Biogenic silica in the Bay of Bengal during the southwest monsoon

Biogenic silica
Lithogenic silica
Particulate organic carbon
Composition of biogenic matter

Silice biogénique
Silice lithogénique
Carbone organique particulaire
Matière biogénique

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ABSTRACT

During RV *Gaveshani* cruise No. 235 (August-September, 1993), particulate matter was collected from euphotic and deeper waters in the Bay of Bengal and analysed for biogenic silica (BSi), lithogenic silica (LSi) and particulate organic carbon (POC). Mean depth profiles of BSi showed a minimum in the surface waters and a maximum in the middle depths of the euphotic zone. The deepening of BSi maxima from north to south coincides with the deepening of the thermocline and thickening of the surface layer. In coastal waters, the contribution of BSi to total particulate silica was high (> 80 %); in offshore waters it was 60-70 %. BSi/POC (0.086) and LSi/POC (0.023) ratios show that particulate matter consists mostly of biogenic material, while the BSi/LSi (1.61) ratio revealed the dominance of siliceous phytoplankton in the euphotic zone. High concentrations of BSi (0.49 μmol l^{-1}) and LSi (1.89 μmol l^{-1}) in deeper waters are due to a high sedimentation rate, the resuspension of bottom sediments and the flow of large amounts of riverine siliceous material.

RÉSUMÉ

Silice biogénique dans le golfe du Bengale pendant la mousson du sud-ouest.

Au cours de la campagne 235 du N.O. *Gaveshani* dans le golfe du Bengale (août-septembre 1993), des prélèvements de matière particulaire ont été effectués dans la couche euphotique et dans les eaux profondes : la silice biogénique (BSi), la silice lithogénique (LSi) et le carbone organique particulaire (POC) y ont été analysés. Les profils de silice biogénique présentent un minimum dans les eaux superficielles et un maximum aux profondeurs moyennes de la couche euphotique; les maxima plongent du nord au sud avec la thermocline.

Dans les eaux côtières, la silice biogénique constitue plus de 80 % de la silice particulaire totale, mais sa contribution n'est que de 60 à 70 % dans les eaux du large. Le rapport silice biogénique/carbone organique particulaire est de 0,086 et le rapport silice lithogénique/carbone organique particulaire est de 0,023, ce qui indique la nature biogénique de la matière particulaire. Le rapport silice biogénique/silice lithogénique (1,61) révèle la dominance du phytoplancton siliceux dans la couche euphotique.

Dans les eaux profondes, les concentrations élevées en silice biogénique (0,49 μmol l^{-1}) et en silice lithogénique (1,89 μmol l^{-1}) sont dues à la sédimentation, à la remise en suspension des sédiments et à l'apport de matières siliceuses par les fleuves.

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INTRODUCTION

The role of silicate as a potential limiting factor of phytoplankton growth is the subject of wide attention. Silicon plays a dominant role in controlling the production cycle and phytoplankton species succession in coastal upwelling systems (Nelson, Goering, 1977, 1978; Nelson *et al.*, 1981). Silicon cycling is a consequence of uptake by phytoplankton in the surface layer, incorporation into organic and structural plant matter, and the subsequent degradation of this surface-produced biogenic material at intermediate depths. Although silicon distribution and cycling in the world ocean are well documented, there have been few studies on biogenic silica. Nelson and Gordon (1982) and Tréguer *et al.* (1988, 1990) have investigated biogenic silica in the waters of the Pacific, Indian and Atlantic sectors of the Antarctic Circumpolar area. Tréguer *et al.* (1990) studied the distribution of biogenic and lithogenic silica in the Scotia Sea during autumn, while Leynaert *et al.* (1991) reported the composition of biogenic particulate matter in the Weddell and Scotia Seas during spring. However, no such reports have as yet been forthcoming from the Bay of Bengal. The present paper concentrates principally on the distribution of biogenic silica in relation to particulate matter composition in this Bay.

MATERIAL AND METHODS

The study was based on observations and data collected during RV *Gaveshani* cruise No. 235 (August-September, 1993) in the Bay of Bengal. Station locations are shown in Figure 1. Stations 1, 5 and 8 are considered as coastal and the remainder as offshore. Sea-water samples for biogenic silica (BSi), lithogenic silica (LSi) and particulate organic carbon (POC) were collected from depths of 0, 10, 30, 50, 75, 100, 150 and 200 m in the euphotic zone and 500, 1000, 1500, 2000 and 3000 m in the deeper waters, using acid-precleaned Niskin bottles of 5 l capacity. All samples were transferred into acid-precleaned polyethylene carboys and agitated well prior to immediate filtration, in order to ensure a homogeneous suspension of particulate matter. For determination of BSi and LSi, a 1 l sample was filtered through a 0.2 μm Millipore membrane using plastic filter towers, and dried for 12 h at 60 °C. For POC, a 1 l sample was filtered through Whatmann GF/C filter paper (precombusted at 450 °C). The filters were finally stored at −20 °C in plastic petridishes (Millipore filters) and glass petridishes (GF/C filters) for further analysis in the laboratory. BSi was determined by digesting the filter with 4 ml of 0.2M NaOH for one hour at 100 °C (Paasche, 1973 *a*). After neutralization with 1 ml of 1M HCl, 0.5 ml of supernatant clean solution was diluted to 10 ml and analysed for reactive silica. After NaOH treatment, the LSi in the membrane was allowed to dissolve with 0.2 ml of 2.9M HF for 48 h at room temperature (Brzezinski, Nelson, 1989) and then diluted to 65 ml to negate the interference of the HF with subsequent reactions; and finally the reactive silica was analysed. The corrections for BSi and LSi in coastal waters were given as demonstrated by Ragueneau and Tréguer (1994). POC was analysed by

