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Bay of Bengal nutrient-rich benthic layer

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Abstract

A nutrient- and carbon-rich, oxygen-poor benthic layer is observed in the lower 100 m of the central and western Bay of Bengal, at depths between 3400 to 4000 m. The observed ratios for the biogeochemical anomalies in the benthic layer water are similar to those observed for phytoplankton blooms in open oceans and hence suggest that the source of the high silica, phosphate, nitrate and carbon is likely to be due to decomposition of marine plankton deposited on the Ganges fan. While similar sediment types are expected to exist across a more extensive area of the Bay of Bengal, accumulation of nutrients only within a confined pool of bottom water is due to a greater degree of ventilation elsewhere. To the north of the nutrient-rich benthic pool, in shallower water, inflow of water from West Australian Basin minimizes anomalous benthic properties. To the south, in deeper water, ventilation by bottom water of the Central Indian Basin lifts the Bay of Bengal nutrient-rich benthic water off the sea floor. Thus the nutrient-rich benthic layer occupies zone between better ventilated regions. A counter-clockwise flow of bottom water is suggested for the Bay of Bengal, with nutrient-rich bottom water flowing westward south of Sri Lanka.

1. Introduction

Edmond et al. (1979) and Broecker et al. (1980), using GEOSECS stations 445 (8°30′S; 86°00′E) and 446 (12°30′N; 84°30′E) data obtained in 1974 (Spencer et al., 1982), described a nutrient-rich benthic layer within the Bay of Bengal. They noted a sharp increase in silicate, phosphate and nitrate with an accompanying decrease in oxygen concentration at the sediment–water interface. Total CO_2 and alkalinity also increase as the bottom is approached. They suggested that the source of the silica is dissolution of diatomaceous sediments produced under upwelling conditions of the northern upwelling regions. Edmond et al. (1979) showed that the Bay of Bengal benthic water spreads southward over denser Antarctic Bottom Water, producing a silicate maximum core layer along the 45.94 σ-4 surface, between 3500 and 4000 m. The deep silicate maximum is more pronounced in the central Indian Basin, suggesting that southward advection is most intense west of the Ninety East Ridge. Edmond et al. (1979) also described a similar condition in the Arabian Sea, where bottom silicate >160 μmol/kg occurs at the northern apex of the deep Arabian Sea (Mantyla and Reid, 1995), serving as the source of a western

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Indian Ocean deep silicate maximum near 3500 m. Mantyla and Reid's (1995) mapping of bottom properties shows the Bay of Bengal and Arabian Sea nutrient-rich benthic features are isolated from each other.

The World Ocean Circulation Experiment (WOCE) Indian Ocean hydrographic sections, I-1 and I-9 cross the Bay of Bengal high-nutrient benthic layer (Fig. 1), allowing for further inspection of the nature of the nutrient-rich benthic layer properties and its relationship to bottom circulation.

The Bengal Fan, covering much of the floor of the Bay of Bengal, is underlain by thick sequence of sediments derived from rivers draining eastern India and the Himalayas. Presently, more than 1 billion tons of sediment are discharged into the Bay annually, mostly from the Ganges–Brahmaputra River (Milliman and Meade, 1983). Average sedimentation rate on the fan is 20–30 cm/1000

