U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

PRELIMINARY GEOLOGIC BACKGROUND FOR ROCK SAMPLES FROM NAPLES BEACH AND LIONS HEAD IN THE COOPERATIVE MONTEREY ORGANIC GEOCHEMISTRY STUDY, SANTA MARIA AND SANTA BARBARA-VENTURA BASINS, CALIFORNIA

by

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CONTENTS

INTRODUCTION

This chapter describes the regional and local geology of the Monterey Formation as background for the rock samples in the Cooperative Monterey Organic Geochemistry Study (CMOGS). CMOGS, its purposes and participants, are more generally described in the preface (Chapter A, this report).

Rock samples in the study were taken from the Naples Beach section in the Santa Barbara-Ventura basin (KG-1 to KG-13) and the Lions Head section in the Santa Maria basin (KG-14 to KG-24). Comments mainly focus on the depositional framework of the Naples and Lions Head sections. Discussion of organic matter is restricted to information about total organic carbon (TOC) distribution, abundance, and accumulation rates. No structural history is included in this chapter (see Preliminary *Petroleum Geology Background*, Chapter F, this report).

Bold-faced words are defined and discussed in *Geology Handbook* (Chapter E, this report).

PUTTING THE MONTEREY FORMATION IN PERSPECTIVE

Comparison of the Monterey Formation with California strata as a whole

During most of Cenozoic (0-65 Ma) and late Cretaceous time, the California continental margin was a tectonically active area, and sedimentary deposits varied considerably from area to area. In general, deep-water marine clastic deposits predominated (submarine fans with sandstones and associated coarse clastic sedimentary rocks). Fine-grained biogenic sediments similar to the Miocene Monterey Formation in varying degrees were, however, deposited in some parts of California during Late Cretaceous and Eocene time, and over a large part of southern Baja California during the late Oligocene. These deposits are sometimes viewed as climate-related "events" but may equally plausibly be viewed as the result of margin tectonics and/or sea-level changes. That is, the fine-grained more-or-less Monterey-like deposits can be viewed as occurring within a more-or-less constant eastern boundary current oceanographic system *when and where* there were margin conditions that excluded the generally abundant coarse clastic debris and created large-scale pelagic sediment traps. Like the Monterey Formation, these deposits were all diluted to various degrees by fine-grained terrigenous debris.

Comparison of the Monterey Formation in the Santa Maria-Santa Barbara area with the Monterey Formation as a whole

The Miocene Monterey Formation was deposited in about 8-12 basins which are generally thought to have been separate at the time of deposition (Figures 1 and 2). The relative geographic position of these basins has been much affected by subsequent tectonism, most notably by right-lateral offset along the San Andreas fault estimated at about 300 km since earliest Monterey deposition. What this means is that earliest Monterey strata in the Santa Maria and Santa Barbara-Ventura basins (also Los Angeles, Cuyama, Salinas, La Honda, and Point Arena basins) were deposited about 300 km farther south relative to the San Joaquin and Livermore basins than present positions would suggest. Relative geographic positions may also have been affected by tectonic rotation of the Santa Barbara-Ventura basin; according to the reconstruction by Hornafius and others (1986), the Santa Barbara-Ventura basin would have been oriented north-south directly west and seaward of the Los Angeles basin at the beginning of Monterey deposition (Figure 3).

Although having many broad similarities, the various Miocene basins in which the Monterey Formation was deposited did not have identical histories (e.g. Figure 4). The term "Monterey" is just a name applied to those Miocene strata that are, as a whole, fine-grained and unusually siliceous. Much of the Sisquoc Formation qualifies and was originally included in the Monterey Formation (see *Geology Handbook* under **formation**).

A hallmark of the Monterey Formation is "remarkably rapid variations in thickness and lithologic character that permit few generalizations on the formation as a whole" (Bramlette, 1946, p. 2). With that caution in mind, the following generalizations distinguish the Monterey in the Santa Barbara-Ventura and Santa Maria basins from the Monterey elsewhere:

(1) much higher compositional heterogeneity (Figure 5);
(2) much more abundant calcite; 20-25% of strata was classed by Bramlette as "calcareous shale" in this area (and also Huasna-Pismo and Salinas basins) vs. 0-1% elsewhere;
(3) higher average TOC, and more varying values reported (0.5-23%) (Figure 6);
(4) much more common glassy chert (a conchoidally fracturing silica-rich rock like flint which is regarded as the major fractured reservoir).

Statewide, the most typical strata are clay-bearing siliceous rock with matte surface texture (known as porcelanite), silica-bearing shale or mudstone, and gradations in between; these are represented in the cooperative study samples by KG-7 and KG-8. Statewide, discrete dolomite beds are also widely present, and cherty beds generally rare.

Comparison of the Monterey Formation in the Santa Barbara area with modern marine sediments

Although the depositional environment of the Monterey Formation was not necessarily like any particular modern setting (see below), it is interesting to compare average abundances and accumulation or sedimentation rates in the Miocene Santa Barbara Basin with values in various modern settings (Table 1). Such comparisons are somewhat tricky because rates are well-known to be affected by scale - that is, rates decrease as the time span increases, sometimes very markedly, due to resedimentation and periods of non-deposition (Nittrouer and others, 1984).

Nevertheless, the following generalizations may apply:

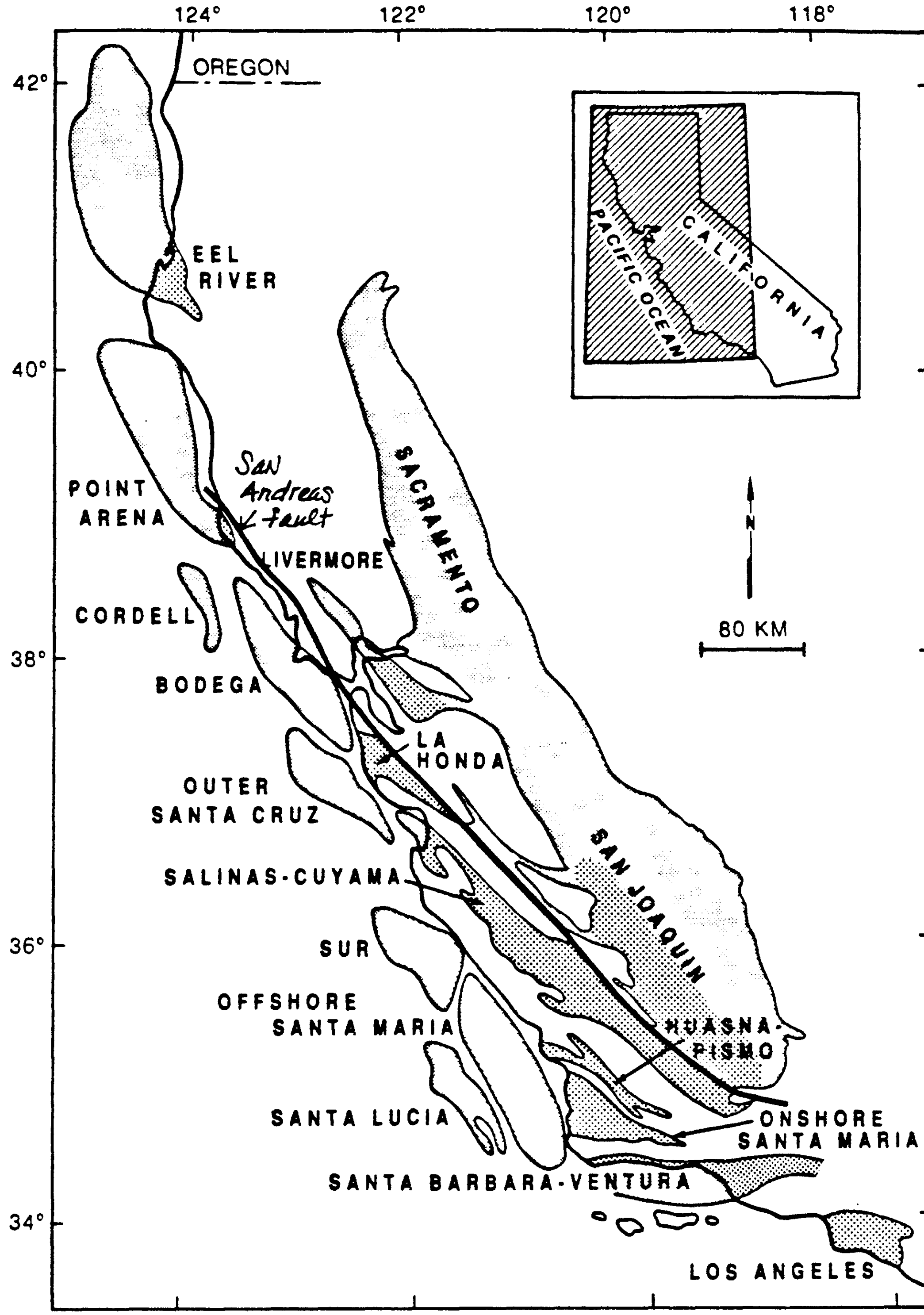
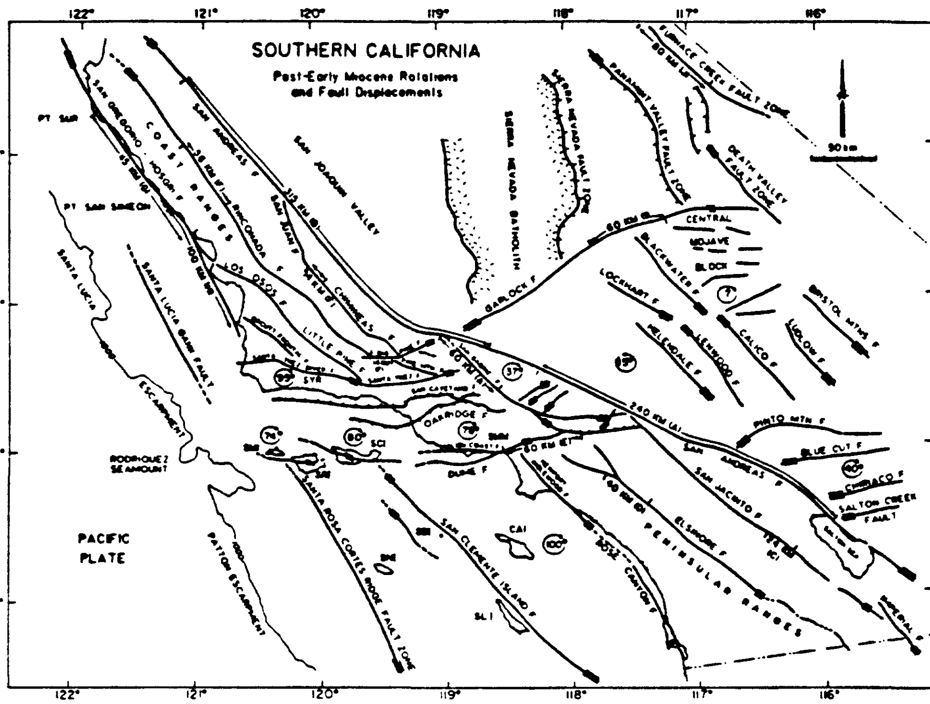


Figure 1. Present location of Neogene and late Cenozoic marine basins in California (after Blake and others, 1978, and McCulloch, 1987), showing the approximate distribution of the Monterey Formation onshore (dot pattern). The map is not representative of Miocene locations; present location may have been affected by Miocene and later block rotations, formation of pull-apart basins, as much as 300 km of lateral fault-movement, and other tectonic events (Blake and others, 1978; Howell and others, 1980; and others).

Figure 2. Oil and gas fields in the Santa Maria and Santa Barbara-Ventura areas, California, and adjacent offshore regions. Labeled fields have significant production or potential from Monterey Formation fractured reservoirs. The Point Arguello field and adjacent offshore fields are included in the offshore Santa Maria basin. Adapted from California Division of Oil and Gas (1974) and Williams (1985).



