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David Donegan for the degree of Master of Science

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Title: MODERN AND ANCIENT MARINE RHYTHMITES FROM THE SEA OF CORTEZ AND CALIFORNIA CONTINENTAL BORDERLAND: A SEDIMENTOLOGICAL STUDY

Abstract approved: Redacted for privacy

(Dr. Hans Schrader)

Laminated marine sediments provide a unique high resolution record of the oceanographic and climatological conditions affecting the waters overlying the sediments at the time of deposition. Occurrences of marine laminae, or varves, have been described from silled basins in various localities i.e. Saanich Inlet (British Columbia), Santa Barbara Basin, Black Sea, and Orca Basin (Gulf of Mexico); and from several non-basinal continental margin regions i.e. the Gulf of California, Northwest Indian Ocean, off Southwest Africa, and off Peru. Of the latter variety, the laminated slope sediments in the central and southern Gulf of California may be the best example of well preserved, nearly continuous laminations, covering long periods of time.

By understanding the varves and the processes that lead to their formation one can better understand the laminated deposits in the

geologic past as well as unravel the climatological significance of recent laminated sediments.

The first section of this thesis is an attempt to characterize the sedimentation and determine the nature of the laminae in the central Gulf of California. Fluctuations in the opal microfloral assemblage, texture, chemical and trace metal content, and mineralogy were documented between light and dark laminae, from two short sequences, in two cores from the central Gulf. The fluctuations were then interpreted with respect to the prevailing climatic regime.

The laminated sediments, in the Gulf, are dominated by diatoms. The light laminae can be distinguished from the dark by assemblage variations of the diatom and silicoflagellate populations as well as by having a higher relative proportion of diatoms. The dark laminae contain more terrigenous material and are enhanced in Cu, Mn, Fe, Ni, Zn, Ca, K, Al, and organic carbon compared to the light laminae. Preliminary interpretations suggest the light laminae are deposited during the dry winter season of northwesterly winds and the dark laminae are deposited during the wet summer season of southeasterly winds.

The second part of the thesis is a comparison of the modern laminae from the Gulf of California (representing deposition along continental slopes where the oxygen minimum zone intersects the sediment water interface) and the laminae from the Santa Barbara Basin (representing deposition in an anoxic basin) with the laminated shales of the upper siliceous member of the Miocene Monterey Formation. The laminae from the Gulf sediments, the Santa Barbara Basin sediments and the Monterey Shale were visually analyzed for the composition and amount of terrigenous and biogenous components and general sedimentological features. Based on these comparisons, the Gulf of California provides a better modern analogue to the Monterey Formation than does the Santa Barbara Basin.

MODERN AND ANCIENT MARINE RHYTHMITES FROM THE SEA OF CORTEZ AND CALIFORNIA CONTINENTAL BORDERLAND: A SEDIMENTOLOGICAL STUDY

by

David P. Donegan

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in charge of major

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Dean of School of Oceanography

Redacted for privacy

Dean of Graduate School

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Typed by Laina R. Hardenburger for David Donegan

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Finally, I would like to thank the people who were willing to discuss things outside of the realms of oceanography and geology and would take the time to go to the mountains or to the coast. These are the people who made my stay at Oregon State profitable from an educational and personal perspective. Although their contributions to this thesis were less direct, they were no less instrumental in the completion of the work. The list of names is too long to mention (which is good) but they know who they are. I would particularly like to thank Todd (the blockhead) and Racq for some of the best excursions in memory. And to the Beanery and Squirrels, thanks for being there when I needed you most. The work was supported by the National Science Foundation, grant ATM 7919458-01.

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BIOGENIC AND ABIOGENIC COMPONENTS OF LAMINATED HEMIPELAGIC SEDIMENTS IN THE CENTRAL GULF OF CALIFORNIA

ABSTRACT

Alternating light and dark submillimeter to millimeter thick rhythmites are found along the slopes of the central and southern Gulf of California where the oxygen minimum zone intersects the sediment water interface. Two short intervals of distinct alternations were sampled lamina by lamina from two cores in the central Gulf. Both cores are from the slope of the Guaymas Basin, one core is from the mainland side, the other core is from the Baja side. Each lamina sample was analyzed for its opal microfloral assemblage, textural character, trace metal and bulk chemical (Cu, Mn, Fe, Ni, Zn, Ca, K, Al, SiO_2 and C-org) content, and mineralogy.

On both sides of the Gulf the light laminae contain more diatom frustules (up to 90%) and less terrigenous clay and organic material than the dark laminae. Texturally, the sediment is predominantly silt sized. The dark laminae contain an added component of terrigenous material which is primarily clay sized (<4μm) on the mainland side and fine silt sized (4 to 20μm) on the Baja side. All chemical species analyzed, except SiO_2, are always higher in the dark laminae and show a high positive correlation to organic carbon. SiO_2 is higher in the light laminae and shows a high negative correlation to organic carbon. Non-opaline material is a secondary constituent, primarily consisting of quartz, plagioclase, and calcite. The <2 μm fraction is dominated by non-clay minerals, particularly opal and

quartz; smectite, illite, and kaolinite are present in the laminae from the mainland side.

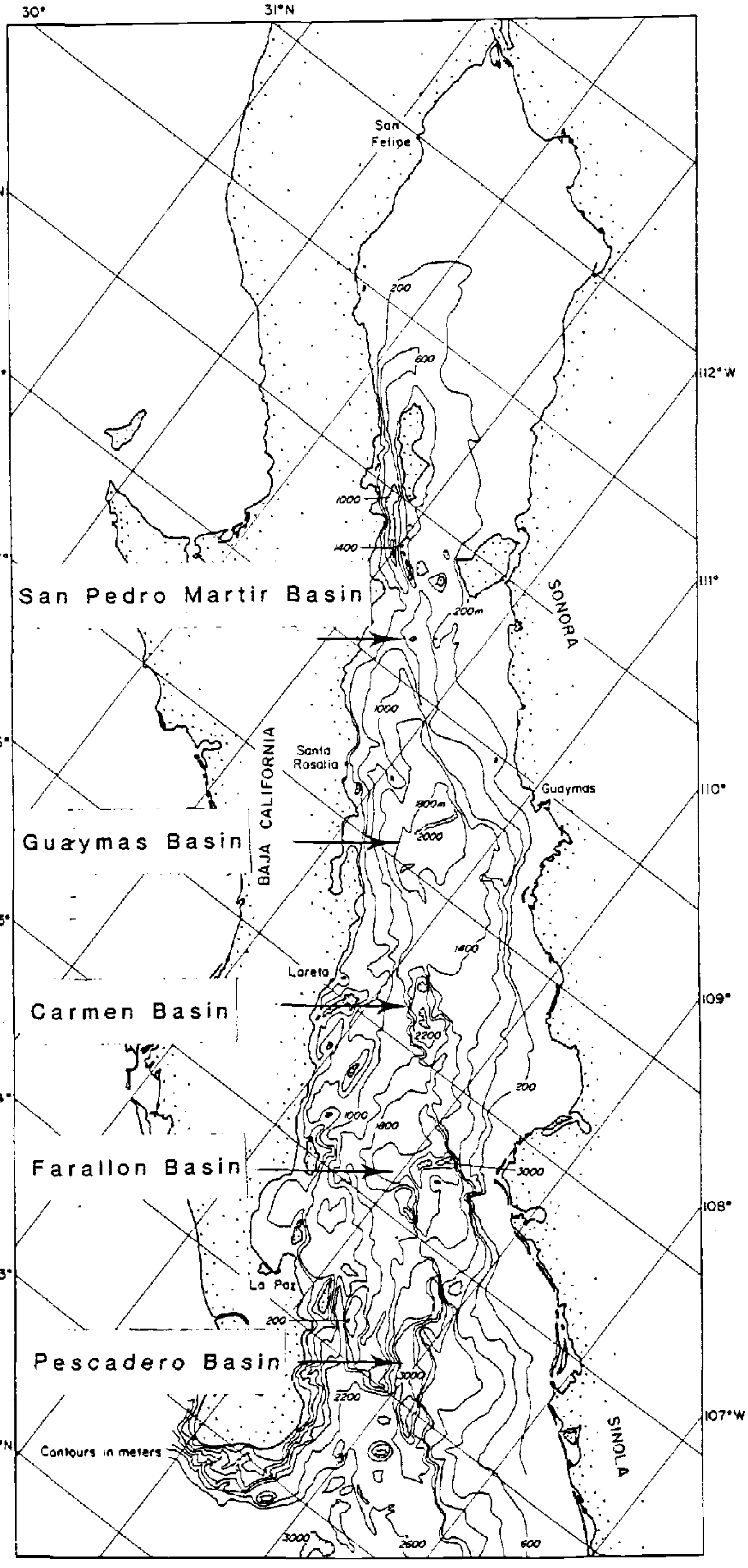
A model proposed for laminae formation in the central Gulf suggests that, in general, on both sides of the Gulf the light laminae represent the dry winter season of northwesterly winds. The dark laminae represent the wet summer season of southeasterly winds.

INTRODUCTION

The Gulf of California, or Sea of Cortez, is a long, narrow evaporative basin closed on three sides and in open communication with the Pacific Ocean at its southern end (Figure 1). The Gulf is approximately 1000 km long and averages 150 km wide. The structural trough continues northward for 200 km with the Imperial Valley being separated from the Gulf by the delta of the Colorado River. The northern Gulf is all at shelf depth and is separated from the southern and central portions by a chain of islands at approximately 29°N (Isla Tiburón, Isla San Estaban, Isla San Lorenzo, and Isla Angel de la Guarda as well as the deep Sal si Puedes Basin). The central and southern Gulf consists of a series of basins (Figure 1) increasing in depth southward from 1000 m to nearly 4000 m (van Andel, 1964).

An interesting feature in the central and southern Gulf is the existence of hemipelagic laminated diatomaceous sediments (Revelle, 1950; Byrne and Emery, 1960; Calvert, 1964). The laminated sediments are found where the oxygen minimum zone intersects the sediment water interface (Calvert, 1964) between approximately 450 m and 800 m depth. The oxygen levels are low enough to prevent the development of a benthic macrofauna, bioturbation is minimal and the sediment accumulates undisturbed. The low oxygen levels (<0.2 ml/ℓ) found within the core of the oxygen minimum zone are the result of oxidation of large amounts of settling organic detritus (Richards, 1957). Primary production is high in the Gulf (however, average yearly data

Figure 1. Configuration and bathymetry of the Gulf of California with the basins noted (from Schrader, 1981, modified from Bischoff and Niemitz, 1980). Depth contours in meters.



30°
31°N
29°N
28°
27°
26°
25°
24°
23°
22°N
112°W
111°
110°
109°
108°
107°W
San Felipe
SONORA
Santa Rosalia
BAJA CALIFORNIA
Guaymas
Loreto
La Paz
SINOLA
Contours in meters
San Pedro Martir Basin
Guaymas Basin
Carmen Basin
Farallon Basin
Pescadero Basin

are not available), comparable to the Bay of Bengal and the upwelling areas off the west coasts of Baja California or North Africa (Zeitzschel, 1969).

The laminated sediments result from interactions in the input of the biogenic and abiogenic sediment components responding to the seasonal differences in the regional climate. The laminae provide a high resolution "proxy" climatic record analogous to dendrochronology.

Byrne and Emery (1960) suggested that the laminae result from a seasonal pulse of diatoms and a relatively constant supply of inorganic sediment. Calvert (1966b) proposed that the laminae reflect a seasonal pulse in terrigenous material and a relatively constant diatom supply throughout the year. However, Calvert oversimplified the problem by only considering the area near the Ballenas Channel where tidal mixing maintains high production throughout the year (Roden, 1964). Recent authors have attributed the laminae to both a seasonal pulse in the supply of terrigenous material and a seasonal pulse in the production of diatoms (Schrader, Kelts, et al., 1980; Schrader, Murray, et al., 1980; Baumgartner and Soutar, in press). Based on the available climatic data it was proposed that the two sides of the Gulf were reacting differently to the changing wind pattern (Schrader, Murray et al., 1980; Donegan and Schrader, 1980).

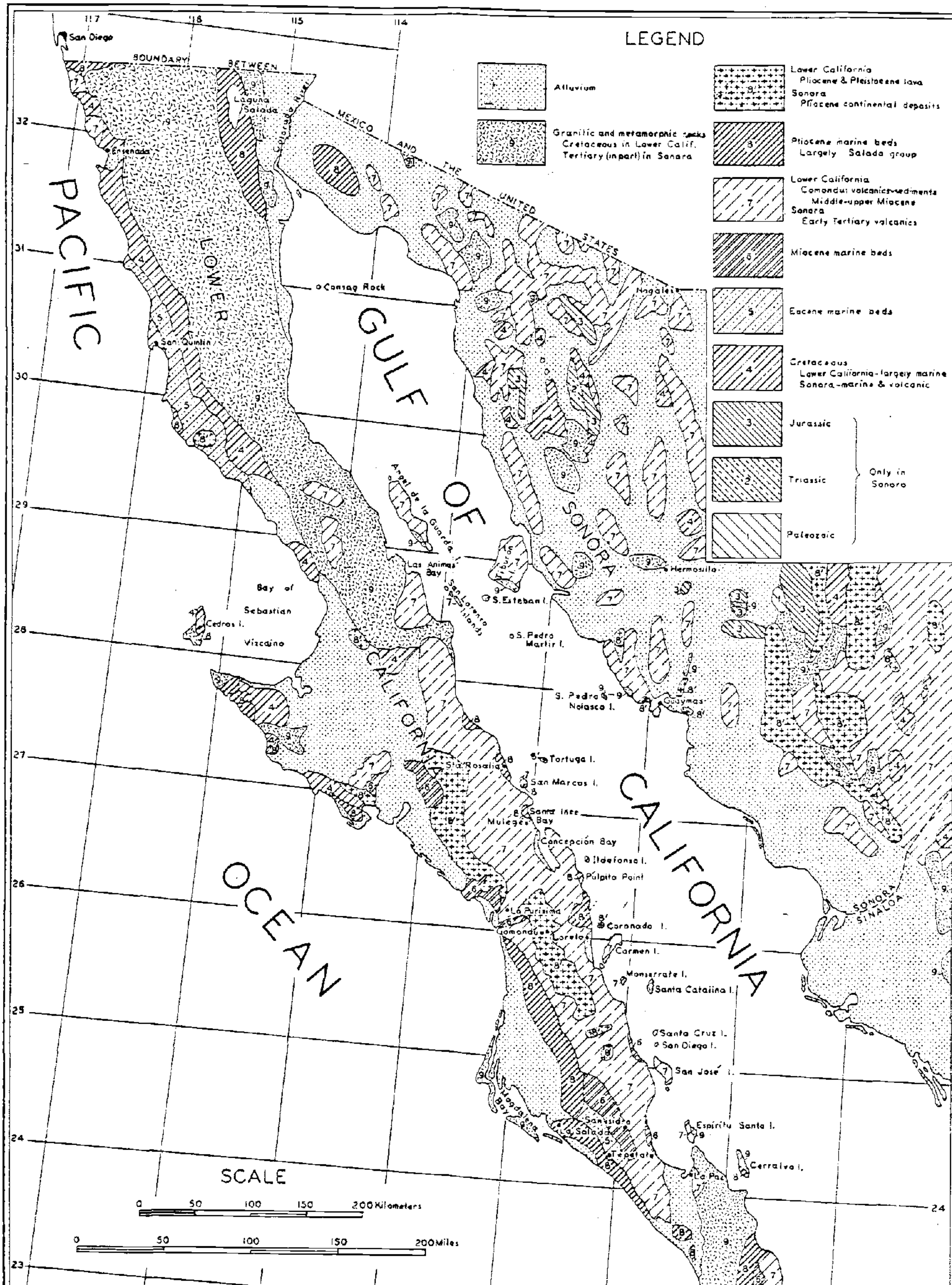
The objective of this paper is to build on Calvert's (1964, 1966a, 1966b) study of the areal distribution of laminated sediments in the central Gulf and the factors affecting their distribution. The main goal of this study is to determine the composition of the laminated sediments by defining their biogenic and abiogenic components and to determine if the components can be related to the seasonally varying climatic regime. Principle questions to be addressed are: 1) Can the individual components be related to seasonal changes in the climate? 2) Can the light laminae be distinguished from the dark laminae on the basis of varying proportions of these components? 3) Do the two sides of the Gulf respond differently to the changing seasons? 4) How do the laminated Gulf sediments compare with other nearshore hemipelagic sediments?

BACKGROUND

The geology of the areas bordering the Gulf was reviewed by Beal (1948), Anderson (1950), and Allison (1964). To the west is the Peninsula of Baja California, a high westward-tilted tableland, which forms a physiographic, oceanographic and geologic barrier separating the Gulf from the eastern Pacific (Allison, 1964). The principle elevations in the northern and southern portion of the peninsula are Late Mesozoic granitic rocks and associated metamorphics. The central portion is capped by a thick sequence of Miocene volcanics and associated epiclastic rocks (Figure 2). To the east a broad plain of Quaternary and Tertiary sediments, penetrated by low mountains of Paleozoic and Mesozoic intrusive and sedimentary rocks, borders the Gulf. Several hundred kilometers inland is the Sierra Madre Occidental consisting of Paleozoic and Mesozoic batholithic rocks and geosynclinal sediments and metamorphics capped by Tertiary volcanics (van Andel, 1964).

The Gulf formed as the result of sea floor spreading and strike slip motion initiated about 4 million years ago (Larson et al., 1968; Moore and Buffington, 1968; Curray et al., 1979). Prior to the opening of the modern Gulf a proto-Gulf trough may have existed since the Middle Miocene, as a marginal basin in the structurally extensional area behind an active subduction zone (Karig and Jensky, 1972; Curray et al., 1979). Spreading centers are located in a series of NE-SW trending en echelon troughs, forming the basins in the southern and central Gulf, connected by a series of NW-SE trending transform

Figure 2. Generalized geologic map of the regions surrounding the Gulf of California (from Anderson, 1950).


LEGEND
Alluvium
Granitic and metamorphic rocks Cretaceous in Lower Calif. Tertiary (in part) in Sonora
Lower California Pliocene & Pleistocene lava
Sonora Pliocene continental deposits
Pliocene marine beds Largely Salada group
Lower California Comondu volcanics-sediments Middle-upper Miocene
Sonora Early Tertiary volcanics
Miocene marine beds
Eocene marine beds
Cretaceous Lower California-largely marine Sonora-marine & volcanic
Jurassic
Triassic
Paleozoic
Only in Sonora
PACIFIC OCEAN
GULF OF CALIFORNIA
LOWER CALIFORNIA
SONORA
BOUNDARY BETWEEN MEXICO AND THE UNITED STATES
San Diego
Ensenada
Laguna Salada
Colorado River
Consag Rock
San Quintin
Angel de la Guarda
Las Animas Bay
San Lorenzo Islands
S. Esteban I.
S. Pedro Martir I.
Tiburon
Nogales
Hermosillo
Bay of Sebastian Vizcaino
Cedros I.
S. Pedro Nolasco I.
Guaymas
Sta. Rosalia
Tortuga I.
San Marcos I.
Santa Inez Bay
Mulege
Concepción Bay
Ildefonso I.
Púlpito Point
La Purisima
Comondu
Loreto
Coronado I.
Carmen I.
Monserrate I.
Santa Catalina I.
Santa Cruz I.
San Diego I.
San José I.
Magdalena Bay
San Ysidro
La Salada
Tepetate
Espiritu Santo I.
Cerralvo I.
La Paz
Cabo San Lucas
SONORA SINALOA
SCALE
0 50 100 150 200 Kilometers
0 50 100 150 200 Miles

faults (Moore, 1973). Active sea floor spreading is occurring in the Guaymas Basin as evidenced by the high heat flow anomalies in the central depression (Lawver et al., 1975). However, intrusive activity is thought to be episodic and discontinuous along the segments of spreading (Williams et al., 1979). The complexity of the tectonics was shown by detailed seismic and magnetic surveys (Henyey and Bischoff, 1973; Bischoff and Henyey, 1974; Sharman, 1976) which indicated that many of the long faults are associated with smaller faults subparallel or oblique to the predominant fault trend with frequent divergence and convergence of faults (Niemitz, 1977).

Oceanographic and meteorologic aspects of the Gulf have been summarized by Roden (1958, 1964) and Alvarez-Borrego (in press). In the winter, water outflow from the Gulf occurs at the surface with water inflow at greater depths. During the summer the situation is reversed (Roden, 1958). Surface circulation is linked to the regional winds which blow from the northwest in the winter (October to June) and from the southeast in the summer (July to September) as a result of the position of the local low-pressure system. The northwest winds are stronger averaging 5 m/sec while the southeast winds average 3 m/sec (Roden, 1964). Initiation of the rainy season is associated with the appearance of the southeasterly winds that carry moist air into the Gulf (Roden, 1958; 1964). Precipitation is greater on the east side than the west side increasing towards the south, and in general, evaporation exceeds precipitation for the Gulf. Based on temperature, salinity, and oxygen profiles, Roden (1964) concluded that the northwesterly winds are associated with extensive upwelling along the mainland coast while the southeasterly winds give rise to less extensive upwelling along the Baja coast.

The thermohaline structure of the southern Gulf is essentially the same as that of the equatorial Pacific, modified at the surface by evaporation and by mixing with California current water (Roden, 1958). Three main water types are found within the upper 200 m. Cold California Current Water ($T < 22°C$, $S \leq 34.6°/oo$) which flows southward along the west coast of Baja California; warm Eastern Tropical Pacific Water ($T > 25°C$, $34.6°/oo < S < 34.9°/oo$) which flows from the southeast; and warm, saline Gulf of California Water ($22°C < T < 25°C$, $S > 34.9°/oo$) formed within the Gulf through evaporation of equatorial waters (Stevenson, 1970; Roden and Groves, 1959). Beneath these three water masses are Subtropical Subsurface Water, having a salinity maximum of about 34.8°/oo; Antarctic Intermediate Water, having a salinity minimum of about 34.5°/oo; and Pacific Bottom Water below this with salinities up to 34.7°/oo (Stevenson, 1970; Griffiths, 1968; Sverdrup, 1941). These deeper water masses are not all seen farther up the Gulf because of the shallower sill depths of the basins to the north.

MATERIALS AND METHODS

Two short intervals of very distinct rhythmites were sampled lamina by lamina from two cores in the central Gulf of California. Kasten core BAV 79 E-9 (Table 1) is from the slope of the Guaymas Basin on the mainland side of the Gulf and Kasten core BAV 79 B-29 (Table 1) is from the slope of the Guaymas Basin on the Baja side (see Figure 3 for core locations). Laminae from core E-9 were sampled between 87-91 cm and those from core B-29 were sampled between 37.5-42.5 cm (see Figure 4). At the time of sampling Pb-210 determined sedimentation rates suggested that these intervals were time correlative (Pb-210 sedimentation rates of .062 cm/year and .130 cm/year for areas B and E respectively). Laminae counting and *Dictyocha epiodon* horizon markers (Hans Schrader, personal communication, 1981) however, suggest that the sedimentation rates at the two sites are about the same so the intervals are probably not time equivalent.

Blocks of wet sediment, approximately 9 cm wide x 6 cm deep x 5 cm long were removed from plastic Kasten core subsampling trays (15 cm x 6 cm x 28 cm) and dried 24 hours in an oven at 80°C. Individual lamina were then scraped from the dried blocks using an x-acto razor knife. Laminae were distinguished by color and texture when separated. A variety of techniques were tested to separate laminae (using both wet and dry material) with this scraping technique on a dried block being most effective. Generally, between 300 and 600 mg of sediment was recovered from each lamina, the narrow band of material comprising the boundary between adjacent laminae was

Table 1. Latitude, Longitude, and water depth of cores used in this study. Detailed sedimentologic descriptions are on file at the Core Repository, School of Oceanography, Oregon State University.

	Total Core Length (cm)	Latitude (°N)	Longitude (°W)	Water Depth (m)
BAV 79 B-26[2] (Box core)	35	26°41.8'	111°25.8'	552
BAV 79 B-29[1] (Kasten core)	197	26°42.0'	111°25.0'	635
BAV 79 E-7[2] (Box core)	30	27°53.5'	111°36.0'	675
BAV 79 E-9[1] (Kasten core)	192	27°53.2'	111°37.2'	660
BAV 79 E-10[3] (Kasten core)	198.5	27°52.2'	111°39.7'	644

[1]These cores were studied in detail on a lamina by lamina basis.

[2]Pb-210 determined sedimentation rates and varve counting sedimentation rates were done on these cores. Cs-137 and Pu-238/Pu-239 sedimentation rates were determined on BAV79 E-7.

[3]Silicoflagellate flora was examined on a lamina by lamina basis in this core.