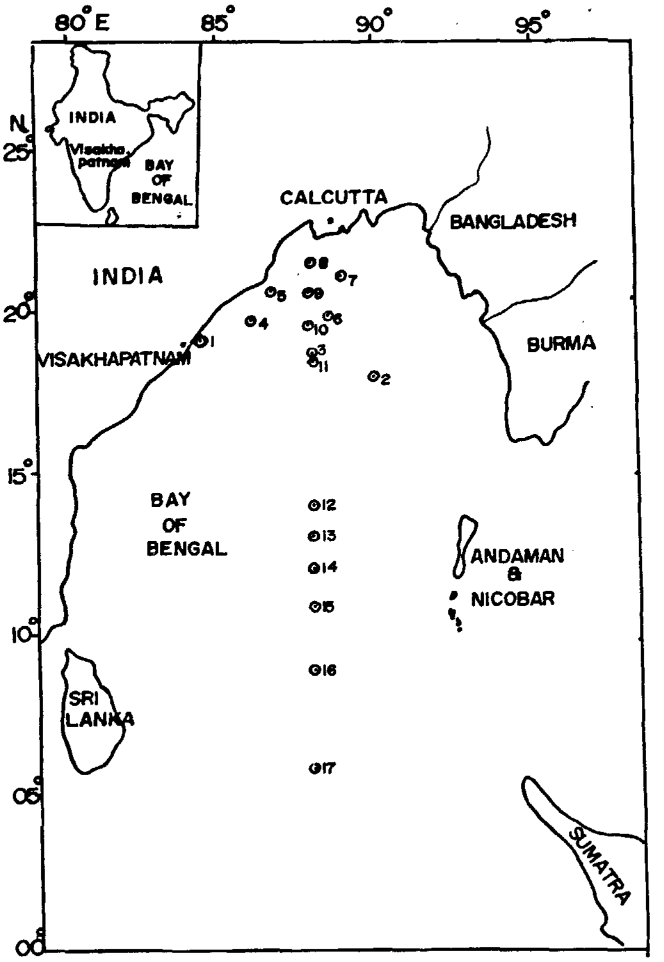

Figure 1

Station location map.

the wet oxidation method as reported in Parsons *et al.* (1984). Orthosilicic acid in dissolved form was determined on board, using the standard method (Grasshoff, 1976). Blanks of BSi, LSi and POC obtained from the above procedures were 0.008, 0.015 and 0.2 μmol l^{-1} respectively, and precisions were 10 % for BSi and LSi and 3 % for POC.

Physical structure

The Bay of Bengal constitutes the northeastern part of the Indian Ocean with a boundary line at 5° N between Sri Lanka and Sumatra basing on the North Equatorial Current of the eastern Indian Ocean (Varkey *et al.*, 1996). The physical structure of the Bay is influenced by the inflow of several major rivers from the east coast of India, Burma and Bangladesh (Anonymous, 1988). During the monsoon, wind direction is mainly from the southwest (Nieuwolt, 1981) and clockwise circulation leads to coastal upwelling along the western margin of the Bay (Currie *et al.*, 1973). The surface layer thickness was found to decrease from 100 m in the south to around 20-30 m in the north (Murty *et al.*, 1992), while Rao and Jayaraman (1968) reported a deepening of the thermocline towards the south. Surface circulation in the northeastern Indian Ocean during the southwest monsoon showed an anticlockwise

Table 1

Range, Mean, SD and SE of BSi, LSi, POC (μmol l^{-1}) and $Si(OH)_4$ (μM) in the euphotic zone of offshore waters.

	Overall (20°-6° N)				North (20°-15° N)				South (14°-6° N)			
	Range	Mean	SD	SE	Range	Mean	SD	SE	Range	Mean	SD	SE
BSi	ND-2.74	0.25	0.41	0.05	ND-2.74	0.17	0.13	0.02	0.03-0.50	0.14	0.09	0.02
LSi	ND-0.81	0.17	0.16	0.02	ND-0.81	0.13	0.12	0.02	0.03-0.38	0.10	0.08	0.01
POC	5.03-14.73	8.93	1.95	0.22	5.03-14.73	8.42	1.84	0.26	6.87-14.1	9.96	1.66	0.29
$Si(OH)_4$	2.31-61.88	24.75	18.01	2.25	2.31-61.88	26.30	19.31	2.63	2.43-70.07	28.05	15.48	2.54

SD: Standard Deviation; SE: Standard Error; ND: Non Detectable.

gyre, influenced wholly by the fresh water influx, in the northwestern Bay (between coastline 13° N and 89° E), and a clockwise southern gyre (south of 13° N), influenced by prevailing southwesterly winds (Varkey, 1986; Legeckis, 1987; Potemra *et al.*, 1991).

