

UPWELLING ALONG THE WESTERN INDIAN CONTINENTAL MARGIN AND ITS GEOLOGICAL RECORD: A SUMMARY

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ABSTRACT

Upwelling along the western Indian continental margin is recorded each year from Cape Comorin to Cochin and further north up to Goa from June to September during the southwest monsoon. During this upwelling heavy phytoplankton blooms develop which contribute to the sediment compositions along the western continental margin. Here, under the influence of coastal upwelling and the resulting intense midwater oxygen minimum, a belt of laminated dark organic-carbon-rich muds is deposited along the upper slope.

These laminations are believed to represent the response of the depositional environment to the annually recurring upwelling events. Distributions of organic carbon, opaline silica, benthic and planktonic faunas, and the preservation of biogenic sediment components can be correlated to the characteristics of the water masses and, thereby, to the intensity and magnitude of upwelling. Benthic and planktonic foraminifers are particularly useful indicators; e.g., the invasion of immigrant populations of *Globigerina bulloides*, and of dextrally coiled *Neogloboquadrina pachyderma typica* through upwelling leave a record of the presence of such water masses in the sediments of that region. The very occurrence of *Globigerina bulloides* and the absence or irregular occurrence of *Globorotalia menardi* also imply upwelling in that region, as does the presence of benthic foraminifers *Hyalinea balthica* and *Ehrenbergina* sp.

UPWELLING ALONG THE WEST COAST OF INDIA

During the southwest monsoon (June-September) in the Arabian Sea and the northwest monsoon (December-March) in the Bay of Bengal,

Table 1. Oceanographic and meteorological data during pre-monsoon and southwest monsoon period (April-September) and upwelling along the Indian west coast (modified after Subrahmanyam and Sarma, 1960)

	April	May	June	July	August	September
Rainfall						
Humidity	74-76%	76-81%	88-93%	92-96%	88-93%	83-91%
Condition of the sea	Calm and clear	Rough, turbid	Rough, turbid	Rough, turbid	Rough, turbid	Calmer, clear
Wind & velocity (V)	From North V=8.2-9.5 mph	North or NW V=7.7-9.9 mph	West V=5.7-7.5 mph	From seaward V=5.7-7 mph	From sea V=5.3-6.5 mph	From seaward V=4.9-6.2 mph
Current	North to South	North to South	Varies	Varies	NE-SW	NE-SW
Temperature (seawater)	29.2-30.5°C	28.4-29.7°C	26.5-28.4°C	24.9-26.3°C	24.3-26.5°C	24.5-26.2°C
Salinity						
(a) Surface	33.87-35.89‰	34.74-35.65‰	22.67-34.62‰	20.74-31.90‰	28.35-32.77‰	31.64-34.96‰
(b) Bottom	33.97-36.08‰	34.69-35.72‰	34.03-35.45‰	33.02-34.53‰	34.08-34.88‰	34.31-34.87‰
Oxygen content	3.62-6.07 ml/l	3.49-4.8 ml/l	2.48-5.43 ml/l	3.51-6.03 ml/l	3.60-5.03 ml/l	2.97-4.97 ml/l
Phosphate/Phosphorus						
(a) Surface	0.322-0.886 µg at/l	0.334-0.805 µg/l	0.23-0.897 µg/l	0.564-1.369 µg/l	0.495-1.932 µg/l	0.690-1.205 µg/l
(b) Bottom	0.322-0.420 µg/l	0.460-1.334 µg/l	0.288-2.036 µg/l	0.513-2.415 µg/l	0.598-2.427 µg/l	0.851-1.564 µg/l
Nitrate/Nitrogen						
(a) Surface	1.36-6.70 µg at/l	0.66-34.00 µg/l	3.20-20.70 µg/l	1.28-26.20 µg/l	0.47-9.80 µg/l	2.37-3.90 µg/l
(b) Bottom	0.77-1.75 µg/l	2.49-8.20 µ/l	Not available	Not available	2.21-5.95 µg/l	0.36-1.20 µg/l
Silicate/Silicon						
(a) Surface	7.21-12.50 µg at/l	7.73-13.86 µg/l	12.50-29.50 µg/l	25.00-34.82 µg/l	22.16-47.22 µg/l	15.11-40.58 µg/l
(b) Bottom	9.17-14.71 µg/l	11.11-19.42 µg/l	10.42-40.47 µg/l	16.67-31.89 µg/l	20.77-33.54 µg/l	12.50-42.34 µg/l