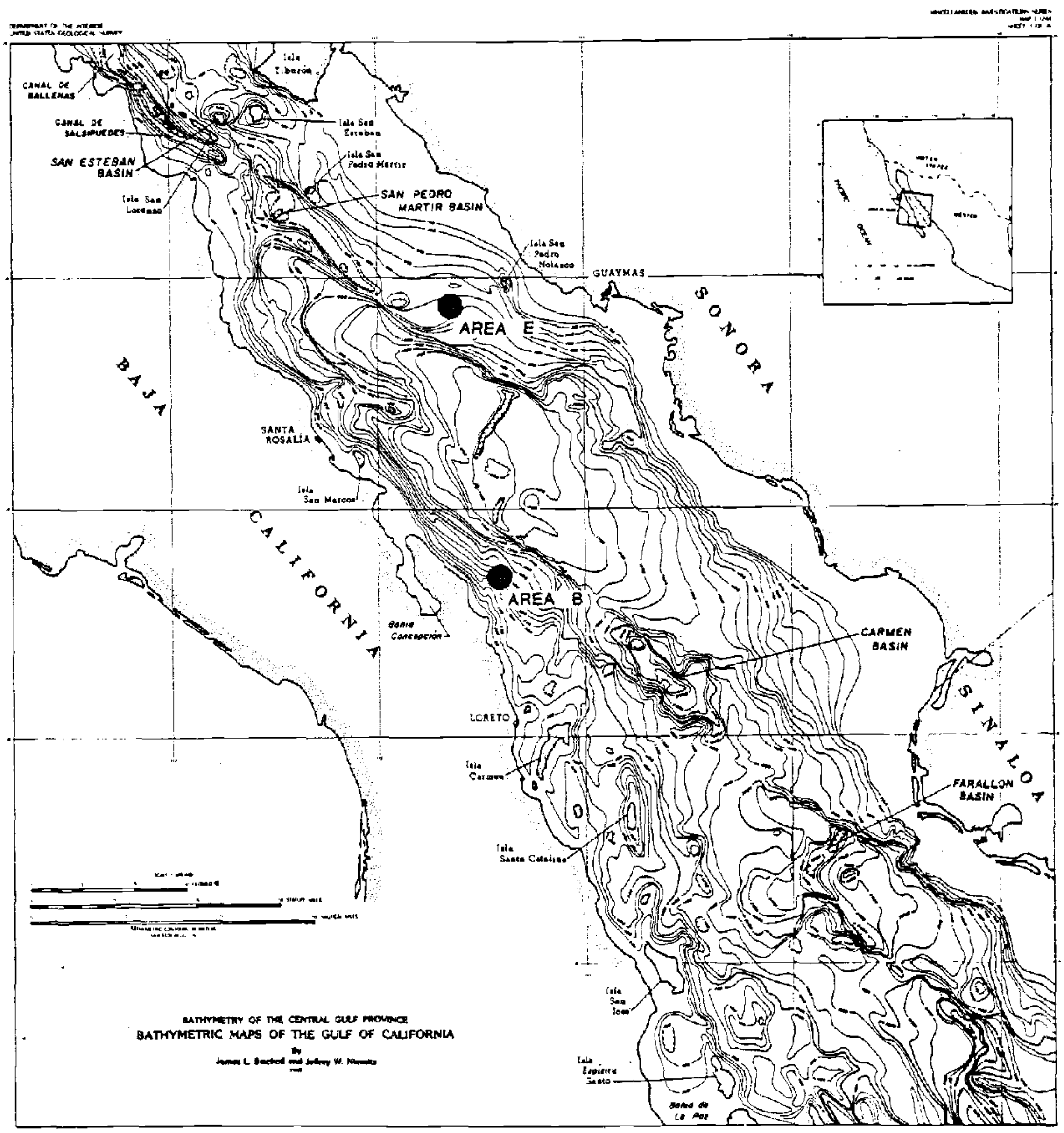
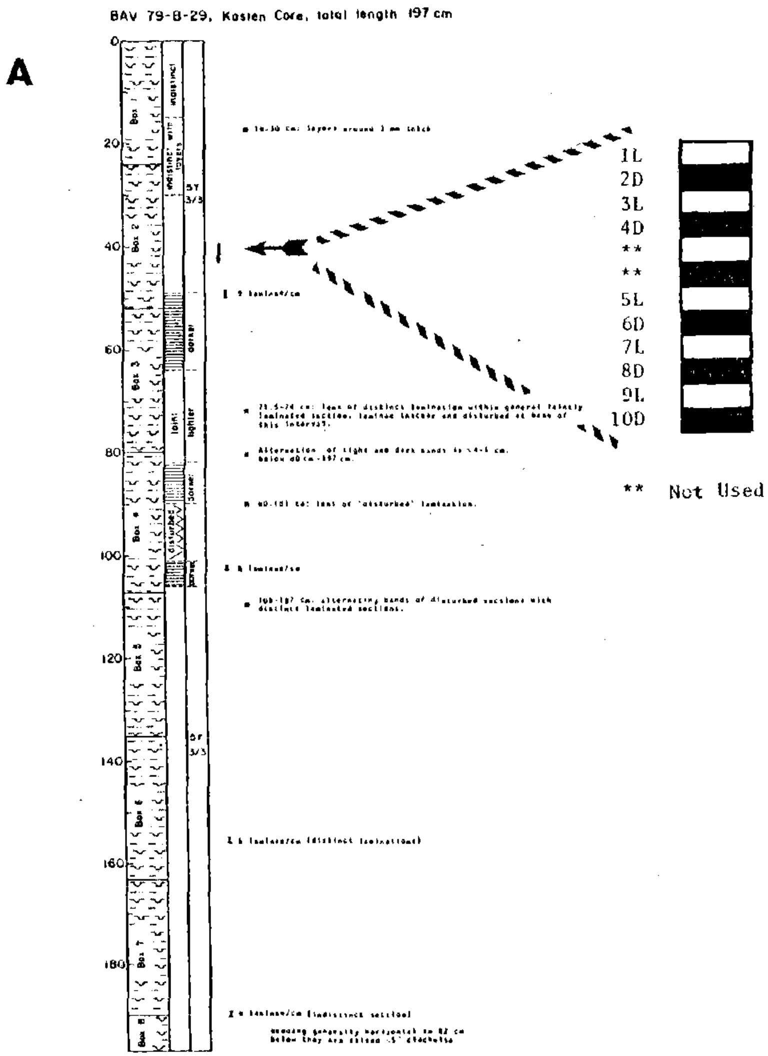
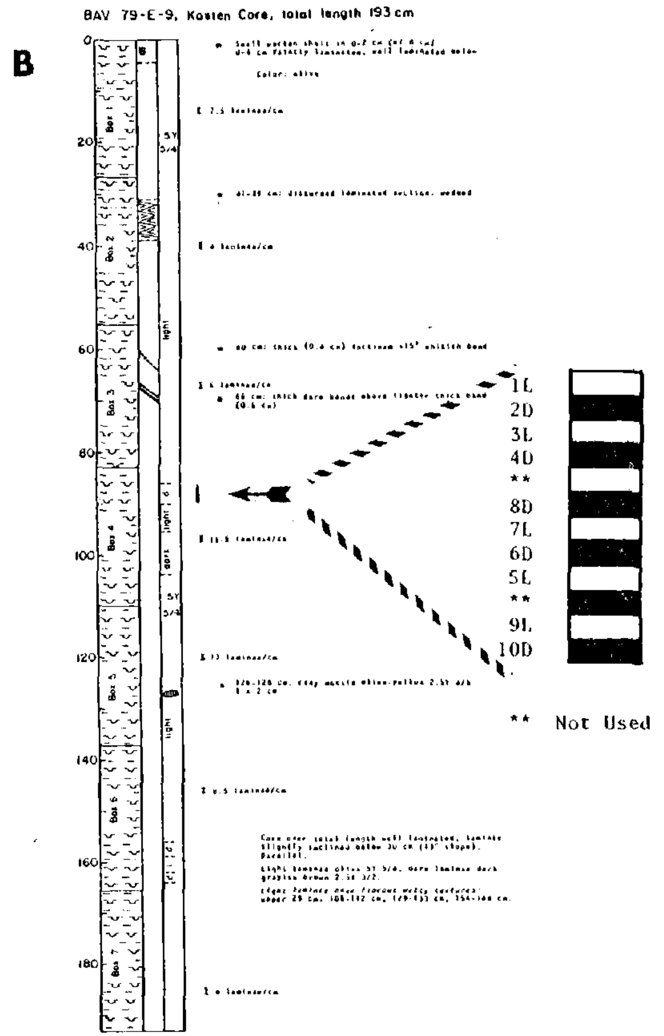
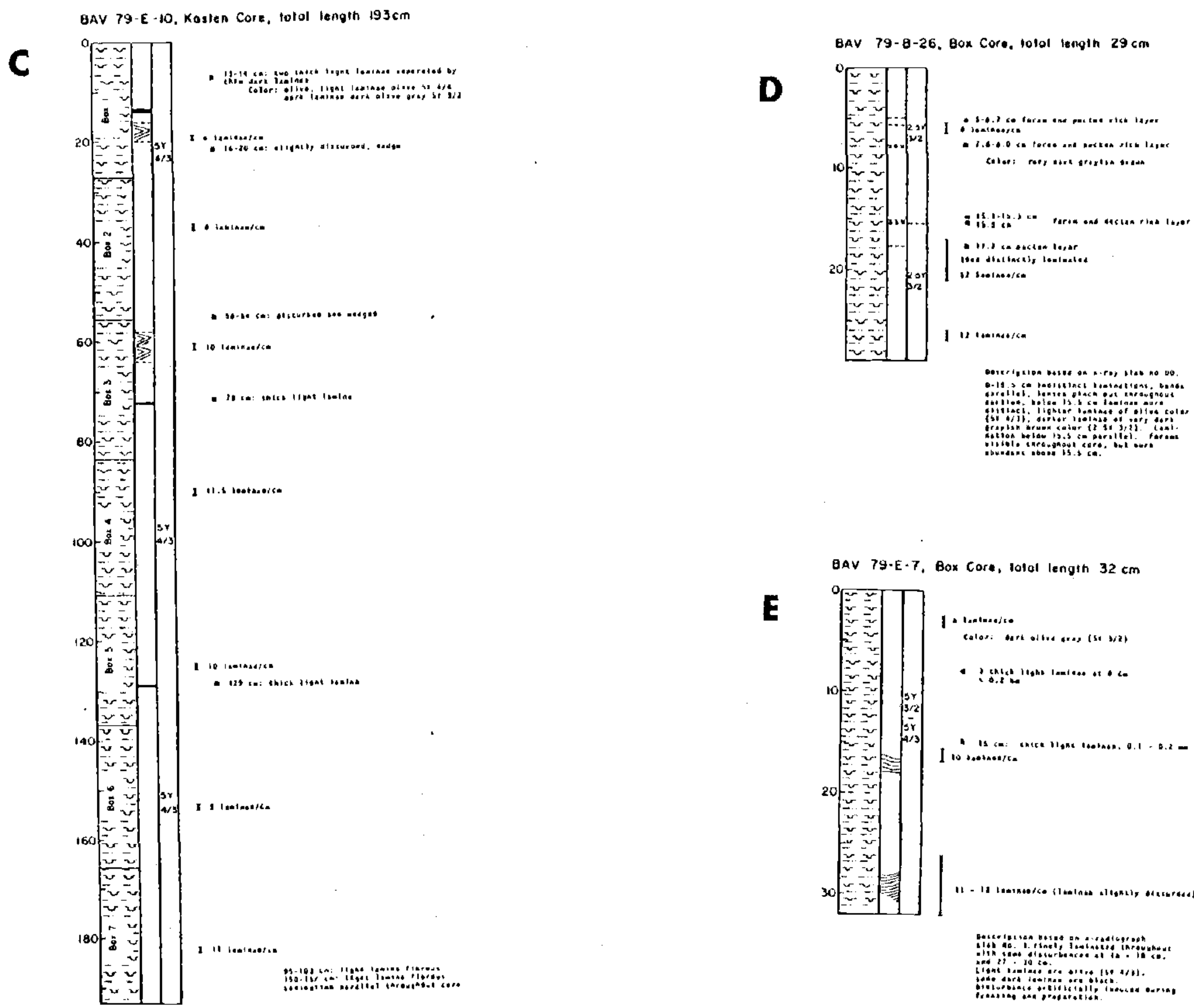


Figure 3. Bathymetry of the central Gulf of California (from Bischoff and Niemitz, 1980). BAV79 E-7, BAV79 E-9, and BAV79 E-10 are within the circle designated as area E. BAV79 B-26 and BAV79 B-29 are within the circle designated area B. Contours are in meters.

Figure 4. Lithologies of cores used in this study: A) BAV 79 B-29, B) BAV 79 E-9, C) BAV 79 E-10, D) BAV 79 B-26, E) BAV 79 E-7. Intervals of detailed laminae sampling indicated by arrows. Laminae intervals are schematic representations (not to scale) to show the order of laminae identification. Cores are stored at the Core Repository, School of Oceanography, Oregon State University.


A
BAV 79-B-29, Kosten Core, total length 197 cm
5Y 3/3
5Y 3/3
1L
2D
3L
4D
**
**
5L
6D
7L
8D
9L
10D
** Not Used


B
BAV 79-E-9, Kosten Core, total length 193 cm
5Y 5/4
5Y 5/4
1L
2D
3L
4D
**
8D
7L
6D
5L
**
9L
10D
** Not Used


C
BAV 79-E-10, Kasten Core, total length 193cm
0
20
40
60
80
100
120
140
160
180
5Y 4/3
5Y 4/3
5Y 4/5
D
BAV 79-B-26, Box Core, total length 29 cm
0
10
20
E
BAV 79-E-7, Box Core, total length 32 cm
0
10
20
30
5Y 3/2 - 5Y 4/3

discarded. Metal contamination due to the x-acto knife is thought to be negligible. Replicate lamina samples were prepared in which half of the lamina was scraped with an x-acto knife and half scraped with a clean glass microscopic slide. For each lamina tested metal contents were essentially the same in the replicates.

From each downcore segment 12 adjacent laminae were sampled. Two laminae from each interval were not used in the analyses because they were either too thin to provide sufficient material to do the analyses or were considered to be mixed during the sampling procedure (Figure 4). The laminae that were used were subsequently numbered 1 through 10. The samples from the Baja side are identified as B-29 1 through 10. Samples 1, 3, 5, 7, and 9 are light laminae (B-29 1L, B-29 3L, etc.) and samples 2, 4, 6, 8, and 10 are dark laminae (B-29 2D, B-29 4D, etc.) see Figure 4. The mainland side samples are E-9 through 10. Again 1, 3, 5, 7, and 9 are light laminae (E-9 1L, E-9 3L, etc.) and 2, 4, 6, 8, and 10 are dark laminae (E-9 2D, E-9 4D, etc.) see Figure 4. For each lamina sample the opal microfloral composition, textural character, and concentration of selected elements was determined; X-ray diffraction analysis of mineral composition was performed on most samples providing there was enough material.

Microscopical Analyses

Between 10 and 15 mg of each sample was placed in a test tube with 3 ml deionized water and several drops concentrated H_2O_2 were added to disaggregate the sediment. Slides were prepared from

100 μl splits by automatic pipeting, Aroclor 4465 (index of refraction = 1.67) being used as mounting medium. The microscopical investigations were carried out on a Leitz-Orthoplan microscope using high power and high resolution plan-apochromatic oil immersion objectives. Diatom counts were made at 1000 times magnification (objective: Pl Apo/Oil 100 x/1.32; ocular: Periplan GW 10 x M). At least 300 valves were counted per slide (not including Chaetoceros resting spores) on random traverses across the middle of the cover-glass with counting procedures after Schrader and Gersonde (1978). The number of Chaetoceros resting spores was estimated based on a sub-sample of 100 diatoms counted from one pass across the middle of the coverglass. Taxonomy is after an in-house catalogue by Schrader and Schuette (unpublished) for the Gulf of California. Silicoflagellate counts were made at 400 times magnification (objective: Pl Apo/Oil 40 x/1.00; ocular: Periplan GW 10 x M). One hundred individuals were counted per slide from random traverses across the coverslip, except in those cases where less than 100 were found after covering the entire slide. Silicoflagellate taxonomy is after Poelchau (1976) and Schrader and Schuette (unpublished).

Texture was estimated microscopically at 1000 times magnification. Estimates were made by recalculating all components to add to 100 percent coverage, including both terrigenous and biogenous particles, and assessing the proportion of particles in the clay sized (<4 μm) range, silt sized (4 to 63 μm) range, and sand sized (63 μm to 2 mm) range using a calibrated ocular. This method is a modification of Shvetsov's method for estimating mineral percentages in rock sections (Terry and Chilingar, 1955) and is similar to DSDP shipboard standards for smear slide analysis (Kulm et al., 1973).

Chemical Analyses

Concentrations of silica, carbon, calcium, potassium, aluminum, copper, manganese, iron, nickel (B-29 samples only), zinc, and lead were determined for each lamina. Copper, manganese, iron, nickel, zinc, and lead were determined by atomic absorption spectrometry on a Varian model AA5R spectrometer. Sample preparation was modified from that of Evans (1977), such that 2 ml HF and 2 ml HNO_3 and were added to 100 to 200 mg of sample in acid washed teflon bottles. The solution was boiled down to salts in a covered sand bath, then 3 ml HNO_3 and 22 ml distilled H_2O were added to make a 25 ml final solution. Background absorbence was corrected for on all determinations.

Silica, calcium, potassium, and aluminum were analyzed from solutions prepared using a modification of Stephenson's (1973, unpublished) procedure (K. Scheidegger, pers. comm., 1980). Outline of the method: 4 ml HF/HNO_3 (1:3) were added to 100 mg sample in polyethylene bottles and placed in an oven at 60°C overnight (after 1 hour the bottles were removed and vigorously shaken for 10 seconds). Twenty-five ml of 37.93 g/l boric acid were added, the bottles were again vigorously shaken and returned to the oven; after 1 hour the samples were removed from the oven and 71 ml of distilled H_2O were added for a final volume of 100 ml.

Silica was determined using a Bausch and Lomb model 88 light spectrophotometer. One ml of original solution was added to 49 ml ammonium paramolybdate solution (4.0 g/l) and analyzed after 45 minutes.

Calcium, potassium, and aluminum were analyzed by atomic absorption on an Instrumentation Laboratory model IL 151/251 AA/AE spectrophotometer. Calcium was diluted 2:50 with 2 ml original solution added to 10 ml 10,000 ppm K solution plus 38 ml distilled H_2O. Potassium was diluted 1:50 with 1 ml original solution added to 5 ml 10,000 ppm Cs solution plus 44 ml distilled H_2O. Aluminum was diluted 2:3 with 20 ml original solution added to 10 ml 3,000 ppm K solution.

Organic carbon and $CaCO_3$ were determined with a Leco model WR-12 automatic carbon determinator following the procedure described by Boyce and Bode (1972). Approximately 40 mg of material was used for each of the two sets of duplicates.

Mineralogical Analysis

Clay minerals were analyzed by X-ray diffraction on oriented mounts of the <2 μm size fraction. The <2 μm fraction was isolated by repeated settling and decantation in liter jars with 8 cm settling distances followed by filtration through porous candle filters (pore diameter $\leq$ .02 μm) to concentrate the suspensions. The slide preparation procedures are similar to those of Heath et al. (1974) and Karlin (1980) with some modifications. Carbonate values are low enough in the Gulf (<1 percent) so it was not necessary to remove the carbonate; and amorphous silica, although a dominant component, was not removed because of the very small amount of sample available. Relative proportions of the clay mineral types were semi-quantitatively estimated using the method of Biscaye (1965).

The quartz and plagioclase feldspar contents of the samples (bulk size fraction) were quantitatively determined by X-ray diffraction of random mounted planchettes after the addition of boehmite (10 percent by weight) as an internal standard. The procedure is described by Scheidegger and Krissek (in press).

All analyses were done on a Norelco diffractometer with a Geiger-Müller counting tube, using monochromatized CuK_{α} radiation. The clay slides were scanned between 2 and 30° 2Θ (3 second scan time, .02° steps) and the random mounts were scanned bwtween 2 and 60° 2Θ (3 second scan time, .02° step). Diffractograms were made after the raw data were smoothed by a 17 point smoothing algorithm on a SWTP 6800 microcomputer.

ASSUMPTIONS

Through the course of this study several assumptions were maintained: 1) two laminae represent one year, 2) all sediment components arrive at the bottom in the same order that they enter the system, 3) the intervals sampled are representative of the entire core, and 4) no contamination or mixing of laminae resulted from the sampling technique.

The first assumption, is probably a fair one despite the fact that the test conducted in this study (see the following section) was not conclusive. For the laminated marine sediments of the Santa Barbara Basin, Koide et al. (1972) found remarkable agreement between varve counting and Pb-210 determined sedimentation rates (.39 cm/year using Pb-210 vs. .40 cm/year using varve counting). Baumgartner et al. (1981) also report good agreement between Pb-210 chronology and varve counting from several cores in the central Gulf (the cores they analyzed are close to E-7 and E-9). Finally, Calvert (1966b) found reasonably good agreement between radiocarbon dating and varve counting for several cores near the Ballenas Channel in the central Gulf.

The second assumption, that all components are deposited in the sediment in the same order that they enter the system, is difficult to verify without detailed sediment trapping or sediment tracer experiments. It is assumed that all particles settle rather quickly out of the water column either by incorporation into planktic fecal pellets (Schrader, 1971; McCave, 1975; Honjo and Roman, 1978; Dunbar and Berger, 1981) or by inorganic agglomeration (Schubel, 1971; Hyne et al., 1979) and not by individual particle settling.

The last two assumptions are also difficult to confirm. An interval of 40 cm downcore in core BAV 79 E-10 (Figure 4) was sampled lamina by lamina and spot checked for silicoflagellate variations. The results were comparable to those in E-9; tentatively suggesting that the intervals tested are representative (Appendix 4).

The consistency of the results for all analyses suggests that artificial mixing or contamination was not a great problem although a very precise study of the techniques employed would be necessary to confirm this.

RESULTS AND DISCUSSION

The rhythmically laminated sediments in the Gulf of California consist of alternating millimeter to submillimeter bands of light pale olive diatomaceous ooze and darker moderate olive brown muddy diatomaceous ooze (Schrader, Kelts et al., 1980). Diatoms comprise 80 to 90 percent of the sediment in the light laminae and 60 to 75 percent in the dark laminae (included in this are silicoflagellates, radiolarians, ebridians, and sponge spicules which together contribute less than 2 to 3 percent). The opaline fraction is always extremely well to moderately well preserved. Terrigenous material generally comprises 5 to 10 percent in the light laminae and 15 to 25 percent in the dark. Clumps of amorphous organic material contribute 5 to 10 percent in the light laminae and 10 to 15 percent in the dark (Donegan and Schrader, 1981).

Sedimentation Rates

Sedimentation rates were estimated by several techniques which suggest that the sediment is accumulating at approximately 200 cm/1000 years. Lead 210 determined sedimentation rates were made on Box cores BAV 79 B-26 and BAV 79 E-7 (Table 1). These cores are very close to B-29 and E-9 respectively and it is assumed that the sediment accumulation rates determined for B-26 are the same at B-29 and that the rates determined on E-7 are the same at E-9. All radionuclide analyses discussed in this section were made by Dr. Thomas Beasley, School of Oceanography, Oregon State University.

Both box cores were sealed upon recovery and transported back to OSU where they were quick-frozen in liquid nitrogen (T = -196°C) and slabbed with a bandsaw. Although laminae disturbance was minimal the cores shortened by several centimeters due to water loss in the time between coring and freezing so that sedimentation rates determined are minimum values. One centimeter thick intervals were then sent to Dr. Beasley for Pb-210 analysis. As a cross check all the laminae were counted and measured in thickness (using a binocular microscope equipped with a calibrated ocular) on a frozen slab from E-7. Laminae counting estimated sedimentation at 185 cm/1000 years for E-7 (assuming 2 laminae equal one year). Pb-210 determined sedimentation was 130 cm/1000 years for E-7 and 62 cm/1000 years for B-26. The comparatively low value for B-26 is considered to be in error because the laminae are about the same thickness in B-26 and E-7. Interestingly, Pb-210 background equilibrium was reached within the upper 4 cm of B-26 (Table 2). Some surface mixing plus a loss of some of the surface material may be the cause of the low value. It should be pointed out that the laminae are least distinct within the upper few centimeters where water contents approach 100 percent.

To check on the validity of the PB-210 rate on E-7 sedimentation rates were also estimated using Cesium-137 and Plutonium-238/Plutonium-239 (Table 3). Cs-137 determined a rate of 170 cm/1000 years and Pu-238/Pu-239 estimated sedimentation at 204 cm/1000 years.

The Cs-137 determined sedimentation rate and Pu-238/Pu-239

Table 2. Total and excess Pb-210 in BAV79 E-7 (top) and BAV79 B-26 (bottom).

