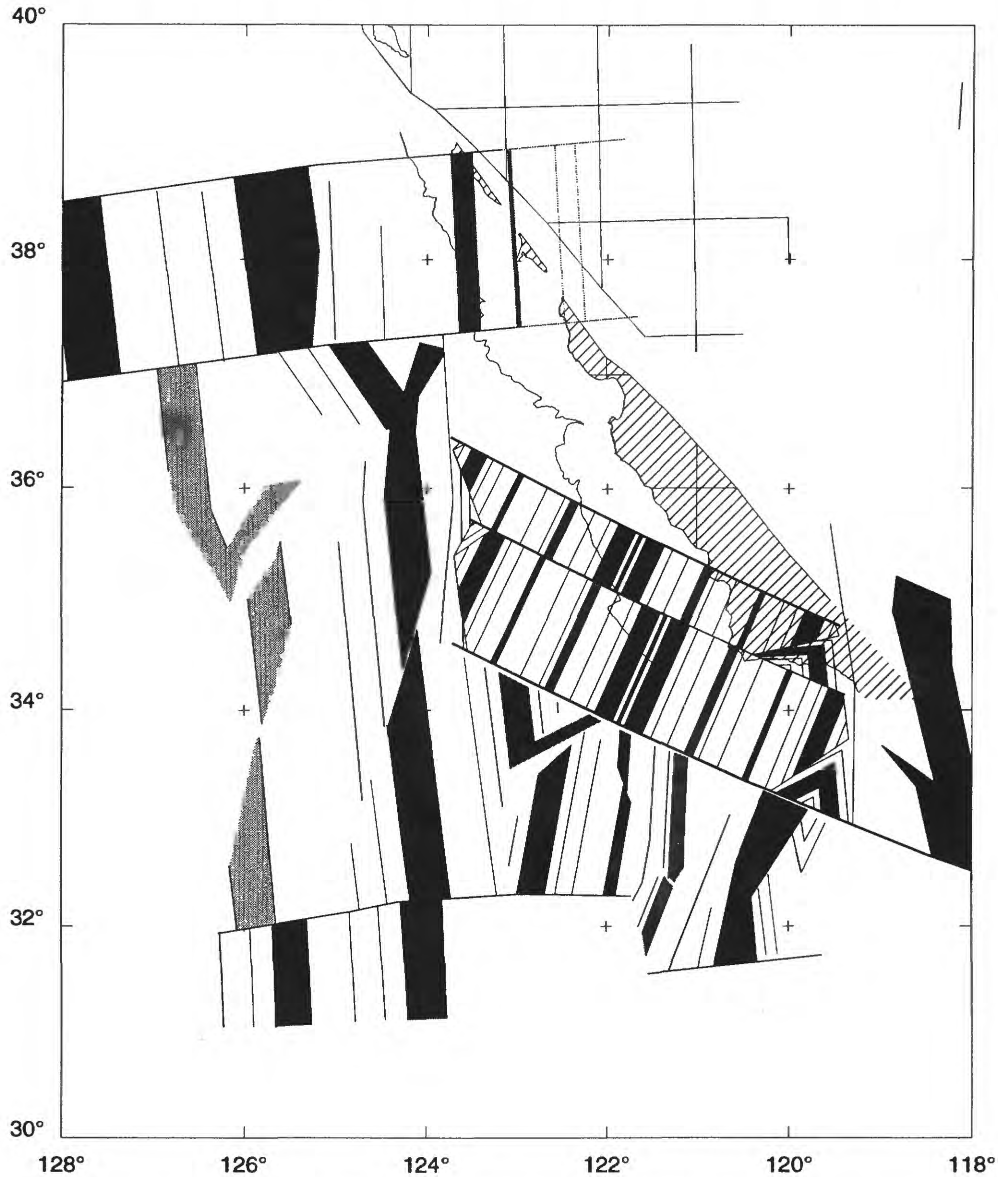

Figure 9*F*. Reconstruction of Pacific and North America Plates with coastal California block fixed, 15.0 Ma. Note that easternmost isochron shown on Pacific Plate counterpart to Arguello Microplate is Anomaly 5E (fig. 9*A*). See fig. 9*A* for explanation of patterns.

Pacific Plate overlaps continental crust of the California continental margin. This overlap is attributed to nonrigid deformation in the North America Plate (the several hundred kilometers of Neogene extension (Wernicke and others, 1988) in the Basin and Range Province). We account for Basin and Range extension in our composites (fig. 9); however, overlaps between plates still occur around 10 Ma. These overlaps give an indirect estimate of the magnitude of the uncertainties in model parameters. Extension and strike-slip displacement across the entire plate boundary limit the precision of these reconstructions.

Despite these limitations, some general inferences can be made about the location and length of the Pacific-North America transform boundary through time. This boundary initiated south of the Pioneer Fracture Zone, apparently shortly after 30 Ma (Atwater, 1970). This age might be a few million years too old if relatively slow Pacific-Monterey ridge spreading extended north to the Pioneer Fracture Zone and if several tens of kilometers of Pacific Plate have subsequently been subducted. By 25 Ma, contact between the Pacific Plate and the North America continental margin had been established between the Mendocino and Pioneer Fracture Zones, yielding a plate boundary with a length of 200 to 300 km (fig. 9*C*). As spreading between the Mendocino and Pioneer Fracture Zones appears to have recorded the same plate pair (Pacific-Juan de Fuca) as is recorded north of the Mendocino Fracture Zone, we expect that the downgoing oceanic slab south of

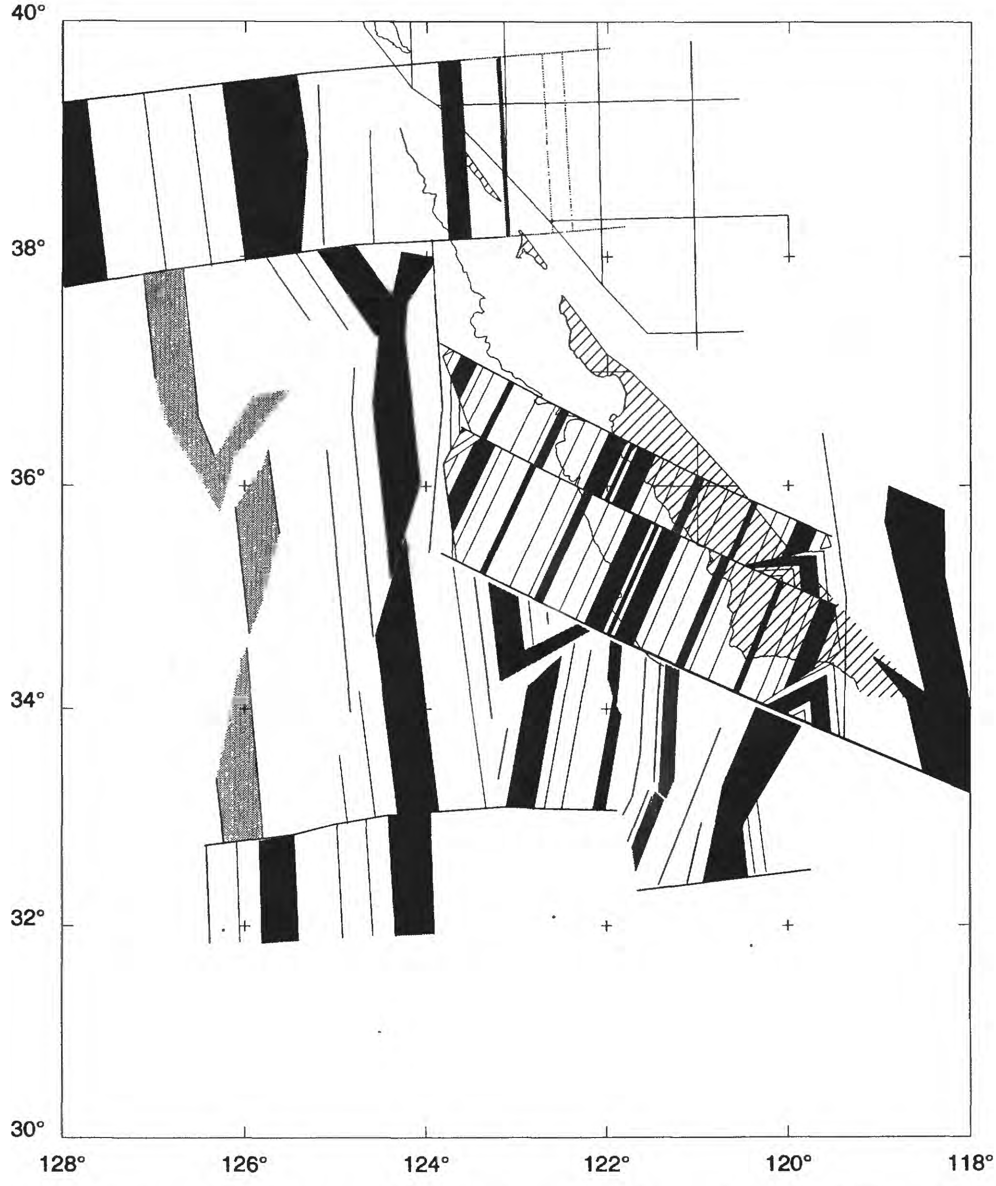

Figure 9*G*. Reconstruction of Pacific and North America Plates with coastal California block fixed, 10.0 Ma. See fig. 9*A* for explanation of patterns.

Mendocino Fracture Zone continued to subduct at the fairly fast rate of the Juan de Fuca Plate (>50 km/m.y.; Wilson, 1988), opening a significant "slabless window." We find it encouraging that this window reconstructs underneath a regionally extensive pulse of volcanism in the California Coast Ranges, mostly west of the San Andreas Fault, dated at 24 to 22 Ma (Stanley, 1987). According to the model of Zandt and Furlong (1982), Coast Ranges volcanism is a result of horizontal motion of the subducted slab causing upwelling of the trailing asthenosphere, a process that produces basaltic melt by the same mechanism that operates at midocean ridges. This model predicts extensive, nearly synchronous volcanism as the subducted slab south of the Mendocino Fracture Zone moves eastward, followed by more localized volcanism produced by the northward movement of the Juan de Fuca slab edge at Mendocino. This pattern of volcanism is exactly that observed by Stanley (1987). A prediction of the Zandt and Furlong's (1982) model not yet observed is an age progression of volcanism that youngs from west to east by 1 to 2 m.y. within the originally extensive volcanic province.

South of the Farallon Fracture Zone, magnetic anomaly 6B (about 23 Ma; figs. 1*A* and 9*A*) is the youngest continuous anomaly (Lonsdale, 1991). Assuming no subduction of the Pacific Plate subsequent to the formation of anomaly 6B, the Pacific-North America transform boundary would have lengthened by about 100 km from 22 to

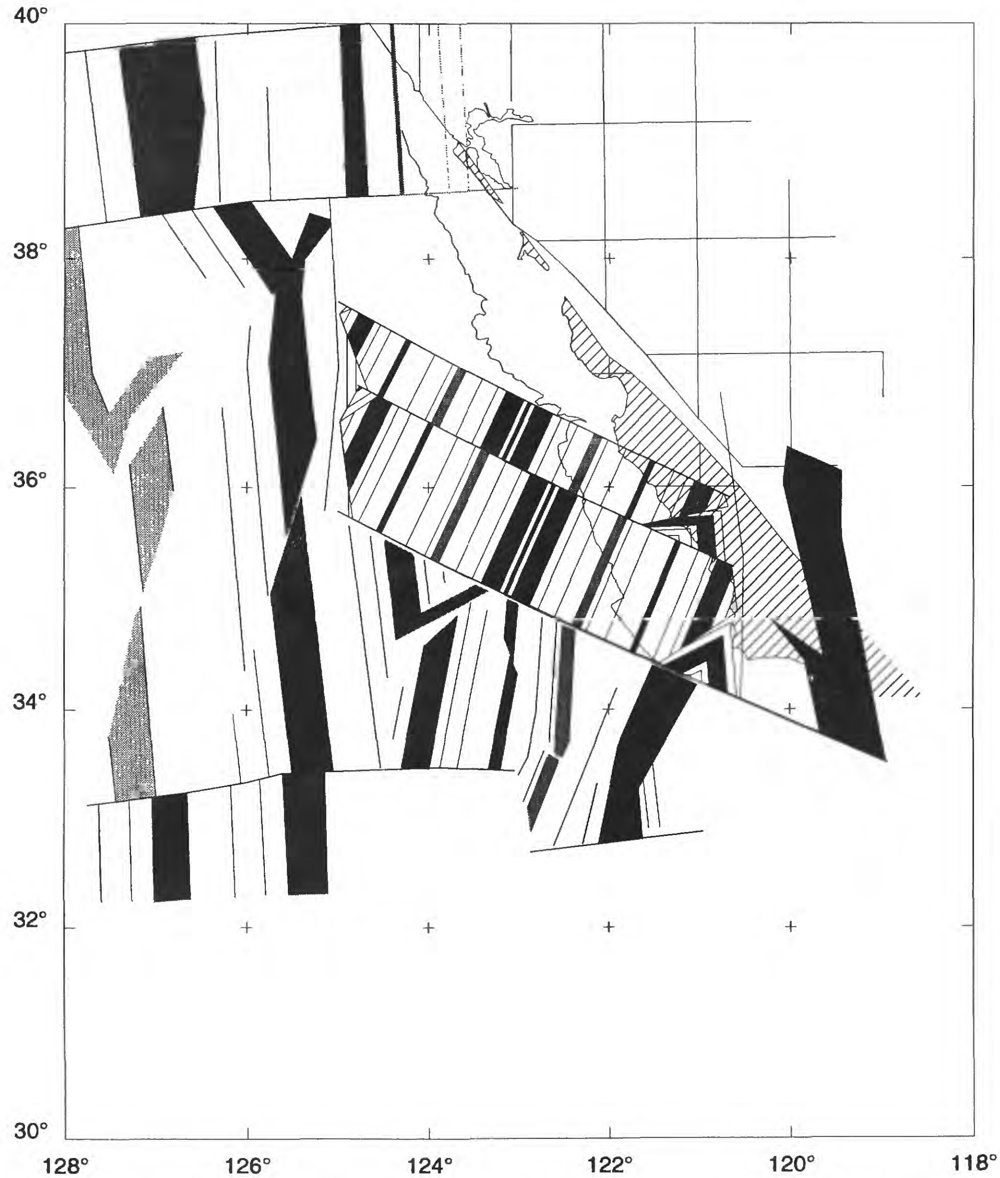

Figure 9*H*. Reconstruction of Pacific and North America Plates with coastal California block fixed, 5.0 Ma. See fig. 9*A* for explanation of patterns.

20 Ma. By 20 Ma, a boundary approximately 400 km in length with mostly transform motion stretched between the Mendocino and Monterey Fracture Zones. We presume that this boundary was at or near the continental margin, perhaps at low angle within the former subduction zone, from a lack of evidence for an inland location. A second transform initiated south of the Monterey Microplate at about 22 Ma, reaching a length of about 100 km by 19 to 20 Ma (Lonsdale, 1991). The Santa Lucia escarpment at the site of this second transform is the only place where the continental margin of California appears to have been modified by high-angle faulting (Lonsdale, 1991; Miller and others, 1992; Howie and others, 1993).