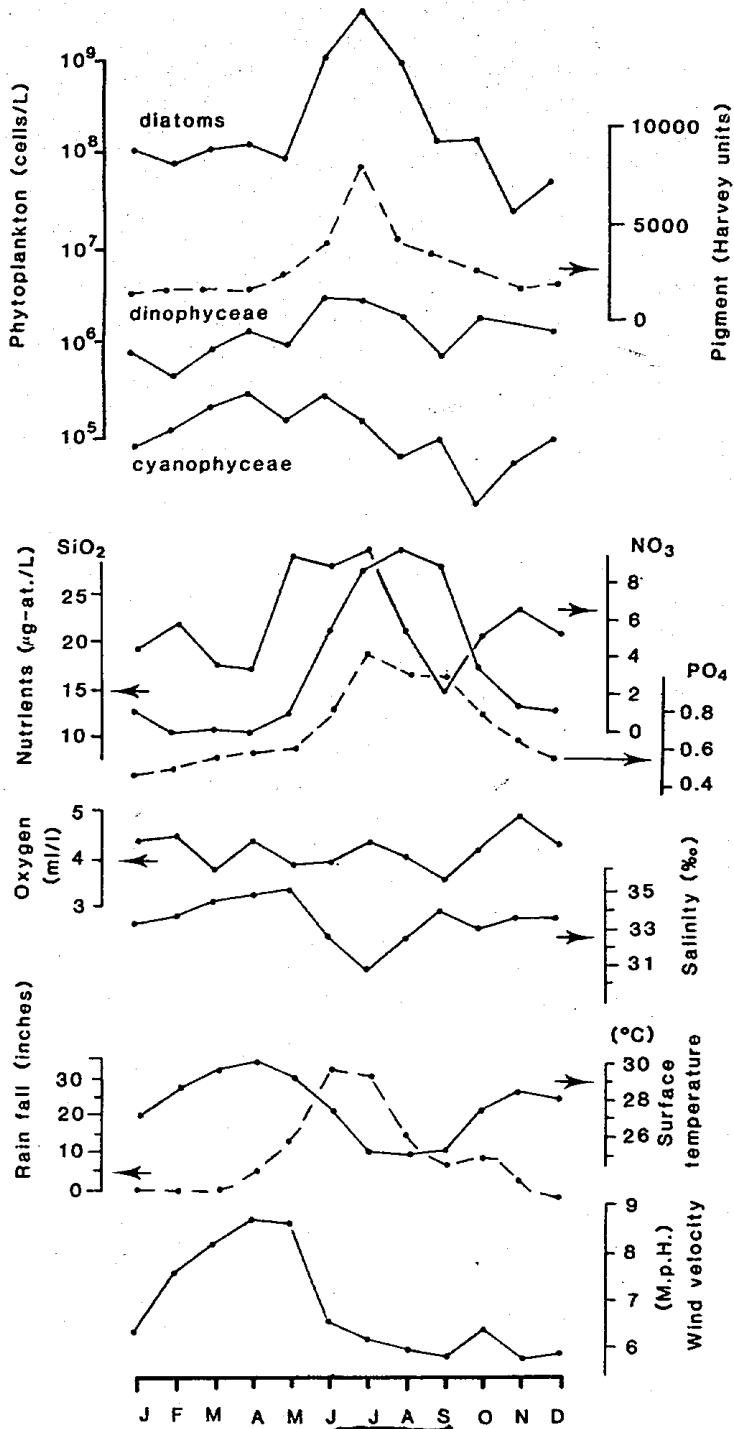


Fig. 1. Seasonal fluctuations in total phytoplankton (*Diatomaceae*, *Dinophyceae*, *Cyanophyceae*), nutrients and some meteorological data (after Subrahmanyam, 1958).