Pb-210 activity (dpm/g dry)

BAV79 E-7

depth interval(cm)	total	excess
0-1	29.4 ± 1.5	25.1 ± 1.6
3-4	17.9 ± 0.9	13.6 ± 1.0
6-7	8.9 ± 0.4	4.6 ± 0.6
9-10	7.3 ± 0.4	3.0 ± 0.6
12-13	5.7 ± 0.3	1.4 ± 0.5
15-16	5.0 ± 0.3	0.7 ± 0.4
18-19	4.5 ± 0.2	—
21-22	4.4 ± 0.3	—
24-25	4.6 ± 0.2	—
27-28	3.5 ± 0.2	—
	equil. = 4.3 ± 0.4	

BAV79 B-26

depth interval(cm)	total	excess
0-1	26.6 ± 1.4	24.1 ± 1.4
1-2	19.0 ± 1.4	16.5 ± 1.4
2-3	14.8 ± 0.8	12.3 ± 0.8
3-4	7.7 ± 0.5	5.2 ± 0.5
6-7	2.2 ± 0.2	—
9-10	2.5 ± 0.2	—
12-13	2.5 ± 0.2	—
15-16	2.1 ± 0.1	—
18-19	2.9 ± 0.2	—
21-22	2.5 ± 0.2	—
24-25	2.4 ± 0.1	—
27-28	3.0 ± 0.2	—
	equil. = 2.5 ± 0.2	

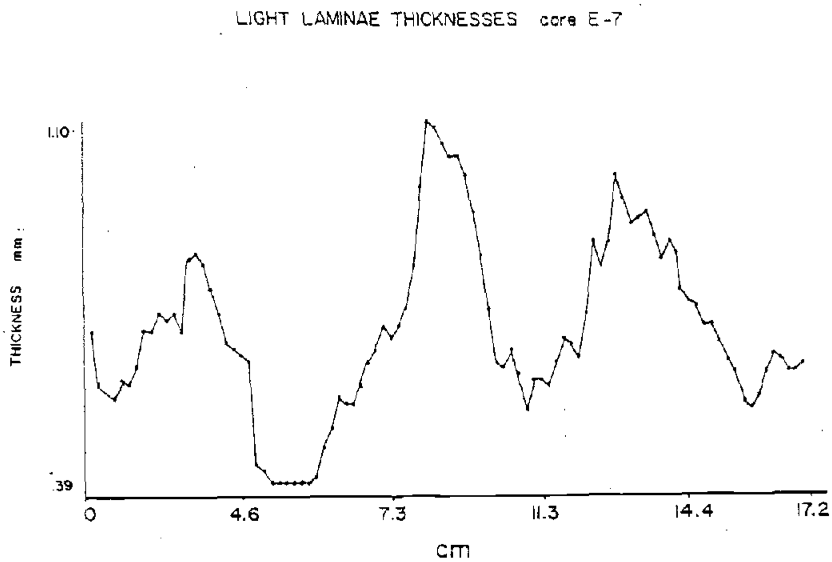
Table 3. Cs-137 activity in BAV79 E-7 (top). Pu-239 activity and Pu-238/Pu-239 ratios in BAV79 E-7 (bottom).

BAV79 E-7

interval (cm)	dpm^{137}Cs/kg
0-1	106 ± 8
1-2	162 ± 8
2-3	78 ± 4
3-4	22 ± 4
4-5	10 ± 3
5-6	—
6-7	—
7-8	—

BAV79 E-7

interval (cm)	dpm^{239}Pu/kg (salt corr.)	^{238}Pu/^{239}Pu
0-1	125 ± 3	0.050 ± 0.005
1-2	129 ± 5	0.073 ± 0.006
2-3	72 ± 3	0.061 ± 0.008
3-4	41 ± 2	0.090 ± 0.013
4-5	15 ± 1	0.032 ± 0.012
5-6	4.2 ± 0.6	0.029 ± 0.025
6-7	3.2 ± 0.6	0.026 ± 0.026
7-8	1.6 ± 0.3	0.097 ± 0.093



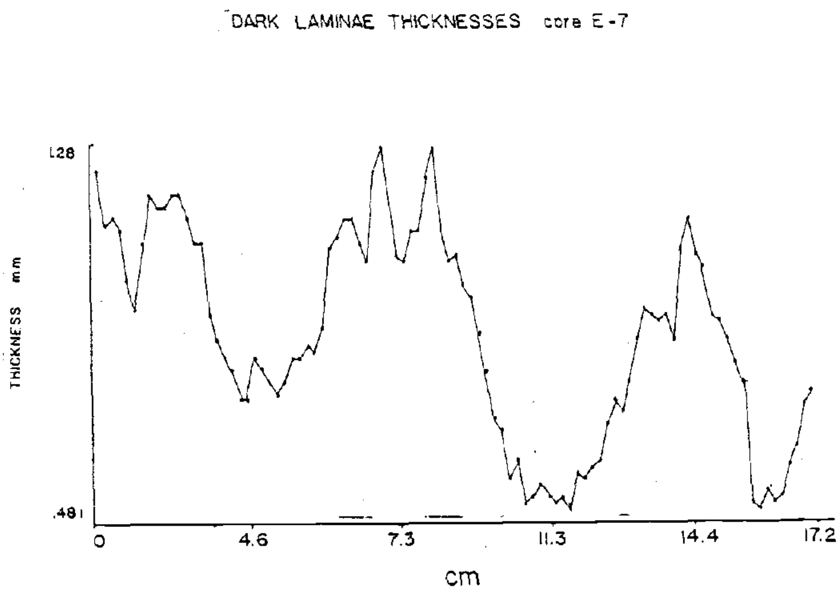


Figure 5. Laminae thicknesses (y-axis) plotted versus laminae number downcore (x-axis), for the upper 210 laminae (105 years) of E-7. Each point is a 10 point running mean of laminae thicknesses beginning at the top of the core. The point farthest to the left is the mean thickness of laminae 1 through 10, the second point is the mean thickness of laminae 2 through 11, etc. The x-axis is not linear, an approximate depth scale, in centimeters has been added.

sedimentation rate are close enough to the varve counting estimated rate to suggest that the assumption of two laminae representing one years deposition is valid. The two radionuclide rates bracket the varve counting rate for E-7 suggesting that varve counting may be the best estimate of sediment accumulation. The discrepancy of the Pb-210 determined sedimentation for E-7 may be attributed to the compaction effect described by Matsumoto and Wong (1977) for high porosity surface sediments.

An interesting outcome of measuring the laminae thicknesses was the finding that the sedimentation has not been constant (Figure 5). Work on other cores in the Gulf by Luis Fok (unpublished data) show this same general trend which may reflect a cyclicity in the sedimentation. A detailed study of laminated sediments will provide interesting results in this regard. Radionuclide methods assume constant sedimentation, at least over relatively long intervals, and should sedimentation be nonuniform any extrapolation beyond the intervals actually analyzed will introduce additional error to the determination.

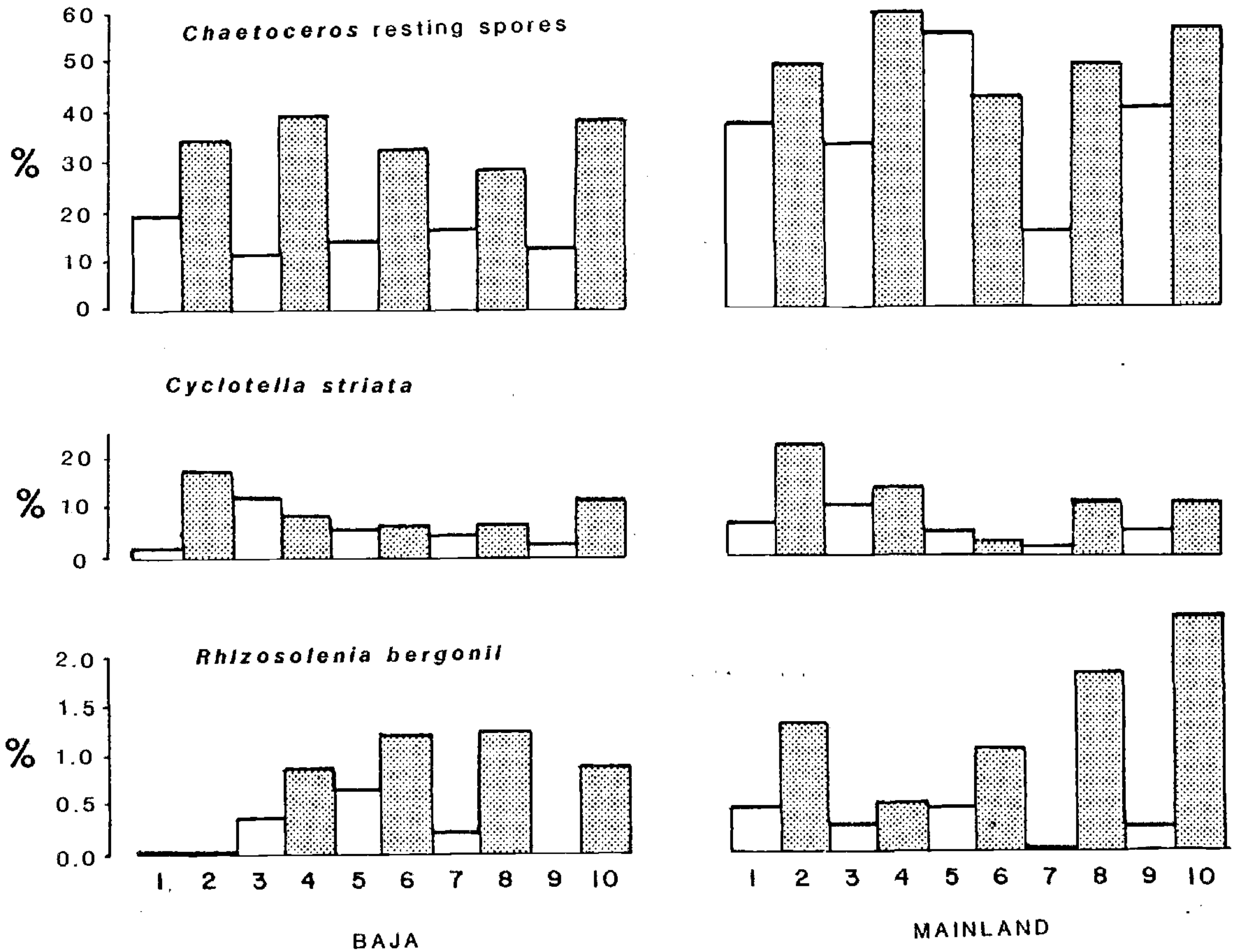
Microfloral Examination

More than 100 species of diatoms are found in the recent laminated sediments from the central Gulf. The assemblage is dominated by *Pseudoeunotia doliolus* and *Thalassiothrix pseudonitzschioides* (a paper on this new species is in preparation by Schuette and Schrader) which together generally comprise 40 to 60 percent of all diatoms present. A list of the relative abundances of the diatom species observed in the 20 individual laminae samples is found in Appendix 1.

Various factor and cluster analyses were performed on the diatom percentage data. However, based on the twenty laminae studied, the conclusions were far from conclusive and the resulting interpretations are speculative. Analysis of considerably longer intervals may provide a more solid data base from which to draw conclusions. Following a discussion of the results all the microfloral data will be interpreted together.

Unfortunately, neither Pseudoeunotia doliolus nor Thalassiothrix pseudonitzschioides showed any systematic variation between light and dark laminae. Chaetoceros resting spores show the most consistent percentage fluctuation between light and dark laminae with higher numbers in the dark laminae (Figure 6). The spores may represent a sedentary or dormant phase in the cells' life cycle (Smayda, 1958), and may be produced in a late stage of species succession when nutrients are virtually exhausted in the euphotic zone and "oceanic" conditions prevail (Guillard and Kilham, 1977). Chaetoceros is one of the genera which dominate the highest productivity stage in the seasonal diatom succession (Guillard and Kilham, 1977) but because the vegetative cells are thinly silicified they are seldom preserved in the sediment. The presence of large numbers of Chaetoceros resting spores within a sediment is generally interpreted to be indicative of high primary production (Hans Schrader, personal communication, 1981).

Figure 6. Relative abundances of *Chaetoceros* resting spores (top). *Cyclotella striata/stylorum* (middle), and *Rhizosolenia bergonii* (bottom) in the ten laminae from the Baja side (core B-29, interval centered at 40 cm) and the ten laminae from the mainland side (core E-9, interval centered at 89 cm). Dark laminae are represented by the stipled pattern and the light laminae are white. Note the different scales.


Chaetoceros resting spores
Cyclotella striata
Rhizosolenia bergonii
%
60
50
40
30
20
10
0
2.0
1.5
1.0
0.5
0.0
1 2 3 4 5 6 7 8 9 10
BAJA
MAINLAND

Rhizosolenia bergonii, an oceanic species (Kanaya and Koizumi, 1966), tends to be more abundant in the dark laminae than the light (Figure 6), however, the percentage variations are fairly small. Cyclotella striata, (including both Cyclotella striata and Cyclotella stylorum) also tends to be more abundant in the dark laminae, but once again the percentage variation is rather small (Figure 6).

The silicoflagellate flora is dominated by Octactis pulchra (Figure 7, Appendix 2) which constituted between 24 and 86 percent of the silicoflagellate assemblage. In general, O. pulchra is more abundant in the light laminae than the dark on both sides of the Gulf. Poelchau (1976) in his Pacific study reported O. pulchra as spotty in most parts of the North Pacific and where it did occur it usually made up less than 1 percent of the silicoflagellate population. But, he reported finding larger percentages in the sediments of the eastern tropical Pacific and near the mouth of the Gulf of California; Poelchau did not sample within the Gulf.

Dictyocha messanensis and D. calida are the next most abundant species and they tend to covary with O. pulchra (Figure 7). Whether their higher proportions in the dark laminae represent a replacement of Octactis pulchra or merely a relative increase as O. pulchra numbers decrease is unresolved. Preliminary interpretations suggest that the increase in D. messanensis and D. calida is just a relative increase because the absolute numbers of D. messanensis and D. calida do not seem to change very much between laminae although quantitative estimates have not been made. Dictyocha sp. 1A, and 1B and D. sp. 2 are species

CUMULATIVE PERCENTAGE PLOTS OF SILICOFLAGELLATE SPECIES

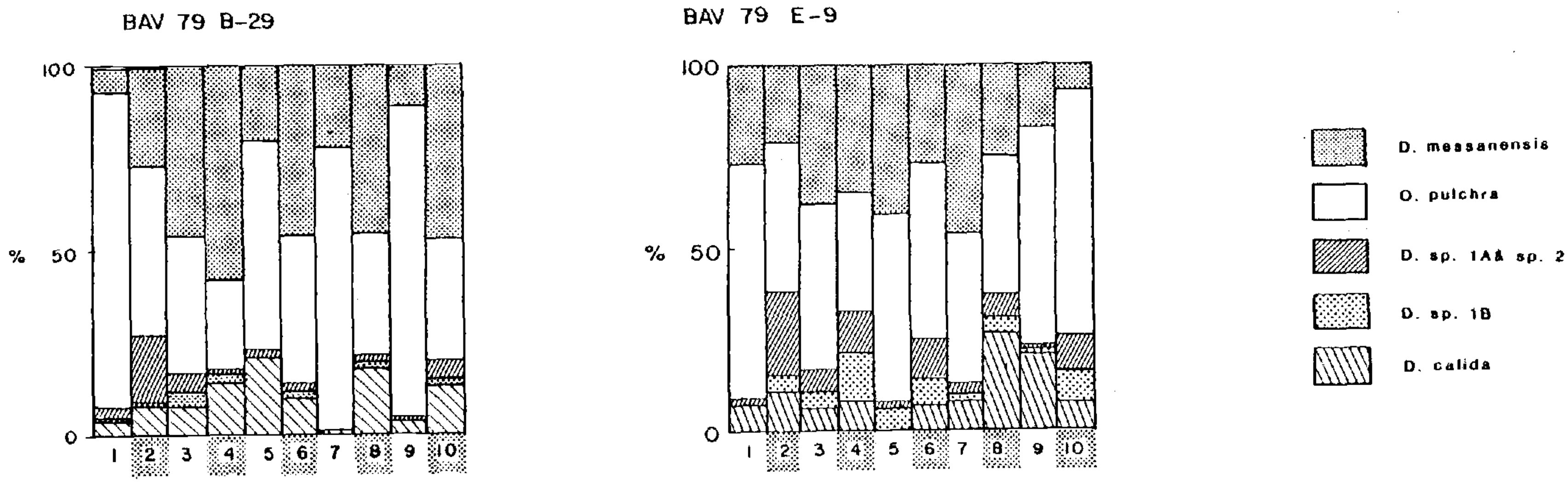


Figure 7. Cumulative percentage plots of silicoflagellate species in the ten laminae from the Baja side (core B-29, interval centered at 40 cm) and the ten laminae from the mainland side (core E-9, interval centered at 89 cm).

which have not previously been described and may be stress related forms of D. calida. D. sp. 1A and 1B and D. sp. 2 are in higher percentages on the mainland side than the Baja side and become more significant in the sediment to the south along the mainland coast (Dave Murray, pers. comm., 1981). Taken together as a group their percentages are generally higher in the dark laminae than the light (Figure 7, Appendix 2).

The microfloral data are interpreted as indicating that on both sides of the Gulf, the light laminae represent higher productivity or upwelling than the dark laminae. Octactis pulchra is interpreted to be an upwelling indicator. Schrader (pers. comm., 1981) reports that some laminae from DSDP Site 480 for which the diatoms are nearly monospecific comprising Chaetoceros radicans and are thought to be an upwelling "end member", are also nearly monospecific in silicoflagellates containing O. pulchra. He has also found laminae from the Gulf which are considered to be "oceanic end members" with diatom assemblages being almost entirely Coscinodiscus nodulifer and with silicoflagellate populations containing no O. pulchra. The abundances of D. sp. 1A and 1B and D. sp. 2 may reflect surface water circulation which is generally counterclockwise in the Gulf with water entering along the east side of the mouth (Roden, 1958; Vonder-Harr and Stone, 1973). The higher abundances in the dark laminae may represent enhanced transport up into the central Gulf during the summer season of southeasterly winds. The higher abundance of Rhizosolenia bergonii, an oceanic species, in the dark laminae would agree with the aforementioned interpretation. The ecological factors responsible for the higher abundance of Cyclotella striata in the dark laminae are not understood at the present time.

Chaetoceros resting spores are generally indicative of high primary productivity although they are found in highest numbers in the dark laminae on both sides of the Gulf. Such observations may indicate that as nutrients become depleted in the euphotic zone the Chaetoceros vegetative cells develop more resting spores. This can happen any time during the upwelling season as most phytoplankton blooms are generally short lived events. Although a certain percentage of resting spores settle out of the euphotic zone, the rest may remain near the surface being periodically buoyed back to the euphotic zone to resume normal vegetative life stages during subsequent upwelling events, until the end of the upwelling season (of northwesterly winds) when they then settle and are deposited with the nonupwelling laminae. The higher relative abundance of Chaetoceros resting spores in the dark laminae than in the adjacent light laminae holds for all the samples from B-29 and all the samples from E-9 except lamina 5L which has a higher than expected percentage of resting spores (Figure 6). Interestingly, lamina E-9 5L also contains a very high percentage (23%) of Skeletonema costatum (Appendix 1), a weakly-silicified dissolution sensitive species (Schuette and Schrader, in press) whose presence in the sediment is indicative of very high production. Lamina E-9 5L may thus represent a season of much higher than average primary production with proportionately more Chaetoceros vegetative cells and subsequently more resting spores having been produced. In general, the *Chaetoceros* resting spores are proportionately more important on the mainland side (Figure 6) which may be indicative of high primary productivity there than on the Baja side (see the background section and Roden, 1964).

Texture

Gross textural composition, as estimated visually, is summarized in Table 4. The sediment is composed primarily of silt sized diatoms and diatom fragments. Significant features to note on Table 4 are: 1) the dark laminae contain more terrigenous material than the light laminae, and 2) the terrigenous material is primarily clay sized (<4 μm) particles on the mainland side of the Gulf and fine silt sized (4 to 20 μm) particles on the Baja side. The difference in the grain size of the terrigenous material can be attributed to two general factors. Core B-29 is situated closer to shore (Figure 3) and a sediment source than core E-9, and the physiography of the bordering lands is different on each side of the Gulf. The east coast of the Gulf is bordered by the Pacific Coastal Plain with the Sierra Madre Mountains 100-200 km farther inland. On the west side the mountainous Baja Peninsula has a steep eastern flank down to the Gulf and little or no coastal plain. The Baja Peninsula is also more arid than the mainland and erosion is more important than chemical weathering. In general, the narrow western margin is characterized by coarser sediments than the eastern margin (van Andel, 1964).

Table 4. Average textural composition of all laminae as estimated visually. The % biogenous/% terrigenous is an estimate of the proportion of particles which are biogenous in origin and terrigenous in origin in each size class.

	Baja Side (Core B-29)		Mainland Side (Core E-9)	
		%-biogenous/%-terrigenous		%-biogenous/%-terrigenous
Light Laminae				
Clay	5-15%	50/50[1]	5-15%	50/50[1]
Silt	75-85%	95-99/1-5	70-80%	95-99/1-5
Sand	1-10%	100/0[2]	1-10%	100/0[2]
Dark Laminae				
Clay	15-25%	35-40/60-65[1]	20-35%	30-35/65-70[1]
Silt	70-80%	85-95/5-15	60-75%	95-99/1-5
Sand	1-10%	100/0[2]	1-10%	100/0[2]

[1]The biogenous material in the clay-sized (<4 μm) fraction is almost entirely diatom fragments.

[2]The sand-sized (63 μm to 2 mm) fraction is entirely large centric diatoms.

Chemical Analyses

A complete list of elemental concentrations from the individual laminae samples can be found in Appendix 3. Average chemical concentrations for light and dark laminae at each site as well as the calculated correlation of each chemical species to organic carbon are summarized in Table 5. The correlation coefficients were calculated using a Hewlett Packard HP-97 calculator with a curve fitting program. The concentration of the element was plotted versus the organic carbon content for each lamina sample and a correlation coefficient was determined.

Organic carbon ranged from 2.9 to 5.1 weight percent on the Baja side and 2.0 to 4.7 percent on the mainland side, always higher in the dark laminae. The higher organic carbon contents along with the increased fine grain terrigenous material in the dark laminae is probably responsible for the darker color of those laminae. Silica values ranged from 53 to 70 weight percent being higher in the light laminae and showed a high negative correlation to organic carbon. Copper, manganese, iron, zinc, nickel, calcium, potassium and aluminum were always higher in the dark laminae and generally showed a strong positive correlation to organic carbon (Figure 8, Table 5, Appendix 3). Lead concentrations were always at or below the detection limits of the instrument and were of the same magnitude as the background absorbance suggesting trace abundances at most.

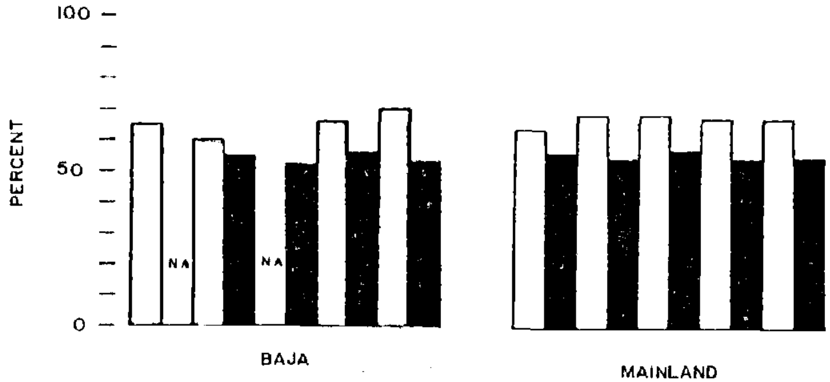
The trace metal concentrations are comparable to what has been

Table 5. Average concentrations of selected chemical species from all examined laminae in the central Gulf of California, r is the correlation coefficient between the constituent and organic carbon. See Appendix 3 for raw data.