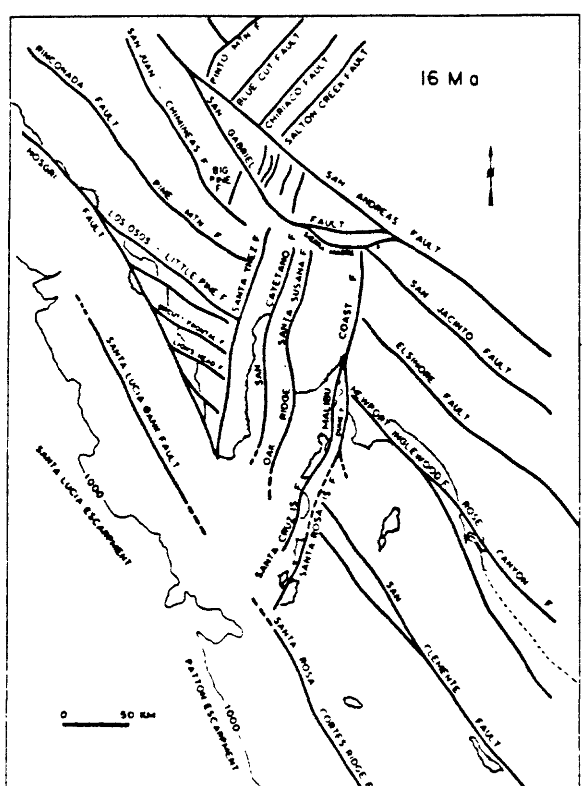


Figure 3. Presentday geography (above) and palinspastic reconstruction at 16 Ma (below) showing presentday faults and shorelines of southern California. Circular arrows indicate the sense and amount of tectonic rotation suggested by paleomagnetic data, with most rotation in the interval 10-16 Ma. Straight arrows indicate the amount of displacement between piercing points along major strike-slip faults. Reprinted from Hornafius and others (1986) by permission.

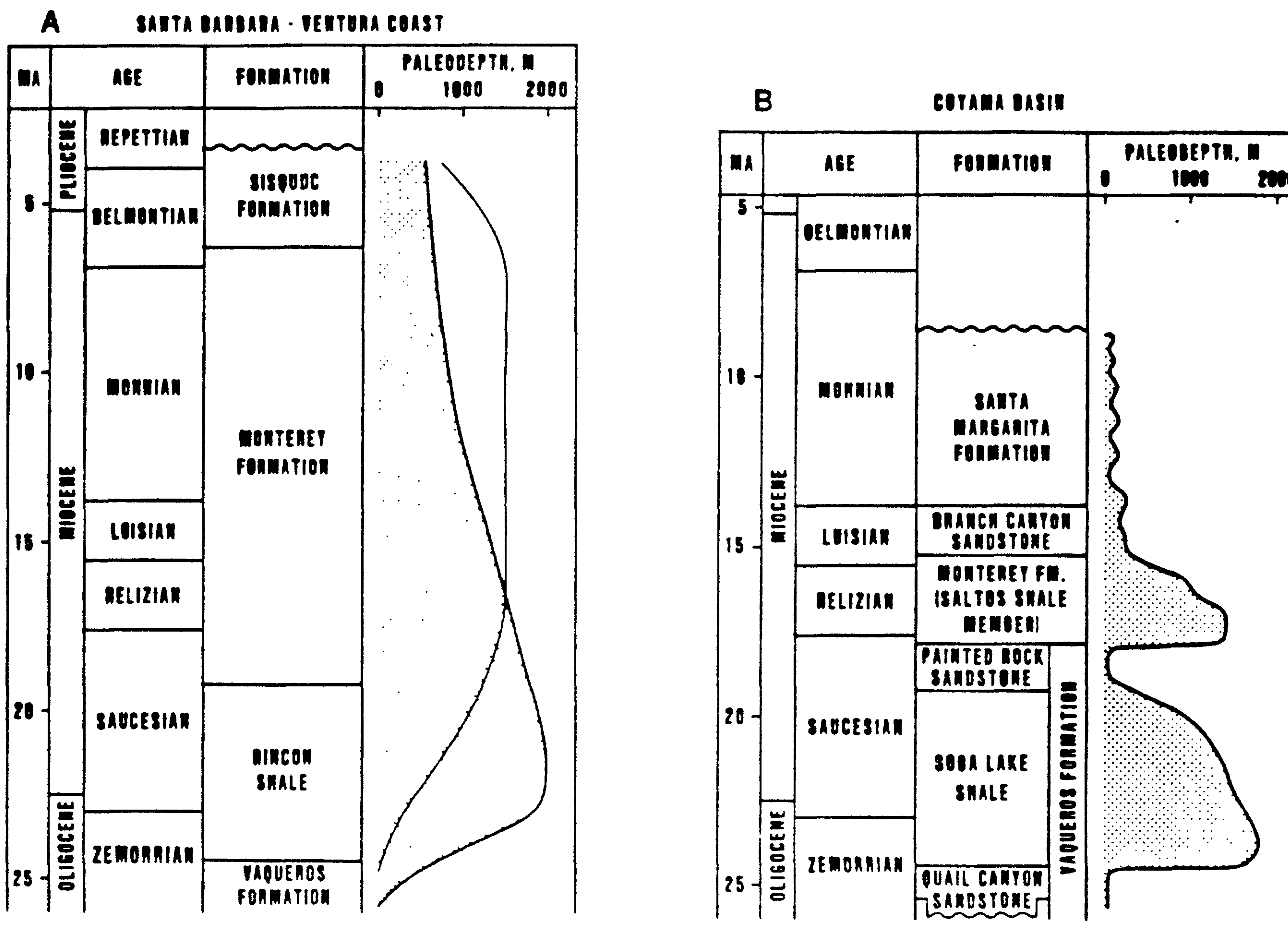


Figure 4. Examples of paleobathymetric curves for the Miocene of California (from Isaacs, 1989). (A) Santa Barbara-Ventura coast compiled from Edwards (1972), R. E. Arnal (written communication, 1978), and Finger (1983). For comparison, the narrow line shows the curve from Ingle (1980) which is also shown in Figure 10. (B) Cuyama basin from Lagoe (1987).

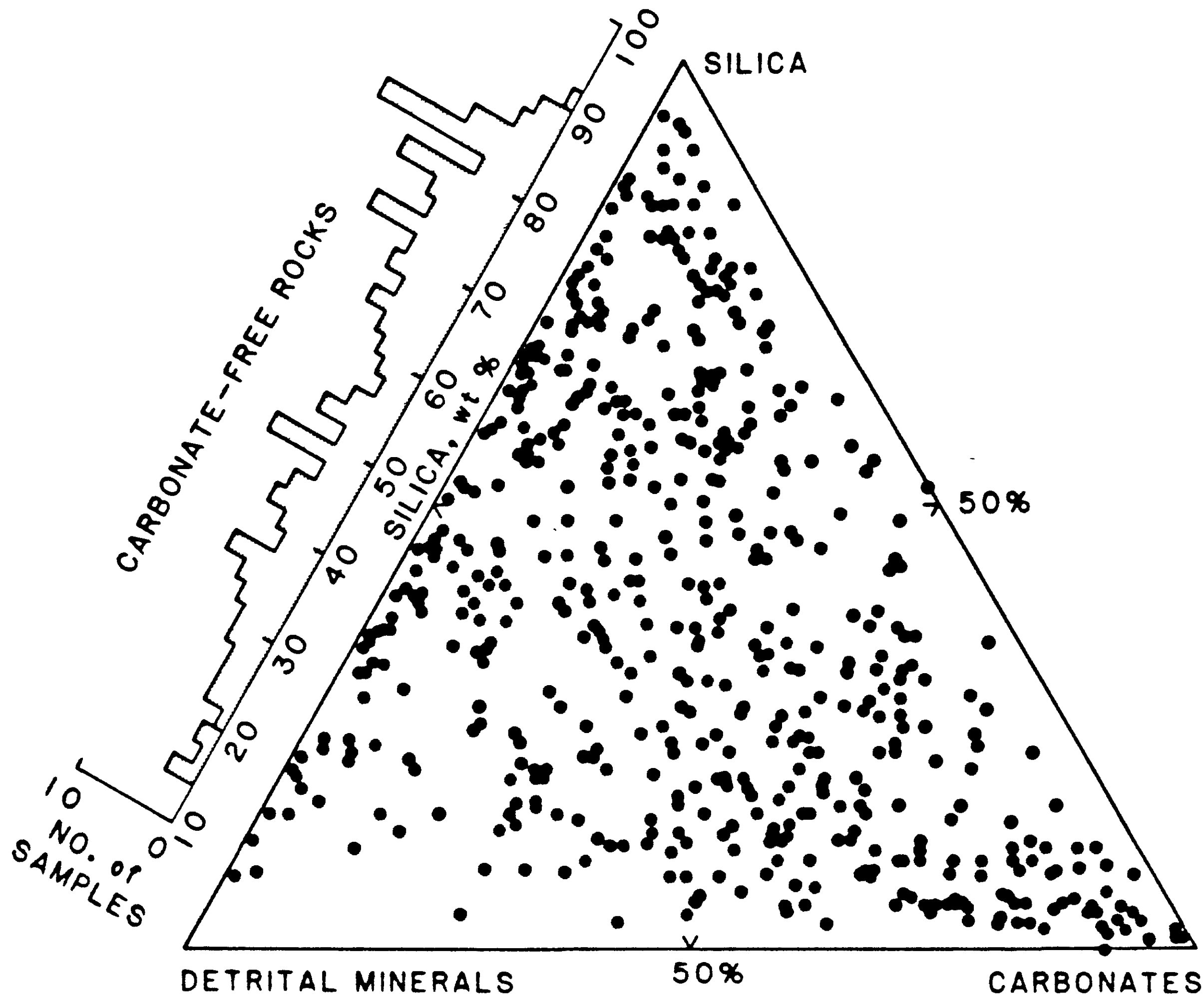


Figure 5. Diagram showing the wide variety of sedimentary compositions among individual beds in the Monterey Formation, Santa Maria and Santa Barbara-Ventura basins. Each data point represent a chemically analyzed sample, and the histogram represents the distribution of detritus-silica compositions of samples containing less than 1% carbonate minerals. Sedimentary components are expressed on an organic-matter-free basis; apatite is included with carbonates. From Isaacs (1985).

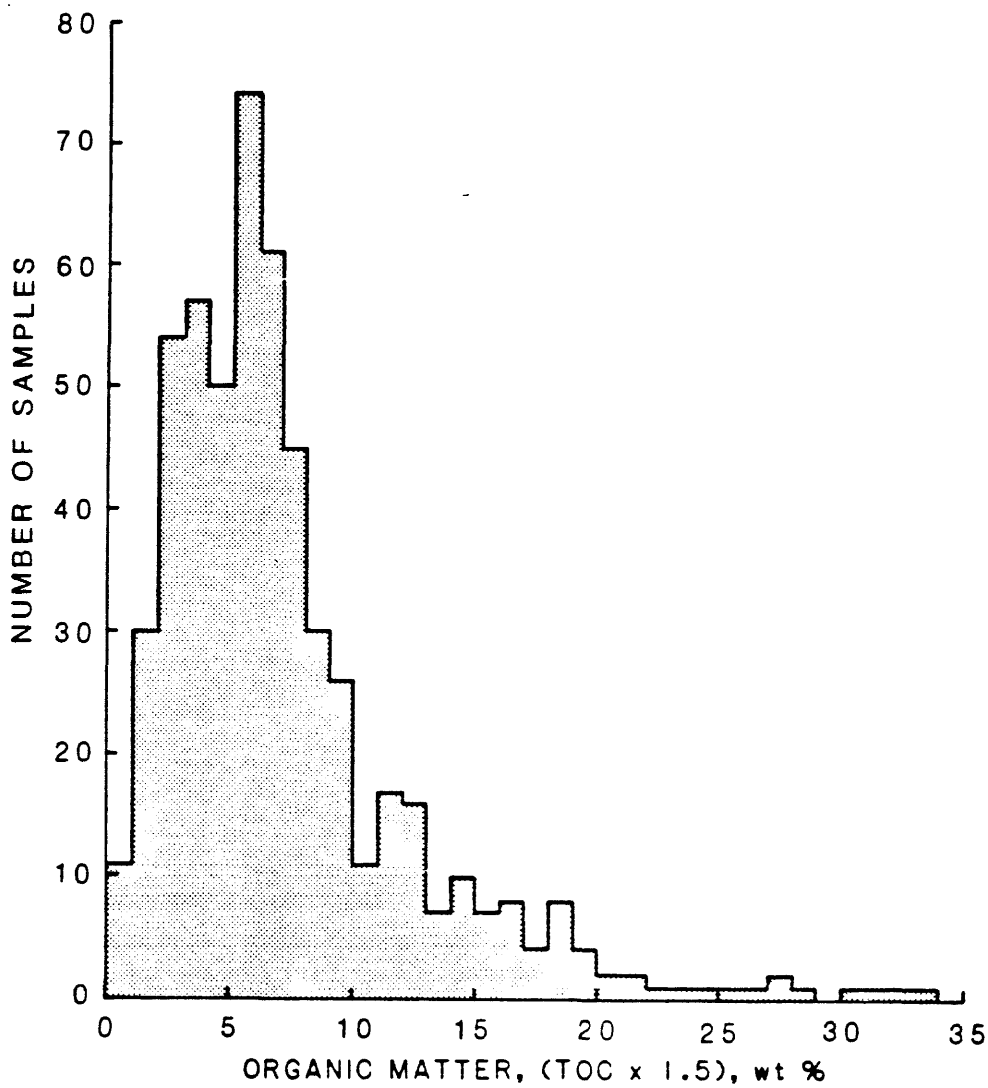


Figure 6. Histogram of the abundance of organic matter (TOC x 1.5) in the Monterey Formation of the Santa Maria and Santa Barbara-Ventura basins. From Isaacs (1987).

