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Paleogeography of the Western Transverse Range Province, California: New Evidence From the Late Oligocene and Early Miocene Vaqueros Formation

Stratigraphy of the Fine-Grained Facies of the Sisquoc Formation, Santa Maria Basin, California—Paleoceanographic and Tectonic Implications

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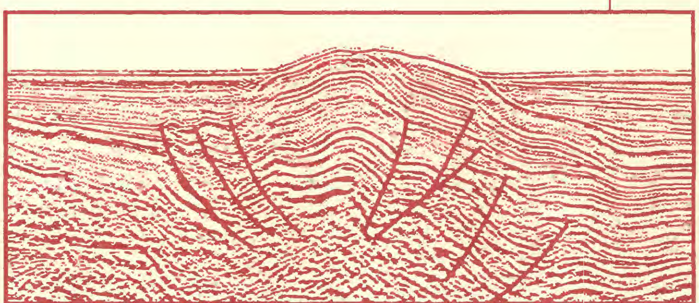

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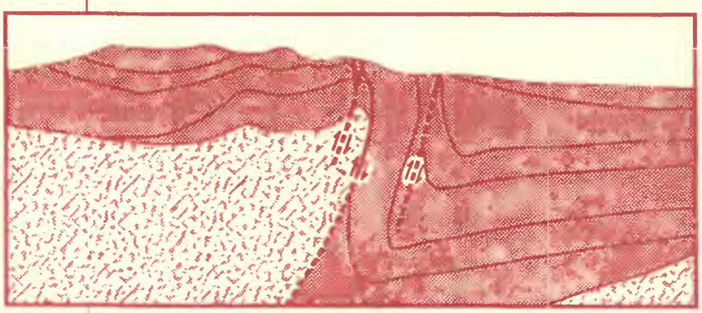

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SANTA MARIA PROVINCE

Edited by Margaret A. Keller

U.S. DEPARTMENT OF THE INTERIOR
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Chapter T

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By CATHERINE A. RIGSBY

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CONTENTS

Paleogeography of the Western Transverse Range Province, California: New Evidence From the Late Oligocene and Early Miocene Vaqueros Formation

By Catherine A. Rigsby[1]

Abstract

Outcrops of the Vaqueros Formation in the westernmost Transverse Ranges, and Vaqueros hydrocarbon reservoir strata in the adjacent Santa Barbara Channel, reveal dual sediment sources and a complex late Oligocene/early Miocene shoreline geometry. Shelf deposits in the central Santa Ynez Mountains separate a gently sloping, west- and southwest-facing mainland shoreline to the east (eastern Santa Ynez Mountains and Santa Monica Mountains; all depositional coordinates are prerotation) from a steep, east- and south-facing shoreline to the west (westernmost Santa Ynez Mountains). The western and central regions are dominated by lithic-rich arenites and by Franciscan-clast conglomerates (petrofacies one) derived from an emergent portion of an early Tertiary trench-slope break. The eastern region is dominated by lithic-poor quartzofeldspathic sandstones (petrofacies two) derived from older (Upper Cretaceous and (or) Paleogene) sandstones on the mainland to the east. The two lithofacies interfinger in the central region.

During the late Oligocene, sediment was shed onto the Vaqueros Formation shelf from both the mainland to the east and the partially emergent trench-slope break to the west. Later, during the early Miocene, transgression proceeded across the region, drowning the westernmost shoreline. Strontium isotopic analyses suggest apparent ages for Vaqueros strata that get younger in the paleo-landward directions. These strata record deposition in a complex forearc basin within an obliquely convergent continental margin. The geometry of this basin was the product of early to middle Tertiary plate interactions.

INTRODUCTION

The Vaqueros Formation in the western Transverse Ranges occupies a key position, both temporally and spatially, in the development of the southern California transcurrent continental margin. The Vaqueros strata also record the onset of eustatic sea level rise in a tectonically active marginal basin (Howard, 1988, 1995; Rigsby 1988b, 1994a). An appreciation of the Vaqueros sedimentary record is important in understanding the tectonic history of this complex area of southern California.

This paper details the stratigraphy of the Vaqueros Formation in the western Transverse Ranges (fig. 1) and presents a paleogeographic reconstruction of the study area during late Oligocene/early Miocene time. This reconstruction uses petrologic and lithofacies data from the Vaqueros Formation and is presented as a starting point for future, more detailed investigations, which should include age-equivalent strata to the north of the study area as well as detailed (and as yet proprietary) subsurface data from the adjacent Santa Barbara Channel. The data and interpretations based on the Vaqueros Formation and presented in this report provide new information and insights into the evaluation of tectonic models, based on paleomagnetic data, for the Tertiary history of southern California. Without sedimentological data, these models cannot be fully evaluated or tested.

ACKNOWLEDGMENTS

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TECTONIC SETTING

Paleomagnetic declinations in rocks of the western Transverse Ranges suggest that a structural block bound on the north by the Santa Ynez fault, on the east by the San Gabriel fault, and on the south by the Malibu Coast fault (fig. 1) was tectonically rotated (approximately 90°) from an original north-south orientation during middle Miocene time (Luyendyk and others, 1980, 1985). This rotation occurred during deposition of the Monterey Formation and corresponds in age to a regional disconformity within the Monterey (Luyendyk and others, 1985). The lack of an angular unconformity at this position in the stratigraphic record suggests that the rotation was not accompanied by tectonic compression within the rotating block. Further, the lack of throughgoing strike-slip faults, along with a systematic decrease in magnetic declination with decreasing age, suggests that the western Transverse Ranges were rotated as a single, coherent crustal block (Luyendyk and others, 1985). This rotation is attributed to the northwest-southeast-oriented shear couple that has existed between the Pacific and North American plates since the Oligocene (Cox, 1980; Luyendyk and others, 1985).

On the basis of paleomagnetic and stratigraphic data from the western Transverse Ranges, Hornafius (1985) suggested that there was no significant change in paleogeography be-

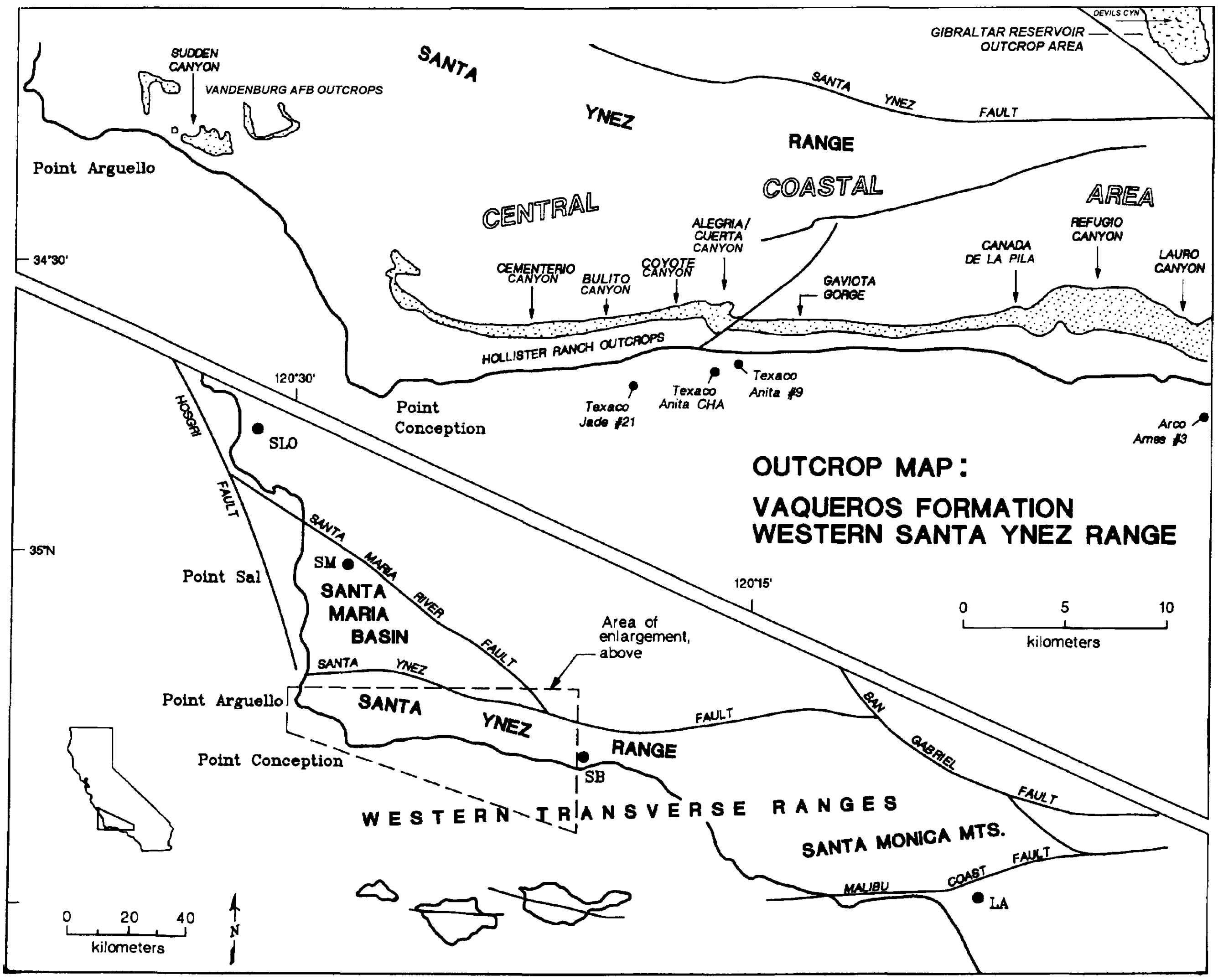

Figure 1. Map showing extent of Vaqueros Formation in the western Transverse Ranges study area. Outcrop pattern modified after Dibblee (1950). Abbreviations: SLO, San Luis Obispo; SM, Santa Maria; SB, Santa Barbara; LA, Los Angeles.

tween early Tertiary and Miocene time. In his model (fig. 2), the Santa Ynez fault marks the hingeline of the early Tertiary forearc basin, the Santa Maria basin is an emergent segment of the Oligocene trench-slope break, and the area now occupied by the southern Santa Ynez Range is situated on the continentward margin of that trench-slope break and on the oceanward side of the forearc basin (Hornafius, 1985; Rigsby, 1989a,b). Paleogeographic interpretations based on stratigraphic, petrologic, and depositional data from Vaqueros Formation strata in the western Transverse Ranges are presented here as a partial test of this model.

STRATIGRAPHY

Lithostratigraphy

The Vaqueros Formation is part of a regional late Oligocene and early Miocene deepening-upward sequence that

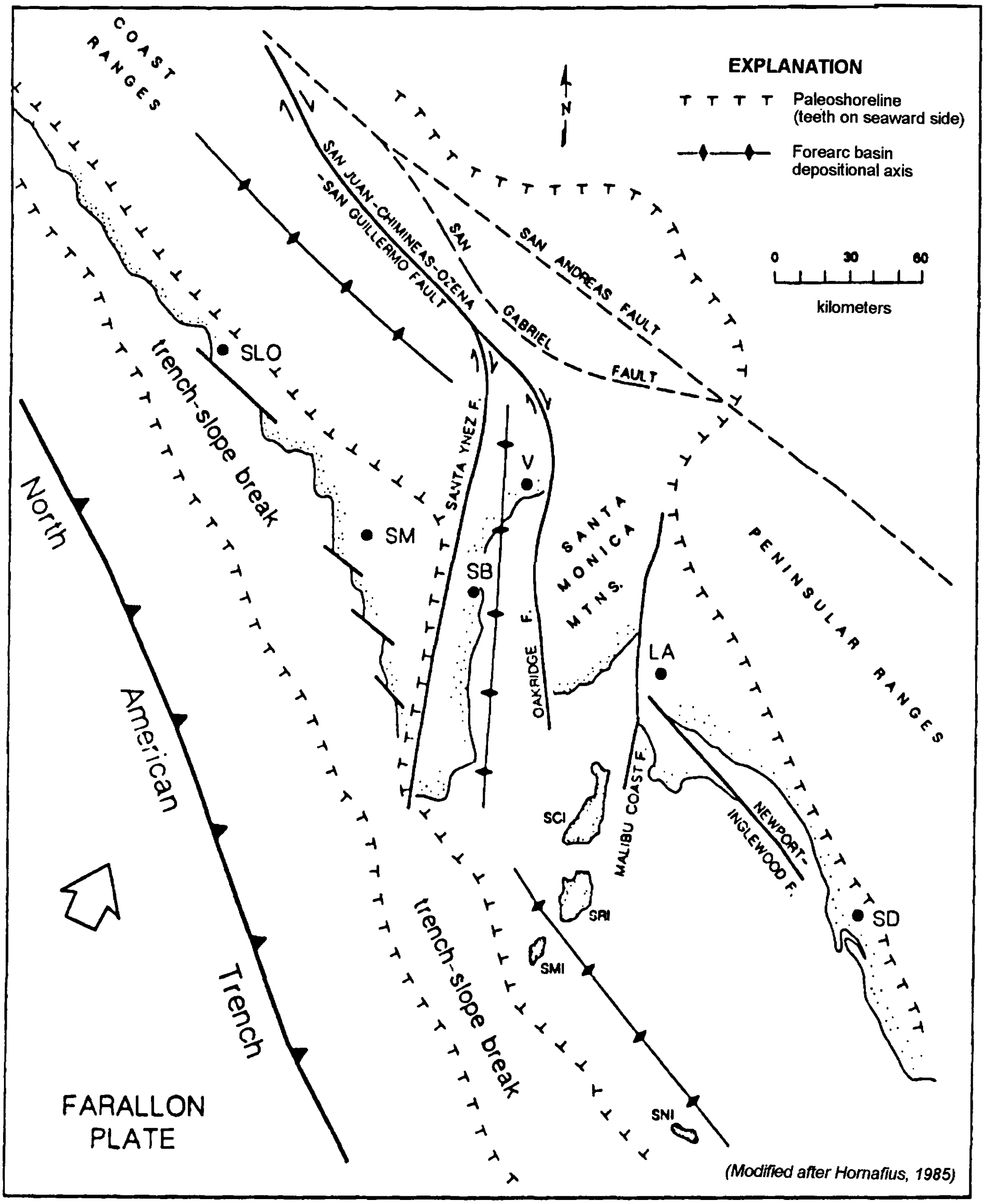

Figure 2. Palinspastic reconstruction of southern California during early Tertiary time (modified after Hornafius, 1985). Abbreviations: SLO, San Luis Obispo; SM, Santa Maria; SB, Santa Barbara; V, Ventura; LA, Los Angeles; SD, San Diego; SCI, Santa Cruz Island; SRI, Santa Rosa Island; SMI, San Miguel Island; SNI, San Nicolas Island; F, fault.

correlates with a second-order eustatic sea level rise (fig. 3). Sea level lowstand is represented by the upper member of the Sespe Formation which forms a widespread nonmarine base to this transgressive sequence (Howard, 1988, 1995). With the onset of sea level rise, the Sespe continental deposits were onlapped by nearshore and shelf sediments of the Vaqueros Formation. The Vaqueros, in turn, is overlain by shelf and slope strata of the Rincon Formation, which correlates with the highest stands of sea level during early Miocene time. The nature of the contacts between the Vaqueros Formation and these adjacent units and a detailed knowledge of local stratigraphy are important for a regional stratigraphic and sedimentologic understanding.

The contact between the Vaqueros Formation and underlying formations is complex. The Sespe Formation grades westward into paralic and shelf facies of the Alegria Formation (Dibblee, 1950; Howard, 1988). In the eastern part of the study area — for example, east of Lauro Canyon (fig. 1) and still farther east in the Santa Monica Mountains (Edwards, 1971; Lane, 1987) — the Vaqueros lies conformably and, locally, gradationally on the Sespe Formation. In the central part of the study area, at Canada de la Pila and Gaviota Gorge (fig. 1), for example, and in off shore wells at Hondo field (Miles and Rigsby, 1990; Rigsby and Schwartz, 1990) the Vaqueros sharply and conformably overlies paralic facies of the Alegria Formation. Farther west, the contact with the Alegria Formation becomes unconformable. The unconformity becomes progressively more angular westward, attaining a maximum angularity of 10°. In the northern part of the study area, at Gibraltar Reservoir, the basal Vaqueros contact is poorly exposed, but Vaqueros strata appear to be conformable with the underlying Sespe. Viewed regionally, the basal surface of the Vaqueros Formation progresses from an angular unconformity in the west to a transgressive surface — a surface cut by wave and current activity in a marine environment during or subsequent to a marine transgression, not a subaerial erosion surface (Nummendal and Swift, 1987) — in the central and offshore regions, to a conformable surface in the east and the north (Rigsby, 1988b).

The contact between the Vaqueros Formation and overlying units is most commonly a sharp boundary. In the westernmost part of the study area (at Rodeo Canyon (fig.1), for example), this contact marks the change from fine-grained sandstone and siltstone of the Vaqueros to silty mudstone of the Rincon Formation. In outcrops along the central coastal region, the contact is between coarse-grained sandstone (at Canada de la Pila) and conglomerate (at Gaviota Gorge) of the Vaqueros and siltstone and mudstone of the Rincon. At the Hondo and Capitan fields (see fig. 5), the Rincon-Vaqueros contact is either sharp or gradational over a short vertical distance (Miles and Rigsby, 1990; Rigsby and Schwartz, 1990). In these oil fields, the contact marks the transition between sandstone and siltstone of the Vaqueros and siltstone and shale of the Rincon.

Only in the Gibraltar reservoir area (fig. 1) is the upper contact of the Vaqueros Formation more complex. In this area, massive amalgamated sandstones of the Vaqueros, with thick beds of intervening siltstones, grade upward into the thinner sandstone beds of the Rincon Formation (Dibblee, 1973), which contain thin siltstone interbeds. The sandstone beds become thinner and finer upward across the contact. No mudstones are present at this locality. This gradational contact is present throughout most of the Gibraltar Reservoir area. The Rincon thins northward and eastward, however, and pinches out entirely near the northern boundary of the study area. At Devil's Canyon — the northernmost outcrop in this study — the Rincon is not present. The Vaqueros Formation at Devil's Canyon is overlain by the fossiliferous, shallow-marine, lower Miocene Temblor Forma-

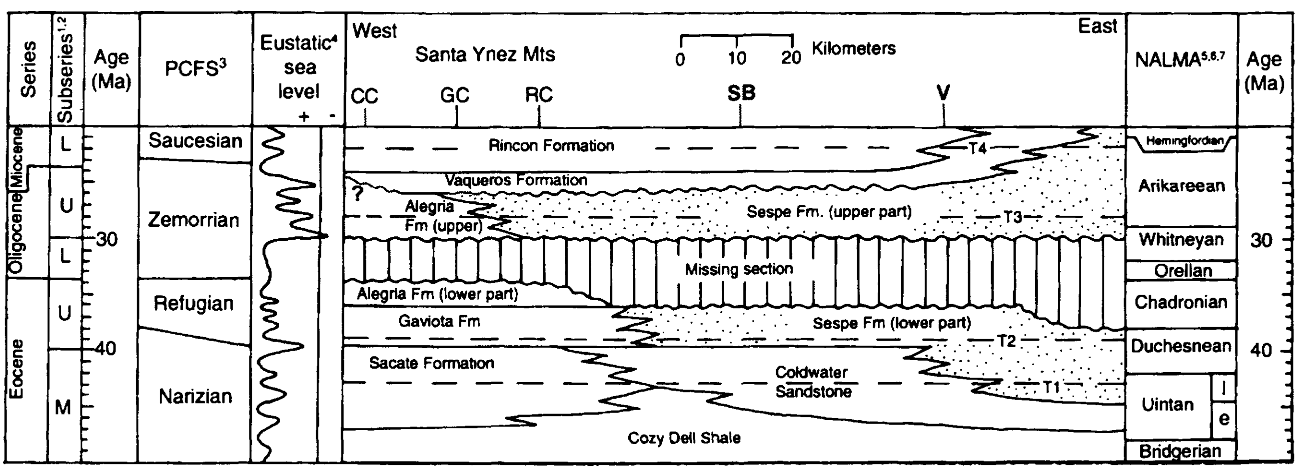

Figure 3. Facies relations between the Vaqueros Formation and laterally equivilent units in the western Transverse Ranges province. Modified after Howard (1995) to show decrease in age of the base of the Vaqueros Formation to the west, as discussed in text. See figures 1 and 2 for locations. Abbreviations: CC, Cementerio Canyon; GC, Gaviota Gorge; RC, Refugio Canyon; SB, Santa Barbara; V, Ventura; time lines T1 through T4 illustrate Howard's offlap-onlap relationships; PCFC, Pacific coast foraminiferal stages; NALMA; North American land mammal ages. L, lower; M, middle; U, upper; e, early; l, late. References for chronological framework: 1, Berggren and others (1992); 2, Cande and Kent (1992); 3, Bartow (1991); 4, Haq and others (1987); 5, Woodburne (1987); 6, Swisher and Prothero (1990); 7, Prothero and Swisher (1992).

TABLE I. Strontium isotope data and apparent equivalent ages for samples from the Vaqueros (Tv), Rincon (Tr), Temblor (Mt), and Alegria (Ta) Formations in the study area.

[Sample locations marked (c) are from the coastal portion of the study area — the Hollister Ranch and central coastal areas. Sample locations marked (n) are from the northern portion of the study area — the Gibraltar Reservoir area. Ratios marked * are normalized to NBS 986 = 0.71014. Ratios marked ** are normalized to NBS 987 = 0.70914. Check marks (ü) in the last column indicate that the sample is thought to have provided a reliable apparent age. Refer to text for additional discussion.]

Sample #	Location	Brief description of sample location	$^{87}Sr/^{86}Sr$	Percent residue	Sample type	Apparent equivalent age	Reliability of age
HR-B1-Tv	Bulito Road (c)	From center of small outcrop of poorly sorted fossil conglomerate	0.708156 ± 28*	0.60	Fibrous oyster	24 ± 1	ü
	Bulito Road (c)	As above	0.708512 ± 27*	0.60	Bivalve fragments	18 ± 1	
H R-C6-Ta	Cementario Canyon (c)	Several feet below Vaqueros contact	0.707772 ± 30*	0.50	Bivalve fragments	34 ±1	
	Cementario Canyon (c)	As above	0.707936 ± 20*	0.20	Bivalve fragments	29 ±1	
H R-C2B-Tv	Cementario Canyon (c)	Uppermost Vaqueros lithofacies in this outcrop	0.708367 ± 14*	2.10	Bivalve fragments	20 ± 1	
H R-AC8B-Tv	Alegria/Cuarta Cyn. (c)	From the conglomeratic portion of a Tv fining upward lithofacies (2nd lithofacies from top of Tv outcrop)	0.708804 ± 26*	0.00	Mixed mollusks	12 ± 1	
HR-COY-Tv	Coyote Canyon (c)	From near center of small outcrop	0.708307 ± 31*	0.00	Bivalve fragments	21 ± 1	
B ULITO 1-Tv	Bulito Canyon (c)	Middle of exposure	0.708404 ± 8*	0.10	Oyster fragments	20 ± 1	
P R-23-Tv	Paradise Road (n)	Just below channelized facies, in thinly bedded sandstone and siltstone	0.708880 ± 22*	2.10	Oyster fragments	8 ± 1	
SY3 -Tv	Paradise Road (n)	Near base of Vaqueros	0.70858 ± 3**	0.90	Pearly oyster fragments	17 ± 1	
	Paradise Road (n)	As above	0.70821 ± 3**	1.00	Fibrous, dense oyster frags.	23 ± 1	ü
SY4-Tv	Paradise Road (n)	At load structures near top of outcrop	0.70891 ± 2**	-	Chalky bone fragments	-	
SY7 -Tv	Paradise Road (n)	At Tv/Tr contact	0.70836 ± 4**	0.60	Chalky pecten fragments	-	
SY-Tr	Paradise Road (n)	As above	0.70848 ± 2**	0.00	Pearly oyster fragments	19 ± 1	ü
	Paradise Road (n)	As above	0.70880 ± 2**	7.30	Fibrous oyster fragments	~12(?)	
SY9-Mt	Paradise Road (n)	From Temblor "algal" bed	0.70875 ± 2**	1.70	Dense carbonate	~13(?)	
LG1 -Tv	Paradise Road (n)	Near top Vaqueros	0.70945 ± 3**	0.70	Spar fragments	-	

TABLE 2. Apparent age of the Vaqueros Formation in various parts of the western Transverse Ranges as reported by this and other studies.

[Only the three samples considered "reliable" (see table 1 and discussion in text) are included in the apparent age list for this study. Ages marked (b) are from the base of the Vaqueros; ages marked (t) are from the top of the Vaqueros.]

	Dickinson and others (1987) (Total Vaqueros Fm. age estimate)	This study (Age of base or top of Vaqueros Fm.)
Hollister Ranch area		24±1 Ma (b)
Gaviota Pass area	27–25 Ma	
Santa Barbara area	26–24 Ma	
Ventura area	26–23.7 Ma	
Gibraltar Reservoir area		23±1 Ma (b), 19±1 Ma (t)

tion (also called Vaqueros by some workers, such as Dibblee, 1973). The Temblor Formation is not present elsewhere in the study area.