Subduction of the Monterey Microplate continued until about 19 Ma, when the Pacific-Monterey ridge segment, adjacent to the Santa Maria basin area, stopped spreading, and the relict Monterey Microplate was transferred to the Pacific Plate. With this transfer, the Pacific-North America Plate boundary again became contiguous from the Mendocino Fracture Zone to near the Arguello Fracture Zone, a distance of about 700 km. At this time, the plate boundary appears to move into the North American Continent.

Lengthening of the transform boundary to the southeast continued as spreading at the north end of the East Pacific Rise brought more of the Pacific Plate into contact with North America. The transform boundary rapidly lengthened by about 300 km over the interval from 18 to 16 Ma, encompassing all the area now offshore from the California Continental Borderland. Offshore from much of

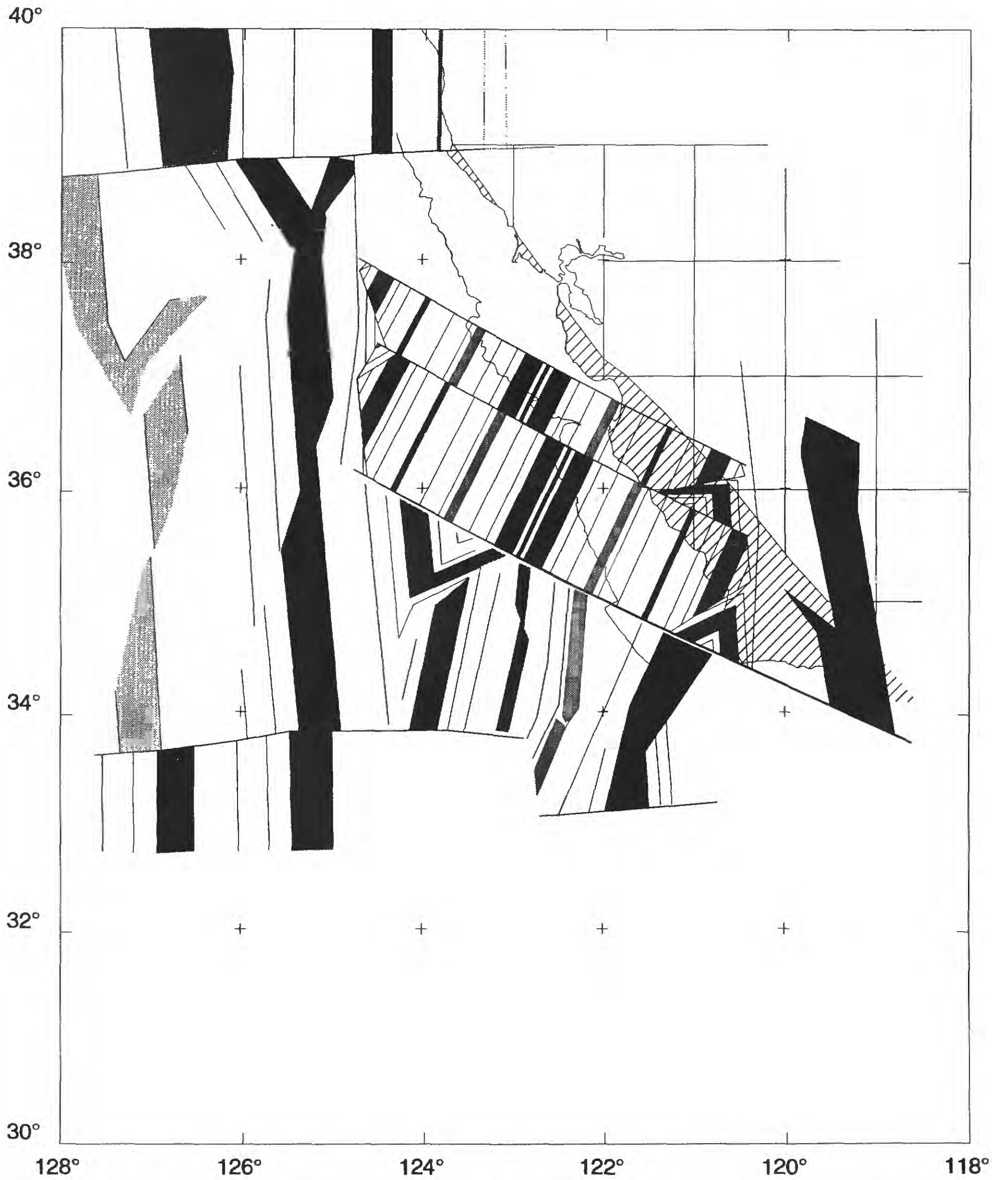

Figure 9*I*. Modern configuration of Pacific Plate, relict Monterey Microplate, and North America Plate. See fig. 9*A* for explanation of patterns.

the California Continental Borderland, magnetic anomaly 5D (about 17.5 Ma) is the youngest identifiable isochron constraining the cessation of spreading to post-17.5 Ma, likely about 16 Ma (Fernandez and Hey, 1991). The voluminous Conejo Volcanics erupted in the Santa Monica Mountains (15.5–13.5 Ma; Dibblee and Ehrenspeck, 1993; Weigand and Savage, 1993) following cessation of spreading in the borderland area. In summary, the Pacific-North America transform margin lengthened by about 1,000 km between 30 and 16 Ma, even though relative displacement between the Pacific and North America Plates was only about 400 km during this interval (fig. 10).

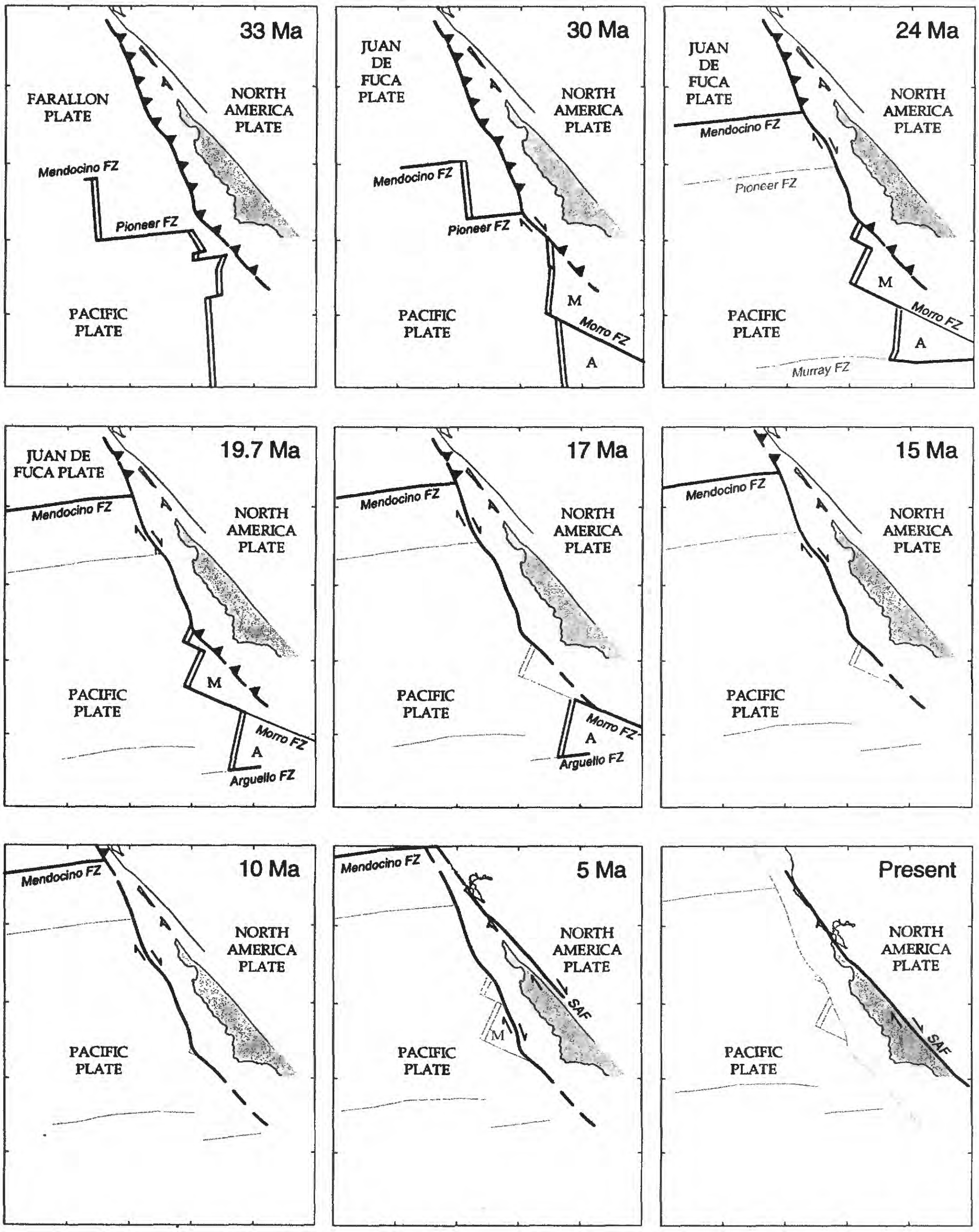

Figure 10. Simplified summary diagram of figure 9 showing change in plate boundaries through time and transfer of coastal California (stippled) from North America Plate to Pacific Plate. Active boundaries are shown with thick lines (paired arrows show relative motion) and inactive boundaries are shown with dotted lines: Paleo-spreading ridge shown by double lines; paleo-subduction zone shown by barbed line. FZ, fracture zone; M, Monterey Microplate; A, Arguello Microplate; SAF, San Andreas Fault. Reappearance of relict Monterey Microplate at 5 Ma is an artifact reflecting insufficient data.

DISCUSSION

The early Cenozoic record of tectonism in the Santa Maria province is fragmentary and will not be addressed here. However, the early Cenozoic was apparently a period of oblique subduction of young oceanic crust, and if the southern Cascadia margin can be used as an analog for margin response to oblique subduction of young buoyant plates, strong coupling between the accretionary margin and underlying oceanic lithosphere can be inferred, resulting in folding and uplift of the margin (McCrory, 1989).

Recent plate motion studies document a clockwise reorientation of the Pacific Plate velocity vector (Cande and others, 1992) and adjacent microplate vectors (Fernandez and Hey, 1991) in the latest Oligocene (about 26 Ma). This reorientation increased the obliquity of convergence across the microplate-North America plate boundary. Oblique relative motion in central California during the earliest Miocene may have been partitioned into normal and parallel components of relative motion. For example, the Russell Fault, in Cuyama basin, underwent a relatively short, intense period of right-lateral movement (23–19 Ma) followed by quiescence (Yeats and others, 1989),

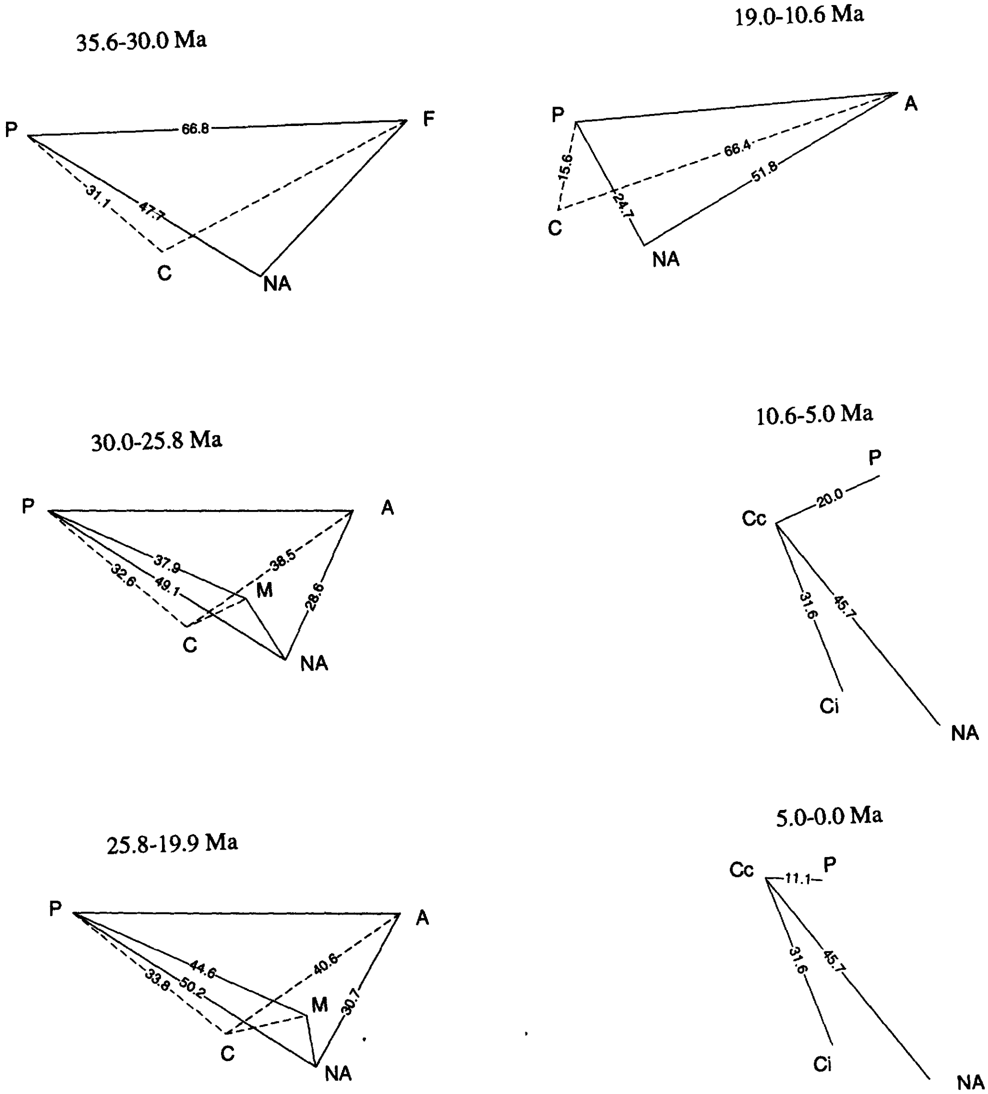

Figure 11. Plate vectors in velocity space at 35° N., 122° W. with coastal California fixed (Pacific-North America total poles from Stock and Molnar, 1988; DeMets and others, 1990; stage poles modified from Wilson, 1988; Harbert, 1991; McWilliams, 1991; Cande and others, 1992). Note that for 19.0 to 10.6 Ma vectors, Arguello Microplate motion ceased about 16.0 Ma. A, Arguello Microplate; C, California Microplate; Cc, coastal California Microplate; Ci, interior California Microplate; F, Farallon Plate; M, Monterey Microplate; NA, North America Plate. Numbers along vectors represent plate speeds in mm/yr.

Table 2. Model for relative motion of western North America microplates

[positive rotation angle rotates plate 2 counterclockwise, forward in time, relative to plate 1. Lat, latitude; Lon, longitude; Ang, angle; deg, degrees; N, north; E, east]

Plate 1	Plate 2	Time (Ma)	Rotation pole Lat (deg N)	Lon (deg E)	Ang (deg)
North America.	Interior Calif.	36-0	53.4	-106.4	-14.2
Interior Calif.	Coastal Calif.	10-0	47.8	-82.8	-5.7
Coastal Calif.	Santa Barbara.	15-0	34.4	-120.4	-80.0

implying that shear strain was accommodated in this area until Monterey subduction ceased at about 19 Ma.