Table 1. Preliminary comparison of abundances and accumulation rates in Miocene-Pliocene deposits of the Santa Barbara coastal area and sediments in various modern settings.

	Accumulation (mg/cm²/yr)	Abundance (wt %)	Ref
Biogenic silica:			
Pacific Equatorial Zone	0.001-0.01	10	4
Northern Pacific Ocean	0.01-0.1	10	4
Santa Catalina & San Nicholas Basins*	0.1-0.3	1-2	10
Santa Cruz & Santa Monica Basins*	0.3-2.2	2	10
Southern Diatom Belt	0.1-3	55	4
Rincon Shale (S. Barbara)	1-2	12	9
Monterey Fm (S. Barbara)	0.4-6	40	9
Peru-Chile Coast	3	13	4
Bering Sea	2-4	25	4
Sea of Okhotsk	2-5	30	4
Farallon and Pescadero Basins**	2-7	6	1
Santa Barbara Basin*	4-7	5	4,7,10
Sisquoc Fm (S. Barbara)	>5->22	30	9
Sisquoc Fm (S. Maria)	7-34	30-40	11
Delfin and San Pedro Martir Basins**	12-54	11-17	1
Walvis Bay, So. Africa	35-45	40	4
Guaymas Basin**	8-174	18-35	1
Terrigenous debris (detritus):			
Monterey Fm (S. Barbara)	0.5-5	25	9
Tanner Basin* (av 0-12,000 yrs)	6-7	60-70	2
Rincon Shale (S. Barbara)	5-9	65	9
Velero, Colnett, No Name, and So. San Quentin Basins*	3-18	70-90	5
Sisquoc Fm (S. Barbara)	>9->45	60?	9
San Clemente Basin*	12-50	85	5
Sisquoc Fm (S. Maria)	18-43	55-70	11
Santa Barbara Basin*	40-85	85	4,7
Guaymas Basin**	12-270	50-70	1
Farallon and Pescadero Basins**	40-90	85	1
Delfin Basin**	250	80	1
Calcium carbonate:			
Monterey Fm (S. Barbara)	0.1-3	5-45	9
Rincon Shale (S. Barbara)	2-3	10-20	9
Santa Cruz Basin* (0-12,000)	2-3	8-18	3

Santa Monica Basin* (surface)	2-5	5-16	6
Gulf of California (0-5000)	2-5	3-12	1
San Clemente Basin*	2-6	10-20	5
Tanner Basin* (av 0-12,000 yrs.)	3-4	30-40	2
Santa Barbara Basin*	2-10	2-10	8,10
Total organic carbon (TOC):			
Velero, Colnett, No Name, South San Quentin Basins* (17,000 yrs)	0.05-0.2	1-3	5
Tanner Basin* (av 0-12,000 yrs)	0.3-0.4	3-4	2
Monterey Fm (S. Barbara)	0.1-0.5	4-9	9
Rincon Shale (S. Barbara)	0.4-0.6	3-4	9
Sisquoc Fm (S. Maria)	0.3-1.4	0.3-3	11
San Clemente Basin*	0.3-1.8	2-3	5
Northern Borderland Basins*	0.5-4	1-5	6,10
Santa Barbara Basin*	0.5-4	2.5-3.5	4,8,10
Gulf of California (0-5000)	≈1.8-3	2-7	1
Total sedimentation:			
Pacific Equatorial Zone	0.01-0.1		4
Northern Pacific Ocean	0.1-1.0		4
Southern Diatom Belt	1-7		4
Monterey Fm (S. Barbara)	2-11		9
Sea of Okhotsk	5-16		4
Tanner Basin* (av 0-12,000 yrs)	9-10		2
Rincon Shale (S. Barbara)	9-14		9
Peru-Chile coast	11-35		4
Santa Clemente Basin*	15-60		5
Santa Monica Basin* (surface)	20-40		6
Sisquoc Fm (S. Barbara)	>15->72		9
Sisquoc Fm (S. Maria)	25-72		11
Santa Barbara Basin*	80-130		10
Gulf of California	23-500		1

* Borderland basins off Southern California and northern Baja California; ** Gulf of California basins.

References: (1) van Andel (1964) and Calvert (1966); (2) Gorsline and others (1968); (3) Gorsline and Prensky (1975); (4) Lisitzin (1972) and DeMaster (1981); (5) Pao (1977); (6) Malouta and others (1981); (7) Pisias (1981); (8) Thornton (1981); (9) Isaacs (1984, 1985); (10) Schwalbach and Gorsline (1985); (11) Ramirez (1990).

(1) Average biogenic silica accumulation in the Monterey Formation was not unusually rapid, at the low end of values in modern upwelling areas. The Sisquoc Formation by contrast had unusually rapid silica accumulation, more comparable to the Guaymas slope in the modern Gulf of California (Table 1).
(2) Average TOC accumulation in the Monterey Formation was not unusually rapid, about an order of magnitude slower than rates in the modern Santa Barbara basin and Gulf of California.
(3) What is most distinctive about the Monterey Formation is the unusually slow sedimentation of detritus, much below values in most modern margin basins.

Incidentally, in sediments of the modern California Borderland, biogenic silica is extremely sparse (generally in the range 1-2%; Schwalbach and Gorsline, 1985), and productivity variations are interpreted from variations in calcite accumulation (e.g. Gorsline and Prensky, 1975).

Regional paleogeographic framework of the Monterey in the Santa Maria and Santa Barbara-Ventura basins

Published paleogeographic models of the Monterey Formation in this area are mainly just schematic models of the modern California borderland. Although they provide a useful framework for explaining the varying amounts of coarse clastics in various areas, it is important to remember that these models are *not* generalized from observed relations in the rock record. They are just models of how things are today, and - by analogy - ideas about how things might have been in the Miocene. The same is true for schematic models of the oxygen-minimum zone.

In the last year or so, a number of geologists have been reviewing and re-evaluating what is really known about the depositional framework of the Monterey Formation in the Santa Barbara-Ventura and Santa Maria areas. One lingering idea - that the Monterey was mainly deposited on a flat basinfloor - seems less and less plausible, as more and more individual sequences or parts of sequences are identified as having features showing ongoing downslope movement and soft-sediment deformation (e.g. Bohacs, 1990).

Difficulties in creating a regional paleogeographic model include:

(1) the long time span. Because it is a single formation, it is easy to suppose that the depositional system was constant during deposition of the Monterey Formation. However, 10-12 million years is a long time in a tectonically active continental margin. For examples of changes in paleogeography and paleobathymetry that can happen in a few million years, see Figures 3 and 4.
(2) deep water deposition. The resolution of paleodepths is highest in shallow water where environmental conditions change most markedly. Much of the Monterey Formation in this area was deposited at upper middle bathyal (≈500-1500 m) or undifferentiated upper bathyal/upper middle bathyal depths (≈150-1500 m). As pointed out by Hornafius (1991), lateral or stratigraphic differences in paleodepth of 500 m or so may

not even be detected. (See also *Geology Handbook* under **paleodepth** for other uncertainties.)

(3) biostratigraphic limitations. In practice, mainly due to poor preservation, most microfossils provide poor age-resolution after 14 Ma (e.g. DePaolo and Finger, 1991; Chapter E, this report). The exception is diatom frustules, but these are destroyed when opal-CT forms unless preserved in early-formed dolostone concretions (see *Geology Handbook* under **silica diagenesis and dolomite authigenesis**). As a result, most biostratigraphy is sketchy for Monterey strata younger than 14 Ma.

(4) lithologic heterogeneity. To establish compositional trends (such as clay abundance that might be related to sources of terrigenous debris), quality compositional data is needed. The problem is the high level of heterogeneity which makes averaging difficult. Compositional heterogeneity in the Monterey Formation in this area is not just a scatter of outlying values around a well-defined mean. Figure 5 shows the distribution of major sediment components in the area; distributions are not Gaussian, and normal statistics do not apply. Calculations show that disregarding analytical precision, about 100 *randomly selected* samples would be needed to be 90% confident of getting within 5 wt% of a mean 50% biogenic silica for a sequence (Isaacs, 1987; and unpublished data). With 25 samples, you would be right about half the time, and with 25 *randomly selected* samples from another sequence with a mean 40% biogenic silica you would have an 11% chance of correctly distinguishing that the means differed by an amount within the range of 5-15 wt%. The result is that compositional trends are hard to determine reliably, and evidence of trends based on surface sections mainly meaningless.

(5) proprietary restrictions. An added problem in the area is that much of the work that has been done is unavailable. Because of industry exploration interest in the 1980s and proprietary restrictions (mainly due to *reservoir* characteristics), little industry work has been published on Monterey sequences in this area except for a few surface sections. For example, the only public information on the Hondo oil field (discovered in 1969) is an environmental impact statement based on reports by the operating company (U.S. Geological Survey, 1974; partially reprinted in 1983). In addition, very little coring was in fact attempted during recent decades. For example, an extensive core of the Monterey in the South Elwood field was not taken until the mid-1980s even though the Monterey reservoir was discovered in 1969; no information about that core has yet been publicly released.

(6) lack of models for fine-grained rocks. In Potter and others' (1980) overview book *Sedimentology of Shale*, they say: "Because our knowledge of shales lags so far behind that of sandstones and carbonates, there are very few studies of shaly basins which we can use as specific models and *as yet no general 'mud models' for mudrocks and shales*" (p. 121). In clastic-dominated California basins, identification of basin morphology (slopes, submarine fans, etc.) is based entirely on well-studied characteristics of coarse clastic sedimentary rocks such as sandstones. In the Santa Barbara-Ventura and Santa Maria basins, there are a thousand km or so of fine-grained rocks that are complex varying mixtures of biogenic and detrital components all deposited in deep water. What

sedimentological differences would provide clues to the paleogeography? to basin position? to sources of sediment?

Available evidence requires the conclusion that Monterey sequences in the two basins (Santa Maria and Santa Barbara-Ventura) and in different parts of the same basin have significantly different paleobathymetric histories (Ingle, 1980, 1981, and unpublished data) and have unsimilar and difficult-to-correlate lithostratigraphic sequences (Bohacs, 1990; Dunham and others, 1991; Hornafius, 1991); sequences may also represent different time-spans of deposition.

Some ideas that have been used in trying to make sense of the Monterey Formation in this area include: (a) that thickest sequences represent basin floor deposits; (b) that more abundant silica represents deposition in deeper water; (c) that the stratigraphic sequence marks ocean-wide influences that could be used for areal correlation; (d) that seismic markers reflect worldwide sea-level changes that could be used for areal correlation; (e) that concentrations of apatite represent winnowing on banktops (e.g., Pisciotto and Garrison, 1981; Isaacs, 1984; Bohacs, 1990; Hornafius, 1991). Although counter-examples abound, some of these notions may be plausible. However, at this time they might best be classed as speculative possibilities rather than as firm frameworks for interpreting the Monterey Formation in the area.

DEPOSITIONAL ASPECTS OF ORGANIC MATTER DISTRIBUTION

High organic matter abundance in the Monterey Formation is widely attributed to marine algal (mainly **diatom**) debris rapidly deposited in **anoxic** bottom water during a period of high surface plankton **productivity**. However, for the Santa Barbara coastal area as a whole, the following relations are observed:

(1) Highest organic matter is associated with abundant **calcite**, both at the scale of members (Figures 7A and 7B) and at the scale of hand specimens (Figure 8); where calcite is absent, highest organic matter is associated with abundant terrigenous detritus (Figure 8). Least organic matter is associated with abundant biogenic silica at both scales.
(2) Highest organic matter is associated with lowest **sedimentation rates**, both for total sediment and organic matter (Figure 7B).
(3) Highest organic matter is associated with least plankton productivity as interpreted by diatom assemblages, abundance of biogenic silica, proportion of biogenic silica to biogenic calcite, etc. Conversely, lowest organic matter is associated with highest plankton productivity. (See also *Geologic Handbook* under **productivity**.)
(4) Highest organic matter is not associated with lowest oxygen bottom waters (as interpreted from varve-like layering); and where low-oxygen strata are interbedded with more oxygenated strata (as interpreted by massive bedding), low-oxygen strata consistently have *less* organic matter. (Cf. Figure 15; see also *Geologic Handbook* under **aerobic**.)

