

SEDIMENTATION PATTERNS OF DIATOMS, RADIOLARIANS, AND SILICOFLAGELLATES IN SANTA BARBARA BASIN, CALIFORNIA

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ABSTRACT

We report on fluxes of siliceous microorganisms (diatoms, radiolarians, and silicoflagellates), organic carbon, calcium carbonate, biogenic silica, and lithogenic particles in the Santa Barbara Basin (34°14'N, 120°02'W), offshore of California, in a sediment trap set 540 m deep, from August 1993 to November 1994. Although total mass flux was dominated by lithogenic components throughout the sampling period, we believe that overall flux variations at 540 m were closely coupled with oceanographic conditions at the surface. Organic carbon and biogenic silica fluxes show distinct variations, with maxima during the upwelling period, from May to July 1994, and low fluxes from September to March. Diatoms were the main contributor to the biogenic opal fraction (mean daily flux = 3.98×10^5 valves $m^{-2} d^{-1}$), followed by radiolarians (mean = 7.05×10^3 tests $m^{-2} d^{-1}$) and silicoflagellates (mean = 1.48×10^3 skeletons $m^{-2} d^{-1}$). Each group showed a distinct pattern, with marked production maxima at different times of the year: radiolarians in late summer and fall, silicoflagellates in winter, and diatoms in spring. In total, 150 diatom and 165 radiolarian taxa were identified. Species composition associated with flux peaks differed, reflecting seasonal changes in circulation patterns and the source of water masses in the basin. Spring upwelling is reflected by the co-occurrence of deep-living intermediate radiolarian fauna (mainly *Lithomelissa setosa*) and diatom resting spores (mainly *Chaetoceros radicans*). Non-upwelling conditions, summer through winter, with water entering the basin from the west or the east, are represented by a warm-water, surface-dwelling radiolarian fauna and diatoms that are typically found in temperate and temperate-warm offshore waters. The intra-annual sequence of events, each characterized by a distinct diatom assemblage, can be identified in the laminated sediments of the Santa Barbara Basin. *Chaetoceros* resting spores dominate fluxes in spring, the most productive season, in both the trap and sedimentary records. Thus the effect of preservation in the sedimentary record does not seem to remove information from the most productive season, as is the case in most other areas of the world. Since species in the plankton and in the trap occur simulta-

neously and are observed within the surface sediment layer in pristine conditions, we assume that dissolution is minimized by rapid descent through the water column. Dissolution seems to take place immediately below the sediment/water interface, and weakly silicified species are removed from the sedimentary record.

INTRODUCTION

In order to use the fossil record to interpret past climatic conditions it is necessary to understand the nature of seasonal representation in the sediments (see review of Anderson 1996). With the increasing interest in high-resolution paleoceanographic studies and the closer linkage to climate modeling, it is crucial to assess the quality and accuracy of the information preserved in the sedimentary record (Sancetta 1992). Transformations associated with the settling of biogenic material from the uppermost layers of the ocean to the seafloor provide clues for understanding mechanisms involved in the formation of sediments, the supply of food to the deep-sea benthos, and the formation and fate of new and recycled organic matter (Berger et al. 1989).

Work conducted by several investigators in different areas of the World Ocean indicates that in terms of abundance and diversity, the diatom assemblage reaching the ocean floor is not only impoverished with respect to the surface community, but also affected by dissolution at the sediment/water interface (e.g., Reimers et al. 1990; Sancetta 1992, 1995; Lange et al. 1994; Treppke et al. 1996). To resolve the questions of seasonal variability recorded in the sediments, it is necessary to examine the sequence from production in the upper water column, through vertical settling, to final burial in the sediment, at time scales of days to months. This is now possible with the use of moored sediment traps (see review in Lange and Boltovskoy 1995).

We report on fluxes of diatoms, radiolarians, and silicoflagellates in the Santa Barbara Basin (SBB), offshore of California, in a sediment trap set at about 500 m deep, from August 1993 to November 1994. Although several studies have used sediment traps to measure fluxes for short periods of time in the SBB (Soutar et al. 1977; Dunbar and Berger 1981; Dymond et al. 1981) our study represents the first attempt to monitor biweekly changes in the flux of siliceous microorganisms in this basin over

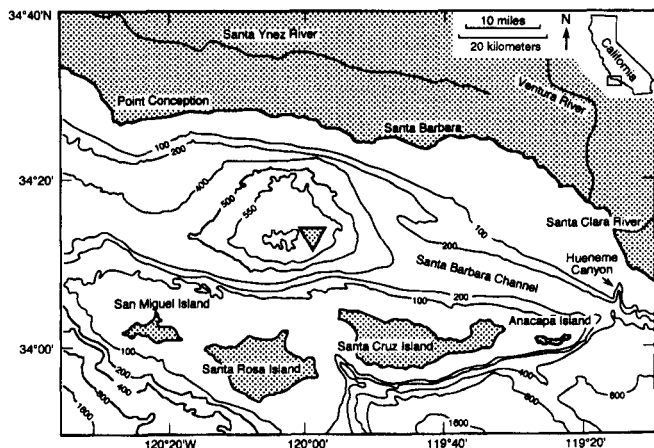


Figure 1. Bathymetry (in meters) of Santa Barbara Basin and location of sediment trap mooring (triangle).

a 15-month cycle. This work is part of an ongoing trapping program being carried out by the University of South Carolina (Thunell et al. 1995) with the goal of monitoring seasonal changes in sediment fluxes in the SBB and evaluating varve formation. We demonstrate that flux patterns of the siliceous components of the plankton are a response to changes in upper-ocean conditions in the SBB, and that the shifts in species composition reflect the complicated hydrography of the area. Our results should aid micropaleontologists in interpreting the climatic signal contained in the laminated sediments of the SBB.