Chronostratigraphy

Although rarely cited as a true chronostratigraphic stage, the "Vaqueros Stage" of Addicott (1977) is useful in that it denotes a group of megafossils distinctive to the Vaqueros Formation. A wide range of these Vaqueros Stage fauna was identified from Vaqueros outcrops on Vandenberg Air Force Base, on Hollister Ranch, and in the Gibraltar Reservoir area. Species present in the western and northern outcrop areas include the following: *Lyropecten magnolia* (a good Vaqueros Stage index fossil), *Turritella inezana*, "*Trophon*", *Ostrea eldridgei?* or *subtititan?*, *Neverita reclusiana*, *Dosinia* sp., *Tivela inezana*, and *Saxidomus* sp. or *Periglypta* sp. No identifiable forms are present in the central or eastern coastal outcrops, although the Cañada de la Playa section contains abundant coarse sand-sized fossil fragments.

In addition to fossil evidence, this study compared data obtained from strontium isotopic analysis (table 1) of samples from outcrops in the Santa Barbara coastal region and in the Gibraltar Reservoir region to the seawater strontium curve of DePaolo (1986; DePaolo and Ingram, 1985) to ascertain the chronostratigraphy of the Vaqueros Formation in the study area. High quality, datable material is scarce in these areas and, as indicated in table 1, samples of various type and quality were analyzed. In the best cases, large unaltered shell fragments were available and were collected and analyzed. In the worst cases, small slightly altered shell fragments were the only material available and, as such, were collected and analyzed. As a result of this variation in sample type and quality, analyses yielded a wide range of apparent ages for the strata.

Fibrous oyster samples, such as those from Bulito Road and Paradise Road (table 1), yielded the best dates. Barnacle fragments also yielded usable ages. At Little Sespe Creek, for example, barnacles and oysters from the same unit yielded identical ages. Bivalve fragments are of questionable reliability as age indicators. This unreliability may be the result of changes in the marine $^{87}Sr/^{86}Sr$ signal brought about by freshwater flux — either after deposition or in the original marginal marine environment (Bryant and others, 1995).

Other sample types are generally unreliable. The mixed mollusk fragments from Alegria/Cuarta Canyon (although they appeared fresh in hand sample) yielded anomalously young apparent ages. The bivalve fragments from Coyote Canyon and the oyster fragments from Bulito Canyon also yield low ages. As expected, samples that were noticeably weathered in the field yielded consistently anomalous data. At Paradise Road (Gibraltar Reservoir), for example, only two of the samples yielded believable apparent ages — a Vaqueros Formation sample at 23±1 Ma and a Rincon sample 19±1 Ma. The other ages were anomalously low and (in some cases) inverted, implying that the marine $^{86}Sr/^{87}Sr$ signal has been affected..

Although the data presented in table 1 show apparent ages that are widely scattered and that in some cases may not be reproducible, careful examination suggests that at least 3 of the 17 samples yielded reasonable data: one of the 2 Bulito Road samples and 2 of the 9 Paradise Road samples. The apparent ages of these samples allow a reasonable reconstruction of Vaqueros Formation chronostratigraphy.

The COSUNA Project chart for southern California (Bishop and Davis, 1984) indicates that the Vaqueros Formation in the central Santa Ynez Mountains ranges from 31 to 23.1 Ma (top of Zemorrian Stage). Within the error of this method, the strontium data presented here suggest that the Vaqueros strata in the Hollister Ranch and Paradise Road (Gibraltar Reservoir) areas were deposited 18 to 25 Ma. As reported by other workers, based on provincial foraminiferal stages in the overlying Rincon Formation (table 2), Vaqueros strata in the Gaviota Pass, Santa Barbara, and Ventura areas are slightly older (23.7-27 Ma; total Vaqueros Formation age range). Previous workers have suggested that the Vaqueros "youngs" landward — to the east (fig. 3; Howard, 1995) and the north (T.H. McCulloh, oral commun., 1987). These strontium and foraminiferal data do not contradict these landward-younging hypotheses; instead — when viewed in the context of the early Tertiary paleogeography — they suggest that landward younging took place over a very complex late Oligocene and early Miocene topography. This complexity is outlined in detail in the discussions of Vaqueros lithofacies that follow and has been alluded to by previous workers (Hornafius, 1985; Rigsby, 1989a, 1994a,b).

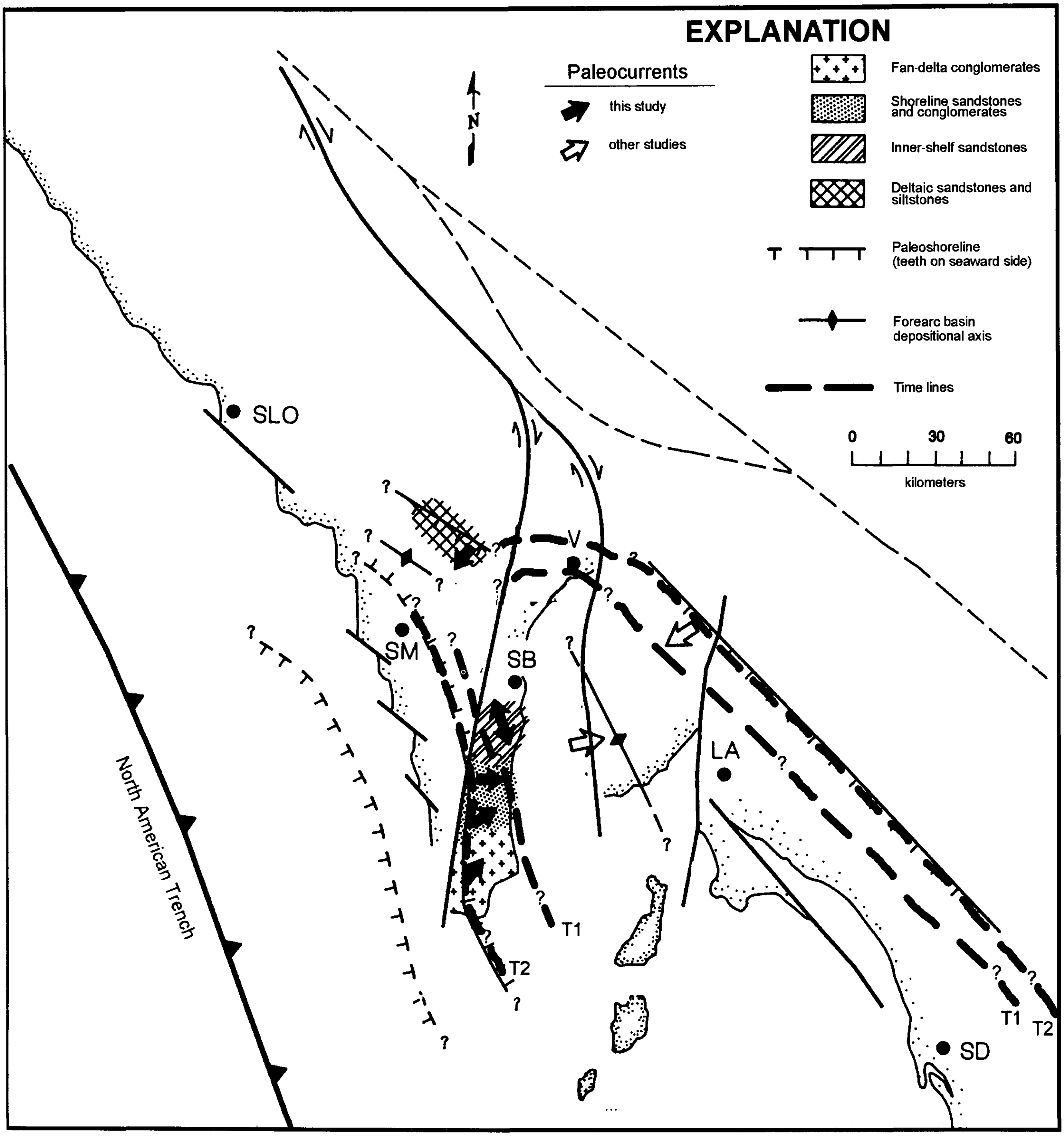

Figure 4. Hypothetical chronostratigraphy of the Vaqueros Formation. The hypothetical time lines (T1 is older, T2 is younger) are based on the strontium isotope ages reported in this study, on the Vaqueros age ranges reported by Dickinson and others (1987), and on geological evidence (such as the positions of paleoshorelines) presented in this paper and in work by Howard (1988), Hornafius (1985), and others. As discussed in the text, this hypothesis suggests that the Vaqueros Formation decreases in age in all landward directions. Base map is the early Tertiary palinspastic reconstruction of southern California (Hornafius, 1985). See figure 2 for abbreviations.

When hypothetical time lines — based on the data in presented table 2 and on geological data, such as the positions of paleoshorelines — are plotted on the palinspastic reconstruction of early Tertiary southern California (fig. 4), a pattern of landward younging does emerge. In this hypothesis, the older Vaqueros Formation strata (T1 on fig. 4) are approximately latest Oligocene to earliest Miocene and the younger Vaqueros Formation strata (T2 on fig. 4) are approximately early Miocene. Further, the time lines parallel the complex topography suggested by the paleomagnetic models. This chronstratigraphic reconstruction implies a time-transgressive nature for the Vaqueros Formation in this area. The Vaqueros transgression probably happened rapidly and at about the same time (late Oligocene) throughout the region and in adjacent areas (Stanley and others, 1992; Lagoe, 1988; Rigsby, 1989a; Keller and others, in press).

LITHOFACIES

Interpretation of lateral and vertical facies changes based on outcrop observations and on analysis of subsurface data (sparse public-domain well logs and cuttings as well as proprietary data from the Hondo, Capitan, and Elwood fields) suggests that the Vaqueros Formation in the study area may be divided into four major lithofacies tracts for the purpose of paleogeographic reconstruction. A facies tract is defined here as an area in which a single depositional system is predominant. The four Vaqueros depositional systems are summarized below. This summary is based primarily on previous work (Rigsby, 1988a,b, 1989a, 1994b). The present-day geographic extent of each depositional system is illustrated in figure 5 and selected, generalized measured sections are presented in figure 6. All directions used in this discussion are based on present-day geographic orientations (that is, relative to modern coordinates).

Fan-Delta Conglomerates

The Vaqueros Formation fan-delta conglomerates, described in detail by Rigsby (1989a, 1994b), are exposed exclusively in the westernmost Santa Ynez Mountains. They consist of coarse-grained, matrix-supported, variably fossiliferous conglomerate overlain by extensively bioturbated, locally crossbedded, coarse- to fine-grained sandstone (Sudden Canyon and Cementerio Canyon in fig. 6). Fan-delta plain, fan-delta front, and fan-delta slope units are present in a consistently deepening-upward sequence that documents the effect of late Oligocene and early Miocene sea level rise. Pebble imbrications throughout the sequence and channel orientations and crossbedding in the fan-delta front units record paleoflow to the east and southeast (Rigsby, 1989a, 1994b). No well data were available for examination in the area offshore of this facies tract.

Shoreline Sandstones and Conglomerates

Shoreline sequences (fig. 5; Alegria/Cuarta Canyon in fig. 6) present in the central coastal portion of the study area — on Hollister Ranch (fig. 1) — consist of crossbedded, sharp-based beds of sandstone and conglomerate overlain by surf-zone sandy conglomerate and, finally, by inversely graded, planar-laminated, coarse-grained sandstone (Rigsby, 1988b, 1989a,b). These strata represent deposition in a prograding shoreface-beach environment similar to that described by Hunter and others (1979). Paleocurrent indicators in the surf zone strata record a southeast-directed paleoslope.

Similar rocks occur in Vaqueros Formation outcrops studied by Edwards (1971) and Lane (1987) in the Santa Monica Mountains, where paleocurrent indicators record northwest paleoslope directions.

Cuttings and electric logs from wells offshore of the central coastal portion of the study area indicate that the Vaqueros Formation in the offshore is thin and discontinuous (Rigsby, 1989a). Examination of public domain well data reveals that the Vaqueros is present only in the Texaco Anita Block (fig. 5). The Texaco Anita CHA and the Texaco Anita #9 wells (fig. 1) encountered approximately 60 feet of coarse-grained sandstone overlain by fine-grained sandstone and siltstone of the Rincon Formation and underlain by Alegria Formation sandstones. In wells to the west, such as the Texaco Jade #21 (fig. 1), and to the east, such as the Arco Ames #3 (fig. 1), the Rincon Shale directly overlies the Alegria Formation with no intervening Vaqueros strata.

Inner-Shelf Sandstones

Outcrops along the eastern coastal portion of the study area are exemplified by the stratigraphic sequence at Canada de la Pila [referred to as Canada de la Playa in Rigsby (1988a,b) and as Quemado Canyon on fig. 6]. These strata consist of coarse-grained to granular sandstone that exhibit medium- to large-scale trough and planar crossbedding, and recording bidirectional paleoflows (Rigsby, 1988b, 1989a). Interpreted as inner shelf (tidal?) sand wave deposits, these units are conformable, but in sharp contact, with interbedded deltaic and nonmarine strata of the Alegria and Sespe Formations below and with shelf and slope strata of the Rincon Formation above.

Inner-shelf sandstones are identifiable in the subsurface in both the Hondo and Capitan fields (fig. 5). In the Hondo field the Vaqueros Formation consists of massive, bioturbated, medium-grained sandstone with few preserved inorganic sedimentary structures (Miles and Rigsby, 1990). In the Capitan field, the Vaqueros consists of medium- to coarse-grained, bioturbated, locally crossbedded and laminated sandstone (Rigsby and Schwartz, 1990). The lack of wave-formed sedimentary structures and the extensive bioturbation in Vaqueros strata in both areas suggest that these strata were deposited in

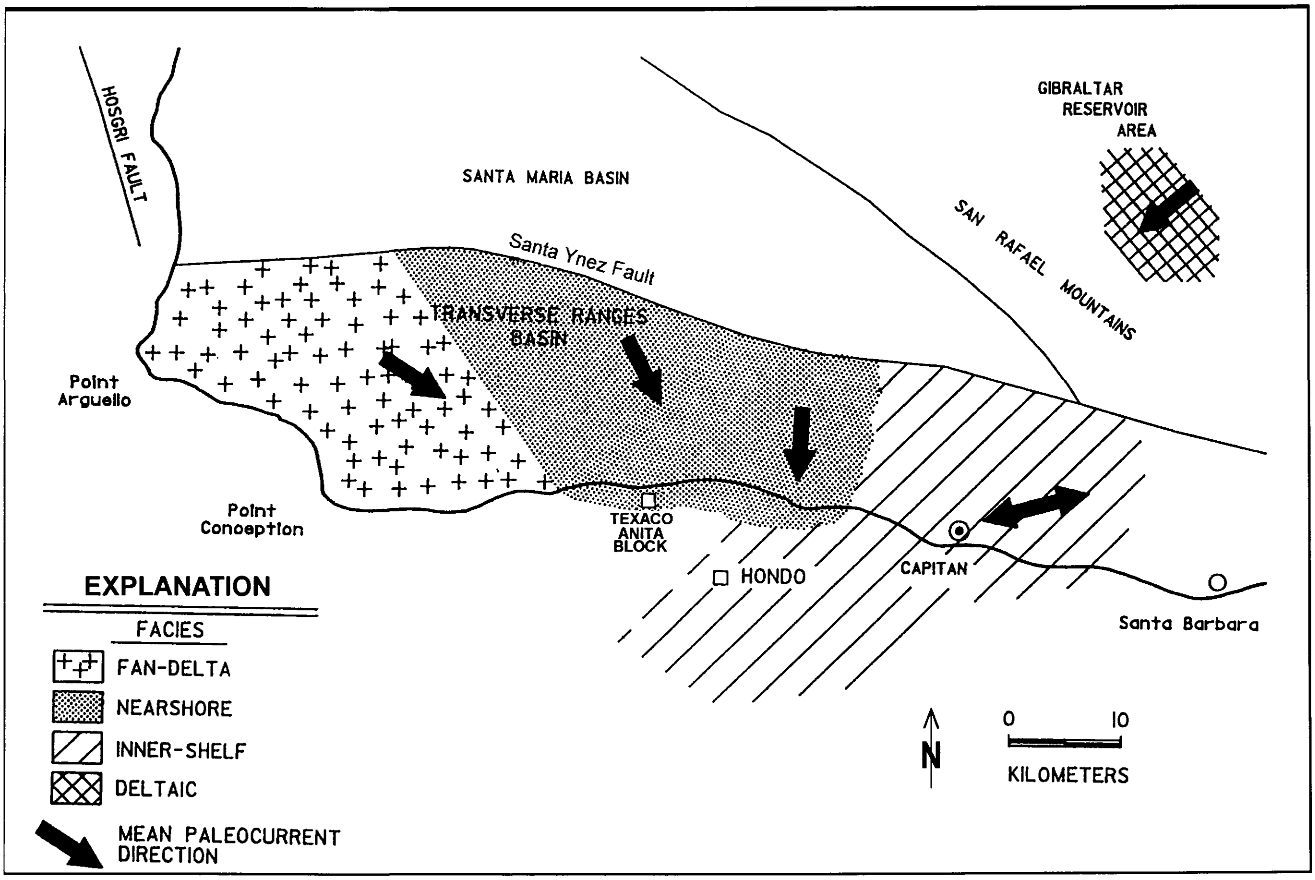

Figure 5. Present-day geographic extent of Vaqueros Formation lithofacies tracts in the western Transverse Ranges and in the offshore (modified after Rigsby and Schwartz, 1990). Paleocurrent directions are estimated from qualitative field examination of Vaqueros outcrops.

an inner-shelf environment where coarse-grained material was available, but where depositional energy was low enough to allow extensive faunal development.

In general, the inner-shelf facies of the Vaqueros Formation (as recorded in outcrops, as well as in the Capitan and Hondo fields) fines, thins, and becomes more pervasively bioturbated in the present-day offshore direction. The preservation of laminations and crossbedding and the lack of significant amounts of fine-grained material in the Vaqueros sandstone in the Capitan field indicate that the sandstones in this field occupied a more proximal position than that of the Vaqueros sandstones in the Hondo field. Furthermore, the intensity of the bioturbation and the occurrence of fine-grained sandstone and claystone at the tops of some Vaqueros intervals in the Capitan field suggest that the Vaqueros Formation in the Capitan field strata occupied a more distal position than the Vaqueros outcrops along the eastern coastal portion of the study area.

The outcrops and the nature of the Vaqueros Formation strata in the subsurface suggest that the inner-shelf sandstone environment may trend parallel to the paleoshoreline as a series of discontinuous, lens-shaped, medium- to coarse-grained sandstone bodies as is common in the deposits of shelf strata in the Cretaceous of the western interior of North America (Tillman and Martinsen, 1984). These sandstone bodies may be separated by areas of thinner bedded, finer grained sandstone and siltstone that may be difficult to distinguish from the Alegria Formation in both wireline logs and cores.

Deltaic Sandstones and Siltstones

The Vaqueros Formation in the Gibraltar Reservoir area (Rigsby, 1989a), as well as in parts of the Santa Monica Mountains to the east (Edwards, 1971; Lane, 1987), consists of deltaic sandstone and siltstone.

Gibraltar Reservoir Area

In the Gibraltar Reservoir area the deltaic facies is a 700-m-thick (maximum thickness; the lowermost part of the sequence contains an unknown thickness of fault-repeated section) coarsening- and thickening-upward sequence of sandstone and interbedded siltstone. The lower portion of the sequence is poorly exposed along the tops of canyon walls in Arroyo Burro (fig. 1). It consists of fine- to medium-grained, buff to yellow, extensively bioturbated and locally crossbedded

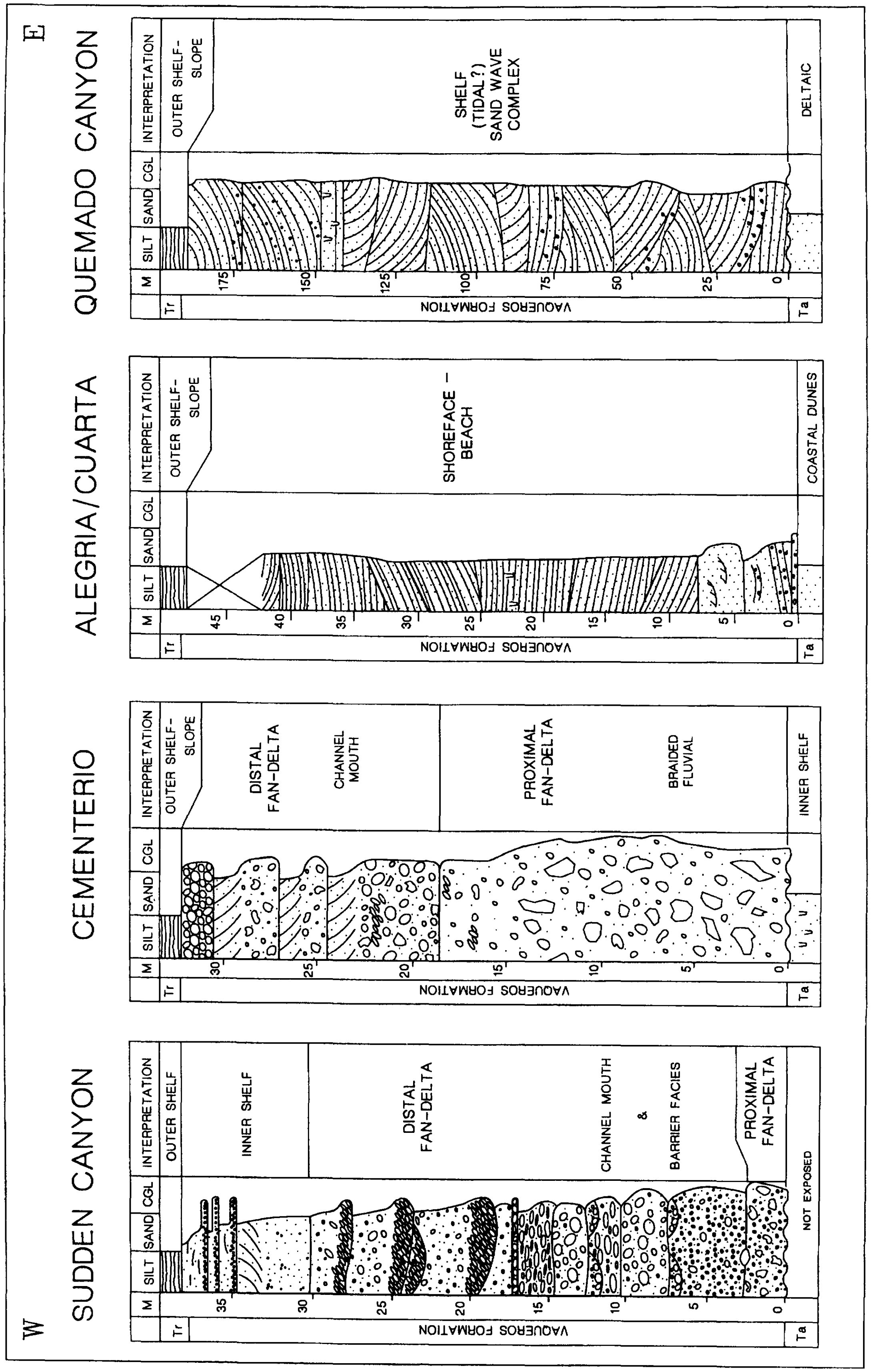

Figure 6. Generalized, diagrammatic measured sections of the Vaqueros Formation in the coastal area outcrops.

sandstone interbedded with muddy siltstone. The siltstone in this part of the section occur as grass-covered slopes separating isolated sandstone outcrops.

The middle 200 m of the sequence consists of fining-upward packets of medium- to coarse-grained, bioturbated and locally horizontally laminated and penecontemporaneously deformed (fig. 7A) sandstone interbedded with planar-laminated and bioturbated siltstone and mudstone. The fining-upward intervals coarsen upward into an uppermost 200-m-thick unit that consists of amalgamated channels of medium- to coarse-grained sandstone (fig. 7B).

Detailed paleocurrent studies were not possible because of the scarcity of sedimentary structures. However, the axes of large-scale (3-6 meter thick and tens of meters wide) channels in the upper unit generally trend northeast-southwest, suggesting a southwest-facing paleoslope.

These strata are interpreted as a progradational delta sequence based on the coarsening- and thickening-upward nature of the sequence, the lateral continuity of the sandstone beds in the lower and middle units, the uniformity of orientation of channel axes in the upper unit, the abundance of bioturbation in both mudstone and the sandstone, and the high mudstone/sandstone ratio (Coleman and Prior, 1980). Strata of the deltaic facies lie conformably between nonmarine sandstone and shale of the Sespe Formation below and shelf and slope turbidites of the Rincon Shale above, making a deltaic interpretation stratigraphically reasonable. It is possible sea level rise resulted in the abrupt submergence of the prograding delta at the end of Vaqueros Formation deposition. The inaccessibility of the steep cliff outcrops, combined with the lack of outcrops through large sections of the lower portion, prevent more detailed sedimentological interpretations.