The onset of late early Miocene extension along the central California continental margin is likely linked to the transition from subduction to strike-slip tectonics as inferred for other extensional events along the western North American continental margin (see Dickinson and Snyder, 1979b; Glazner and Bartley, 1984). If this is the case, other basins along the central and southern California continental margin should contain records of early Miocene extension and subsidence following the cessation of spreading on the adjacent oceanic-ridge segment.

The onset of volcanism in Santa Maria basin also appears to be linked with the cessation of microplate subduction; however, there was a lag time for the transit of magma up through the accretionary margin. Bimodal volcanism dated at about 18 to 16 Ma, which accompanied initiation of late early Miocene extension, has a mixed magma source composed of oceanic-ridge and continental-crust materials (Cole and Basu, 1992). This period of volcanism is attributed to upwelling of oceanic magma into the "slabless window" formed behind the subducted Monterey Microplate. However, this was not a simple "slabless window," as a fragment of relict Monterey Microplate remains beneath central California and can be traced as far east as the San Andreas Fault (Howie, 1991). The precise location of this remnant oceanic crust beneath a reconstructed California continental margin when spreading ceased at about 19 Ma is unknown given both the uncertainties in the global-circuit reconstructions and the uncertainties in the reconstruction of strike-slip faults such as the Hosgri Fault. Our California continental margin reconstructions show the Monterey Microplate remnant to be just south of the Santa Maria basin area (fig. 9*E*) during this pulse of volcanism, with the volcanic material erupting above a true "slabless window" followed by northwestward movement of the remnant beneath the margin with the Pacific Plate. However, available constraints allow the possibility that the microplate remnant was already beneath the central California continental margin at 19 Ma and that magma upwelled into a "slabless window" formed by delamination of the oceanic crust and subduction of the lower lithosphere (Howie, 1991).

Transfer of the Monterey Microplate to the Pacific Plate when spreading ceased (about 19 Ma) would have created a wide Pacific-North America subhorizontal boundary zone at depth. The low angle boundary perhaps allowed shear to be distributed between the oceanic crust and overlying relict accretionary complex (Howie and others, 1993), until the oceanic lithosphere cooled and coupled to the overlying margin, completing transfer of the margin to the Pacific Plate. This postulated distributed shear is a possible mechanism for in place rotation of fault-bounded blocks, such as the western Transverse Ranges, above a subhorizontal shear zone. In fact, dilatation and initial subsidence of the Santa Maria basin may have been accompanied by oblique normal slip, also beginning about 18 Ma, associated with initial clockwise rotation of the western Transverse Ranges about a pivot located near Point Arguello (Hornafius, 1985; Luyendyk and Hornafius, 1987).

Miocene subsidence occurred in two stages. The initial rapid phase from about 18 to 16 Ma, associated with volcanism, is attributed to extreme local extension of the continental crust associated with the beginning of western Transverse Range rotation and triggered by Monterey Microplate capture. The subsequent slower phase (about 16 to 7 Ma) is attributed to thermal subsidence associated with cooling of underplated young oceanic lithosphere that had moved northwestward with the Pacific Plate to a location beneath the Santa Maria basin area.

Recent plate-motion studies shift the Pliocene clockwise reorientation of the Pacific Plate velocity vector and onset of transpression across the Pacific-North America transform boundary from about 3.9 to 3.4 Ma (Harbert and Cox, 1989; Harbert, 1991) back to about 6 to 5 Ma (Cande and others, 1992). This older age for onset of transpression is approximately coeval with the time of dip-slip faulting and bathymetric inversion seen in Santa Maria basin. This inversion had previously been attributed to normal faulting (Namson and Davis, 1990), but the pattern of uplift and subsidence documented by backstrip analysis is more easily explained by crustal shortening, an explanation that agrees with a transpressive stress regime. This shift in timing of the Pacific velocity change leaves the uplift event that occurred at about 3.5 Ma, documented in our backstrip plots (figs. 4*C*, 5*C*, 6*C*, 7*C*, and 8*C*), unexplained.

Subhorizontal detachment faults or distributed ductile shear within the lower part of the Franciscan Complex near the base of the seismogenic zone (9–14 km deep) are inferred beneath the southern Coast Ranges as far east as the Nacimiento Fault (Crouch and others, 1984; Howie, 1991; Miller and others, 1992). This postulated detachment zone could provide a mechanism for continued distribution of transform motion across a broad area.

SUMMARY

Integration of backstrip plots with new, more complete reconstructions of plate motions shows that Neogene sedimentary and volcanic events in central California basins can be interpreted in terms of the interactions of microplates with each other and the larger Pacific, Farallon, and North America Plates. When oblique subduction ceased west of central California about 19 Ma by cessation of spreading on the Pacific-Monterey ridge segment, Pacific-North America transform motion was accommodated by distributed strike-slip motion across a broad zone. About 6 to 5 Ma, the direction of Pacific-North America relative plate motion became oblique to strike-slip fault zones and should have caused transpression along them, producing up to 10 mm/yr of shortening in central California. Since about 3 Ma, the plate boundary has been partitioned between strike-slip movement along the San Andreas Fault system and shortening along reverse faults and associated folds to the west and east of the San Andreas Fault system.

The continuation of microplate subduction along the California continental margin in the Miocene has significant implications for the evolution of the San Andreas Fault system. In particular, this system clearly began as two separate segments, one in northern central California and the other in southern Baja California. These segments propagated toward each other over a period of several million years and finally linked about 16 Ma, at the termination of Arguello subduction.

The central California continental margin experienced a period of volcanism, normal faulting, and rapid tectonic subsidence starting about 18 Ma. A 10-m.y. interval of slow subsidence followed this period. About 6 Ma, the margin underwent a period of shortening, reflected in rapid bathymetric inversion. A 2-m.y. interval of slow uplift followed this period. About 3 Ma, the margin again experienced a period of intense shortening reflected in large-scale folding of Neogene strata. This latest shortening event is ongoing, as documented by modern geodetic measurements and earthquakes with reverse-fault mechanisms.

Documented geologic constraints are consistent with a plate kinematic mechanism for tectonism along the central California margin during the Neogene. However, uncertainties about palinspastic restoration of extension across western North America and uncertainties about reconstruction of tectonically disrupted California hamper the reliability of these correlations. The implications of this kinematic model for the dynamics of transform plate margins can be tested with detailed backstrip modeling of La Honda, Santa Cruz, Salinas, and other central California continental margin basins.

Clearly much better constraints are needed on the timing and amount of extension and shearing in Santa Maria province. Currently, strike-slip faulting is not well enough constrained to be tied with specific plate tectonic events. Also, there is not enough data to verify or discount the model of eastward migration of the transform boundary, but it appears that this shift of transform motion from the western edge of the continental margin to the San Andreas Fault is linked to behavior of the relict Monterey slab.

In summary, available data indicate that Pacific Plate behavior in the late Cenozoic dominated tectonic events along the central California continental margin. While subduction of the Farallon Plate and its derivatives was ongoing, Pacific Plate influence was indirect, expressed by reorientation of spreading ridges and subsequent rotation of microplates. Since subduction ceased, Pacific Plate behavior has affected the margin directly, initially by capture of the underthrust relict slab and later by changes in relative motion that induced a component of compression across the transform boundary, compression expressed as regional uplift as well as reverse faulting and folding.

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APPENDIX—DATA USED IN BACKSTRIP PROGRAMS

Data used in backstrip program for Cost well (OCS-CAL 78–164–1)

[Age and depth refer to top of unit listed unless otherwise noted. See figure 4 for sources of data. Water depth at well is 435 m. Units enclosed within quotes are considered to be offshore stratigraphic equivalents of named onshore units. Mud, mudstone/shale; Sand, undifferentiated sandstone; Carb, undifferentiated limestone; Sil, biosiliceous sediment; Mic, micritic carbonate

Unit	Age (Ma)	Depth (m)	Lithology (percent)					Water depth (m)		Eustatic sea level
			Mud	Sand	Carb	Sil	Mic	Min	Max	(m)
Quaternary deposits	0.0	0.0	80?	20?	0	0	0	450	450	0
Volcaniclastic conglomerate and sandstone.										
Horizon A	1.5	163.1	0	100	0	0	0	500?	2000?	0
Horizon B	1.7	172.2	0	100	0	0	0	1500	2000	0
Sandstone	1.8	224.0	20	80	0	0	0	1500	2000	0
Siltstone	2.0	373.4	80	20	0	0	0	1500	2000	0
"Careaga" Sandstone										
Horizon A	2.2	511.2	20	80	0	0	0	1500	2000	0
Horizon B	2.5	663.0	20	80	0	0	0	2000	2500	0
"Foxen" Mudstone										
Horizon A	2.6	681.2	75	10	0	0	15	2000	2500	0
Horizon B	4.2	845.9	60	10	0	15	15	500	2000	0
Sisquoc Formation	6.5	1004.3	60	5	0	20	15	500	1500	0
Monterey Formation										
Horizon A	7.2	1321.3	60	5	0	20	15	500	1500	0
Horizon B	8.2	1614.0	20	5	0	75	0	500	1500	0
Horizon C	8.8	1778.5	20	5	0	75	0	500	1500	0
Horizon D	9.7	1812.7	70	10	0	0	20	500	1500	0
Horizon E	14.0	1970.6	70	10	0	0	20	500	1500	0
Horizon F	15.5	2345.5	70	10	0	0	20	500	1500	0
Conglomerate and sandstone.	17.5	2434.5	100	0	0	0	0	0?	500?	0
Base of Neogene section.	18.0?	2520.7	100	0	0	0	0	0?	500?	0

Data used in backstrip program for Texaco Nautilus well (OCS-P 496-1), Santa Maria basin, offshore

[Age and depth refer to age at top of unit listed unless otherwise noted. Hiatus between Monterey Formation and unnamed volcaniclastic rocks is estimated to represent time interval between 17.5 and 9.5 Ma. See figure 5 for sources of data. Water depth at well is 375 m. Units enclosed within quotes are considered to be offshore stratigraphic equivalents of named onshore units. Mud, mudstone/shale; Sand, undifferentiated sandstone; Carb, undifferentiated limestone; Sil, biosiliceous sediment; Mic, micritic carbonate]

Unit	Age (Ma)	Depth (m)	Lithology (percent)					Water depth (m)		Eustatic sea level
			Mud	Sand	Carb	Sil	Mic	Min	Max	(m)
Quaternary and upper Pliocene deposits.	0.0	0	75	25	0	0	0	375	375	0
"Foxen" Mudstone										
Horizon A	3.4	198	100	0	0	0	0	2000	2500	0
Horizon B	3.8	259	90	5	0	0	5	2000	2500	0
Horizon C	4.0	289	100	0	0	0	0	2000	2500	0
Sisquoc Formation										
Horizon A	4.1	300	100	0	0	0	0	1500	2000	0
Horizon B	4.3	335	100	0	0	0	0	500	1500	0
Horizon C	4.7	390	95	5	0	0	10	500	1500	0
Horizon D	4.9	420	95	5	0	0	0	150	500	0
Horizon E	5.1	442	80	20	0	0	0	150	500	0
Horizon F	5.7	530	80	20	0	0	0	150	2500	0
Monterey Formation, upper part.										
Horizon A	6.5	650	80	20	0	0	0	2000	2500	0
Horizon B	6.9	670	55	20	0	25	0	2000	2500	0
Horizon C	7.3	686	40	20	0	40	0	2000	2500	0
Horizon D	7.7	704	20	15	0	55	10	2000	2500	0
Monterey Formation, middle part.	9.3	779	20	15	0	55	10	2000	2500	0
Hiatus	9.5	789	10	60	0	25	5	2000	2500	0
Volcaniclastic deposits										
Horizon A	17.5	789	10	60	0	25	5	0	500	0
Horizon B	17.6	795	10	60	0	25	5	0	150	0
Horizon C	17.8	804	0	100	0	0	0	0	150	0
Conglomerate and sandstone										
Horizon A	18.4	834	30	70	0	0	0	0	150	0
Horizon B	20.4	926	15	70	0	0	15	0	150	0
Base of conglomerate and sandstone unit.	24.5	1124	0	100	0	0	0	0	150	0

Data used in backstrip program for Point Sal composite section (North Beach surface section, Mussel Rock surface section, and Union Los Nietos well subsurface section), Santa Maria basin, onshore

[Age and depth refer to top of unit listed unless otherwise noted. Hiatus within Monterey Formation is estimated to represent time interval between 15.5 and 14.0 Ma. See figure 6 for sources of data. Surface elevation of Union Los Nietos (Leroy A-2) well is 0 m. Mud, mudstone/shale; Sand, undifferentiated sandstone; Carb, undifferentiated limestone; Sil, biosiliceous sediment; Mic, micritic carbonate]

Unit	Age (Ma)	Depth (m)	Lithology (percent)					Water depth (m)		Eustatic sea level
			Mud	Sand	Carb	Sil	Mic	Min	Max	(m)
Holocene deposits and Paso Robles Formation.	0.0	0	50	50	0	0	0	0	0	0
Careaga Sandstone	1.5	137	30	70	0	0	0	0	100	0
Foxen Mudstone										
Horizon A	2.8	206	90	10	0	0	0	100	150	0
Horizon B	3.1	350	90	10	0	0	0	500	600	0
Horizon C	3.8	750	90	10	0	0	0	100	150	0
Sisquoc Formation										
Horizon A	4.0	791	60	30	0	10	0	400	500	0
Horizon B	5.8	1030	60	30	0	10	10	400	500	0
Monterey Formation, upper part.	6.5	1191	25	0	0	55	20	600	700	0
Monterey Formation, middle part.	7.3	1548	20	0	0	70	10	900	1300	0
Hiatus	14.0	1739	20	0	0	70	10	900	1300	0
Monterey Formation, lower part.	15.5	1740	50	15	0	10	40	700	1100	0
Point Sal Formation										
Horizon A	16.0	1991	60	40	0	0	0	500	700	0
Horizon B	16.7	2300	60	40	0	0	0	500	700	0
Horizon C	17.07	2413	90	10	0	0	0	300	700	0
Lospe Formation, upper and middle parts.	17.14	2430	40	60	0	0	0	0	150	0
Lospe Formation, lower part.	17.7	2703	0	100	0	0	0	0	0	0
Base of Lospe Formation.	17.72	2843	0	100	0	0	0	0	0	0

Data used in backstrip program for Union Newlove No. 51 well, Orcutt Field, Santa Maria basin, onshore

[Age and depth refer to top of unit listed unless otherwise noted. See figure 7 for sources of data. Surface elevation of well is 243 m. Mud, mudstone/shale; Sand, undifferentiated sandstone; Carb, undifferentiated limestone; Sil, biosiliceous sediment; Mic, micritic carbonate]

Unit	Age (Ma)	Depth (m)	Lithology (percent)					Water depth (m)		Eustatic sea level
			Mud	Sand	Carb	Sil	Mic	Min	Max	(m)
Careaga Sandstone										
Horizon A	1.4	0	0	100	0	0	0	0	10	0
Horizon B	4.0	150	0	100	0	0	0	0	10	0
Sisquoc Formation										
Horizon A	4.0	150	50	0	0	50	0	150	500	0
Horizon B	6.5	594	50	0	0	50	0	150	500	0
Monterey Formation	6.5	594	0	0	0	90	10	1000	1500	0
Point Sal Formation	16.0	859	60	40	0	0	0	1000	1500	0
Lospe Formation	17.0	1253	0	100	0	0	0	0	0	0
Base of Lospe Formation.	17.7	1300	0	100	0	0	0	0	0	0

Data used in backstrip program for Tidewater Davis No. 1 well, Zaca Field, Santa Maria basin, onshore.