STUDY AREA

The Santa Barbara Channel (SBC) is an elongated basin lying between the California coast and the Channel Islands. An approximately 500-m-deep basin occupies the western part of the central channel (Santa Barbara Basin; figure 1). The SBC is separated from the Southern California Bight to the east by a sill about 200 m deep between Anacapa Island and Port Hueneme. A sill about 400 m deep between Point Conception and San Miguel Island separates the SBC from the open ocean to the west. Below this deeper sill depth, the modern SBB contains oxygen-depleted waters which derive from the Pacific Intermediate Water mass and the Oxygen Minimum Zone off central California. Once within the basin, this low-oxygen (0.1 to 0.3 mL/L; Sholkovitz and Gieskes 1971) water mass is further depleted of oxygen by degradation of organic matter from the highly productive surface waters, rendering the seafloor inhospitable to benthic fauna and preventing bioturbation (Emery and Hülsemann 1962), thus allowing the seasonal sedimentation patterns to be preserved as annually laminated (varved) sequences.

The SBB underlies the highly productive waters of the California Current system, the strength of which

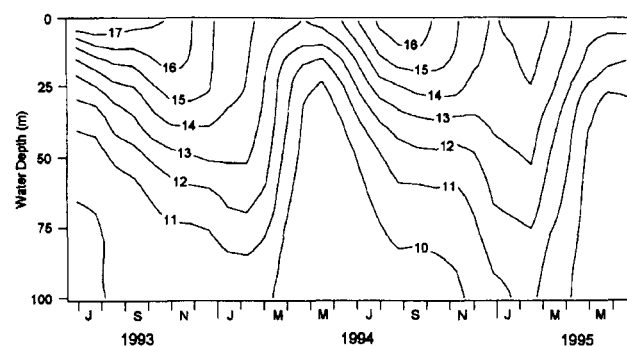


Figure 2. Upper ocean temperature at sediment trap location, derived from biweekly conductivity-temperature-density casts from July 1993 to May 1995. Isotherms are in degrees centigrade.

changes in response to seasonal variations in the winds (Huyer 1983). Prevailing winds around Point Arguello–Point Conception are equatorward, and almost always upwelling-favorable. They are strong and steady during spring and early summer, weaker and far more variable in winter (Hendershott and Winant 1996).

The surface waters of the SBC are primarily mixtures of warm and saline waters from the Southern California Bight, with colder and fresher waters upwelled near Point Conception and Point Arguello (Hendershott and Winant 1996). The California Current flows equatorward past the western mouth of the SBC.

The salient features of the surface circulation are summarized in Hendershott and Winant 1996. In general, surface flow at the eastern mouth of the SBC is poleward except in winter. At the western mouth, surface flow is poleward along the north shore of the channel, and equatorward along the north shore of the Channel Islands. Counterclockwise recirculation occurs here; it is strongest during spring through autumn. Episodes of vigorous eddy motion are frequent in the western half of the channel, especially in spring and summer. Upwelled waters near Points Arguello and Conception enter the SBC eastward along the Channel Islands as part of the recirculation.

During our study period (Aug. 1993–Nov. 1994) the upwelling interval was identified by the shoaling of isotherms (figure 2) and high chlorophyll *a* concentrations in surface waters (Hayward et al. 1994).

MATERIALS AND METHODS

Sediment trap samples were recovered from the center of the SBB (34°14'N, 120°02'W; figure 1) between 12 Aug. 1993 and 1 Nov. 1994, with a small gap of 12 days between 11 and 23 Aug. 1994. Samples were obtained with a cone-shaped trap with 13 cups and a collection area of 0.5 m²; they were poisoned with HgCl₂. Each trap sample represents a two-week period, and samples were collected continuously. The mooring was

deployed in 590-m-deep water, the trap positioned about 50 m off the bottom.

Siliceous microplankton analyses were carried out on 1/64 splits of total material in the original sample. The entire split was first washed with distilled water to remove salt and preservatives, and then acid-cleaned and prepared according to the method of Wigley (1984); permanent slides were mounted with Naphrax (for diatoms and silicoflagellates; refractive index 1.74) and Canada balsam (for radiolarians; refractive index 1.54). Quantitative analysis of the diatoms and silicoflagellates was performed with a Zeiss standard microscope with phase contrast illumination, at 250× magnification. *Chaetoceros* resting spores and occasional very numerous or extremely small diatom valves were counted at 650× magnification. Quantification and identification of radiolarians was done with a Zeiss Photomicroscope I, at 100× magnification. All counts refer to the ≥45-μm fraction. For each of the above taxonomic groups, several traverses across the microslide were examined, depending on abundance, and each organism was identified to the lowest taxonomic level possible. Two microslides per sample were scanned in this fashion.

Fluxes in each sample were determined for the three taxonomic groups surveyed, as well as for individual species; they were standardized to daily rates and are expressed in numbers $m^{-2} d^{-1}$ (Sancetta and Calvert 1988). Relative abundances of individual taxa are given as percentages of the total diatom and radiolarian assemblages.

Specific diversity was computed for diatoms and radiolarians only, using Margalef's (1958) formula $S_i - 1 / \ln N_i$, where S_i is the number of taxa in sample i and N is the total number of individuals in sample i . Diversity was not calculated for silicoflagellates, since only three species were present (*Dictyocha fibula*, *D. speculum*, and *Octactis octonaria* var. *pulchra*).

Radiolarian species were grouped into warm-water, transition, and intermediate environmental groups, according to their biogeographic distribution, as documented by Weinheimer (1994), following the oceanic provinces of McGowan (1974). Warm-water fauna includes species found in warm, high-salinity surface waters entering the California Current system from the west (gyre) or south (tropical waters). Transition fauna is found in cool, low-salinity waters transported southward within the California Current; it includes species from the Subarctic and Transition provinces, as defined by McGowan (1974). Intermediate fauna lives below the thermocline, in cold, high-salinity intermediate waters; along the California coast, it is vertically advected to shallower depths with the shoaling of the thermocline. Ecological affinities and biogeographic distribution of diatoms are well known and have been published elsewhere (e.g., Smayda 1958; Hasle 1976; Semina 1979);

we followed Cupp (1943), Round et al. (1990), and Hasle and Syvertsen (1996). Throughout this text, the term *neritic* refers to those diatoms mainly confined to inshore waters; *oceanic* refers to those typically found in the offshore, open-ocean realm. Each of them, neritic and oceanic, have representatives in cold, temperate, and/or warm waters.