RESULTS

Distribution of biogenic silica in the euphotic zone

Surface concentrations of BSi in offshore waters varied between 0.06 and 1.02 μmol l^{-1}, while LSi varied from non-detectable levels to 0.69 μmol l^{-1}. The highest concentrations of BSi (5.16 μmol l^{-1}) and LSi (1.63 μmol l^{-1}) were observed at coastal stations 5 and 8. The range, mean, standard deviation (SD) and standard error (SE) of BSi, LSi, POC and $Si(OH)_4$ in the studied region are given in Table 1. The highest concentrations of BSi (2.21-2.74 μmol l^{-1}) and LSi (0.69-0.81 μmol l^{-1}) in surface layers along 88 °E (Figs. 2*a*, *b*) in the northern area (20°-15° N) might be due to higher fresh-water discharge at the head of the Bay. The meridional distribution of BSi (Fig. 2*a*) along 88° E showed maxima in the mid-depths of euphotic zone, gradually deepening towards the south, while POC (Fig. 2*c*) showed uniform distribution. High concentrations of silica in the northern area (Fig. 2*d*) reflected the impact of river inputs. Further, the mean depth profiles of BSi (Fig. 3*a*) showed a minimum in the surface layers and a maxima at depths of 30 to 75 m. The mid-depth maxima of BSi were found in the ranges of 30 to 50 m in the northern area (20°-15° N) and 75 to 100 m in the southern area (14°-6° N). LSi profiles (Fig. 3*b*) also showed the same pattern as that of BSi. However, POC depth profiles (Fig. 3*c*) showed fluctuations, and the range varied between 5.03 and 16.72 μmol l^{-1} throughout the studied region. Dissolved silica concentrations (Fig. 3*d*) of 8.14 μM at the surface and 55.42 μM at 200 m depth indicate a typical nutrient profile.

DISCUSSION

The vertical profiles of BSi (Fig. 3*a*) coincide with the vertical distributions of total phytoplankton in the shelf waters off the Krishna and Godavari river mouths in the Bay of Bengal (Rao, Sarojini, 1992). These authors showed that phytoplankton, dominated by diatoms, was high in shelf waters and preferred different depths in the euphotic zone of the Bay of Bengal. Prakash and Raman (1992) found 33 % of diatoms and 9 % of dinoflagellates in the total phytoplankton population in surface waters of the northwestern part of the Bay. They further reported that diatoms, presumably after an initial dominance of blue-green algae, were prominent in the southern Bay, characterized by intense upwelling and the regeneration of nutrients during the premonsoon season. Variations in vertical distribution might be due to changes in hydrographical conditions and in the light requirements of the species (Hendey, 1964; Marshall, 1966). Also, Keifer and Kremer (1981) proposed that the vertical distribution of phytoplankton is largely determined by the dynamics of formation of the seasonal thermocline. Further, the gradual deepening of BSi maxima (Fig. 2*a*) towards the south coincides with the deepening of the thermocline (Fig. 2*e*), as reported by Rao and Jayaraman (1968), and increased surface layer thickness (Murty *et al.*, 1992). Thus, physiological changes occurring in the euphotic zone may be responsible for phytoplankton growth and BSi distribution. However, the uniform distribution of POC (Fig. 2*c*) in the euphotic zone showed that it is linked to total (autotrophic and heterotrophic) plant biomass. Although no studies were made of primary productivity in the investigations reported here, mean primary productivity values of 146 and 92 mgC m^{-3} d^{-1} in shelf and oceanic regions in the upper euphotic zone off the southeast coast of India during August 1987 were reported by Selvaraj *et al.* (1990). The average column primary productivity values reported by Prakash and Raman (1990) for shelf, slope and offshore areas were 1.01, 1.68 and 0.99 gC m^{-2} d^{-1}, respectively, in the southwest Bay of Bengal during December 1986. Further, Deuser *et al.* (1988) and Muller-Karger *et al.* (1988) reported that river plumes enriched in nutrients, together with turbulent mixing, can significantly increase primary production. Thus, the offshore waters in the euphotic zone of the Bay of Bengal are productive, and this explains the present distributions of both POC and BSi.

Composition of biogenic matter from the euphotic zone

The chemical composition of biogenic matter was elucidated on the basis of the interrelationships of BSi and LSi with POC. Significant positive correlations were observed for BSi *vs* POC (Fig. 4*a*) and LSi *vs* POC (Fig. 4*b*) in the euphotic zone.

$$\left.\begin{array}{l} BSi = 0.086\,(POC) - 0.51 \\ \\ (R = 0.41;\ N = 75 \text{ at } 99.9\,\%) \end{array}\right\} \quad (1)$$