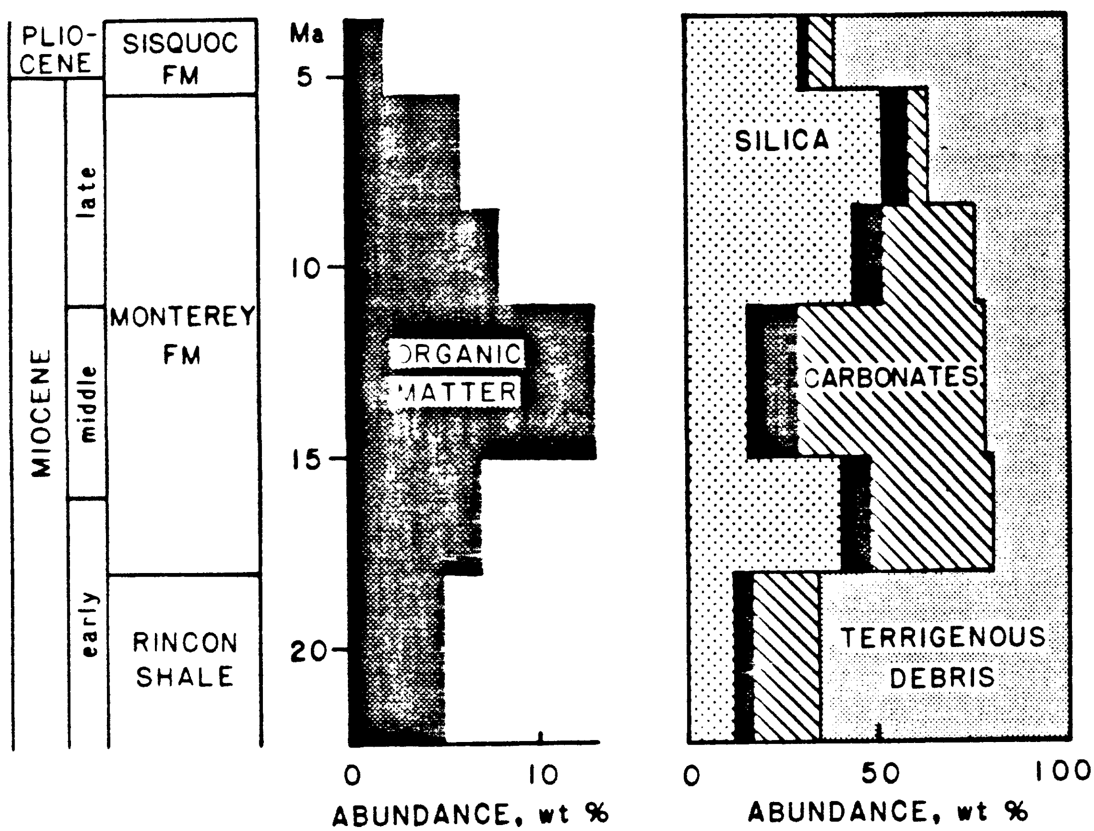


Figure 7A. Comparison of long-term means of organic matter (TOC x 1.5) and major inorganic sedimentary components (right), Santa Barbara coastal area. Values for the Rincon Shale represent upper strata (upper Saucesian) only. From Isaacs (1985).

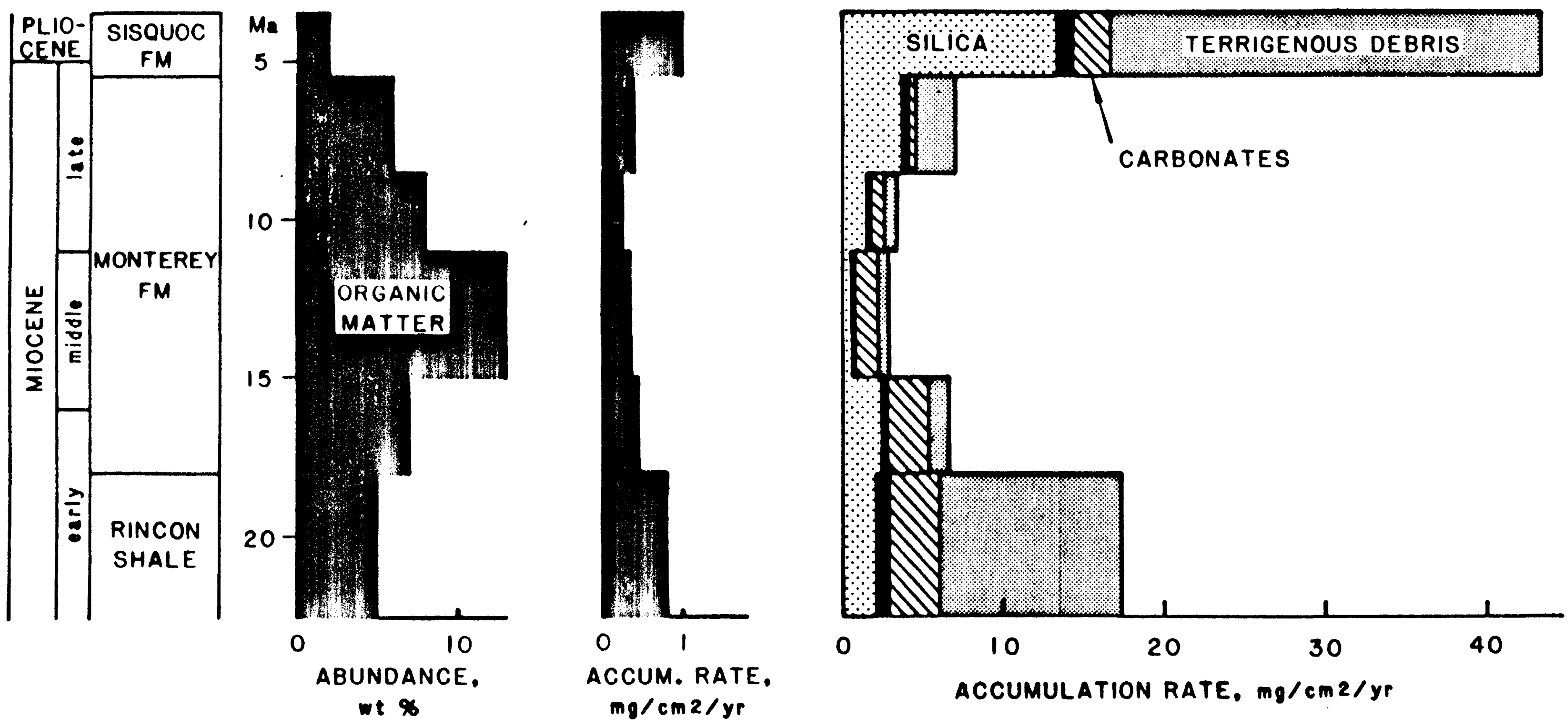


Figure 7B. Comparison of mean abundance of organic matter (left) with long-term accumulation rates of organic matter (center) and of major sedimentary components (right), Santa Barbara coastal area. From Isaacs (1985).

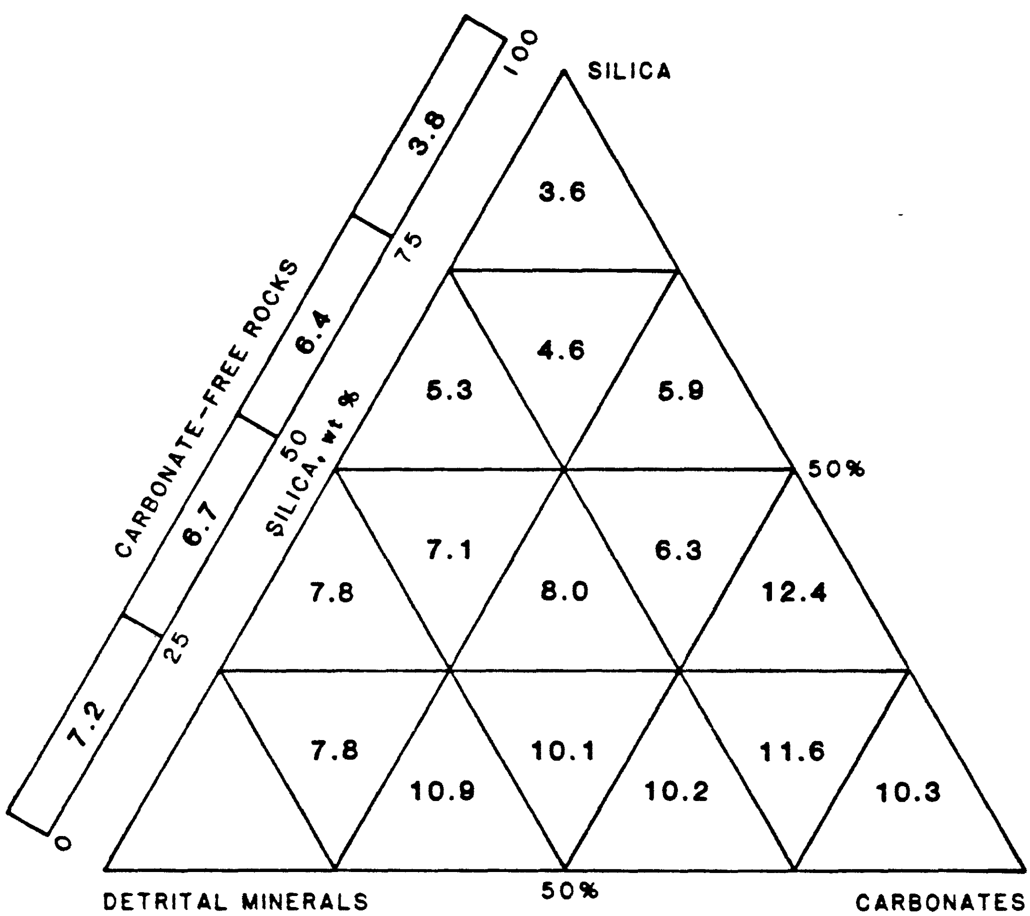


Figure 8. Diagram showing the average organic-matter abundance (TOC x 1.5) of individual beds with various sedimentary compositions in the Monterey Formation of the Santa Barbara coastal area. (Excludes rocks in which dolomite is the predominant carbonate mineral.) From Isaacs (1987).