RESULTS

Particle Fluxes

Bulk-sediment flux data at the SBB mooring are summarized in figure 3, and include daily fluxes of organic carbon, calcium carbonate, biogenic silica, and lithogenic particles, as determined by Thunell et al. (1995). Total mass flux was dominated by lithogenic components (58%–80% range) throughout the sampling period. We contend, however, that overall flux variations at 540 m were closely coupled with oceanographic conditions at the surface. In particular, organic carbon and biogenic silica fluxes show distinct variations, with maxima from May to July (0.08 – $0.18 g m^{-2} d^{-1}$ and 0.3 – $0.9 g m^{-2}$

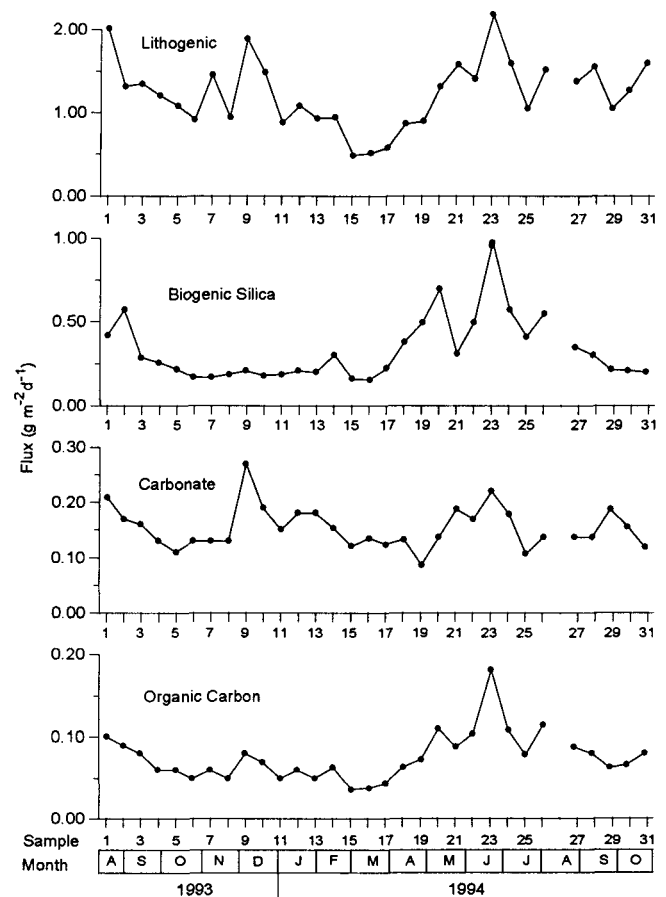


Figure 3. Organic carbon, carbonate, biogenic opal, and lithogenic fluxes (in $g m^{-2} d^{-1}$) measured in two-week-long samples at SBB sediment trap location (~540-m water depth), from August 1993 to November 1994.

d^{-1} , respectively) and low fluxes from September to March (Corg = $0.04\text{--}0.08\text{ g m}^{-2}\text{ d}^{-1}$; silica = $0.2\text{--}0.5\text{ g m}^{-2}\text{ d}^{-1}$). This variability reflects intra-annual changes in upper ocean conditions, with the highest fluxes occurring during the upwelling period (see Study Area). Silica fluxes were typically five times higher than organic carbon fluxes. In contrast, carbonate flux (primarily composed of foraminifers and coccolithophorids) did not vary significantly during the sampling period; the range of values is small ($0.1\text{--}0.3\text{ g m}^{-2}\text{ d}^{-1}$), and the value peaked in winter.

Of relevance for the terrigenous input to our sampling site are the precipitation and runoff patterns into SBB. They are typically greatest during late fall and winter (Soutar and Crill 1977), and this was observed during our study (Thunell et al. 1995); high lithogenic fluxes occurred in October 1994 and November–December 1993 (figure 3). However, lithogenic flux showed a peculiar distribution pattern. In addition to the expected fall–winter peak mentioned above, high lithogenic fluxes were also measured in August 1993 and in spring–early summer 1994. Thunell et al. (1995) attributed this to both the incorporation of terrigenous material into fecal pellets and the scavenging of fine detrital particles from the water column by organic-rich aggregates. We found a good correlation (correlation coefficient $r = 0.8$) between the organic carbon and the lithogenic fluxes, indicating that sedimentation of terrigenous components may be linked to biological processes (Deuser et al. 1983; Wefer and Fischer 1993). Although fecal pellets and aggregates were not quantified, a casual inspection of the trap samples revealed that they are much more common in the April–June samples.

Fluxes of Siliceous Microorganisms

Diatoms were the main contributor to the biogenic opal fraction (mean daily flux = $3.98 \times 10^5\text{ valves m}^{-2}\text{ d}^{-1}$), followed by radiolarians (mean = $7.05 \times 10^3\text{ tests m}^{-2}\text{ d}^{-1}$) and silicoflagellates (mean = $1.48 \times 10^3\text{ skeletons m}^{-2}\text{ d}^{-1}$). Each group showed a distinct pattern, with the timing of peak fluxes reflecting a clear succession of these microplankton groups (figure 4).

Flux maxima for radiolarians were observed in fall 1993, February 1994, and again in early fall 1994. Silicoflagellates peaked in winter 1993–94 and in early fall 1994 (together with radiolarians). Diatoms yielded four flux maxima—in February, two peaks during spring, and in autumn 1994. The highest value of $6.81 \times 10^6\text{ valves m}^{-2}\text{ d}^{-1}$ was measured in April (sample 19, out of scale in figure 4), in coincidence with the spring upwelling period (figure 2) and its associated high chlorophyll a concentrations at the surface (Hayward et al. 1994).