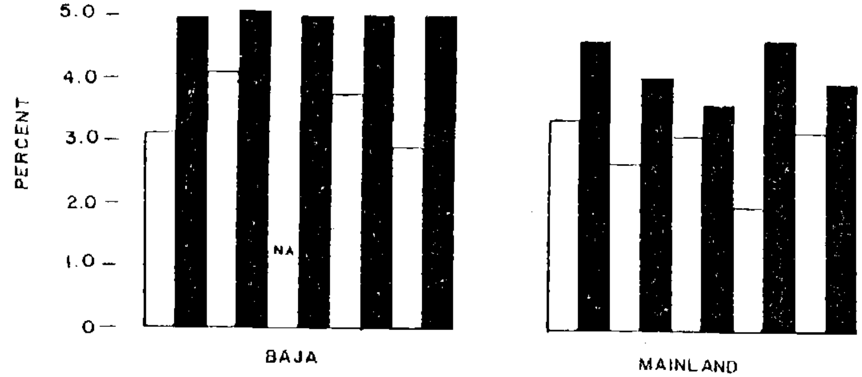
	Baja Side (Core B-29)			Mainland Side (Core E-7)		
	Light Laminae	Dark Laminae	r	Light Laminae	Dark Laminae	r
Cu (ppm)	24.5	36.1	.94	19.4	27.6	.71
Mn (ppm)	132.2	205.6	.96	92.3	184.7	.82
Fe (ppm)	13,475.3	19,751.7	.97	10,456.3	18,766.6	.82
Zn (ppm)	47.5	51.8	.66	55.9	95.6	.82
Ni (ppm)	20.9	34.4	.94	--	--	--
Ca (ppm)	16,093.4	23,880.2	.71	4,510.5	7,679.2	.75
K (ppm)	7,841.9	11,840.8	.90	8,100.4	16,080.4	.76
Al (ppm)	28,710.0	39,767.2	.91	25,806.1	48,439.4	.81
SiO_2 (weight %)	65.2	54.3	-.95	67.3	55.6	-.85
Organic Carbon (weight %)	3.48	5.04	1.00	2.87	4.20	1.00

Figure 8. Concentrations of selected chemical species in the ten laminae from the Baja side (core B-29, interval centered at 40 cm) and the ten laminae from the mainland side (core E-9, interval centered at 89 cm). The dark bars are dark laminae and the light bars are light laminae. In all plots laminae are arranged from left to right 1L, 2D, 3L, 4D, 5L, 6D, 7L, 8D, 9L, 10D.

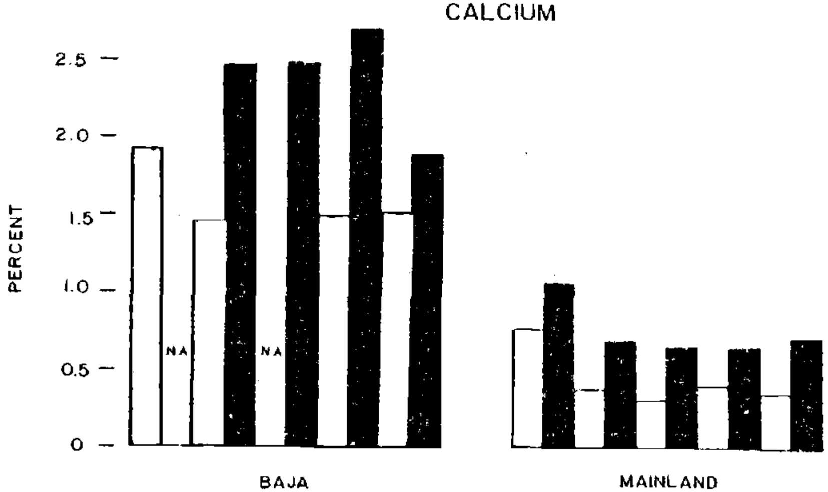
TOTAL SiO_2



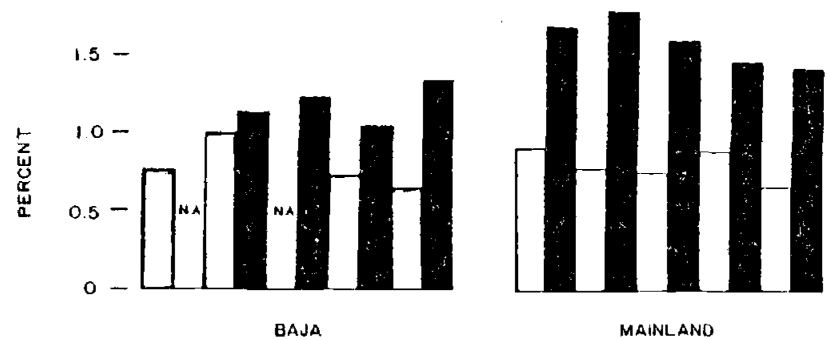
ORGANIC CARBON

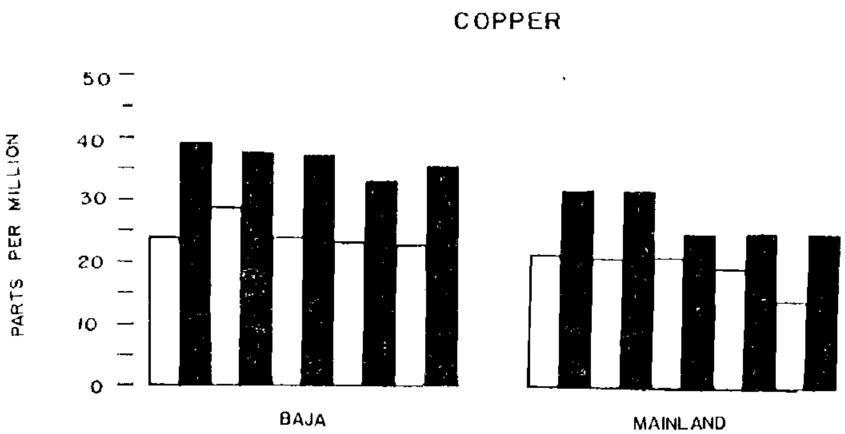


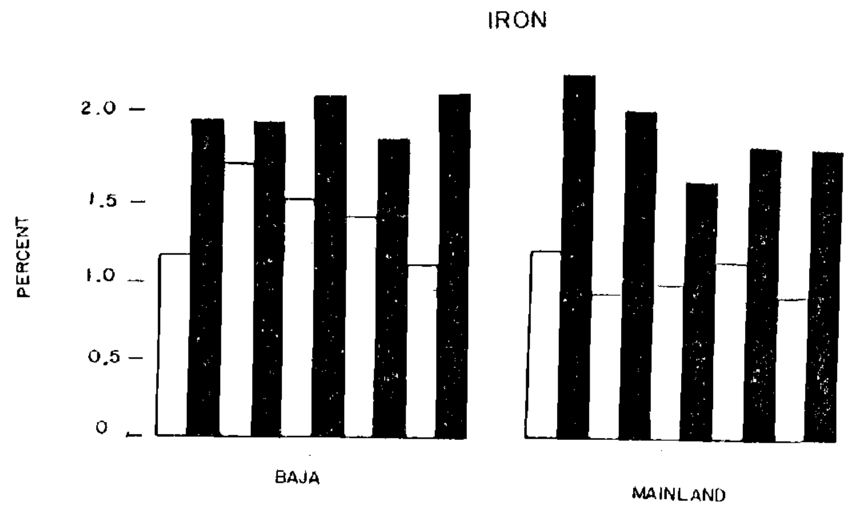
CALCIUM

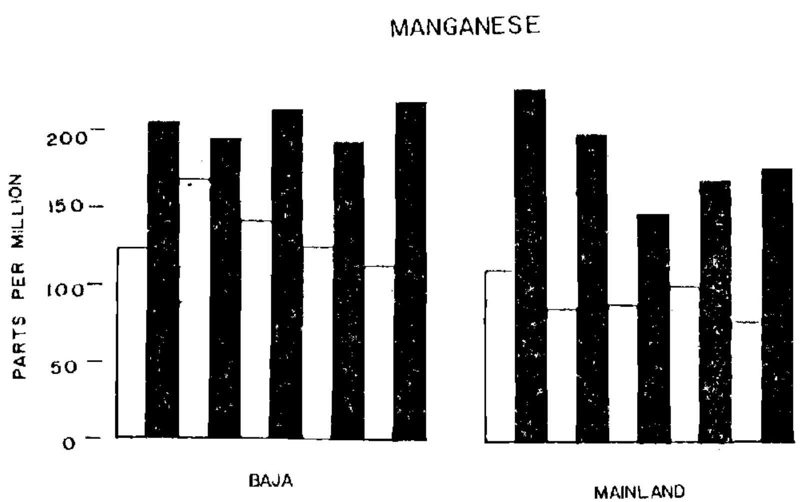


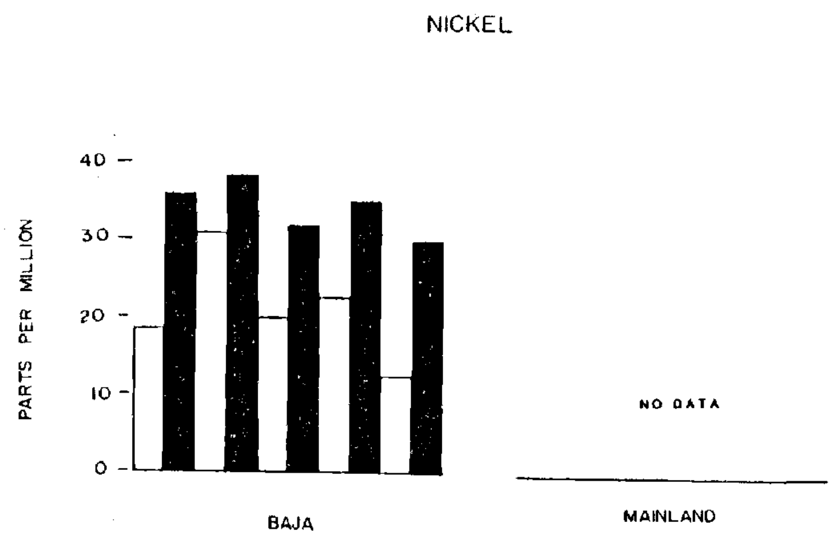
POTASSIUM




COPPER
PARTS PER MILLION
50
40
30
20
10
0
BAJA
MAINLAND


IRON
PERCENT
2.0
1.5
1.0
0.5
0
BAJA
MAINLAND


MANGANESE
PARTS PER MILLION
200
150
100
50
0
BAJA
MAINLAND


NICKEL
PARTS PER MILLION
40
30
20
10
0
NO DATA
BAJA
MAINLAND

reported by other workers for hemipelagic sediments from various localities (Table 6), and somewhat lower than what Wedepohl (1960) reported as average values for nearshore sediments. Gross (1967) in his analysis of minor elements in the diatomaceous sediments of the central basin in Saanich Inlet (Vancouver Island, British Columbia) also examined several laminae couplets. Although the ranges as presented in Table 6 show considerable overlap, in nearly every sample pair the dark laminae had a higher metal concentration than the light (see Gross, 1967, Table 3, page 278 for data). This is similar to what is found in the Gulf sediments.

The high correlation of all constituents to organic carbon suggests an association with organic matter. Calvert and Price (1970) also found reasonably high correlations between organic carbon and Cu, Zn, Ni, and Pb (r = +.707, +.654, +.640, and +.223, respectively) off SW Africa. On the other hand, Murty et al. (1976) found no correlation between Ni and organic carbon contents in sediments recovered from the shelf off the west coast of India, and Hartmann et al. (1976) found no correlation between trace metals and C-org from the NW African shelf. In both areas organic carbon values were found to be generally less than 3 percent. Kuijpers (1974) showed that although significant amounts of metals get transported to the sea floor by being bound to organic detritus much of the metals are soon lost through remineralization. Hartmann et al. (1976) suggested that only in areas with extremely high organic carbon values will there be a correlation between these metals and organic carbon.

Table 6. Comparison of minor element concentrations in the laminated sediments of the central Gulf of California with other hemipelagic sediments.

	Copper (ppm)	Nickel (ppm)	Lead (ppm)	Zinc (ppm)	Manganese (ppm)	Iron (%)
Gulf of California (this study)						
Baja Side (core B-29)						
Dark Laminae	33-38	30-38.5	0-Tr	42-73	193-219	1.8-2.1
Light Laminae	23-29	12.5-31	0-Tr	20-90	103.5-169	1.1-1.6
Mainland Side (core E-9)						
Dark Laminae	25-32	NA	0-Tr	80-111	148-229	1.5-2.2
Light Laminae	14-21	NA	0-Tr	51-61	78-111	0.9-1.2
Saanich Inlet, central basin sediments (Gross, 1976)						
Composite samples	30-120	19-34	Tr*	48-180	270-370	1.2-2.9
Dark Laminae	27-47	21-37	0-160	NA	250-670	1.7-2.8
Light Laminae	20-36	15-25	0-Tr	NA	190-410	1.0-2.3
NW African Continental Margin (Hartmann et al., 1976)	11-70	NA	NA	28-120	59-1800**	.76-5.03
SW African Shelf (Calvert and Price, 1970)	18-129	35-455	3-32	18-337	NA	NA
Gulf of Paria, clay samples (Hirst, 1962)	15-20	22-34	13-32	NA	NA	NA
Average values for nearshore sediments (Wedepohl, 1960)	48	55	20	95	850	4.83

Tr = trace
NA = not analyzed
*One sample had 7 ppm.
**One sample had 3725 ppm.

The organic carbon values on the shelf off SW Africa are extremely high, exceeding 20 percent in some cases (Calvert and Price, 1970). However, the high correlation between organic carbon and trace metals found in the laminated sediments in the central Gulf of California where C-org values are generally between 3 and 5 percent suggests that other factors may affect the metal remineralization (and conversely accumulation) rates other than just absolute C-org values. The simplest factor may be the sedimentation rate, which as Müller and Suess (1979) have shown, the fraction of primary produced organic carbon preserved is directly related to the sedimentation rate. The sedimentation rate on the SW African shelf may be as high as 150 cm/1000 years (Schuette and Schrader, 1981 as reported by Meyer, 1973) while on the NW African shelf the rates are generally less than 12 cm/1000 years (Hartmann et al., 1976). Sedimentation as estimated by varve counting indicates that the laminated sediments in the central Gulf of California are accumulating at approximately 185 cm/1000 years (see the section of this paper on sedimentation rate determinations). Thus, high sedimentation rates may protect metals at the sediment water interface by inhibiting the remineralization process at the sediment surface. This alone however does not explain why absolute concentrations of metals are so similar on the NW African shelf (Hartmann et al., 1976) , the SW African shelf (Calvert and Price, 1970) and in the central Gulf.

A better method than absolute concentrations of metals when comparing different areas is metal accumulation rates. Accumulation rate calculations include a sedimentation rate factor which eliminates dilution effects. The factor of 10 slower sedimentation of the NW African shelf sediments will result in proportionately lower accumulation rates. Metal accumulation rates were calculated using the expression of Dymond and Veeh (1975), $A = C \cdot S \cdot \rho \left(\frac{100-W}{100}\right)$, where

A = accumulation rate (mg/cm^2/1000 years)

C = concentration of element (mg/g)

S = sedimentation rate (cm/1000 years)

ρ = wet bulk density of the sediment (g/cm^3)

w = water content (percent)

A wet bulk density of 1.11 g/cm^3 and a water content of 84 percent are typical for the laminated sediments in the central Gulf (unpublished data, BAM 1980 cruise), and were used in the calculations. A sedimentation rate of 185 cm/1000 years was used in the calculations (Table 7).

When determining the contribution of the dark versus light laminae, sedimentation rates of 432 cm/1000 years and 103 cm/1000 years, respectively were incorporated. These values were derived from average dark and light laminae thicknesses (1.08 mm and 0.77 mm, respectively) and assumed depositional time of the light and dark laminae (3 months and 9 months, respectively). The average laminae thicknesses were determined by counting and measuring all the laminae in Box core BAV 79 E-7 (Table 1) using a binocular microscope equipped with a calibrated ocular. Rainfall data (from the Secretaria de Recursos Hidraulicos, compiled in Calvert, 1966b) show that more than 70 percent of the rain within the central Gulf falls in the months of July through

September. I am assuming that the dark laminae represent the 3 month rainy season and the light laminae represent the 9 month dry season.

Although the same bulk density and water content values were used in calculating the accumulation rates for the laminae as were used for the composite samples, this is not strictly accurate. The dark laminae are heavier than the light and probably contain less water, but no suitable method was found to determine wet bulk density and water content on individual laminae.

The metal accumulation rates are summarized in Table 7. Also in Table 7, for comparison, are metal accumulation rates reported by Niemitz (1977) for the Farallon Basin and Pescadero Basin in the southern Gulf of California (compare Figure 1), a value for the East Pacific Rise (Bender et al., 1971) and a value for the Bauer Deep (Dymond et al., 1976). Accumulation rates calculated in this study are similar on both sides of the Gulf and are about an order of magnitude higher than the other reported values. Niemitz's values, which are more comparable to those from the East Pacific Rise and Bauer Deep, were calculated using sedimentation rates 50 to 70 percent less than what I determined for the slope deposits and used in my calculations. Aside from Fe, most of the difference between Niemitz's data (from the basins) and the slope data can be accounted for by the sedimentation rate differences. If the Fe is associated with detrital phases as Niemitz suggests, then the discrepancy may be due in part to the greater distance from continental sources of the basin samples. I agree with Niemitz's conclusion that the Gulf of California and East Pacific Rise region

Table 7. Metal accumulation rates of composite samples and average accumulation rates of dark and light laminae for the laminated slope sediments in the central Gulf of California. For comparison, metal accumulation rates reported for basin sediments in the southern Gulf of California and the Southeast Pacific are included.

Sample Name and Location	Water Depth (m)	Sed. Rate (cm/1000yr)	Wet Bulk Density (g/cm^2)	Water Content (%)	Accumulation Rates ($mg/cm^2/1000yr$)				
					Cu	Mn	Fe	Zn	Ni
Gulf of California Slope Sediments:									
Composite Samples									
Baja Side (BAV79 B-29)									
Composite sample from 37.5-42.5 cm	635	185	1.11	84	0.995	5.549	545.853	1.631	0.908
Mainland Side (BAV79 E-9)									
Composite sample from 87-91 cm	660	185	1.11	84	0.820	5.094	514.317	2.367	--
Individual laminae samples (average values)									
Baja Side (BAV79 B-29)									
Dark Laminae	635	432	1.11	84	2.770	15.774	1515.414	3.974	2.639
Light Laminae	635	103	1.11	84	0.448	2.418	246.501	0.869	0.382
Mainland Side (BAV79 E-9)									
Dark Laminae	660	432	1.11	84	2.118	14.171	1439.834	7.335	--
Light Laminae	660	103	1.11	84	0.355	1.688	191.275	1.023	--
Gulf of California Basin Sediments									
Farallon Basin[1]									
R-82	3,165	100	1.0	53	0.056	8.60	66.0	0.68	0.033
Pescadero Basin									
R-47	2,822	46	1.0	63	0.14	1.17	41.5	0.36	0.12
South East Pacific									
East Pacific Rise[2]									
V19-54	2,830	1.5	1.34	61	--	28.0	82.0	--	0.16
Bauer Deep[3]									
DSDP Site 319 (0-8 m)	4,290	0.11	1.16	79	--	0.86	2.9	--	0.022

[1]Niemitz, 1977
[2]Bender *et al.*, 1971
[3]Dymond *et al.*, 1976

are not strictly relatable and that the Gulf sediments should be compared to other hemipelagic nearshore sediments. Unfortunately little if any work has been done with metal accumulation rates in hemipelagic sediments.

The role phytoplankton play in controlling the flux of trace metals to the sediment is not well understood. Plankton are known to concentrate some metals to levels higher than that of the surrounding seawater (Riley and Roth, 1971; Knauer and Martin, 1973; Sunda, 1975; Evans, 1977). Brongersma-Saunders (1965, 1969) suggested that the sediments may then be directly enriched in these metals and that beneath areas of high primary productivity one would expect to find higher concentrations than in comparable shelf sediments. Gross (1967) and Calvert and Price (1970) however found the highest trace metal concentrations in sediments containing the least biogenous material. Both authors attributed this to a dilution of the metal contents by diatom frustules which are presumably metal free, because organisms concentrate the metals in their cytoplasm and not in their skeletal material (Riley and Chester, 1971; Collier, 1981).

The factors affecting the concentrations of trace metals in seawater and sediment were studied by Krauskopf (1956). He concluded that the concentrations in the water are controlled chiefly by adsorption (by ferrous sulphide, hydrated ferric oxide, hydrated manganese oxide, clay, and organic matter) with some concentration supplemented by organic reactions and by precipitation in sulphide-rich environments. Most subsequent authors felt that in nearshore sediments the metals are primarily associated with the terrigenous rather than biogenous or authigenic fractions (Wedepohl, 1960; Hirst, 1962; Gross, 1967; Murty et al., 1970). This would seem consistent with individual laminae data of the Gulf which shows higher trace metal contents in the terrigenous rich dark laminae (Table 5, Appendix 3). But considering the high degree of correlation of trace metal concentrations to organic carbon and since the bulk of the organic matter is of marine origin (Simoneit et al., 1979) it seems possible that the clays may be adsorbing the organic material in which the trace metals are already bound.

Microscopic examination shows that the organic matter consists primarily of humic substances (C. Reimers, pers. comm., 1981). Humus is known to both concentrate inorganic trace elements (Sholkovitz, 1976) and to be absorbed onto the surface of minerals (Gjessing, 1976). Since the microfloral analyses suggest that the most intense upwelling is represented by the light laminae, the light laminae are then associated with the highest production of organic material. The presence of less terrigenous material in the light laminae would then mean less organics could be adsorbed with resultingly less trace metals accumulated. While the ultimate accumulation of trace metals may be due to the availability of terrigenous particles to act as binding sites for the organics the original concentration of the metals and transport to the sea floor may be controlled by phytoplankton.

Two other sources in the Gulf which may affect metal concentrations in the sediment should be mentioned. On the Baja side there may be a direct enrichment of metals due to runoff from the metalliferous rich volcanic rocks of the central Baja Peninsula. The Boleo copper deposit, Lucifer manganese deposit (both found near Santa Rosalia), and the Punta Conception manganese deposit are all near the western side of the Guaymas Basin. The samples analyzed were deposited prior to the initiation of mining operations in the late 19th century (see the section on sedimentation rates); however, some metal enrichment to the sediments is likely. The amount of metals added to the system from this source was not estimated but is probably not important.

There may also be an enrichment of metals in the sediment due to hydrothermal activity. No thermal anomalies which could be associated with modern hydrothermal venting have been found in the Gulf (Lawver et al., 1975; Williams et al., 1979; Lonsdale et al., 1980). However, some surface metallogenic enrichment has been reported for sediments of the central basin (M. Kastner in Williams et al., 1975) and a hydrothermal crust was sampled by Lonsdale et al. (1980) which are evidence of recent hydrothermal activity. Metals from hydrothermal sources are probably insignificant farther up the slope where the high sedimentation rates mask the input.

Mineralogy

The individual laminae were analyzed by X-ray diffraction for clay mineralogy (<2 μm fraction) and the total mineral assemblage.

The X-ray diffractograms indicate that the <2 μm fraction is dominated by nonclay minerals, specifically biogenic opal which forms a broad bulge between approximately 17° and 29° 2Θ and quartz, with its characteristic 101 peak at 26.7° 2Θ (Figures 9 and 10).

On the mainland side of the Gulf (samples from BAV 79 E-9) all diffractograms of the <2 μm fraction, of the 10 laminae, show peaks of smectite (17 Å), illite (10 Å) and kaolinite/chlorite (7 Å). Using Biscaye's (1964) criteria for distinguishing kaolinite and chlorite, it was observed that very little chlorite is present. Because characteristic clay mineral peaks from the individual laminae were very small, sediment from the five light laminae were combined to form a compound light laminae sample and sediment from the five dark laminae were combined to form a compound dark laminae sample. Diffractograms of the compound dark and light laminae contain larger more distinct clay peaks than the individual laminae samples (Figure 9). The relative abundances of the three principle clay types were determined semi-quantitatively on the compound laminae samples using Biscaye's (1965) factors:

	light laminae	dark laminae
smectite	28.4%	17.5%
illite	45.0%	51.2%
kaolinite	26.6%	31.2%

The difference in the clay mineral composition between light and dark laminae, in view of the small peak areas and the general relation that precision diminishes as peak areas decrease, is not very significant. However, many more samples would need to be analyzed to determine if

Figure 9. X-ray diffractograms (3 to 30° 2Θ) of the <2 μm fraction of a compound light laminae (top) and a compound dark laminae (bottom) from the ten laminae sampled on the mainland side (core E-9, interval centered at 89 cm). Note the opal bulge between 17 and 29° 2Θ, the quartz peak, and the clay mineral peaks of smectite, illite, and kaolinite.