[Age and depth refer to top of unit listed unless otherwise noted. Hiatus between Sisquoc Formation and Careaga Sandstone is estimated to represent time interval between 4.0 and 2.8 Ma. See figure 8 for sources of data. Surface elevation at well is 311 m. Mud, mudstone/shale; Sand, undifferentiated sandstone; Carb, undifferentiated limestone; Sil, biosiliceous sediment; Mic, micritic carbonate

Unit	Age (Ma)	Depth (m)	Lithology (percent)					Water depth (m)		Eustatic sea level
			Mud	Sand	Carb	Sil	Mic	Min	Max	(m)
Holocene deposits and Paso Robles Formation.	0.0	0	0	100	0	0	0	-311	-311	0
Careaga Sandstone	1.5	61	0	100	0	0	0	0	100	0
Hiatus	2.8	415	100	0	0	0	0	100	150	0
Sisquoc Formation	4.0	416	0	15	0	85	0	400	500	0
Monterey Formation	6.5	965	0	0	0	100	0	600	700	0
Point Sal Formation	16.0	1819	50	50	0	0	0	500	700	0
Base of Point Sal Formation.	17.0	1859	50	50	0	0	0	500	700	0

Chapter K

Diatom Biochronology of the Sisquoc Formation in the Santa Maria Basin, California, and Its Paleoceanographic and Tectonic Implications

By MICHAEL P. DUMONT and JOHN A. BARRON

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EVOLUTION OF SEDIMENTARY BASINS/ONSHORE OIL AND GAS INVESTIGATIONS—
SANTA MARIA PROVINCE

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1. Stratigraphically important diatoms in Sweeney Road section K7

Diatom Biochronology of the Sisquoc Formation in the Santa Maria Basin, California, and Its Paleoceanographic and Tectonic Implications

By Michael P. Dumont[1] *and* John A. Barron

Abstract

Diatom biostratigraphy allows correlation and dating of the Sisquoc Formation within the Santa Maria basin, Calif. The diatom stratigraphy of the Sweeney Road section, east of Lompoc, is presented and that of six additional sections in the Santa Maria basin is summarized. The base of the Sisquoc Formation coincides with the base of the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone and is 6.0 Ma (latest Miocene) in age. Most exposures of the Sisquoc Formation in the Santa Maria basin do not range younger than the basal part of the *Thalassiosira oestrupii* Partial Range Zone or 5.0 Ma. However, the contact of the Sisquoc Formation with the overlying Foxen Mudstone in the Harris Grade section in the center of the basin falls higher in the *T. oestrupii* Zone and is estimated to be about 3.8 Ma in age.

The basal contact of the Sisquoc Formation with the underlying Monterey Formation is variable and may be difficult to recognize. Typically, the contact is a paraconformity, and occasionally, the contact coincides with the break between underlying porcellaneous rocks and overlying diatomaceous rocks. Such a diagenetic contact, however, can be diachronous over relatively short distances (3 km or less) in the Santa Maria basin and is a poor choice for distinguishing the Sisquoc Formation from the Monterey Formation. Although the Sisquoc Formation may closely resemble the Monterey Formation, it has a greater terrigenous component overall, is typically not as finely laminated, and has more prevalent massive diatomaceous mudstone than the Monterey Formation. Such criteria, however, may be difficult to establish in the subsurface or in the field. Diatoms, on the other hand, offer a reliable means for distinguishing younger (post-6.0 Ma) biosiliceous rocks that are usually age-equivalent to the Sisquoc Formation from the older (pre-6.0 Ma) rocks of the Monterey Formation.

The Sisquoc Formation was deposited during a time of relatively high eustatic sea level, which was bracketed by sea level falls that occurred at approximately 6.3 and 3.8 Ma. The tectonic reorganization of the California continental margin was intensified in the early Pliocene during Sisquoc deposition, causing uplift of the Coast Ranges and leading to an increased supply of clastic material to the Santa Maria basin.

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INTRODUCTION

Study of the Miocene-Pliocene boundary Interval in California

Throughout much of the Santa Maria and Santa Barbara basins, the Monterey Formation is overlain by diatom-bearing mudstones and sandstones of the Sisquoc Formation. Woodring and Bramlette (1950) recognized both a fine-grained basin facies and a marginal sandstone facies in the Sisquoc Formation, and they stated that within the Santa Maria basin as much as 1,524 m (5,000 ft) of rocks assignable to the formation are exposed. The soft diatomaceous and hard porcellaneous strata of the basin facies of the Sisquoc may seem indistinguishable from those of the underlying Monterey Formation; however, massive diatomaceous mudstone is more prevalent in the Sisquoc Formation, and the two formations are often separated by an unconformity in the Santa Maria basin (Woodring and Bramlette, 1950).

The Sisquoc Formation has been traditionally correlated with the "Delmontian" benthic foraminiferal stage of Kleinpell (1938, 1980). Recent diatom biostratigraphic studies (Barron, 1986a; Dumont, 1986; Barron and Baldauf, 1986; Dumont and others, 1986) suggest that rocks of the Sisquoc Formation contain the Miocene-Pliocene boundary.

Traditionally in California, the Miocene-Pliocene boundary has been drawn between Kleinpell's (1938) late Miocene "Delmontian" Stage and Natland's (1953) early Pliocene Repettian Stage. Subsequent work by Pierce (1972), Ruth (1972), and Barron (1976) demonstrated that the benthic foraminifers and diatoms found in the type "Delmontian" Stage section are middle and early late

Miocene in age. Consequently, the term "Delmontian" has been modified (now generally placed in quotation marks) to refer to the interval above the Mohnian Stage and below the Repettian Stage. This "Delmontian" interval is equivalent to the type *Bolivina obliqua* Zone of Kleinpell (1938). Kleinpell (1980), however, modified his "Delmontian" Stage to also include the *Bolivina foraminata* Zone, which underlies the *B. obliqua* Zone.

The California benthic foraminiferal stages, however, are time transgressive when compared to the radiolarian, diatom, and planktonic foraminiferal biostratigraphies (Ingle, 1967; Bandy, 1972; Crouch and Bukry, 1979). Moreover, studies during the past 30 years have shown that benthic foraminiferal faunas migrate up and down the continental slope in response to water mass changes.

The great majority of calcareous planktonic zonations (planktonic foraminifers and calcareous nannofossils) were developed in low latitudes using tropical and subtropical species. As a result of high-latitude climatic cooling during the late middle Miocene (Kennett, 1977, Savin, 1977), calcareous plankton declined in diversity in California waters and developed a cool to warm-temperate affinity (Ingle, 1967, 1981), making use of low latitude planktic zonations difficult. Consequently, correlations based on tropical calcareous planktonic microfossils are generally problematic in California sections after the early middle Miocene. Also, planktonic foraminifers and calcareous nannofossils are generally lacking in uppermost Miocene and lowermost Pliocene ("Delmontian" Stage) rocks in coastal California.

Diatoms, on the other hand, are generally abundant and diverse in the uppermost Miocene and lowermost Pliocene hemipelagic rocks of coastal California. Studies of the diatoms of the Sisquoc Formation have included those of Woodring and others (1943), Simonsen and Kanaya (1961), Wornardt (1963, 1967, 1986), Barron (1974, 1975, 1976), Hornafius and others (1982), Dumont (1986), Akers and others (1987), Barron and Baldauf (1986), Arends and Blake (1986), and Barron and Ramirez (1992). During the last ten years, diatom biostratigraphy has undergone considerable refinement (Barron, 1992a), and it seems appropriate at this time to synthesize the diatom biostratigraphy of the Sisquoc Formation and to provide an updated correlation with the geologic time scale. Such a refined correlation can provide the necessary framework for recognizing the effect of regional and global tectonic and eustatic sea level events on the deposition of the Sisquoc Formation (Ramirez and Garrison, written commun., 1994).

Sisquoc Formation Diatom Biostratigraphy

Diatom Zonation

Studies of diatoms from the Sisquoc Formation in stratigraphic sections at Sweeney Road near Lompoc (Dumont, 1986), at Harris Grade north of Lompoc (Barron and Baldauf, 1986), and at the Point Pedernales, Mussel Rock, Lompoc Hills, and Casmalia sections (Barron and Ramirez, 1992) (fig. 1) provide the framework for constructing a diatom biostratigraphy for the Sisquoc Formation. The diatom zonation we use merges the California diatom zonation of Barron (1986a) and Barron and Baldauf (1986) with zones proposed by Dumont (1986).

Dumont (1986) subdivided Barron and Baldauf's (1986) Subzone (b) of the *Nitzschia reinholdii* Zone into three zones. In ascending order these three zones are the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone, the *Thalassiosira hyalinopsis* Partial Range Zone, and the *Thalassiosira praeoestrupii* Partial Range Zone. The *T. miocenica/N. miocenica* Interval Zone is defined as the interval above the last common occurrence of *Rouxia californica* and below the first occurrence of *Thalassiosira hyalinopsis* that contains the nominative species. The overlying *T. hyalinopsis* Partial Range Zone is the interval from the first occurrence of *T. hyalinopsis* to the first occurrence of *T. praeoestrupii*. The interval between the first occurrence of *T. praeoestrupii* and the first occurrence of *T. oestrupii* is referred to as the *T. praeoestrupii* Partial Range Zone.

Barron's (1986a) Subzone (a) of the *Nitzschia reinholdii* Zone was renamed by Dumont (1986) as the *Rouxia californica* Partial Range Zone. This zone encompasses the range of the common or consistent presence of *Rouxia californica* above the last occurrence of *Thalassionema schraderi*.

The diatom zonations of Dumont (1986) and Barron (1986a) are correlated with the geologic time scale of

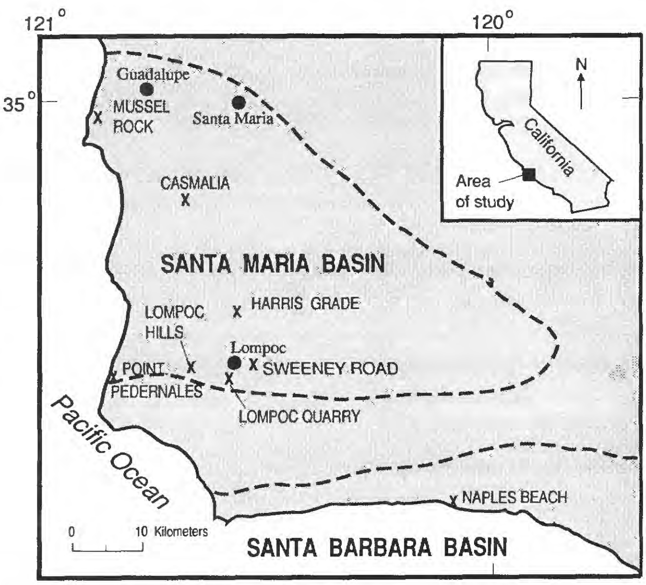

Figure 1. Map of Santa Maria and Santa Barbara basins in southern California showing location of Sisquoc Formation sections (X) discussed in text.

Berggren and others (1985) and with other microfossil zonations in figure 2. Age estimates for the zones of Dumont (1986) are derived from the paleomagnetic stratigraphy of the Santa Cruz section of the Purisima Formation in northern California, which was completed by Madrid and others (1986) (see Dumont and others, 1986). Age estimates for older diatom zones are mostly derived through indirect correlation to paleomagnetic stratigraphy and (or) radiometric ages (Barron, 1986a, 1992a).

The radiolarian zonation of Weaver and others (1981) and the calcareous nannofossil zonation of Okada and Bukry (1980) as recognized by Bukry (1973, 1981) off California are correlated to the diatom zones after Barron (1986a, 1992a). Low diversity and low abundance of age-diagnostic calcareous nannofossil taxa prevents further subdivision of the calcareous nannofossil zones. The benthic foraminiferal zones of Kleinpell (1938,1980) and the corresponding benthic foraminiferal stage boundaries are correlated to the geologic time scale following Barron (1986a) and Blake (1991).

Two alternatives for placement of the Miocene-Pliocene boundary are shown on figure 2 based on the results of Berggren and others (1985) and the results of Zijderveld and others (1986). The placement of Berggren and others (1985) is followed in this report because it is currently the standard accepted correlation. However, we recognize that the younger placement of Zijderveld and others (1986) is receiving increasing support from biostratigraphers and paleoceanographers and probably represents the correct correlation.

Recently, a new magnetic-polarity time scale was proposed by Cande and Kent (1992) that resulted in slightly older age estimates for events near the Miocene-Pliocene boundary. The Cande and Kent (1992) time scale, however, is not followed in this paper because detailed recalibration of the diatom biostratigraphy of Barron (1981, 1986a) and Dumont (1986) is beyond the scope of this paper.

Diatom Ranges

Figure 3 shows the stratigraphic ranges of important diatom taxa in the uppermost Miocene and lowermost Pliocene rocks of California. This figure was compiled from the results of Barron and Baldauf (1986), Dumont (1986), Barron and Ramirez (1992), and Barron (1992a, b).

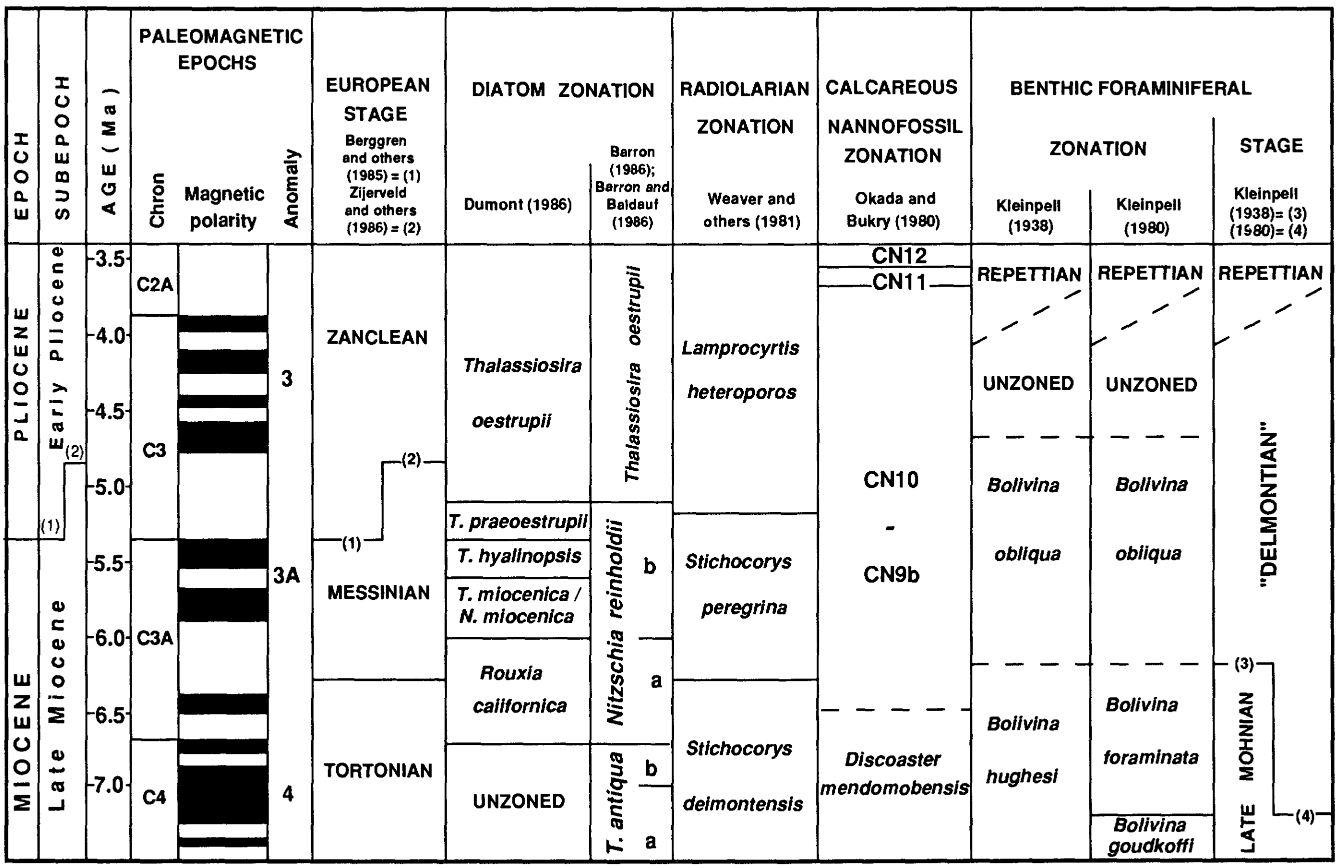

Figure 2. Correlation of California microfossil zones and California benthic foraminiferal stages of Kleinpell (1938, 1980) with geologic time scale of Berggren and others (1985) in vicinity of Miocene-Pliocene boundary. Miocene-Pliocene boundary (1) of Berggren and others (1985) is followed in this paper; (2), Miocene-Pliocene boundary of Zijderveld and others (1986). Dark bars, normal polarity.