The specific diversity of diatoms and radiolarians was related to their flux (figure 5); positive correlation for

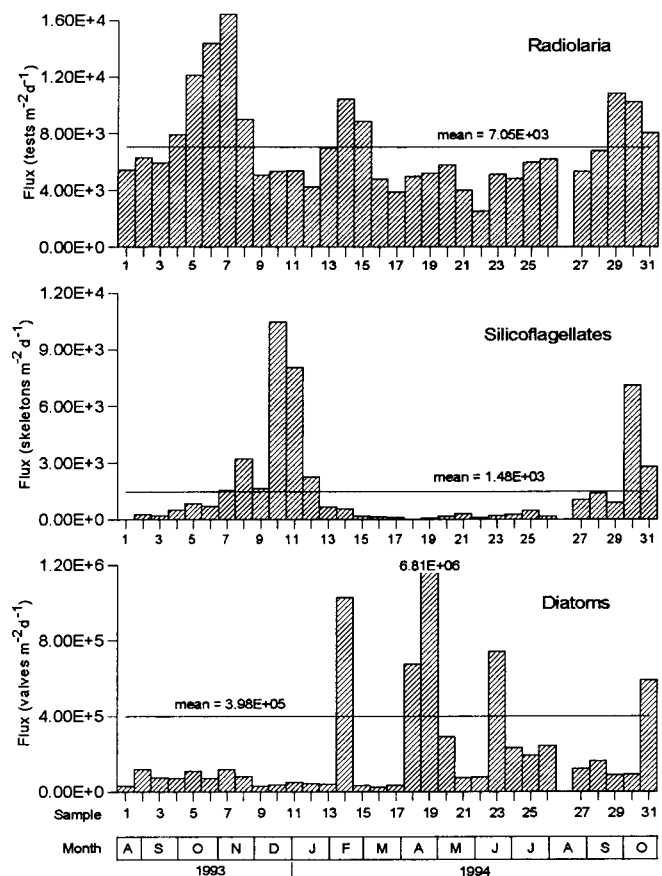


Figure 4. Time-series fluxes of radiolarians, silicoflagellates, and diatoms at SBB sediment trap location (~540-m water depth), from August 1993 to November 1994.

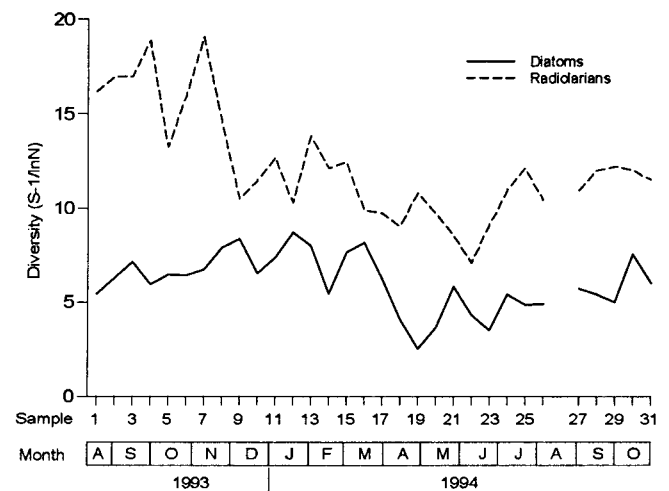


Figure 5. Radiolarian and diatom specific diversity, as measured by the Margalef (1958) index, at SBB sediment trap location (~540-m water depth), from August 1993 to November 1994.

radiolarians ($r = 0.5$) and negative correlation for diatoms ($r = -0.5$). In general, highest diatom fluxes yielded lowest diversities; this is especially noticeable in spring (diversity index <4 ; figure 5). In contrast, radiolarian

TABLE 1
 Selected Diatom and Radiolarian Species
 (Species or Species Groups with $\geq 5\%$ in at Least
 One Sample) Used in Cluster Analysis

Diatoms	
<i>Bacteriastrium elongatum</i>	
<i>B. furcatum/delicatulum</i>	
<i>Chaetoceros</i> spp. resting spores:	<i>C. affinis</i> , <i>C. compressus</i> , <i>C. debilis</i> , <i>C. diadema</i> , <i>C. lorenzianus</i> , <i>C. sp. cf.</i> <i>C. lorenzianus</i> , <i>C. radicans</i> , <i>C. seiracanthus</i> , <i>C. vanheurckii</i>
<i>Chaetoceros</i> spp. vegetative cells:	<i>C. concavicornis</i> , <i>C. radicans</i>
<i>Coscinodiscus</i> spp.:	<i>C. centralis</i> , <i>C. perforatus</i> , <i>C. radiatus</i>
<i>Rhizosolenia robusta</i>	
<i>Thalassionema frauenfeldii</i>	
Non-planktonic diatoms: <i>Arachnoidiscus ehrenbergii</i> , <i>Aulacodiscus kittonii</i> , <i>Campylodiscus clypeus</i> , <i>Cerataulus turgidus</i> , <i>Coconeis scutellum</i> , <i>Navicula praetexta</i> , <i>Pleurosira laevis</i> , <i>Rhabdonema adriaticum</i> , <i>Stictodiscus californicus</i> , <i>Trigonium formosum</i> <i>f. quadrangularis</i>	
Radiolarians	
<i>Arachnocorallium calvata</i> group*	
<i>Botryostrobos aquilonarus</i>	
<i>B. auritus/australis</i>	
<i>Dictyophimus gracilipes</i>	
<i>Larcopele butschlii</i>	
<i>Lithomelissa setosa</i>	
<i>Pterocorys minythora</i>	
<i>Spongodiscid</i> sp.	
<i>Spongopyle osculosa</i>	
<i>Spongurus</i> sp. cf. <i>S. elliptica</i>	

**A. calvata* group includes skeletons with a wide range of morphological variability, and probably combines closely related taxa (Boltovskoy and Riedel 1987).

diversity was higher overall (index range 7–19 vs. 2–9 for diatoms), and peaks in diversity were generally associated with flux maxima (except in late summer 1993).