strong upwelling takes place in the coastal waters bordering the Indian subcontinent (George, 1953; La Fond, 1954; 1958; Jayaraman and Gogate, 1957; Banse, 1959). Sastry and d'Souza (1972) consider that upwelling off the west coast of India is the result of divergence in the current field and the formation of a cyclonic cell in the neighborhood of the Lacadive and Maldive islands. With the onset of the monsoon, upwelling is reported in the coastal waters of Sri Lanka, off Cape Comorin and Cochin. It extends to the southern part of Goa in the north, lasting through the entire southeast monsoon season. Sea surface temperatures are lowered by 4-5°C from a maximum at 29°C in April and May to 25°C in July and August. A remarkable increase to 29-30°C in October/November indicates that upwelling is strongest during July and August and that it lasts until October (George, 1953). Table 1 summarizes the oceanographic and meteorological conditions which exist during the southeast monsoon (Subrahmanyam and Sarma, 1960).

BIOLOGICAL AND OCEANOGRAPHIC IMPLICATIONS OF COASTAL UPWELLING OFF SOUTHWEST INDIA

Though coastal upwelling regimes cover only small parts of the total ocean area, they are very fertile in comparison to the adjacent regions. Exceedingly high primary production occurs in those regions where a large supply of nutrients is transferred to the surface waters. These regions sustain blooms of phytoplankton in the very shallow waters near the coast during upwelling periods, as can be illustrated for the coastal upwelling regime along western India (Fig. 1). There, in the post-monsoon period after the cessation of upwelling, the phosphate concentration of the surface waters seems to vary inversely with the amount of diatoms present. Concentrations of 2.4-3.5 $\mu\text{g-at./l}$ of phosphate were measured above the sea floor (Seshappa and Jayaraman, 1956). High phosphate contents, often accompanied by a decrease in temperature, were observed in the upwelled surface waters off the Indian west coast (George, 1953).

Oxygen concentrations in upwelling waters off the southwest coast of India are commonly below 0.25 $\text{ml O}_2/\text{l}$ (less than 5% of the normal concentration) on the shelf (Fig. 1; Banse, 1959). The oxygen in the water becomes depleted below the thermocline in wide areas along the entire coast. Waters of 23°C present on the shelf during the entire southeast monsoon season usually do not have oxygen concentrations $>2 \text{ ml O}_2/\text{l}$, and waters of 22°C are likely to be close to 1 $\text{ml O}_2/\text{l}$ when surfacing, according to Banse (1968). On the shelf, the oxygen is further depleted by contact with the sea floor as observed off Cochin. During the post-monsoon period, however, oxygen concentrations increase to 3.16-4.52 $\text{ml O}_2/\text{l}$ (Setty and Gupta, 1972).

The low oxygen but high nutrient concentrations of the cool upwelled water in the shelf region further augment phytoplankton devel-

opment in the euphotic zone. Plant pigment concentrations measured for seven years off Calicut (Subrahmanyam and Sarma, 1967) and off Cochin (Banse, 1968) indicated an increase that was roughly ten times higher during the upwelling season than during the off-season of any year. This suggests that short-term massive productivity in the surface waters accounts for high organic carbon contents in the underlying sediments. Thus, the accumulating organic matter may contribute to the overall oxygen depletion which results in strong anoxic conditions near the sediment surface. This can, for example, promote the generation of hydrogen sulfide and the deposition of pyrite as infillings in tests of foraminifers. Such infillings are observed in samples collected off Mangalore (Setty, 1979).

UPWELLING AND SEDIMENTARY RECORDS

The general sediment zonation along the western Indian continental margin seems to reflect a response to the monsoonal upwelling regime (Fig. 2). According to von Stackelberg (1972), the sediments in the shallowest water are highly reworked and layered as a result of currents running parallel to the coast. The sediment is progressively finer from the coast to approximately 50 m of water depth. On the outer shelf it becomes coarse again in a zone containing relict deposits where fine-grained material is stirred up, whirled and transported away thus leaving large areas without any recent sediment cover. Relict sands with ooids were formed in shallow turbulent waters during Pleistocene times. The fine material carried away from the zone of relict sands of the outer shelf is believed to be found in deposits along the uppermost part of the slope where laminated fine-grained sediments accumulate, sedimentation rates are high, and low oxygen concentrations persist in the bottom waters. The laminations observed in these sediments are believed to reflect annual variations in deposition which may be attributed to the seasonality of the southeast monsoon. The lower boundary of the laminated muds on the continental slope coincides with the lower boundary of the intensive oxygen minimum layer.

