NOTES

Seasonal spillover and varve formation in the Santa Barbara Basin, California

Abstract—A temporal record of oxygen and NO_3^- concentrations in the bottom water of the Santa Barbara Basin indicates that outside waters spill over into the basin seasonally. It is proposed that an annual bottom-water cycle leads ultimately to varve production.

As evidence in support of a benthic mechanism for varve formation, we present results of surface sediment and pore-water analyses, from box-core collections during three seasons in 1988. The greater degree of bottom-water oxygen depletion that occurs regularly in late summer and fall was coincident with a smaller pool of pore-water Fe, penetration of ΣH_2S up to the sediment–water interface, maximal numbers of benthic Foraminifera, and bacterial mat growth. The latter was indicated by increases in concentrations of extractable ATP, organic C, and total N in sediments from the depth intervals 0–0.25 and 0.25–0.5 cm. The greatest numbers of siliceous phytoplankton skeletons were found on the sea floor soon after the late spring, surface-water, Chl *a* maximum. This event coincides with additions of new and more-oxygenated seawater to the deep basin.

Varves are repetitious sedimentary couplets (or triplets) that reflect the annual climatic cycle (Anderson 1986). In the Santa Barbara Basin, California, varves contain alternating "light" and "dark" laminae with distinct density and compositional differences. These differences have been ascribed to seasonally varying sources of terrigenous and diatomaceous sediment (Hülsemann

and Emery 1961; Fleischer 1972). Also, they have been attributed to the response of a benthic bacterial mat to seasonal changes in deposition (Soutar and Crill 1977). Here we report evidence that it is not seasonal sedimentation, but an annual cycle of oxygen replenishment and depletion in bottom waters that is the primary factor regulating varve formation.

Systematic quarterly hydrographic sampling from the sea surface to the floor (~ 580 m) of the Santa Barbara Basin was initiated in 1986 by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program. This record indicates that there is a pronounced seasonal cycle in bottom-water characteristics which is in phase with the occurrence of extremes in surface temperature and, to a lesser extent, chlorophyll concentrations (Fig. 1). Sholkovitz and Gieskes (1971) demonstrated that oxygenation and nitrate enrichment of basin bottom waters is the result of flow over the basin's sill that contributes colder, denser, more oxygenated, and NO_3^--rich water to the lower basin. After a spillover event, NO_3^- concentrations continue to vary with oxygen because at the seabed, NO_3^- reduction outweighs nitrification, and NO_3^- reduction and oxygen consumption rapidly remove both oxidants (Sholkovitz and Soutar 1975).