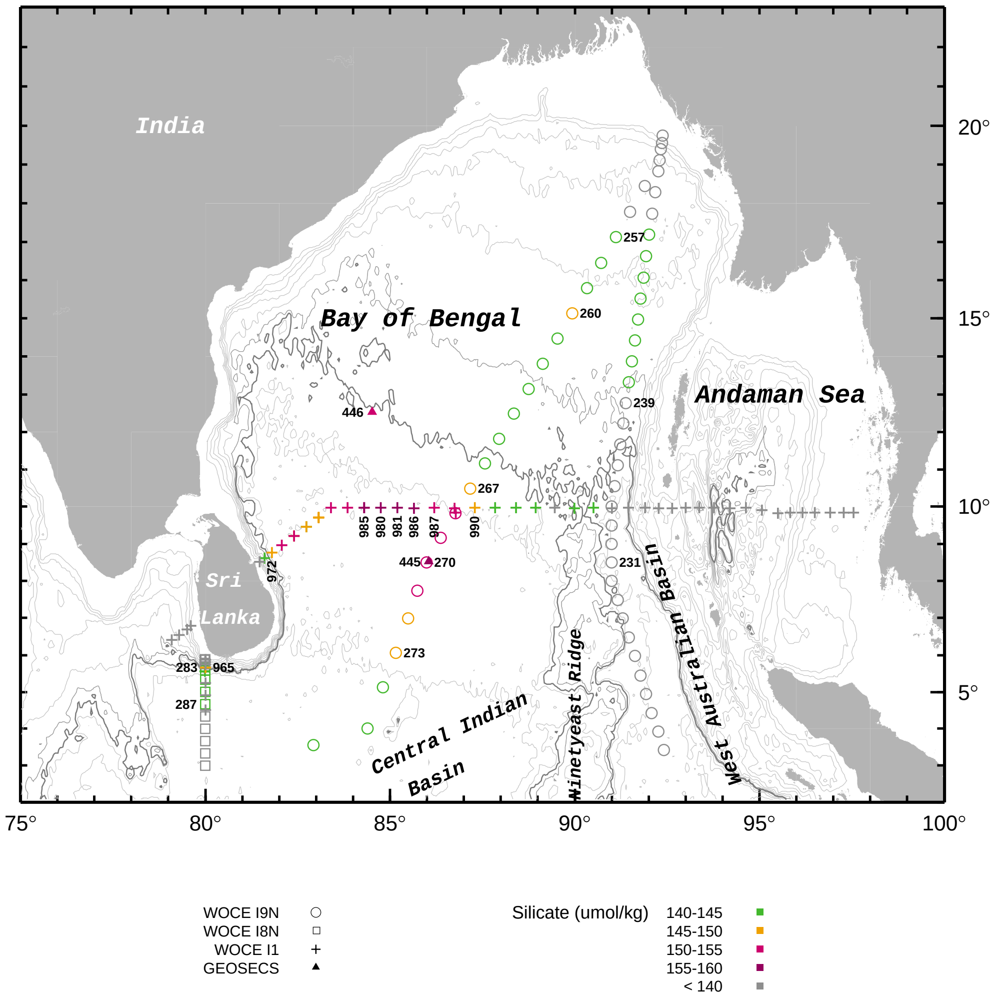

Fig. 1. Average silicate in μmol/kg for the lower 100 m of the water column within the Bay of Bengal and surroundings. Station numbers are shown near select stations including those referred to in the text. Stations with bottom silicate >155 μmol/kg are shown in dark red; between 150 and 155 μmol/kg in light red; between 145 and 150 μmol/kg in orange; between 140 and 145 μmol/kg in green. Stations with bottom silicate <140 μmol/kg are shown in black. Bathymetry contour interval is 500 m. The 3300 m isobath is shown in darker gray.

years (Wetzel and Wijayananda, 1990). The sediments in the center and deeper parts of the Bay are known to be rich in calcareous tests of organisms. The sediments in the northern part of the Bay are terrigenous deposits, discharged from the land by the large rivers that drain the slopes of the Himalayas. Maximum river discharge occurs during the southwest 'summer' monsoon, and coincides with the maximum observed flux of particulate matter. The nutrient input within the river plumes will increase the primary productivity, which may enhance particle flux to deep, offshore waters (Ittekkot et al., 1991). Illite-rich clay material is derived from the Ganges–Brahmaputra Rivers, whereas smectite-rich clay is derived from the peninsular Indian rivers (Ramaswamy et al., 1997). The central axis of the Bengal Fan is incised by numerous 'distribution' channels cut into the sediment, which appear to be inactive in recent times (Heezen and Hollister, 1971).

The WOCE section I-1 obtained in October 1995 along 10°N crosses the Andaman Sea (which, based on the temperature and salinity profiles obtained by that cruise, is isolated from the Bay of Bengal below a depth of $\approx$1400 m); the northern tip of the West Australian Basin, where it is constricted by the Ninety East Ridge and the Andaman Island Arc Ridge; and the northern end of the Central Indian Basin, over the Bengal Outer Fan to Sri Lanka. There are also a few I-1 stations along the WOCE I-8 section at 80°E. Section I-8 was obtained in April 1995. WOCE I-9 section of March 1995 provides two nearly meridional sections within the Bay of Bengal. The eastern section runs along the trough of the West Australian Basin, just east of the Ninety East Ridge, entering the Bengal Fan at 11°N. The western section runs a diagonal across the center of the Bay of Bengal. At most WOCE stations three to four water samples were collected for chemical analysis in the lower 200 m.

The spatial distribution of the high-nutrient benthic layer is defined by a bottom silicate concentration >145 μmol/kg (Fig. 1). Bottom silicate values >145 μmol/kg occur at stations 267 (sea floor at 3413 m) to 273 (sea floor at 3930 m), along the western I-9 section. Along the zonal I-1 section bottom silicate >145 μmol/kg is observed from 87.3°E, station 990 (sea floor 3480 m) to the eastern continental slope of Sri Lanka, station 972 (3740 m). GEOSECS station 446 (bottom depth of 3316 m) shows that the >145 μmol/kg bottom silicate values extends well to the northwest of the WOCE coverage, but the available hydrographic data do not resolve the full extent of high silicate to the northwest (no other archived data for bottom silicate within lower 100 m was found). Bottom silicate >155 μmol/kg defines the center (within the limits of station coverage) of the silicate-rich bottom benthic pool: at GEOSECS station 445 and at I-1 stations 980–981 and 985–986 (84.3°–85.6°E, near 10°N) in 3500–3600 m of water. The 3 μmol/kg difference between the co-located stations I-9 270 and GEOSECS 445, reflects either temporal changes or measurement uncertainties. South of Sri Lanka station I-1 965 in 3200 m of water and I-8 stations 283–287 in water depths from 3200 to 4300 m, have bottom silicate values >140 μmol/kg. This implies that the nutrient-rich benthic water of the southwest Bay of Bengal may slip westward along the sea floor over the base of Sri Lanka continental slope.

Within the central region of the silicate-rich (>155 μmol/kg) benthic layer, potential temperature and salinity values diminish only slightly as the sea floor is approached (Fig. 2). A more dramatic structure is revealed within 100 m of the sea floor in the non-conservative parameters, with a sudden increase in silicate, phosphate, nitrate, total CO_2 and alkalinity, and a decrease in oxygen. At I-9 station 260 (sea floor at 2670 m), the deep silicate profile within the lower 50 m (not shown) displays two levels where the silicate concentration is slightly >145 umol/kg, the other parameters display far less pronounced anomalous properties relative to the deeper waters to the south.