In total, 150 diatom and 165 radiolarian taxa were identified. These numbers may underestimate the actual number of species present in the area, because they also include instances where organisms were identified to genus only (e.g., diatoms: *Navicula* spp., *Pleurosigma* spp.; radiolarians: *Porodiscus* spp., *Lophophaena* spp.).

Annual Cycle of Species Assemblages

During the 15-month study (Aug. 1993–Nov. 1994) diatom and radiolarian species showed clear changes in their relative and absolute abundances. In order to define a monthly pattern, we performed a cluster analysis of samples, based on the relative abundances of species or species groups (e.g., *Arachnocorallium calvata* group, nonplanktonic diatoms) present in the $\geq 45\text{-}\mu\text{m}$ fraction with $\geq 5\%$ in at least one sample (table 1), and the log-transformed total fluxes of diatoms, radiolarians, and silicoflagellates. Clusters were based on the correlation matrix (distance metric is 1–Pearson correlation coefficient), using average-linkage clustering (SYSTAT, Inc.). Five distinct clusters can be defined (figure 6).

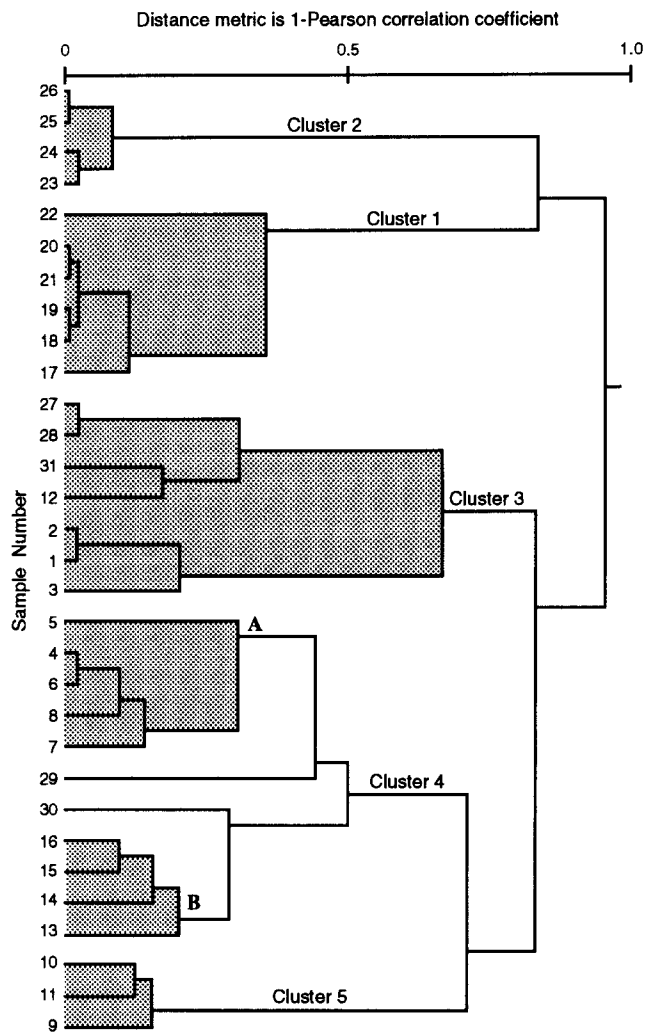


Figure 6. Cluster analysis (average-linkage clustering) of SBB sediment trap samples based on the relative abundances of diatom and radiolarian species or species groups with $\geq 5\%$ in at least one sample (table 1), and the log-transformed fluxes of total diatoms, radiolarians, and silicoflagellates (clustering of samples as function of taxon assemblage and total microorganism flux values).

The clustering of samples reflects the changes in hydrography and associated surface production, and species makeup (figures 6, 7), as follows:

Cluster 1 (late March to mid-June; samples 17–22) characterizes the spring upwelling period defined by a shoaling of the thermocline (figure 2), high surface chlorophyll a concentration (Hayward et al. 1994), highest diatom and low radiolarian fluxes (figure 4). High relative abundances of *Chaetoceros radicans* resting spores ($>60\%$; figure 7A) and *Lithomelissa setosa* ($\sim 14\%$; figure 7B) dominate the diatom and radiolarian assemblages. *Chaetoceros radicans* is a common member of the spring diatom plankton in the southern California area (Cupp 1943), a typically coastal taxon indicative of newly upwelled waters (Pitcher 1990). *Lithomelissa setosa* is a deep-living radiolarian (intermediate fauna) brought to