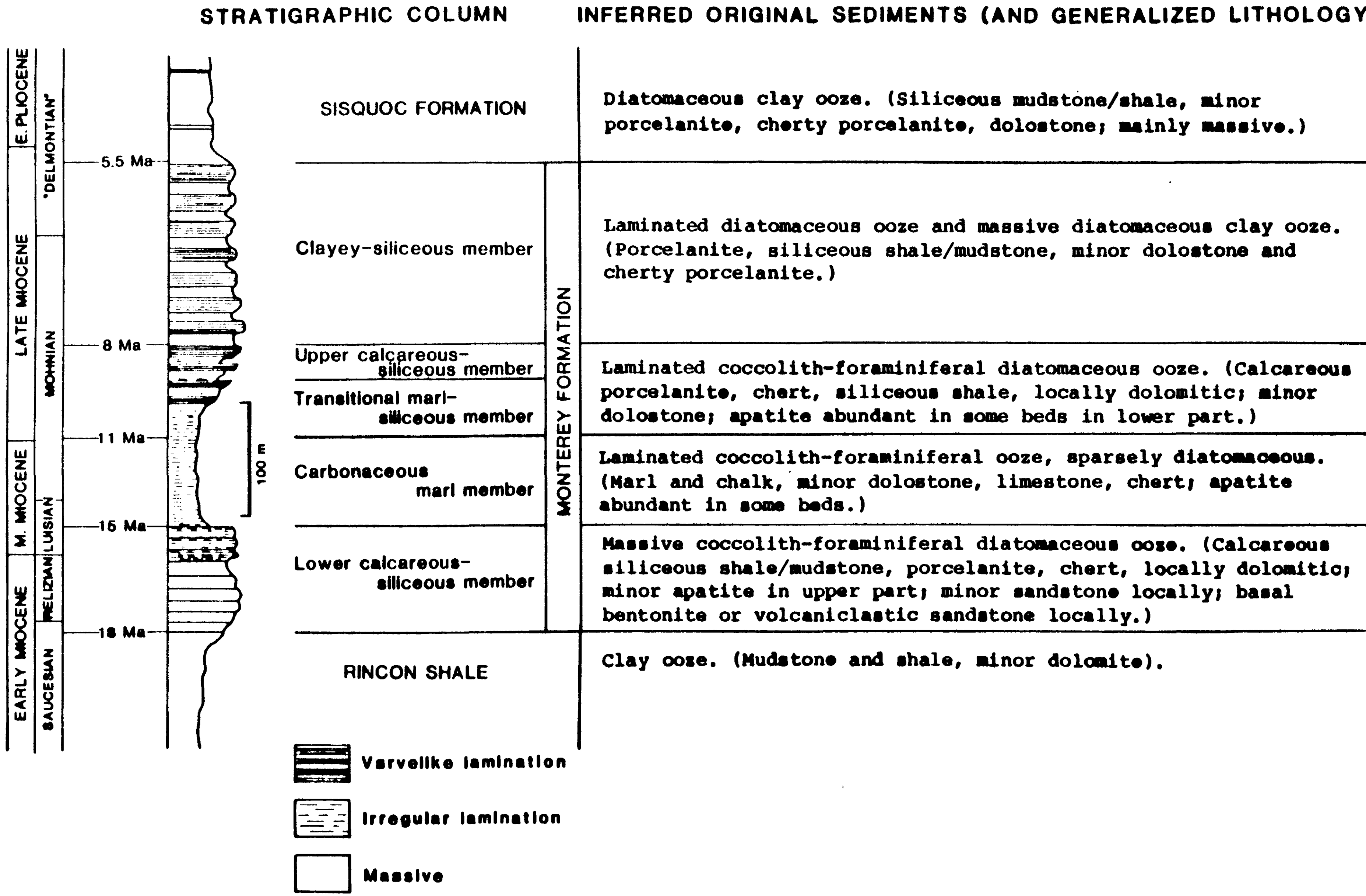


Figure 9. Generalized stratigraphic column of Miocene strata in the Santa Barbara coastal area, showing sedimentologic diversity in the Monterey Formation. From Isaacs (1985). Note that this column does not represent the the Naples section to scale; also, the interbedded rock types have been exaggerated for this figure - laminated and massive interbeds are commonly 0.5-2 m in thickness.

NAPLES SECTION (KG-1 to KG-13)

Purpose of sample set

The overall purpose of this sample set is to investigate and evaluate variations in the organic matter related to depositional and early diagenetic conditions. The geologic interest is not confined to petroleum sources but to the entire organic matter system: what the sources of the organic matter were, how much the sources varied among closely bedded strata and stratigraphically, what the causes of varying sources were, what conditions preserved organic matter, how preservational conditions varied among closely bedded strata and stratigraphically, what caused varying preservation, what surficial changes occurred in organic matter abundance and characteristics, what early diagenetic changes occurred in organic matter abundance and characteristics, what influence bacteria had, whether a subset of strata can be identified as the petroleum-source, if so what organic matter characteristics and environmental conditions typify this subset, etc.

Reasons for selection of Naples section

This section was selected for the cooperative study because (1) it is the least diagenetically advanced Monterey sequence on the Santa Barbara-Ventura coast available in fresh unweathered exposure; (2) the lithostratigraphic sequence there is almost completely and continuously exposed from the Rincon Shale underlying the Monterey through the Sisquoc Formation overlying the Monterey (Figure 9); and (3) it is the *only* Monterey sequence in the Santa Maria and Santa Barbara areas for which extensive biostratigraphy has been published.

Published material

Published material specifically on the Naples section includes **biostratigraphy** (Kleinpell, 1938, 1980; Wornhardt, 1972; Arends and Blake, 1986; Barron, 1986; DePaolo and Finger, 1991), **strontium isotope stratigraphy** (DePaolo and Finger, 1991), **lithostratigraphy** (Bramlette, 1946; Bohacs, 1990), **paleobathymetry** (Arends and Blake, 1986), **silica diagenesis** (Isaacs, 1981, 1982), and various field guides. Generalized material for the Santa Barbara-Ventura coastal area which covers the Naples section includes lithostratigraphy (Dibblee, 1950, 1966; Isaacs, 1981, 1984), paleobathymetry (Ingle, 1980, 1981), and long-term accumulation or **sedimentation rates** (Isaacs, 1984, 1985).

Ideas about paleogeographic position and paleobathymetry through time:

The entire Santa Barbara-Ventura coast area was interpreted by Hornafius (1985) as representing the eastward-facing paleoslope on the seaward side of a north-south basin during deposition of the Rincon Shale and lower part of the Monterey; subsequent rotation to the present relative position occurred mainly before 10 Ma (Figure 3). Since the rotation occurred as a structural block, Hornafius' interpretation is hereafter stated relative to presentday orientations for convenience. Bohacs (1990) viewed the overall section as equivalent to a lower or upper slope setting, with deposition in deep water under persistent low oxygen conditions but varied sediment supply rates and widely varying bottom energy levels. Based on evidence of slumping and widespread features showing soft-sediment deformation, other authorities (e.g. R.E. Garrison, personal communication, 1991) also regard the sequence as a slope deposit.

Rincon Shale (KG-3, KG-9):

Paleogeography and paleobathymetry (see also Figure 10): The area in which the Naples section is located was interpreted by Edwards (1971, 1972) as representing a deep (1500-2000 m) northward-facing paleoslope of an east-west trending basin. Ingle (1980) showed the upper part of the Rincon in the central Santa Barbara coastal area as a slope deposit at about 1000-1200 m depths. Ingle (in Global Geochemistry, 1985) later showed the Rincon Shale at Naples as a sequence deepening from very shallow depths to about 400-700 m at the top of the formation. Hornafius (1991) argued that the area was a southward-facing paleoslope because distinctive southerly derived sands found south of Naples in both the South Elwood and Hondo offshore fields have not been reported in coastal outcrops.

Brief lithologic description (for the Santa Barbara coastal area as a whole): the Rincon Shale is mainly mudstone with minor dolomite beds. The mudstone is mainly massive, generally contains calcareous microfossils and fish debris, locally contains apatite pellets (e.g. KG-3), and is virtually identical to the lower part of the Monterey in core samples except for much more abundant detritus. Organic matter abundance (TOC x 1.5) ranges from 2 to 10% (av. 4.5%).

Monterey Formation - lower calcareous-siliceous member (KG-10, KG-11):

Paleogeography and paleobathymetry (see also Figure 10): In the central Santa Barbara coastal area generally, Ingle (1980) regarded this lower part of the Monterey as a slope deposit deepening from about 1200 m to about 1400 m, and Isaacs (1984) inferred from that depth and the characteristic layering that the basin was not silled. In the Naples section, this part of the Monterey was interpreted by Ingle (in Global Geochemistry, 1985) as a sequence deepening from about 400-700 m to about 700-1000 m. Arends and Blake (1986) interpreted this part of the Monterey as a sequence deepening from about 1000 m to about 1150 m. Bohacs (1990) interpreted the sequence as a land-influenced slope setting deposit with some minor mass-flow deposits (turbidites, slump/slide zones etc.) including a breccia with burrowed clasts transported downslope.

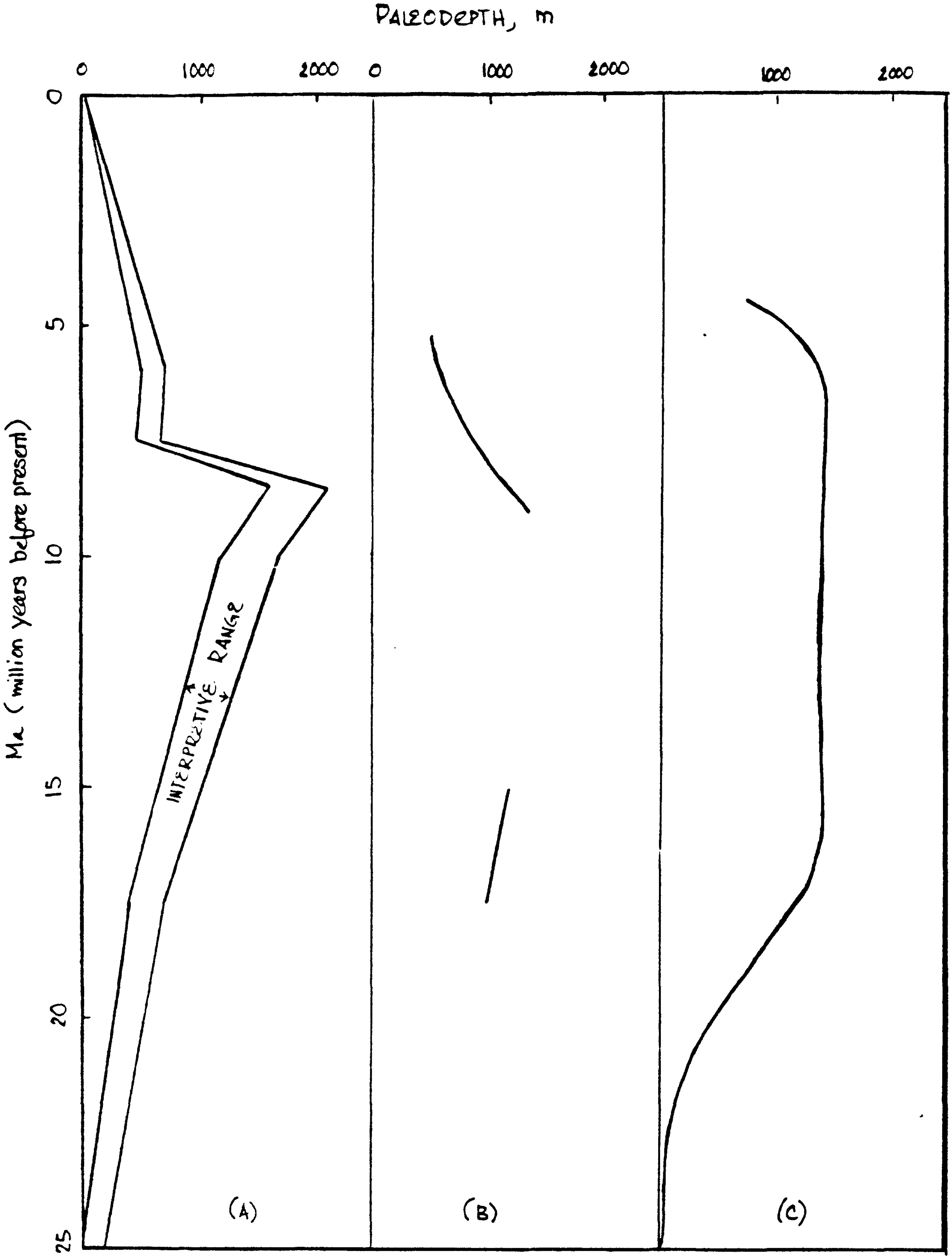


Figure 10. Paleobathymetric curves for the central Santa Barbara coastal area and Naples section. (a) Naples section from Ingle (in Global Geochemistry, 1985); (b) Naples section from Arends and Blake (1986); (c) central Santa Barbara coastal area from Ingle (1980). Note that most depths fall within the upper middle bathyal zone, corresponding to the broad range between 500 m and 1500 m, so that major stratigraphic changes in depth could occur without being easy to decipher (cf. Figure 4). See also discussion under **paleodepth.**