BAV 79 E-9

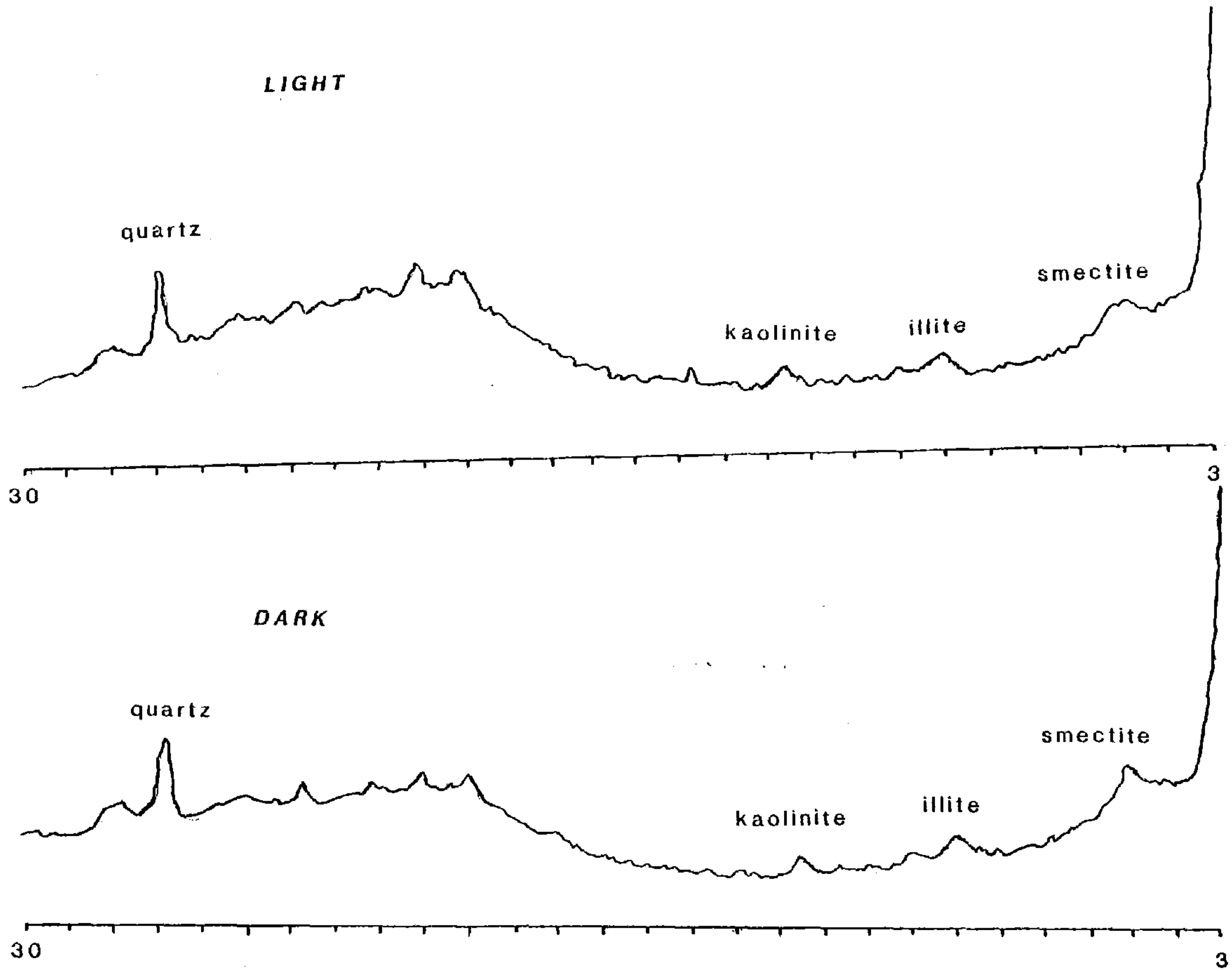
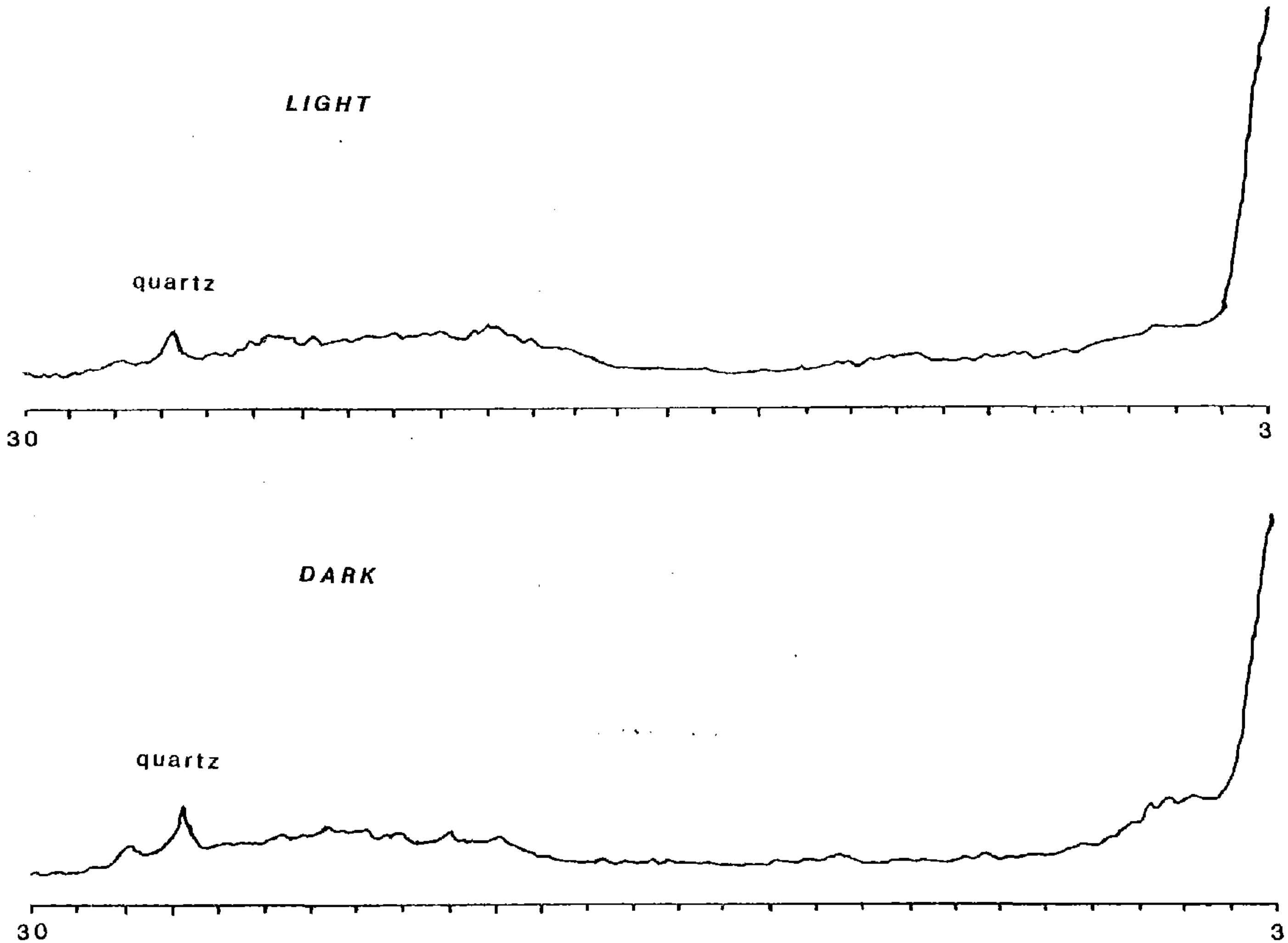

LIGHT
quartz
kaolinite
illite
smectite
30
3
DARK
quartz
kaolinite
illite
smectite
30
3

Figure 10. X-ray diffractograms (3 to 30° 2Θ) of the <2 μm fraction of a compound light laminae (top) and a compound dark laminae (bottom) from the ten laminae sampled on the Baja side (core B-29, interval centered at 40 cm). Similar to Figure 9 there is an opal bulge (17 to 29° 2Θ) and a quartz peak, but there are no well defined clay mineral peaks.

BAV 79 B-29



a clay mineral difference between laminae actually exists or not.

On the Baja side clay minerals are an even more subordinate member of the <2 μm fraction than on the mainland side. None of the diffractograms from the 10 individual laminae showed any clay mineral peaks. Compound light and dark laminae were again made, and although small peaks of smectite (at ∿ 5.2°2Θ) and kaolinite (at ∿ 12.5°2Θ) may be present, they are poorly defined (Figure 10). While this may be an artifact of the sample sizes it may also reflect a greater preponderance of mechanical than chemical weathering than is found on the mainland side. In general, the Gulf sediments are very immature and derived primarily from local and rather unstable sources (van Andel, 1964). The source areas around the Gulf are mountainous with an arid climate resulting in little chemical weathering and rapid erosion. This is particularly true for the Baja peninsula which has no permanent streams and sediment is supplied by arroyos, alluvial fans, and coastal erosion.

The weight percentages of quartz and plagioclase feldspar were determined quantitatively by X-ray diffraction using random oriented mounts of the bulk size fraction (Figures 11 and 12). Four laminae samples from each core were analyzed and the quartz and plagioclase weight percentages determined (Table 8). The quartz content is approximately 4 to 6 percent on both sides of the Gulf and is slightly higher in the dark laminae at both areas. Such quartz values are low for nearshore sediments (e.g., see Heath et al., 1974) and can be accounted for by dilution by diatom frustules (these values are not an

Table 8. The weight percentages of quartz and plagioclase, and the quartz : plagioclase ratio of 8 laminae from the central Gulf of California.

Sample number	percent quartz	percent plagioclase	Quartz / plagioclase
B-29 4D	6.01	8.51	.706
6D	5.54	11.32	.490
3L	4.20	16.11	.261
7L	4.17	12.01	.347
E-9 4D	4.73	7.35	.643
6D	5.98	6.27	.954
1L	4.10	3.68	1.115
3L	4.62	3.74	1.234

opal free percentage). The plagioclase, which is bytownite, is higher on the Baja side than the mainland side and this may reflect the volcanic nature of the Baja Peninsula (Allison, 1964). The plagioclase percentage is higher in the light laminae than the dark on the Baja side. The quartz : plagioclase ratio accentuates the difference at the two sites. Quartz : plagioclase values are similar in the dark laminae (between approximately 0.5 and 0.9) on both sides of the Gulf yet in the light laminae the ratio equals 0.2 to 0.3 on the Baja side and 1.1 to 1.2 on the mainland side (Table 8).

The quartz and plagioclase contents were determined by analyzing the bulk size fraction but as Gibbs (1967) pointed out, quartz and feldspar show a grain-size dependency so that the quartz : plagioclase ratio can vary within different size fractions of the same sample. Gibbs showed that feldspar are most abundant in the 10 to 12 μm range and quartz most abundant in the 5 to 7 μm range. This frequency distribution is consistent with the textural character of the non-biogenous Gulf sediments which are primarily clay sized particles on the mainland side and fine silt sized particles on the Baja side. While grain-size effects may have some influence on quartz : plagioclase ratios, Scheidegger and Krissek (in press) have shown the effect is probably not sufficient to explain the much higher plagioclase content on the Baja side.

Aside from quartz and plagioclase the only other mineral which appears on the diffractograms is calcite. Although not determined quantitatively calcite appears more abundant on the Baja side (Figures

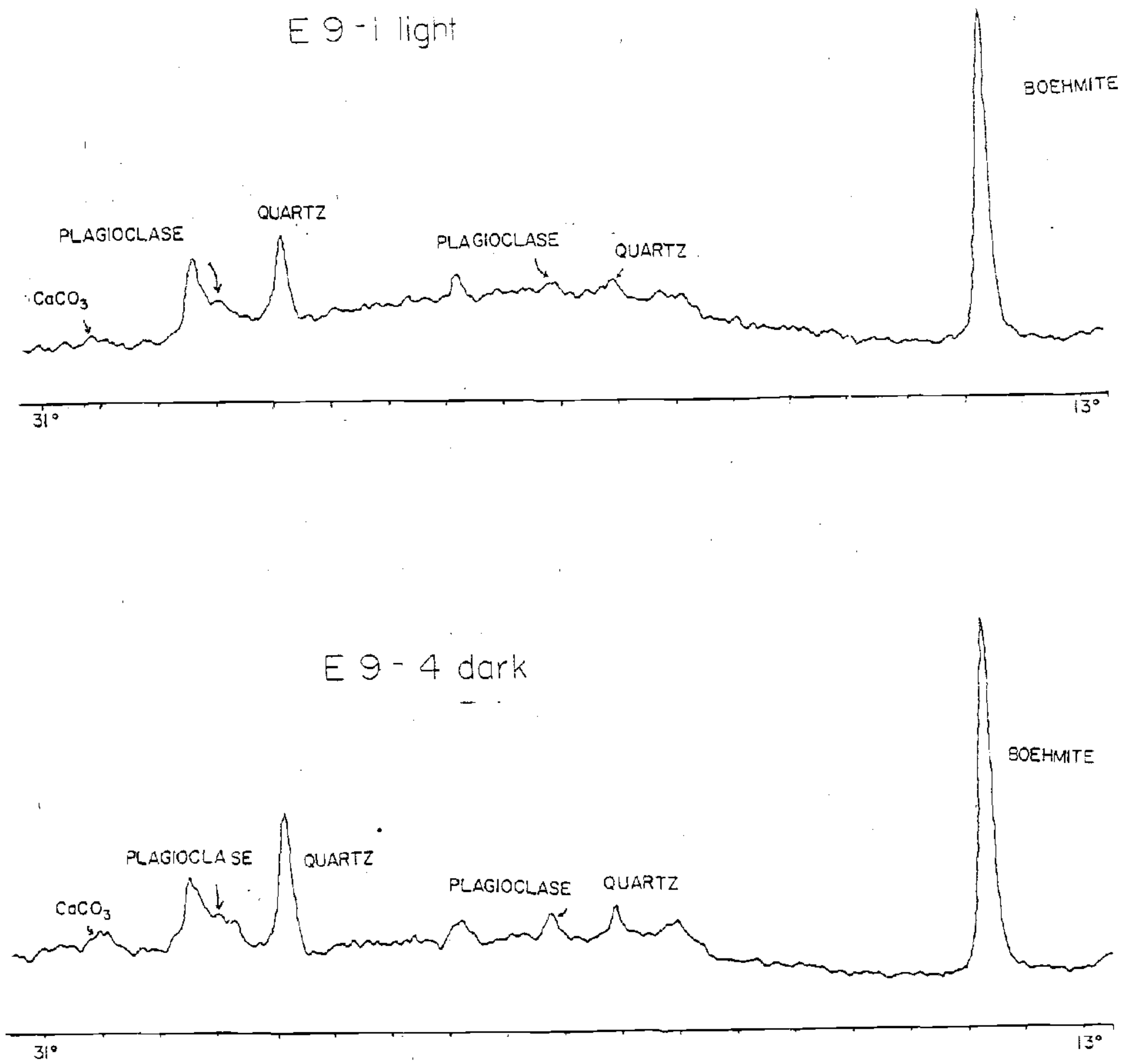


Figure 11. X-ray diffractograms (from 13 to 31°2Θ) of the dried original materials of lamina E-9 1L (top) and lamina E-9 4D (bottom), both are from the mainland side.

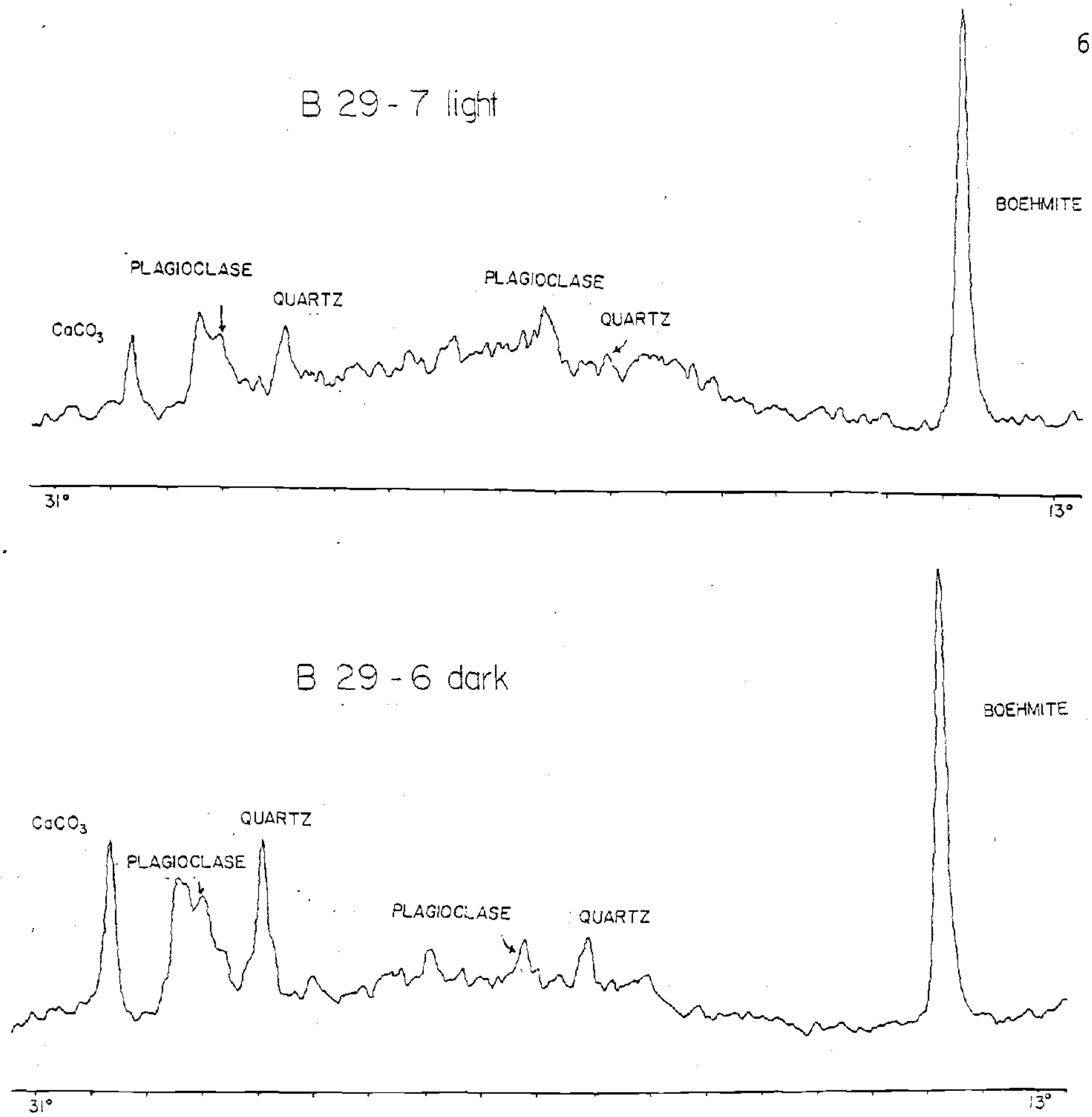


Figure 12. X-ray diffractograms (from 13 to 31°2Θ) of the dried original material of lamina B-29 7L (top) and lamina B-29 6D (bottom), both are from the Baja side.

11 and 12), an observation, consistent with the higher calcium content of these sediments. Microscopic examination suggests that the calcite is both authigenic/detrital and biogenic (calcareous nannoplankton). Calcareous nannoplankton were not observed in the samples from the mainland side.

The amount of terrigenous material which enters the Gulf via eolian transport is unknown but may be significant. The Gulf is located in a semiarid region and though the prevailing winds trend parallel to the axis of the Gulf the land-sea breeze system dominates near the coast (Roden, 1964). Should the offshore winds inject fine material up into the atmosphere deposition within the Gulf is not unlikely.

The role of eolian transport in the deposition of fine grain terrigenous particles is poorly understood and often a matter of conjecture. It is difficult to evaluate the quantitative contribution of eolian material, but globally transported dust may account for a few millimeters of sediment per 1000 years (Windom, 1969; Windom, 1975). While this is a proportionately significant contribution to the deep ocean, it amounts to a negligible addition for nearshore sediments. However, those values deal with world averages and not localized effects which may be important sources of sediment in arid regions.

Bonatti and Arrhenius (1965) reported a silty clay layer, 5 to 6 meters thick, in the Pacific Ocean west of the Baja Peninsula which they interpreted to be eolian in origin. Radiocarbon dating indicated that the deposit was older than 40,000 years. So, though not an indication of modern day eolian transport near Baja it emphasizes the importance of localized increases of eolian sediment in arid regions.

In summary, the mineralogy of the laminated sediments in the Gulf of California is dominated by biogenic opal. The non-opaline fraction consists of quartz, plagioclase (bytownite), calcite, and clay minerals. Quartz averages 5 to 6 percent (weight percent of untreated dry sediment) and is slightly higher in the dark laminae reflecting the higher terrigenous component of the dark laminae. Plagioclase ranges 3 to 16 percent (weight percent of untreated dry sediment) and is generally higher on the Baja side which is probably a combination of provenance and grain size effects. The plagioclase values are highest in the light laminae on the Baja side although the cause of this is not understood. The clay minerals present are smectite, illite, and kaolinite and were only identified in diffractograms of sediment from the mainland side of the Gulf.

Future work on individual laminae in the Gulf may provide interesting insights on the sedimentological processes occurring there if the problems inherent in working with small sample sizes can be overcome. The clay mineralogy can provide information regarding seasonal input or distribution fluctuations from the seasonally changing climatic regime. Should seasonal changes in the sediment input exist clay mineral analyses may also provide a clue as to the eolian influence on the sedimentation. An independent means for studying the seasonality of the laminae would be by pollen changes between individual laminae but this was not done in this study.

Laminae Formation

From the preceeding sections the interpretations are summarized as follows. On both sides of the central Gulf the light laminae represent the season of highest primary production as suggested by the higher abundances of the silicoflagellate Octactis pulchra in the light laminae. Higher numbers of Chaetoceros resting spores, a high productivity indicator, in the dark laminae is thought to reflect maximum production of the resting spores at the end of the highest productivity season and subsequent deposition during the next season. The higher abundances of Rhizosolenia bergonii, an oceanic diatom, and higher abundances of Dictyocha sp. 1 form A, Dictyocha sp. 1 form B, and Dictyocha sp. 2, interpreted to be stress related forms of Dictyocha calida reflecting increased Eastern Tropical Pacific Water entering the Gulf during the summer season of SE winds, all suggest a more oceanic flora in the dark laminae. In general, the mainland side has higher productivity than the Baja side as indicated by the higher numbers of Chaetoceros resting spores on the mainland side. The dark laminae on both sides of the Gulf have a higher terrigenous fraction than the light laminae and represent the rainy season.

These interpretations are contingent on the assumptions that: 1) two laminae equal one year, 2) there is no differential lag time between input into the system and deposition for the various components, and 3) the two short intervals analyzed are representative of the depositional scheme. Although exceptions to the last assumption undoubtably exist, i.e. dry summer seasons or wet winter seasons, a generalized model for laminae formation in the central Gulf can be postulated. This model pertains only to the portion of the central Gulf discussed in this paper. The region near the Ballenas channel, where tidal mixing maintains high productivity throughout the entire year, was discussed by Calvert (1966b).

In general, during the dry winter season of northwesterly winds, surface mixing occurs over the central Gulf with additional coastal upwelling triggered by Ekman transport on the mainland side. The winter season results in high productivity, relatively terrigenous free, light laminae on both the mainland and Baja sides. During the wet summer season, the weaker southwesterly winds also cause some surface mixing in the central Gulf but not as much as is caused by the northwesterly winter winds. Although localized coastal upwelling may also occur during the summer in the lees of capes and islands on the Baja side the response is not noticeable in the slope sediments. The southeasterly winds are associated with the rainy season which is responsible for the terrigenous input producing the dark summer laminae on both sides of the Gulf.