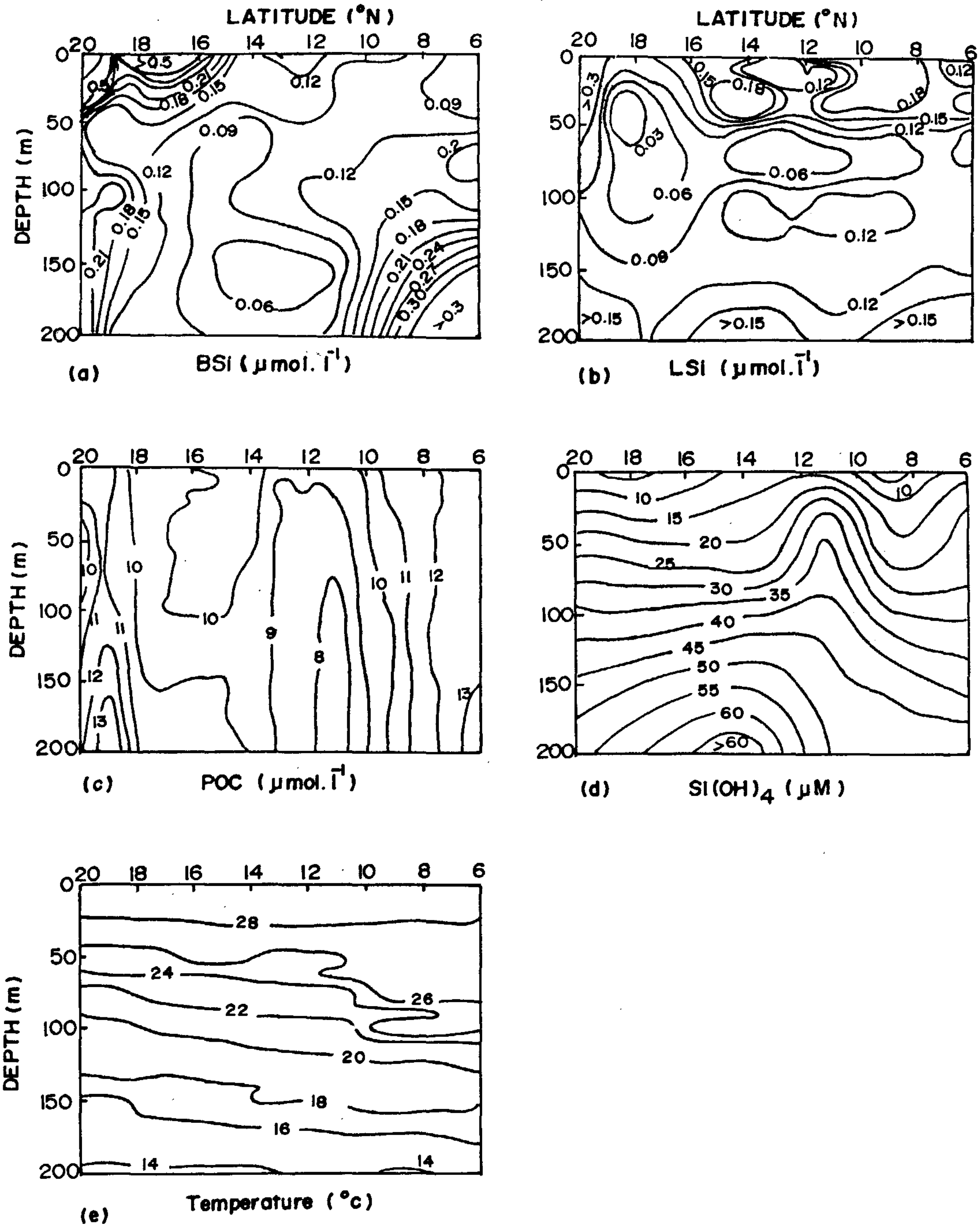

Figure 2

Meridional distribution of (a) BSi (μmol l^{-1}), (b) LSi (μmol l^{-1}), (c) POC (μmol l^{-1}), (d) $Si(OH)_4$ (μM) and (e) Temperature (°C) along 88°E.

$$\left.\begin{aligned} & \mathrm{LSi} = 0.023\,(\mathrm{POC}) - 0.037 \\ & (\mathrm{R} = 0.33;\ \mathrm{N} = 63 \text{ at } 99\,\%) \end{aligned}\right\} \qquad (2)$$

This mean BSi/POC ratio of 0.086 was less than the value of 0.19 reported from the Indian sector of the Southern Ocean (Tréguer *et al.*, 1988), but comparable with mean values of 0.13 observed in the Weddell Sea (Nelson *et al.*, 1987) and 0.09 in the Weddell-Scotia Sea (Leynaert *et al.*, 1991). Further, Ragueneau *et al.* (1994) reported a mean BSi/POC of 0.09 for a diatom-dominated bloom during late spring in the Bay of Brest, with the diatom *Chaetoceros sociale* accounting for 70 % of primary production (14 μmolC l^{-1} d^{-1}) (Quéguiner, 1982). However, BSi/POC values show large fluctuations in the northern and southern parts of the Bay of Bengal, probably because of differences in plankton abundance and primary productivity in oceanic waters along the east coast of India.

From equations 1 and 2, the ratio of their slopes (BSi/POC to LSi/POC) was approximately 4, reflecting the dominance of biological material in particulate matter. Further, Rao (1985) reported 60 to 80 % of combustible organic matter in suspended solids, showing that most of the particulate