PALEOCURRENTS

Paleocurrent data obtained from Vaqueros Formation outcrops are summarized in figure 5. From west to east (present-day orientations) along the coastal outcrop strip, Vaqueros paleocurrent directions rotate from generally southeast directed to south directed to bidirectional with northeast-southwest paleoflow indicators. Farther to the east, work by Edwards (1971) and by Lane (1987) indicates southwesterly flow directions in shoreline and inner shelf sandstones of the Vaqueros. The Vaqueros outcrops in the Gibraltar Reservoir area suggest south- to southwest-directed paleocurrents. Paleocurrent indicators in Sespe Formation strata to the east of the study area (in the Santa Monica Mountains and near Ventura) that are age equivalent to the Vaqueros record westerly flow directions, as do indicators in the older Alegria Formation and Sespe strata that underlie the Vaqueros throughout the central coastal regions of the study area (Howard, 1988).

The diversity of paleoflow directions, when viewed in conjunction with the facies tracts discussed above and the sedimentary petrology discussed below, suggests a complex physiography during late Oligocene and early Miocene time in the western Transverse Range province.

PROVENANCE

Differences in sandstone and conglomerate composition between Vaqueros Formation strata west of Refugio Canyon and Vaqueros strata east of Refugio Canyon (and the underlying Alegria Formation sandstones) serve to reinforce interpretations of stratigraphic and paleocurrent relationships. The nature of these differences implies regional sedimentological and tectonic significance.

Representative samples from Vaqueros Formation sandstones and conglomerates throughout the study area and from underlying Alegria Formation sandstones were examined for variations in grain and clast composition. Conglomerate clasts were identified via visual examination in the field by examining freshly broken clast surfaces with the aid of a hand lens. Visual estimates of dominant clast types and percentages were made at each outcrop locality. Approximately 100 thin sections from Alegria and Vaqueros sandstones were examined to measure variations in framework mineralogy. Representative thin sections from each lithofacies and locality were point counted using the Gazzi-Dickinson point-counting method (Ingersoll and others, 1984).

Data on the framework mineralogy of point counted sandstones were normalized and are displayed in two ternary diagrams (fig. 8) emphasizing source area and compositional maturity. Both the QFLt and the QtFL plot show a significant difference between the composition of Vaqueros Formation sandstones west of Refugio Canyon and the other sandstones (Rigsby, 1988a). This difference, combined with field estimates of conglomerate composition and with hand lens and binocular microscope examination of limited well cuttings, allow the definition of two petrofacies: a coarse-grained, lithic-rich petrofacies (petrofacies 1) and a sandy, micaceous, quartzofeldspathic petrofacies (petrofacies 2).

Petrofacies 1

Petrofacies 1 consists of coarse- to medium-grained lithic-rich sandstone and pebble- to boulder-conglomerate that outcrops in the southern Santa Ynez Mountains west of Refugio Canyon and is present in well cuttings in the area directly offshore and to the west of Canada de la Pila. As indicated on the ternary diagrams, the sandstones in this area (the fan-delta and nearshore strata and the westernmost portion of the inner-shelf strata) are more lithic rich than those east of Refugio Canyon (the deltaic strata) and Vaqueros Formation strata in the Santa Monica Mountains; they are also more lithic rich than sandstones of the underlying Alegria Formation. Total lithics in the western sandstones average 36 percent. Predominant grain types are chert and graywacke fragments (81 per-

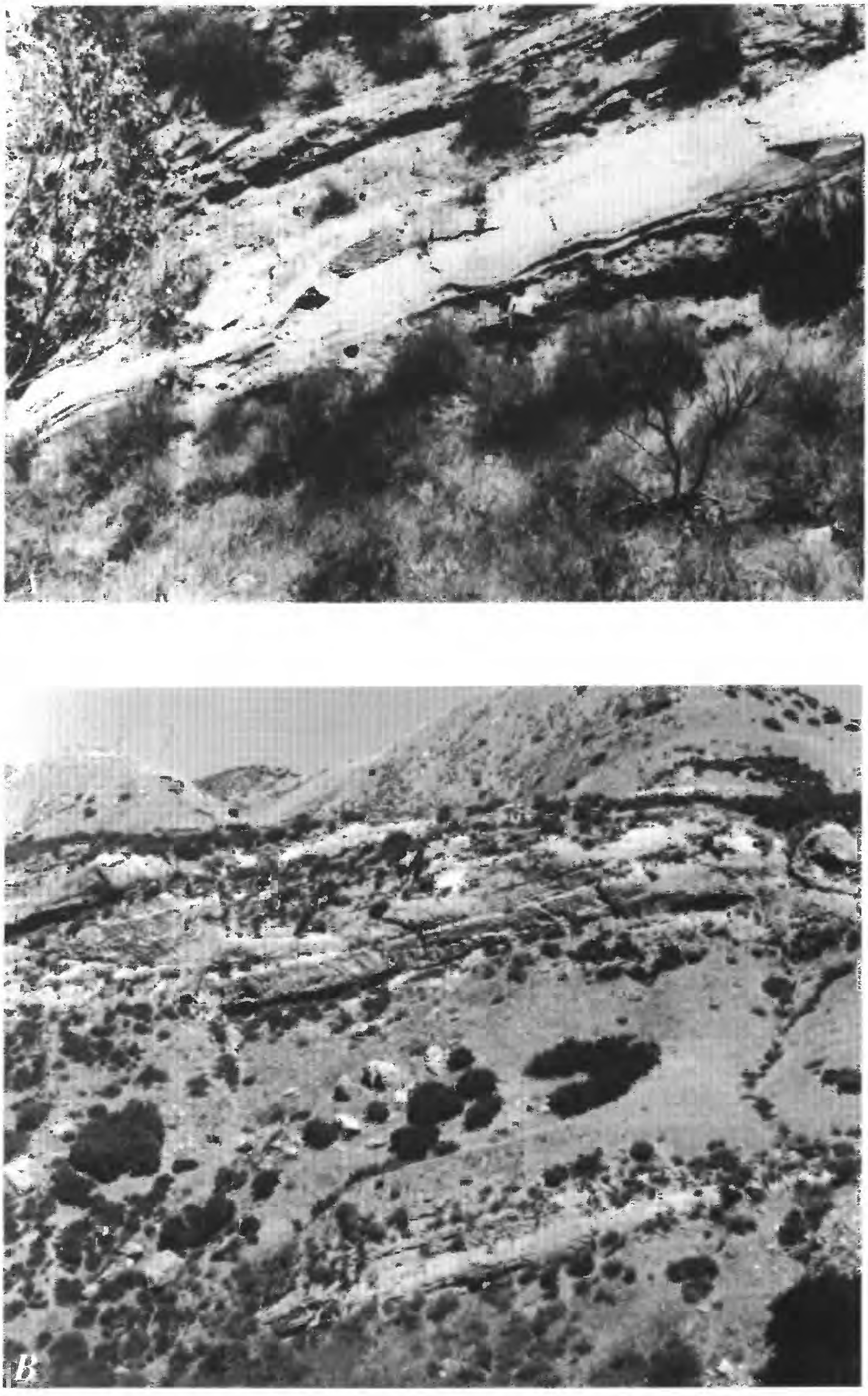

Figure 7. Vaqueros Formation strata of the deltaic facies tract in the Gibraltar Reservoir area.

cent). Conglomerate clast compositions in this petrofacies mirror those of the lithic grains. The dominant clast types are buff to brown, well-indurated graywacke and red, black, and green (locally radiolarian-bearing) chert. Subordinate amounts of dark gray to black, fine-grained volcanic and metavolcanic clasts are also present.

The abundance of radiolarian-bearing chert and of graywacke, as well as the occurrence of volcanics and metavolcanics, suggest a Franciscan provenance for this petrofacies. Extensive outcrops of Franciscan assemblage rocks (also called the Fransican Complex by some workers) around the perimeter of the Santa Maria basin to the north (the paleo-upslope direction) is consistent with a Franciscan provenance. Neither of these criteria, however, unequivocally confirms such a provenance. The Jurassic Coast Range ophiolite (Hopson and others, 1981), which outcrops locally within and around the Santa Maria basin (although not directly in line with measured paleocurrents), also contains radiolarian chert and, as such, may have been a source for the chert in this petrofacies. Likewise, the Upper Jurrasic and Lower Cretaceous Espada Formation (Dibblee, 1950), which outcrops locally in the Santa Ynez Mountains may have contributed fragments of lithic-rich wacke as well as chert reworked from beds of chert-pebble conglomerate. Hence, cherts could be derived from the Cretaceous Franciscan mélange, from the Point Sal ophiolite (Hopson and Franco, 1977) and correlative units, or from the Espada Formation chert-pebble conglomerates.

Petrofacies 2

Petrofacies 2 consists of fine-grained quartzofeldspathic sandstone of the Vaqueros Formation that outcrops east of Refugio Canyon and in the northern portion of the study area (in the deltaic strata), and that occurs in offshore wells east of Refugio Canyon and at Hondo and Capitan fields (in inner-shelf strata). This sandstone is identical in framework grain composition to the underlying sandstones of the Alegria Formation. Unlike petrofacies 1, sandstones of petrofacies 2 average only 25 percent lithic fragments. These lithics are evenly divided between volcanic (primarily microlitic) and sedimentary rock fragments. If rock fragments containing sand-sized mineral grains (and thus counted as the mineral grain) are included in the total rock fragment count for all samples, the difference in lithic content between the two petrofacies becomes even greater. In addition, Vaqueros sandstones east of Refugio Canyon and in the Gibraltar Reservoir area commonly contain granitic rock fragments that are not present in sandstones west of Refugio Canyon.

Conglomerate is rare in these eastern strata. Where it does occur (predominantly as thin lags in channel bases), the clasts are dominantly locally dervied, fine-grained quartzofeldspathic sandstone, mudstone (usually rip-ups), and rare fine-grained volcanics.

The quartzofeldspathic composition of these sandstones and the occurrence of granitic lithics suggest a granitic source for this petrofacies. Granitic rocks crop out extensively in the southern Sierra Nevada to the east and are the dominant source rocks for many older Tertiary units (Edwards, 1971; Lane, 1987; Howard, 1988). The dominant southwest and west paleocurrent directions recorded in the deltaic strata near Gibraltar Reservoir suggest a similar source for the Vaqueros Formation in that area. The variation in framework grain composition within the petrofacies 2 inner shelf strata, especially as documented for Vaqueros strata by Rigsby and Schwartz (1990), suggests that the Vaqueros inner shelf strata were derived, at

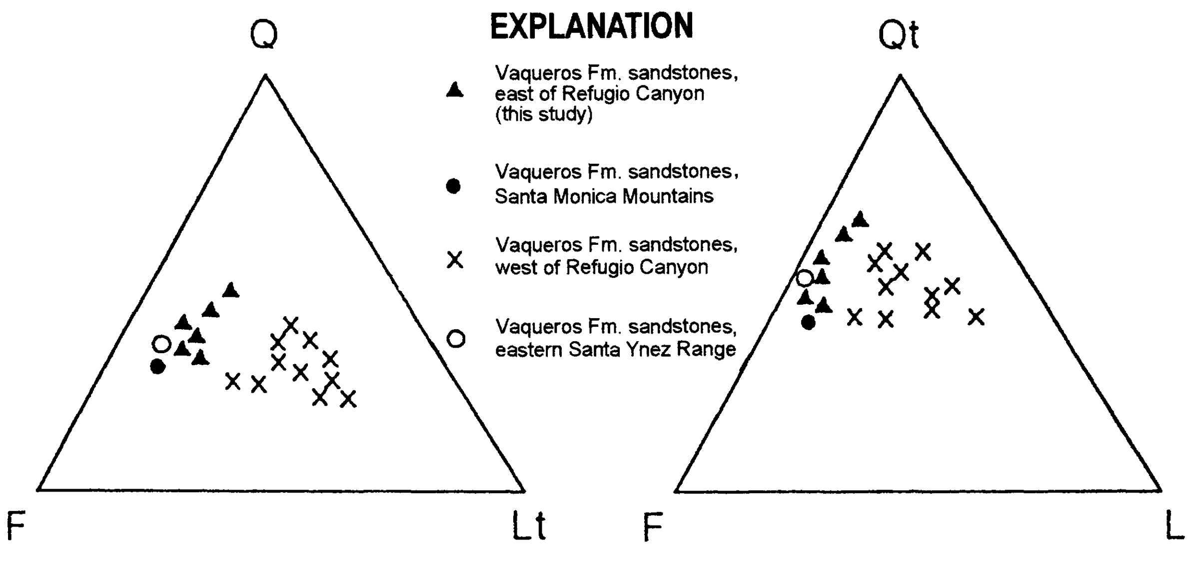

Figure 8. Sandstone QFLt and QtFL triangular diagrams showing two Vaqueros Formation petrofacies.

least in part, from the reworking of older shelf material. If this is indeed the case, the lateral variability of framework grain composition seen in petrofacies 2 strata may be controlled primarily by local variations in the rate of sediment supply — that is, by the amount of "dilution" of relict sediments by new, extrabasinal sediments (Rigsby and Schwartz, 1990).

DISCUSSION

Regional Paleogeography

East-directed paleocurrents in nearshore deposits in the westernmost Santa Ynez Mountains along with dual petrofacies in Vaqueros Formation sandstones and conglomerates indicate that the geographic and geologic setting of Vaqueros deposition was complex. A world-wide sea level lowstand during the late Oligocene (fig. 3) resulted in the widespread deposition of fluvial-alluvial Sespe Formation strata (Howard, 1988, 1995) and in the initiation of deposition of the shallow-marine Vaqueros Formation. As sea level subsequently rose, strata of the Vaqueros Formation transgressed over the former fluvial-alluvial depositional surface. Facies differences in the Vaqueros reflect variations in local topographic relief of that surface.

A model for the paleogeography of the western Transverse Ranges province during Vaqueros Formation deposition is depicted in figure 9. The base map for this reconstruction is the palinspastic map of southern California proposed by Hornafius (1985). This map incorporates all of the paleomagnetic data for the region and has been used as a paleogeographic base map by Howard (1988) in work on the Sespe Formation and by Lane (1987) in work on the Vaqueros Formation in the Santa Monica Mountains. The distribution of Vaqueros sedimentary environments in the western Transverse Ranges and data from the previous studies referenced above require a paleogeographic model that includes both continentward and oceanward sides of the forearc basin. Hence, the data presented here serve as geologic confirmation of the paleomagnetically derived tectonic reconstruction used as the base map in figure 9.

All of the paleocurrents from this study, and from the studies by Lane (1987) and by Howard (1988), with the exception of paleocurrents from the Gibraltar Reservoir area, were rotated 90° counterclockwise as required by the paleomagnetic data. Rotation is unnecessary for the Gibraltar Reservoir paleocurrents because the area is north of the boundary of tectonic rotation (north of the Santa Ynez fault) and has experienced no significant rotation (Hornafius, 1985).

The Vaqueros Formation outcrops located south (modern position) of the Santa Ynez fault are all situated on the oceanward side of the Oligocene and early Miocene forearc basin. The fan-delta and shoreface-beach deposits delineate the Vaqueros shoreline position along the offshore emergent high. Rotated paleocurrent directions indicate a source area to the west and an east-facing paleoslope, confirming the existence of the emergent high to the west. The nature of the uplifted landmass is unknown, but Hornafius (1985) suggested that it may have been similar to islands formed by emergent portions of the trench-slope break near northern Sumatra. The position of the western trench-facing shoreline in figure 9 is based on his model.

The inner-shelf deposits are, in part, petrographically similar to petrofacies 1 and exhibit rotated paleocurrents with northeast-southwest orientations. As sand wave deposits (whether or not tidally influenced), these strata suggest that the shoreline was even farther to the west in this area — within what is now Santa Maria basin.

Deepwater Vaqueros Formation deposits in the western Santa Monica Mountains (represented by the westernmost open arrow near the Santa Monica Mountains in fig. 9) were situated on the oceanward side of the forearc basin but closer to the basin axis than fan-delta, nearshore, and inner-shelf facies tracts (facies tracts 1, 2, and 3). These deeper water deposits record east-directed paleocurrents (fig. 9) and were probably derived from the same landmass as facies tracts 1, 2, and 3 (Lane, 1987).

The deltaic deposits in the Gibraltar Reservoir area delineate a position for the mainland shoreline in the northern part of the study area that is approximately 100 km southwest of the shoreline modeled by Hornafius (1985) on the basis of regional stratigraphic relationships. The southwest-directed paleoslopes recorded in the Gibraltar Reservoir strata do, however, confirm the orientation of his predicted shoreline. Because of the thick, prograding nature of the delta deposits, the shoreline on the paleogeographic map is placed at a nonspecific point within the outcrop belt. The placement of the southern continuation of the mainland shoreline is based on work by Lane (1987), which in turn is based on the eastward pinchout of shallow-marine Vaqueros Formation deposits and on the interfingering relations with nonmarine strata of the Sespe Formation.

Stratigraphic Implications

The paleogeographic scheme illustrated in figure 9 explains the variations in the nature of the Vaqueros Formation lower contact. Nearshore deposits, which conformably overlie the Sespe Formation in the eastern (present-day orientation) Santa Monica Mountains, were situated on the mainland and represent a west-facing shoreline (east-flowing paleocurrents); shelf deposits (Rigsby, 1988a, 1989a,b) in the central part of the study area accumulated on the oceanward side of the forearc basin; and fan-delta and shoreface-beach sequences in the western study area were deposited on the eroded edge of a locally emergent accretionary wedge. The regional variations in the nature of the contact are the result of late Oligocene to early Miocene eustatic sea level rise, regional tectonic setting, and contemporaneous tectonic activity asso-

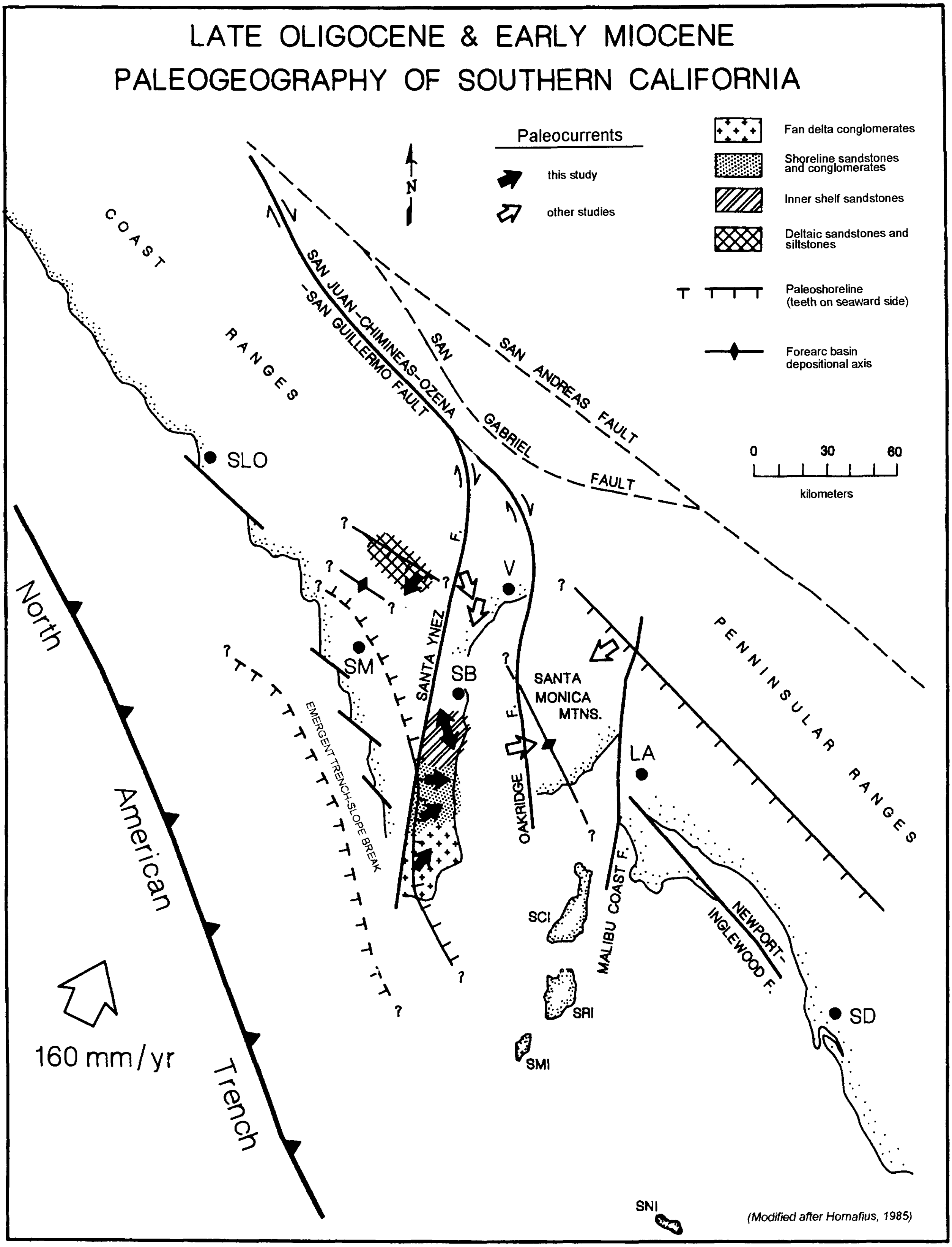

Figure 9. Palinspastic paleogeographic map of the western Transverse Ranges province during deposition of the late Oligocene and early Miocene Vaqueros Formation.

ciated with the final stages of subduction of the Farallon plate beneath North America (Hornafius, 1985; Rigsby, 1989a).

Tectonic Implications

Any sedimentological or structural model for the history of the western Transverse Ranges must consider the implications of the approach and ultimate subduction of the East Pacific Rise beneath the North America continental margin at a location very near the latitude of the Transverse Ranges province (Atwater, 1970; Atwater and Molnar, 1973; Dickinson and Snyder, 1979a,b; Engebretson and others, 1985). Although the exact latitude of the initial contact between the Rise and the North American plate is not well constrained, various workers (Christensen and Lipman, 1972; Atwater and Molnar, 1973; Dickinson and Snyder, 1979a,b; Engebretson and others, 1985; Molnar and Stock, 1985) have suggested that the first contact took place at a latitude somewhere between the Transverse Ranges and northern Baja California. Many of the geologic complexities in the western Transverse Ranges may be accounted for, however, if the East Pacific Rise first made contact at the latitude of the Transverse Ranges. The East Pacific Rise was close to the continental margin by about 38 Ma and first achieved contact about 29 Ma (Atwater, 1970; Engebretson and others, 1985). As a topographic consequence of ridge subduction, DeLong and Fox (1977) predict a gradual shoaling culminating in the subaerial exposure of the forearc basin followed by gradual basin submergence. The late Eocene and Oligocene sedimentary sequence in the western Transverse Ranges records a similar sequence of events (Howard, 1988, 1995): sedimentary offlap in the lower part of the Sespe Formation records a late Eocene gradual shoaling, a basin-wide early Oligocene unconformity in the Sespe records a period of subaerial exposure, and backfilling of the Sespe basin records the gradual submergence of the forearc basin.

Hornafius (1985) suggested the existence of an emergent section of the early Tertiary trench-slope break in the location of the present-day Santa Maria basin. The Vaqueros Formation fan-delta facies in the westernmost Santa Ynez Mountains (Rigsby, 1994b) confirms the existence of such a high within the forearc basin as late as 24±1 Ma. The existence of shelf deposits in conformable contact above the underlying fan-delta slope deposits (Rigsby, 1989a,b) and the drowning of the shelf-sand wave deposits with slope deposits of the Rincon Formation (at Canada de la Pila) is a record of the rapid submergence of this high and, thus, of the complete submergence of the early Tertiary forearc basin system.

As noted by Howard (1988, 1995), although the Sespe-Vaqueros-Rincon series of depositional events is remarkably similar to that predicted as a consequence of ridge-transform subduction, the timing coincides with several globally-recognized eustatic sea level drops (and subsequent rises; fig. 3); hence, these depositional events may not have been solely the result of plate tectonics. Indeed, the deepening-upward fan-delta sequence in the Hollister Ranch area (Rigsby, 1988b; 1989a,b; 1994a) suggests that although initial deposition was in response to uplift of the paleo-trench-slope break, sea level rise also may have played an important role in deposition. However, the existence of nearly contemporaneous shallowing- and deepening-upward sequences and of paleobathymetric subsidence that exceeded eustatic sea level fluctuation (Pinkerton and Rigsby, 1991) indicate that the eustatic sea level changes in the area were overprinted by local and regional tectonics.

The Vaqueros Formation paleogeography as presented here is a reflection of a complex, tectonically influenced physiography. The overprint of sea level fluctuations on that physiography is recorded in both the large-scale, regional, deepening-upward sequence (from nonmarine Sespe Formation deposits through deep-marine Monterey Formation deposits) and in the remarkable variation in vertical sequences found within the facies of the Vaqueros Formation.