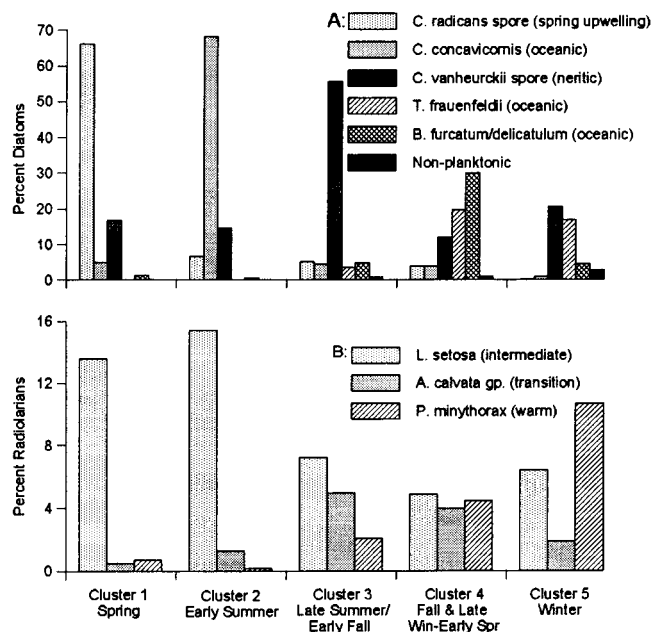


Figure 7. Seasonal succession of selected diatom (A) and radiolarian (B) species and species groups based on the clustering of samples as a function of taxa content. For diatoms, resting spores of *Chaetoceros radicans* indicate the upwelling period; *Chaetoceros concavicornis* and *Bacteriastrum furcatum/delicatulum* are representatives of temperate waters, and *Thalassionema frauenfeldii* is representative of temperate-warm offshore waters. Spores of *Chaetoceros vanheurckii* represent coastal conditions after the spring bloom, mainly summer-fall. The category of non-planktonic diatoms encompasses all marine, epiphytic, epipsammic, benthic, and freshwater taxa (table 1). Selected radiolarian taxa—*Lithomelissa setosa*, *Arachnocorallium calvata* group, and *Pterocorys minythora*—are indicators of upwelling, California Current waters, and warm waters, respectively.

shallower depths by upwelling. In the region of the California Current system, it lives below the salinity minimum, in cold, high-salinity waters that are upwelled along the California coast (Boltovskoy and Riedel 1980; Kling and Boltovskoy 1995). We believe that the co-occurrence of these two species represents a coastal upwelling-controlled assemblage characteristic of spring.

Cluster 2 (mid-June to August; samples 23–26) represents the early summer, a time when upwelling conditions fade, thermal stratification of the upper waters begins (figure 2), and pigment concentrations start to decline after the spring bloom (Thunell et al. 1995). Moderate radiolarian fluxes and high-moderate diatom fluxes are observed at this time (figure 4). The temporal coverage of this cluster includes the termination of the upwelling period given by a last spike of *L. setosa*, and the transition into summer conditions indicated by increased representation of *Arachnocorallium calvata*, a transition-group radiolarian (figure 7B). Large *Chaetoceros* cells (vegetative cells of *C. concavicornis*), representative of offshore waters (Cupp 1943), become important (relative abundances of ~70%; figure 7A).

Cluster 3 (mid-August to October; samples 1–3, 27, 28, 31) defines the midsummer through early fall pe-

riod, when surface waters in the SBB are warm (>16°C) and there is a strong stratification of the upper ocean (figure 2). Ten-meter chlorophyll a is moderately low (Hayward et al. 1994, 1995), and diatom fluxes are low (figure 4). At this time, the neritic diatom *Chaetoceros vanheurckii* reaches highest relative abundances (spores >50%), and small numbers of warm-water oceanic diatoms occur (figure 7A). A rather mixed radiolarian fauna is present; *L. setosa* abundances decline; and the shallow-dwelling species *A. calvata* and *Pterocorys minythora* enter the basin (figure 7B).

Cluster 4 includes two groups of samples representative of fall (*cluster 4A*, late September to early December, samples 4–8) and late winter-early spring conditions (*cluster 4B*, February to mid-March, samples 13–16), before the onset of the upwelling period. In the fall, thermal stratification of the upper ocean is still strong, and water temperatures are still high (figure 2). Total radiolarians and warm-water radiolarians show highest fluxes and proportions (figures 4, 7B). The contribution of oceanic diatoms of temperate-warm origins, such as *Thalassionema frauenfeldii* (up to 58%), is greatest at this time (figure 7A). The late winter-early spring is a transitional period between true winter conditions (low temperatures and a deep thermocline), and true upwelling conditions (low temperatures and a shallow thermocline). A diverse flora and fauna is present (figure 5) and is represented by taxa of different ecological affinities (figure 7B). During both of these hydrographic regimes, surface chlorophyll concentrations are generally low (Hayward et al. 1994, 1995), and diatom fluxes are minimal (with the exception of sample 14; see below).

An unexpected diatom flux peak was observed in February 1994 (sample 14; figure 4); it was dominated by long chains of *Bacteriastrum furcatum/delicatulum*, an oceanic species of temperate origin (Cupp 1943), and the radiolarians *A. calvata* group and *L. setosa*. We speculate that this peak is related to a “flood east” circulation pattern described by Hendershott and Winant (1996), and that California Current water with its associated flora and fauna moved into the SBB for a short time (Winant, pers. comm.).

Cluster 5 (December to January, samples 9–11) is characteristic of the winter period, when surface waters in SBB cool and the upper 60–80 m of the water column become nearly isothermal (figure 2); chlorophyll concentrations are low (Hayward et al. 1994). Silicoflagellates peak at this time (figure 4); *Dictyocha fibula* dominates the assemblage. A mixed diatom assemblage composed of temperate-warm oceanic (*Thalassionema frauenfeldii*) and typically coastal taxa (spores of *C. vanheurckii*) is observed (figure 7A). Warm-water radiolaria, as represented by *P. minythora*, reach highest relative abundances (>10%). Most probably, both warm-water flora and fauna were

brought into the SBB from the Southern California Bight through the eastern mouth of the channel (Hendershott and Winant 1996).

The contribution of non-planktonic diatoms is highest in December (reaching 6% of the entire diatom assemblage). We assume that their presence in the central SBB is associated with high precipitation and runoff into the basin characteristic of the winter rainy season (Soutar and Crill 1977). Of course, resuspension, downslope transport, and redeposition cannot be ruled out (Sancetta 1992), and may explain the moderately high (~20%) contribution of *C. vanheurckii* resting spores.

DISCUSSION

Santa Barbara Basin flux patterns described from the sediment trap data may reflect seasonal changes in upper ocean conditions. In particular, organic carbon and biogenic silica flux records showed distinct fluctuations, with low fluxes in the fall–winter period and high values in spring (upwelling period) that last into the summer. Diatoms dominated the biogenic silica fraction by at least an order of magnitude; they were followed by radiolarians and then silicoflagellates. Fluxes of the three groups showed a clear monthly sequence, with distinct production maxima at different times of the year: radiolarians in late summer and fall, silicoflagellates in winter, and diatoms in spring (figure 4).