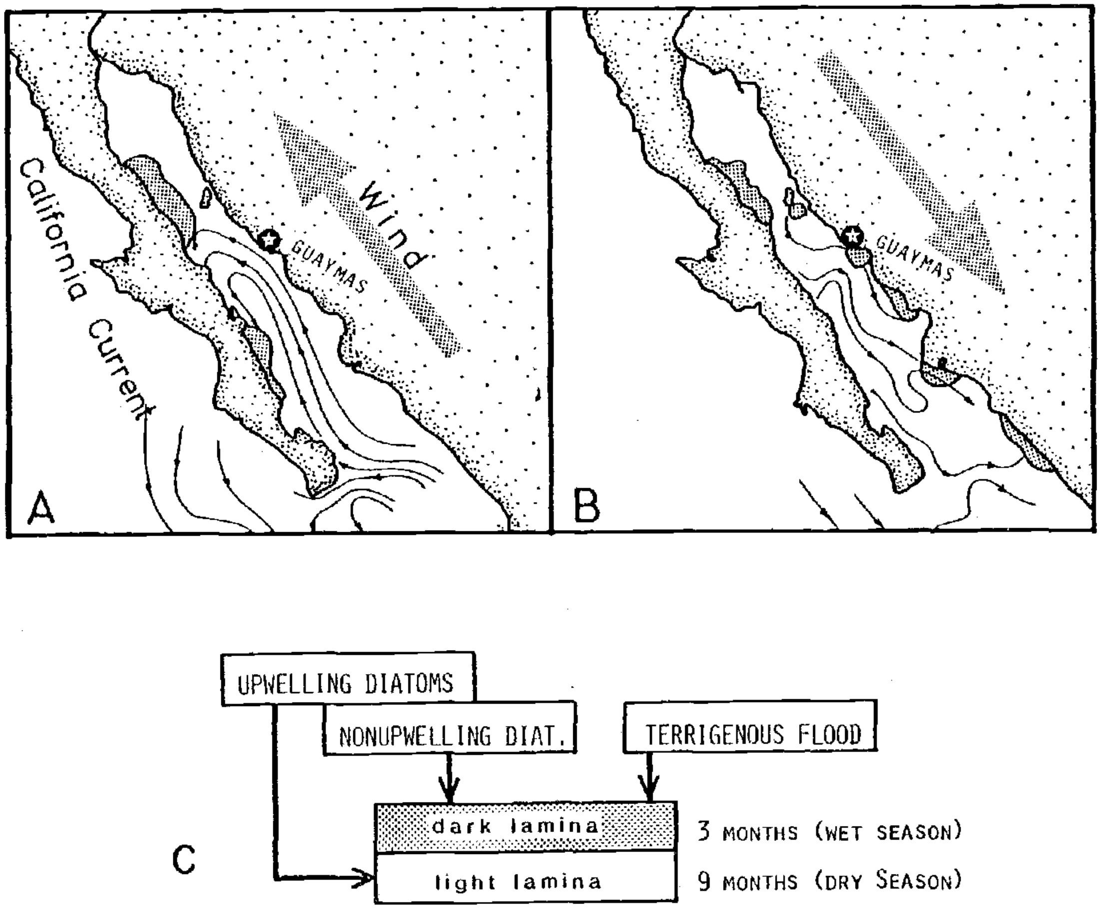


Figure 13. Generalized wind circulation and a model for laminae formation in the central Gulf of California. Wind circulation (large arrows), surface water currents (small arrows), and upwelling regions (hatched areas) during the wet season (A) and the dry season (B). Data from CALCOFI 5-23 June 1957 (A) and 6-26 February 1957 (B). Laminae formation model for the central Gulf (C): during the wet summer season of SE winds (A) there is a nonupwelling phytoplankton population and a terrigenous component, during the dry winter season of NW winds (B) there is an upwelling phytoplankton population and little terrigenous input.

CONCLUSIONS

1) The laminated slope sediments of the central Gulf are an example of a nearshore depositional system dominated by sedimentation of biogenous opal. The light laminae can be distinguished from the dark laminae by microfloral content, texture, trace metal and bulk chemical concentrations, and mineralogic composition.

2) Microfloral analysis suggests that on both sides of the Gulf the light laminae represent periods of higher productivity than the dark laminae, and in general, the mainland side has somewhat higher primary productivity than the Baja side.

3) The dark laminae contain more terrigenous material than the light laminae. The terrigenous material is primarily < 4 μm on the mainland side and 4 to 20 μm on the Baja side.

4) SiO_2, Cu, Mn, Fe, Zn, Ni, Ca, K, and Al all show a high correlation to organic carbon. SiO_2 is higher in the light laminae than the dark, and all other constituents are higher in the dark laminae. Values are comparable to those reported for other nearshore sediments underlying regions of high primary productivity, e.g., Southwest Africa, Northwest Africa, and Saanich Inlet.

5) Quartz, plagioclase, calcite, and clay minerals are present in the non-opaline fraction. The < 2 μm fraction is dominated by nonclay minerals; smectite, illite, and kaolinite are present in the sediments from the mainland side. Quartz ranges from 4 to 6 percent (weight percent untreated sediment) on both sides, being higher in the dark laminae. Plagioclase ranges from 3 to 16 percent (weight percent

untreated sediment); higher concentrations are found on the Baja side with the highest concentrations in the light laminae. Calcite although not measured quantitatively, appears to be more abundant on the Baja side than on the mainland and more abundant in the dark laminae.

6) A model proposed for laminae formation in the central Gulf suggests that both the mainland side and Baja side experience highest productivity in the dry winter season of northwesterly winds which result in the light laminae. During the wet summer season of south-easterly winds both sides of the central Gulf receive a pulse of terrigenous material which result in the dark laminae. Although both sides of the Gulf respond synchronously to the changing climatic regime the biological and sedimentological response is not exactly the same on each side.

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Appendix 1. Relative abundances of the opal microflora in the 10 laminae from the Baja side (BAV79 B-29, interval centered at 40 cm) and in the 10 laminae from the mainland side (BAV79 E-9, interval centered at 89 cm).

	BAJA SIDE										MAINLAND SIDE									
	1L	2D	3L	4D	5L	6D	7L	8D	9L	10D	1L	2D	3L	4D	5L	6D	7L	8D	9L	10D
Actinocyclus curvatulus	1.39	0.85	0.18	0.52	1.97	0.40	0.00	0.50	0.17	0.00	2.72	0.98	0.81	0.51	0.23	0.51	1.18	0.22	0.00	0.48
Actinocyclus octonarius	0.00	0.00	0.00	0.00	0.22	0.00	0.18	0.00	0.00	0.17	0.00	0.33	0.27	0.51	0.00	0.00	0.00	0.00	0.25	0.71
Actinocyclus subtilis	0.35	0.64	0.36	0.52	0.88	0.61	0.71	0.34	0.00	0.70	0.23	0.98	0.00	0.00	0.00	0.26	0.00	0.00	1.00	0.00
Actinoptychus senarius	8.36	7.46	2.74	3.10	7.67	3.64	2.32	3.70	1.20	4.01	9.42	3.61	6.50	4.36	3.99	1.29	6.19	4.72	9.25	2.38
Actinoptychus splendens	2.79	2.13	0.00	0.69	0.22	0.20	1.25	0.67	0.17	0.87	0.91	1.97	0.54	0.77	2.66	0.51	1.18	2.70	1.75	1.19
Amphora sp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00
Asteramphalus arachne	0.17	0.00	0.00	0.34	0.22	0.00	0.00	0.00	0.00	0.52	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00
Asteramphalus flabellatus	0.17	0.00	0.18	0.17	0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.45	0.00	0.24
Asteramphalus heptactis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.25	0.00
Bacteriastrum sp.	0.00	0.43	0.00	1.03	0.44	1.01	1.96	1.01	0.00	1.92	0.00	0.33	0.27	0.00	0.23	0.77	0.88	1.35	0.00	0.48
Cocconeis sp.	0.35	0.21	0.00	0.17	0.22	0.00	0.00	0.17	0.00	0.17	0.00	0.00	0.00	0.51	0.00	0.26	0.00	0.00	0.00	0.24
Coscinodiscus crenulatus	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.34	0.34	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coscinodiscus nodulifer	0.00	0.00	0.73	1.03	0.66	2.02	5.70	11.28	0.00	1.57	0.45	0.66	16.26	2.82	0.46	0.26	0.59	1.35	1.00	0.95
Coscinodiscus obscurus	0.52	0.43	0.18	0.34	0.22	0.00	0.18	0.00	0.00	0.00	0.91	0.33	0.54	0.51	0.00	0.00	0.00	0.00	0.75	0.00
Coscinodiscus oculus-iridis	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.45	0.00	0.27	0.00	0.23	0.00	0.00	0.22	0.00	0.00
Coscinodiscus perforatus	0.35	0.00	0.18	0.00	0.22	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coscinodiscus radiatus	2.61	2.34	2.19	3.27	3.73	1.21	1.43	2.19	0.85	2.09	0.68	0.33	1.90	2.82	0.46	0.26	0.59	1.57	2.25	0.71
Coscinodiscus stellaris	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.34	0.00	0.23	0.00	0.00	0.51	0.46	0.51	0.29	0.00	0.25	0.00
Cyclotella striata/stylorum	1.92	17.06	11.86	7.57	4.60	6.06	3.92	5.89	1.88	10.98	6.35	22.29	10.38	13.33	4.36	2.83	1.18	9.66	4.75	10.48
Dictyocha calida	0.00	0.21	0.00	0.44	0.00	0.00	0.00	0.00	0.00	0.17	0.23	0.00	0.27	0.26	0.00	0.00	0.00	0.45	0.25	0.00
Dictyocha messanensis	0.17	1.07	0.73	3.96	0.66	0.81	0.18	1.35	0.34	1.04	0.23	0.00	0.27	0.51	0.46	0.26	0.29	0.45	0.75	0.24
Dictyocha sp. 1A	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.00
Dictyocha sp. 1B	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.33	0.00	0.77	0.23	0.00	0.00	0.00	0.00	0.00
Dictyocha sp. 2	0.00	1.92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ditylum brightwellii	0.00	0.21	0.36	0.34	0.66	0.20	0.71	0.34	0.00	0.34	0.00	0.66	0.27	0.00	0.00	0.51	0.29	0.67	0.25	0.00
Hemidiscus cuneiformis	0.35	0.64	0.18	0.52	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00

	BAJA SIDE										MAINLAND SIDE									
	1L	2D	3L	4D	5L	6D	7L	8D	9L	10D	1L	2D	3L	4D	5L	6D	7L	8D	9L	10D
Nitzschia bicapitata	0.00	0.00	0.00	1.55	0.44	3.43	0.53	0.67	1.20	1.57	0.91	0.98	0.27	0.77	0.00	4.38	0.88	0.90	0.50	4.50
Nitzschia marina	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.98	0.27	0.51	0.00	0.00	0.00	0.90	2.00	0.71
Nitzschia sicula	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.24
Octactis pulchra	4.70	3.41	1.28	1.03	1.53	1.82	2.32	0.84	0.85	1.74	0.45	1.31	0.27	1.03	0.92	1.03	0.59	1.12	1.50	1.43
Ondontella sp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.77	0.29	0.22	0.25	0.00
Plagiogramma interruptum	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Planktoniella sol	0.87	0.43	0.91	0.00	0.00	0.20	0.00	1.01	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pseudoeunotia doliolus	43.55	20.68	16.79	25.99	19.96	22.02	39.39	36.19	24.10	20.73	10.65	17.38	18.97	12.56	22.48	13.66	29.79	8.09	18.50	13.57
Rhizosolenia alata	0.35	0.21	0.55	0.34	1.32	0.40	0.36	0.17	0.17	1.04	0.23	0.66	0.54	1.03	1.60	1.03	0.29	0.67	0.25	1.19
Rhizosolenia bergonii	0.00	0.00	0.36	0.86	0.66	1.21	0.18	1.18	0.00	0.87	0.45	1.31	0.27	0.51	0.46	1.03	0.00	1.80	0.25	2.38
Rhizosolenia calcar-avis	0.00	0.43	0.91	0.52	0.44	0.00	0.36	0.50	0.17	1.39	0.68	1.31	0.27	1.28	0.23	1.80	0.00	1.80	0.50	1.67
Rhizosolenia robusta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00
Rhizosolenia setigera	0.00	0.00	0.18	1.03	0.22	1.41	0.71	0.67	0.00	0.70	0.00	0.33	0.00	0.00	0.00	1.03	0.29	1.80	0.00	0.95
Rhizosolenia styliformis	0.17	0.21	0.18	0.17	0.00	0.40	0.18	0.00	0.34	0.00	0.23	0.66	0.27	0.26	0.46	1.29	0.00	0.67	0.50	1.43
Roperia tesselata	2.79	9.59	22.44	3.96	1.32	1.41	3.39	2.52	0.00	1.74	0.68	3.93	1.35	1.03	2.29	2.83	1.18	3.59	15.00	1.19
Skeletonema costatum	0.00	0.00	0.00	0.69	0.00	0.20	0.36	0.67	0.00	0.00	2.49	0.00	0.00	0.00	22.71	2.06	0.59	0.00	5.25	2.62
Stephanopyxis turris	0.00	0.00	0.00	0.34	0.44	0.00	0.00	0.17	0.00	0.00	0.68	0.00	0.27	0.00	1.38	0.51	0.59	0.67	0.50	0.24
Surirella fastuosa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	0.00
Synedra indica	0.00	0.00	0.00	0.34	0.22	1.82	1.07	0.67	1.03	0.00	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	1.19
Synedra sp.	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.17	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalassionema bacillaris	0.00	0.00	0.00	0.34	0.00	2.02	1.43	1.51	3.20	1.92	1.36	0.98	1.35	1.79	0.92	2.32	2.36	1.35	1.00	0.48
Thalassionema nitzschioides	0.00	0.43	0.18	0.00	0.44	0.20	0.00	0.00	0.00	0.17	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalassionema nitzschioides v. parva	1.74	0.21	2.01	3.79	6.14	4.44	2.85	2.02	17.95	1.74	0.45	0.33	1.63	1.03	0.23	3.09	7.37	3.15	1.00	1.90
Thalassionema sp. 1	0.00	0.00	0.00	0.17	0.22	0.00	0.18	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalassiosira eccentrica	2.09	0.85	0.91	0.34	0.88	1.01	0.71	0.34	1.03	0.17	0.00	0.00	0.27	0.26	0.69	0.26	0.00	0.45	0.50	0.00
Thalassiosira leptopus	0.00	0.21	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.23	0.33	0.27	0.00	0.00	0.77	2.36	0.22	3.25	0.48
Thalassiosira lineata	0.70	0.64	0.55	0.17	0.22	0.61	0.00	0.50	0.00	0.70	0.91	0.33	0.27	0.00	0.46	1.55	0.00	0.00	0.25	0.95
Thalassiosira oestrupii	1.04	1.28	0.73	2.92	2.63	2.22	3.56	2.69	1.71	1.74	3.17	2.62	4.06	2.05	0.69	3.35	0.29	1.35	0.75	0.48

	BAJA SIDE										MAINLAND SIDE									
	1L	2D	3L	4D	5L	6D	7L	8D	9L	10D	1L	2D	3L	4D	5L	6D	7L	8D	9L	10D
Thalassiosira pacifica	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.26	0.00	0.26	0.00	0.00	0.00	0.24
Thalassiosira plicata	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalassiosira punctifera	0.00	0.00	0.18	0.00	0.00	0.61	0.53	0.00	0.51	0.17	0.00	0.00	0.54	0.00	0.23	0.51	0.00	0.00	0.00	0.00
Thalassiosira simonsenii	0.17	0.00	0.00	0.17	1.97	0.61	0.18	0.67	0.34	0.52	0.23	0.00	0.00	0.00	0.00	0.00	0.00	1.12	0.25	0.48
Thalassiosira sp.	0.52	0.43	0.55	0.69	1.32	1.01	1.43	0.00	0.68	1.39	2.04	1.64	2.71	1.03	1.83	0.77	0.59	0.90	0.25	0.24
Thalassiosira spinosa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00
Thalassiosira symmetrica	0.35	0.00	0.91	0.34	0.00	1.21	0.53	0.17	0.00	0.00	0.23	0.33	1.63	0.77	0.23	1.03	0.00	0.67	0.75	0.95
Thalassiosira tenera	0.00	0.00	0.55	0.00	0.00	0.00	0.00	0.00	0.17	0.17	0.00	0.00	0.54	0.77	0.23	0.51	0.00	0.22	0.00	0.00
"small" Thalassiosira*	3.66	3.20	2.92	1.03	1.32	2.22	0.53	1.35	0.85	0.87	0.68	1.97	0.27	1.79	0.23	1.80	0.00	1.12	0.00	0.95
Thalassiothrix longissima	0.52	0.00	0.91	1.20	0.44	0.00	0.36	0.17	0.34	1.24	0.45	1.64	0.81	3.59	1.38	1.03	2.06	2.92	0.75	1.97
Thalassiothrix mediterranea	0.17	0.00	0.18	0.69	0.22	0.20	0.89	0.34	0.00	0.34	0.23	1.97	1.08	1.79	0.69	0.26	1.18	1.35	0.25	0.71
Thalassiothrix pseudonitzschioides	13.59	18.12	20.62	23.58	32.02	31.11	18.00	14.98	37.44	29.09	48.53	25.90	22.76	36.41	26.38	42.53	35.10	38.88	22.52	38.57
Thalassiothrix vanhoeffenii	0.00	0.43	0.00	0.17	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total counted	574	469	548	581	456	495	561	594	585	574	441	305	369	390	436	388	339	445	400	420
Chaetoceros resting spores**	19.0	34.0	11.0	39.0	14.0	32.0	16.0	28.0	12.0	38.0	37.0	49.0	33.0	59.0	55.0	42.0	15.0	49.0	40.0	56.0

* Centric diatoms less than 10 μm diameter which could not be distinguished by valve structure were grouped as "small" Thalassiosira.

** The percentage of Chaetoceros resting spores is based on a subsample of 100 diatoms counted from one pass across the middle of the coverglass.

Appendix 2. Relative abundances of silicoflagellate species observed in the 10 laminae from the Baja side (BAV79 B-29, interval centered at 40 cm) and the 10 laminae from the mainland side (BAV79 E-9, interval centered at 89 cm).

		Octactis pulchra	Dictyocha messanensis	Dictyocha calida	Dictyocha species 1 form A	Dictyocha species 1 form B	Dictyocha species 2	Total
B-29	1L	86	6	4	3	1	0	102
	2D	45	27	8	3	1	15	108
	3L	37	46	8	1	4	4	102
	4D	24	58	14	2	2	0	122
	5L	57	20	21	1	0	1	101
	6D	40	46	10	1	2	1	116
	7L	77	22	1	0	0	0	126
	8D	34	45	18	2	2	0	103
	9L	84	11	4	1	0	0	100
	10D	33	47	13	4	2	1	100
E-9	1L	64	27	7	2	0	0	100
	2D	40	21	11	21	4	2	84
	3L	45	38	6	6	5	0	100
	4D	32	35	8	11	13	1	100
	5L	52	41	0	2	6	0	101
	6D	48	27	7	11	7	0	90
	7L	41	46	8	2	2	1	90
	8D	38	25	27	4	4	2	100
	9L	60	17	21	1	1	0	100
	10D	67	7	8	8	8	2	101

Appendix 3. Concentrations of chemical species in the 10 laminae from the Baja side (BAV79 B-29, interval centered at 40 cm) and the 10 laminae from the mainland side (BAV79 E-9, interval centered at 89 cm).

		Cu (ppm)	Mn (ppm)	Fe (ppm)	Zn (ppm)	Ni (ppm)	Ca (ppm)	K (ppm)	Al (ppm)	SiO_2 (weight percent)	org C (weight percent)
B-29	1L	24.0	123.1	11,787.3	39.0	18.5	19,379.7	7,713.9	---	64.9	3.14
	2D	38.2	206.8	19,461.9	42.4	36.1	---	---	---	---	5.01
	3L	28.75	168.7	16,701.0	56.6	31.0	14,647.8	10,099.0	34,248.5	59.9	4.12
	4D	37.1	195.1	19,309.1	45.2	38.5	24,712.8	11,189.5	38,606.7	55.9	5.10
	5L	23.85	140.8	14,377.9	89.9	19.6	---	---	---	---	---
	6D	37.2	214.0	20,723.0	74.0	32.3	24,720.0	12,203.0	40,927.8	52.2	5.02
	7L	23.0	124.7	13,277.1	31.9	22.7	15,021.4	7,221.9	23,171.6	66.05	3.76
	8D	32.9	193.3	18,290.7	47.7	35.1	27,068.1	10,518.9	---	56.2	5.04
	9L	22.8	103.5	11,233.2	20.3	12.5	15,324.8	6,332.9	---	70.0	2.89
	10D	35.1	218.75	20,973.75	49.5	30.0	19,019.7	13,451.6	---	52.9	5.03
E-9	1L	21.3	111.3	12,094.25	56.6	---	7,787.9	9,232.9	28,576.5	64.2	3.36
	2D	31.8	229.0	22,470.1	111.3	---	10,789.9	17,026.1	56,536.5	56.7	4.63
	3L	20.7	86.4	9,313.8	57.1	---	3,772.8	7,945.1	25,903.3	68.8	2.67
	4D	31.9	199.8	20,239.7	104.2	---	7,186.2	18,027.1	52,934.2	54.7	4.05
	5L	21.2	84.5	9,985.9	50.7	---	3,186.7	7,552.4	23,006.8	68.9	3.13
	6D	24.7	147.9	15,567.6	80.1	---	6,587.2	16,205.1	40,145.0	56.9	3.63
	7L	19.25	101.2	11,536.4	61.5	---	4,130.85	9,024.7	28,685.7	67.5	1.98
	8D	24.9	170.5	17,856.1	97.0	---	6,661.6	14,772.0	45,167.1	54.6	4.67
	9L	14.1	78.0	9,351.3	53.6	---	3,674.2	6,746.7	22,858.1	67.2	3.19
	10D	24.95	176.4	17,699.5	85.4	---	7,171.15	14,371.3	47,414.0	55.0	4.01

Appendix 4. Relative abundances of silicoflagellate species in 13 laminae from BAV79 E-10 (interval centered at 40 cm).

		Octactis pulchra	Dictyocha messanensis	D. calida	D. sp 1 A	D. sp 1 B	D. sp 2	Total
E-10	1L	92	8	0	0	0	0	100
	2D	74	16	3	4	2	1	100
	3L	82	13	3	1	0	0	99
	4D	53	24	3	10	4	4	210
	5L	90	7	1	0	0	1	200
	6D	62	7	10	9	1	10	155
	7L	80	6	4	8	1	0	200
	8D	78	14	4	3	0	2	200
	9L	82	10	4	4	0	0	200
	10D	93	3	2	1	1	0	500
	11L	80	17	0	3	0	0	100
	12D	82	6	0	6	4	2	200
	13L	95	4	0	0	0	0	300

MODERN ANALOGUES OF THE MIOCENE DIATOMACEOUS MONTEREY SHALE OF CALIFORNIA: EVIDENCE FROM SEDIMENTOLOGIC AND MICROPALEONTOLOGIC STUDY

by

Dave Donegan

and

Hans Schrader

School of Oceanography
Oregon State University
Corvallis, Oregon 97331

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MODERN ANALOGUES OF THE MIOCENE DIATOMACEOUS MONTEREY SHALE OF CALIFORNIA: EVIDENCE FROM SEDIMENTOLOGIC AND MICROPALEONTOLOGIC STUDY

ABSTRACT

The late Miocene diatomaceous shales of the Monterey Formation are compared to recent laminated sediments from the Gulf of California and the Santa Barbara Basin. The modern examples represent two different depositional environments: a) an anoxic basin (the Santa Barbara Basin) and b) continental slopes where the oxygen minimum zone impinges on the sediment water interface (the central and southern Gulf of California). Based on compositional (both amount and composition of terrigenous and biogenous components) evidence the sediments being deposited on the slopes in the Gulf of California provide a better modern analogue to the laminated siliceous shales of the Monterey Formation than do the sediments in the Santa Barbara Basin (see Table 1).

INTRODUCTION

The Monterey Formation has long been recognized as a major oil producing formation in California, prompting considerable research interest over the past few decades. The Monterey is thought to represent a basinal facies within the generalized Neogene sequence found in the central and southern coast ranges of California (Ingle, 1980). This basinal facies consists of three distinct sedimentary units: 1) a lower calcareous unit, 2) a middle transitional unit of phosphatic shales, and 3) an upper siliceous unit (Pisciotto, 1978).

Bramlette's (1946) treatise on the upper siliceous unit provides the most thorough description to date. He describes a lower portion of altered diatomaceous shale interbedded with chert and porcellanite, and an upper unaltered diatomaceous member. A widespread and conspicuous feature of this siliceous unit is thin rhythmic bedding consisting of submillimeter to millimeter thick dark and light layers. These rhythmites alternate with homogeneous beds several centimeters in thickness. Recognizing that the preservation of the laminated structure and the paucity of benthic macrofossils in laminated intervals suggests deposition in low turbulence, low oxygen conditions, Bramlette (1946) proposed that the sediments were originally formed below wave or current action in an offshore basin. He further concluded that of the very fine laminae each couplet represented an annual deposit and the thicker homogeneous beds were due to periodic flooding from land. Hülsemann and Emery (1961) recovered laminated sediments from the Santa Barbara Basin and noting "the similarity of the ancient laminae [of the Monterey Formation] to the modern ones" suggested similar origin, i.e., deposition in a series of middle bathyal anaerobic basins having sill depths within the oxygen minimum zone. The geographic proximity of the Santa Barbara Basin to the Monterey Formation as well as the visual similarity of the sedimentary structures contributed to the Santa Barbara Basin being considered as a modern analogue to the siliceous, laminated Monterey shales. However, our analysis of laminated sediments suggests that the Gulf of California sediments provide a better modern analogue to the siliceous shales of the Monterey Formation.

DEPOSITIONAL SETTING

Santa Barbara Basin

The Santa Barbara Basin is one of the numerous submarine basins located off southern California and is one of the most interesting (along with the Santa Monica and San Pedro Basins) because of the low oxygen content of its bottom water (Hülsemann and Emery, 1961). The basin is silled at approximately 475 m depth (maximum depth in the basin is about 590 m) and is about 18 miles in diameter at the depth of the sill (Emery, 1960). Laminated sediments are restricted to the anaerobic part of the basin below sill depth (Hülsemann and Emery, 1961). Oxygen levels are low enough within the deeper parts of the basin to prohibit the development of a benthic infauna which would bioturbate the sediment. Recent research has shown the annual nature of the laminae (Koide et al., 1973) and the potential for using the varves as a high resolution palaeoclimatic tool (Soutar and Isaacs, 1969; Soutar and Isaacs, 1974; Soutar and Crill, 1977).