This peculiar microenvironment results in intensive differential preservation of opaline and calcareous skeletal material (von Stackelberg, 1972). Total phosphorus reaches its highest concentrations (2.14-1.12 mg/g or 1.04-0.84 wt-% P_2O_5 on a carbonate-free basis) in the upper 7.5 cm of the slope sediments and attains its minimum concentrations (0.105-0.80 mg/g or 0.025-0.020 wt-% P_2O_5) in similar deposits on the shelf. The organic carbon fluctuates closely with the increase and decrease in phosphorus and ranges from 4.7 wt-% C-org with 1.04 wt-% P_2O_5 in the top part of cores from the slope to 0.4 wt-% C-org with 0.16 wt-% P_2O_5 in the bottom parts of those from the shelf. The close relationship between phosphorus and organic carbon contents is indicative of "fresh" organic matter believed to be due to upwelling, luxuriant organic productivity, a non-depositional environment and the presence of abundant carbonates (Setty and Rao, 1972).

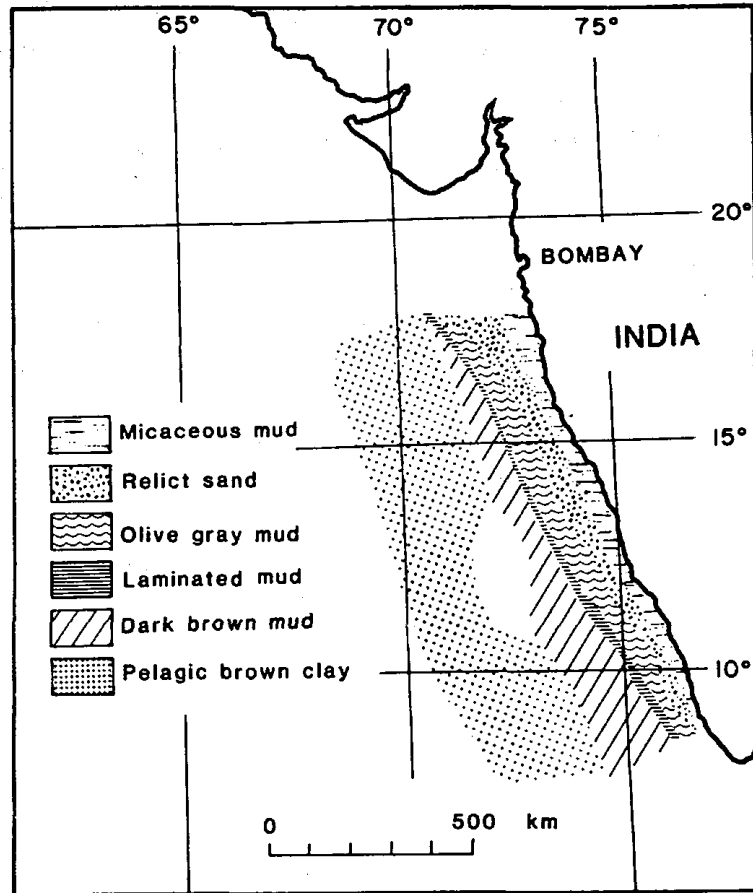


Fig. 2. Sediment distribution pattern on the shelf-slope region of Western India (modified after von Stackelberg, 1972).

The intensity and extent of the upwelling regime are preserved in the sediments as sedimentological, biogenic and isotopic signals (Duplessy, 1982), and biogenic particles especially provide some of the very best signals. The ratios of planktonic to benthic foraminifers, the organic carbon and opal contents, distributions of foraminifer, diatom, and radiolarian assemblages have all been used to identify and estimate the magnitude of past upwelling (Prell and Curry, 1981).