Species composition associated with flux peaks differed, reflecting seasonal changes in circulation patterns and the source of water masses in the basin (figure 8). Following Hendershott and Winant's (1996) scheme of synoptic circulation patterns in the SBB, spring upwelling with strong eastward flow is reflected by the high fluxes of deep-living intermediate radiolarian fauna and *Chaetoceros* resting spores (mainly *C. radicans*; Cluster 1), and a shoaling of the thermocline (figure 8). Non-upwelling conditions (i.e., flood east/flood west, and cyclonic flow), summer through winter, with water entering the basin from the west or the east, are represented by a warm, surface-dwelling radiolarian fauna and oceanic diatoms (clusters 2–5); warm surface waters and a deep thermocline are characteristic of this period (figure 8). As an indication of the tight coupling between circulation and microorganism fluxes, a flood east event with California Current waters entering the basin took place in the winter of 1994 (Winant, pers. comm.) and was represented by anomalously high fluxes of temperate oceanic flora and intermediate fauna during an otherwise warm, low-productivity period.

Because the flux records presented here represent only 15 months of data collection, continued monitoring is being carried out to establish whether a seasonal pattern of fluxes and species assemblages does exist in the SBB, and to assess interannual variability in flux patterns.

Preliminary results for 1995–96 point to a repetition of the patterns described above, with high fluxes for the spring–summer period (Thunell, pers. obs.) and *Chaetoceros* species dominating the spring plankton assemblage (Venrick, pers. comm.).

Relevance of Trap Data to the Sediments

Sediment trap and biological oceanographic studies reveal that particle flux from the surface ocean to the deep sea is highly episodic (e.g., Berger and Wefer 1992; Berger et al. 1989), yet in most marine depositional environments, the combination of low sediment-accumulation rates and vigorous benthic mixing does not allow preservation of these short-term events, and makes most deep-sea sediments suitable only for studying millennial-scale climate change. High-resolution studies, with annual-to-century-scale resolution, are best achieved in marginal basins where discrete annual laminations (varves) of accumulating sediment are preserved in an oxygen-depleted depositional environment (see review in Kemp 1996).

According to Sancetta and Calvert (1988), the environment chosen for such a study should be one of high productivity and of marked seasonal variation, where organisms that produce preservable hard parts are a significant component of the plankton and are known to occur in local sediments. Moreover, sedimentation rates should be high so that a year of trap material can be compared directly with the equivalent accumulation in the surface sediments. The SBB represents an ideal setting for such a study. It is part of the CalCOFI time-series grid, and a well-known site for work on physical oceanography (e.g., Hendershott and Winant 1996); surface-water pigment concentration and primary productivity; zooplankton biomass; fish population dynamics (e.g., Hayward et al. 1996; McGowan et al. 1996; California Department of Fish and Game 1996); and the varved sedimentary record (Baumgartner et al. 1992; see review in Lange et al. 1996 and articles in Kennett et al. 1995).

Our results from a 15-month sediment trap study confirm earlier hypotheses that there is a significant intra-annual variability in both the quantity and composition of sedimentary particles delivered to the seafloor in the SBB (e.g., Hülsemann and Emery 1961; Soutar and Crill 1977). This variability plays an important role in the accumulation of sediment laminae. Laminated sediments in the SBB are characterized by intimate juxtaposition of light-colored (light olive to olive) biosiliceous layers and darker-colored (dark olive) layers enriched with terrigenous detritus, reflecting spring–summer and late fall–winter deposition, respectively (Hülsemann and Emery 1961; Emery and Hülsemann 1962; Soutar and Crill 1977; Reimers et al. 1990; Lange et al. 1996).