The last occurrences of *Synedra jouseana* and *Asteromphalus darwinii* are secondary markers that approximate the base of the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone (Barron, 1976, 1986a), as do the first occurrences of *Azpeitia vetustissimus* sensu Barron and Baldauf (1986) and *Coscinodiscus subtilis*. Together, these datum levels and the last common occurrence of *Rouxia californica* typically correspond with the Monterey-Sisquoc boundary (Dumont, 1986; Barron, 1986a; Barron and Baldauf, 1986; Barron and Ramirez, 1992). As noted by Dumont (1986) and Barron and Baldauf (1986), the first occurrence of *Lithodesmium cornigerum* is a secondary marker for the base of the *Thalassiosira praeoestrupii* Partial Range Zone. *Rossiella tatsunokuchiensis*, *Hemidiscus ovalis*, and *Rhaphoneis fatula* appear to be restricted to the lower part of the *Thalassiosira oestrupii* Partial Range Zone in California (Barron and Baldauf, 1986; Dumont, 1986; Barron and Ramirez, 1992). The upper part of the *T. oestrupii* Zone is distinguished by the absence of *L. cornigerum* and *L. minusculum*, which have last occurrences in California sections at about 4.2 to 4.4 Ma (Barron and Ramirez, 1992; Barron, 1992b).

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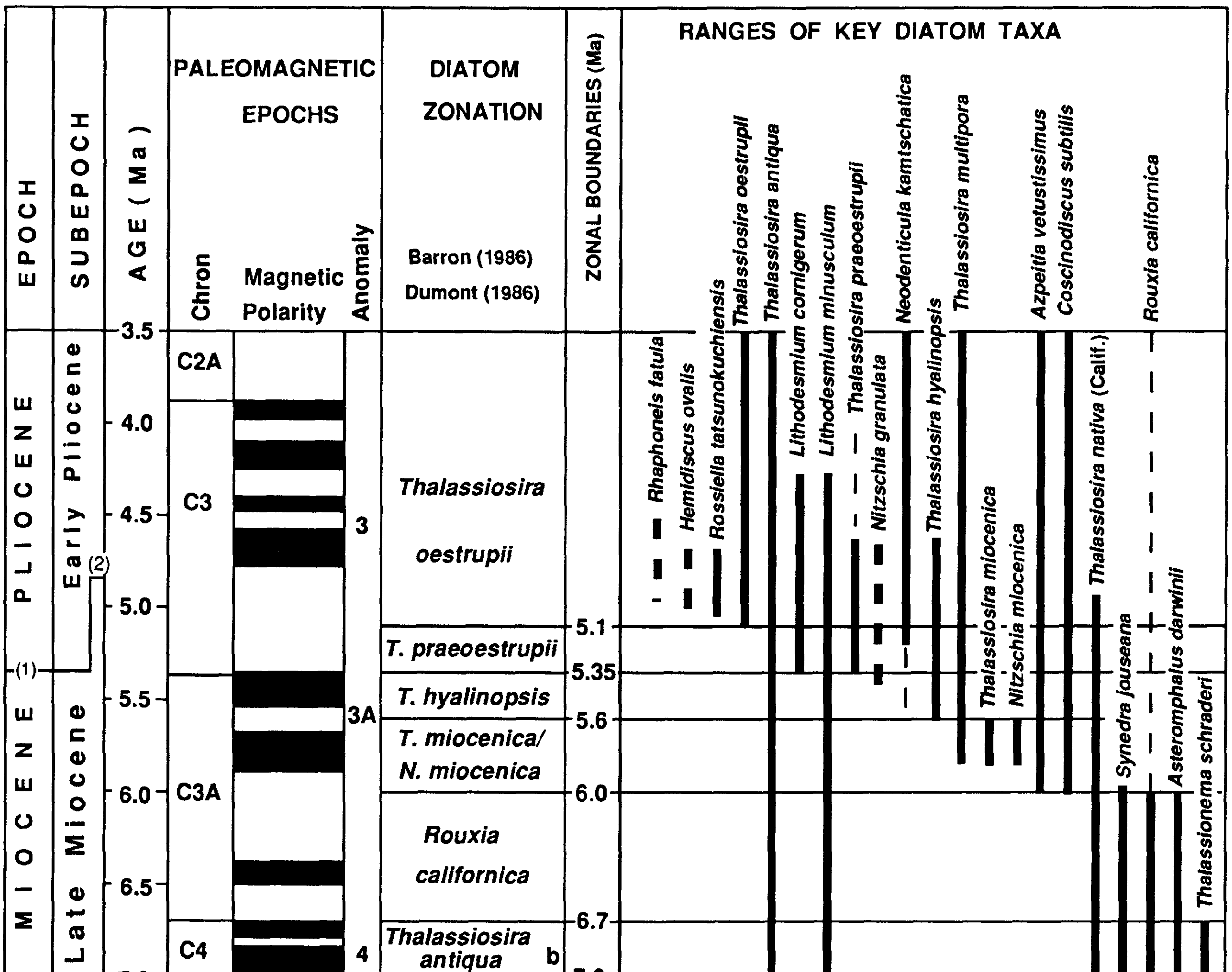

Figure 3. Ranges of biostratigraphically useful diatoms in latest Miocene and earliest Pliocene of California. (1), Miocene-Pliocene boundary of Berggren and others (1985); (2), Miocene-Pliocene boundary of Zijderveld and others (1986).

thanked for the permission to publish this paper. Finally, the senior author is grateful for the inspiration provided by his mother, [the late] Laddie Dumont.

DIATOM STRATIGRAPHY OF SISQUOC FORMATION SECTIONS

Sweeney Road

The Sweeney Road section is located about 3 km east of Lompoc, Santa Barbara County, along the north bank of the Santa Ynez River (Lompoc Quadrangle 7.5-minute series U.S. Geological Survey topographic map). The outcrop is composed of a continuous sequence of finely laminated porcellanites of the siliceous member of the Monterey Formation (Isaacs, 1981; Dumont, 1986; Ramirez, 1990) and overlying diatomaceous mudstones and shales of the Sisquoc Formation (Dibblee, 1950; Dumont, 1986; Ramirez, 1990). The base of the section studied by Dumont (1986) and Ramirez (1990) is located at the apex of a small anticline within the finely laminated porcellanites of the upper part of the Monterey Formation. This is about 2.4 km southeast of the junction of Sweeney Road and Highway 1, east of Lompoc, just north of the confluence of Salsipuedes Creek and the Santa Ynez River where the river starts to bend to the northwest (fig. 4).

A detailed study of the diatom stratigraphy of the Sweeney Road is presented in Dumont (1986); because this study is not readily available in the published literature, it is summarized in some detail in this report.

Twenty-nine samples were collected initially at 30.48 m (100 ft) horizontally-measured intervals along the diatomaceous exposure at Sweeney Road (fig. 4). To refine the diatom biostratigraphy across the Miocene-Pliocene boundary, six additional samples were collected from an interval lying 275 to 355 m above the base of the same section. The lithologic column of Sweeney Road section after Ramirez (1990) showing Dumont's (1986) samples 1 through 27 is shown in figure 5. The stratigraphic level of

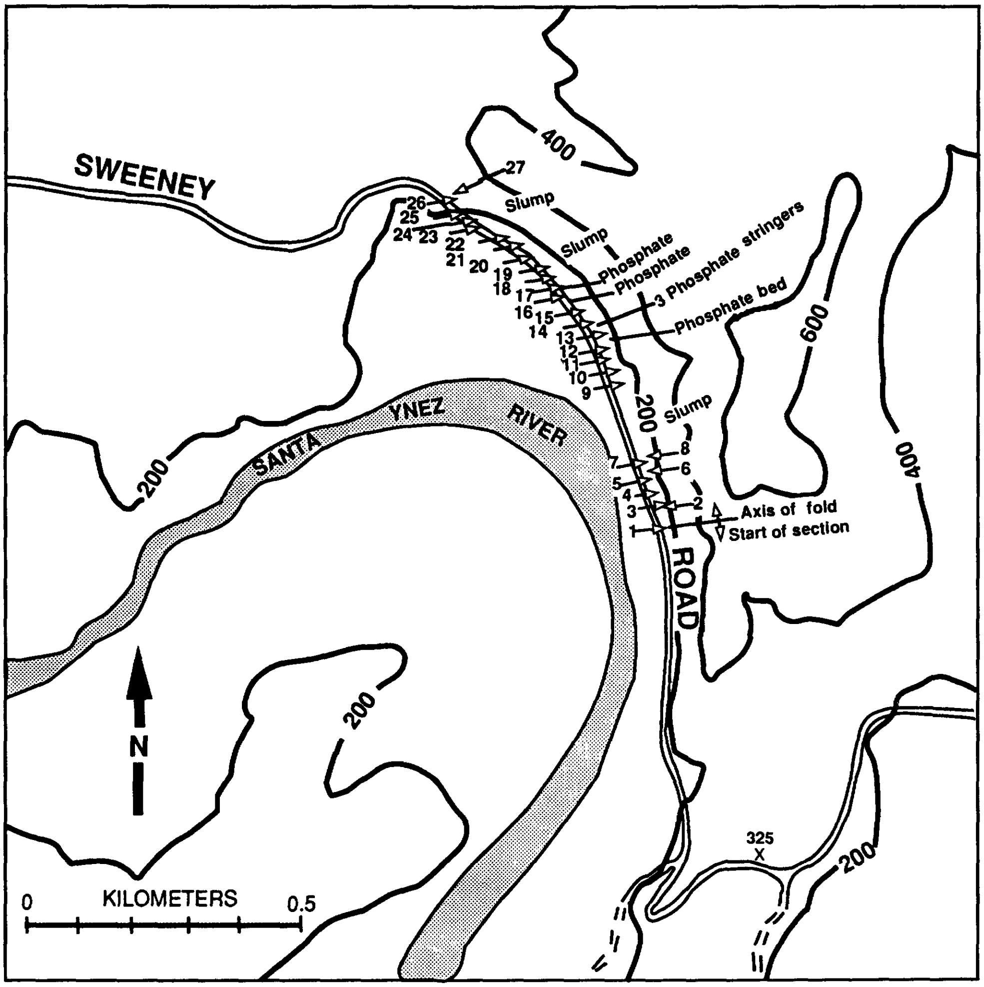

Figure 4. Map of Sweeney Road section (fig. 1), east of Lompoc, showing the samples studied (Dumont, 1986; this report) and location of phosphatic conglomerate beds. Contour interval equals 200 ft.

these samples is shown according to the measured section of Ramirez (1990) because his measurements were more detailed and employed more measurements of bedding attitudes than those of Dumont (1986).

All the samples used for this study were prepared employing a modified technique of Schrader (1973b) and counted using the techniques of Schrader and Gersonde (1978) (see Dumont, 1986, for details).

The 37 m of finely laminated porcellanites lying at the base of the section are correlated with the *Rouxia californica* Partial Range Zone on the basis of the occurrence of *Rouxia californica* in samples 1 (6 m) and 3 (31 m), the first occurrence of *Nitzschia reinholdii* in sample 5 (37 m), and the absence of *Thalassionema schraderi.* The lower porcellanite interval of the Sweeney Road section may also be correlated to the upper part of magnetic polarity Chron 6 (Subchron C3Ar.2r of Cande and Kent, 1992) on the basis of an estimated age for the last consistent occurrence of *Rouxia californica* as 6.0 Ma (Barron and Keller, 1983; Dumont, 1984), an occurrence which approximates the first occurrence of *Nitzschia reinholdii* in the California Continental Borderland (Barron, 1981).