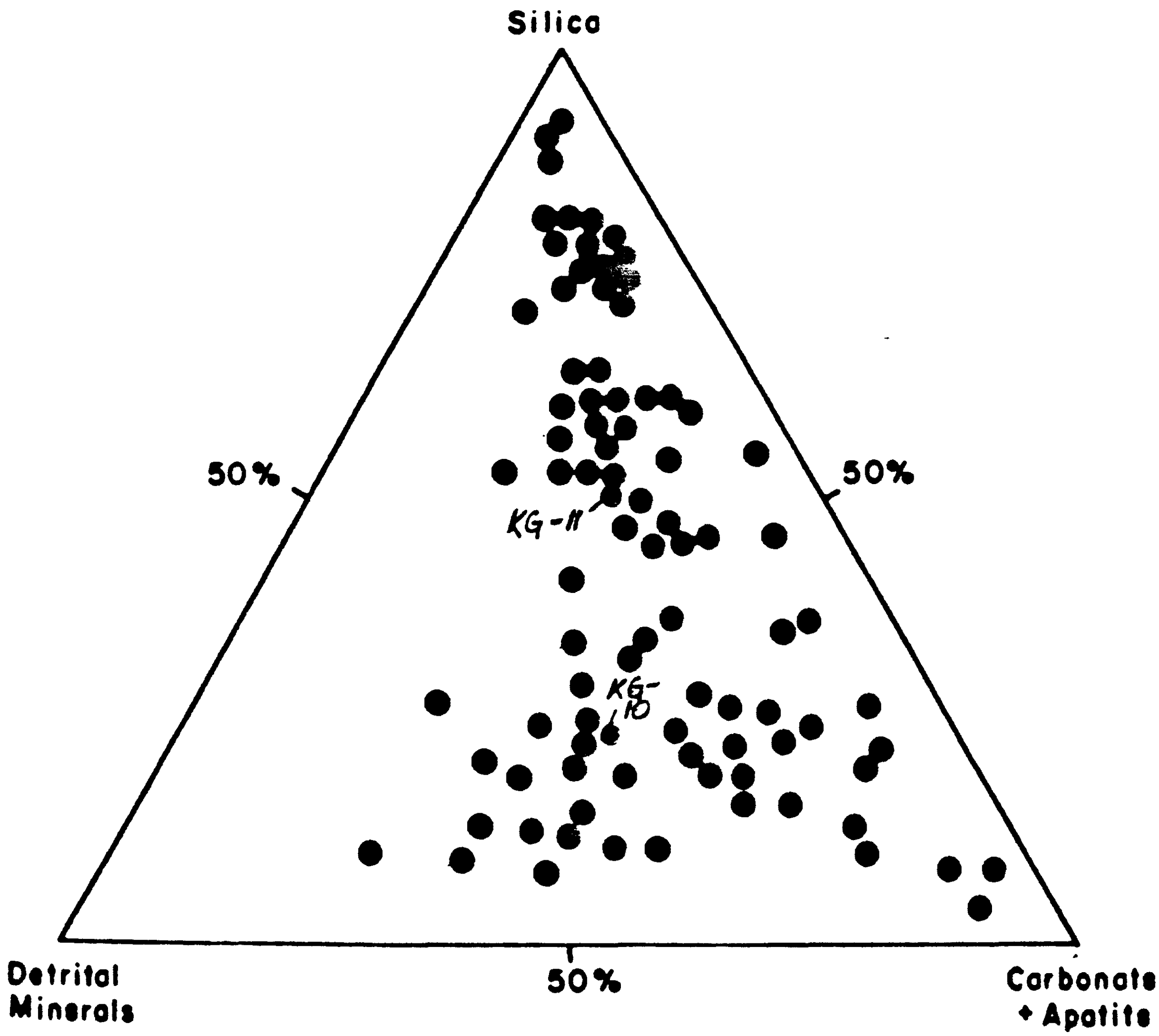


Figure 11. Preliminary compilation of sedimentary compositions among individual beds in the lower calcareous-siliceous member of the Monterey Formation, Santa Barbara coastal area, showing KG samples. See Figure 5 for explanation of points. Modified from Isaacs (1981).

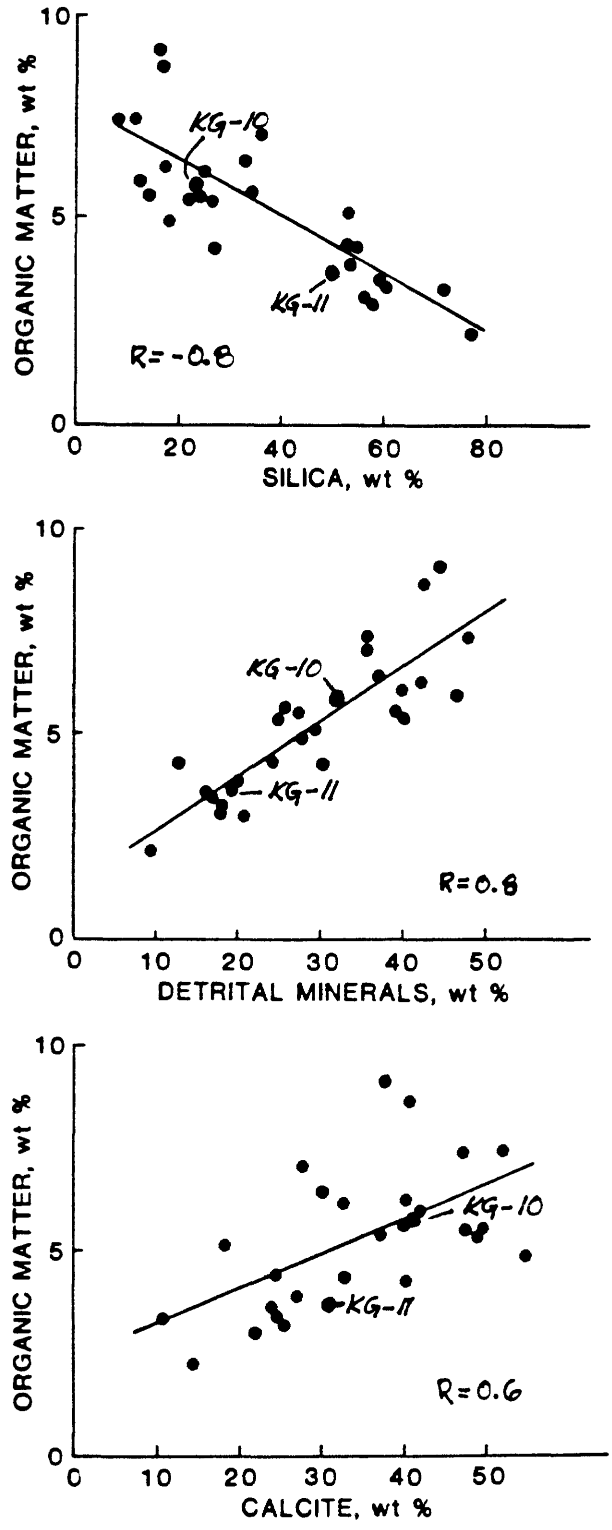


Figure 12. Correlations between the abundances of organic matter (TOC x 1.5) and major sedimentary components in individual beds of the early Miocene lower calcareous-siliceous member of the Monterey Formation, Santa Barbara coastal area (from Isaacs, 1984). For KG-10 and KG-11, inorganic data is from *Preliminary Rock Sample Data* (Chapter C, this report) and TOC values from B. J. Katz (written communication, 1990).

Brief lithologic description (for the Santa Barbara coastal area as a whole): this member is mainly composed of strata with a wide abundance range of calcite, detritus, and biogenic silica (Figure 11). Layering is massive (or very faintly and locally layered) in the lower part (KG-10, KG-11), and distinctly but irregularly layered in the upper part. Organic matter abundance (TOC x 1.5) ranges from 2 to 18% (av 7%) and is inversely proportional to silica, proportional to detritus, and more-or-less proportional to calcite (Figure 12).

Monterey Formation - carbonaceous marl member (KG-1, KG-2, KG-4):

Paleogeography and paleobathymetry (see also Figure 10): In the central Santa Barbara coastal area generally, Ingle (1980) regarded this part of the Monterey as an anaerobic basin deposit at paleodepths of about 1400 m, and Isaacs (1984) suggested that layering differences compared to older strata suggested a deepening of the oxygen-minimum zone or the formation of a sill within the oxygen-minimum zone. In the Naples section, this part of the Monterey was interpreted by Ingle (in Global Geochemistry, 1985) as representing a deepening sequence from about 700-1000 m in the lower part (including KG-1, KG-2, and KG-4) to about 1600-2100 m at the top. Arends and Blake (1986) place this part of the Naples section at about 1150 m depth including a hiatus of 5 million years. Garrison and others (1987) state that deposition occurred on a slope, citing Isaacs. This part of the Monterey at Naples was interpreted by Bohacs (1990) as representing a quiet slow pelagic deposit (with little land influence), and by Hornafius (1991) as representing a slightly elevated "bank top" deposit where phosphatic lag deposits were formed by repeated scouring by bottom currents.

Brief lithologic description (for the Santa Barbara coastal area as a whole): this member is mainly composed of highly calcareous shales (and some mudstones) with minor apatite and biogenic silica (Figure 13); some dolomite layers and highly siliceous layers are also present, as well as some highly phosphatic lag deposits thought to represent periods of nondeposition. Strata are commonly laminated but laminations are irregular and discontinuous, not varve-like. Organic matter (TOC x 1.5) is very abundant, in the range 2 to 24% (av 13%), but much less abundant in the rare dolostones and cherts.

Monterey Formation - transitional and upper calcareous-siliceous member (KG-5, KG-6):

Paleogeography and paleobathymetry (see also Figure 10): In the central Santa Barbara coastal area generally, Ingle (1980) regarded this part of the Monterey as an anaerobic basin deposit at paleodepths of about 1400 m, and Isaacs (1984) suggested cycles of weak oxygen-minimum coupled with low productivity alternating with cyles of strong oxygen-minimum coupled with high productivity. This part of the Naples section was interpreted by Ingle (in Global Geochemistry, 1985) as a rapidly shallowing sequence from about 1600-2100 m in the lower part to about 450-650 m at the top, by Arends and Blake (1986) as a sequence shallowing from about 1300 m to about 750 m, and by Bohacs (1990) as representing a hemipelagic (land-influenced) deposit.

Brief lithologic description (for the Santa Barbara coastal area as a whole): these two members are composed of strata with a wide gradational abundance range of calcite, detritus, and biogenic silica (Figure 14); in the lower member, highly calcareous shale with apatite is also common. Layering varies from vaguely laminated (in silica-poor rocks) to varve-like laminated (in silica-rich rocks). Organic matter (TOC x 1.5) ranges from 2 to 20% (av 10% in the transitional member, 6% in the upper calcareous-siliceous member) and is somewhat variable but lowest in silica-rich rocks (cf. Figure 12).

Monterey Formation - clayey-siliceous member (KG-7, KG-8):

Paleogeography and paleobathymetry (see also Figure 10): In the central Santa Barbara coastal area generally, Ingle (1980) regarded this part of the Monterey as an anaerobic basin deposit at paleodepths of about 1400 m, and Isaacs (1984) suggested cycles of weak oxygen-minimum coupled with low productivity alternating with cycles of strong oxygen-minimum coupled with high productivity. This part of the Naples section was interpreted by Ingle (in Global Geochemistry, 1985) as representing deposition at about 500-700 m depth, and by Arends and Blake (1986) as representing a sequence shallowing from about 700 m to about 600 m. The absence of calcareous microfossils (a common feature statewide during this time period) is attributed to calcite **dissolution** by highly corrosive bottom water.

Brief lithologic description (for the Santa Barbara coastal area as a whole): in contrast to all underlying strata, this member contains virtually no carbonate (generally <0.1%) except dolomite in discrete layers and nodules probably representing about 5% of strata; more common strata represent a wide gradational range of biogenic silica and detritus (see histogram on left side in Figure 5). Layering varies from distinctly massive (in silica-poor rocks) to varve-like laminated (in silica-rich rocks). Organic matter (TOC x 1.5) ranges from 2 to 12% (av 6%) and is lowest in silica-rich laminated rocks (Figure 15).

Sisquoc Formation (KG-12, KG-13):

Paleogeography and paleobathymetry (see also Figure 10): In the central Santa Barbara coastal area generally, Ingle (1980) regarded the lower part of the Sisquoc Formation as an anaerobic basin deposit at paleodepths of about 1400 m shallowing to a slope deposit at 750 m. The Sisquoc Formation at Naples was interpreted by Ingle (in Global Geochemistry, 1985) as representing a sequence shallowing from about 500-700 m, and by Arends and Blake (1986) as a sequence shallowing from about 500-600 m.

Brief lithologic description (for the Santa Barbara coastal area as a whole): this formation is composed of siliceous shale and mudstone having a fairly narrow range of biogenic silica and detritus abundance, though the range varies from place to place. Also present are dolomite layers or nodules, probably representing about 5% of strata. Layering is in part very distinctly laminated, in part massive. Organic matter is fairly constant in the range 1-3%.