A silicate section constructed from I-9 and I-8 data (Fig. 3) shows that the highest bottom silicate (>145 μmol/kg) is observed from about 3400–4000 m (stations 265–273). South of 5°N, the 140 μmol/kg contour defines the deep-water silicate maximum (Edmond et al., 1979; Spencer et al., 1982).

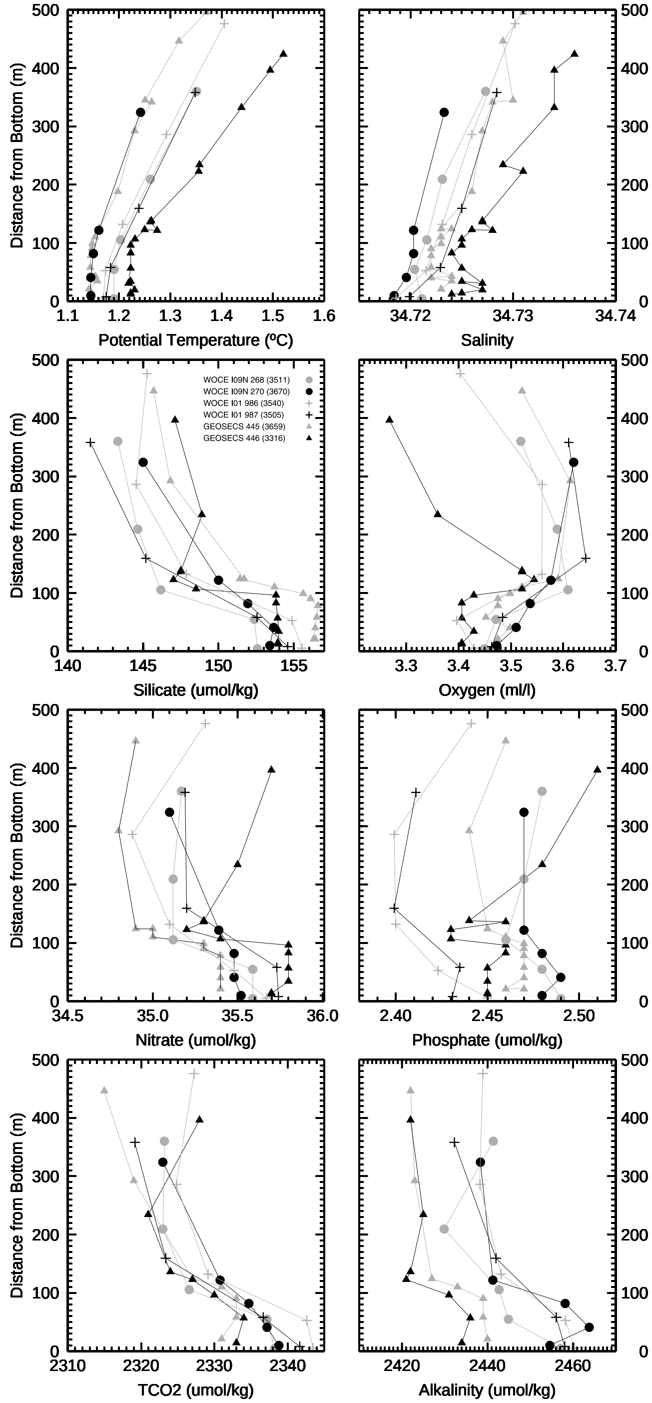

Fig. 2. Profiles of potential temperature, salinity, oxygen, nutrients, total CO_2 and alkalinity for the lower 500 m of stations within the region of highest benthic silicate concentrations.