Gulf of California

The Gulf of California is an evaporative trough 600 miles long and between 60 and 110 miles wide. The Gulf can be divided into two sections separated by an island chain. The northern part, with the exception of Sal si Puedes Basin, is all at shelf depth. The central and southern Gulf consists of a series of basins which increase in depth southward from about 900 m to 3700 m (van Andel, 1964). Laminated diatom-rich sediments are now being deposited along the continental margin slopes of the central and southern Gulf where the oxygen minimum layer intersects the sediment water interface, between approximately 450 m and 800 m water depth (Calvert, 1964; Schrader, 1979; Schrader, 1981). Dissolved oxygen levels of less than 0.2 mℓ O_2/ℓ are maintained through oxidation of falling organic matter and are low enough to prevent the occurrence of a benthic infauna to bioturbate and homogenize the sediment. An oxygen minimum zone is found throughout the eastern Pacific (Phleger and Soutar, 1973) but the very low values in the Gulf are due to considerable fluxes of suspended organic detritus resulting from the high primary productivity in the overlying water. The oxygen values are probably low through the entire year as evidenced by the existence of laminae at all since a bioturbating infauna can mix down several centimeters, and must have been stable for thousands of years to explain the long interval of recent laminations. The high primary productivity results from intense coastal upwelling and mixing processes (Zeitschel, 1969).

Unlike the Santa Barbara Basin, all the deep basins (except the San Pedro Martir Basin) in the Gulf are in open communication with the Pacific Ocean and none are stagnant (Calvert, 1964). Both above and below the oxygen minimum the sediments support a rich infauna which prevents the formation of laminated sediments. Intermediate waters, in the oxygen minimum zone, although not stagnant cannot replace the oxygen as fast as it is being consumed.

Evidence of the biological mediation of the oxygen minimum zone is found in recent studies which show that under the Peru coastal upwelling system this feature is associated with a suspended particle maxima, a nitrite maxima and a nitrate minima (Pak et al., 1980).

RESULTS

The purpose of this study was to compare the rhythmites from the Gulf of California and the Santa Barbara Basin by microscopic analysis to see which modern depositional setting best provides an analogue to the siliceous shales of the Monterey Formation. Cores BAV 79-E-10 recovered in the Gulf of California in September 1979 at 27°52.2'N latitude, 111°39.7'W longitude, and 644 m water depth (Figure 1) and W7802 GC8 collected in the Santa Barbara Basin in March 1978 (34°15.0'N latitude, 120°05.2'W longitude, and 584 m water depth) (Figure 2) were used (both cores are stored at the OSU Core Laboratory Facility) and compared to samples of the siliceous Monterey Shale collected in October 1980 at the Johns-Manville Quarry in Lompoc, California. Compositional changes in individual laminae were visually estimated by microscopical smear slide analysis according to DSDP standards. The sections studied were from well laminated intervals which we assume represent the truest record of undisturbed sedimentation. Samples from the recent material came from the half meter section centered at 40 cm in each core (Figures 3 and 4). Quantitative estimates of the number of diatoms per gram dry material were made for each interval tested; samples were dried, weighed, and prepared by standard dispersal and settling techniques (Schrader and Gersonde, 1978).

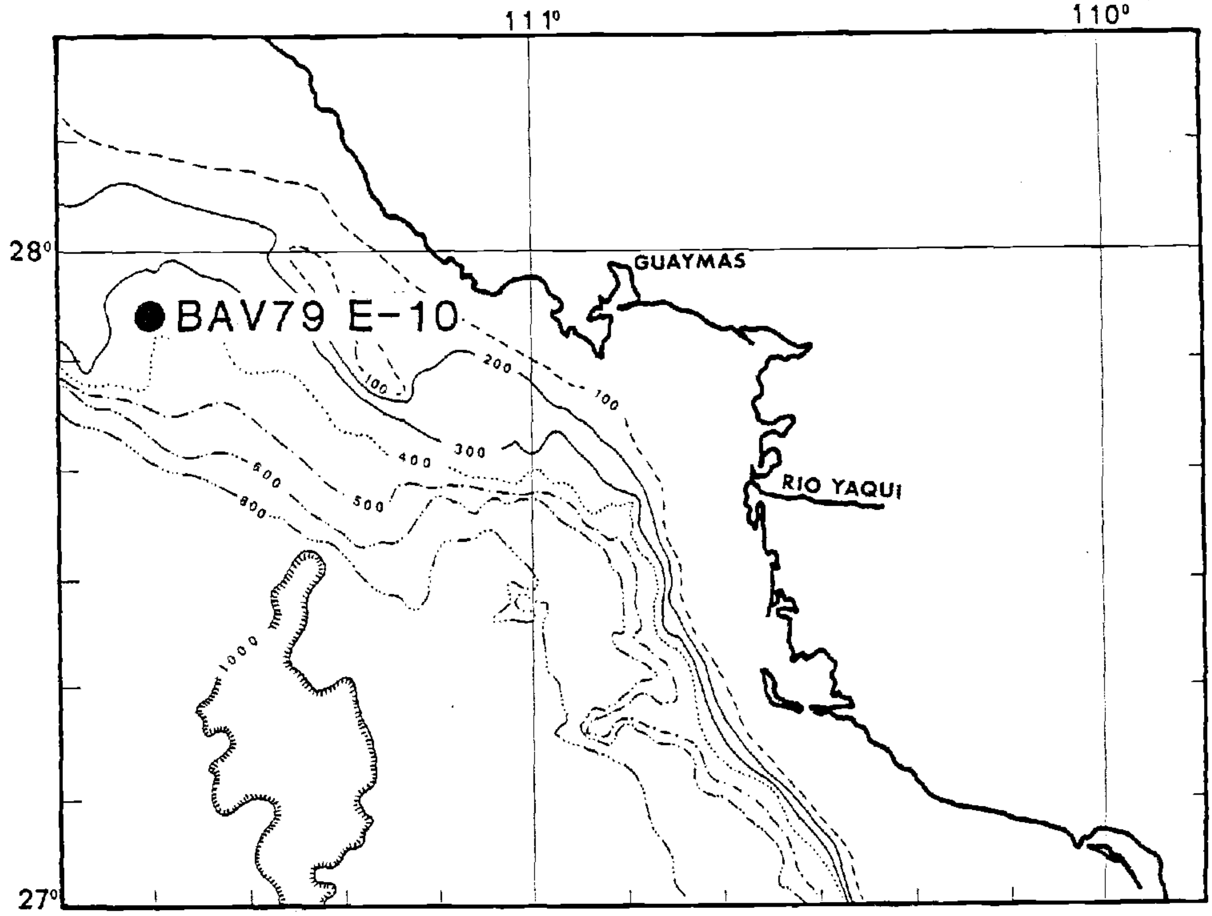

Figure 1. Location of BAV79 E-10 and general topography north and east of the Guaymas Basin, central Gulf of California. Depth contours in fathoms.

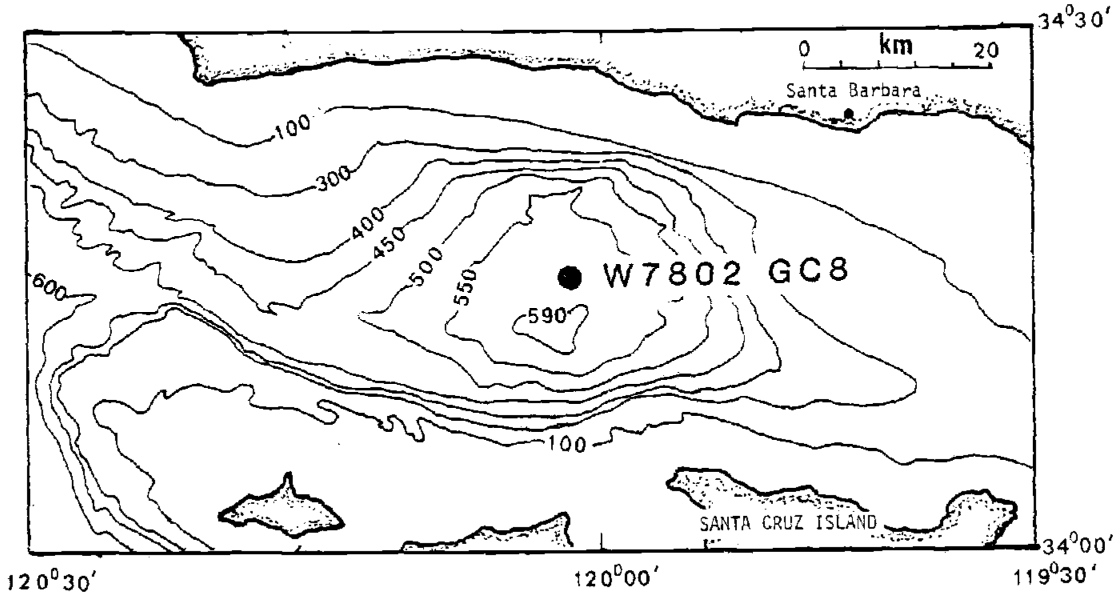

Figure 2. Location of W7802 GC8 and general topography of the Santa Barbara Basin, off southern California (from Sholkovitz and Gieskes, 1971). Depth contours in meters. The mouth of the Santa Clara River is 30 miles SE of the city of Santa Barbara.

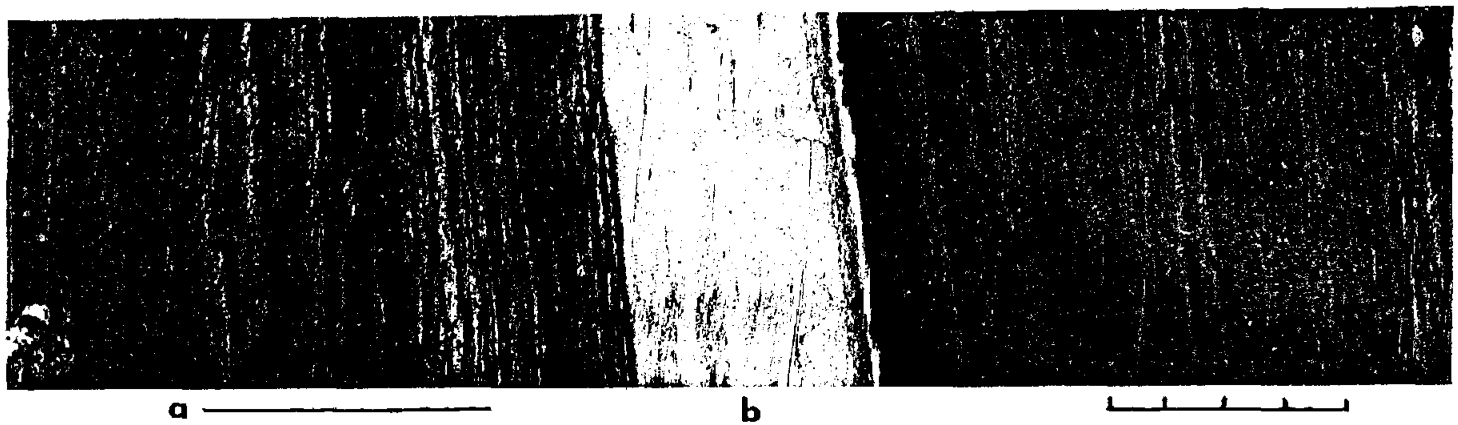

Figure 3. Surface photograph (normal room light) of W7802 GC8 (Santa Barbara Basin), a large diameter gravity core (width of core is 10 cm, photograph trimmed). Section is from 39.3 to 62 cm downcore, up is to the left. Interval of detailed laminae sampling is indicated by the bar (a). Light gray silty layer at 49 to 53.2 cm indicated by (b), note coarser material in the bottom of the layer at 52.5 to 53.2 cm. Scale is in centimeters.

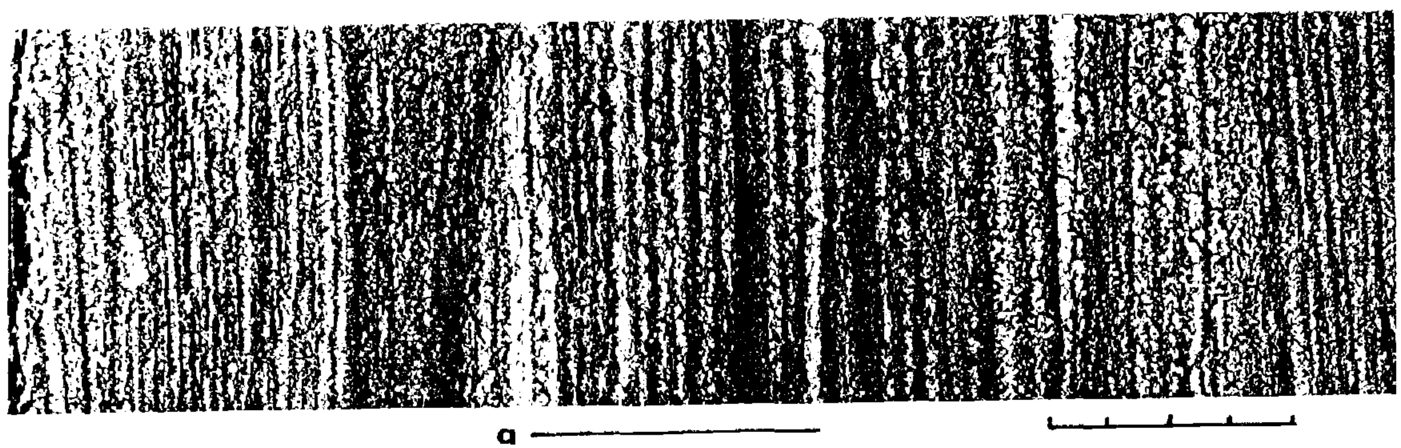

Figure 4. Surface photograph (normal room light) of BAV79 E-10 (central Gulf of California), a kasten core (width of slab is 15 cm, photograph trimmed). Section is from 30 to 50 cm downcore, up is to the left. Interval of detailed laminae sampling is indicated by the bar (a). Scale is in centimeters.

Figure 5. Photograph (normal room light) of a slab (cut by bandsaw and smoothed with a plane) of the clay-rich subfacies of the siliceous shales of the Monterey Formation collected at Lompoc, California. Finely laminated intervals indicated by "L", homogeneous intervals indicated by "H". Scale (left) in centimeters.

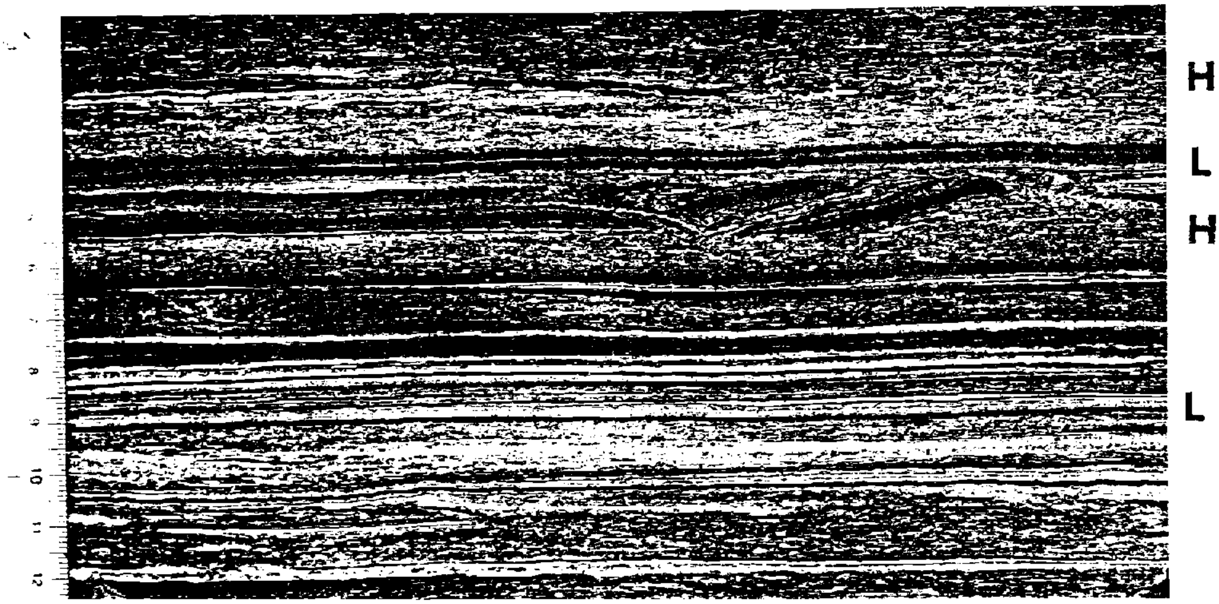

Figure 6. Photograph (normal room light) of a slab (cut by bandsaw and smoothed with a plane) of the organic-rich subfacies of the siliceous shales of the Monterey Formation collected at Lompoc, California. Finely laminated intervals indicated by "L", homogeneous intervals indicated by "H". Scale (left) in centimeters.

Sediment Components

Santa Barbara Basin

In the Santa Barbara Basin the rhythmites are alternating black and dark green layers (Figure 3). Terrigenous material is the dominant component accounting for 45 to 60 percent of the sediment (Table 1), with approximately two thirds of this, being clay sized particles (<4 μm) and the remainder being silt sized (4 to 63 μm). The sediment contains 15 to 30 percent carbonate (Figure 7a), which consists primarily of calcareous nannofossils with up to 10 percent detrital or diagenetic carbonate. Diatoms comprise from less than 5 percent to 30 percent (Figure 7b), but are generally less than 10 percent. The diatom flora is dominated by heavily silicified *Chaetoceros* resting spores of various species and abundant girdle bands of different centric diatoms. Girdle bands of some centric species are more heavily silicified than the diatom valves and are more apt to be preserved (Schrader, 1971, 1972). The presence of a flora containing mostly girdle bands and *Chaetoceros* resting spores without remnants of *Chaetoceros* vegetative cells and other weakly silicified species, is indicative of a poorly preserved assemblage. *Thalassionema nitzschioides* and various species of *Thalassiothrix*, *Thalassiosira*, and *Coscinodiscus* are also present in low percentages. The remainder of the sediment is composed of 10 to 20 percent amorphous organic matter; Emery (1960) reported 5.8 percent total organic carbon for Santa Barbara Basin sediments. Silicoflagellates, sponge spicules,

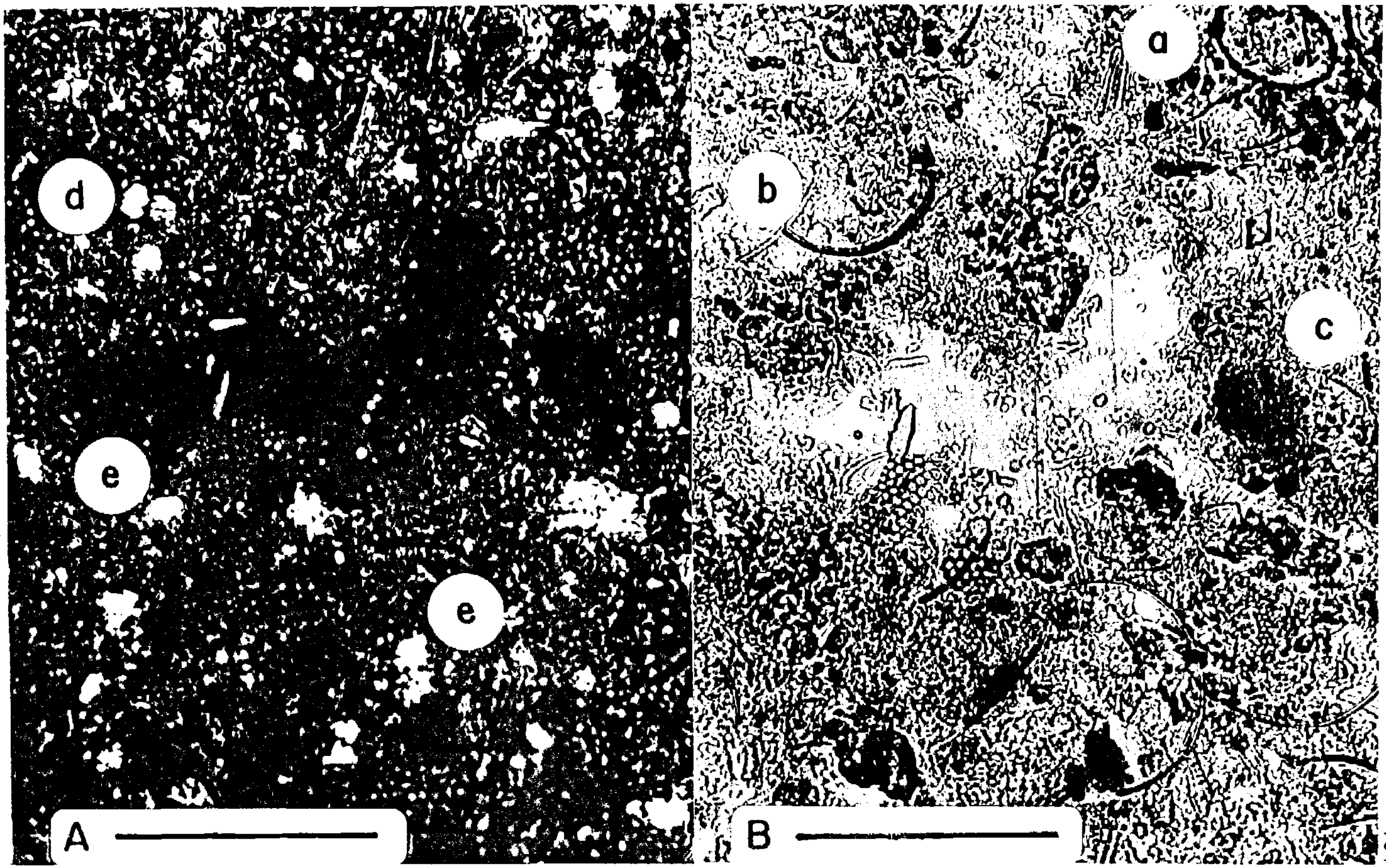

Figure 7. Photomicrograph of Santa Barbara Basin sediment (Core W7802 GC8, approximately 45 cm): (A) polarized light, (B) same view, transmitted light. Note: (a) Chaetoceros resting spore, (b) girdle band fragment of a centric diatom, (c) organic clump, (d) detrital carbonate, and (e) calcareous nannofossils. Bar equals 50 μm.

foraminifers, and pyrite together comprise less than 2 to 3 percent.