The 1986–1989 CalCOFI data (Fig. 1) suggest that spillover events transport water into the Santa Barbara Basin more regularly than was previously thought (Sholkovitz and Gieskes 1971; Sholkovitz and Soutar 1975). Spillover is greatest in spring when surface and subsurface flow over the continental slope off Point Conception becomes equatorward, causing a large upward shift in density surfaces toward the coast and the basin's sill (Lynn and Simpson 1987); that is,
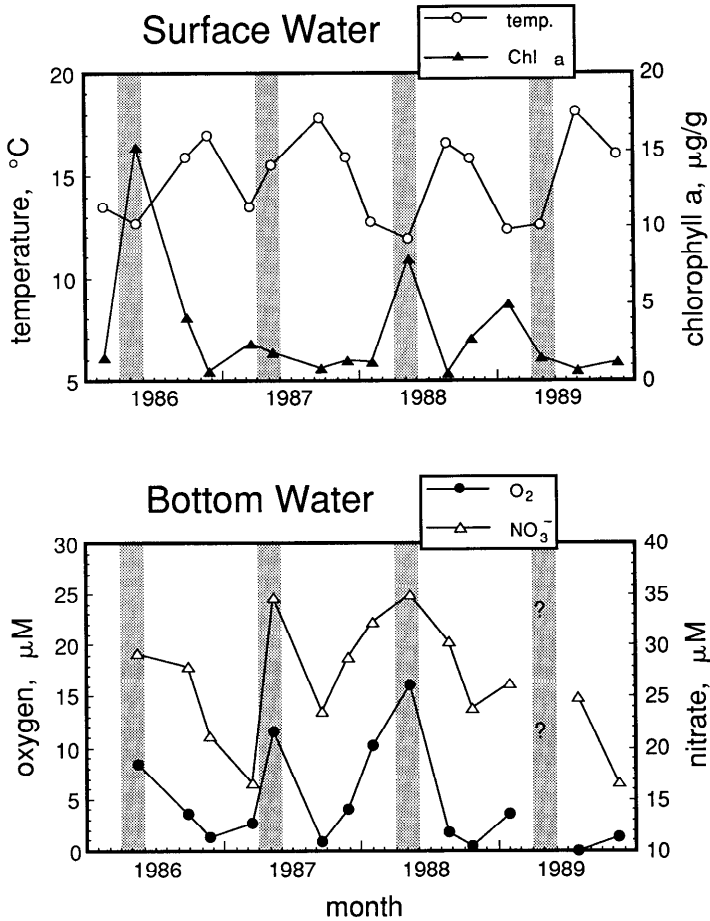
Fig. 1. Quarterly variations in surface- and bottom-water properties over 4 yr in the Santa Barbara Basin. These data were collected for the CalCOFI program (Scripps Inst. Oceanogr. 1986–1990). April–May is highlighted in each year. The time series are based on determinations from water samples collected in the depth ranges of 0–2 and 552–572 m for the surface- and bottom-water records, respectively. Before May 1986 and in April–May 1989, the CalCOFI hydrographic casts did not include samples below 520 m at the Santa Barbara Basin station.

during upwelling (Jackson 1986). Tempered by physical controls, basin bottom waters are most oxygenated during periods of peak phytoplankton production and sedimentation.

We collected eight Soutar-style box cores of surface sediment from the sea floor of the Santa Barbara Basin in February, June, and October 1988, thereby spanning most of an annual deposition cycle. All coring locations were within 6 km^2, bounded north and south by 34°14.6′ and 34°13.5′N, and east and west by 120°01.0′ and 120°02.6′W. Briefly, we extruded and sectioned subcores of these box cores into horizontal depth in-

tervals of 0.25–1.0 cm [with an apparatus described by Shaw (1989), at a temperature about equal to the in situ condition (6°C) and under a N_2 atmosphere]; from these samples we determined profiles of several pore-water constituents, extractable ATP (adenosine triphosphate), porosity, microplankton and benthic foraminiferal abundances, as well as solid-phase organic and inorganic C, total N, and total P content (Table 1). Because our purpose here is to describe changes at the sediment–water interface that may be caused by seasonal forcing, we have presented results from only the uppermost sediment layers (Figs. 2–4, Table

Table 1. Methods of pore-water (1–2), bulk sediment (3–4), and solid-phase (5–8) analysis.

Analysis	Technique	References
1. Fe	Ferrozine spectrophotometry	Stookey 1970; Canfield 1989
2. ΣH_2S	Monobromobimane-HPLC; and mixed diamine reagent spectrophotometry*	Vetter et al. 1989; Cline 1969
3. ATP	Cold 0.5 M H_3PO_4 extraction followed by lucifer-in-luciferase luminescence photometry	Craven et al. 1986
4. Porosity	Dry weight and chlorinity measurement	Reimers and Smith 1986
5. Inorganic C	Acid liberation and CO_2 coulometry	Reimers and Smith 1986
6. Organic C	Difference between total C determined by CHN analyzer† and inorganic C	
7. ΣN	CHN analyzer†	
8. ΣP	1 N HCl extraction of $PO_4{}^{3-}$ after ashing at 500°C followed by molybdate-blue spectrophotometry	Aspila et al. 1976

* Total sulfide in pore waters collected in February determined by the monobromobimane-HPLC method. June and October samples were analyzed with the mixed diamine reagent method.
† A Perkin-Elmer model 2400 CHN elemental analyzer was used.