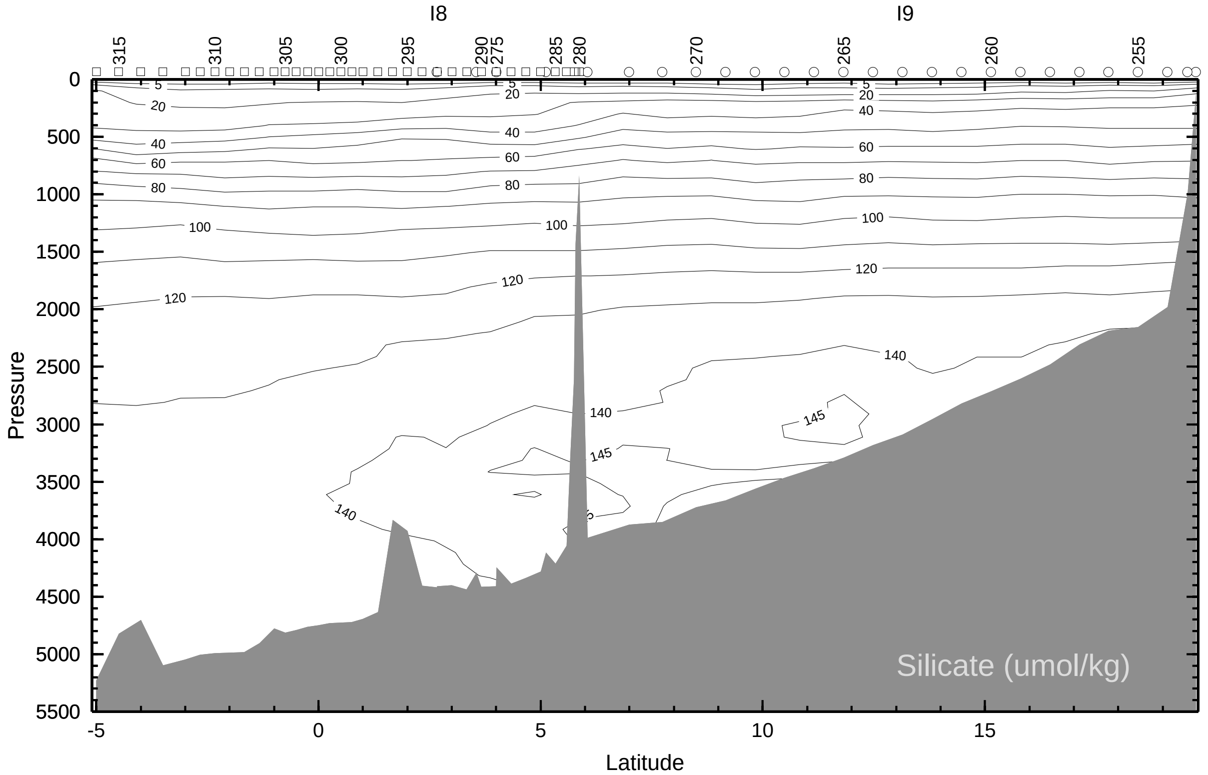

Fig. 3. Silicate (μmol/kg) section constructed from WOCE I-9 and I-8 data. Open circles denote I-9 stations; open boxes denote I-8 stations.

2. Regional stratification

The regional profiles for the water column deeper than 2500 m show two branches for the waters deeper than ≈3400 m (Fig. 4a; there are also cold benthic layers from 3100 to 3600 m, discussed below). The colder, fresher branch, with higher oxygen and lower nutrients, is confined to the West Australian Basin. The warmer branch falls within the Central Indian Basin. I-9 stations 268 and 267 within the warmer branch of the profiles mark the northern extreme of the silicate-rich benthic layer expression.

Stations 231–239, along the eastern section of I-9 in water of 3600–3100 m depth, reveal a thin cold benthic layer, with relatively high oxygen and lower nutrient concentration (Fig. 4a). As the potential temperature—salinity (θ/S) relationship is relatively linear (Fig. 4b) this benthic layer is not a distinct water mass, but rather it represents shallowing, by about 200–350 m, of relatively well-ventilated deep water of the West Australian Basin onto the eastern Bengal sediment fan. As the I-9 section between 6° and 12°N follows the eastern flank of the Ninety East Ridge, it samples the axis of the western boundary of West Australian Basin (Warren, 1981, 1982). Possibly the boundary current with its relatively well-ventilated water, rides up to shallower topography at the northern apex of the basin in response to geostrophic balance as the flow curls clock-wise into the interior of the West Australian Basin.

Along the western section of I-9 within the Bay of Bengal, the cold benthic layer is present but not as pronounced. A weak expression of colder, oxygen-rich bottom water is found at stations 264 and 265, near 3300 m. On proceeding southward across the 3400 m isobath to station 267, the benthic characteristics are abruptly replaced by the nutrient-rich, oxygen-poor waters, with the most