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Chapter U

Stratigraphy of the Fine-Grained Facies of the Sisquoc Formation, Santa Maria Basin, California—Paleoceanographic and Tectonic Implications

By PEDRO C. RAMIREZ and ROBERT E. GARRISON

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

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Stratigraphy of the Fine-Grained Facies of the Sisquoc Formation, Santa Maria Basin, California—Paleoceanographic and Tectonic Implications

By Pedro C. Ramirez[1] *and* Robert E. Garrison[2]

Abstract

A detailed stratigraphic analysis of five measured sections (Casmalia, Mussel Rock, Sweeney Road, Lompoc Hills, and Pedernales) and of two sections (Lompoc Quarry and Harris Grade) previously studied of the fine-grained, mostly slope-deposited upper Miocene and lower Pliocene Sisquoc Formation provide the framework for correlating lithologic changes with paleoceanographic and tectonic events. In the Santa Maria basin, high-resolution diatom biostratigraphy indicates that the Sisquoc Formation examined in the measured sections, which predominantly consists of alternating laminated and massive diatomaceous lithologies and lesser amounts of phosphatic and chert-rich conglomerates, was deposited between approximately 6.0 and 4.8 Ma. In some areas of the basin (for example, Mussel Rock and the Lompoc Quarry), an erosional surface overlain by a phosphatic conglomerate marks the contact between the Sisquoc and the underlying Monterey Formation. The basal Sisquoc conglomerate in the Mussel Rock section may be related to a 6.3 Ma sea level drop and probably represents the erosion of the basin margin. The deposition of diatomaceous sediment continued uninterrupted in deeper areas (Casmalia, Sweeney Road, Pedernales, Lompoc Hills, and Harris Grade) of the basin. Prolific diatom sedimentation in the Sisquoc Formation in the Santa Maria basin is probably related to this sea level drop, as biologic productivity is hypothesized to have increased owing to intensified oceanic circulation and coastal upwelling. Furthermore, the flux of detritus (mostly clays) increased as more sediment was transported across the exposed narrow borderland shelves and into the basin during this sea level drop. Superimposed on major sea level changes and productivity variations were smaller scale variations in sea level and (or) productivity, generating the alternating massive and laminated units in the Sisquoc.

Opal-CT and quartz chert clasts in conglomerates and phosphatic conglomerates, which occur in the upper part of the Sisquoc in the Mussel Rock section, probably resulted from rapid uplift of basin margins. Compositional variations in the clasts of these conglomerates record the de-roofing of Monterey-type lithologies (opal-CT and quartz cherts) to levels that were probably not attainable by sea level drops alone. Additionally, these upper Sisquoc conglomerates were deposited from 5.3 to 5.0 Ma, or during a rise in eustatic sea level, thereby supporting tectonic activity.

Relatively high detrital contents in the Sisquoc may also be related to erosion associated with this episode of tectonic activity in the Santa Maria basin. This interpretation is in accord with a number of previously published studies that indicate that the late Miocene and early Pliocene was a tectonically active period in the California borderland. The stratigraphy and sedimentological characteristics of the Sisquoc Formation, therefore, are the product of the complex interaction of paleoceanography and tectonic activity.

INTRODUCTION

This study refines the late Miocene and early Pliocene stratigraphy of the Santa Maria basin and through correlations across the basin provides the framework for documenting through time changes in oceanographic and tectonic conditions. Additionally, this refined stratigraphy, which suggests that the Sisquoc Formation studied is late Miocene and early Pliocene in age (see discussion in section below on Stratigraphy, Ramirez (1990), and Barron and Ramirez (1992)), sets the foundation for future studies of upper Miocene and lower Pliocene rocks in the Santa Maria basin. Stratigraphic correlations for this study are based on diatom biostratigraphy. Barron (1976, 1981, 1986), Barron and Ramirez (1992), Dumont (1984, 1986, 1989), and Dumont and Barron (1995) provide the biostratigraphic foundation for this study.

Canfield (1939), Woodring, Bramlette, and Lohman (1943), and Woodring and Bramlette (1950) established much of the original stratigraphic framework for the Santa Maria area. These studies reveal that the Sisquoc represents a portion of the Neogene succession infilling the Santa

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Maria basin. Initial basin subsidence probably began in the early Miocene with the deposition of the Lospe Formation (Stanley and others, 1996) and basin-infilling culminated with the deposition of the Plio-Pleistocene Careaga Sandstone. The Sisquoc reflects the commencement of a late Miocene basin-infilling phase. The underlying Monterey Formation records maximum basin subsidence, whereas the overlying Foxen Formation generally represents the continuation of basin-infilling, following initial but local tectonic subsidence and paleobathymetric deepening (Behl and Ingle, this volume).

Sisquoc Formation exposures occur along the central California coastal area and, more specifically, throughout the Santa Maria and Santa Barbara basins. In the Santa Maria basin (fig. 1), the Sisquoc consists of a more proximal, loosely consolidated sandstone facies and a deep-marine predominantly mudstone facies. Originally, the Sisquoc was named for its sandstone facies, which is exposed in the eastern Santa Maria basin (Porter, 1932). However, Porter also determined that fine-grained rocks in the basin, which were previously referred to as the Monterey Formation, were, in part, correlative with the sandstone and, therefore, part of the Sisquoc Formation. Woodring, Bramlette, and Lohman (1943) and Woodring and Bramlette (1950) felt that the more extensively exposed fine-grained facies, which is the focus of this study, was more representative of the Sisquoc and relegated the sandstone to member rank (Tinequaic Sandstone Member). These authors also noted lithologic variations in the fine-grained facies of the Sisquoc. Woodring, Bramlette, and Lohman (1943) and Woodring and Bramlette (1950) identified a typically dark, relatively dense, massive to indistinctly laminated and relatively diatom-poor mudstone and designated it the Todos Santos Claystone Member.

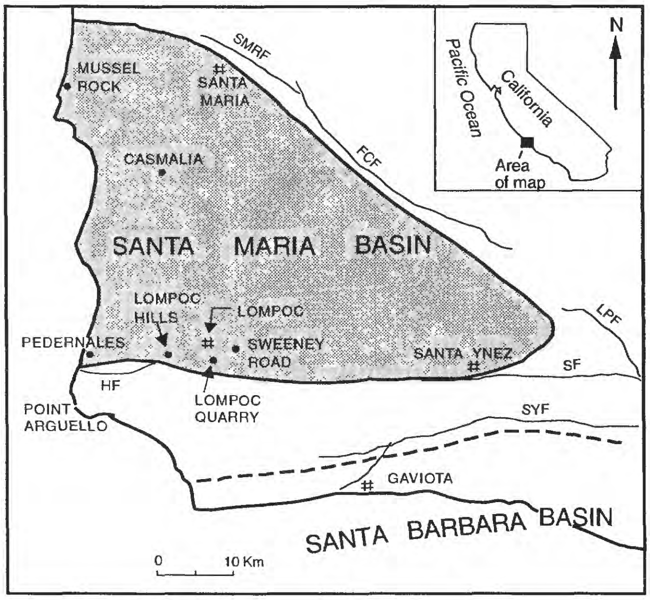

Figure 1. Index map depicting the fault-bounded Santa Maria basin and measured surface sections (darkened circles), as well as other sections (darkened rectangles) studied. Also shown is a portion of the Santa Barbara basin. SMRF, Santa Maria River Fault; FCF, Foxen Canyon Fault; LPF, Little Pine Fault; SF, Solvang Fault; SYF, Santa Ynez Fault; and HF, Hondo Fault (faults depicted are from Hall, (1978).

Recent efforts have been made to sedimentologically characterize the Sisquoc Formation and to determine its depositional environment. Woodring and Bramlette (1950) described the Sisquoc and speculated that it was deposited at moderate water depths and below active wave base. Ingle (1981b) determined that the Sisquoc in the Santa Ynez Mountains was probably deposited at upper bathyal depths. Isaacs (1980, 1983, 1985) calculated silica and detritus accumulation rates in the Monterey and Sisquoc Formations and concluded that the Sisquoc was deposited in a marine environment where the accumulation rates of silica and detritus exceeded those of the Monterey. Henderson (1983) and Henderson and Ramirez (1990) indicate that Sisquoc deposition probably occurred on a slope. Ramirez (1987, 1990), on the basis of detailed sedimentologic analysis, also concluded that much of the Sisquoc was deposited on the slope. This report represents an extension of the aforementioned studies.

Five surface sections (Mussel Rock, Pedernales, Casmalia, Sweeney Road, and Lompoc Hills) containing the fine-grained Sisquoc and some of the underlying Monterey Formation were measured and examined in detail for this study (fig. 1). Data from the Lompoc Quarry and Harris grade sections, which were studied by Barron (1975), Dumont (1986), and Barron and Ramirez (1992) are also incorporated in this study. The freshly washed, coastal exposures of the Mussel Rock and Pedernales sections reveal well-preserved, small-scale sedimentary structures and a variety of trace fossils, both of which aid the interpretations of depositional processes and environments (fig. 2). In contrast, intense weathering of the inland Casmalia, Sweeney Road, and Lompoc Hills sections results in bleached outcrops and the masking of sedimentary structures, as well as any subtle lithologic variations that might occur in the rocks. Consequently, the sedimentary structures and lithologic variations in the two coastal sections served as guides for the identification of structures and lithologic variations in the noncoastal sections.

LITHOLOGIES, COMPOSITION, SEDIMENTARY STRUCTURES, AND DEPOSITIONAL ENVIRONMENTS

The distal facies of the Sisquoc Formation, like the underlying siliceous facies of the Monterey Formation, consists largely of varying proportions of diatoms and clays and lesser amounts of silt, sand, and sponge spicules, as well as scarce foraminifers. Variations in the amounts of diatoms and clays largely control the variable lithologies in the Sisquoc. These lithologies range from a nearly pure mudstone to diatomite, with diatomaceous mudstone dominating in the measured sections. Diagenetic alteration of diatomaceous strata brought about by increased temperatures and pressures associated with burial (Isaacs, 1980, 1981a) produced siliceous mudstone, porcellanite, and minor chert (see Isaacs (1981b) and Ramirez (1990) for definitions of these lithologic terms). Strata modified by silica diagenesis are generally restricted to the Monterey and the basal Sisquoc in the sections examined. Also present in the Sisquoc Formation are relatively minor amounts of stratiform and nodular dolomite and some sedimentologically important phosphatic and chert-rich conglomerates.

A conspicuous feature of the Sisquoc and the upper Monterey Formations in the Santa Maria basin is the alternation of massive and laminated beds. Generally, the Sisquoc contains a greater proportion of massive to laminated units compared to the Monterey (Ramirez, 1990). Massive units in the Sisquoc, which vary from two to tens of meters thick, are not entirely structureless but usually exhibit a bioturbated fabric, which in places consists of excellently preserved trace fossils. The two to tens of meters thick laminated units in the Sisquoc Formation consist mostly of regularly alternating planar light-colored, 1 to 2 mm thick, diatom-enriched layers and thicker (up to 2 cm), darker layers usually composed of clay and lesser amounts of silt and diatoms.

Utilizing a variety of analytical methods, Ramirez (1990) showed that, compositionally, the Sisquoc is enriched in detritus (mostly clays) relative to biogenic silica (mostly diatoms) (fig. 3*A*). Comparatively, the underlying Monterey contains more silica and less detritus than the Sisquoc. Possible interpretations for these compositional trends from the Monterey into the Sisquoc include increased detritus entering the Santa Maria basin during Sisquoc deposition, decreased flux of silica during the deposition of the Sisquoc, or a combination of the two. Another possibility is that silica sedimentation increased during Sisquoc deposition but was masked by detritus accumulation that also accelerated during this time (fig. 3*A*). Ramirez (1990) calculated rates of silica and detritus accumulation in the Sisquoc and found that accumulation rates of detritus generally exceeded those of silica during the deposition of the Sisquoc (fig. 3*B*). Figure 3*B* also shows that rates of silica and detritus accumulation in the Sisquoc exceed those of the underlying Monterey Formation in the Santa Maria basin. Isaacs (1983, 1984, 1985) reached a similar conclusion in her study of accumulation rates in the Monterey and Sisquoc Formations in the Santa Barbara coastal area. Therefore, lithological differences between the Monterey and the Sisquoc in the central California coastal area reflect changes in the rates of silica and detritus accumulation. As documented by Ingle (1981a, 1981b), Isaacs (1983, 1984), Barron (1986), and Ramirez

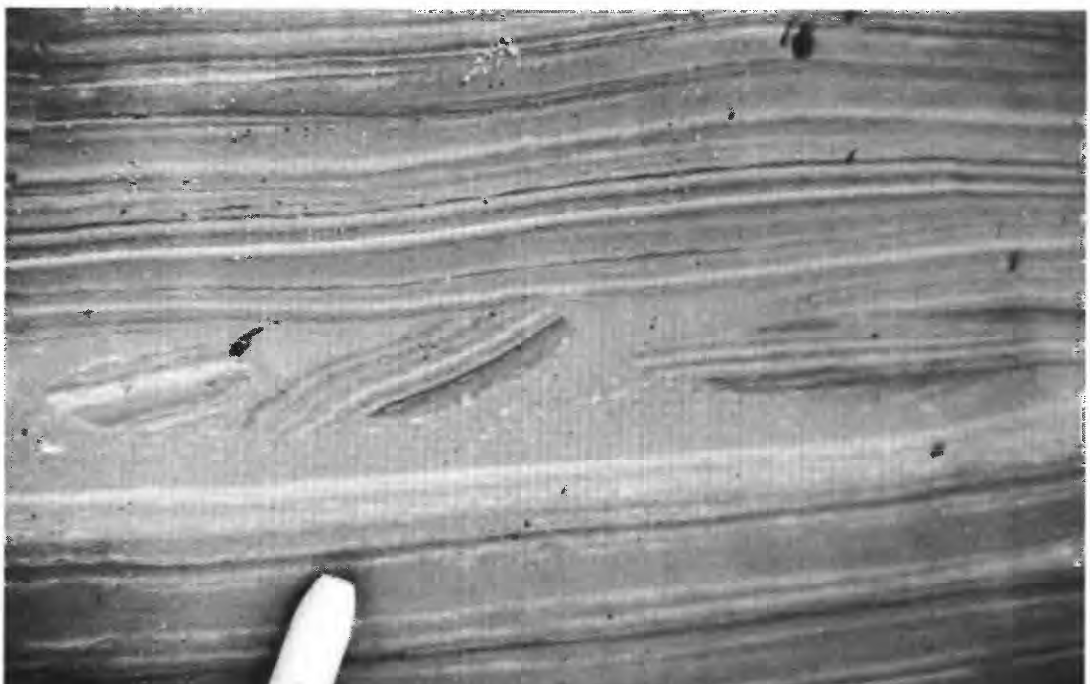

Figure 2. Closeup view of typical Sisquoc Formation exposure in the Pedernales area. Light-colored laminae are composed almost entirely of diatoms and darker-colored ones are composed mostly of clays with some silt and diatoms. Note the small-scale intraformational breccia. Marker at base of the photograph is approximately 1 cm wide.

(1990), the abundance of diatoms in the uppermost portions of the Monterey Formation and in the Sisquoc Formation reflect deposition beneath a highly productive late Miocene and early Pliocene upwelling system.

The absence or scarcity of environmentally diagnostic benthonic taxa, such as foraminifers or mollusks, and the fine-grained nature of the strata make it difficult to accurately determine the depositional settings of this facies of the Sisquoc. However, based on the presence of small-scale sedimentary structures, such as slump folds, intraformational breccias (see fig. 2), and angular discontinuities, Ramirez (1990) concluded that the deposition of much of the fine-grained facies of the Sisquoc occurred in a slope to upper slope-shelf-edge environment. Henderson (1983), also concluded that Sisquoc deposition probably occurred in a slope environment. The sedimentary structures mentioned likely reflect instability and sediment reworking within the slope environment.

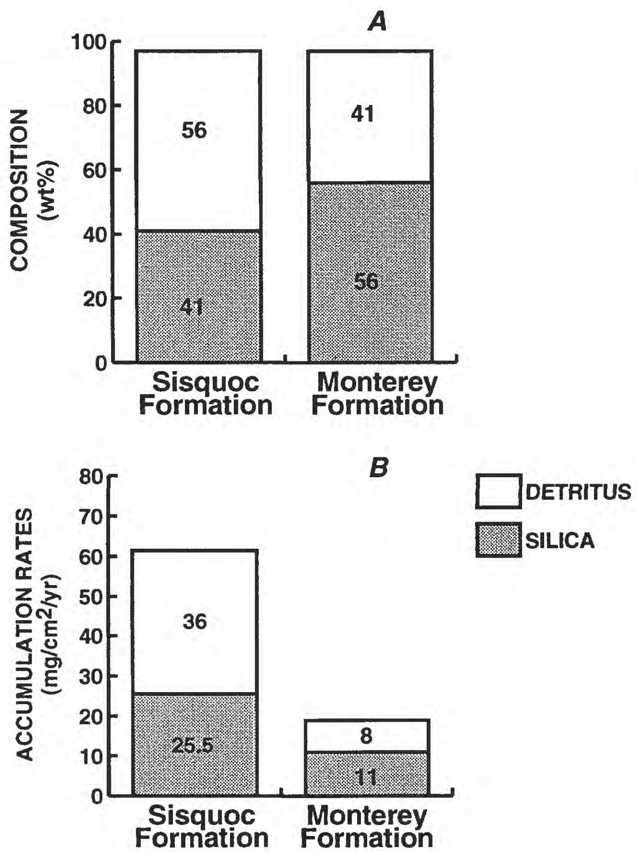

Figure 3. (*A*) Mean abundances of detritus and biogenic silica in both the Monterey and Sisquoc Formations in the Santa Maria basin. A total of 178 samples from the Sisquoc Formation and 27 from the Monterey Formation were analyzed for major oxides; this analysis was then used to calculate mean abundances of detritus, silica, calcite, and dolomite using conversion factors developed by Isaacs (1980). Calcite, dolomite, and, apatite are relatively minor constituents of these rocks, and their abundances are not presented here. See Isaacs (1980) and Ramirez (1990) for additional information on the analytical techniques employed. Numbers in individual bars in graph represent relative percents. (*B*) A comparison of mean accumulation rates of silica and detritus in the Monterey and Sisquoc Formations of the Santa Maria basin. Isaacs (1985) and Ramirez (1990) present discussions of the methods used to calculate accumulation rates in fine-grained siliceous strata. Numbers in individual bars in graph represent relative accumulation rates. From Ramirez, 1990.

STRATIGRAPHY

To better understand how sedimentologic changes occurred through time and to determine whether these changes relate to known late Miocene and early Pliocene oceanographic events, we developed a detailed biostratigraphic framework for the late Miocene rocks discussed in this study. Because foraminifers and molluscs in outcrop are for the most part either absent, scarce, and (or) poorly preserved in the fine-grained Sisquoc, diatoms became the logical choice for dating Sisquoc lithologies. Recent refinements of diatom zonations for the central California coastal area yield age resolutions of 250,000 to 450,000 years for the latest Miocene and about 250,000 for the earliest Pliocene (see Dumont, 1986; Dumont, 1989; Ramirez, 1990; and Barron and Ramirez, 1992). Figure 4 shows the central California diatom zonation used for upper Miocene and Pliocene strata in the Santa Maria basin. The age resolution plus the datum points provided by the late Miocene and early Pliocene diatom zones of central California allow accurate and detailed biostratigraphic correlations of Sisquoc strata and refined calculations of bulk and component accumulation rates. The diatom biostratigraphy upon which much of this work is based is found in Barron and Ramirez (1992) and Dumont and Barron (1995), who use Berggren, Kent, and Van Couvering's (1985) geologic time scale.

Figure 5 is the key to lithologic symbols used in figures 6 and 7. Figure 6 is a chronostratigraphic diagram of our measured sections, and figure 7 shows the results of our correlations. Note that in the Lompoc Hills, Pedernales, and Sweeney Road sections the Monterey grades into the Sisquoc, while in the Mussel Rock section an erosional surface exists between the two formations. The contact between the Monterey and Sisquoc Formations has been the source of considerable discussion (see review of criteria used in distinguishing the Monterey from the Sisquoc in Ramirez, 1990, and also in Dumont and Barron, 1995). In the Mussel Rock section, a phosphatic conglomerate overlies the erosional surface present and clearly marks the formational boundary between the Monterey and the Sisquoc (fig. 8). Diatoms extracted from the uppermost Monterey and the lowermost Sisquoc in the Mussel Rock section indicate that, according to Dumont's (1986) and Dumont and Barron's (1995) proposed diatom zonations, the top of the Monterey coincides with the top of the *Rouxia californica* zone and the base of the *Thalassiosira* *miocenica-Nitzschia miocenica* zone. The boundary between these two diatom zones falls at about 6.0 Ma (Dumont, 1986; Dumont and Barron, 1995). Similarly, at the Lompoc Quarry (see fig. 1 for location), where a phosphatic conglomerate also overlies an erosional contact between the Monterey and the Sisquoc, the top of the Monterey is dated at about 6.0 Ma (Barron and Ramirez, 1992). Based on extrapolated age-thickness plots, the Monterey-Sisquoc contact is also dated at about 6.0 Ma in the Casmalia section (Ramirez, 1990). Although an unconformity is absent, a lithologic change is present at the Monterey-Sisquoc contact in the Casmalia section. This change, which is visible in outcrop and which is confirmed by whole rock chemical analysis, is marked by laminated porcellanite of the Monterey Formation passing upward into a dense, dark, massive siliceous mudstone (Woodring, Bramlette, and Lohman's (1943) Todos Santos Claystone Member of the Sisquoc Formation) that is enriched in detritus and depleted in silica relative to the Monterey Formation.

The above discussion indicates that the contact between the Monterey and the Sisquoc at Mussel Rock, the Lompoc Quarry, and in the Casmalia section falls at about 6.0 Ma. In other sections, however, there is neither a sharp physical break nor a lithologic contrast between the two units (for example, Pedernales, Lompoc Hills, and Sweeney Road sections; fig. 6). Therefore, for the purpose of discussion and comparative analysis, in these sections at Lompoc Hills, Sweeney Road, and Pedernales, where the Monterey grades into the Sisquoc, we have chosen arbitrarily to locate the formational contact biostratigraphically at the boundary between the *Rouxia californica* and the

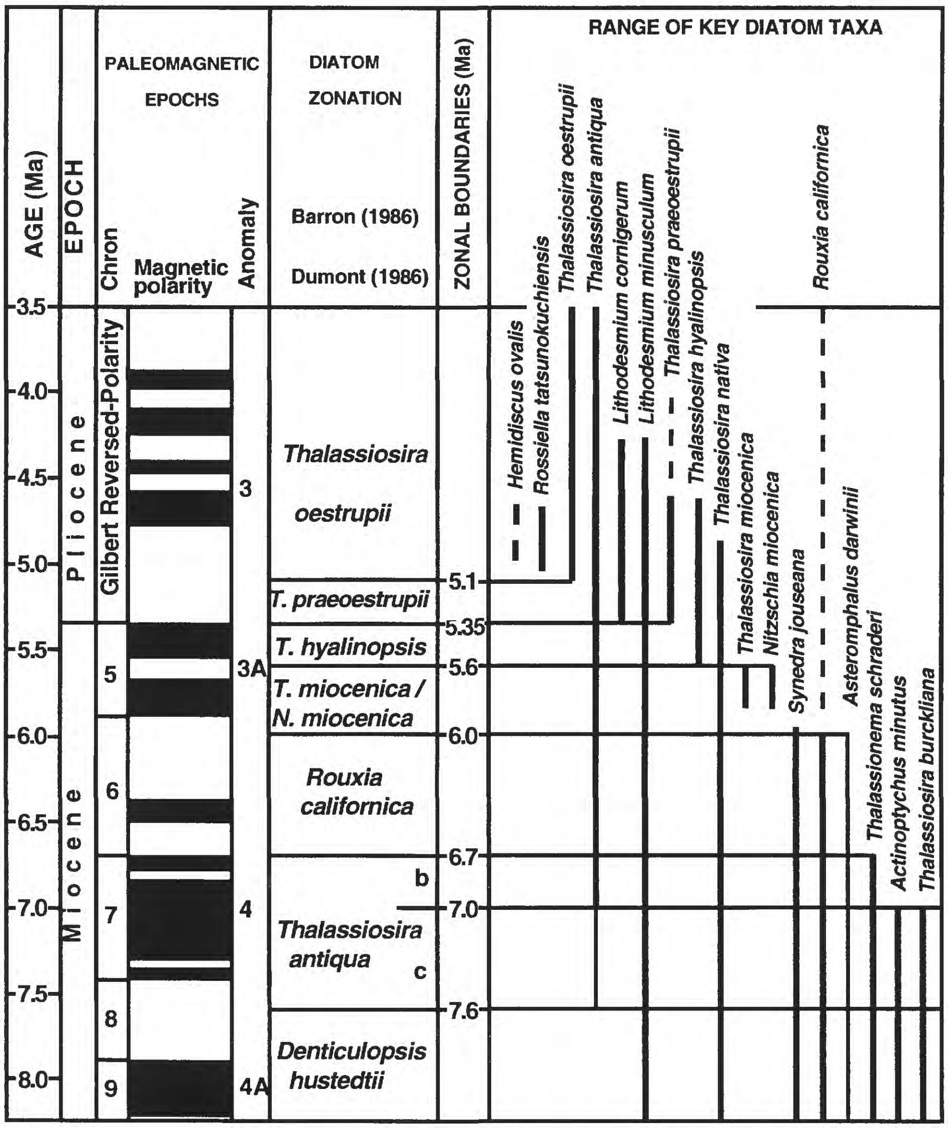

Figure 4. Diatom zones and species ranges used in this study. Also depicted are the key diatom taxa and their ranges. Slightly modified from Barron and Ramirez (1992).