2). Each 0.25 cm of surface sediment represents on average $\sim$4-month bulk accumulation, calculated from an average bulk accumulation rate = 0.092 g cm^{-2} yr^{-1} (Bruland et al. 1981), an average surface porosity = 0.95 cm^3$_{water}$ cm^{-3}$_{bulk}$, and an average density of total solids = 2.3 g cm^{-3}$_{solid}$. Given that molecular diffusion coefficients for ions in high-porosity marine sediments are between 10^{-5} and 10^{-6} cm^2 s^{-1}, however, over a period of 4 months, molecular diffusion can propagate a pore-water signal originating at the sediment surface to a depth between 3 and 10 cm.

Striking variations in pore-water Fe^{2+} and ΣH_2S profiles were exhibited between our 4-month sampling intervals (Fig. 2). During February and June when the bottom water of the basin was relatively oxygenated, pore-water Fe^{2+} concentrations increased in NO$_3{}^-$-containing surface sediment (NO$_3{}^-$ data not shown) to produce high, near-surface maxima. Within the same cores, dissolved sulfide was not detectable in the topmost 2–4 cm of sediment (detection limit = 0.5 μM), and sulfide concentrations did not begin to increase rapidly until depths where dissolved Fe was no longer measurable. Analogous chemical patterns have been observed in pore waters from other marine sediments (Sørensen and Jørgensen 1987; Chanton et al. 1987) and in the water columns of anoxic lakes (Hutchinson 1957) and marine basins (Murray and Izdar 1989). They indicate that Fe^{3+} oxides and oxyhydroxides can be important bacterial oxi-

dants that result in Fe^{2+} liberation and precipitation of sulfide produced during bacterial SO$_4{}^{2-}$ reduction (Canfield 1989).

In contrast to the February and June distributions, in October 1988, depth profiles of interstitial-water Fe^{2+} had much lower peak concentrations, and sulfide was detectable in the first 0.25 cm of sediment collected from the basin. These changes coincide with the fall minimum in bottom-water oxygen (Fig. 1) but could also be

Table 2. Numbers and abundances (as percent of the total microplankton) of diatom valves in 0–0.25-cm sediment intervals collected from the Santa Barbara Basin in 1988.