UPWELLING AND PLANKTONIC FORAMINIFERAL RECORDS

Zobel (1971; 1973) and Bé and Hutson (1977) recorded the occurrence of *Globigerina bulloides* in the upwelled waters of southwest India (Fig. 3), and Prell and Curry (1981) considered its occurrence

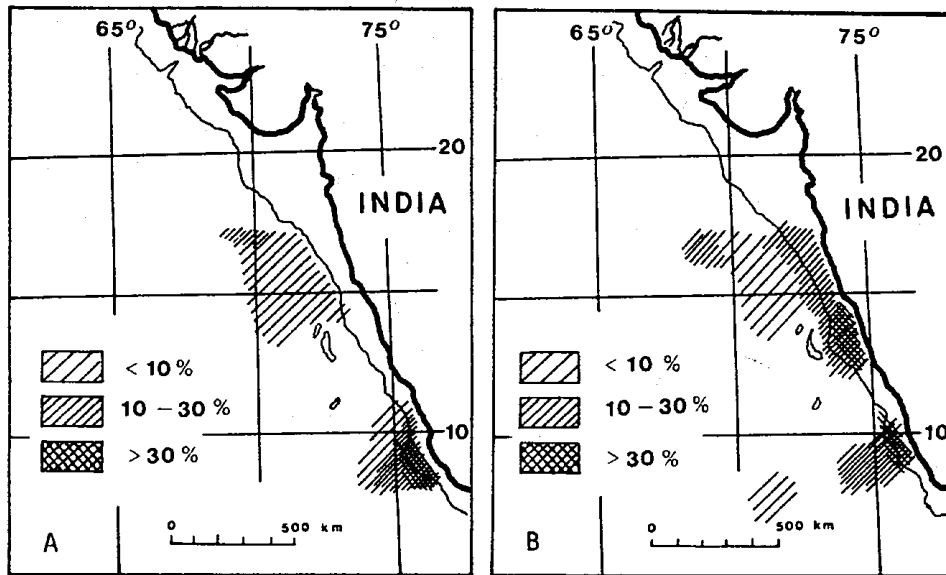


Fig. 3. Frequency distribution pattern of *Globigerina bulloides* (in total planktonic foraminifers): (A) in plankton tows from 200-0 m water depth; (B) in surface sediments along shelf-slope part of Western India (modified after Zobel, 1973).

as highly correlated to upwelling. It is noted from post-southwest monsoonal plankton tows that *Globigerina bulloides* and *Globigerinoides ruber* are most abundant, while *Globigerinoides quadrilobatus sacculifer*, *Globigerinella aequilateralis* and *Globorotalia menardii* are common (Setty, 1972). However, the complete absence of *G. menardii* from the surface sediments near the upwelling zone off Cochin attests to the result of the complexity of this region since it usually inhabits tropical water masses (Setty, 1972). Though *G. menardii* and its subspecies are definitely tropical planktonic foraminifers, they do live in deep or intermediate water masses (Bé and Tolderlund, 1971) and therefore show very irregular occurrences in upwelling regions (Thiede, 1975; Cifelli and Stern, 1976). The presence of *G. bulloides* in coastal sediment off western India (Fig. 3) seems in itself indicative of coastal upwelling in that region (Zobel, 1973; Bé and Hutson, 1977). Zobel also stated that this view coincides with the observations made earlier by Beljaeva (1964). Distribution of such planktonic foraminifers as *G. bulloides*, dextrally coiled *Neogloboquadrina pachyderma typica* s.s., and *Globoquadrina dutertrei* with *G. menardii* relates to tropical warm waters and to the areas of cool upwelled waters. Dextrally coiled *Neogloboquadrina pachyderma typica* s.s., a cold to cool water species which appears in very small numbers in sediments up to 23°N along the western Indian coast, is considered to originate in upwelled waters and be transported to the region and deposited in the sediments (Setty, 1977). Phleger (1960)