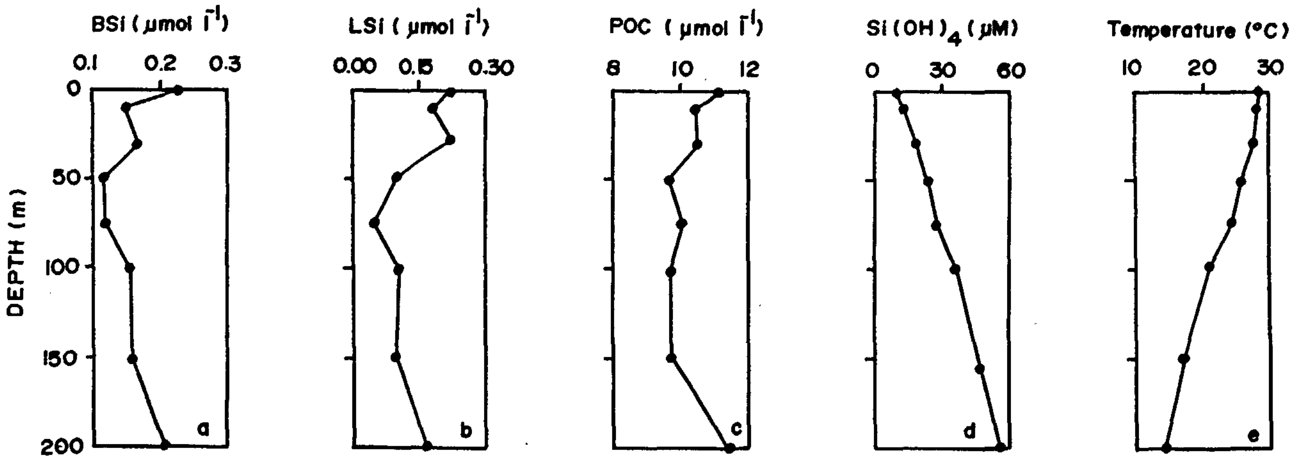

Figure 3

Mean depth profiles of (a) BSi (µmol l⁻¹), (b) LSi (µmol l⁻¹), (c) POC (µmol l⁻¹), (d) Si(OH)₄ (µM) and (e) Temperature (° C) in the euphotic zone.

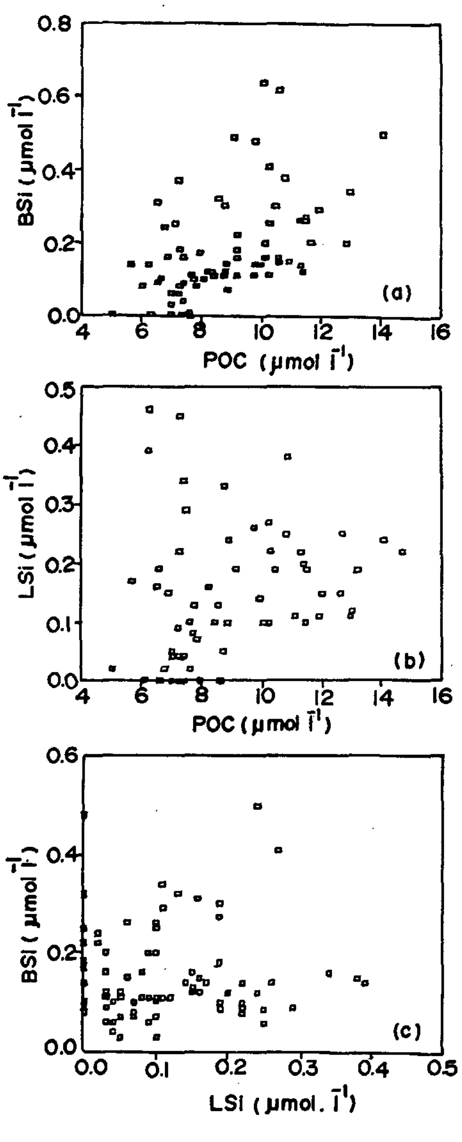

Figure 4

Correlation analysis of (a) BSi vs *POC, (b) LSi* vs *POC, and (c) BSi* vs *LSi.*

matter in the Bay of Bengal is derived from biological activity. In order to substantiate the presence of living phytoplankton in the euphotic zone, we examined the regressions of BSi with LSi (Fig. 4*c*).

$$\left.\begin{array}{l} BSi = 1.61\,(LSi) - 0.003 \\ (R = 0.62;\ N = 87 \text{ at } 99.9\,\%) \end{array}\right\} \quad (3)$$

High ratios of BSi/LSi (1.61) and BSi/POC (0.086) revealed the presence of living phytoplankton enriched with silica. From equation 3, it is clear that total particulate silica (PSi) is the sum of BSi and LSi only. In the present study, the highest percentage fraction of BSi (80-85 %) to PSi in coastal waters is probably due to runoff, with high (60-99 %) diatom-dominated phytoplankton (Saha *et al.*, 1975) from the Hooghly estuary at the head of the Bay. The BSi contribution (60-70 %) to PSi in offshore waters indicates the growth of siliceous phytoplankton. Ramaswamy and Nair (1993) and Ramaswamy (1994) showed that lithogenic particles account for only between 22 and 35 % of total annual flux in the Bay of Bengal, indicating the dominance of biogenic flux in the particulate matter. Honjo *et al.* (1982) also found biogenic materials to account for 86 to 93 % in shallow traps and 40 to 70 % in offshore traps of Pacific and Atlantic abyssal plains. Sarma and Kumar (1991) reported the subsurface chlorophyll maxima in northwestern Bay of Bengal to be due to the growth of the photosynthetically active phytoplankton community. This also coincides with the distribution of BSi in the euphotic zone of offshore waters.