The first occurrence of the warm-water species *Thalassiosira miocenica* was recorded in sample 6 (72 m), followed by the first occurrence of *Nitzschia miocenica* in sample 7 (76 m) (table 1, fig. 5), which is within laminated diatoma-

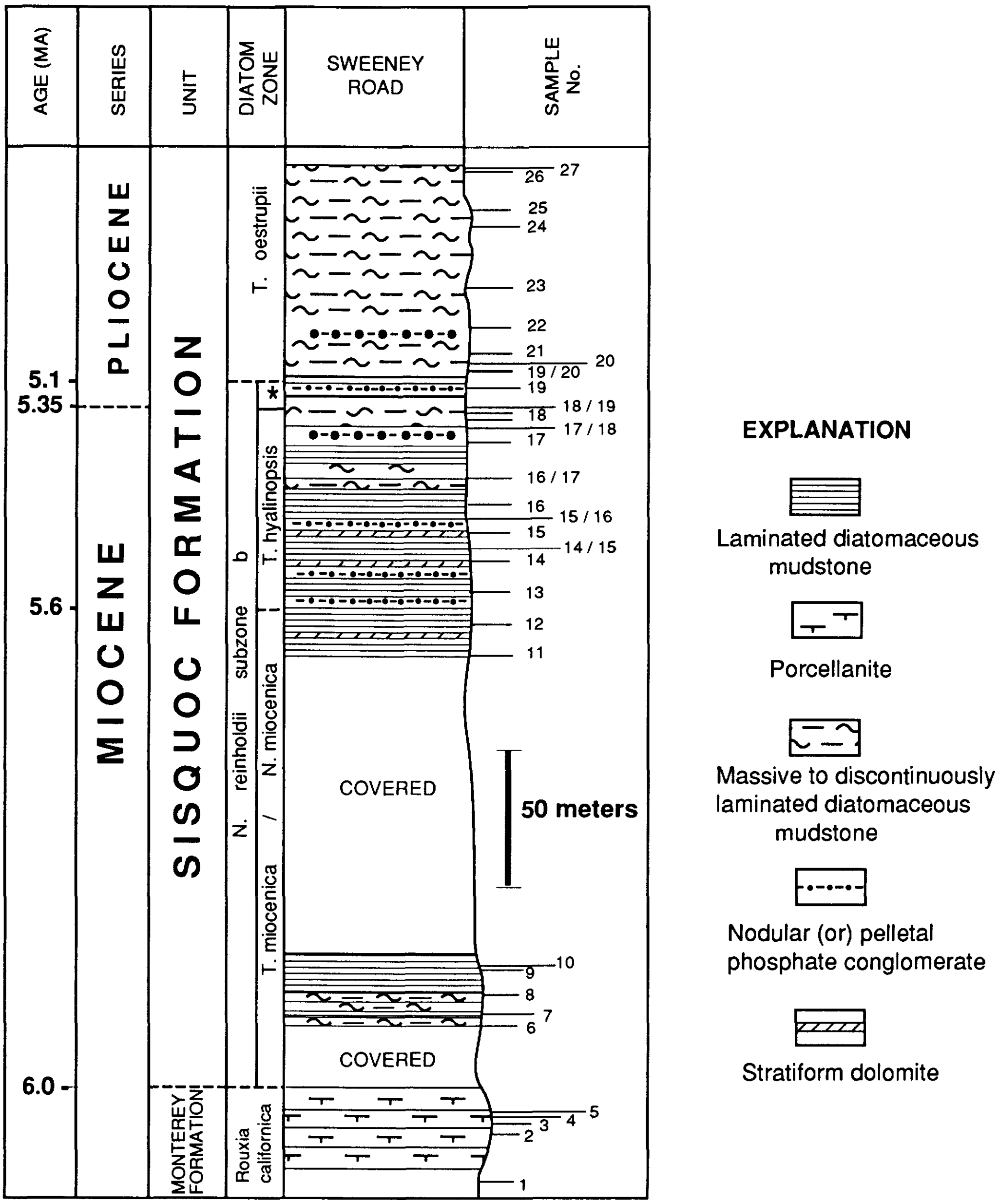

Figure 5. Sweeney Road lithologic section of Ramirez (1990) showing samples studied for diatoms (Dumont, 1986; this report) and diatom zones of Dumont (1986), Barron and Baldauf (1986), and Barron (1986a). *, *Thalassiosira praeoestrupii.*

Table 1. Stratigraphically important diatoms (per sample) in Sweeney Road section after Dumont (1986)

[Stratigraphic position of Dumont's (1986) samples have been redetermined in order to conform with lithologic column of Ramirez (1990) (fig. 5) and was accomplished by identification of marker beds and extent of exposed outcrops]

Sample No.	Stratigraphic position (m)	*Coscinodiscus subtilis*	*Lithodesmium cornigerum*	*Neodenticula kamtschatica*	*Nitzschia miocenica*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Rhaphoneis fatula*	*Rossiella tatsunokuchiensis*	*Rouxia californica*	*Thalassiosira* sp. (small form)	*Thalassiosira antiqua*	*Thalassiosira hyalinopsis*	*Thalassiosira miocenica*	*Thalassiosira multipora*	*Thalassiosira nativa* (Calif.)	*Thalassiosira oestrupii*	*Thalassiosira praeoestrupii*	*Thalassiosira symbolophora*	Total counted	DIATOM ZONE
27	440	29	1	0	0	9	0	21	1	0	0	321	3	0	4	0	3	1	7	948	***Thalassiosira oestrupii***
26	439	9	2	0	0	3	0	2	5	0	0	363	1	0	5	0	5	0	0	799	
25	430	6	19	0	0	1	0	0	1	0	0	562	8	0	5	0	7	0	0	953	
24	422	0	12	0	0	1	1	0	0	0	0	397	172	0	44	6	3	4	5	1144	
23	393	0	7	0	0	0	2	0	0	0	1	284	131	1	2	1	6	0	2	766	
22	379	0	16	0	0	1	3	0	0	0	0	379	132	0	0	0	1	0	1	971	
21	367	0	2	0	0	0	0	1	0	0	0	233	33	0	10	4	7	0	4	733	
20	360	0	2	0	0	0	1	0	0	0	0	353	64	0	9	1	4	0	2	820	
19/20	355	6	3	1	0	0	0	0	0	0	0	207	33	0	7	1	1	3	4	612	
19	345	1	3	0	0	0	1	0	0	0	0	234	10	0	4	0	0	4	3	724	***Thalassiosira praeoestrupii***
18/19	336	8	1	0	0	0	3	0	0	0	0	130	36	0	1	0	0	1	1	412	
18	332	0	0	0	0	1	12	0	0	0	2	189	46	0	0	0	0	0	0	525	***Thalassiosira hyalinopsis***
17/18	327	2	0	0	0	0	18	0	0	0	0	454	461	0	5	1	0	0	0	1422	
17	322	0	0	0	0	4	6	0	0	0	2	330	204	0	2	1	0	0	0	790	
16/17	307	9	0	2	0	1	31	0	0	0	0	616	125	0	2	5	0	0	0	1095	
16	294	9	0	0	0	1	13	0	0	0	3	77	55	0	6	5	0	0	1	685	
15/16	288	14	0	0	0	4	7	0	0	0	0	548	153	0	1	2	0	0	1	995	
15	282	2	0	0	0	0	9	0	0	0	1	335	14	0	0	7	0	0	5	555	
14/15	275	13	0	0	0	4	34	0	0	0	4	104	195	0	6	2	0	0	1	942	
14	271	15	0	0	0	1	10	0	0	0	0	295	2	3	4	4	0	0	0	646	
13	257	0	0	2	0	4	19	0	0	0	1	176	4	0	7	2	0	0	0	582	
12	244	0	0	0	0	0	7	0	0	0	9	127	0	0	0	0	0	0	0	587	***T. miocenica / N. miocenica***
11	230	24	0	0	4	1	18	0	0	0	25	185	0	1	0	0	0	0	0	988	
10	99	20	0	0	0	2	28	0	0	0	21	188	0	7	0	0	0	0	0	734	
9	94	29	0	0	0	6	21	0	0	0	0	165	0	1	0	5	0	0	0	704	
8	84	0	0	0	2	0	0	0	0	0	0	44	0	4	0	2	0	0	0	329	
7	76	0	0	0	1	2	3	0	0	0	0	68	0	0	0	16	0	0	0	263	
6	72	5	0	0	0	0	1	0	0	0	0	48	0	5	0	15	0	0	0	285	
5	37	0	0	0	0	1	1	0	0	0	0	80	0	0	0	14	0	0	0	329	***Rouxia californica***
4	35	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	82	
3	31	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	155	
2	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	
1	6	0	0	0	0	0	0	0	0	1	0	2	0	0	0	2	0	0	0	36	

ceous shale of the basal Sisquoc Formation (Dumont, 1984, 1986). Sample 11 (230 m) contains the last occurrences of *T. miocenica* and *N. miocenica* within a finely-laminated diatomaceous shale (laminae 1-2 cm thick). The last occurrence datum of *T. miocenica* occurs at the base of the reversed-polarity event of Chron 5 (Subchron C3Ar.1r of Cande and Kent, 1992) within the Purisima Formation at Santa Cruz in northern California (Dumont, 1986; Dumont and others, 1986), suggesting an age of 5.68 Ma for sample 11 (Berggren and others, 1985).

Between 244 and 257 m above the base of the section, the first of six phosphatic conglomerate beds is found (fig. 5). Sample 13 (257 m), which was collected within a massive diatomaceous shale, contains the first occurrence of *Thalassiosira hyalinopsis*. Correlation to the first occurrence of *T. hyalinopsis* in the Purisima section at Santa Cruz suggests that sample 13 lies within the middle of the reversed-polarity event of Chron 5 (Subchron C3Ar.1r of Cande and Kent, 1992), with an estimated age of 5.6 Ma (Dumont, 1984; Berggren and others, 1985; Dumont and others, 1986).

The first occurrence of *Thalassiosira praeoestrupii* and *Lithodesmium cornigerum* are found in sample 18/19 (336 m). The first occurrence of *T. praeoestrupii* coincides closely with the top of polarity Chron 5 (Chron C3A of Cande and

Kent, 1992) (Dumont, 1984; Dumont and others, 1986; Madrid and others, 1986) and the Miocene-Pliocene boundary within the Santa Cruz section (5.35 Ma). A precise correlation of the *T. oestrupii* datum at Sweeney Road with the Santa Cruz section cannot be made because of the apparent unconformity identified within the Gilbert Reversed-Polarity Chron (Chron C3) at Santa Cruz (Madrid, 1982). However, the first occurrence of *T. oestrupii* was correlated to a level within the lower reversed-polarity event of the Gilbert Reversed-Polarity Chron (Subchron C3Ar.4r of Cande and Kent, 1992) in the equatorial Pacific Ocean by Burckle (1978) and has an estimated age of 5.1 Ma (Baldauf, 1985; Barron and others, 1985). Available correlations (Burckle, 1978; Barron, 1981) suggest that the *T. oestrupii* datum is isochronous between the tropics and California.

A benthic, cosmopolitan diatom marker for the Pliocene, *Rossiella tatsunokuchiensis*, was first recorded in sample 25 (430 m) in the Sweeney Road section. This diatom was also recorded in the last two samples, 26 (439 m) and 27 (440 m), at the top of the section. Another Pliocene benthic species, *Rhaphoneis fatula* (Barron and Baldauf, 1986), was first recorded in sample 21 (379 m).

A multisiliceous microfossil study (radiolaria, diatoms, and silicoflagellates) of the Sweeney Road section has been published by Akers and others (1987). The radiolarian biostratigraphy suggests that the Sweeney Road section ranges in age from late Miocene to undifferentiated Pliocene, on the basis of the occurrences of *Stichocorys peregrina*, *Lychnocanoma grande*, and *Lamprocyrtis heteroporos*. However, the diatom stratigraphy presented in Akers and others (1987) is difficult to interpret. Basically, Akers and others (1987) recorded diatom species (for example, *Pseudoeunotia doliolus*, *Rhizosolenia praebergonii*, and *Actinocyclus oculatus*) from the Sweeney Road section that are younger than the ages represented by the radiolarians they report. Aside from the internal inconsistencies among the microfossil groups (radiolaria, diatoms, and silicoflagellates), their report suggests that radiolaria may be useful in the time interval represented in this section.

In figure 6 an age versus stratigraphic-height (sedimentation rate) curve is plotted for the Sweeney Road section on the basis of the stratigraphic placement of diatom datum levels that have been calibrated to paleomagnetic stratigraphy at Santa Cruz by Dumont and others (1986) (fig. 6). Two alternatives are given for placement of the first occurrence of *Thalassiosira oestrupii* within the Sweeney Road section—one, between sample 19 (345 m) and 19/20 (355 m), based on Dumont's (1986) study (table 1), and the other, between samples 22 (379 m) and 23 (393 m) based on Barron's previous studies (1975; unpub. data, 1993) and preliminary examination of Dumont's (1986) samples. The sedimentation-rate curve in figure 6 is drawn through the latter alternative because it fits on a linear extrapolation of the line through the first occurrences of *T. hyalinopsis* and *T. praeoestrupii*. The two alternative stratigraphic placements are probably due to slight differences in the two author's taxonomic concept of *T. oestrupii.*

The sedimentation curve in figure 6 indicates that the lower part of the Sisquoc Formation at Sweeney Road (50-230 m; about 6.0 to 5.65 Ma) accumulated at a post-compaction sedimentation rate of about 600 m/m.y. This is in good agreement with sedimentation rates estimated for

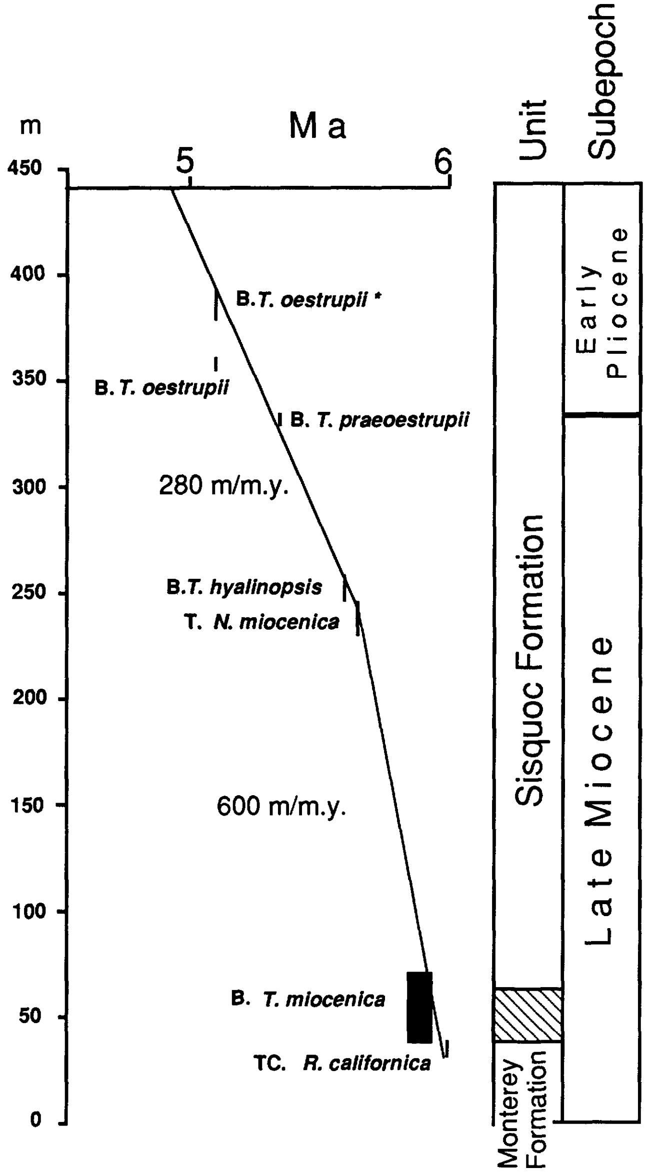

Figure 6. Age versus stratigraphic height plot for Sweeney Road section. Estimated sedimentation rates for lower and upper segments of plot are 600 and 280 m/m.y., respectively. Ages used are those of figure 2; bar shows stratigraphic constraint of datum level; B, first occurrence; T, last occurrence; TC, last common occurrence; *, lowest *Thalassiosira oestrupii* observed by Barron (unpub. data, 1993, differs from that of Dumont, 1986). Hachured area represents covered interval that obscures Monterey-Sisquoc contact.

the Sisquoc Formation at Casmalia and Point Pedernales (600 and 580 m/m.y., respectively) by Ramirez (1990) and at Harris Grade (about 540 m/m.y.) by Barron and Ramirez (1992). Diatom stratigraphy suggests that the post-compaction sedimentation rate in the upper part of the Sisquoc Formation at Sweeney Road (230-440 m) declines to 280 m/m.y at about 5.6 Ma. The extrapolated age for the top of the exposed Sisquoc Formation at Sweeney Road is 4.9 Ma. The lower part of this upper interval is marked by numerous phosphatic conglomerate beds (fig. 5) (Dumont, 1986; Ramirez, 1990). Therefore, it is possible that these beds correspond to unconformities where relatively brief intervals of time, beyond the resolution of diatom biostratigraphy, are missing.

Lompoc Quarry

At the Lompoc (Johns-Mansville now Cellite) diatomite quarry about 4 km south of Lompoc (fig. 1), about 23 m of massive Sisquoc Formation rocks overlie a 50-cm-thick phosphatic conglomerate bed at the top of the Monterey Formation. This phosphatic conglomerate was recognized as an unconformity by Barron (1975, 1986a) and Dumont (1984) at which Sisquoc rocks assignable to the *Thalassiosira hyalinopsis* Partial Range Zone overlie Monterey rocks assignable to the *Rouxia californica* Partial Range Zone. A minimal sediment interval corresponding to the *T. miocenica/N. miocenica* Interval Zone (6.0 to 5.6 Ma) is missing at this unconformity (fig. 7).