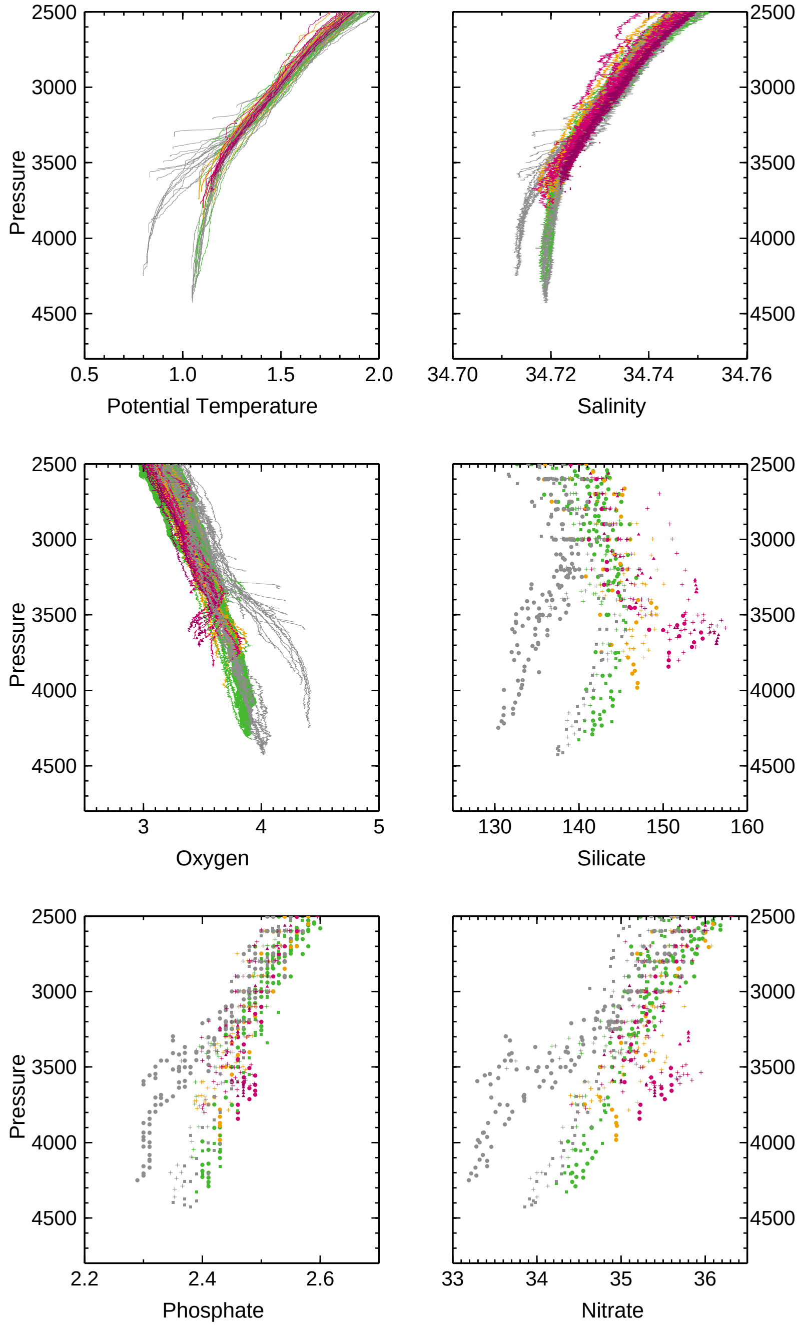

Fig. 4. (a) Profiles for the water column deeper than 2500 m of the stations displayed in Fig. 1, using the same color coding for bottom silicate concentrations. The potential temperature, salinity and oxygen profiles are from the CTD sensors. The nutrient values (μmol/kg) are derived from bottle samples. (b) Oxygen (ml/l), silicate (μmol/kg) and salinity versus potential temperature for water colder than 2.0°C. Insert on each panel shows the full water column. Sigma-4 lines are added to the potential temperature salinity plot. The position of the nutrient-rich benthic layer is shown on the oxygen and silicate plots.

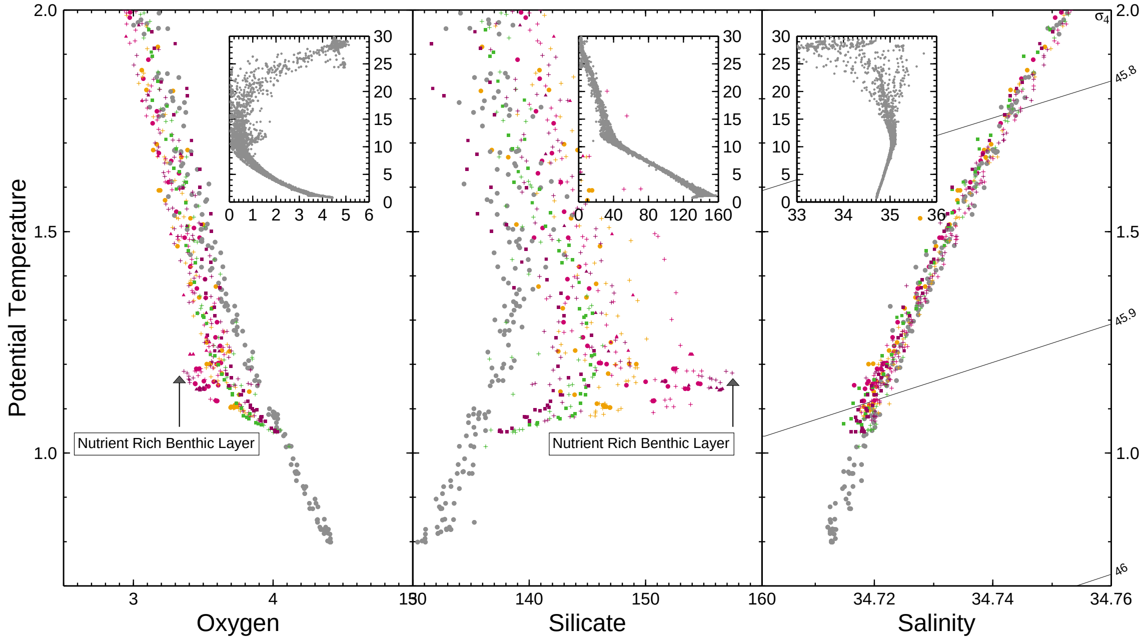

Fig. 4 (*Continued*).

extreme benthic values between 3500 and 3700 m (Fig. 4a) near the 1.15°C isotherm (Fig. 4b). It is suggested that bottom water shallower than ≈3400 m is exposed to the slightly better ventilated waters derived from the West Australian Basin, whereas deeper levels are shielded from West Australian Basin water by the crest of the Ninety East Ridge.

The silicate concentrations increase steadily with increasing depth. Only below 3500 m near the 1.15°C isotherm, does the slope reverse, as the better ventilated Antarctic Bottom Water layer is encountered. A gradient change of the silicate versus potential temperature relationship also occurs near the 400 m deep 12°C isotherm (see insert in Fig. 4b). The lowest silicate values at this knee are coupled with an oxygen maximum. This core is associated with the presence of Subantarctic Mode Water introduced into the eastern Indian Ocean.