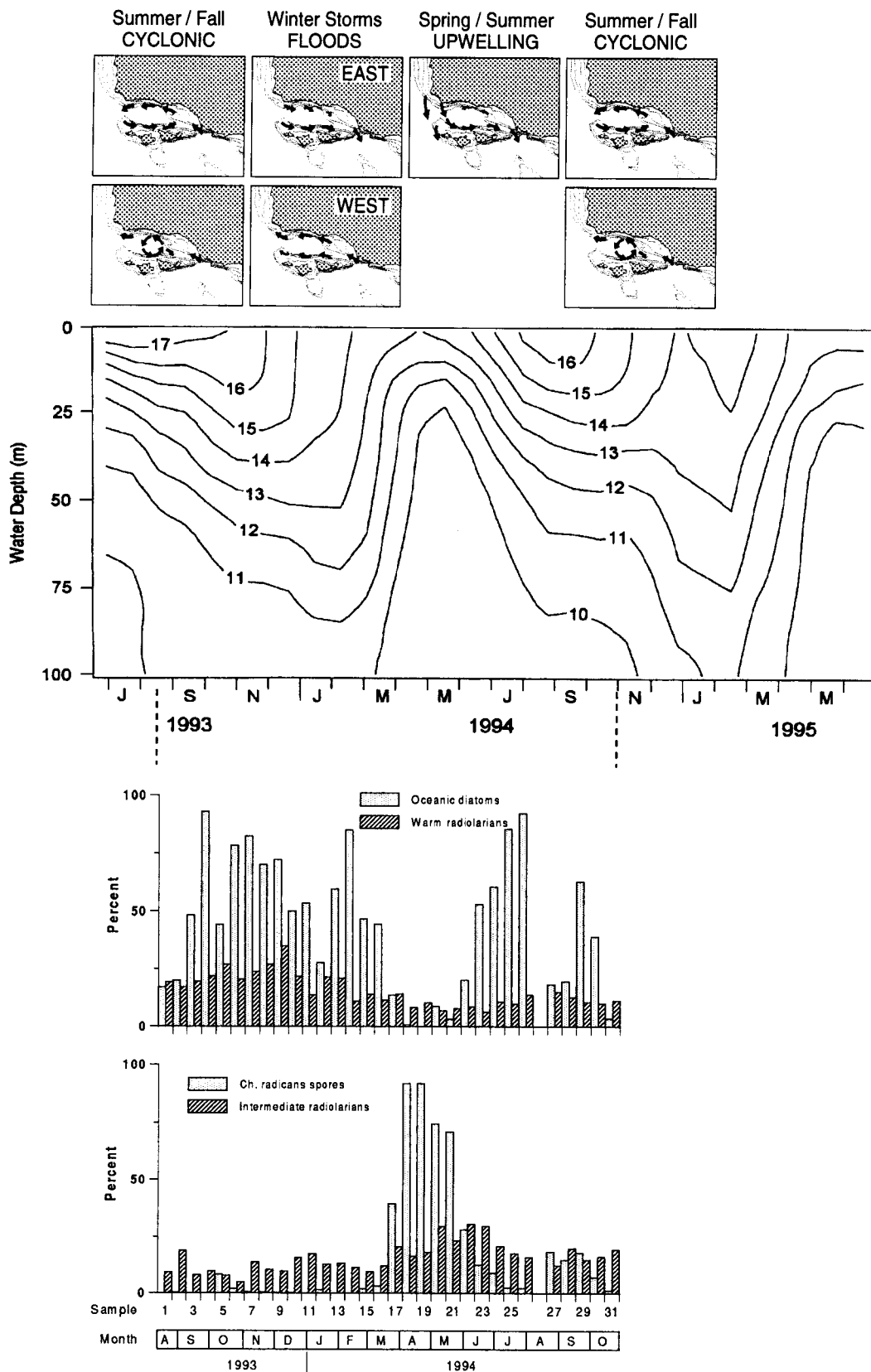


Figure 8. Summary of seasonal synoptic circulation patterns in the SBB (from Hendershott and Winant 1996), temperature profile, and associated diatom and radiolarian species groups representative of upwelling (intermediate radiolarians and *Chaetoceros radicans*) and non-upwelling (warm radiolarians and oceanic diatoms) conditions.

In the trap, we observed that during late fall and winter more than 80% of the total sediment flux is lithogenic material, while biogenic fluxes are low. This combination results in the deposition of dark laminae. In contrast, biogenic fluxes (organic carbon and silica) are highest and least diluted by detrital material during spring–summer, and we suggest that light laminae are formed at that time. Preliminary results of the 1995–96 trap monitoring program show a similar depositional pattern (Thunell, pers. comm.). Flux maxima of organic carbon and biogenic silica were measured in spring 1995 and 1996, and summer 1995. Lithogenic contribution ranged between 64% and 72% during spring–summer; it reached 86% of the total mass flux in winter 1995–96.

As for the biogenic assemblages contained in the varved sediments of the SBB, we need to know what processes resulted in the creation of any assemblage, and how accurately the fossil assemblage reflects the original living assemblages, before any paleoceanographic interpretation can be attempted.

Diatoms in the trap occur as short chains (e.g., *Pseudonitzschia*, *Chaetoceros*); as aggregates (mainly of *Chaetoceros* resting spores); as complete individual cells (with or without plastids); or as intact valves, or fragments (mainly *Thalassiothrix* and broken setae of *Chaetoceros* and *Bacteriastrium*). The occurrence at our 540-m-deep site of intact delicate radiolarian species (*Cladococcus* spp. and *Sethophormis* spp.), and of weakly silicified diatom species such as *Haslea* sp., *Leptocylindrus danicus*, *Nitzschia bicapitata*, as well as complete cells with chloroplasts argues against any significant dissolution and may reflect fast settling through the water column. Moreover, the fact that these species occur within the topmost surface sediment layer of the SBB in pristine conditions (Lange, pers. obs.) may indicate that dissolution is minimized by rapid descent from surface waters to the subjacent seafloor (sinking velocities $> 100 \text{ m d}^{-1}$, Alldredge and Gotschalk 1989; see reviews in Bull and Kemp 1996; and Grimm et al. 1996).

Dissolution of the diatom assemblage does occur immediately below the sediment/water interface (Reimers et al. 1990), and weakly silicified species and the vegetative cells of *Chaetoceros* are rarely preserved in the sedimentary record. In addition, large taxa like the rhizosolenids are usually fragmented. However, and in contrast to other areas (e.g., offshore Oregon: Sancetta 1992; eastern equatorial Atlantic: Lange et al. 1994), the seasonal sequence of events, each characterized by distinctive diatom taxa (figure 7), can be identified in the sediment laminae of the SBB (e.g., Bull and Kemp 1996), as is also the case in Saanich Inlet and the Gulf of California (see review in Sancetta 1996). Commonly observed species in the varves belong to the Thalassiosiraceae and Coscinodiscaceae groups. However, the

Chaetoceros resting-stage assemblage is invariably the one that dominates the sedimentary imprint (Reimers et al. 1990; Bull and Kemp 1996; Grimm et al. 1996; Lange et al. 1996).

Chaetoceros resting spore ooze laminae, including setae-rich sublamina, are prominent in SBB sediment samples. Excellent preservation of fine ornamental structures indicates that they were deposited without being grazed (i.e., fecal pelleting is not the major mechanism of deposition) or affected by significant dissolution (Bull and Kemp 1996; Grimm et al. 1996). Each spore lamina is believed to represent a phytoplankton population that was sedimented by rapidly sinking flocs at the end of a discrete bloom event (Alldredge et al. 1995). The most common species identified in modern flocs (Alldredge and Gotschalk 1989), *Chaetoceros radicans*, is also the commonest species identified in the Pleistocene and Holocene diatom ooze laminae. It was the most abundant diatom taxon in the April plankton of CalCOFI station 82.47, reaching concentrations of 400,000 vegetative cells l^{-1} and about 29,000 resting spores l^{-1} (Venrick, pers. comm.). In the trap, this taxon accounts for 92% of the diatom assemblage from 8 April to 5 May 1994 (samples 18 and 19) and represents the most productive spring season (figures 3, 4, 7, 8). Thus, in the SBB the effect of preservation in the sediment record does not seem to remove information from the most productive season.

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