|	Time of collection		
	Feb	Jun	Oct
No. of valves × 10^6 (g salt-free sediment)$^{-1}$	82.5	361	198
No. of diatom taxa	76	77	76
Abundance of major taxa (%)			
Chaetoceros spp. resting spores	59.3	51.9	53.4
Chaetoceros spp. vegetative cells	2.8	8.2	2.8
Skeletonema costatum	5.6	12.6	13.4
Rhizosolenia spp.	1.0	0.2	2.8
Pseudoeunotia doliolus	1.9	0.2	<0.1
Thalassionema nitzschioides & *Thalassionema bacillaris*	10.7	0.4	1.6
Nitzschia seriata & *Nitzschia pungens*	1.8	3.1	3.9
Other *Nitzschia* spp.	1.3	0.5	0.8
Misc. benthic diatoms	6.6	1.3	1.2
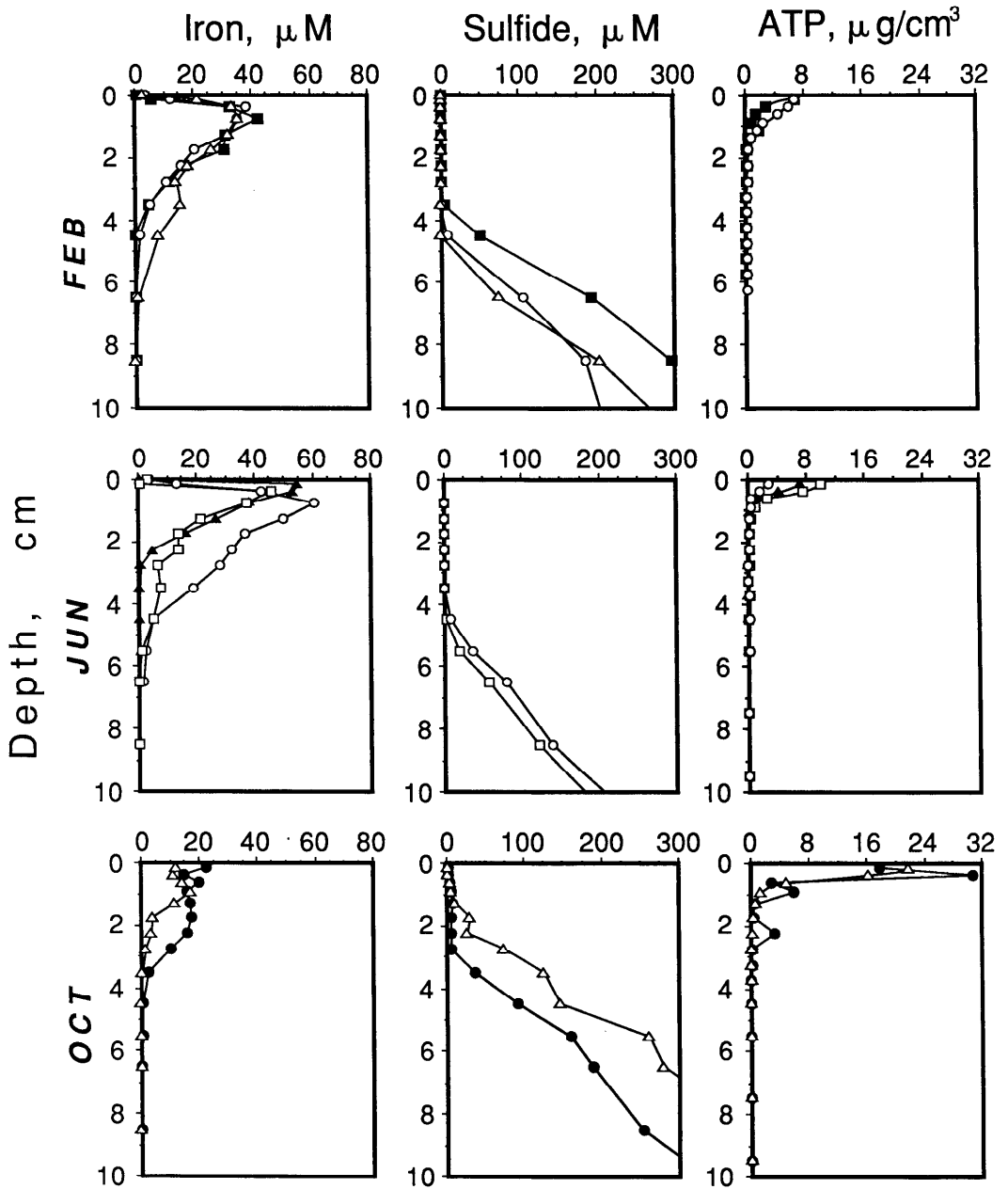
Fig. 2.   Vertical distributions of dissolved Fe, ΣH_2S, and extractable ATP in box cores collected from the Santa Barbara Basin between 23–27 February, 21–24 June, and 4–8 October 1988. Symbols designate specific cores.