The oxygen profile for the whole water column (not shown) reveals a thick layer of near zero concentrations (0.04–0.9 ml/l) from 70 to 600 m. Below that level, closer to 1000 m, phosphate and nitrate values attain their maximum values. Below the oxygen minimum layer and phosphate and nitrate maximum cores, oxygen increases while phosphate and nitrate decrease with increasing depth. Only within the Bay of Bengal nutrient-rich benthic layer do the slopes reverse, producing a deep oxygen maximum and phosphate and nitrate minimum at ≈3300 m. It is likely that this layer is produced by spreading of slightly better ventilated West Australian Basin water over the denser nutrient-rich benthic layer.

3. Benthic layer chemical properties

The concentrations of nitrate, phosphate, silica, CO_2 and alkalinity in the benthic mixed-layer waters (about 100 m thick) are anomalously higher, and that of oxygen significantly lower than those in the overlying waters. Since the Ganges fan sediments appear to be the source of silica in the deep waters of the Bay of Bengal, the chemical anomalies observed in the benthic layer would serve to characterize the biogeochemical species being fluxed out of the sediments into the abyssal waters. Because the anomalies are centered at a potential temperature of 1.17+0.01°C, the magnitudes of anomalies have been estimated at this temperature using the chemical data from 16 stations (WOCE Stations 265–271 and 978–990 and GEOSECS Stations 445 and 446) and are listed in Table 1. The positive anomaly in TCO_2 is due to the decomposition of soft organic tissues and the dissolution of $CaCO_3$, which is estimated on the basis of alkalinity increase. About 45% of the excess total CO_2 was derived from the decomposition of organic matter, and about 55% from $CaCO_3$. The silica anomaly is likely from the dissolution of biogenic opaline silica (Gupta and Sarma, 1997). The mole ratios for anomalies are found to be consistent with the remineralization P/N/C_{org}/–O_2 ratios of 1/15 (±1)/106 (±4)/(137–175) for biogenic particulates in deep waters (Redfield et al., 1963; Takahashi et al., 1985; Anderson and Sarmiento, 1994). Table 1 also shows that the silica/organic carbon ratio is 1.5+0.4. This is broadly comparable to the silica/carbon utilization ratio of 0.66+0.02 observed in the Pacific Sector of the Southern Ocean 67–70°S (Rubin et al., 1998) and 0.60–0.65 observed during diatom blooms in the Ross Sea (Nelson and Smith, 1986; Nelson et al., 1996). Therefore, the source material for the benthic anomaly is considered to be a product of marine phytoplankton blooms rich in diatoms.

Benthic layers with similar chemical anomalies as the Bay of Bengal are found in the Arabian Sea (Edmond et al., 1979; Mantyla and Reid, 1995). The Arabian Sea silicate maximum is observed (WOCE sections I-1 and I-7 station data) between sigma-4 of 45.84 (potential temperature of 1.54°C, about 3000 m deep) and 45.76 (potential temperature of 1.40°C, about 3500 m deep).

4. Indian Ocean bottom water

The cold end-member of the deep water column is Antarctic Bottom Water (Fig. 4b). Cold, highly oxygenated bottom water enters the West Australian Basin directly from the south, within a gap between the Naturaliste Plateau and Broken Ridge at 30°S. This water is derived from Antarctic Bottom Water formed south of Australia (Rodman and Gordon, 1982; Mantyla and Reid, 1995). Bottom water is inhibited by topography from flowing freely into the southern Central Indian Basin. Instead the bottom water of the Central Indian Basin is drawn by density overflow from the West Australian Basin at a saddle in the Ninety East Ridge near 10°S (Warren, 1981, 1982; Mantyla and Reid, 1995).

The WOCE data provide a more detailed view of bottom potential temperature (Fig. 5) than shown by Mantyla and Reid (1995). The coldest bottom water is found in the West Australian Basin, with bottom water colder than 0.8°C reaching along the western boundary well into

Table 1
Chemical anomalies observed in the benthic waters of the Bay of Bengal in the area, 7.5–13.0°N latitudes and 83–88°E longitudes, at depths of about 3500 m. The mean anomalies have been estimated at a potential temperature of 1.17±0.01°C based upon the observations made at 16 stations, and the uncertainties indicated represent one standard deviation

Properties	Mean anomalies	Anomaly ratios	
ΔO_2	−11±3 μmol/kg	$-\Delta O_2/\Delta(TCO_2)_{org}$	1.8±0.7
ΔTCO_2	+18±4 μmol/kg	$-\Delta O_2/\Delta PO_4^{-3}$	138±51
ΔAlkalinity	+23±5 μeq/kg	$\Delta NO_3^-/\Delta PO_4^{-3}$	10±3.5
ΔNO_3^-	+0.8±0.2 μmol/kg	$\Delta(TCO_2)_{org}/\Delta PO_4^{-3}$	75±45
ΔPO_4^{-3}	+0.08±0.02 μmol/kg	$\Delta(TCO_2)_{org}/\Delta NO_3^-$	7.5±4.5
ΔSiO_3^{-2}	+9±2 μmol/kg	$\Delta SiO_3^{-2}/\Delta NO_3^-$	11±4
		$\Delta SiO_3^{-2}/\Delta PO_4^{-3}$	113±40
$\Delta(TCO_2)_{org}$	+6±3 μmol/kg[a]	$\Delta SiO_3^{-2}/\Delta(TCO_2)_{org}$	1.5±0.4
$\Delta(TCO_2)_{cb}$	+12±2 μmol/kg[a]	$\Delta SiO_3^{-2}/\Delta(TCO_2)_{cb}$	0.8±0.3
		$\Delta(TCO_2)_{org}/\Delta(TCO_2)_{cb}$	0.5±0.3

[a] $\Delta(TCO_2)_{cb}$ is $CaCO_3$ added to the benthic water, and has been computed by the relationship: $(\Delta alkalinity+\Delta NO_3^-)/2$. $\Delta(TCO_2)_{org}$ represents the amount of CO_2 added due to the oxidation of organic matter, and has been computed using $(\Delta TCO_2-\Delta(TCO_2)_{cb})$.