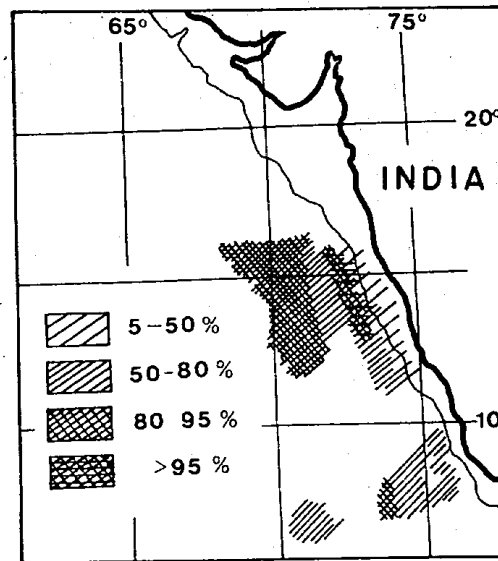


Fig. 4. Distribution of planktonic foraminifers (in percent of total foraminiferal faunas) in the surface sediments. Benthic foraminifers are extremely rare in a zone on the upper continental slope (modified after Zobel, 1973).

refers to such a condition as invasion of immigrant populations with the bottom water. This invasion leaves a record in the sediment of the presence of that water mass and may be an aid to understanding the mechanisms of water exchange and water movement.

UPWELLING AND BENTHIC FORAMINIFERAL RECORDS

Whereas planktonic foraminifers provide information about surface and subsurface water masses of upwelling regions, benthic foraminifers offer insight into the conditions at and close to the sea floor. The ratio of planktonic to benthic foraminifers changes drastically in response to the increasing water depth and changing oceanographic conditions under the western Indian upwelling regime. Figure 4 illustrates the frequency distribution of planktonic foraminifers and reveals a zone on the upper continental slope which is very poor in benthic foraminifers, probably due to the influence of the oxygen minimum layer. The benthic foraminiferal faunas along the western Indian continental margin is quite well studied, but often it is not quite clear how it is related to the upwelling regime in detail.

According to Zobel (1973) *Ehrenbergina* sp., which had a concentration of 17% in cores taken at 230 m depth off Karwar and 150 m

depth off Cochin, shows a sharp decline when the upwelled waters with oxygen minima appear at this depth. *Ammonia* and its variants which are characteristic of shallow waters were observed to be reworked with *Operculina complanata*, an offshore form of the relict sediment present in the fine-grained laminated slope sediments. White, abraded and iron-stained larger foraminiferal species like *Amphistegina papillosa*, *Cellanthus craticulatus*, *Operculina ammonoides*, *Borelis schlumbergeri*, *Heterostegina suborbicularis* and *Gypsina globula* occur in the offshore relict sediments off Karwar. *Eyalinea balthica* a cold to temperate, normal marine form having a depth range from 0-1000 m was found with a concentration of 17% in the Cochin region (Zobel, 1973; Setty, 1974). Its occurrence is considered indicative of upwelling. *H. balthica* is living today in the Atlantic in a temperature gradient of 12°-5°C and also in a 10°-22°C gradient of the Persian Gulf.

DISCUSSION: SEDIMENT-WATER MASS-BIOGENIC COMPONENT RELATIONSHIPS

Parameters such as those discussed above which can be measured in the sediments can be correlated to the characteristics of the deep water or bottom water masses. In the oxygen minima laminated muds, complete or partial dissolution of siliceous tests is caused by the development of an alkaline environment, while in the oxygen high areas partial dissolution of calcareous tests result (von Stackelberg, 1972; Zobel, 1973; Setty, 1974). If frequency of benthic fossils and abundance of the organic carbon component is controlled by surface water dynamics, they may not correlate with the sediment (Diester-Haass, 1976), but their characteristics may reflect changes of the bottom water. Von Stackelberg (1972) recognized that organic carbon contents are comparable for the laminated muds of cores from the upper continental slope off Cochin (3.46%) and off Karwar (3.91%) as they represent the rhythm of the southwest monsoon.