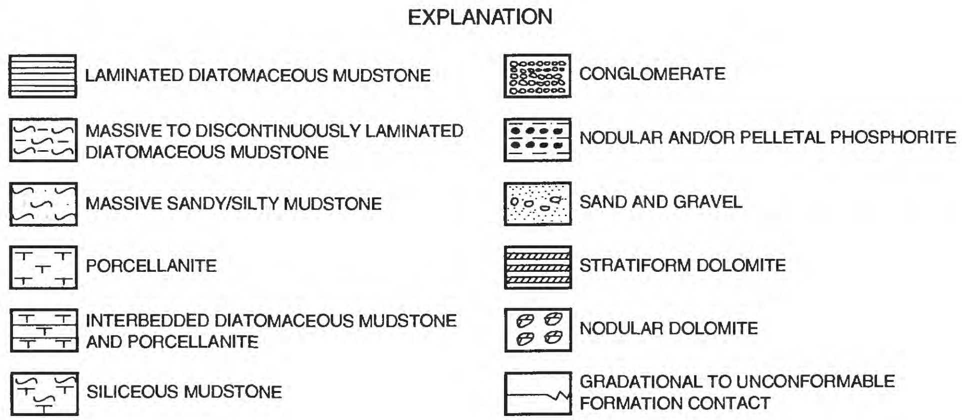

Figure 5. Key to lithologic symbols used in figures 6, 7, 10, and 11.

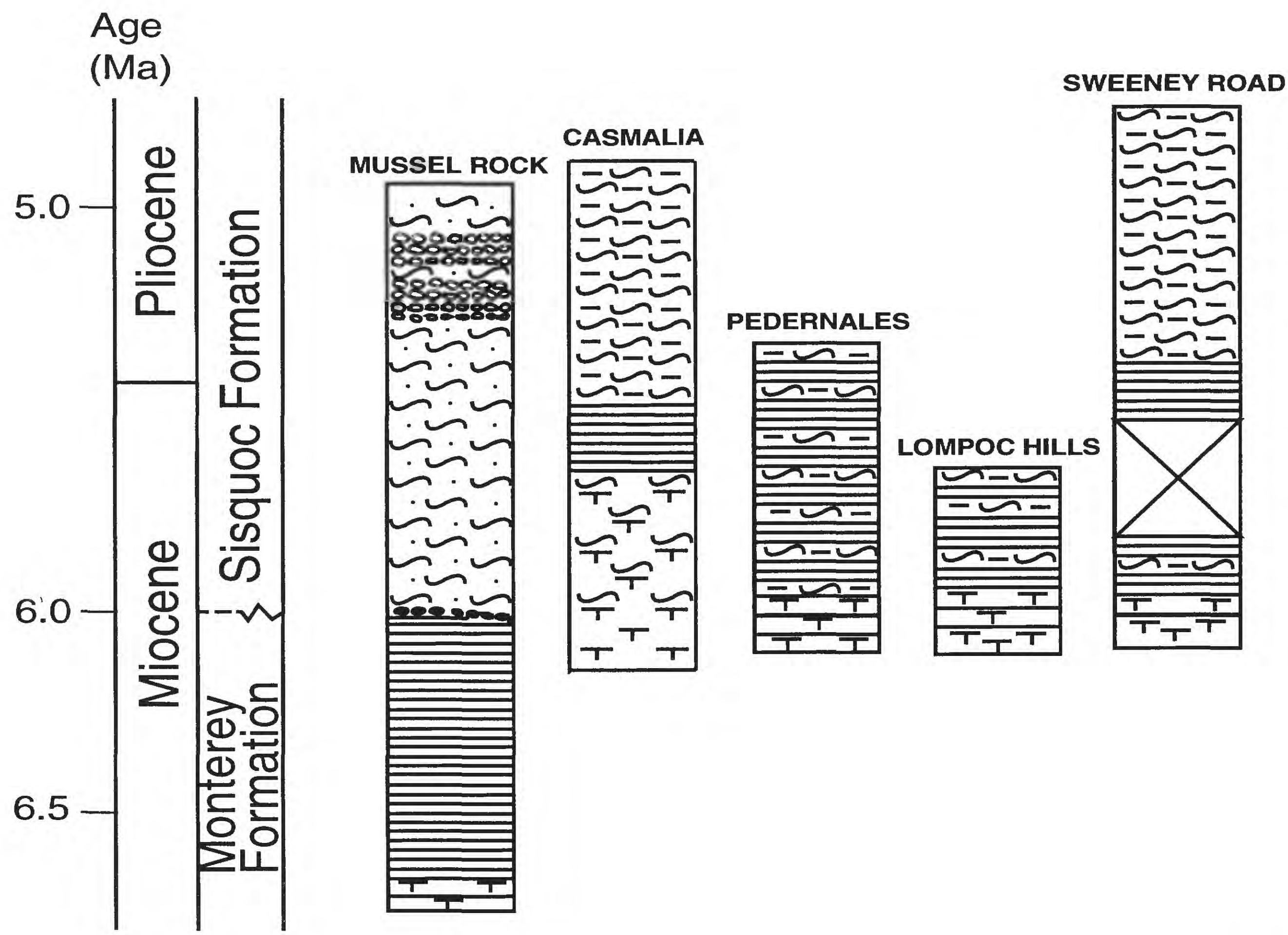

Figure 6. Chronostratigraphic diagram and characteristic lithologies of sections examined in this study (for section locations, see fig. 1). Age dates from Dumont (1986) were used to construct the Sweeney Road column. Lithologic symbols are shown in figure 5.

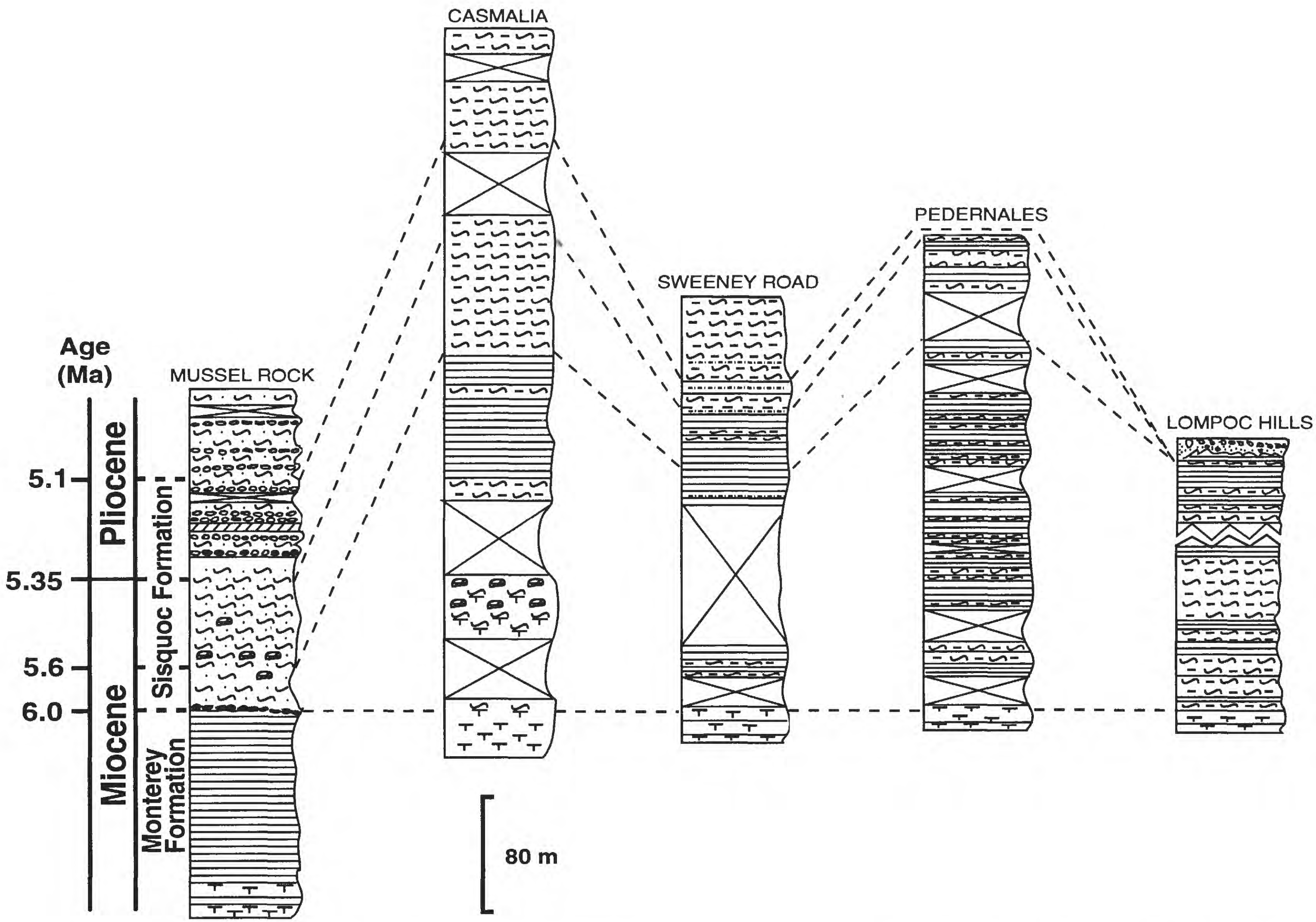

Figure 7. Correlation chart of the various sections examined. Dashed lines represent isochrons that are tied to diatom biostratigraphy. Figure 5 contains the keys to the lithologic symbols. Diatom ages from Dumont (1986) were used to construct the Sweeney Road column. Diatom correlations from Barron and Ramirez (1992) and Dumont and Barron (1995).

Thalassiosira miocenica-Nitzschia miocenica diatom zones. This boundary correlates with the known age of the contact in those sections where it is unequivocal. While not a proper basis for defining formation contacts, the biostratigraphy provides an anchoring point for the late Miocene-early Pliocene stratigraphy which in turn forms the basis for our speculations on the changing oceanographic and tectonic conditions in the basin.

As with the Monterey-Sisquoc contact, preliminary work appears to indicate that the stratigraphic relation between the top of the Sisquoc and the base of the overlying Foxen Mudstone is also complex (see Behl and Ingle, this volume). The Casmalia and Harris Grade sections are the only sections studied that extend from the Sisquoc into the overlying Foxen Formation. In the Casmalia section, on the basis of extrapolated age-thickness plots, the Sisquoc-Foxen contact, which is covered, is dated at about 4.8 Ma. Barron and Ramirez (1992) also estimate that at Harris Grade the Sisquoc-Foxen contact lies at about 3.8 Ma. Behl and Ingle (this volume), relying on the work of Dumont and Barron (1995), indicate that the Sisquoc-Foxen contact in the Santa Maria basin may be as young as 3.8 Ma. Furthermore, Barron (1992) and Behl and Ingle (this volume) believe that the change from Sisquoc to Foxen deposition is probably related to a shift in relative motion between the Pacific and North American Plates at about that time. The incongruous ages for the Sisquoc-Foxen contact mentioned above suggest a diachronous formational contact. Published California Division of Oil and Gas (1974) maps show a gradational to unconformable Sisquoc-Foxen contact; in the Casmalia area, subsurface data indicate that the contact is erosional. Perhaps the Sisquoc was eroded to deeper stratigraphic levels in the Casmalia area than in the Harris Grade area, thereby accounting for the older age of the Sisquoc near Casmalia. In the Santa Maria basin, therefore, it appears that the Sisquoc may extend from about 6.0 to about 3.8 Ma.

Figure 8. Vertically dipping nodular, clast-supported phosphatic conglomerate marking the contact in the Mussel Rock section, between the underlying laminated diatomaceous mudstone of the upper part of the Monterey Formation to the right and the overlying massive, silty mudstones of the Sisquoc Formation. Note that this phosphatic conglomerate is graded, suggesting that it may have been deposited by turbidity or other bottom currents. Hammer shown for scale.

The termination of silica sedimentation in the Santa Maria basin does not correlate with the end of Sisquoc deposition. Behl and Ingle (this volume) report that siliceous mudstones ranging from 30 to 100 m thick occur locally at the base of the Foxen Formation. Woodring and Bramlette (1950) also observed local occurrences of siliceous lithologies at the base of the Foxen Formation.

Our detailed section measurements and correlations also reveal important features which illuminate sedimentation patterns in the Santa Maria basin and which allow us to speculate on the causes responsible for these sedimentation patterns. Conglomerates were deposited in the Mussel Rock area during Sisquoc accumulation, while concurrently, other portions (Pedernales, Casmalia, Sweeney Road) of the basin received the hemipelagic sediments most characteristic of the fine-grained facies of the Sisquoc (see figs. 6 and 7). Compositional differences that occur upsection in the clasts of the conglomerates in the Sisquoc Formation of the Mussel Rock section provide clues to tectonic activity in the Santa Maria basin. The lowermost major phosphatic conglomerate marking the Monterey-Sisquoc boundary in the Mussel Rock section gives way upsection to conglomerates consisting of intermixed clasts of phosphate nodules, diatomaceous mudstone, dolomite, and minor chert. These conglomerates subsequently give way further upsection to conglomerates composed almost entirely of clasts of opal-CT and quartz chert.

Our section correlations also reveal a temporal and spatial relationship between the massive and laminated intervals of the Sisquoc Formation. Apparently, laminated units were deposited in some areas of the basin while contemporaneous massive units were deposited in other basin localities. For example, the base of the Sisquoc in the Sweeney Road area is mostly laminated while the base of the Sisquoc in the Casmalia section is massive. Moreover, the Sisquoc in the Pedernales section regularly alternates between massive and laminated units, whereas the Mussel Rock section is almost entirely massive. Associated with these laminated and massive units are distinct trace-fossil assemblages that hold important implications for paleoxygen levels in the Santa Maria basin (see Savrda and Bottjer, 1986, 1987a, 1987b, and Ramirez, 1990). Across the Monterey-Sisquoc contact in the Mussel Rock section, the relatively scarce trace-fossil assemblages change from one dominated by *Planolites* and *Chondrites* in the Monterey to a more abundant, diverse and larger-bodied trace fossil assemblage (*Chondrites*, *Planolites*, *Thalassinoides*, and other unidentified trace fossils) in the Sisquoc (Ramirez, 1990). This change in trace fossil assemblages signifies an abrupt and sustained increase in oxygen levels and, as discussed in the succeeding section, probably results from changing tectonic and oceanographic conditions.

In contrast, the more regular alternation of laminated and massive intervals in the Sisquoc Formation at Pedernales records a change from mostly Chondrites trace fossils in laminated intervals to a combination of Chondrites, Planolites, and Thalassinoides in the massive intervals. These regular alternations in trace fossils, record (unlike the Mussel Rock section) a sustained period of regularly changing oxygen levels.

The duration or age span of the laminated and massive units in the Sisquoc is also variable. In the Pedernales section, the duration of a massive unit is a few thousand years, whereas in the Casmalia section, which records only a slightly higher sedimentation rate than the Pedernales section (fig. 9), the basal massive unit (including the covered zone that occurs within this massive interval) spans about 300,000 years. Moreover, in the Mussel Rock section, where sedimentation rates are the lowest of any section examined (fig. 9), the Sisquoc is completely massive over a stratigraphic interval representing about one million years. These types of spatial and temporal variations have not been documented in the underlying Monterey Formation. In fact, our study indicates that in comparison to the Monterey Formation, the onset of Sisquoc deposition was marked by more repeated oscillations in the oxygen minimum zone as evidenced by the interbedded massive and laminated units in the formation. Isaacs (1981c) also noted that the proportion of massive to laminated rocks increase in the Sisquoc of the Santa Barbara basin, in comparison to the underlying Monterey.

PALEOCEANOGRAPHIC AND TECTONIC CONTROLS ON SISQUOC SEDIMENTATION

The abrupt appearance of phosphatic conglomerates marking the Monterey-Sisquoc contact in the Mussel Rock and Lompoc Quarry areas and the presence of a silty unit containing phosphatic nodules and pebbles from the Franciscan Complex and Monterey Formation at the base of the Sisquoc in the southern Santa Maria basin (Woodring and Bramlette, 1950) suggest fundamental changes in sedimentation in the late Miocene Santa Maria basin. Furthermore, the relatively abrupt change to detritus-enriched rocks occurring between the upper part of the Monterey Formation and the Sisquoc Formation in the Mussel Rock and Casmalia sections combined with the overall compositional differences existing between the Monterey and the Sisquoc probably result, as mentioned, from accelerated rates of silica and detritus accumulation during Sisquoc deposition. The aforementioned sedimentologic changes together with the highly variable occurrence of laminated and massive units in the Sisquoc, as discussed below, are tied to shifting oceanographic and tectonic conditions.

The onset of Sisquoc deposition at about 6.0 Ma is probably related to an eustatic sea level lowstand at about 6.3 Ma (Haq, Hardenbol, and Vail, 1987). Important events closely associated with this sea level drop include the growth of the Antarctic ice cap (Shackleton and Kennett, 1975; Mayewski, 1975; Mercer, 1976) and increased silica production between 6 to 5 Ma in the eastern margins of the Pacific (see Isaacs, 1983, 1984, 1985; Barron and Baldauf, 1990; Ramirez, 1990). In the central equatorial Pacific, decrease in silica production occurs at about 6.0 Ma, or nearly coincident with the 6.3 Ma sea level drop, and may represent a shift in the silica sink from the central Pacific to the eastern Pacific (Leinen, 1979). Accelerated

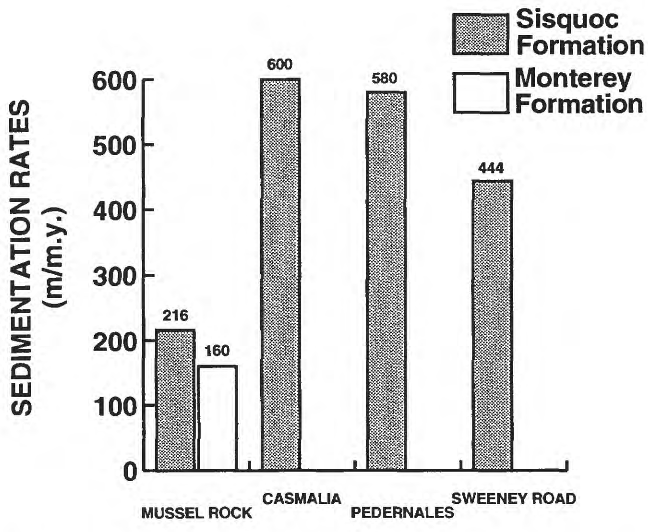

Figure 9. Sedimentation rates (uncorrected for compaction) for the Mussel Rock, Casmalia, Pedernales, and Sweeney Road sections. Note that only in the Mussel Rock section, where more than one biostratigraphic datum point occurs in the Monterey Formation in the measured section, were sedimentation rates calculated for the Monterey Formation. Shown above each bar is the average sedimentation rate in m/m.y.

rates of silica accumulation in the Sisquoc relative to the underlying Monterey Formation probably reflect the increased silica production in the eastern margins of the Pacific coincident with the 6.3 Ma sea level drop. The Miocene growth of the Antarctic ice cap probably resulted in the lowering of sea level and, as suggested by Brewster (1980) and Ingle (1981a), in intensified ocean circulation through increased latitudinal thermal gradients. Intensified oceanic circulation led to invigorated upwelling on the Pacific margins and subsequently to increased silica production and accumulation. Barron and Baldauf (1990) note that increased opal accumulation rates in the Sisquoc are related to steepened biologic productivity gradients resulting from regional changes in the patterns of opal accumulation. These variations in biologic productivity and in the patterns of opal accumulation are associated with a cooling event beginning at about 6.3 Ma.

More recently, Dumont and Barron (1995) note the significance of the 5.5 Ma sea level drop of Haq, Hardenbol, and Vail (1987) in influencing diatom sedimentation during the deposition of the Sisquoc. These authors suggest that intensified upwelling and increased primary productivity in the California borderland are associated with this sea level drop. Therefore, accelerated rates of silica accumulation at about 6.0 Ma do appear to suggest that the late Miocene sea level changes considerably modified sedimentation patterns in the California continental borderland.

Lowered sea levels during the late Miocene could also account, in part, for the increased accumulation rates of detritus in the Sisquoc as greater amounts of fine-grained sediment were transported across the exposed narrow shelves of the borderland and deposited in basin slope and floor environments during the lowstands. Additionally, the deposition of local phosphatic conglomerates at the base of the Sisquoc combined with the deposition of silty and sandy mudstones and phosphatic and chert-rich conglomerates in the uppermost part of the Sisquoc in the Mussel Rock section probably resulted, in part, from increased erosion on the basin margin due to lowered sea level. The conglomerates and mudstones in the Mussel Rock section may have been funneled through slope-incised channels developed during a period of lowered sea level (Ramirez, 1990). The lack of sands in the Mussel Rock section is likely related to the probable upper slope to shelf-edge depositional setting of the Sisquoc in this area (Ramirez, 1990). Sands were probably transported to deeper water environments. Garrison and Ramirez (1989) noted that conglomerates and breccias occur at the base of the Sisquoc in exposures along the Santa Maria and Santa Barbara coastal areas. They suggest that these conglomerates and breccias are in part attributable to a period of lowered sea level.

Superimposed on the major sea level changes influencing the sedimentologic character of the fill in the late Miocene-early Pliocene Santa Maria basin, were smaller-scale shifts in oceanographic conditions. Small-scale fluctuations in the position of the oxygen-minimum zone (OMZ) are hypothesized to have generated the interbedded massive and laminated units of the Sisquoc. These small-scale fluctuations of the OMZ may have resulted from localized changes in sea level (Govean, 1980; Govean and Garrison, 1981) or from productivity variation in the water column, as suggested by Schrader and Baumgartner (1983) in their study of massive and laminated units in the Gulf of California. According to these authors, during times of increased biologic productivity, increased quantities of oxygen-consuming organic matter descend through the water column, leading to reduced oxygen levels, expansion of the OMZ, and the deposition of laminated sediments. In contrast, decreased productivity in the water column leads to a weakened oxygen minimum zone, increased oxygen-availability, and the proliferation of substrate-churning organisms, and, consequently, to the generation of massive intervals.