The composition of biogenic matter can also be elucidated from POC/Chl*a* ratios. The high POC/Chl*a* ratios in the Southern Ocean systems (Smith, Nelson, 1985; Tréguer *et al.*, 1988; Nelson *et al.*, 1989) and in the equatorial Pacific Ocean (Peña *et al.*, 1991) could be largely due to the presence of heterotrophs and detritus within the suspended matter. Taking the average value of 0.47 mg m^{-3} for chlorophyll (Sarma, Kumar, 1991) in the offshore waters of the Bay of Bengal during the SW monsoon, the mean POC/Chl*a* ratio was found to be ≈ 20 in the studied region, probably due to high biomass when living phytoplankton were dominant. This ratio is comparable to

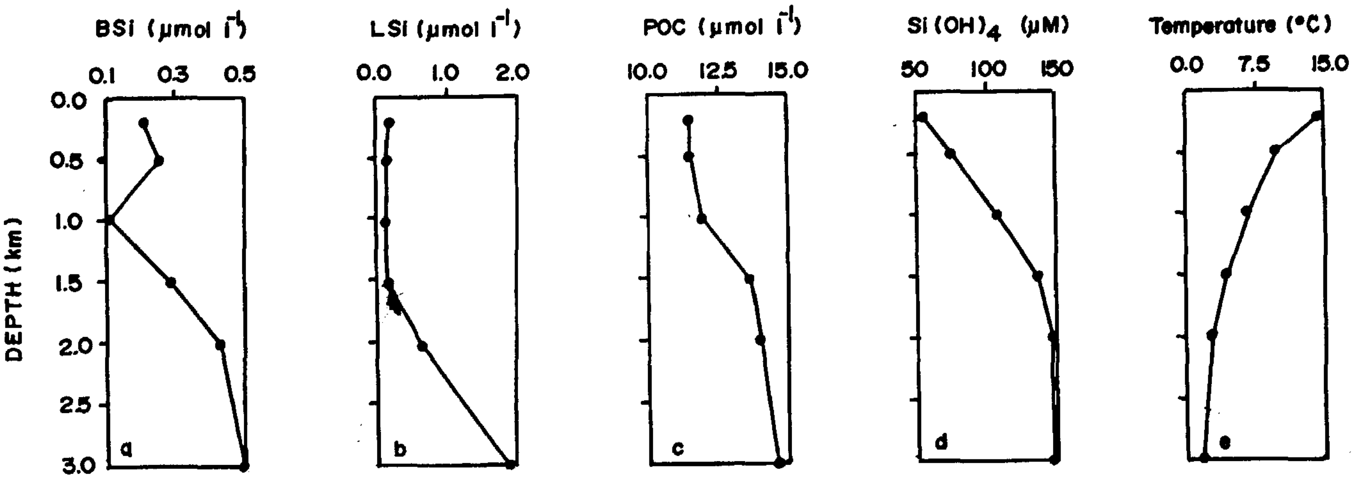

Figure 5

Mean depth profiles of (a) BSi (μmol l⁻¹), (b) LSi (μmol l⁻¹), (c) POC (μmol l⁻¹), (d) $Si(OH)_4$ (μM) and (e) Temperature (°C) in deep waters.

the usual ratio of 35 for phytoplankton cultures (Redfield *et al.*, 1963). Thus, the BSi maxima in the euphotic zone was observed near subsurface chlorophyll maxima in the Bay of Bengal, representing a typical tropical structure. Due to the relatively high growth rate of phytoplankton, a rapid turnover of the nutrients might exist in the Bay of Bengal (Satyanarayana *et al.*, 1991; Sarma, Kumar, 1991). Herbland and Le Bouteiller (1981) and Herbland *et al.* (1985) also stressed the importance of small phytoplankton organisms in equatorial waters. Pak *et al.* (1988) concluded that the vertical distribution of chlorophyll was predominantly caused by photoadaptation of cells on shorter time scales (Cullen, Lewis, 1988), although particle maxima were observed near the depth of subsurface chlorophyll maxima within the equatorial upwelling region.

Distribution of biogenic silica in deeper waters

The mean depth profile of BSi (Fig. 5*a*) in deeper waters showed a constant value (0.21-0.26 μmol l^{-1}) down to 500 m, followed by a sudden decrease (0.11 μmol l^{-1}) in the intermediate waters (1000 m) and an increase (0.49 μmol l^{-1}) in the bottom waters (> 2000 m). Uniform concentrations of LSi (0.11-0.17 μmol l^{-1}) were observed in the intermediate waters (Fig. 5*b*), followed by a steep increase (1.89 μmol l^{-1}) in the bottom waters. However, POC concentrations (Fig. 5*c*) showed a constant increase (11.47-14.61 μmol l^{-1}) in the deeper waters. These distributions are in agreement with previous reports in the Pacific sector (Nelson, Gordon, 1982) and in the Indian sector (Tréguer *et al.*, 1988). Significant concentrations of BSi and LSi in the bottom waters are due to a high sedimentation rate (Dileep Kumar, Li, 1996), and the presence of strong, well-developed, near-bottom seasonal gyres and transient current cells (Varkey *et al.*, 1996) causes the resuspension of sediments. Such reports have also been made in Antarctic Ocean (Dunbar *et al.*, 1985; Tsunogai *et al.*, 1986; Tréguer *et al.*, 1990). Less than 15 % of the particulate matter reaching the 3000 m depth is preserved in sediments (Ramaswamy, Nair, 1994) in the Bay of Bengal, indicating that the benthic boundary layer is the major site of organic matter degradation (Honjo *et al.*, 1982; Cole *et al.*, 1987), and thus reflecting high concentrations of POC in bottom waters. A dissolved silica (Fig. 5*d*) concentration of 150 μM and a temperature (Fig. 5*e*) of 1.73 °C at 3000 m were observed in the present study. On the basis of a physical mixing model, regenerated silica of 50 μmol kg^{-1} at 2300 m (Dileep Kumar, Li, 1996) and 24.7 μmol kg^{-1} at 3000 m (Rao *et al.*, 1996) is reported in the Bay of Bengal, which may be due to the dissolution of riverine sediments. Ittekkot *et al.* (1991) reported siliceous material of 7.9 g m^{-2} y^{-1} flux at 2000-3000 m in the Bay of Bengal. These conclusions lead us to state that BSi and LSi distributions in the deeper waters are determined by the high sedimentation rate, resuspension of bottom sediments and flow of large amounts of riverine siliceous matter. Detailed studies on nutrient recycling, on differences in the structure of the food webs and on particle transport are essential to assess the role of BSi in the silicon budget.