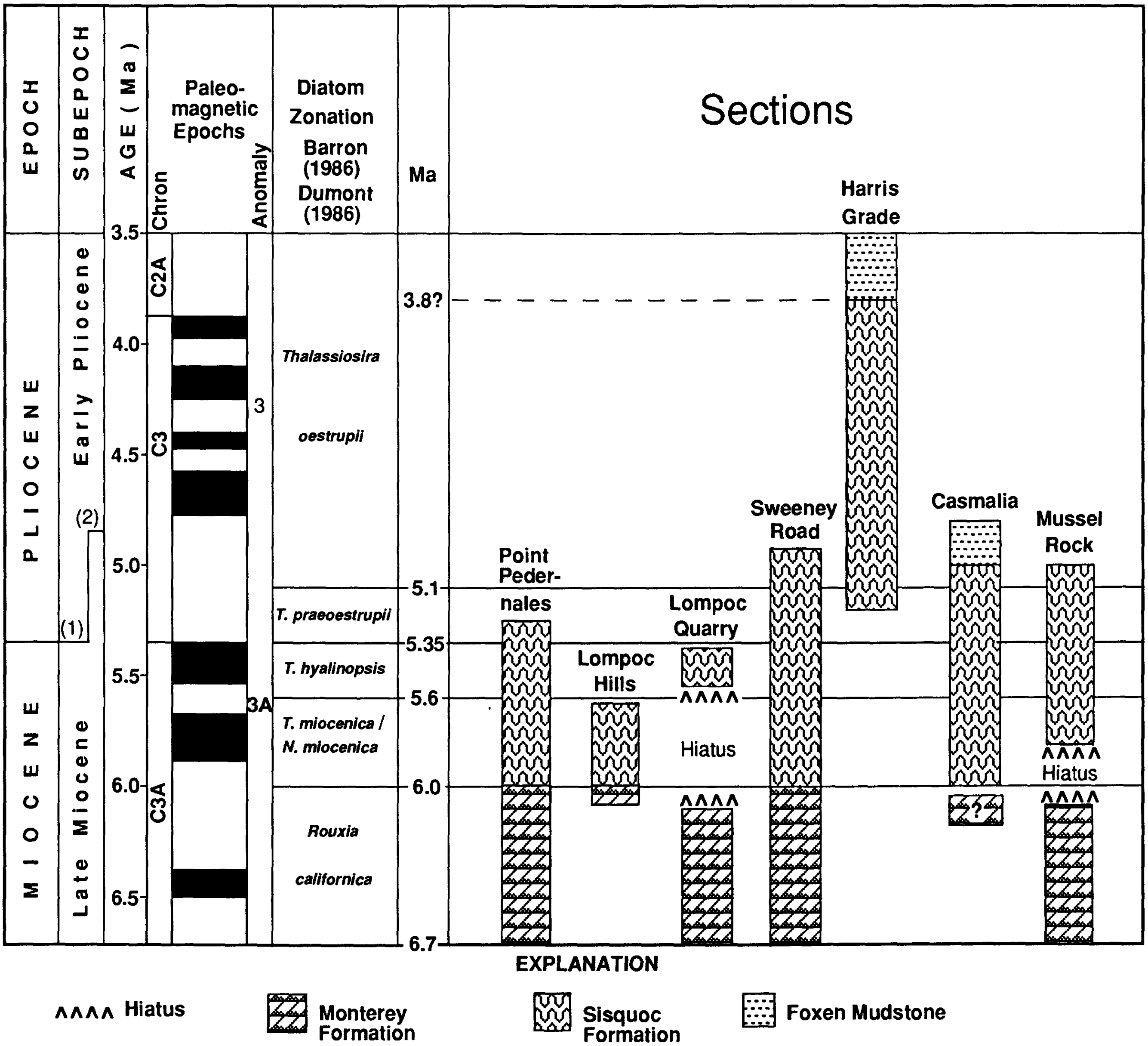

Figure 7. Correlation of various Sisquoc Formation sections in Santa Maria basin to geologic time. Miocene-Pliocene boundary (1) of Berggren and others (1985) is followed in this paper; (2), Miocene-Pliocene boundary of Zijderveld and others (1986). Dark bars, normal polarity.

Lompoc Hills

The Lompoc Hills section lies in the hills approximately 2.5 km west of Lompoc (fig. 1). A 200-m section of interbedded massive and laminated beds of the Sisquoc Formation overlying porcellaneous beds of the Monterey Formation was measured at this locality by Ramirez (1990). The lower 20 m of the measured Monterey section consists of finely laminated lenticular to continuous porcellaneous beds that are 3 to 8 cm thick (Ramirez, 1990). These porcellaneous beds alternate with 30 to 50 cm thick packages of massive and laminated diatomaceous strata. Above the porcellanites, banded and massive beds of the Sisquoc Formation dominate the section. The Monterey-Sisquoc boundary is placed at the change from finely laminated to banded rocks, a change which also approximates the change from opal-CT rocks below to opal-A rocks above. The Sisquoc Formation is truncated by sandstones and siltstones of the Pliocene Careaga Sandstone (Woodring and Bramlette, 1950).

The absence of *Thalassiosira hyalinopsis*, *T. praeoestrupii*, and *T. oestrupii* in the Lompoc Hills section suggests that the section is older than the *T. hyalinopsis* Partial Range Zone (Barron and Ramirez, 1992). Sporadic occurrences of *Nitzschia miocenica* and the absence of *Rouxia californica* and *Synedra jouseana* in all samples above the basal samples of the section argues for correlation of the bulk of the Sisquoc Formation in the Lompoc Hills section with the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone. The basal samples are tentatively correlated with the *Rouxia californica* Zone.

Point Pedernales

The Point Pedernales section is located along the coast approximately 5 to 6 km southwest of the southeast entrance to Vandenberg Air Force Base (fig. 1). At Point Pedernales, Ramirez (1990) measured and described approximately 400 m of mostly well-exposed strata of the Monterey and Sisquoc Formations along steep seacliffs containing exposures up to 4 m in height. The strata consist largely of alternating massive and laminated diatomaceous units ranging from less than 0.5 to greater than 5 m in thickness (Ramirez, 1990). The lower 10 m of the section was assigned to the Monterey Formation by Ramirez (1990) on the basis of biostratigraphic correlation with the Monterey-Sisquoc boundary at Mussel Rock (fig. 1; see below). Biostratigraphic determination of the Monterey-Sisquoc formational contact was utilized because the Sisquoc Formation grades into and is lithologically similar to the underlying Monterey Formation and because an insufficient number of samples were taken from the Monterey Formation to compositionally distinguish it from the Sisquoc Formation (Ramirez, 1990).

The basal sample of the Point Pedernales section was assigned to the *Rouxia californica* Partial Range Zone on the basis of the rare occurrence of *Rouxia californica* and *Synedra jouseana* (Barron and Ramirez, 1992). The interval from 10 to 350 m is placed in the *T. miocenica/N. miocenica* Interval Zone, below the first occurrence of *Thalassiosira hyalinopsis* at 355 m. The *T. hyalinopsis* Zone then extends from 355 m upsection to a level immediately below the first occurrence of *Thalassiosira praeoestrupii* at 456 m, the level of the highest sample taken in the section. Whereas Hornafius and others (1982) reported *Thalassiosira oestrupii* from the upper part of the Point Pedernales section, Barron and Ramirez (1992) did not observe this diatom and assign the top of the Pedernales section to the older *Thalassiosira praeoestrupii* Partial Range Zone (5.35-5.1 Ma).

Harris Grade

The Harris Grade section, which is located about 10 km north of Lompoc on old California Highway 1 (fig. 1), contains a 900-m-thick section of the Sisquoc Formation overlying a faulted anticline. The Sisquoc Formation is conformably overlain by the relatively diatom-poor Foxen Mudstone in the Harris Grade section. Barron and Baldauf (1986) recognized a 50-m section of the *Thalassiosira praeoestrupii* Partial Range Zone above a 140-m-thick interval of porcellanites at the base of the Harris Grade section. The bulk of the Harris Grade section is assignable to the *Thalassiosira oestrupii* Partial Range Zone, and Barron and Baldauf (1986) demonstrated that the top of the Sisquoc Formation is well above (at least 900 m) the Miocene-Pliocene boundary. Barron and Baldauf (1986) followed Stanley and Surdham (1984) in estimating that the Sisquoc-Foxen contact at the top of the Harris Grade section corresponded with the 4.2-Ma sea level fall identified in the global eustatic sea level curve by Vail and Hardenbol (1979), but Barron and Ramirez (1992) suggested that this boundary may correlate with the 3.8 Ma sea level fall of Haq and others (1987). This 3.8-Ma age for the top of the Sisquoc Formation in the Harris Grade section is based on an estimated sedimentation rate of 540 m/m.y., which was obtained by Barron and Ramirez (1992) for the Harris Grade section by applying Barron's (1992b) independent age estimates to the diatom events of Barron and Baldauf (1986) in the Harris Grade section.

Casmalia

A 700-m-thick composite section containing the uppermost Monterey Formation, the Sisquoc Formation, and the basal Foxen Mudstone was measured along Black Road and along the railroad tracks that run parallel to the road (Ramirez, 1990) north of the town of Casmalia (fig. 1). The lowermost 30 m of the measured section consists of continuously to discontinuously banded and finely laminated porcellaneous rocks assigned to the Monterey Formation. Upsection, platy-weathering rocks of the Monterey Formation pass into massive, dense, siliceous mudstones of the Todos Santos Claystone Member of the Sisquoc Formation (Ramirez, 1990).

The successive first occurrences of *T. hyalinopsis* (437 m), *T. praeoestrupii* (557 m), and *T. oestrupii* (677 m) mark the respective bases of the *T. hyalinopsis*, *T. praeoestrupii*, and *T. oestrupii* Partial Range Zones according to the diatom stratigraphy of Barron and Ramirez (1992). The Sisquoc-Foxen contact is estimated to be 5.0 Ma in age at the Casmalia section on the basis of the extrapolation upsection of a 600 m/m.y. post-compaction sedimentation rate suggested by diatom biostratigraphy (Ramirez, 1990; Barron and Ramirez, 1992). Thus, the Sisquoc-Foxen contact at Casmalia may be as much as 1.2 m.y. older than it is at Harris Grade (figs. 7, 8). This diachroneity may reflect a more basin-marginal depositional setting for the Casmalia section than for the Harris Grade section and an earlier appearance of the more clastic-rich, diatom-poor sediments of the Foxen Mudstone. Alternatively, this 1.2 m.y. interval (about. 5.0–3.8 Ma) may have been removed at a yet to be recognized unconformity in the Casmalia section.

Mussel Rock

The Mussel Rock section is exposed along the coast (fig. 1) southwest of the town of Guadalupe. A 400-m-thick section was measured by Ramirez (1990) from the opal-A to opal-CT transitional zone of the upper part of the Monterey Formation to the top of exposed rocks of the Sisquoc Formation. An additional 300+ m of Monterey Formation strata crops out to the south along the shore below the measured section according to Pisciotto (1981). The layered rocks of the Monterey Formation contrast sharply with the overlying massive and intensively bioturbated rocks of the Sisquoc Formation, which become increasingly conglomeratic upsection. A distinct phosphatic conglomerate marks the contact between the layered Monterey and massive Sisquoc Formations. Ramirez (1990) measured this phosphatic conglomerate as 23 cm in thickness, but it apparently varies laterally in thickness.

The last common occurrence of *R. californica* in the uppermost part of the Monterey Formation at this section defines the top of the *R. californica* Partial Range Zone, a correlation which is supported by the last occurrences of *Synedra jouseana* and *Hemiaulus polymorphus* in the same sample. About 30 m of *T. miocenica/N. miocenica* Interval Range Zone is present in the basal Sisquoc Formation at Mussel Rock according to the diatom biostratigraphy of Barron and Ramirez (1992). The *T. hyalinopsis*, *T. praeoestrupii*, and *T. oestrupii* Partial Range Zones are recognizable by the successive first occurrences of the nominative taxa in the Sisquoc Formation at Mussel Rock (Barron and Ramirez, 1992).

Comparison of Sisquoc Formation Sections

Based on the comparison of the ages of seven sections of the Sisquoc Formation in the Santa Maria basin (fig. 7), it is apparent that the Monterey-Sisquoc formational boundary typically coincides with the boundary between the *Rouxia californica* Partial Range Zone and the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone (6.0 Ma). However, in some sections, such as the Point Pedernales section, no distinct lithologic break occurs at this 6.0 Ma time horizon, and the Monterey Formation is difficult to distinguish from the Sisquoc Formation. Most of the Sisquoc Formation outcrop sections do not extend much younger than the basal *Thalassiosira oestrupii* Partial Range Zone (about 5.0 Ma).

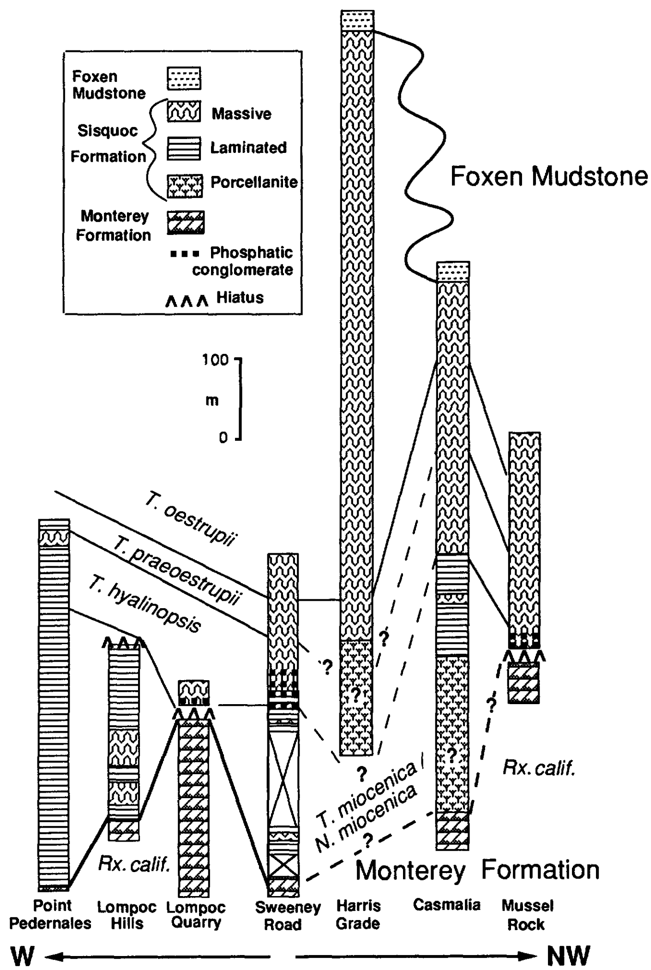

Figure 8. Correlation of various Sisquoc Formation sections in Santa Maria basin showing stratigraphic thickness and generalized lithology. W, west; NW, northwest; *Rx. calif.*, *Rouxia californica*.

The Harris Grade section, however, extends considerably younger according to the diatom studies of Barron and Baldauf (1986).