Shifting paleoceanographic conditions were not the only factors influencing the composition and fabric of the Sisquoc Formation. The increased detrital component of the Sisquoc relative to the underlying Monterey Formation can also be attributed, in part, to a period of late Miocene and Pliocene tectonism in and around the Santa Maria basin. Several lines of evidence support this notion. First, although the deposition of the most prominent basal phosphatic conglomeratic unit in the Mussel Rock section may be related to a sea level drop, subsequently deposited phosphatic and chert-rich conglomeratic units of the Sisquoc were deposited mostly during a rise in sea level (fig. 10). The majority of the conglomerates at Mussel Rock were deposited from about 5.3 to 4.8 Ma. A sea level drop occurred at about 5.5 Ma and a subsequent rise in sea level commenced at about 5.3 Ma (Haq and others, 1987). The sea level rise beginning at about 5.3 Ma correlates with a period of maximum conglomerate deposition in the Mussel Rock area of the Santa Maria basin (fig. 10), indicating that there may have been significant relief on the margins of the basin. The presence of significant relief on the basin margin is also supported by common elongate, subrounded conglomerate clasts with pholad borings. These clasts suggest relatively rapid erosion, limited transport, and temporary deposition in a nearshore environment prior to their redeposition to a deeper marine environment. In addition, upsection compositional changes in the clasts of the conglomerates in the Sisquoc of the Mussel Rock section indicate considerable erosion. The change from phosphatic clasts at the base of the Sisquoc in the Mussel Rock section to clasts of dolomite, diatomaceous mudstone, and phosphate in the middle portion of the section and finally to clasts of opal-CT and quartz cherts in the top part of the section reflects unroofing, to progressively deeper depths, of Monterey-type siliceous lithologies. This upsection compositional variation in the clast composition may be inter-

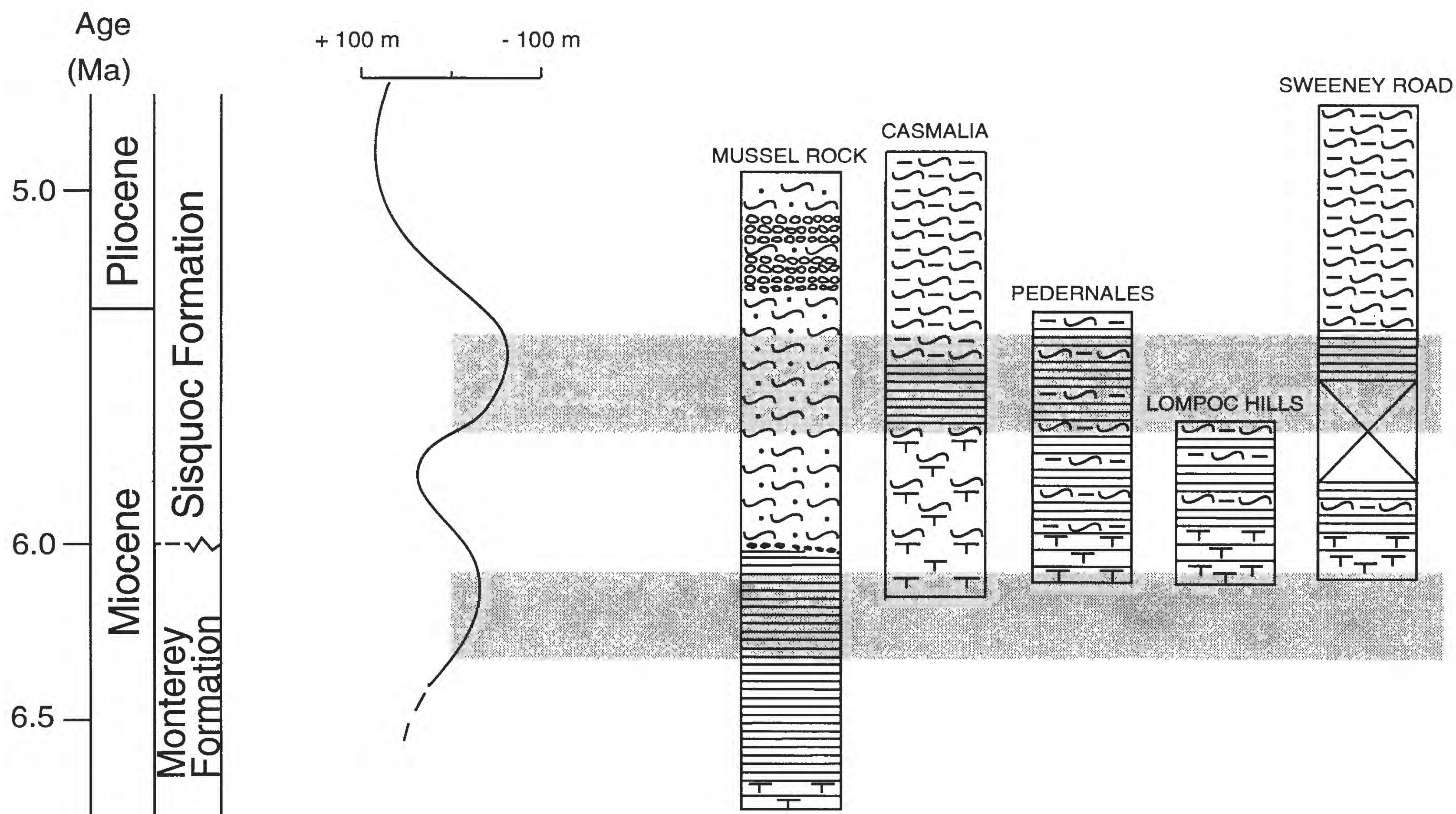

Figure 10. Eustatic sea level curve from Haq, Hardenbol, and Vail (1987) plotted with the sections examined in this study. Shaded areas correspond to periods of relatively lower sea level. Note that in the Mussel Rock section the uppermost thick chert-rich conglomerate correlates with rising sea level. The onset of deposition of the massive to discontinuously laminated intervals that occur in the uppermost portions of the Casmalia and Sweeney Road sections correlate with lower sea level. Lithologic symbols are shown in figure 5.

preted to reflect, first, the erosion of shelf-deposited phosphatic nodules followed by the erosion of diatomaceous mudstone and dolomites. With deeper erosion, opal-CT and quartz chert lithologies were exposed and eroded. The opal-A/opal-CT diagenetic boundary occurs at a burial depth of about 750 m and the opal-CT/quartz change at a burial depth of about 1,300 m in parts of the Santa Maria basin (Pisciotto, 1978). In the Santa Barbara basin, Isaacs (1981a) estimated that the opal-A/opal-CT and opal-CT/quartz boundaries occurred at burial depths of about 500 and 1,550 m respectively. Lowered sea level by itself could not account for the depth of erosion necessary to expose the opal CT and quartz lithologies, indicating that tectonic uplift of parts of the basin occurred.

The deposition of laminated intervals in some areas of the basin and correlative massive intervals in other regions of the basin seems difficult to reconcile, considering that the laminated and massive units were deposited in nearly identical depositional environments. Tectonic uplift, especially in the Mussel Rock area, along with changing sea level probably combined to generate the spatial and temporal variations in the bedding types of the Sisquoc Formation. Tectonic activity on the margins may have uplifted portions of the basin above the OMZ so that subsequently deposited sediments were churned by burrowing infauna leading to the production of thicker massive units. Large- and small-scale changes in sea level led to shifts in the position of the OMZ and consequently, to the production of more regularly alternating massive and laminated sediments along its margin.

Other evidence suggestive of tectonic activity in the Santa Maria basin during the late Miocene is the absence of the basal Sisquoc in the Lompoc Quarry area and its presence in nearby sections (fig. 11; see fig. 1 for location). Based on a conservative estimate of sedimentation rates, Ramirez (1990) suggested that approximately 500 m of Sisquoc section are missing in the Lompoc Quarry. Sea level changes alone could not account for such localized erosion, and adjacent sections in similar depositional environments should have also been affected by the erosional affects attributable to a sea level lowering. Therefore, tectonism was probably responsible for the uplift and contemporaneous erosion concentrated in the Lompoc Quarry area.

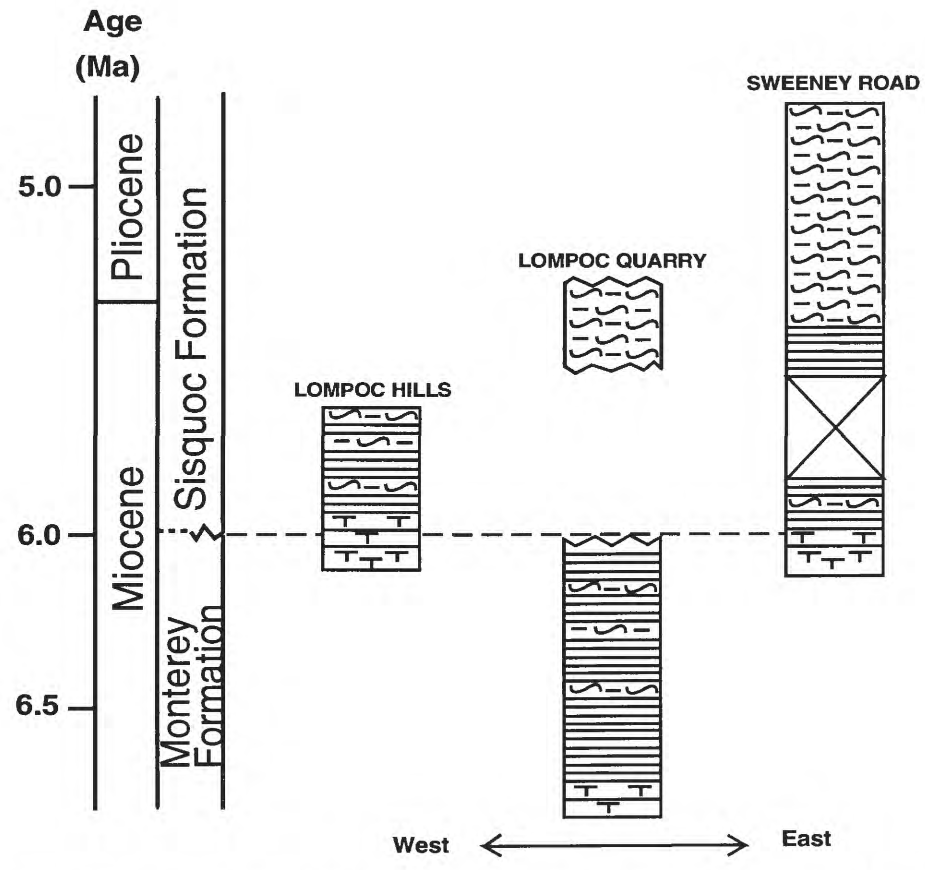

Figure 11. Chronostratigraphic diagram showing the east to west alignment of the Lompoc Hills, Lompoc Quarry, and Sweeney Road sections. The absence of the basal Sisquoc Formation in the Lompoc Quarry section and its presence in the Lompoc Hills and Sweeney Road sections suggests the presence of short-lived topographic highs, which probably resulted from tectonic activity in the Santa Maria basin. The Lompoc Quarry section is highly generalized and incorporates data from Barron (1975) and Dumont (1986). Lithologic symbols are shown in figure 5.

This suggestion of middle Neogene uplift is supported by a number of studies indicating a late Miocene to Pliocene phase of tectonic activity in the Santa Maria basin and the central California continental borderland in general. Subsidence history plots for several borderland basins depict a late Miocene to early Pliocene phase of tectonic uplift (Dickinson and others, 1987). Furthermore, Hornafius (1985), Luyendyk and Hornafius (1987), and Luyendyk (1988) suggested a late Cenozoic (middle Miocene to Pliocene) phase of rotation of the Transverse Ranges, which border the southern margin of the Santa Maria basin. Any episode of rotation of the Transverse Range would probably have also impacted the Santa Maria basin. McCulloch and Lewis (1988) reported that strike-parallel folds in the offshore central California margin probably developed between approximately 5 to 3 Ma as a result of an episode of compressional motion between the Pacific and North American Plates. Porter (1932), Woodring and Bramlette (1950), and Crawford (1971), citing the thinning of late Miocene and Pliocene units on anticlinal ridges, suggested that many of the anticlinal ridges in the Santa Maria basin probably formed in the late Miocene or early Pliocene. Moreover, Porter (1932), Dibblee (1966), and Ingle (1981b) suggested that uplift of the Santa Ynez Range, which bounds the southern portion of the Santa Maria basin, may have occurred in the early Pliocene, which is coincident with the onset of deposition of the Sisquoc Formation. Additionally, Shepard and Emery (1941) and Teng and Gorsline (1989) indicated that much of the physiography of the present day borderland developed during late Miocene time, implying that late Miocene tectonic activity was prevalent during deposition of the Sisquoc. Barron (1992) also discusses the tectonic controls on the Pliocene diatom record of California.

SUMMARY

Stratigraphic and sedimentologic information indicates that both tectonism and oceanographic changes played a major role in shaping the sedimentological trends exhibited by the late Miocene and early Pliocene Sisquoc Formation in the Santa Maria basin. A phosphatic conglomerate marking the Monterey-Sisquoc contact in the Mussel Rock section is probably related to a eustatic sea level change at about 6.3 Ma. The increased accumulation of diatoms in the Sisquoc is probably related to changes in circulation and coastal upwelling patterns in the late Miocene ocean, resulting from polar cooling that also caused the growth of the Antarctic ice cap and led to an eustatic sea level drop. Alternating massive and laminated units were generated through small-scale variations in productivity and (or) sea level changes. Conglomerates in the upper part of the Sisquoc were deposited during a sea level rise and record evidence of significant erosion associated with tectonic uplift of the basin margin. This evidence for late Miocene and early Pliocene uplift is in accord with a number of studies indicating an episode of tectonic activity at this time in the Santa Maria basin and in the California borderland in general.

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Chapter V

The Sisquoc Formation–Foxen Mudstone Boundary in the Santa Maria Basin, California: Sedimentary Response to the New Tectonic Regime

By RICHARD J. BEHL and JAMES C. INGLE, Jr.

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

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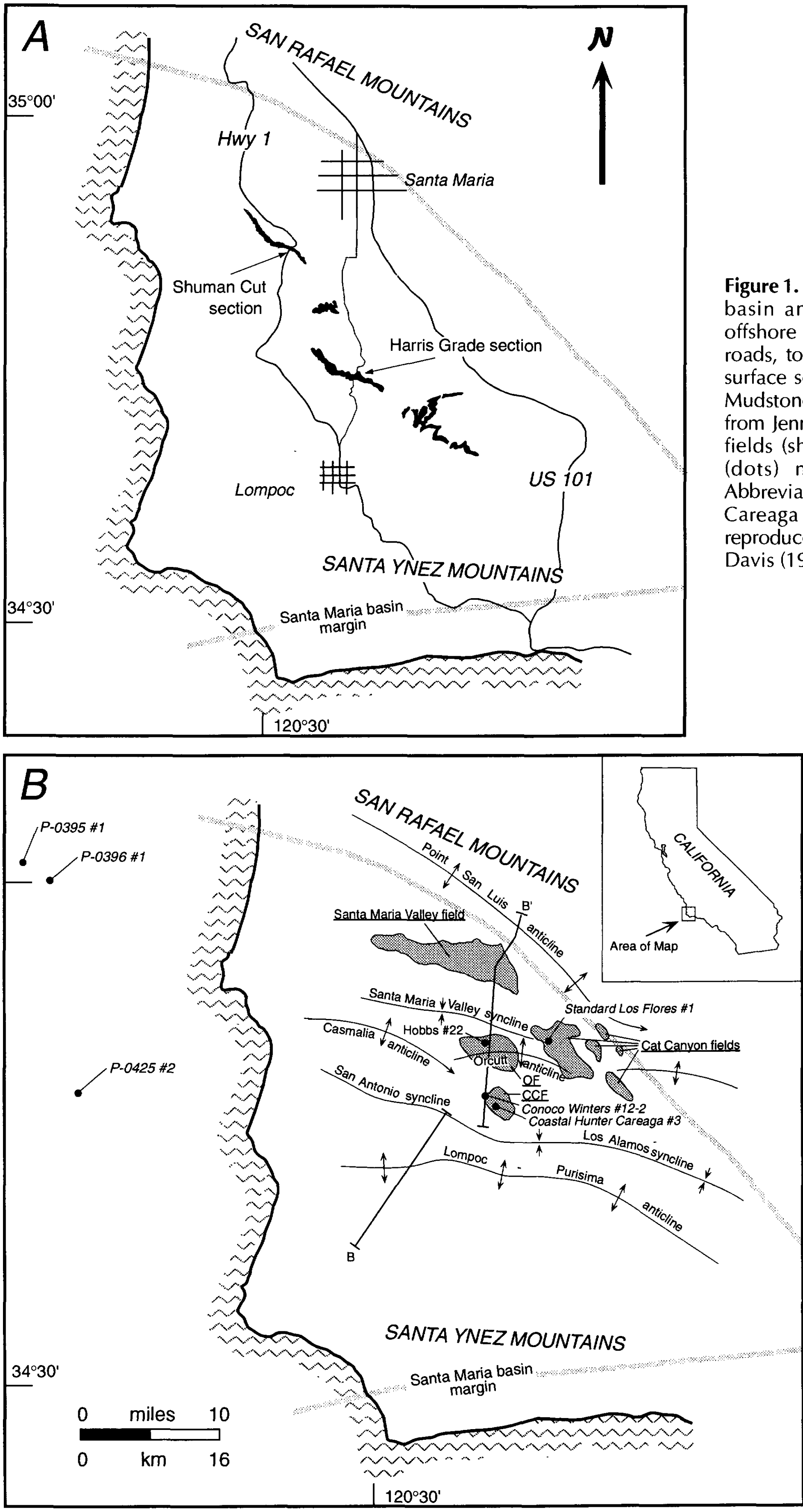

Figure 1. Map of the onshore Santa Maria basin and proximal portions of the offshore basin. *A*, Locations of major roads, towns, outcrops, and important surface sections of the Pliocene Foxen Mudstone. Foxen outcrop distribution from Jennings (1959). *B*, Structures, oil fields (shaded regions), and oil wells (dots) mentioned in this report. Abbreviations: OF = Orcutt field, CCF = Careaga Canyon field. Section *B–B'*, reproduced in fig. 4, is from Namson and Davis (1990).

trend of basin shoaling (Canfield, 1939; Woodring and others, 1943; Woodring and Bramlette, 1950; Natland, 1957; Ramirez, 1990; McCrory and others, 1995), between the slope to shelf-edge deposits of the Sisquoc Formation (Ramirez, 1990) and the littoral deposits of the Careaga Sandstone (McCrory and others, 1995).

Scope of study

A distinctive lithofacies of opal-CT chert, porcelanite, siliceous mudrocks, or dolostone has been penetrated in the lowermost part of the Foxen Mudstone by many oil wells drilled in the Santa Maria Valley and the Los Alamos–San Antonio Valley synclines, and by some wells in the offshore Santa Maria basin (fig. 1). The rocks of this interval (hereafter referred to as the "hemipelagic Foxen" or "basinal lowermost Foxen," for convenience) are dissimilar from the rest of the siliciclastic-dominated Foxen and the underlying hemipelagic, diatomaceous Sisquoc Formation, and they differ also from known Foxen exposures in surface sections. This study investigates the environmental and tectonic significance of this unique facies. Foraminiferal assemblages and structural relationships in the subsurface suggest that localized subsidence in synclinal sections resulted from compressive tectonic deformation during deposition near the start of Foxen sedimentation. In this study, we propose that these lithologic and faunal changes at the Sisquoc–Foxen boundary record the sedimentologic and environmental response to thrust-related tectonic load subsidence during the local initiation of regional transpressive tectonics, about 3.8–3.4 Ma, rather than that of simple progradation and shoaling of sedimentary facies.

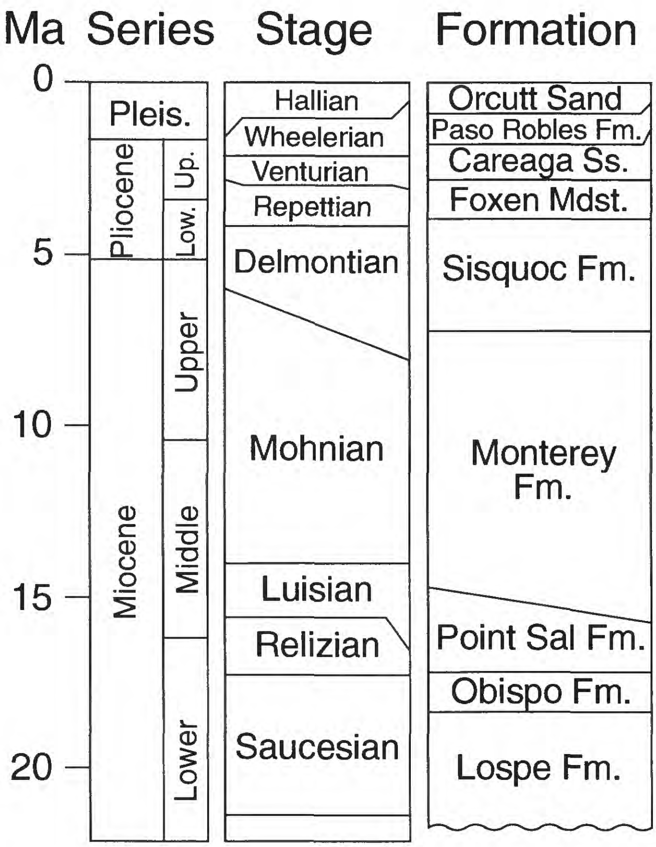

Figure 2. Neogene stratigraphy of the onshore Santa Maria basin (after Namson and Davis, 1990).

METHODS

Material

The data for this study are chiefly derived from petrologic and microfaunal analysis of well cuttings and cores. Geophysical well logs (resistivity, spontaneous potential and gamma ray) were used for supplemental stratigraphic analysis and lateral facies identification. Surface exposures of the Sisquoc Formation and Foxen Mudstone at Harris Grade in the Purisima Hills and at Shuman Cut in the Casmalia Hills (fig. 1A) were examined for comparison with subsurface sections.

Drill Cuttings Versus Outcrop Data

Data collected from the analysis of drill cuttings differ from data collected at stratigraphic sections in outcrop. Cuttings are collected from the mud circulation system of a drilling rig and are therefore not directly sampled from a precisely known stratigraphic interval, as is possible with core or outcrop. Continuous attention is required while drilling to accurately and consistently determine the depth of the cuttings' origin. This process involves monitoring penetration rate, pump output, and the true annular volume of the borehole. All of these values diverge from theoretical or optimal estimates in an irregular manner and must be frequently determined by empirical methods. Most of the cuttings examined for this study are composite samples collected at 10–30 ft intervals by one of the authors (RJB) and colleagues at Epoch Well Logging, Inc., and the assigned depth of samples are probably accurate to ±5–10 ft (2–3 m).

Two potential problems that arise with use of drill cuttings (or mud log) data are the accurate assignment of lithologic percentages and sample contamination. As cuttings are produced by the grinding or chipping away of rock by a rotating drill bit, the cuttings of well-indurated lithologies are overrepresented in the samples compared with poorly consolidated mudrocks that are crushed into fine-grained suspensions in the mud system. Lithologic contamination of the samples from uncased strata above the drill bit occurs as fragments cave in or are knocked off by the rotating drill string and mix with the fresh cuttings on their way to the surface. If drilling conditions are good, this is not a serious problem and the contamination, or "slough," can be identified or removed from the samples. In poor conditions, however, unwanted slough can form a substantial portion of the cuttings samples and prevent the reliable quantitative assessment of in situ lithologic percentages at any specific depth. During drilling related to this study, conditions were generally good and contamination from cavings were minimal.

Foraminiferal Analysis and Paleobathymetry

Pioneering studies by Natland (1933, 1957), Crouch (1952), and Bandy (1953) early demonstrated the usefulness of benthic foraminifers for interpretation of paleoenvironments and water depths (that is, paleobathymetry) in the evolving Neogene basins of coastal California. More recent studies have utilized quantitative distributional patterns among Holocene foraminifera and associated data on water masses, substrate, and other environmental parameters to further enhance paleoceanographic, depositional, and paleobathymetric analyses (Douglas and Heitman, 1979; Ingle, 1980; Douglas, 1981; Blake, 1985). Concepts and techniques presented by these latter authors were employed to analyze foraminiferal faunas and interpret paleoenvironments and paleobathymetric trends within the Neogene sequence of the Santa Maria basin, including the Foxen Mudstone. Benthic foraminifers previously reported from Neogene units, as well as those analyzed during this study, were assigned to individual biofacies (for example, littoral biofacies, inner shelf biofacies, etc.) following the paleoenvironmental classification and biofacies definitions and compositions of Ingle (1980, 1985).

Benthic foraminifers were originally common to abundant in the Neogene marine deposits of the Santa Maria basin, as shown by the contents of early diagenetic concretions. Weathering and other diagenetic processes have affected the preservation of foraminifers in every lithofacies, however, and are responsible for the complete destruction of foraminiferal tests in some horizons. Calcareous foraminiferal tests are commonly leached from surface exposures of the Foxen Mudstone, whereas well-preserved faunas are often recovered from subsurface samples of the more siliciclastic facies of this formation.

Nine core samples from the Standard Los Flores No. 1 well in the Cat Canyon fields (fig. 1B) yielded well-preserved foraminiferal faunas from the upper part of the Sisquoc Formation and lower part of the Foxen Mudstone (Ingle, 1985). Samples were disaggregated in kerosene, washed on a 250-mesh screen (0.062-mm openings), dried, and quantitatively analyzed following standardized procedures reviewed by Ingle (1967). Separate counts were made of planktonic and benthic species. Relative abundances of selected benthic species and cumulative percentages of benthic biofacies were then plotted stratigraphically and used to interpret variations in water depth and paleoenvironments during deposition of Sisquoc and Foxen sediments in the Cat Canyon area (fig. 3).

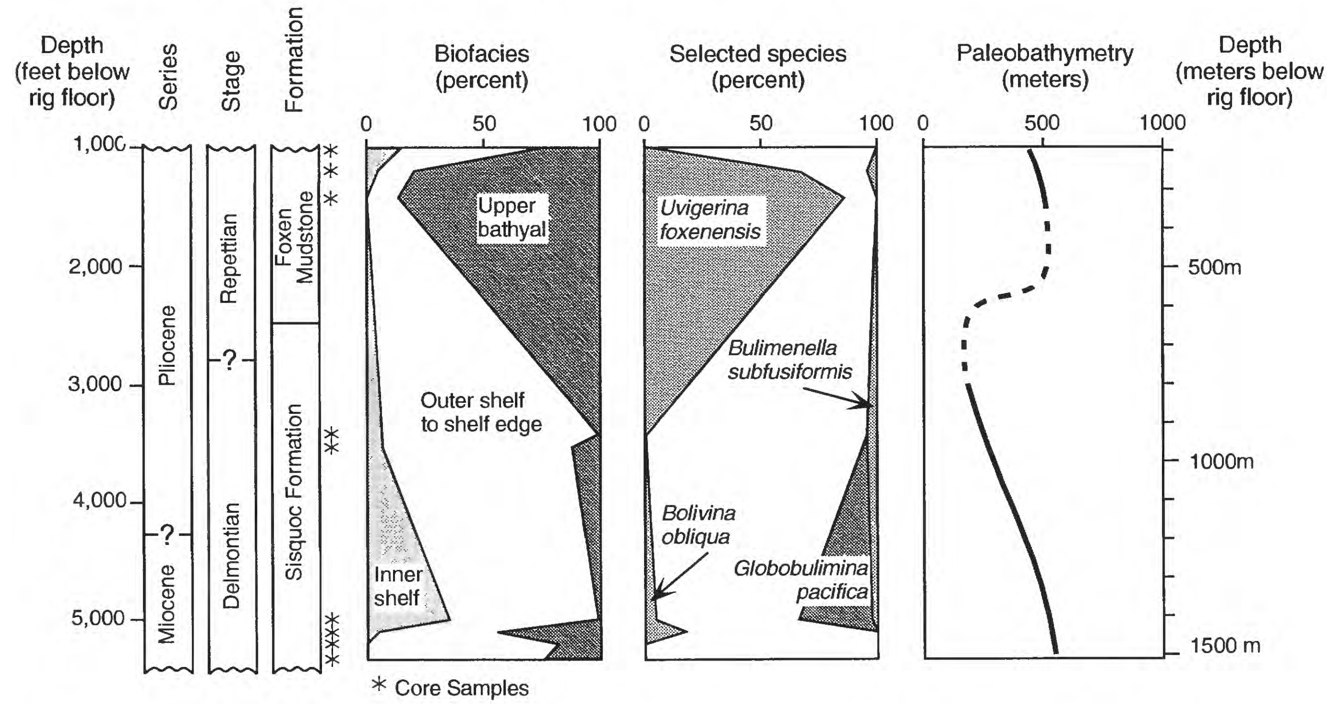

Figure 3. Quantitative distribution of benthic foraminiferal biofacies, variation in relative abundance of selected benthic foraminifers, and estimated paleobathymetry in the upper part of the Sisquoc Formation and lower part of the Foxen Mudstone as analyzed in core samples from the Standard Los Flores No. 1 well from the Cat Canyon fields, Santa Maria basin, California. Modified from Ingle (1985).