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REFERENCES

Anonymous (1988). Water resources of India, New Delhi : Central Water Commission.

Brzezinski M.A., D.M. Nelson (1989). Seasonal changes in the silicon cycle within a Gulf Stream warm-core ring. *Deep-Sea Res.* **36**, 1009-1030.

Cole J.J., S. Honjo, J. Erez (1987). Benthic decomposition of organic matter at a deep water site in the Panama Basin. *Nature* **327**, 703-704.

Cullen J.J., M.R. Lewis (1988). The kinetics of algal photoadaptation in the context of vertical mixing. *J. Plankt. Res.* **10**, 1039-1063.

Currie R.I., A.E. Fisher, P.M. Hargreaves (1973). Arabian Sea upwelling. In: *The biology of the Indian Ocean*, B. Zeitschel, Gerlach S.A. ed., Berlin, Springer Verlag, 37-53.

Deuser W.G., F.E. Muller-Karger, C. Hemleben (1988). Temporal variations of particle fluxes in the deep subtropical and tropical North Atlantic: Eulerian *versus* Langragian effects. *J. Geophys. Res.* **93**, 6857-6862.

Dileep Kumar M., Y.H. Li (1996). Spreading of water masses and regeneration of silica and ^{226}Ra in the Indian Ocean. *Deep-Sea Res.* **43**, 83-110.

Dunbar R.B., A.J. MacPherson, G. Wefer (1985). Water-column particulate flux and sea-floor deposits in the Bransfield Strait and southern Ross Sea. *Antarctic J. of U.S.*, Review, 90-100.

Grasshoff K. ed. (1976). *Methods of seawater analysis*, Verlag Chemie, Weinheim, New York, 317 p.

Hendey N.I. (1964). *An introductory account of the smaller algae of British coastal waters*, H.M. Stationary Office, London, 317 p.

Herbland A., A. Le Bouteiller (1981). The size distribution of phytoplankton and particulate organic matter in the equatorial Atlantic Ocean: importance of ultraseston and consequences. *J. Plankt. Res.* **3**, 659-673.

Herbland A., A. Le Bouteiller, P. Raimbault (1985). Size structure of phytoplankton biomass in the equatorial Atlantic Ocean. *Deep-Sea Res.* **32**, 819-836.

Honjo S., S.J. Manganini, J.J. Cole (1982). Sedimentation of biogenic matter in deep ocean. *Deep-Sea Res.* **29**, 609-625.

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

Keifer D.A., J.N. Kremer (1981). Origins of vertical patterns of phytoplankton and nutrients in the temperate open ocean: a stratigraphic hypothesis. *Deep-Sea Res.* **28**, 1087-1105.

Legeckis R. (1987). Satellite observations of a western boundary current in the Bay of Bengal. *J. Geophys. Res.* **92**, 12974-12978.

Leynaert A., P. Tréguer, B. Quéguiner, J. Morvan (1991). The distribution of biogenic silica and the composition of particulate organic matter in the Weddell-Scotia Sea during spring 1988. *Mar. Chem.* **35**, 435-447.

Marshall H.G. (1966). Observations on the vertical distribution of cocolithophores in the northwestern Sargasso Sea. *Limnol. Oceanogr.* **11**, 432-435.

Muller-Karger F.E., C.R. McClain, P.C. Richardson (1988). The dispersal of the Amazons water. *Nature* **333**, 56-58.

Murty V.S.N., Y.V.B. Sarma, D.P. Rao, C.S. Murty (1992). Water characteristics, mixing and circulation in the Bay of Bengal during southwest monsoon. *J. Mar. Res.* **50**, 207-228.

Nieuwolt S. (1981). The climates of continental southwest Asia. In: *World survey of climatology, vol. 9: Climates of southern and western Asia*, K. Takahasi, H. Arakawa ed., Amsterdam, Elsevier Science, 1-38.

Nelson D.M., J.J. Goering (1977). Near-surface silica dissolution in the upwelling region off northwest Africa. *Deep-Sea Res.* **24**, 65-73.

Nelson D.M., J.J. Goering (1978). Assimilation of silicic acid by phytoplankton in the Baja California and the northwest Africa upwelling systems. *Limnol. Oceanogr.* **23**, 508-517.

Nelson D.M., L.I. Gordon (1982). Production and pelagic dissolution of biogenic silica in the Southern Ocean. *Geochim. Cosmochim. Acta.* **46**, 491-501.

Nelson D.M., J.J. Goering, D.W. Boisseau (1981). Consumption and regeneration of silicic acid in three coastal upwelling systems. In: *Coastal Upwelling*, F.A. Richards ed., American Geophysical Union, Washington, DC, 242-256.

Nelson D.M., W.O. Smith, L.I. Gordon, B.A. Huber (1987). Spring distributions of density, nutrients and phytoplankton biomass in the ice-edge zone of the Weddell-Scotia Sea. *J. Geophys. Res.* **92**, 7181-7190.