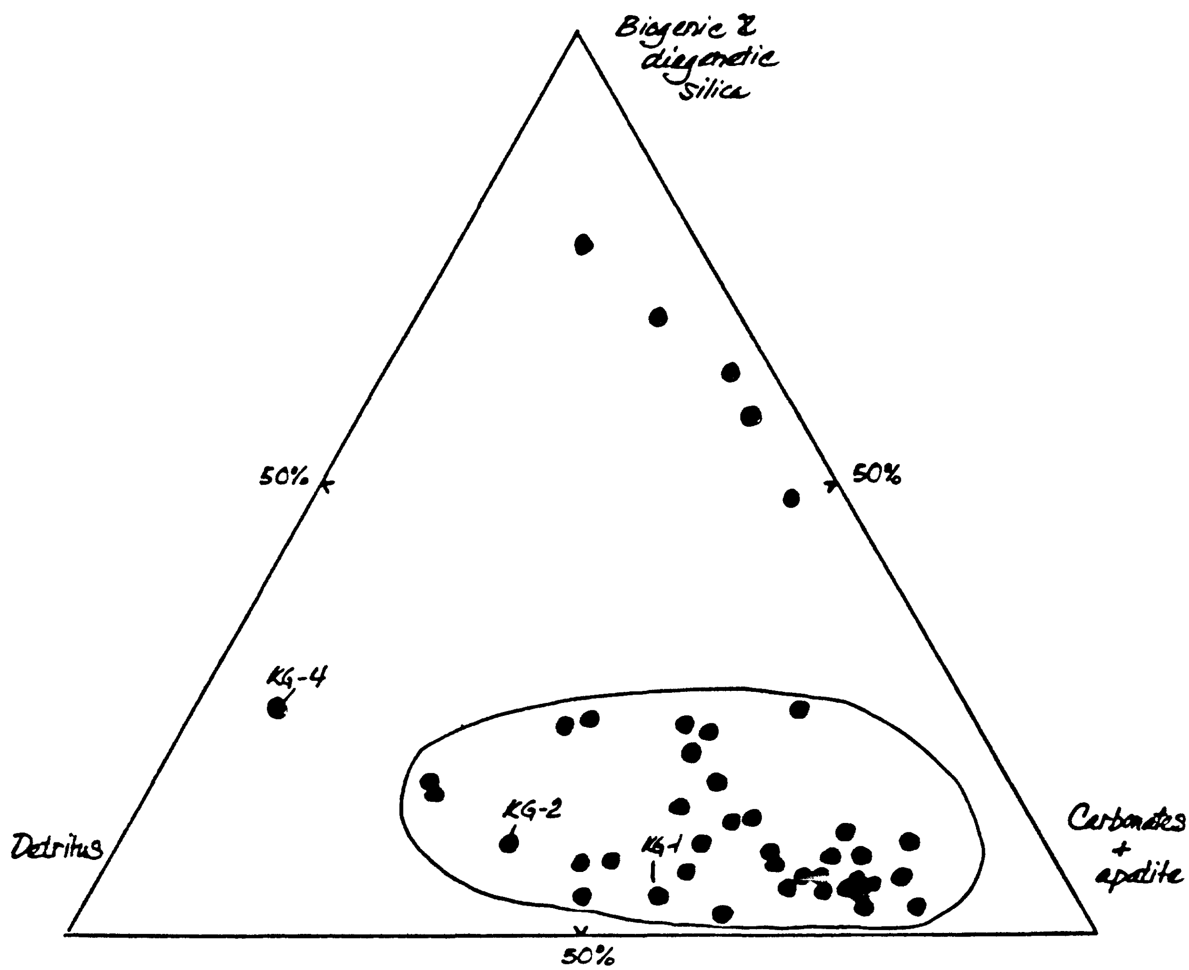


Figure 13. Preliminary compilation of sedimentary compositions among individual beds in the carbonaceous marl member of the Monterey Formation, Santa Barbara coastal area, showing KG samples. See Figure 5 for explanation of points.

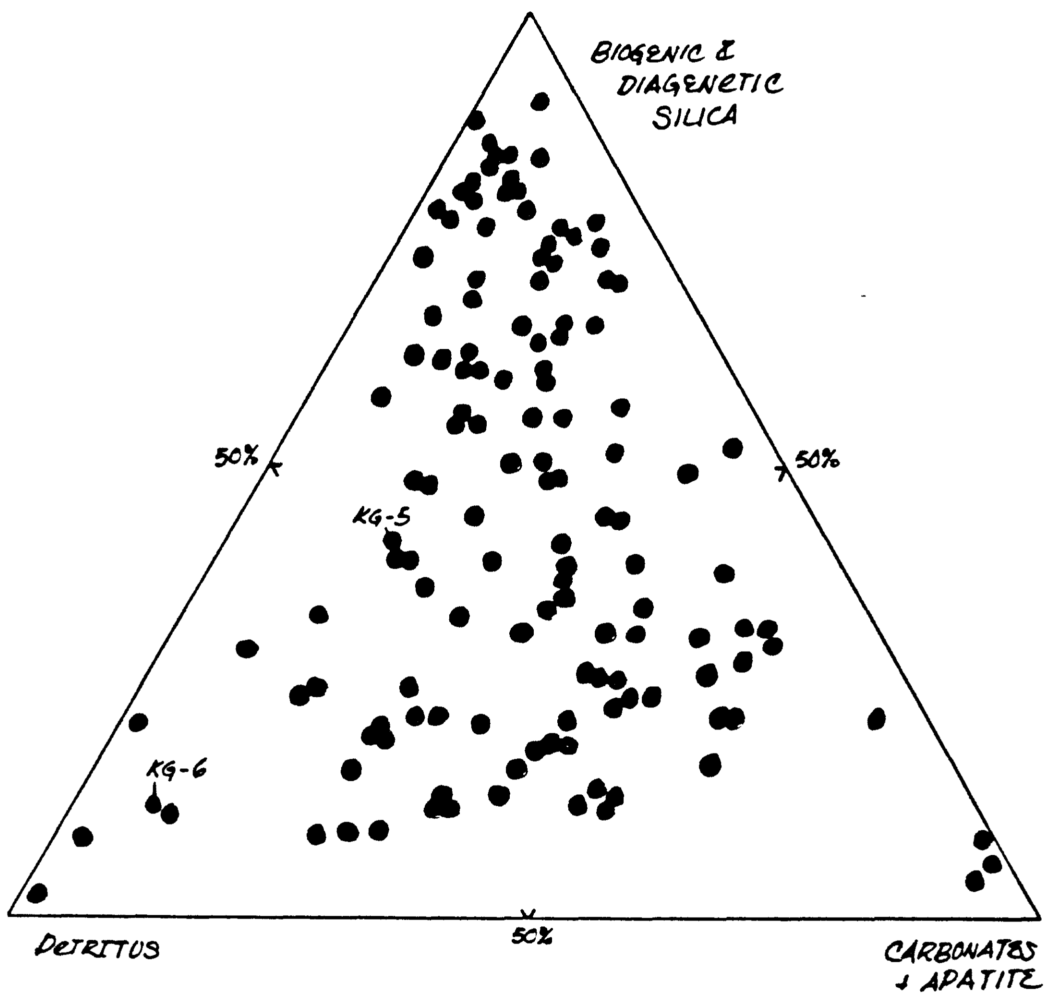
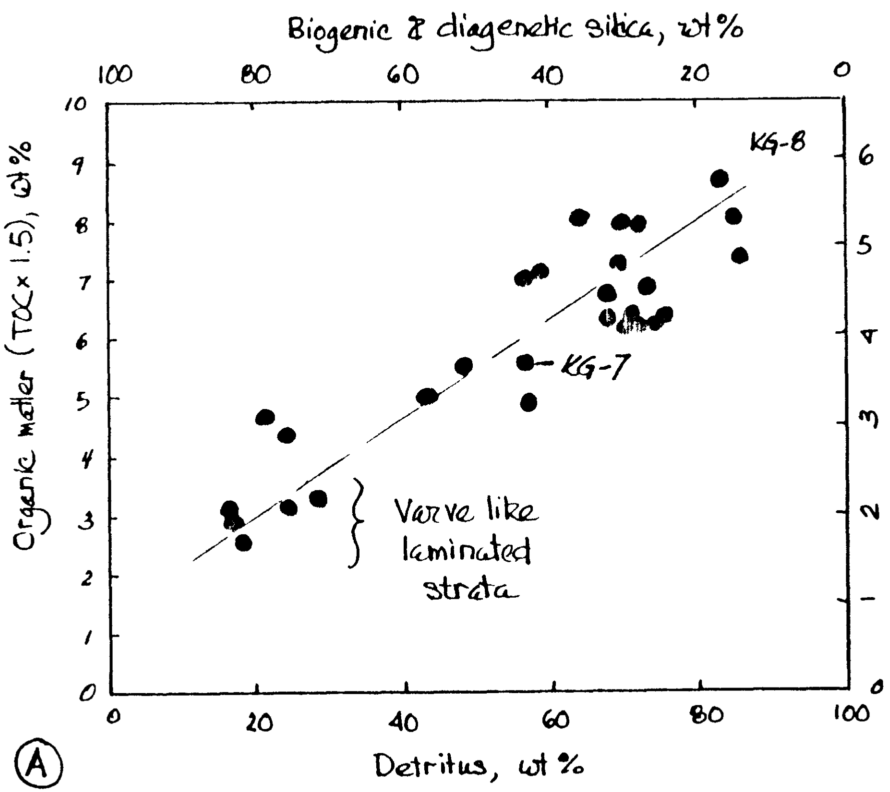
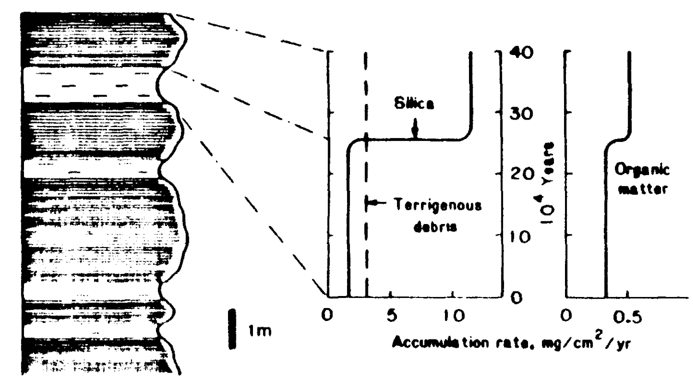


Figure 14. Preliminary compilation of sedimentary compositions among individual beds in the upper calcareous-siliceous and transitional-marl-siliceous members of the Monterey Formation, Santa Barbara and Ventura coastal areas, showing KG samples. See Figure 5 for explanation of points.





B

	Varvelike	Massive
Abundance, weight %		
Silica	76	32
Terrigenous debris	21	62
Organic matter	3.4	6.4
Accumulation rate, mg/cm^2/yr		
Silica	11	1.6
Terrigenous debris	3.1	3.1
Organic matter	0.5	0.3
Total	15	5.0

Figure 15. (A) Correlation between the abundances of organic matter, silica, and detritus in individual beds of the clayey-siliceous member of the Monterey Formation, Santa Barbara coastal area, showing KG samples. For KG-7 and KG-8, inorganic data is from *Preliminary Rock Sample Data* (Chapter C, this report) and TOC values from B. J. Katz (written communication, 1990). (B) Detail of representative interbedded varvelike and massive beds in the clayey-siliceous member, showing layering characteristics, average sedimentary composition, and short-term accumulation-rate model. Modified from Isaacs (1985).

MATURATION OF MONTEREY ORGANIC MATTER

A widespread view is that the maturity of Monterey organic matter is hard to evaluate, that Rock-Eval and TAI results are problematic, that vitrinite is too sparse to be useful, that variation in O/C and H/C ratios is small, etc. However, there is little data in the public domain on any of these relations - or on biomarker maturity parameters, or on how these might be affected by lithology.

LIONS HEAD SECTION (KG-14 to KG-20, KG-22, KG-24)

Purpose of sample set

The overall purpose of this sample set is to investigate and evaluate (1) changes in the organic matter due to increased thermal exposure and (2) variations in organic matter maturation characteristics related to varying lithology of specific samples and varying environmental conditions through time.

Reasons for selection of Lions Head section

Ideally, a complete section would have been sampled that was exactly comparable to the Naples section but more thermally mature. Although such sections exist along the Santa Barbara coast, they are (1) creek sections and thus more weathered than desirable; and (2) not the most mature possible choices in the surface.

The Lions Head section was selected for the cooperative study because (1) it is the most mature (organically speaking) surface section in the area, as based on Giger and Schaffner (1981) and unpublished rumor; and (2) it is available in fresh unweathered exposure. An additional advantage is that some **biostratigraphy** and **chronostratigraphy** are available or in progress for the section. Disadvantages are that the section (1) is equivalent to only part of the Monterey sequence at Naples (Figure 16), and does not include the Sisquoc Formation, the upper Monterey sequence (KG-7, KG-8), or the Rincon Shale (KG-3, KG-9); and (2) most likely was deposited in a basin separate from the deposit at Naples, thus introducing another set of variables.