related to seasonal variations in rates of organic matter sedimentation and mineralization. More simply, since dissolved Fe and sulfide concentrations are coupled through Fe-sulfide precipitation, a decrease in the amount of Fe liberated in the uppermost sediments or an increase in the amount of sulfide produced by SO_4^{2-} reduction could explain the observed temporal pore-water variations. We suspect that it is the former
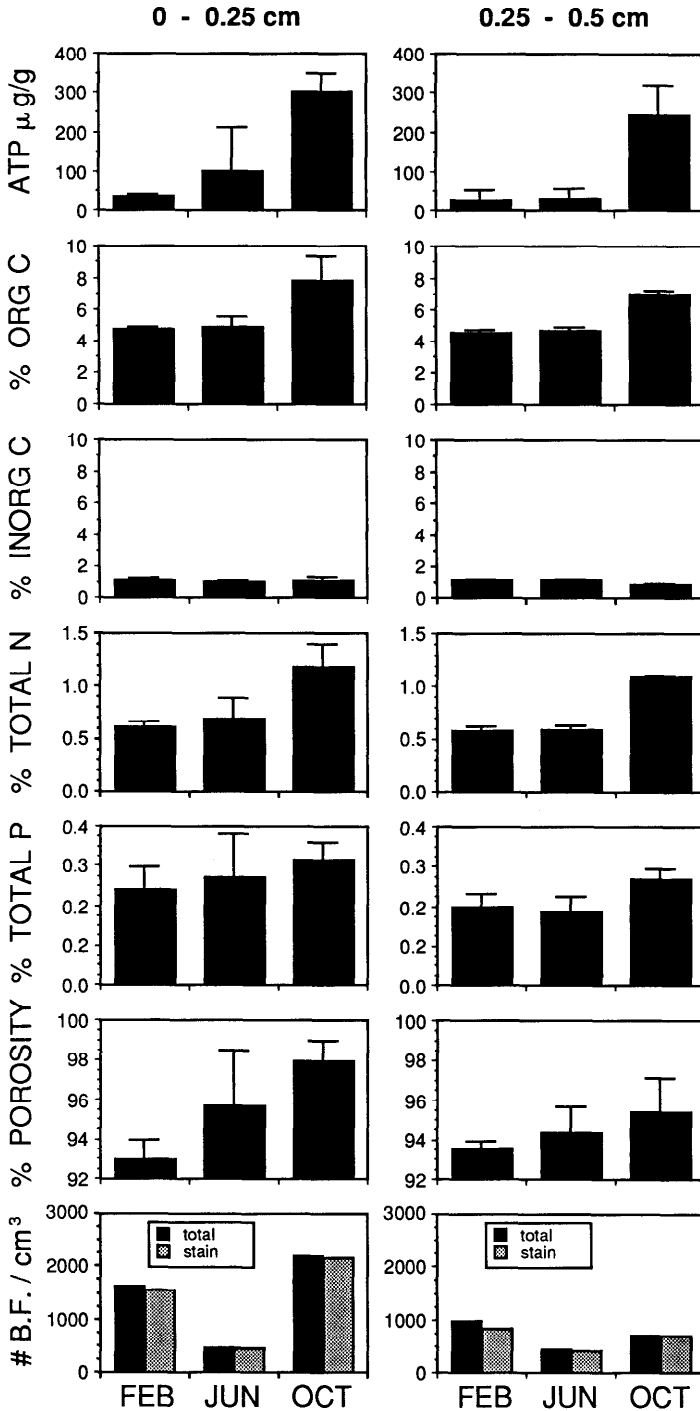
Fig. 3. Surface sediment properties during the months sampled. Compositional data are expressed relative to salt-free dry weights. Error bars represent the standard deviations of analyses of multiple cores (three per analysis in February and June, two per analysis in October). Only one core was analyzed for numbers of benthic Foraminifera (B.F.) in each month.

effect that is important. In fall, increased concentrations of suspended, Fe-enriched particles have been measured in subsill waters (Shiller et al. 1985). This observation suggests that when the oxygen content of the basin is at or very near zero, liberated Fe diffuses out and then is mixed more readily away from the sediment, to be reprecipitated in the basin bottom waters, rather than at the sediment–water interface (where fresh Fe precipitates would again be available for recycling).