Nomenclature and Significance of Siliceous Rocks

This paper follows the field terminology for siliceous rocks of Bramlette (1946) and Isaacs (1981). Chert is the nearly pure siliceous rock that is hard, dense, fractures conchoidally, and has a vitreous or waxy luster. Porcelanite is the impure siliceous rock that is less hard, less dense, and less vitreous than chert, and has a matte texture similar to that of unglazed porcelain. Disregarding carbonate content, porcelanite typically contains 60–85 percent silica (Isaacs, 1981), whereas chert contains >85 percent; most vitreous cherts have between 95 and 99 percent silica (Behl and Garrison, 1994). Classification of a diagenetic rock as chert or porcelanite is independent of the polymorph of silica present, so that either rock can be composed of opal-CT or quartz-phase silica. For the stratigraphic sections discussed herein, X-ray diffraction indicates that only opal-CT phase authigenic silica is present in the upper part of the Sisquoc Formation and the Foxen Mudstone.

Nearly all Phanerozoic chert and porcelanite formed by the diagenesis of biogenic silica, which was originally deposited as radiolarian tests, diatom frustules, or sponge spicules (Garrison, 1974). With sufficient time or burial, chert and porcelanite can form by one or two dissolution/reprecipitation steps. First, biosilica (opal-A) transforms to metastable opal-CT (cristobalite-tridymite), and second, opal-CT converts to diagenetic quartz (Murata and Larson, 1975). The purest diatomaceous deposits tend to undergo diagenesis from opal-A to opal-CT at much shallower burial depths than more detrital-rich deposits (Isaacs, 1981; Behl and Garrison, 1994). The Neogene deposits of much of the Pacific Rim are characterized by their abundant diatomaceous sediments or their diagenetic descendants—chert, porcelanite, and siliceous mudstone (Ingle, 1981).

STRATIGRAPHY OF THE FOXEN MUDSTONE

Vertical and Lateral Distribution

In the onshore Santa Maria basin, the lower to upper Pliocene Foxen Mudstone overlies the upper Miocene and lower Pliocene Sisquoc Formation, and is overlain by the upper Pliocene Careaga Sandstone (Canfield, 1939; Woodring and others, 1943; Woodring and Bramlette, 1950) (fig. 2). Grain size and percent terrigenous material generally increase upsection from the Miocene Monterey Formation (which underlies the Sisquoc Formation) through the youngest sediments (for example, the upper Pliocene to lower Pleistocene Paso Robles Formation). These sedimentologic trends are associated with gradual shoaling (Canfield, 1939; Woodring and others, 1943; Woodring and Bramlette, 1950; Ramirez, 1990; McCrory and others, 1995) and decreased flux of diatom frustules (Barron, 1986, 1992). The upsection increase in detritus dilutes the biogenic component and complicates the application of microfossil biostratigraphy and the construction of an integrated chronostratigraphy (Barron, 1992). In spite of the latter problem, it is clear that Foxen deposition occurred during some part of the late-early [so-called middle(?)] to late Pliocene (Canfield, 1939; Woodring and others, 1943). Foxen strata display extreme lateral variation in thickness and lithofacies in a northeast-southwest cross section across the central Santa Maria basin (fig. 4). Subsurface synclinal troughs accumulated up to 1,000 m of Foxen sediments (Canfield, 1939), whereas anticlinal ridges (Pliocene paleobathymetric highs) completely lack Foxen deposits or contain presumably correlative condensed, sandy phosphatic sections only a few meters thick that are usually included in the overlying Careaga Sandstone (Canfield, 1939; Woodring and others, 1943; Woodring and Bramlette, 1950). Exposures of Foxen strata in the Santa Maria basin are very limited (fig. 1A). The thickest surface sections, located on the northern slopes of the Purisima and Casmalia Hills, are less than 300 m thick. The Foxen thickens toward the axes of two paleotroughs [the modern Santa Maria Valley and San Antonio–Los Alamos synclines (fig. 1B)], and seaward, to the west or northwest (Canfield, 1939; Woodring and others, 1943; Woodring and Bramlette, 1950). The Foxen may also be present in the subsurface of the Santa Rita syncline to the south, but we are unaware of any oil well penetrations to confirm this conjecture (fig. 4).

The geometry and distribution of the Foxen Mudstone (or its lithostratigraphic equivalents) are less well known for the offshore Santa Maria basin than is the case for the onshore basin, which has a much simpler structural architecture. This is, in part, because many fewer wells have been drilled and, in part, due to the different structural fabric (NNW. offshore versus WNW. onshore) and many smaller fault blocks than onshore (Sorlein, 1994). Late Neogene tectonic deformation and the consequent local accumulation and geometries of post- and syndeformational sedimentary units also have slightly different histories and timings between the onshore and offshore Santa Maria basins (McCrory and others, 1995). As in the onshore basin, offshore deposits of the Foxen Mudstone or its approximate equivalents tend to thin over modern structural highs and thicken into structural depressions (Clark and others, 1991; Sorlein, 1994; McCrory and others, 1995). Because most of the published studies of the offshore are based on seismic stratigraphy, which relies upon stratal discontinuities or unconformities to distinguish between stratigraphic packages, the precise thickness and distribution of the lithostratigraphically equivalent Foxen Mudstone are not well known. Although this study focuses on the onshore Santa Maria basin, electric logs, mud logs, and well cuttings from a number of offshore wells were examined to establish that the lowermost hemipelagic Foxen

Mudstone directly overlies the Sisquoc Formation in at least a few sites in the offshore basin (described in a following section).

Age of the Foxen Mudstone

Woodring and others (1943) and Woodring and Bramlette (1950) assigned the Foxen Mudstone to the middle(?) and upper Pliocene on the basis of benthic foraminifers and molluscan fossils. The Foxen is considered to be age-equivalent to Repettian Stage (lower Pliocene) deep-water sediments in the offshore Santa Maria basin (Dunham and others, 1991; McCrory and others, 1995), but its provincial foraminiferal fauna cannot be strictly assigned to the Repettian stage due to the absence of defining marker species (M.L. Cotton-Thornton, 1992, oral commun.). In any case, Foxen strata are younger than the underlying strata of the Delmontian Stage in the upper part of the Sisquoc Formation (Barron and Baldauf, 1986), and these Delmontian floras and faunas are not younger than 4.0 Ma (Warren, 1980; see discussion in Barron and Baldauf, 1986). Diatom assemblages from the lower part of the Foxen at Harris Grade are early Pliocene in age (Barron and Baldauf, 1986) and the conformable contact with the underlying Sisquoc Formation here is extrapolated to 3.8 Ma (Barron, 1992).

In the offshore Santa Maria basin, the base of Foxen Mudstone-equivalent(?) strata is placed at the early-late Pliocene unconformity, estimated at 3.4 Ma (Clark and others, 1991). The total likely age range (4.0–3.4 Ma) for the lower contact of the Foxen Mudstone reflects different methods of determination as well as the time-transgressive nature of the Sisquoc Formation–Foxen Mudstone boundary (described in a following section). Also of chronologic significance is a warm-temperature planktonic foraminiferal biofacies containing unusual abundances of *Globorotalia crassaformis* and *G. puncticulata* present in the lower part of the Foxen (above the basal facies) of the Standard Los Flores No. 1 well (Ingle, 1985). This distinctive fauna can be correlated with a well-established middle(?) Pliocene warm climatic episode recorded in deep-sea and onshore sequences along the Pacific Coast of North America (Ingle, 1977) that occurred between approximately 4.0 and 3.2 Ma (Keller, 1979).

Dumont and Barron (1995) estimated that the uppermost Sisquoc Formation in the Shuman Cut section of the Casmalia Hills was deposited at approximately 5.0 Ma, apparently placing the formational contact considerably older than the other estimates reviewed here. The age of the top of the Sisquoc Formation is probably too old for initial Foxen Mudstone deposition, as a significant gap in sedimentation is indicated by an angular unconformity or by a bored, phosphatic hardground at the top of the Sisquoc in all exposed or cored contacts in the Casmalia Hills or adjacent Santa Maria Valley oilfield (Canfield, 1939; Woodring and Bramlette, 1950). The contact between the Sisquoc Formation and Foxen Mudstone is not exposed in the Shuman Cut section, and up to 1.2 m.y. may be missing in an undetected unconformity (Dumont and Barron, 1995).

The contact between the Foxen Mudstone and the overlying Careaga Sandstone has received little attention and is poorly constrained by biostratigraphy. Woodring and Bramlette (1950) consider the macrofaunas of the upper part of the Foxen and lower part of the Careaga (Cebada

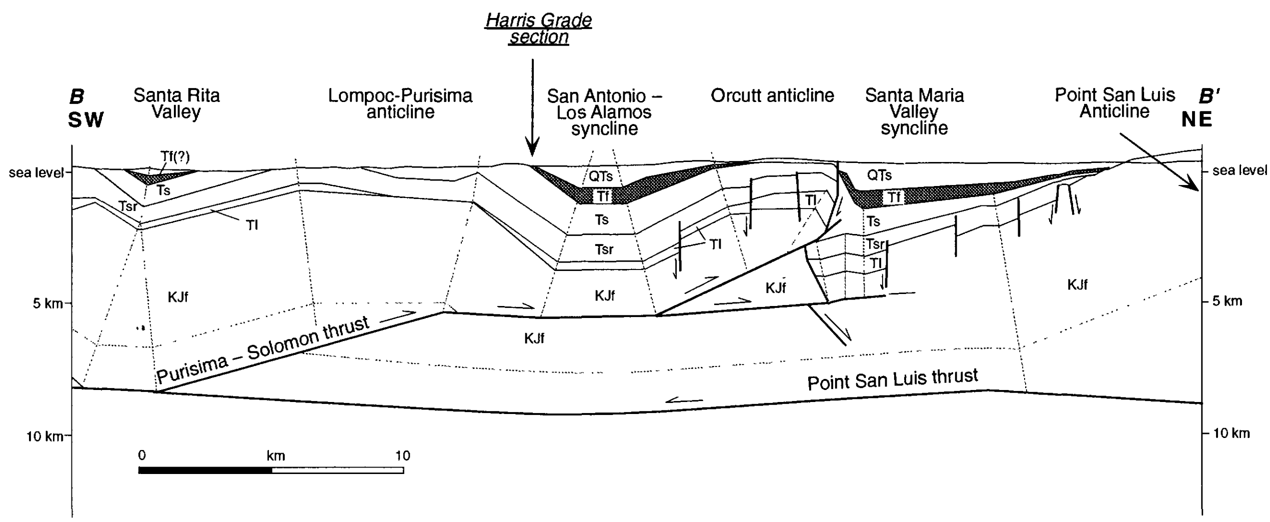

Figure 4. Regional cross section *B-B'* of Namson and Davis (1990) modified to show thickness of the Foxen Mudstone based on information in Woodring and Bramlette (1950), AAPG (1959), and Crawford (1971). Note that the Foxen (Tf) thickens in synclines and thins or disappears on anticlines. Heavy lines are faults; dotted lines are arbitrary structural markers. Abbreviations: KJf, Franciscan Complex and Jurassic Coast Range Ophiolite; Tl, lower Miocene Lospe and Obispo Formations; Tsr, middle to upper Miocene Point Sal and Monterey Formations; Ts, upper Miocene to lower Pliocene Sisquoc Formation; Tf, Pliocene Foxen Mudstone; QTs, upper Pliocene Careaga Sandstone, Pliocene and Pleistocene Paso Robles Formation, and Pleistocene Orcutt Sandstone.

Member) to be similar and assigned them both to the late Pliocene. The upsection change from sandy mudstones of the Foxen to the sand and gravel facies of the Careaga may be the result of the global eustatic sea level fall at 3.0 Ma and subsequent sea level oscillations (Haq and others, 1988; cf. fig. 6 of this paper).

In summary, available biostratigraphic and lithostratigraphic evidence from the Sisquoc Formation, Foxen Mudstone, and Careaga Sandstone indicates that Foxen sediments were deposited during the early to late Pliocene, probably initiating no earlier than 4.0 Ma, but likely between 3.8 and 3.4 Ma, and continuing to approximately 3.0 Ma. This age range for the Foxen Mudstone may not be consistently applicable in distal offshore locations due to the time-transgressive nature of the Foxen's upper and lower boundaries (Canfield, 1939) and slightly different deformational histories of small depocenters and adjacent local positive structures (Clark and others, 1991; Sorlein, 1994; McCrory and others, 1995).

Lithology of the Foxen Mudstone

Surface Observations

Two stratigraphic sections of the Foxen Mudstone were described by Woodring and Bramlette (1950) at Harris Grade and Shuman Cut (fig. 1A). The Harris Grade section is exposed in roadcuts of the old California Highway 1 on the north slope of the Purisima Hills between Lompoc and Santa Maria. At this location, the Foxen Mudstone conformably overlies the Sisquoc Formation and is approximately 244 m thick (Woodring and Bramlette, 1950). It consists chiefly of poorly exposed, weathered mudstone and siltstone with widely spaced dolostone beds and nodules. The mudrocks are notably diatomaceous in the lower part and contain increasing amounts of sponge spicules upsection. Dolostone horizons are not always clearly exposed but can be inferred at many levels by accumulations of dolostone fragments and nodules in the weathered, disaggregated mudstone. Eighteen kilometers to the northwest, the Shuman Cut section is exposed in a Southern Pacific Railroad cut adjacent to the Airox quarry on the north slope of the Casmalia Hills (Casmalia section of Dumont and Barron, 1995). The Foxen Mudstone here is about 175 m thick and is generally much coarser grained than in the Harris Grade section, consisting of interbedded sandstone, siltstone, mudstone, and dolostone. Sandstone beds are generally poorly sorted and silty to coarse grained; many contain abundant bioclastic debris, including foraminifer, echinoderm, mollusk, and barnacle fragments (see measured section in Woodring and Bramlette, 1950). Smear slides of the mudrocks show abundant sponge spicules, locally composing up to 50 percent of the siltstone beds (by volume). Carbonate beds in both surface sections of the Foxen are chiefly pure, dense, microsucrosic dolomite and are more common than in the underlying, generally calcitic Sisquoc Formation. The contact with the underlying Sisquoc Formation is not exposed at the Shuman Cut section. At nearby locations in similar positions on the north limb of the Casmalia anticline, Woodring and Bramlette (1950) described a discontinuous basal conglomerate containing chert and porcelaneous shale clasts from the Monterey Formation and phosphatic nodules that pipe down into borings or fractures in the underlying Sisquoc Formation.

Subsurface Observations

In the subsurface of the onshore and offshore Santa Maria basins, the rocks of the Sisquoc Formation and Foxen Mudstone are easily distinguished, and the depth of the formational contact can be clearly identified in core or in cuttings (fig. 5). The Foxen is chiefly composed of olive-brown to olive-green, interbedded mudstone, siltstone, and fine-grained sandstone (Canfield, 1939; Woodring and Bramlette, 1950). The mudstone of the lowermost Foxen is dark grayish- to yellowish-brown, and when drilled in deeper parts of the basin it is well indurated and forms hard, angular drill cuttings. Upsection, it becomes increasingly sandy, uncemented, and grades in color from brown to olive green. The underlying, upper part of the Sisquoc is quite distinct from the Foxen; it is a more homogeneous deposit, composed mostly of light-gray, massive to thickly laminated, silty diatomaceous claystone or silty clayey diatomite. In most wells, the upper part of the Sisquoc is so poorly indurated that, when drilled, >80 percent is crushed into clay-size particles and dispersed in the circulating drilling mud. This contrasts sharply with the better preservation of the coarser grained, more indurated Foxen sediments.

Hemipelagic Strata of the Lowermost Foxen Mudstone

Canfield (1939) noted that in the deeper parts of the Santa Maria Valley field, the lower part of the Foxen Mudstone consists of "a hard chocolate-brown somewhat siliceous siltstone." Aside from that observation, the entire Foxen has been considered a siliciclastic lithologic unit (Woodring and others, 1943; Woodring and Bramlette, 1950; Natland, 1957; Namson and Davis, 1990; Dunham and others, 1991). Our examination of drill cuttings from wells in the onshore and offshore Santa Maria basin, however, finds a distinctive siliceous and dolomitic lithofacies present at many locations. Because cores are not available from this interval, and this lithofacies does not crop out at the surface, the facies is known and described solely from drill cuttings. Opal-CT phase siliceous mudstone, porcelanite, chert, and dolostone occur at the base of the Foxen Mudstone in the subsurface of the Careaga Canyon field and beneath the San Antonio/Los Alamos Valley of the onshore Santa Maria basin (fig. 1). Dolostone and less abundant diatomaceous or opal-CT phase mudstone or porcelanite also occur in age-equivalent (Repettian to indeterminate Pliocene) sediments in the Lion Rock and Santa Maria Units (wells P-0395 No. 1, P-0396 No. 1, and P-0425 No. 2) of the offshore Santa Maria basin. As this study focuses on the onshore Santa Maria basin, we have only confirmed the existence and have determined the lithologic character of the basal hemipelagic Foxen facies in the offshore basin. It may, in fact, be more widespread in the offshore than indicated by the three wells discussed here.

The hemipelagic (that is, siliceous and dolomitic) interval of the basal Foxen Mudstone varies from 30 m to nearly 100 m in thickness, extending upward from the Sisquoc Formation–Foxen Mudstone contact. Although chiefly composed of diatomaceous or siliceous mudstone, purer diagenetic porcelanite and chert make up 5 to 30 percent of the cuttings sampled from each 10 or 30 ft (~3 or 9 m) interval; dolostone and limestone contribute another 5 to 20 percent. Mudstone cuttings are variably siliceous, slightly phosphatic, and contain scattered, poorly preserved foraminifers. The dark grayish-brown to yellowish-brown mudstone grades compositionally and texturally to porcelanite and chert. The chert and porcelanite are composed of opal-CT phase silica and are distinguished from mudrocks by their resinous luster, smooth to slightly matte texture, conchoidal fracture, and reddish-brown color. All rock types locally display faint, thin (<1 mm thick) laminations; the drill cuttings are too small to exhibit larger sedimentary structures.

The dolostone (rather than limestone) cuttings are stratigraphically associated with the most siliceous intervals and are the dominant nonsiliciclastic lithology in the basal hemipelagic Foxen Mudstone in the offshore Santa Maria basin (wells P-0395 No. 1, P-0396 No. 1, and P-0425 No. 2). The dolostone is composed of pure, dense, crystalline dolomite, similar to the carbonates observed in surface exposures of the Foxen at Harris Grade and Shuman Cut.

The Sisquoc Formation–Foxen Mudstone Boundary

In the Santa Maria Valley field the lowermost Foxen Mudstone strata overlie the Sisquoc Formation with a slight angular unconformity, which defines a transgressive surface that becomes younger in the landward direction to the east and north (Canfield, 1939). In shallower, more proximal parts of the field, a thin, discontinuous basal conglomerate and thicker, cross-bedded sandy siltstone (the Foxen "tar sand") mark the formational contact (Canfield, 1939). In outcrop exposures on the northern slope of the Casmalia Hills, Woodring and Bramlette (1950) described a basal Foxen conglomerate containing phosphatic nodules, chert, and porcelanite clasts from the Monterey Formation that overlies and pipes down into the underlying, bored or fractured Sisquoc Formation. Thus, throughout much of the Santa Maria basin, the basal Foxen is marked either by a coarse-grained facies in proximal or ridge flank locations, or by hemipelagic (siliceous/dolomitic), detritus-poor strata in distal, synclinal locations; these two facies may represent different relative bathymetric and structural positions in the early Pliocene basin. Very thin layers (<1 cm) of sand (observed in cuttings and accidental cores while removing metal "junk" from wells) are locally associated with the bottom of the basal siliceous strata. These may be distal lithostratigraphic equivalents to the proximal Foxen "tar sand." Wherever it is observable in core or outcrop, the Sisquoc Formation–Foxen Mudstone contact is marked by an unconformity, with the only known exception being the Harris Grade section (Barron and Baldauf, 1986; Dumont and Barron, 1995).

The Sisquoc Formation–Foxen Mudstone contact is easily recognized in the subsurface by geophysical well logs (fig. 5). The Sisquoc is characterized by a nearly invariant "shale baseline" in the spontaneous potential and deep induction logs, whereas gamma-ray logs show limited activity due to minor compositional variation. The lower part of the Foxen is identified by sharply increased and more variable gamma-ray and induction logs, and a negative shift with more activity in spontaneous potential logs.

In the central onshore basin, Foxen Mudstone sediments are more organic-rich than in the underlying upper part of the Sisquoc Formation (fig. 6). In the Union Hobbs No. 22 well in the Orcutt field, Isaacs and others (1990) report analyses indicating that the weight percent of total organic carbon (TOC) of bulk cuttings increases from 0.7–4.4 percent (1.6 percent average) in the Sisquoc to 8.1–17.2 percent (11.2 percent average) in the Foxen Mudstone. In the Careaga Canyon field to the south, we measured a similar, but smaller, increase in organic content across the formational boundary in the Coastal Hunter Careaga No. 3 well. Cuttings from the uppermost 30 m (100 ft) of the Sisquoc Formation contain 1.1–1.3 percent TOC (1.2 percent average), whereas TOC of the basal Foxen siliceous mudstone, porcelanite, and dolostone is three times greater (3.3–4.1 percent, 3.7 percent average). The lower TOC values from the siliceous basal Foxen in the Coastal Hunter Careaga No. 3 reflect the typically inverse relationship between biogenic silica and organic content in the Neogene rocks of California (Isaacs, 1984). Differences in average TOC between the two wells are also likely influenced by their depositional and structural settings in that the Hobbs No. 22 well is located on a structural high that largely developed since deposition of the lower Foxen, whereas the Hunter Careaga No. 3 well is located on the southern flanks of the structure in what was originally a thick, synclinal section (Namson and Davis, 1990).

Biofacies and Paleoenvironments

Five of the core samples analyzed from the Standard Los Flores No. 1 well span the upper part of the Sisquoc Formation and the lower part of the Foxen Mudstone. Although we have no samples from directly above or below the formational

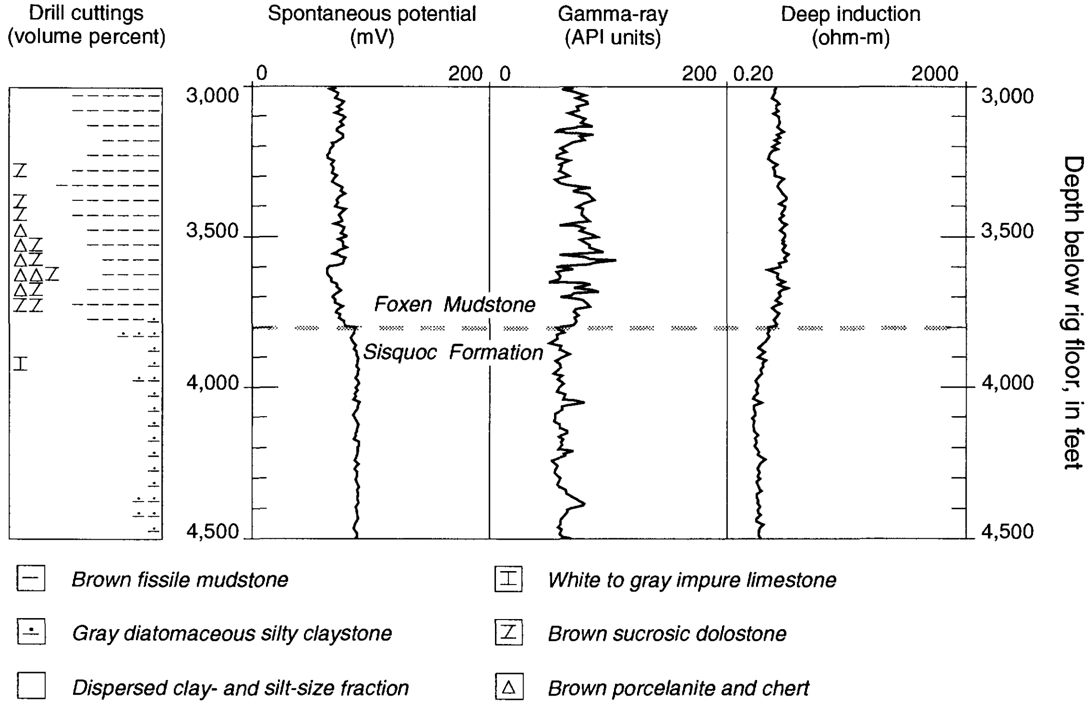

Figure 5. Typical mud log lithostratigraphic column and electric log response across the Sisquoc Formation–Foxen Mudstone boundary in thick, synclinal sections. Figure based on the Coastal Hunter Careaga No. 3 well and other wells in the Careaga Canyon field (north limb of the San Antonio–Los Alamos syncline).