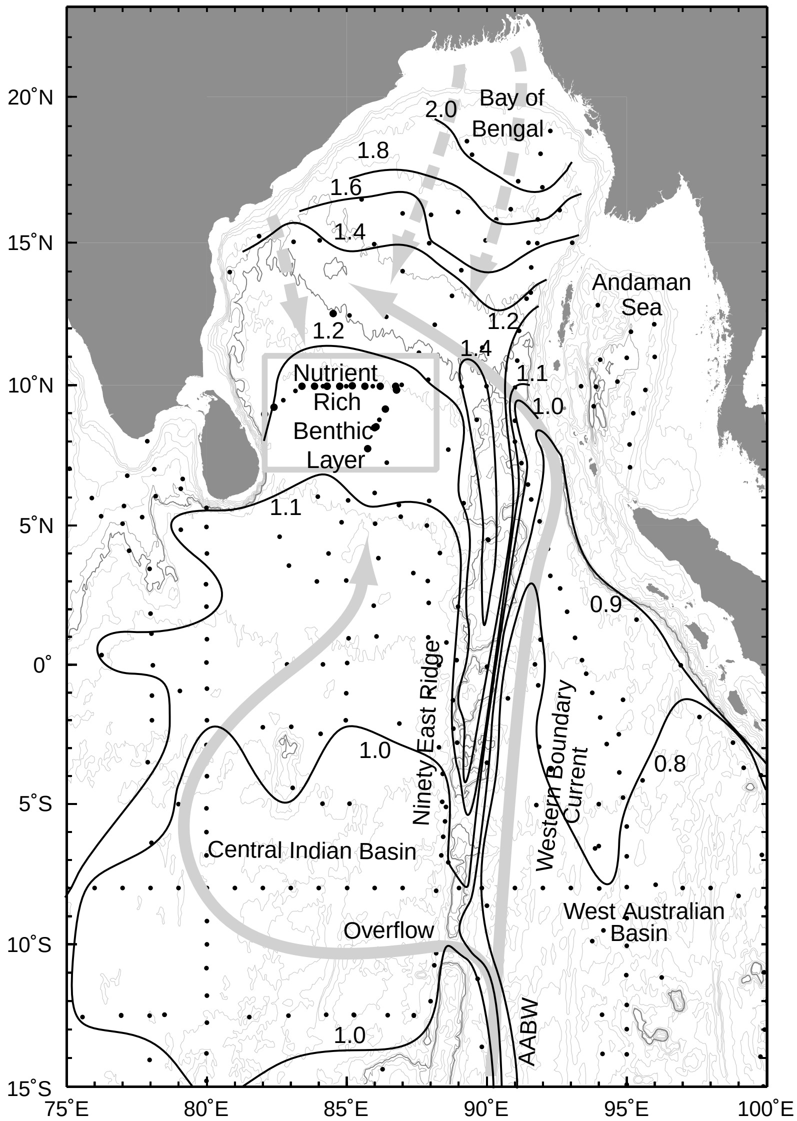

Fig. 5. Bottom potential temperature for waters deeper than 2000 m; data averaged within the lower 100 m of the water column for each station. WOCE and archived hydrographic NODC data is used. A schematic of bottom circulation in the Bay of Bengal is added. Solid arrows represent the spreading of Antarctic Bottom Water, which approaches the nutrient-rich benthic layer from two directions: from the West Australian Basin and from the Central Indian Basin. The nutrient-rich area falls in a zone between these two ventilating pathways. The dashed lines represent the transport of sediment on the Ganges Fan.

the narrowed northern apex of the West Australian Basin. Water colder than 1.2°C enters the eastern Bay of Bengal. Overflow into the Central Indian Basin through the 10°S saddle produces a pool of <1.0°C. Comparison of the potential temperature profiles from WOCE I-2 along 8°S indicate an effective sill depth of 3700 m, somewhat shallower than the 3900 m depth suggested by Warren (1982). The overflow water spreads northward, warmed by mixing to 1.2°C upon reaching the Bay of Bengal silicate-rich benthic layer. Thus there are two paths for <1.2°C bottom water to ventilate the floor of the Bay of Bengal, both derived from waters of the West Australian Basin: an eastern path directly from the West Australian Basin and the overflow path via the Central Indian Basin. The former associated with a western boundary current over the eastern flank of the Ninety East Ridge, provides the better ventilated deep-water masses.

5. Conclusions

Within the bottom water of the southwest Bay of Bengal, high nutrient and carbon concentrations with diminished oxygen levels are observed in the WOCE sections I-9 and I-1, a feature first seen by the 1974 stations of GEOSECS (Edmond et al., 1979; Broecker et al., 1980; Spencer et al., 1982). Bottom water nutrients are high throughout the Bay of Bengal relative to the global ocean, with silicate values in excess of 140 μmol/kg (Fig. 1). Only in the northern apex of the West Australian Basin in the southeast Bay of Bengal are values below 140 μmol/kg. The highest bottom silicate values are found in the southwest Bay of Bengal, from 3400 to 4000 m (Fig. 1).