Fe-oxidizing bacteria have been observed in surface sediment samples from the Santa Barbara Basin with much larger concentrations of filamentous, S-oxidizing *Beggiatoa* spp. (Soutar and Crill 1977; Stolz et al. 1986; Reimers et al. 1990) and benthic Foraminifera (Emery and Hülsemann 1962; Phleger and Soutar 1973). Adenosine triphosphate (ATP) concentrations provide an assay of total biomass (Hodson et al. 1976; Craven et al. 1986). The enhanced sulfide flux to the sediment–water interface in October 1988 was coincident with sizable increases in the ATP, organic C, and total N contents of the sediments from the depth intervals of 0–0.25 and 0.25–0.50 cm, with increases in the porosities and total P contents of these intervals, and with maximal numbers of benthic Foraminifera in the 0–0.25-cm layer (Figs. 2 and 3). The mean organic C : ATP weight ratios for October surface samples (264, with a SD of ±82 for the 0–0.25-cm interval; 309±83 for 0.25–0.50 cm) are remarkably similar to the average ratio of 250 reported for marine microbial, meiofaunal, and macrofaunal organisms by Hodson et al. (1976) and ratios of 309 and 291 reported for two very different benthic foraminiferan species by DeLaca (1986). This result indicates nearly 100% of the organic C at the sediment–water interface in October was within living biomass, compared to <20% in February and June (mean organic C : ATP ratios > 1,250.

The very high numbers of benthic Foraminifera found in the topmost sample from October and our finding that nearly all these surface specimens absorbed Rose Bengal stain (Walton 1952) (Fig. 3) is interpreted as evidence that most individuals in October were alive and that they may survive periods of total oxygen depletion. The most abundant taxa present in the surface samples from all 3 months were *Textularia earlandi* (21–44%), *Suggrunda eckisi* (7–31%), *Chilostomella ovoidea* (3–10%), and *Nonionella monicana* (9–19%). Some of these species have been observed in subsurface sediments devoid of oxygen elsewhere (Bernard unpubl.), but these and most other forms may be unable to tolerate prolonged exposure to dissolved sulfide.

The *Beggiatoa* spp. are gliding bacteria which, unlike benthic Foraminifera, grow optimally at the expense of available sulfide and within an interfacial mat (Nelson et al. 1986). A change in the appearance of the box-core surfaces between June and October and the ATP data indicate that these bacteria increased in biomass during late summer or early fall in response to the fluctuating redox conditions in the basin's surface sediments. These conditions, we contend, vary seasonally in response to bottom-water changes induced by spillover into the basin. Bacterial growth and associated bacterial mat thickening at the sediment–water interface is thus a definite mechanism to initiate the formation of the detritus-poor, high-porosity "light" layers that are typical of annual pairs of varved sediment. "Dark" bands, in contrast, emerge from a winter–spring, low-biomass condition (typified by our February observations).

June must normally represent a transitional period in the basin. Diatom plankton contained in the June surface mat showed high diversity and the greatest abundances, suggesting recent sedimentation after the spring chlorophyll maximum (Table 2). In-