There is considerable variation in the thickness of individual diatom zones in Sisquoc Formation sections (fig. 8). For example, the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone is over 330 m thick in the Point Pedernales section, but it is totally removed at an unconformity in the Lompoc Quarry section. Generalized lithology is also quite variable (Ramirez and Garrison, written commun., 1994); for example, the interval of the *Thalassiosira hyalinopsis* Partial Range Zone is generally represented by laminated sediments in the Point Pedernales section, massive diatomaceous sediments in the Sweeney Road, Casmalia, and Mussel Rock sections, and by porcellanites in the Harris Grade section. On the other hand, laminated beds are consistently common within the *T. miocenica/N. miocenica* Interval Zone in all Santa Maria basin sections studied. Similarly, phosphatic conglomerate beds, which often represent unconformities, are more typical of an interval embracing the upper *T. miocenica/N. miocenica* Interval Zone to lower *T. hyalinopsis* Partial Range Zone.

THE MONTEREY-SISQUOC BOUNDARY PROBLEM

As early as 1913, Louderback (1913) recognized the problem of distinguishing the upper part of the Monterey Formation from the overlying Sisquoc Formation in the Lompoc-Santa Maria-Santa Barbara region. At several localities in this region, the depositional sequence appears continuous (Arnold and Anderson, 1907; Kleinpell, 1938; Bramlette, 1946; Dibblee, 1950), but at the Lompoc (Johns-Mansville now Cellite) diatomite quarry south of Lompoc, an unconformity is recognized at the top of the Monterey Formation (fig. 2) (Barron, 1975; Dumont, 1984). This unconformity was recognized and interpreted by earlier workers as relatively brief and coincident with both the Miocene-Pliocene boundary and the Monterey-Sisquoc formational contact (Bramlette, 1946; Wornardt, 1963; Barron, 1975). These observations were the origin of the hypothesis equating the Miocene-Pliocene boundary with the top of the Monterey Formation, a simple formula which some workers continue to apply.

Bramlette's (1946) classic paper, the first definitive geologic study of the Monterey Formation, emphasized the Monterey Formation's characteristic rhythmic bedding and extremely high organic content and speculated on its origin. At about the same time, biostratigraphic studies referred to the basal Sisquoc Formation as being either latest Miocene (benthic foraminifers) or earliest Pliocene (mollusks) in age (Woodring and Bramlette, 1950).

In the past, different lithologic features have been used to delineate the contact between the Monterey and Sisquoc Formations in coastal southern California (Arnold and Anderson, 1907; Mulryan, 1936; Canfield, 1939; Bramlette, 1946; Woodring and Bramlette, 1950; Dibblee, 1950; Wornardt, 1963; Isaacs, 1981). One approach was to differentiate the Monterey Formation from the overlying Sisquoc Formation on the basis that the Monterey Formation was finely laminated (Canfield, 1939),whereas the Sisquoc Formation contained a higher proportion of mudstone and was characterized by cruder bedding (Isaacs, 1981). However, interbedded, finely laminated and massive diatomaceous shales are often present in the basal Sisquoc Formation (Ramirez and Garrison, written commun., 1994) (figs. 5, 8), prompting Woodring and Bramlette (1950) to state that the Monterey-Sisquoc boundary is gradational in some places in the Santa Maria basin and difficult to place.

Another approach was to place the contact between the Monterey and Sisquoc Formations at a depositional break marked by the unconformity, represented by the thin phosphatic conglomerate unit as seen at the Lompoc diatomite quarry (Mulryan, 1936; Bramlette, 1946; Wornardt, 1963, 1983). However, in some sections, such as the Naples Beach section of the Santa Barbara basin (fig. 1) (Isaacs, 1981), there is no apparent unconformity or phosphatic conglomerate at the formational boundary, whereas in other sections (for example, the Sweeney Road section) there may be numerous phosphatic conglomerate units (fig. 5) (Dumont, 1984, 1986; Ramirez, 1990).

Dibblee (1950) placed the contact between the Monterey and Sisquoc Formations at the break between the porcellaneous shales (porcellanite/chert) and overlying diatomaceous shales. Isaacs (1981) described the porcellanites as "an aphanitic rock with a somewhat rough, matte surface texture; *** even where laminated or well bedded." Application of this description would appear to be the most consistent field method to differentiate the shales that determine the Monterey and Sisquoc formational boundary in the Santa Maria-Lompoc region. However, Isaacs (1981) pointed out that the top of the porcellaneous section migrates upward across different lithologic units of the Monterey Formation, becoming successively younger as one proceeds westward along the coast from Santa Barbara to Point Conception.

Diatom studies have placed the age of the top of the porcellanite unit at the Sweeney Road section at approximately 6.0 Ma (figs. 5, 7) (Dumont, 1984, 1986; Dumont and others, 1986; Ramirez, 1990). However, the top of the porcellanite in the nearby Lompoc diatomite quarry section is over 1 m.y. older (Barron, 1975, 1986a; Dumont, 1984, 1986), as it contains diatoms assignable to Barron's (1986a) northeastern Pacific Diatom Subzone (a) of the *Thalassiosira antiqua* Partial Range Zone (7.6–7.0 Ma). This represents an age difference of as much as 1.5 m.y. for the top of the porcellanite at these two localities (Dumont, 1986).

An additional approach, proposed by Isaacs (1981) and emphasized by Ramirez and Garrison (written comm., 1994), focused on the much greater detrital mineral content of the Sisquoc Formation compared to that of the Monterey Formation. The Sisquoc Formation contains a "greater average abundance of detrital minerals," and a "much higher proportion of massive mudstone," than the laminated Monterey Formation (Issacs, 1981). This method, however, may be difficult to apply in the field, as the diatomaceous rocks at the base of the Sisquoc Formation and the top of the Monterey Formation can be visually indistinguishable (Woodring and Bramlette, 1950).

All of the above criteria can be applied, with varying success, on isolated sections to distinguish the upper part of the Monterey from the overlying lower part of the Sisquoc Formation. It can be demonstrated by diatom biostratigraphy that none of the above criteria can be used independently to distinguish the Miocene-Pliocene boundary.

In summary, the stratigraphic position of the Monterey-Sisquoc formational contact can differ at many of the sections found in the Santa Maria and Santa Barbara basins depending on the lithologic criteria employed to determine it. However, the Miocene-Pliocene boundary can be consistently defined within this region by diatom biostratigraphy. Where the basal Sisquoc Formation is visually distinguishable from the underlying Monterey Formation, the Monterey-Sisquoc formational contact consistently coincides with the base of the *Thalassiosira miocenica/Nitzschia miocenica* Interval Zone of Dumont (1986) (latest Miocene). Where a more gradational transition occurs between the Monterey and Sisquoc Formations, this 6.0 Ma time horizon can be accurately placed by diatom biostratigraphy (Barron, 1975; Dumont, 1984, 1986) (fig. 7).

PALEOCEANOGRAPHIC IMPLICATIONS

Middle to late Miocene climatic cooling accompanied by the intensification of upwelling and increased primary productivity within the eastern boundary current region of coastal California was ultimately responsible for the increased diatom blooms that contributed to the biosiliceous richness of the rocks of the upper part of the Monterey Formation and the overlying Sisquoc Formation (Ingle, 1981; Barron, 1986b). Superimposed on this biogenic sedimentation pattern in coastal California is an increase in clastic deposition that began in the latest Miocene and intensified in the early Pliocene (Crouch, 1979; Ingle, 1980; Isaacs, 1981, 1983; Dumont, 1986; Teng and Gorsline, 1989; Barron, 1992b).

High-latitude cooling and a fall in global eustatic sea level at 5.5 Ma (fig. 9) are marked by the last occurrence of a warm-water biofacies containing *Thalassiosira miocenica* and *Nitzschia miocenica* in the Sweeney Road section (5.6 Ma), an occurrence which is followed by an increase of neritic versus planktonic diatoms in this section (table 1). A similar increase in neritic diatoms occurs in other Sisquoc sections in the basal *T. hyalinopsis* Partial Range Zone within the Santa Maria basin (Barron, unpub. data, 1993), as well as in the Purisima Formation at Santa Cruz (Dumont, 1986). The increase of neritic diatoms in coastal California is coupled with a marked increase of siliciclastic debris in the samples (Dumont, 1986). This agrees with the findings of Isaacs (1981) and Ramirez and Garrison (written commun., 1994) who noted an abrupt increase in sedimentation of detrital minerals during Sisquoc Formation depositional time.

Other potential evidence for the 5.5 Ma sea level fall includes the presence of phosphatic conglomerate beds in the lower *T. hyalinopsis* Partial Range Zone at Sweeney Road (fig. 5), as well as the phosphatic conglomerates associated with unconformities between the Monterey and Sisquoc Formation in the Lompoc quarry and Mussel Rock sections (fig. 8).

In a broader sense, these events, which occurred approximately the time of deposition of the Monterey-Sisquoc contact, may be considered a response to the late Miocene climatic deterioration and buildup of polar ice (Kennett, 1977; Savin, 1977; Barron and Keller, 1983; Dumont, 1986), which in turn caused a fall in sea level.

TECTONIC IMPLICATIONS

The lithologic character and diatom content of the onshore Pliocene sections in California were strongly influenced by tectonic events (Barron, 1992b). Tectonic reorganization of the California Continental Borderland began in the latest Miocene (Crouch, 1979) and was intensified during the Pliocene as the Coast Ranges of California were uplifted and adjoining basins underwent subsidence (Ingle, 1980; Teng and Gorsline, 1989). An eastward jump in the San Andreas Fault system at 5.5 Ma (Sedlock and Hamilton, 1991) and a major change in the motion of the Pacific Plate between 3.9 and 3.4 Ma (Harbert and Cox, 1989) appear to have been responsible for this tectonic reorganization (fig. 9). Increased deposition of clastic-rich sediments followed these tectonic events and also coincided with global falls in sea level at 5.5 and 3.8 Ma. Basins formed during the Miocene in California were rapidly filled with Pliocene clastic sediments, and diatoms persisted as a major component only in sediments deposited in the center of basins and only until about 4 Ma.

CONCLUSIONS

Diatom biostratigraphy offers a valuable means for correlating and subdividing the Sisquoc Formation as well as recognizing the Miocene-Pliocene boundary. Our study of the diatom biostratigraphy of the Sweeney Road section, east of Lompoc, Calif., and summaries of the diatom biostratigraphy of the Lompoc quarry, Lompoc Hills, Point Pedernales, Harris Grade, and Mussel Rock sections of the Santa Maria basin reveal that the base of the Sisquoc Formation typically coincides with the base of the *Thalassiosira miocenica/Nitzschia miocenica* Partial Range Zone and has an age of approximately 6.0 Ma. Diatom biostratigraphy, thus, represents a reliable means for recognizing the 6.0 Ma time horizon that typically coincides with the Monterey-Sisquoc boundary. Other criteria for recognizing the Monterey-Sisquoc boundary, such as the laminated (Monterey Formation) versus massive (Sisquoc Formation) expression of the rocks or their porcellaneous (Monterey Formation) versus diatomaceous (Sisquoc Formation) character are either inconsistent or time transgressive.

The top of the Sisquoc Formation in outcrop sections of the Santa Maria basin is typically about 5.0 Ma; however, the Sisquoc Formation may be as young as 3.8 Ma in the Harris Grade section in the center of the basin.

The Sisquoc Formation was deposited during a relatively high stand of eustatic sea level bracketed by lowstands dated at 6.3 and 3.8 Ma. Clastic materials, however, increase in many Sisquoc sections beginning at 5.0 Ma in response to regional tectonism.

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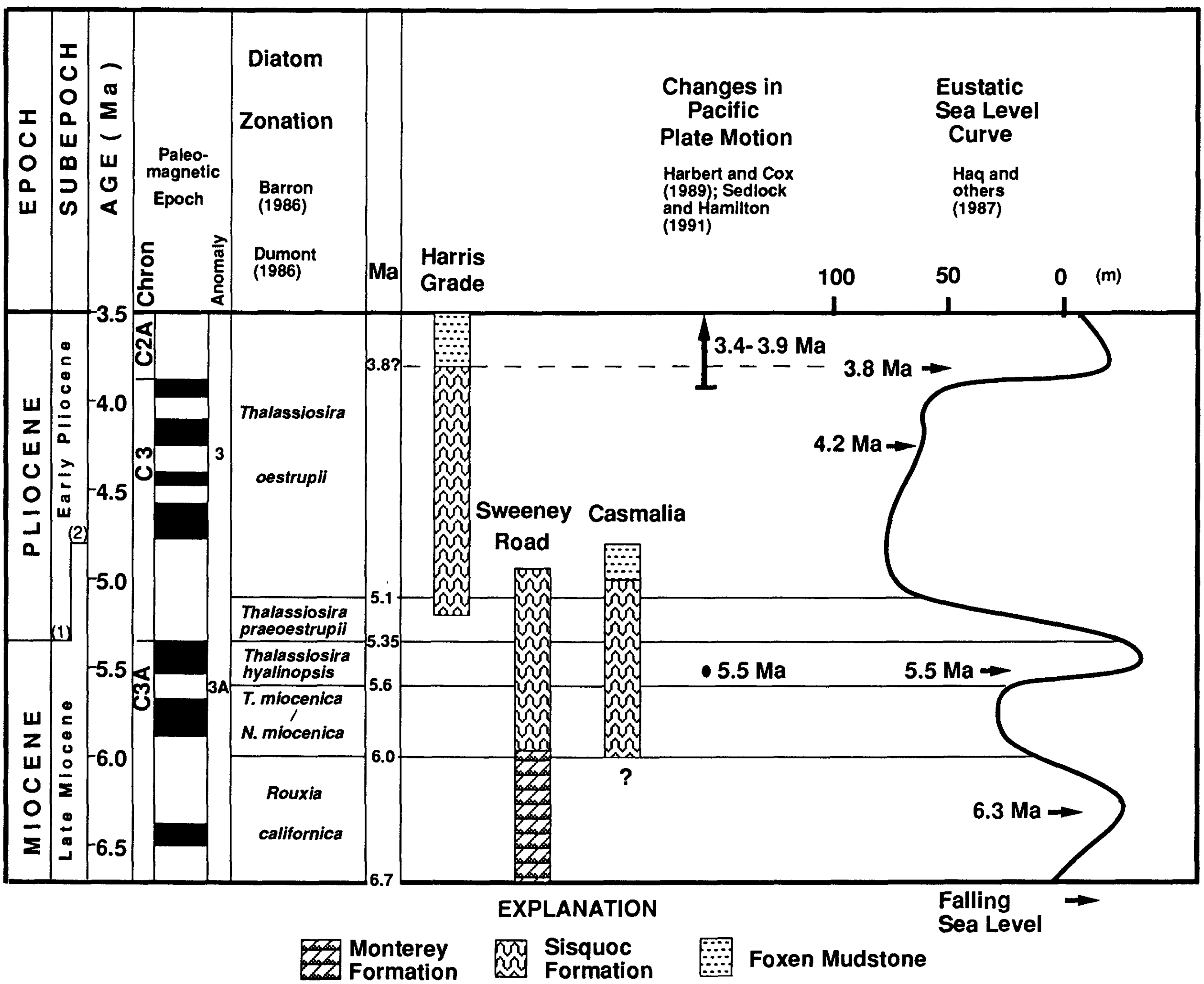

Figure 9. Comparison of key Sisquoc Formation sections to eustatic sea level curve of Haq and others (1987) and changes in motion of Pacific Plate after Harbert and Cox (1989) and Sedlock and Hamilton (1991).

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