Gulf of California

In the Gulf of California the rhythmites are easily defined, alternating pale olive and olive brown layers (Figure 4). Diatoms are the dominant component comprising 80 to 90 percent of the sediment in the light (Figure 8) and 60 to 75 percent in the dark laminae (Figure 9) (included in these values are silicoflagellates, radiolarians, ebridians and sponge spicules which together account for less than 2 to 3 percent). Terrigenous material is 5 to 10 percent in the light laminae and 15 to 25 percent in the dark. This terrigenous material is almost entirely clay sized particles. Clumps of amorphous organic material comprise 5 to 10 percent of the light laminae and 10 to 15 percent of the dark. Total organic carbon, determined by LECO carbon/carbonate analyzer, averages 4 to 5 percent in dark laminae and 3 to 4 percent in light laminae. No calcareous nannoplankton or foraminifers were observed in the smear slides (Table 1). The diatom population consists primarily of Pseudoeunotia doliolus, a Thalassionema/Thalassiothrix intergrade (a paper on this species in preparation by Schrader), species of Thalassiothrix, Thalassionema nitzschioides, and Chaetoceros resting spores. Species of Thalassiosira, Coscinodiscus, Actinocyclus, Actinoptychus, Rhizosolenia, and Cyclotella are also present in significant numbers. The light laminae can be distinguished from the dark by having more weakly silicified diatom species (such as Skeletonema costatum, Synedra indica, Chaetoceros radicans,

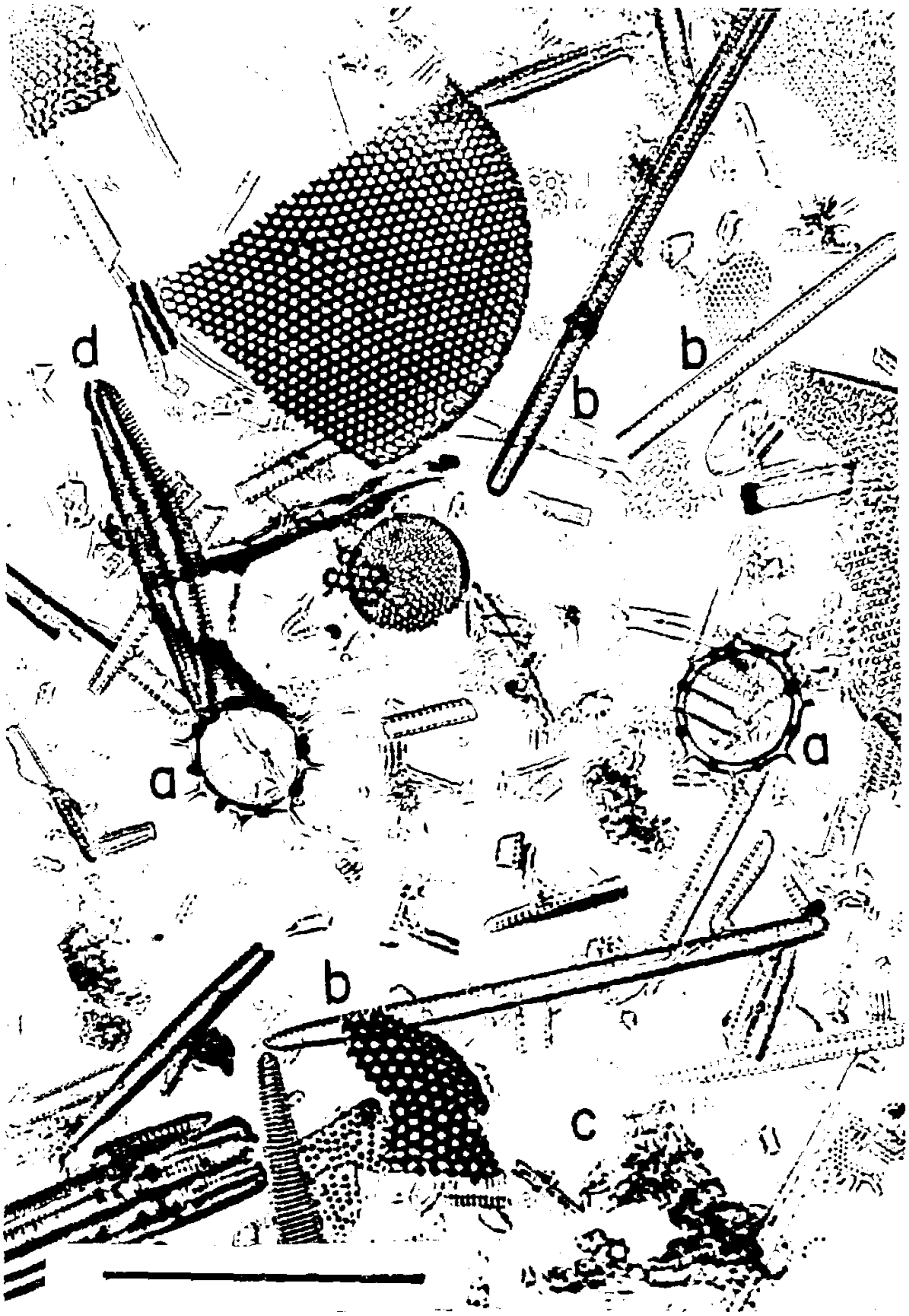

Figure 8. Photomicrograph of a light lamina from the Gulf of California sediment (BAV79 E-10, approximately 40 cm) (transmitted light). Note: (a) Octactis pulchra, (b) needle-shaped Thalassionema and Thalasiothrix diatoms, (c) organic clump, and (d) Pseudoeunotia doliolus. Bar equals 50 μm.

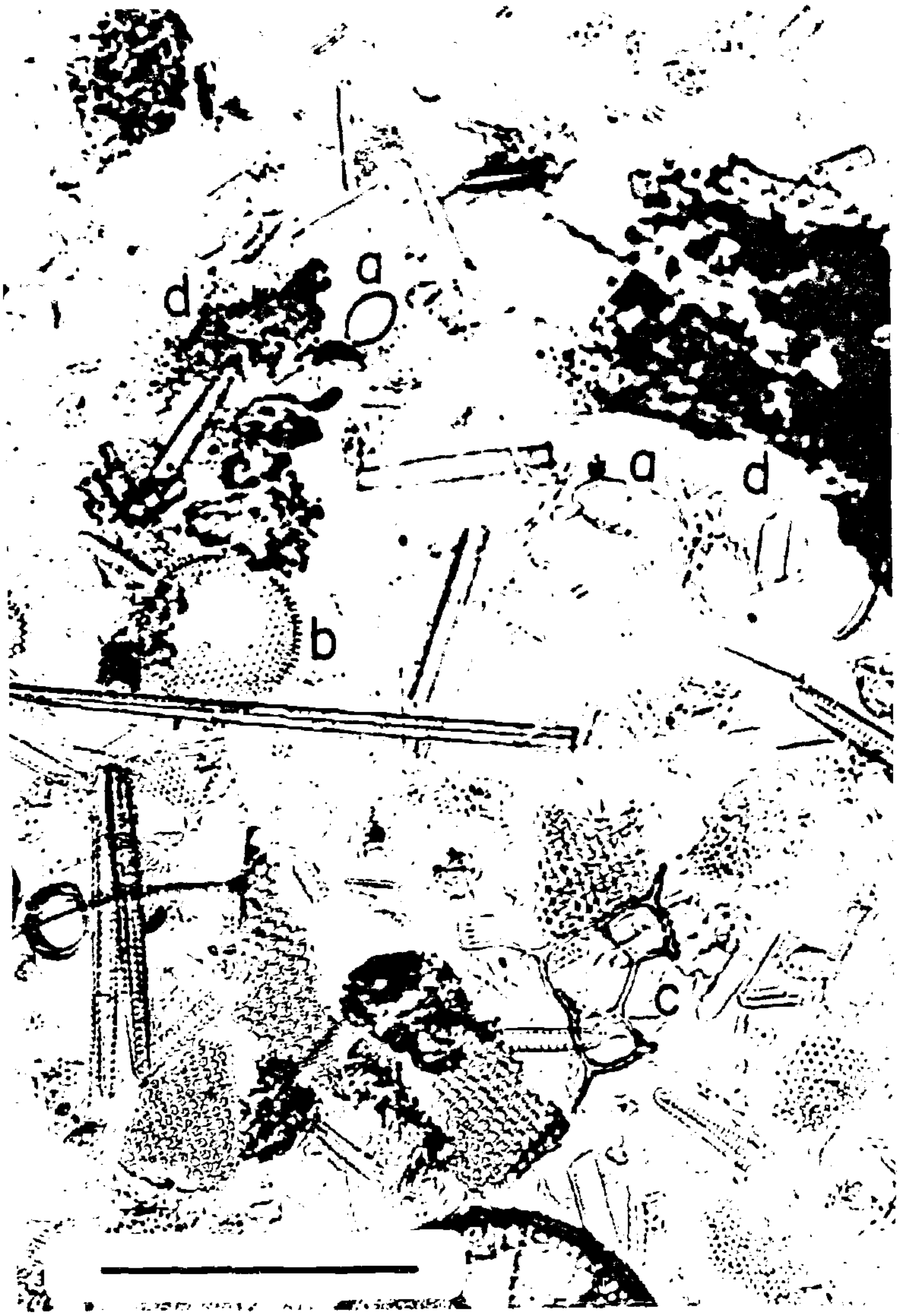

Figure 9. Photomicrograph of a dark laminae from the Gulf of California sediment (BAV79 E-10, approximately 40 cm) (transmitted light). Note: (a) <u>Chaetoceros</u> resting spores, (b) <u>Thalassiosira</u>, (c) silicoflagellate, and (d) organic clumps, notice that there is more fine terrigenous material in the background than in Figure 8. Bar equals 50 μm.

Nitzschia bicapitata, and Nitzschia sicula) and more Octactis pulchra, a silicoflagellate which appears to be associated with the upwelling season, as well as less terrigenous debris.

Monterey Formation

We examined two subfacies of the upper unaltered siliceous shale of the Monterey Formation from the Lompoc quarry. One was described as "clay-rich" (Figure 5) the other described as "organic-rich" (Figure 6) by the personnel at the Johns-Manville Quarry (Bob Fullerton, pers. comm., 1980); both subfacies are well laminated and the laminae can be distinguished by color.

In the clay-rich group the laminae are tan and cream colored alternations (Figure 10). Diatoms comprise 60 to 80 percent of the sediment in the light colored laminae and 40 to 60 percent in the dark. Terrigenous material is 10 to 20 percent in the light and 20 to 30 percent in the dark, it consists almost entirely of clay size particles. Amorphous clumps of organic material comprise 5 to 15 percent of the light and 20 to 35 percent in the dark laminae (Table 1). Silicoflagellates, radiolarians, ebridians and sponge spicules together make up less than 5 percent of the opaline fraction. The diatom assemblage is dominated by Thalassiothrix, Thalassionema fragments and Chaetoceros resting spores.

In the organic-rich group the alternations are olive brown and buff colored (Figure 11). Diatoms comprise 80 to more than 90 percent in the light laminae and 70 to 80 percent in the dark. Terrigenous

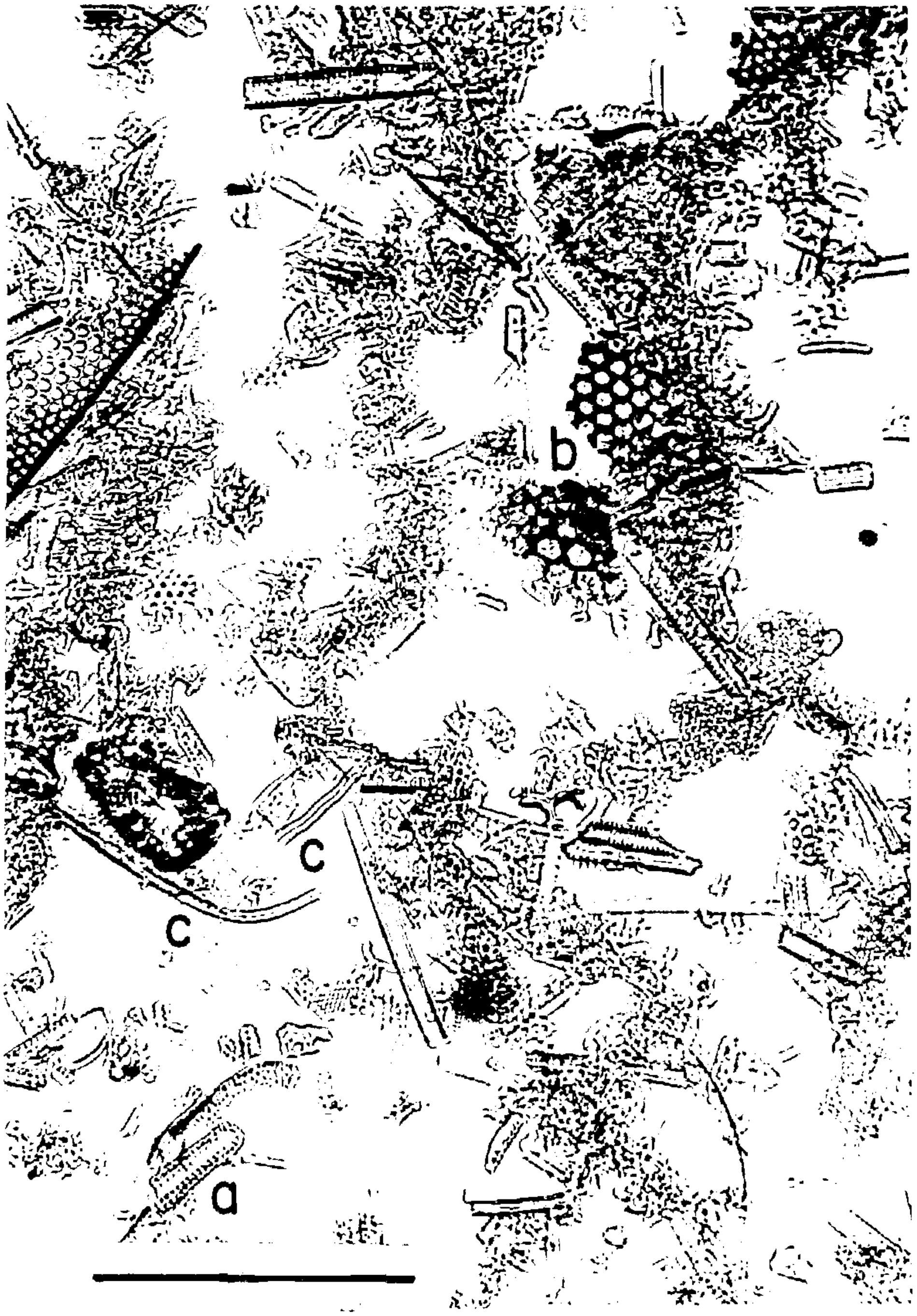

Figure 10. Photomicrograph of the clay-rich subfacies from the Monterey Formation (transmitted light). Note: (a) Thalassionema fragment, (b) fragments of Coscinodiscus, (c) bristles from Chaetoceros vegetative cells. Bar equals 50 μm.

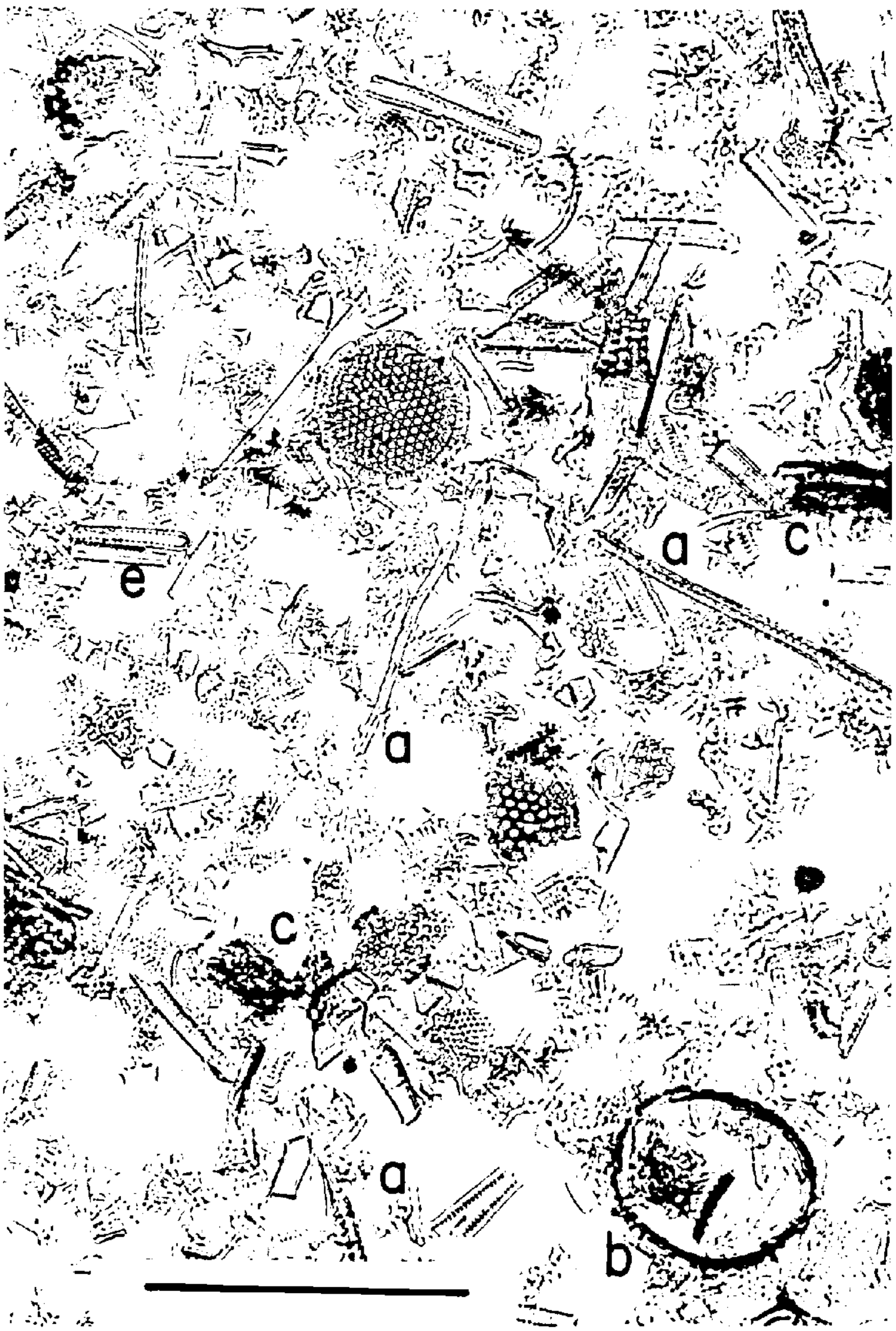

Figure 11. Photomicrograph of the organic-rich subfacies of the Monterey Formation (transmitted light). Note: (a) bristles from Chaetoceros vegetative cells, (b) girdle bands of centric diatom, (c) organic clumps, (d) Thalassiosira, and (e) Thalassionema. Bar equals 50 μm.

material and amorphous organic clumps each range from less than 5 to 15 percent in both light and dark (Table 1), again the terrigenous material is clay sized. Silicoflagellates, sponge spicules, radiolarians and ebridians make up less than 2 to 3 percent of the total opaline fraction. Thalassiothrix, Thalassionema fragments and Chaetoceros resting spores dominate the diatom fraction (light laminae can be distinguished by their higher content of well preserved needle-shaped diatoms with Thalassiothrix and Thalassionema species). Calcareous nannoplankton or foraminifers were not observed in any of the smear slides.

Homogeneous Sections

In the Gulf and Santa Barbara Basin sediments and in the Monterey Shale, non-laminated homogeneous intervals are often interbedded with laminated intervals. The laminated sediments of the Santa Barbara Basin are interrupted by two types of homogeneous intervals, olive homogeneous sections (the same color range as the laminated sediments) and distinctive light gray silt layers. The olive sections, which are more abundant in shallower depths and towards the margin of the basin (Hülsmann and Emery, 1961) are compositionally similar to the laminated material, and are thought to be due to increased oxygen concentrations within the basin (Emery and Hülsemann, 1962). The higher oxygen levels are thought to depend on the introduction of new more oxygenated waters from shallower depths around the margin of the basin or from the open sea over the basin sill (Emery and Hülsemann, 1962;

Sholkovitz and Gieskes, 1971; Sholkovitz and Soutar, 1975). Increased oxygen levels in this interpretation allows the development of a benthic fauna responsible for the homogeneity of the sediments.

The other type of homogeneous lithology common in the Santa Barbara Basin are very distinctive light gray silt layers which may or may not show textural grading. These layers which are found mainly in the deeper parts of the basin (Fleischer, 1972) were interpreted by Hülsemann and Emery (1961) to be turbidity current deposits. They were later reinterpreted by Fleischer (1972) to be suspended-load deposits from large floods of the Santa Clara River. These grey layers contain no biogenous material and are so completely different from the laminated and olive non-laminated sediments as to suggest an extra-basinal origin.

In the Gulf, Core BAV79 E-10, non-laminated intervals are olive gray diatomaceous mud of the same color range as the laminated intervals. They show no textural grading to suggest that they have been redeposited and we suggest that these homogeneous intervals reflect a weaker oxygen minimum zone which could support a benthic fauna capable of bioturbation.

Crawford and Schrader (in press) examined the coarse fraction (>150 μm) of DSDP Site 480, from the central Gulf of California, and showed that the long homogeneous sections in that core contain more benthic and planktic Foraminifera and fewer diatoms and radiolarians than the laminated sections (although diatoms are still the dominant component). They concluded that these thick homogenous sections represent glacial periods with less productive surface waters and a less intense oxygen minimum at the sediment water interface.

In our samples of the siliceous shales of the Monterey Formation the homogeneous sections are of intermediate color and show no textural grading. Microscopic analysis reveals that these intervals contain a mixture of diatom frustules and terrigenous particles, we interpret these intervals as analogous to the olive homogeneous sections found in the Gulf of California and Santa Barbara Basin; i.e., they are probably due to an increase of the dissolved oxygen level at the sediment water interface permitting bioturbation. No homogeneous intervals were found in our samples of the Monterey siliceous facies or in BAV79 E-10 from the central Gulf of California which were comparable to the light gray silty homogenous (microfossil barren) intervals found in the Santa Barbara Basin.

SUMMARY

The laminated Santa Barbara Basin sediments are predominantly clay and silt sized terrigenous material, calcareous nannofossils are common and diatoms are a subordinate component. Diatoms are poorly preserved and heavily silicified girdle bands and Chaetoceros resting spores dominate the opaline fraction. Light laminae cannot be distinguished from dark laminae by floral composition or relative abundance of diatoms (as far as our preliminary analysis indicates). The laminated Gulf of California sediments and the laminated siliceous shales of the Monterey, on the other hand, are predominately diatomaceous and contain an excellently to moderately well preserved opal phytoplankton population. Light laminae can be differentiated from dark by their differing opal phytoplankton flora. Terrigenous material is a secondary component and calcareous nannofossils are rare or absent.

In the oceanic realm organic-rich (greater than 3 percent) well-laminated sediments (Soutar, 1971) are found: a) in anoxic basins and b) on continental margins which meet certain criteria. These criteria are: 1) a distinct climatic seasonality which produces a periodically varying sediment input, and 2) oxygen levels of bottom water low enough to prevent the development of a benthic infauna capable of homogenizing the sediment, and 3) spatial coincidence of the high biotic and/or terrigenous sediment input (i.e. resulting from coastal upwelling and seasonal continental runoff) and an oxygen minimum on the sea floor; that is, the margin configuration must be

Table 1. Summary of biogenic and abiogenic sediment components determined microscopically from analysis of smear slides.

	diatom frustules	terrigenous material	amorphous organic material	carbonate	$\frac{\text{diatoms}}{\text{cm}^2/\text{year}}$ $(\times 10^6)$
I Recent					
Santa Barbara Basin sediments	< 5-30%	45-60%	10-20%	15-30%	1.4
(can't distinguish microscopically between light and dark laminae)	generally <10%				
Gulf of California sediments					
light laminae	80-90%	5-10%	5-10%	absent or trace[1]	6.1
dark laminae	60-75%	15-25%	10-15%	absent or trace[1]	
II Ancient					
Siliceous Shales of Monterey Formation					
clay-rich facies light laminae	60-80%	10-20%	5-15%	absent or trace[1]	3.0[2]
dark laminae	40-60%	20-30%	20-35%	absent or trace[1]	
organic-rich facies light laminae	80->90%	<5-15%	<5-15%	absent or trace[1]	2.9[2]
dark laminae	70-80%	<5-15%	<5-15%	absent or trace[1]	

[1]Although no calcareous nannoplankton or foraminifers were observed when the slides were analyzed for this study, they have occasionally been seen by the authors in this material in the past.

[2]These estimates may be low because the Monterey material is more fractionated than the other material.

such that the seasonally variable sediments accumulate where an oxygen minimum impinges on the sediment water interface.

In general, it can be said that all oceans have a zone of low oxygen. Usually these oxygen values are not low enough to exclude a benthic macrofauna and to do so must be depressed through the oxidation of large quantities of settling organic detritus. This can be accomplished along a continental margin characterized by high primary productivity.

Laminated sediments though usually restricted to silled basins, i.e., the Santa Barbara Basin, the Black Sea (Ross and Degens, 1974), Orca Basin in the Gulf of Mexico (Tompkins and Shephard, 1979) and Saanich Inlet, British Columbia (Gross et al., 1963) are a widespread feature in the southern Gulf of California. Laminated sediments not associated with stagnant basins, similar to those in the Gulf of California, though rare in modern oceans, have also been observed in the northwestern Indian Ocean by von Stackelberg (1972) and off Peru (Veeh et al., 1973; Busch, 1981).

Laminated diatomaceous sediments being deposited on the slopes in the central and southern Gulf of California provide a modern analogue to the laminated siliceous shales of the Monterey Formation. The similarity in composition of the Gulf and Monterey Shale sediments suggest that the sedimentological environment responsible for deposition of the Monterey Shale was similar to what is found in the modern Gulf of California. At the time of deposition conditions along the continental borderland were favorable for the accumulation of laminated diatom rich sediments characterized by: 1) very high upwelling/ mixing rates to develop high primary productivity of more than 250 g C/m^2/year (Lisitzin, 1976), 2) little biogenic carbonate production, and 3) a stable oxygen minimum zone. The lack of sedimentary beds of extrabasinal origin, analogous to the silty light gray layers in the Santa Barbara Basin, although certainly not indicative of basin slope deposition would be consistent with this model. That is, these flood pulses if present, may by-pass the slope and accumulate in the basin. This model can easily fit into the already established Neogene basin sequence (Ingle, 1980) and seems more reasonable in explaining the spacially and temporally tremendous siliceous deposits of the Monterey than by deposition in a series of anoxic basins.

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