The observed ratios for the biogeochemical anomalies in the benthic layer water are similar to those observed for phytoplankton blooms in open oceans and hence suggest that the source of the high silica, phosphate, nitrate and carbon is likely to be due to decomposition of marine plankton deposited on the Ganges fan. Benthic layers with similar biogeochemical anomalies have also been found in the north central Arabian Sea. The restriction of the nutrient-rich benthic layer to the 3400–4000 m isobaths in the southwestern Bay of Bengal may be explained by bottom circulation. The location of the nutrient-rich benthic layer falls within a zone of minimum ventilation of the benthic layer, at the boundary between ventilation provided from two sources (Fig. 5): West Australian Basin deep water, influencing the sea floor shallower than about 3400 m, north of the anomalous layer, and Central Indian Basin deep water, which ventilates the sea floor south of the anomalous layer. The nutrient-rich benthic layer occupies the least ventilated zone, falling at the junction of long residence time and available organic sediments. The Arabian Sea does not have bottom ventilation from two sources, so its nutrient-rich benthic layer resides at the northern apex of the deep Arabian Sea.

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References

Anderson, L.A., Sarmiento, J.L., 1994. Redfield ratios of remineralization determined by nutrient data analysis. Global Biogeochemical Cycles 8 (1), 65–80.

Broecker, W., Toggweiler, R., Takahashi, T., 1980. The Bay of Bengal—a major nutrient source for the deep Indian Ocean. Earth and Planetary Science Letters 49, 506–512.

Edmond, J., Jacobs, S., Gordon, A., Mantyla, A., Weiss, R., 1979. Water column anomalies in dissolved silica over opaline pelagic sediments and the origin of the deep silica maximum. Journal of Geophysical Research 84 (C12), 7809–7826.

Heezen, B.C., Hollister, C.D., 1971. The Face of the Deep. Oxford University Press, Oxford, 659pp.

Gupta, G.V., Sarma, V.V., 1997. Biogenic silica in the Bay of Bengal during the southwest monsoon. Oceanologica Acta 20 (3), 4930–5000.

Ittekkot, V., Nair, R., Honjo, S., Ramaswamy, V., Bartsch, M., Manganini, S., Desai, B., 1991. Enhanced particle fluxes in Bay of Bengal induced by injection of fresh water. Nature 351, 385–387.

Mantyla, A.W., Reid, J.L., 1995. On the origin of deep and bottom waters of the Indian Ocean. Journal of Geophysical Research 100, 2417–2439.

Milliman, J.D., Meade, R.H., 1983. World delivery of river sediment to the ocean. Journal of Geology 1, 1–21.

Nelson, D.M., Smith Jr., W.O., 1986. Phytokplankton bloom dynamics of the western Ross Sea ice edge. II. Mesoscale cycling of nitrogen and silicon. Deep-Sea Research 33 (Part A), 1389–1412.

Nelson, D.M., DeMaster, D.J., Dunbar, R.B., Smith Jr., W.O., 1996. Cycling of organic carbon and biogenic silica in the Southern Ocean: estimates of water-column and sedimentary fluxes on the Ross Sea continental shelf. Journal of Geophysical Research 101, 18519–18532.

Ramaswamy, V., Kumar, B.V., Parthiban, G., Ittekkot, V., Nair, R.R., 1997. Lithogenic fluxes in the Bay of Bengal measured by sediment trap. Deep-Sea Research 44 (5), 793–810.

Redfield, A.C., Ketchum, B.H., Richards, F.A., 1963. The influence of organisms on the composition of sea water. In: Hill, M.N. (Ed.), The Sea, Vol. 2. Interscience Publishers, New York, pp. 26–77.

Rodman, M.R., Gordon, A.L., 1982. Southern Ocean bottom water of the Australian–New Zealand sector. Journal of Geophysical Research 87 (C8), 5771–5778.

Rubin, S.I., Takahashi, T., Chipman, D.W., Goddard, J.G., 1998. Primary production and nutrient utilization ratios in the Pacific Sector of the Southern Ocean based on seasonal changes in seawater chemistry. Deep-Sea Research 45, 1211–1234.

Spencer, D., Broecker, W., Craig, H., Weiss, R., 1982. GEOSECS Indian Ocean Expedition. Vol. 6 Sections & Profiles. Super of Docs, US Gov Printing Off, Washington, DC, 140 plates.

Takahashi, T., Broecker, W.S., Langer, S., 1985. Redfield ratio based on chemical data from isopycnal surfaces. Journal of Geophysical Research 90, 6907–6924.

Warren, B.A., 1981. Transindian hydrographic section at Lat. 18°S: property distributions and circulation in the south Indian Ocean. Deep-Sea Research 28, 759–788.

Warren, B.A., 1982. The deep water of the Central Indian Basin. Journal of Marine Research 40 (Suppl.), 823–860.

Wetzel, A., Wijayananda, N.P., 1990. Biogenic sedimentary structures in the outer Bengal Fan deposits drilled during Leg 116. Proceedings of the Ocean Drill Progress, Science Research 116, 15–24.