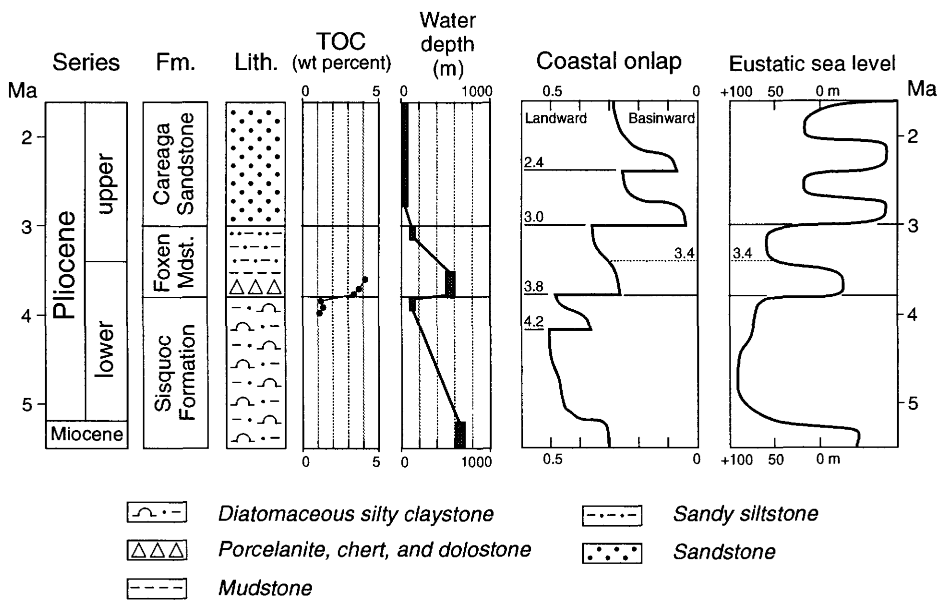

Figure 6. Late Neogene correlation figure for synclinal sections of the onshore Santa Maria basin. Chronologic relations of formations (Fm.), general lithology (Lith.), total organic carbon (TOC), water depth, coastal onlap, and eustatic sea level curves (Haq and others, 1988). Note that TOC and water depth are from different wells, but both are from synclinal sections. Foraminiferal paleobathymetry is from the Standard Los Flores No. 1 well and from reconsideration of faunal data from Woodring and Bramlette (1950). Dimensions of shaded rectangles in the water depth column represent uncertainty in paleobathymetry and in age of samples. TOC is of cuttings from the Coastal Hunter Careaga No. 3 well. Age of the Foxen Mudstone (3.8–3.0 Ma) is estimated by this study.

boundary, contrasting foraminiferal biofacies indicate a distinct change in paleobathymetry and paleoenvironment between deposition of the upper part of the Sisquoc and the lowermost Foxen (fig. 3).

Benthic foraminifers reported from the Sisquoc Formation by Woodring and Bramlette (1950), Natland (1957), and Ingle (1985) indicate that the lower and middle portions of this unit were deposited in upper middle bathyal (500–1,500 m) to upper bathyal (150–500 m) slope environments. Upper bathyal biofacies containing high abundances of *Globobulimina pacifica* also characterize the upper Sisquoc sediments analyzed from the Los Flores No. 1 well. However, these latter faunas are replaced by dominantly shelf-edge and shelf biofacies in the youngest Sisquoc samples, indicating that water depths shoaled from ~500 m to ~100 m during deposition of the uppermost Sisquoc (fig. 3). In contrast, an upper bathyal biofacies characterized by high abundances of the striate-costate species *Uvigerina foxenensis* is present in basal Foxen sediments, indicating that water depth abruptly increased to ~500 m coincident with, or shortly after, the initiation of Foxen Mudstone deposition in the Cat Canyon area. Similar patterns of contrasting benthic biofacies and lithofacies characterize the Sisquoc Formation–Foxen Mudstone boundary elsewhere in the Santa Maria basin (Woodring and Bramlette, 1950) and clearly point to an episode of rapid deepening to bathyal water depths (~500–600 m) during early Foxen deposition (McCrory and others, 1995). Subsequent Foxen deposition involved gradual shoaling as shown by the widespread appearance of shelf biofacies followed by deposition of coarse Careaga sediments containing littoral foraminifers and megafaunas that marked the termination of marine deposition in the onshore Santa Maria basin (Canfield, 1939; Woodring and Bramlette, 1950; Natland, 1957; McCrory and others, 1995).

CONTROLS OF SEDIMENTATION

The lithologic contrast between the Sisquoc Formation and the Foxen Mudstone has previously been interpreted to reflect the upward-shallowing from slope to outer-shelf depositional environments (Natland, 1957; Ramirez, 1990). The data presented in this paper suggest that instead of simple shoaling of a prograding clastic wedge, deposition of Sisquoc and Foxen sediments took place over a sea floor with increasing relief and lateral variation in environment (Canfield, 1939; Woodring and others, 1943; Woodring and Bramlette, 1950; Ramirez, 1990). This increasingly complex bathymetry probably developed as the Santa Maria basin and the rest of the Neogene borderland were deformed in response to a major change in relative plate motion from transform to transpression across the California segment of the Pacific–North American plate boundary. This change in plate vectors was originally proposed to have occurred at about 3.9–3.4 Ma (Harbert and Cox, 1989; Harbert, 1991) but recently has been shifted back to ~5–6 Ma (Cande and others, 1992; D. Wilson, 1994, oral commun.). Evidence for extreme lateral changes in facies and stratigraphic thickness in the lower part of the Foxen combined with sharply increased water depths at some locations indicate that tectonic deformation accelerated abruptly in the onshore Santa Maria basin near the beginning of Foxen deposition at approximately 3.8 Ma.

Sedimentation in marginal marine settings is primarily regulated by the interaction of sea level, oceanography, and tectonism (for example, see Doyle and Pilkey, 1979; Barron, 1986). The rate of siliciclastic sedimentation or erosion, for example, depends chiefly on topographic/bathymetric gradients and base levels controlled by local tectonics and relative sea level. The rate, kind, and preservation of biogenous, hemipelagic sedimentation depends on the characteristics of the overlying water column. Whereas the production of diatomaceous sediments offshore of California is directly related to the upwelling of nutrient-rich intermediate waters, the preservation of organic matter and early diagenesis of sediments are influenced additionally by bottom-water composition. In the Pliocene Santa Maria basin, depositional trends in the Sisquoc Formation and Foxen Mudstone were apparently influenced to a greater degree by tectonism than by eustatic or large-scale paleoceanographic events (Ramirez, 1990; Barron, 1992; Ramirez and Garrison, this volume). In the following sections we address the paleoceanography, sea level record, and tectonic setting of the lowermost Foxen.

Paleoceanography and Eustatic Sea Level

Deposition of the lower part of the Foxen Mudstone above the hemipelagic facies can be correlated to a well-dated oceanographic/climatic event, thus providing some constraint to the timing and setting of the basal Foxen siliceous facies. Planktonic foraminiferal biofacies at Deep Sea Drilling Project (DSDP) Site 173 off of northern California indicate a warming of surface waters at about 4 Ma (Keller, 1979), and both planktonic assemblages and oxygen isotopes indicate a return to colder surface waters at about 3.2 Ma (Shackleton and Opdyke, 1977; Keller, 1979). This warm interval is part of a widespread mid-latitude climatic event documented across the Pacific Ocean (Keller, 1979; Kennett, 1986). Although foraminifera cannot be extracted from the siliceous rocks of the basal Foxen, overlying strata of the lower Foxen, some 400 m above the formational boundary in the Los Flores No. 1 well, contain the distinctive planktonic foraminiferal biofacies of the middle Pliocene warm event, indicating that the basal Foxen strata were deposited prior to the termination of the warm event at 3.2 Ma.

The episode of middle Pliocene warming also corresponds to a longer interval of decreased production and (or) poor preservation of diatoms (4.8–2.6 Ma) at a number of DSDP sites offshore of California (Sites 173, 467, and 469) (Barron, 1992). Because upwelling and productivity along the California margin are largely driven by the strength of the cool, southwardflowing California Current (Sverdrup and others, 1942; Hickey, 1979; Gorsline and Teng, 1989), Barron (1992) argues that the poor diatom record reflects high-latitude warming and the weakening or narrowing of the eastern boundary current. Therefore, although diatom sedimentation continued until the late Pliocene in a few locations (for example, the Santa Maria basin; Barron, 1992), general conditions along the Pliocene California margin were not conducive for widespread production and accumulation of biosiliceous sediments.

The record of Pliocene eustatic sea level (as indicated by seismic sequence stratigraphy) shows a series of sea level lowerings and lesser sea level rises during an overall regressive trend from an early Pliocene highstand (Haq and others, 1988; fig. 6). The Pliocene highstand lasted over 1.2 m.y., from ~5 Ma to 3.8 Ma, and included a minor sea level dip at 4.2 Ma. The highstand was terminated by a sharp fall at 3.8 Ma, followed by others at 3.0 Ma and 2.4 Ma (Haq and others, 1988). The overall trend reflects the growth of the Antarctic ice sheet and the establishment of northern hemisphere continental glaciation after 2.6–2.4 Ma (Kennett, 1986). As the entire Foxen Mudstone was probably deposited between 3.8 Ma and 3.0 Ma (fig. 6), the siliceous strata of the basal Foxen were likely deposited entirely during the early Pliocene lowstand (3.8–3.4 Ma) proposed by Haq and others (1988). Although it is possible that Foxen deposition began as early as 4.0 Ma (see previous discussion of age) in the midst of the early Pliocene highstand, the abrupt and distinct changes in lithology (for example, color, TOC, grain size, and composition) suggest that the depositional environment changed just as markedly, such as across a major drop in eustatic sea level.

Tectonics

The Neogene Santa Maria basin and the California borderland developed within a zone of transform deformation between the Pacific and North American plates (Atwater, 1970, 1989; Blake and others, 1978). Initial tectonic subsidence in the Santa Maria basin took place within a broad strike-slip to transtensional plate margin between about 17.5 Ma and 6.0 Ma (Blake and others, 1978; Atwater, 1989; McCrory and others, 1995). Regional tectonic stresses changed in the latest Miocene and early Pliocene (Ingle, 1980), possibly in response to the eastward jump of the plate boundary from the base of the continental slope to the San Andreas Fault in southern and Baja California at 5.5 Ma (Sedlock and Hamilton, 1991); this new configuration created a restraining margin geometry and initiated a component of compressive shear in many southern and central California basins (Atwater, 1989). The resulting deformation and localized uplift contributed to high terrigenous sedimentation rates during deposition of the Sisquoc Formation (Ramirez, 1990; Barron, 1992; Ramirez and Garrison, this volume). In the late Miocene to early Pliocene, relative motion between the Pacific and North American plates along the California coast rotated 14° clockwise, evolving from chiefly transform to transpressive motion (Harbert and Cox, 1989; Harbert, 1991). This transpressional regime continues to the present day in the Santa Maria basin (Feigl and others, 1990).

Although originally dated as early Pliocene (~3.9–3.4 Ma; Harbert and Cox, 1989; Harbert, 1991), the tectonic reorganization is now thought to have initiated as early as 6–5 Ma (Cande and others, 1992; Wilson, 1993). In fact, the onset of crustal shortening at different locations across the central California margin during the late Neogene was markedly diachronous (McCrory and others, 1995; C. Sorlein, 1995, oral commun.). Yet, throughout the California borderland, lateral variations in formational thickness and facies provide compelling evidence for the Pliocene deformational phase (Ingle, 1980). Canfield (1939), Woodring and others (1943), and Woodring and Bramlette (1950) proposed that the modern anticlines of the Santa Maria basin began to develop during Foxen deposition, controlling the distribution of the thick synclinal deposits and the thin or absent anticlinal sections. This hypothesis is further substantiated by balanced structural cross-sections across the onshore Santa Maria basin which also suggest that regional compression commenced during deposition of the Foxen [estimated by Namson and Davis (1990) as 4.0–2.0 Ma]. Pliocene deformation is also demonstrated by a prominent, widespread early to late Pliocene angular unconformity in the offshore Santa Maria basin, placed at the boundary between the Sisquoc Formation and Foxen-equivalent strata, (Page and others, 1979; Crain and others, 1987; Clark and others, 1991). Clark and others (1991) placed the unconformity and the base of the "Foxen" at ~3.4 Ma. The distinctly dolomitic and siliceous hemipelagic Foxen facies directly overlies the Sisquoc Formation in at least three wells from the offshore Santa Maria basin (P-0395 No. 1, P-0396 No. 1, and P-0425 No. 2; fig. 1).

Namson and Davis (1990) suggest that much of the surface and shallow deformation across the onshore Santa Maria basin reflects thrusting along a deep, blind, north-vergent, low-angle detachment surface—the Purisima–Solomon Thrust—somewhat modified by shallower, high-angle normal and reverse faults (figs. 4, 7). The Lompoc–Purisima anticlinal trend is interpreted as a fault-bend fold that overlies the deep ramp of the Purisima–Solomon Thrust and the Casmalia–Orcutt anticlinal trend as a fault-propagation fold at the shallow, leading edge of the blind thrust. In this scenario, southward tilting and subsidence of the Santa Maria Valley syncline resulted from downdropping and rotation of hanging wall blocks on the north flank of the Casmalia–Orcutt anticline, and by tectonic loading of the footwall (foreland). The San Antonio–Los Alamos syncline is located between the ramps underlying the two anticlinal trends and is shaped by the converging limbs of the Casmalia–Orcutt anticline to the north and the Lompoc–Purisima anticline to the south (fig. 7). As the hanging wall strata in the San Antonio–Los Alamos syncline have been transported past the Lompoc-Purisima ramp, their fault-related motion has been entirely horizontal (fig. 7). In the Santa Maria basin, the uplifted, structurally thickened anticlines are closely spaced with a wavelength of about 15 km. Locations such as the San Antonio–Los Alamos and Santa Maria Valley synclines, which were not actively growing upward during compressional shortening but were adjacent to structurally thickening sections, would likely experience isostatic subsidence in response to the increased tectonic load rigidly supported across the basin (fig. 7).

INTERPRETATION

We propose that the Sisquoc Formation–Foxen Mudstone boundary coincides with the onset or acceleration of crustal shortening and the development of marked bathymetric relief in the Santa Maria basin. Although growth of anticlinal ridges and synclinal troughs may have begun during Sisquoc deposition in the latest Miocene and earliest Pliocene (Ramirez, 1990; Sedlock and Hamilton, 1991) in concert with the initiation of a transpressive relationship between the Pacific and North American Plates, topographic relief increased dramatically with the local acceleration of compressional thrust faulting in the late early Pliocene (3.8–3.4 Ma) along new and reactivated faults striking to the west and northwest from the southeastern corner of the basin (Namson and Davis, 1990).

Canfield (1939) showed that the base of the Foxen Mudstone in the synclinal axis of the Santa Maria Valley field is a transgressive surface, yet the eustatic sea-level curve of Haq and others (1988) shows a sea level fall and lowstand from 3.8 Ma to 3.4 Ma during deposition of the lower part of the Foxen. Concurrently, benthic foraminiferal biofacies [for example, Standard Los Flores No. 1 well (fig. 3) and in Woodring and Bramlette (1950)] document a significant increase in water depth coincident with deposition of basal Foxen sediments (fig. 6). These data show that water depth increased from outer neritic (100–150 m) during deposition of the upper part of the Sisquoc Formation to upper bathyal depths (~500 m) during deposition of the lower part of the Foxen, before the global eustatic sea level rise at 3.4 Ma. We infer that local transgression and increased water depth resulted from subsidence of synclinal areas that outpaced the eustatic sea level fall. Exaggerated relief or bathymetric gradients are suggested by the coarsening-upward trend from the fine-grained upper part of the Sisquoc into the silty sand and conglomerates found in the basal Foxen in some portions of the Santa Maria Valley Field (Canfield, 1939; Woodring and Bramlette, 1950). At the same time that thick Foxen deposits accumulated in subsiding troughs, sediments were winnowed from anticlinal highs and little or no sediment accumulated there (Woodring and others, 1943; Woodring and Bramlette, 1950). Accelerated subsidence of the Santa Maria Valley and San Antonio–Los Alamos synclines was likely due to rigid isostatic compensation for the thrust-related structural thickening throughout the Santa Maria basin; the synclines plummeted while the Lompoc-Purisima and Casmalia-Orcutt anticlines continued to be uplifted over their respective subsurface thrust ramps.

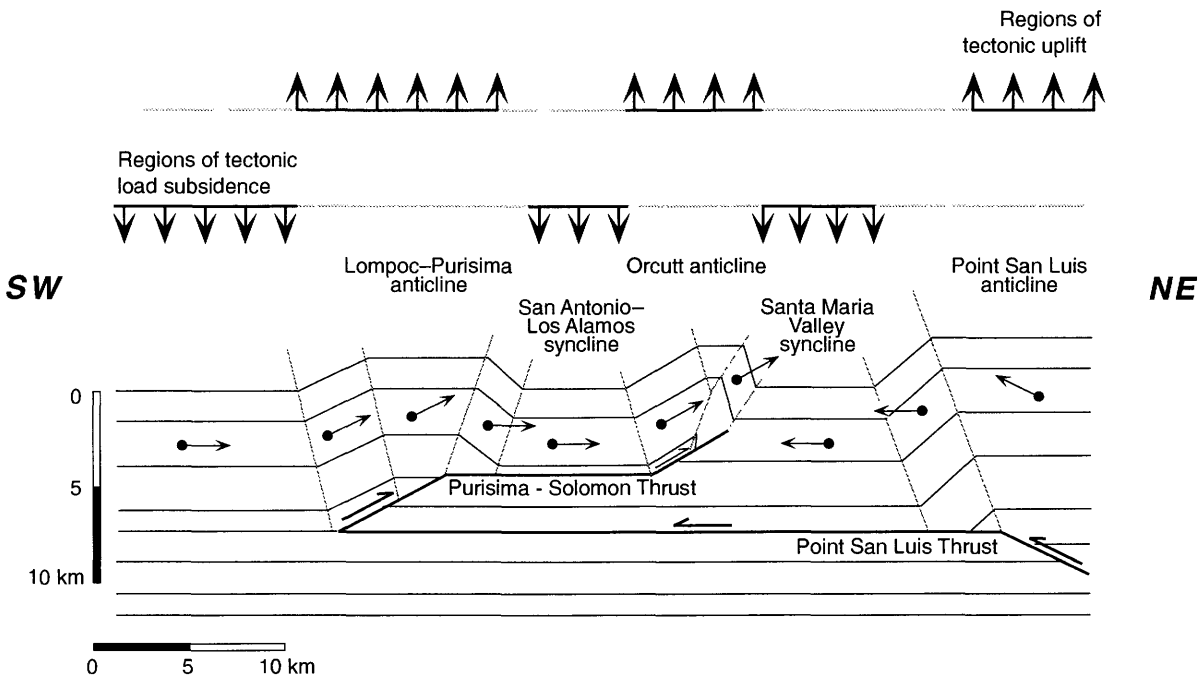

Figure 7. Structural model of section *B–B'* (figs. 1, 4) of compressional structures of the onshore Santa Maria basin. Modified from Namson and Davis (1990) to show regions of thrust ramp-related uplift and regions of tectonic load subsidence. Arrows with balls show vectors of blocks with thrust-related uplift and those with purely horizontal motion. Blocks with strictly horizontal fault motion would be expected to display tectonic load subsidence by increased paleobathymetry until filled by rapid sedimentation.

The siliceous component of the hemipelagic facies of the basal Foxen Mudstone could express increased diatom productivity or decreased dilution of pelagic sediments by terrigenous siliciclastics, or both. Planktonic biofacies and the oxygen-isotope record indicate that surface waters of the late early Pliocene California margin were too warm, and the California Current too weak, to reflect vigorous upwelling and diatom productivity and preservation (Shackleton and Opdyke, 1977; Keller, 1979; Kennett, 1986; Barron, 1992). It is more likely that the local transgression induced by tectonic load subsidence of the late early Pliocene Santa Maria Valley and San Antonio–Los Alamos troughs sequestered terrigenous detritus near the shoreline, resulting in the slow accumulation of relatively pure, hemipelagic, siliceous Foxen sediments in the newly subsiding troughs. Thus, the basal Foxen cherts and porcelanites primarily record a tectonic signal—the tectonic load subsidence of localized depositional troughs due to compressional thrust faulting. In this sense, the tectonic and relative sea level control of sedimentation in the basal Foxen is quite similar to the factors responsible for the deposition of the detritus-poor, biosilica-rich Miocene Monterey Formation (Isaacs, 1984), but for a much briefer interval (~0.5 m.y. for the Foxen, as compared to ~12 m.y. for the Monterey)

The presence of numerous dolostone horizons within the lowermost Foxen Mudstone similarly attests to siliciclastic starvation and slow sedimentation rates. Within organic-rich sediments, dolomite precipitation may be initiated or accelerated during pauses in sedimentation when sulfate and methane can continuously diffuse to the high-alkalinity zone of anoxic methane oxidation (Middelburg and others, 1990). Accordingly, many dolostone horizons in hemipelagic sedimentary sequences are representative of condensed sedimentation and parasequence boundaries (Grimm, 1992; L. White and R. Garrison, 1992, oral commun.). Therefore, the presence of numerous dolostone beds and nodular horizons in the lowermost Foxen suggests siliciclastic sediment starvation and decreased sedimentation rates during the local transgression caused by rapid tectonic subsidence of depositional troughs.

Comparison between sediments from the upper part of the Sisquoc Formation and the lowermost hemipelagic Foxen Mudstone indicates that the formational contact marks an environmental change from oxygenated to oxygen-deficient waters. In the subsurface, the diatomaceous siltstones and claystones of the upper part of the Sisquoc are light colored and massive to weakly banded, whereas siliceous rocks of the lowermost Foxen are dark colored and thinly laminated. Furthermore, the Foxen mudrocks are slightly phosphatic, whereas strata from the upper part of the Sisquoc are not. Upper Sisquoc sediments from the Coastal Hunter Careaga No. 3 well have low total organic carbon (1.1–1.3 percent), probably reflecting active bioturbation under oxygenated waters, whereas the dark-brown color, laminations, phosphate, and higher TOC (3.3–4.1 percent) of the lowermost Foxen sediments all suggest deposition within oxygen-deficient conditions (fig. 6).

Faunal evidence gives minor substantiation to the hypothesis of low-oxygen conditions during deposition of the lowermost Foxen Mudstone. No megafossils have been found from the lower part of the Foxen, whereas the upper part of the Sisquoc Formation contains abundant molluscan body fossils and molds (Woodring and others, 1943). This evidence suggests that larger invertebrates common in the shelf-depth upper Sisquoc sediments were excluded from lower Foxen sediments as synclinal troughs deepened enough (~500 m) to intercept oxygen-depleted upper intermediate waters.

SUMMARY

Plate tectonic reorganization in the late Miocene to early Pliocene shifted the Californian Pacific–North American Plate margin from a transform to transpressive tectonic regime. Crustal shortening within the onshore Santa Maria basin initiated or accelerated at 3.8–3.4 Ma, producing a dynamic relief of high-standing bathymetric ridges separated by low-lying synclinal troughs during deposition of the Pliocene Foxen Mudstone. A distinct change in sedimentation patterns across the Sisquoc Formation–Foxen Mudstone boundary was principally controlled by this tectonism. Rapid tectonic subsidence of the Santa Maria Valley and San Antonio–Los Alamos synclines is locally marked by angular unconformities in the subsurface, by paleobathymetric deepening from outer neritic (100–150 m) to lower upper bathyal environments (~500 m), and by the accumulation of biosiliceous and dolomitic sediments in the synclinal troughs. Biostratigraphic data from the lower part of the Foxen in the Standard Los Flores No. 1 well unequivocally demonstrate that water deepened to 500–600 m before the global eustatic sea level rise at 3.4 Ma, indicating that synclinal subsidence was tectonically driven. The purer siliceous strata of the basal Foxen apparently resulted from a decrease in terrigenous input due to local transgression during a period of global eustatic sea level fall, rather than from an increase in diatom productivity and accumulation. Thick sequences of lower Foxen sediments accumulated only in subsiding synclinal troughs, which were initially semi-isolated and probably held oxygen-deficient waters. This environment is reflected in the dark-brown color, higher TOC, laminations, phosphate, dolomite, and lack of megafauna in the hemipelagic facies of the basal Foxen.

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