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Fig. 4. Photomicrographs of diatom assemblages in Santa Barbara Basin surface sediments (0–0.25 cm) A–C. February samples; note abundant benthic diatoms and detritus: A—*Grammatophora* sp.; B—*Actinoptychus vulgaris*; C—*Cocconeis* sp. D–G. June samples: D and G—*Chaetoceros debilis* cells with resting spores; E—*Nitzschia seriata*; F—*Skeletonema costatum*. H–J. October samples: H—*Rhizosolenia hebetata*; I—*Nitzschia pungens* and *Nitzschia* sp.; J—*Rhizosolenia* sp. Scale bars represent 10 μm.
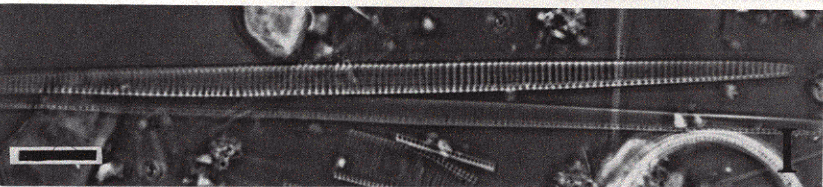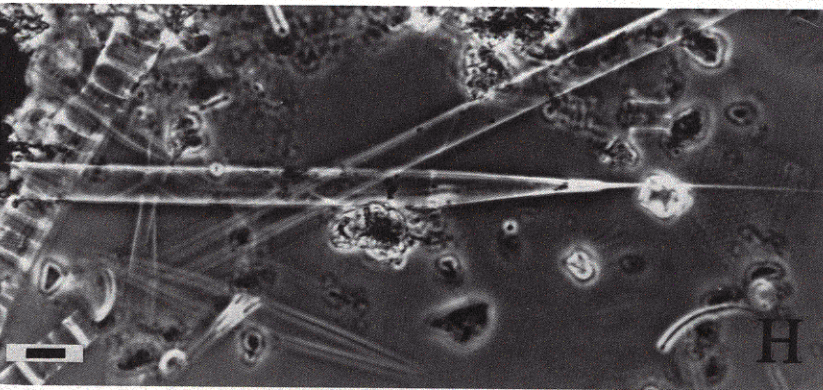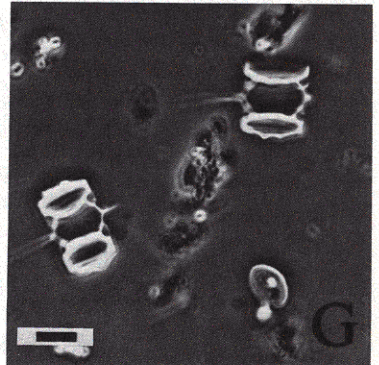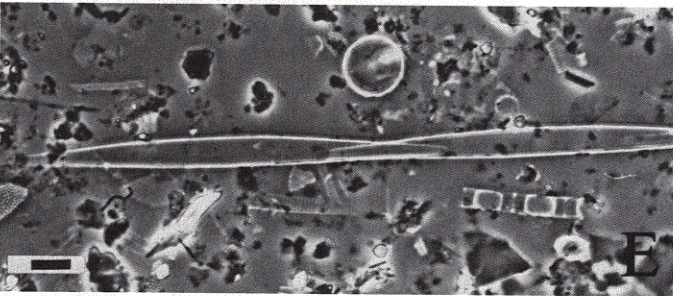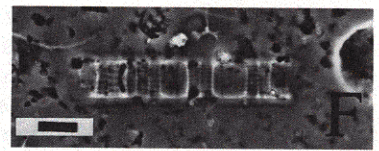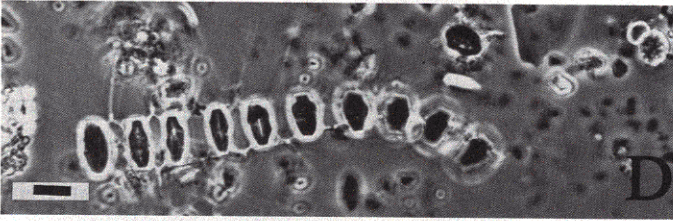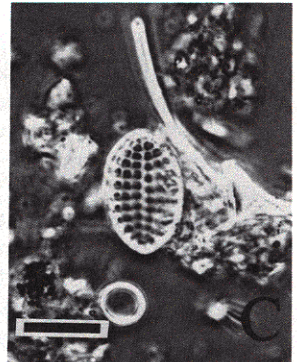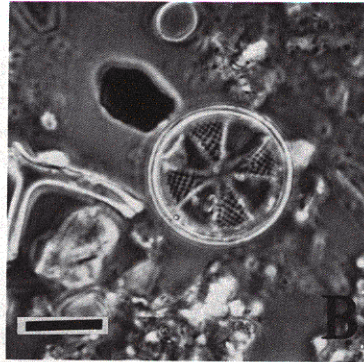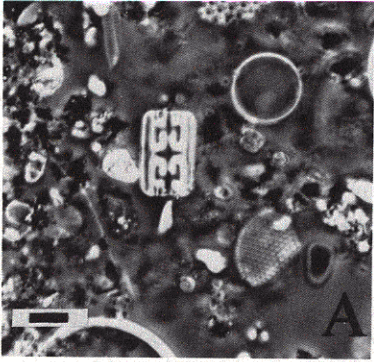
organic C concentrations were roughly constant among months (Fig. 3), implying that the rain of siliceous plankton to the sea floor is more variable than the flux of calcareous plankton. The only relevant sediment trap measurements from the basin are those of Dymond et al. (1981), who reported that SiO_2 fluxes were ~60 times greater than $CaCO_3$ fluxes during multiple 48-d sediment-trap collections in March–April 1978.