The distributions of benthic faunas, opaline silica, and organic carbon may be influenced by bottom water rather than surface water (Pisias, Heath and Moore, 1975). The high percentages of quartz (>10%) along the west Indian margin appear to be confined to shallower depths and areas of relict Pleistocene sands at the outer shelf (von Stackelberg, 1972; Kolla et al., 1981). This high quartz abundance derived from Pre-Cambrian granitic gneisses and other metamorphics reflects terrigenous influxes during Pleistocene and Holocene times whereas kaolinite which extends north-south on the shelf is in part controlled by changing monsoonal winds (Kolla et al., 1981). In wide areas, oolite-rich relict sands are exposed which were formed in shallow waters at the turn of the Pleistocene to Holocene (von Stackelberg, 1972). This is evidenced by the occurrence of some white to translucent, abraded and iron-stained relict foraminifers off Karwar. These relict sands were exposed to violent wave action and areal erosion and were later gradually covered by recent material (von Stackelberg, 1972).

High organic carbon contents coincide with high concentrations of benthic foraminifers (*Uvigerina bellula*, *Canceris sagra*, *Cibicides refulgens*, *Bulimina demudata*, *Hyalinea balthica*, etc.) (Setty, 1974), and planktonic foraminifers (*Globigerina bulloides*), dextrally coiled *Neogloboquadrina pachyderma typica* s.s., *Orbulina universa*, off the Karwar region (Setty and Guptha, 1972). *Globigerina hexagona* and *Globoquadrina conglomerata* occur in offshore Cochin and Karwar (Setty, 1972; Setty and Guptha, 1972; Zobel, 1973). This flux of biogenic components into the sediment is controlled by productivity near the surface and certain hydrographic characteristics of the bottom water mass. The close correlation of foraminiferal abundances and organic carbon concentrations indicates that the bottom water characteristics differ considerably under glacial vs. interglacial conditions, as proposed by Weyl (1968) and Duplessy (1982).

The sea surface temperatures of the pre-monsoon period (April) for the Cochin-Karwar region, ranging from 29.2 to 30.5°C, vary considerably from those of the southwest monsoon and upwelling periods (June-September), ranging from 24.3° to 30.5°C, and will be preserved as an isotopic signal in the tests of foraminifers (Table 1). Table 1 further illustrates the other oceanographic and meteorological parameters prevailing during the southwest monsoon period.

Figure 2 illustrates the seasonal fluctuations of total phytoplankton, classes of algae correlating with certain oceanographic and meteorological factors. It indicates that a fall in temperature (optimum level 23°C-25°C), of salinity (not more than 10% of highest recorded values) and increase in nutrients (phosphate, nitrate and silicate) triggers a phytoplankton bloom, the maximum production taking place during the southwest monsoon and later declining. Diatoms (including *Dinophyceae*, *Cyanophyceae* and others) make the bulk of the crop.

For a precise interpretation of the effects of upwelling all along the coast of India, further collections of living specimens through planktonic tows, benthic foraminifers from the topmost layers of sediment, and cores from shelf through slope to the deep sea, collected at regular intervals during upwelling and pre- and post-monsoonal seasons, will help present a clearer picture.

CONCLUSIONS

1. Upwelling during June to September is a phenomena triggered by the southwest monsoon, along Cape Comorin to Cochin and south of Goa in the shelf-slope region of western India. It results in blooms of phytoplankton in the surface waters which contribute to the composition of the sediment.

2. Laminated muds formed where sedimentation rates are high and upwelling water is low in oxygen, suggesting depositional variations and the rhythm of the southwest monsoon. The biogenic components include very high proportions of planktonic foraminifers (and extremely poor benthic foraminifers) within this zone. Some larger foraminifers occur as reworked fauna from the relict sediments of the outer shelf, which were formed in shallow waters and exposed to erosion at the turn of the Pleistocene to Holocene.
3. The very occurrence of *Globigerina bulloides*, dextrally coiled *Neogloboquadrina pachyderma typica* s.s., and the absence or irregular occurrence of *Globorotalia menardii* implies upwelling in the region. Similarly, the presence of *Ehrenbergina* sp. and *Hyalinea balthica* in the sediments suggest an area of upwelling.
4. Periods of high organic carbon content and ratios of planktonic to benthic foraminifers in sediments off Cochin correlate with those off Karwar.
5. A more thorough understanding of the effects of upwelling would require: living foraminifers from plankton tows (200-0 m), benthic foraminifers from the topmost layers of sediment, and cores from the shelf-slope region from Cape Comorin north to Bombay during the southwest monsoon and pre- and post-monsoonal seasons.

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