Published material

Published material specifically on the Lions Head section includes partial **biostratigraphy** (Woodring and Bramlette, 1950; Dunham and Blake, 1987; White, 1989), **lithostratigraphy** and detailed measured sections (Woodring and Bramlette, 1950; Grivetti, 1982; Dunham and Blake, 1987), sedimentology (Pisciotto, 1981), reservoir and fracture

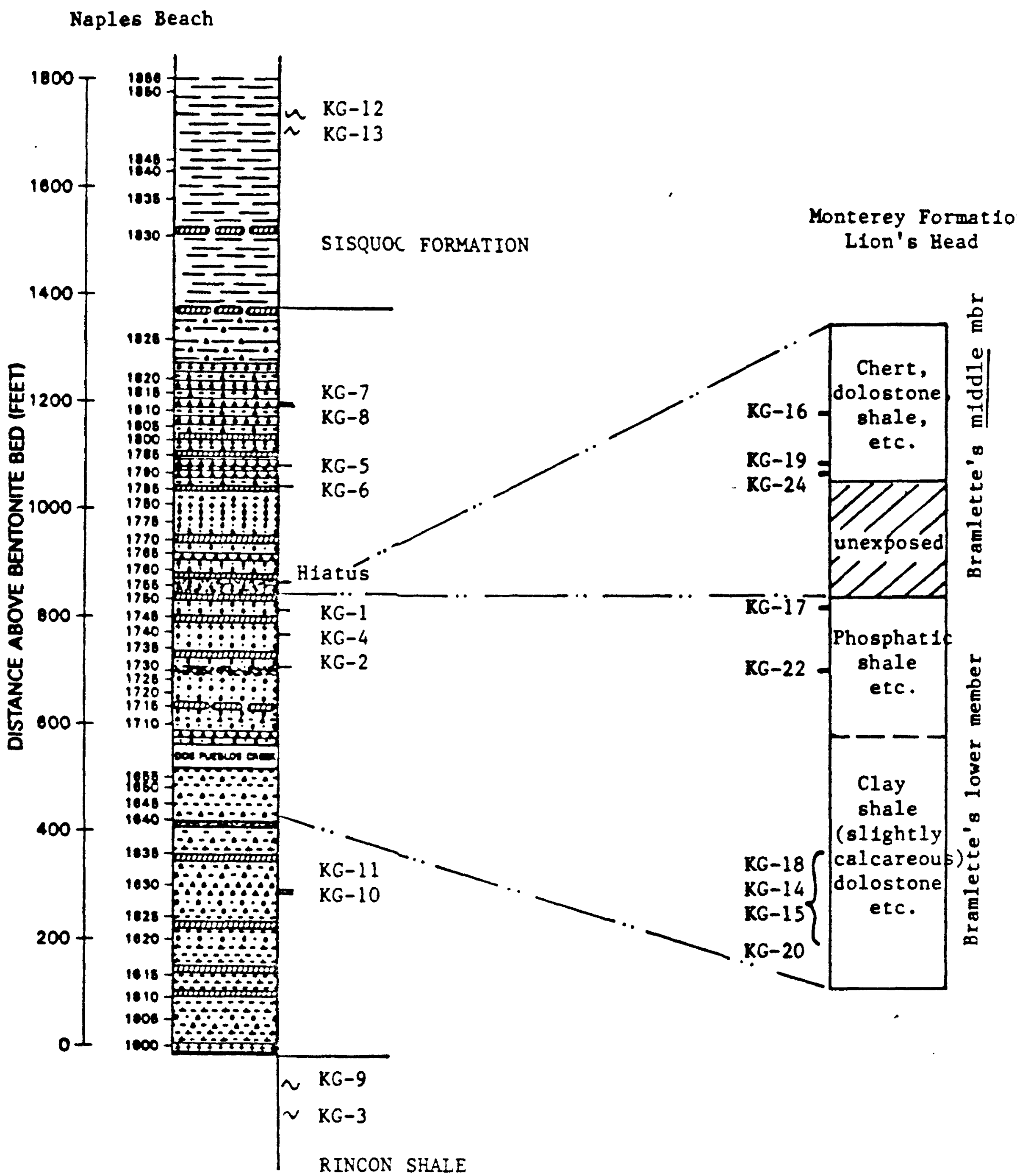


Figure 16. Preliminary biostratigraphic correlation of the Naples and Lions Head sections, showing KG samples. Compiled from Arends and Blake (1986), Dunham and Blake (1986), and White (1989); see also Chapter D, this report. Naples stratigraphic section reprinted from Arends and Blake (1986) by permission.

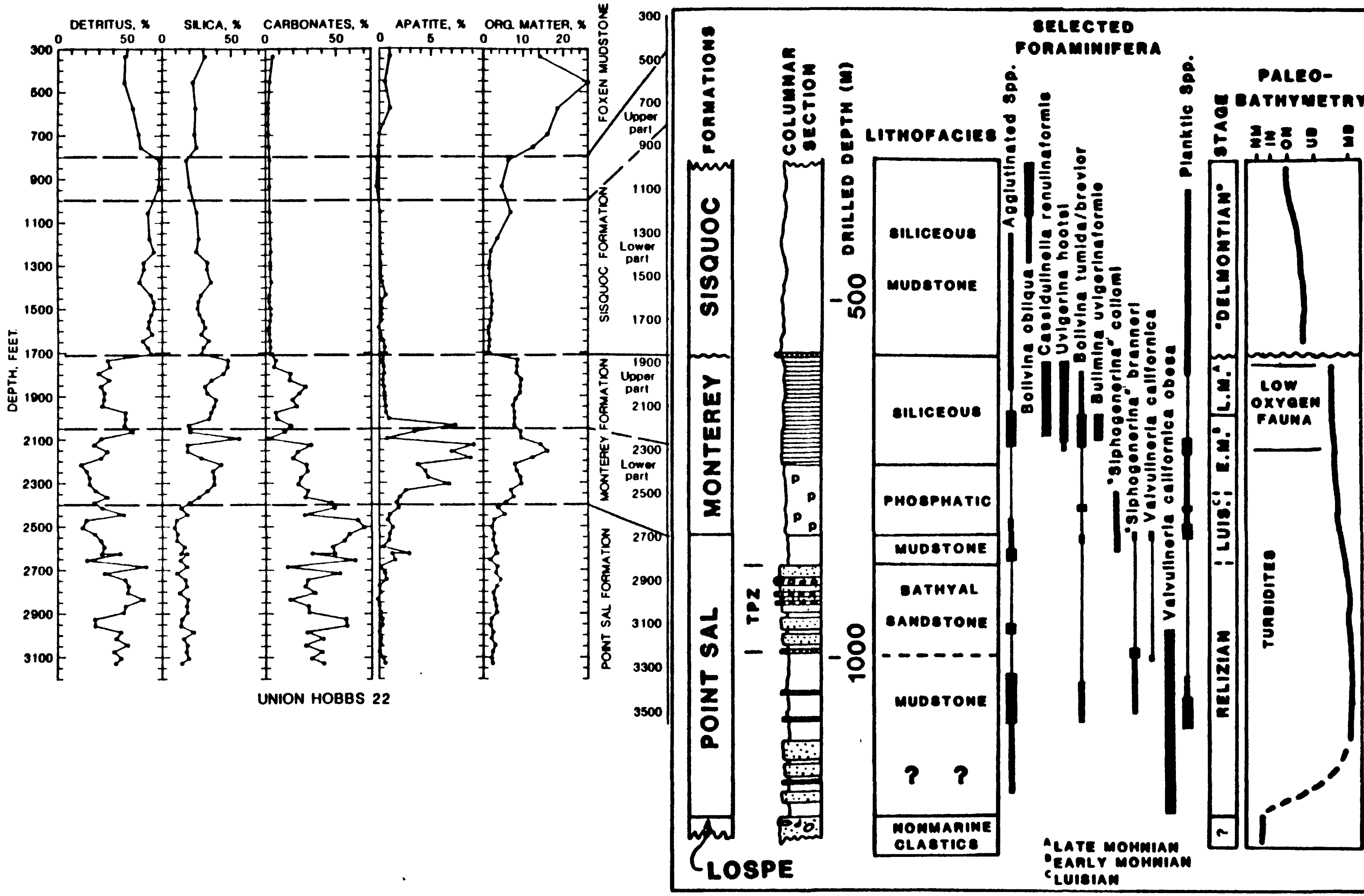


Figure 17. Paleobathymetry from the Union Newlove 51 well (right; Lagoe, 1987) compared to the compositional sequence based on well cuttings from the Union Hobbs 22 well (left; Isaacs and others, 1990), Orcutt field, onshore Santa Maria basin. The two wells are about 1 km apart. The figure on the Union Newlove 51 well (right) is reprinted from Lagoe (1987) by permission.

analysis (Grivetti, 1982; Dunham and Blake, 1987), and field guides (Pisciotto, 1981; Dunham and Blake, 1987; MacKinnon, 1989).

Ideas about paleogeographic position and paleobathymetry through time

Very little published paleogeographic or paleobathymetric study specifically relates to the Lions Head section, but there is some information on nearby sections. The formation of the Santa Maria basin has very recently been dated at about 17.7 Ma, with non-marine deposition through about 17.4 Ma in certain areas, including a section about 5 km north of the Lions Head section (Stanley and others, 1991; and unpublished data). Rapid subsidence to bathyal marine conditions began about 17.4 Ma, and bathyal marine deposits were widespread in the Santa Maria basin thereafter during the entire interval of deposition represented by Monterey strata at Lions Head. Based on the only published paleobathymetry in the area, for the Union Newlove 51 well in the Orcutt field about 20 km east of Lions Head (Lagoe, 1987), the initial deep-water phase (generally called the Point Sal Formation) up to about 16 Ma is represented by deep-water turbiditic sandstones deposited at middle bathyal depths (500-1500 m) in a fan and base-of-slope setting with a source area to the north. Subsequent deposition of the Monterey Formation in the Union Newlove 51 well at Orcutt was interpreted as representing deposition at middle bathyal (500-1500 m) paleodepths shallowing upsequence to nearly upper bathyal (150-500 m) paleodepths, with a low-oxygen fauna indicated only *after* deposition of the highly phosphatic rocks, and overlying Sisquoc strata are interpreted as deposited at outer neritic (50-150 m) paleodepths (Lagoe, 1987). The compositional sequence in the Orcutt field is shown in Figure 17, and Lagoe's (1987) low-oxygen fauna occurs in the upper part of the Monterey Formation as shown in that figure.

The paleogeomorphic position of the Lions Head section is uncertain. According to one authority who has been at the locality numerous times (R. E. Garrison, personal communication, 1991), there are not even features that would serve as a starting-point for exploring the answer to this question.

Monterey Formation, Lower member of Woodring and Bramlette (1950) - lower set (KG-14, KG-15, KG-18, KG-20):

Paleobathymetry: upper to middle bathyal (≈150-1500 m) paleodepth, according to both Dunham and Blake (1987) for the member as a whole and M.L. Cotton (Chapter C, this report) for KG-14, KG-15, and KG-20.

Brief lithologic description: this lower part of the Lions Head section consists mainly of moderately siliceous shale (KG-15) and mudstone, clay shale and mudstone (KG-14), etc. (all somewhat calcareous and in places slightly phosphatic) together with prominent bedded and nodular dolostones (KG-18). This part of the section includes rocks with prominent white bands (KG-20); although often described as phosphatic shale, these generally contain $<1\%$ apatite but sometimes include concentrations of foraminifera. Numerous thin sandstone beds are interpreted as turbidites, and one conglomerate bed containing reworked shallow-marine pelecypod fossils as a debris flow caused by downslope slumping (Woodring and Bramlette, 1950; Dunham and Blake, 1987).

Monterey Formation, Lower member of Woodring and Bramlette (1950) - middle set (KG-17, KG-22):

Paleobathymetry: upper to middle bathyal (150-1500 m) paleodepth, according to both Dunham and Blake (1987) for the member as a whole and M. L. Cotton (Chapter C, this report) for KG-17 and KG-22.

Brief lithologic description: this part of the section is lithologically diverse, including chert, porcelanite, phosphatic calcareous shale (KG-17), calcareous shale and mudstone (KG-22), dolostone, etc. Some phosphorites present are interpreted as lag deposits caused by erosional **winnowing** of originally deposited mud and microfossil debris; these represent periods of non-deposition or very slow deposition (Dunham and Blake, 1987).

Monterey Formation, Lower member of Woodring and Bramlette (1950) - upper cooperative study set (KG-16, KG-19, KG-24):

Paleobathymetry: no information according to either Dunham and Blake (1987) for the member as a whole or M.L. Cotton (Chapter C, this report) for the samples in this study.

Brief lithologic description: this part of the section is lithologically diverse, consisting mainly of thin-bedded siliceous shale (KG-24), chert, and dolomite (KG-19) together with many gradational rock types (KG-16). Most prominently exposed here are highly folded black glassy cherts (Dunham and Blake, 1987).

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