In June, the diatom assemblage contained many more small and weakly silicified forms than were present in February or October (e.g. *Skeletonema costatum, Nitzschia seriata, Nitzschia sicula,* and vegetative cells of *Chaetoceros cinctus, Chaetoceros debilis, Chaetoceros radicans,* and *Detonula pumila;* Table 2; Fig. 4). The October assemblage had the greatest proportion of large forms (e.g. *Ditylum brightwelli, Nitzschia pungens, Nitzschia seriata, Rhizosolenia hebetata, Rhizosolenia styliformis, Thalassiosira eccentrica*), and benthic diatoms that were presumably washed in from the shelf were more abundant in February. In samples from all 3 months, resting spores of *Chaetoceros* spp. were dominant ($\geq 50\%$ of the entire assemblage). By examining sediment varves buried deeper than 2 cm, we have observed that the *Chaetoceros* resting spores remain, but the vegetative and other weakly silicified forms are rarely preserved. In other words, light and dark layers may contain different concentrations of opaline silica, but they are not easily distinguished by the species composition of their microplankton after they are buried. This observation suggests that seasonal changes in the rate of microplankton sedimentation simply augment a varving mechanism that is established by bottom-water chemistry and the benthic bacterial mat.

One important fraction of the sediments of the Santa Barbara Basin we have not attempted to quantify consists of terrigenous materials derived ultimately from continental runoff. Qualitatively, fine-grained terrigenous material did appear most concentrated in our February surface samples. This appearance could have been a function of the changing proportions of biological components, however, not a varying lithogenic flux. During a typical yearly cycle,

terrigenous materials are delivered to the shelf primarily by local rivers and in December–March (Gorsline et al. 1984). The principal transport processes that then make detrital sediment available for basin sedimentation are surface-water turbid plumes, subsurface nepheloid flow, mud turbidity currents, and downslope mass flows (Gorsline et al. 1984; Thornton 1984). Only the first two of these processes have been shown to be more intense in winter (Gorsline et al. 1984). Conversely, aperiodic occurrences of the latter processes, and significant time lags between the introduction of suspended detrital matter and particle removal to the sediment, are courses that may diminish the influence of terrigenous inputs on laminae formation.

Here, definite evidence that diagenetic mobilization, bacterial mat development, and benthic Foraminifera are responsive to seasonal forcing has been presented. These findings suggest a benthic mechanism for the generation of cyclic bedding that may be especially applicable to laminates that were deposited in distal basins or environments otherwise isolated from terrigenous sources during the geologic past. Prime examples are many of the organic-rich, laminated shales found throughout the Miocene Monterey Formation of California (Mertz 1984).

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