Nelson D.M., W.O. Smith, R.D. Muench, L.I. Gordon, C.W. Sullivan, D.M. Husby (1989). Particulate matter and nutrient distributions in the ice-edge zone of the Weddell Sea: relationship to hydrography during late summer. *Deep-Sea Res.* **36**, 191-209.

Paasche E. (1973 *a*). Silicon and the ecology of marine plankton diatoms. I. *Thalassiosira pseudonana (Cyclotella nana)* grown in a chemostat with silicate as the limiting nutrient. *Mar. Biol.* **19**, 117-126.

Pak H., D.A. Kiefer, J.C. Kitchen (1988). Meridional variations in the concentration of chlorophyll and microparticles in the North Pacific Ocean. *Deep-Sea Res.* **35**, 1151-1171.

Parsons T.R., Y. Maita, C.M. Lalli eds. (1984). *A manual of chemical and biological methods for seawater analysis*, Pergamon press, New York, 63-66.

Peña M.A., M.R. Lewis, W.G. Harrison (1991). Particulate organic matter and chlorophyll in the surface layer of the equatorial Pacific Ocean along 135° W. *Mar. Ecol. Progr. Ser.* **72**, 179-188.

Potemra J.T., M.E. Luther, J.J. O'Brien (1991). The seasonal circulation of the upper ocean in the Bay of Bengal. *J. Geophys. Res.* **96**, 12667-12683.

Prakash K.P., A.V. Raman (1990). Primary productivity and phytoplankton pigments in the southwest Bay of Bengal during December, 1986. In: *Proceedings of the first workshop on scientific results of FORV Sagar Sampada*, K.J. Mathew ed., Cochin, India, 55-58.

Prakash K.P., A.V. Raman (1992). Phytoplankton characteristics and species assemblage patterns in northwest Bay of Bengal. *Ind. J. Mar. Sci.* **21**, 158-160.

Quéguiner B. (1982). Variations qualitatives et quantitatives du phytoplancton dans un écosystème eutrophe fortement soumis aux effets des marées : la rade de Brest. Thèse 3^{e} cycle, Univ. de Bretagne Occidentale, Brest, 123 p.

Ragueneau O., P. Tréguer (1994). Determination of biogenic silica in coastal waters: applicability and limits of the alkaline digestion method. *Mar. Chem.* **45**, 43-51.

Ragueneau O., E.D. Varela, P. Tréguer, B. Quéguiner, Y. Del Amo (1994). Phytoplankton dynamics in relation to the biogeochemical cycle of silicon in a coastal ecosystem of western Europe. *Mar. Ecol. Progr. Ser.* **106**, 157-172.

Ramaswamy V. (1993). Lithogenic fluxes to the northern Indian Ocean – an overview under the SCOPE/UNEP Project. *Mitt. Geol.-Paläont. Inst.*, Univ. Hamburg. **76**, 97-111.

Ramaswamy V., R.R. Nair (1994). Fluxes of material in the Arabian Sea and Bay of Bengal-Sediment trap studies. *Proc. Indian Acad. Sci. (Earth Planet Sci.).* **103**, 189-210.

Rao Ch.M. (1985). Distribution of suspended particulate matter in the waters of eastern continental margin of India. *Ind. J. Mar. Sci.* **14**, 15-19.

Rao L.V.G., R. Jayaraman (1968). Hydrographical features of southern and central Bay of Bengal during transition period between winter and summer. *Bull. Natl. Inst. Sci.* India. **38**, 184-205.

Rao M.U., Y. Sarojini (1992). Composition, abundance and vertical distribution of phytoplankton and fungi off Krishna and Godavari river mouths, east coast of India. *Ind. J. Mar. Sci.* **21**, 128-132.

Rao D.P., V.V. Sarma, V.S. Rao, U. Sudhakar, G.V.M. Gupta (1996). On watermass mixing ratios and regenerated silicon in the Bay of Bengal. *Ind. J. Mar. Sci.* **25**, 56-61.

Redfield A.C., B.H. Ketchum, F.A. Richards (1963). The influence of organisms on the composition of sea water. In: *The Sea*, vol. 2, M.N. Hill ed., John Wiley, New York, 26-77.

Saha S.B., B.B. Ghosh, V. Gopalakrishnan (1975). Plankton of the Hooghly estuary with special reference to salinity and temperature. *J. Mar. Biol. Assoc. India.* **17**, 107-120.

Sarma V.V., A. Kumar (1991). Subsurface chlorophyll maxima in the north-western Bay of Bengal. *J. Plankt. Res.* **13**, 339-352.

Satyanarayana D., S.D. Sahu, P.K. Panigrahy, V.V. Sarma, C. Suguna (1991). Subsurface ammonium maxima in northern Bay of Bengal. *Mar. Env. Res.* **31**, 123-136.

Selvaraj G.S.D., A.L. Paulpandian, A. Purushothaman (1990). Primary productivity and plankton abundance along the shelf and oceanic waters off southeast coast of India during August, 1987. In: *Proceedings of the first workshop on scientific results of FORV Sagar Sampada*, K.J. Mathew ed., Cochin, India, 47-53.

Smith W.O., D.M. Nelson (1985). Phytoplankton bloom produced by a receding ice edge in the Ross Sea: spatial coherence with the density field. *Science* **227**, 163-166.

Tréguer P., S. Gueneley, A. Kamatani (1988). Biogenic silica and particulate organic matter from the Indian sector of the Southern Ocean. *Mar. Chem.* **23**, 167-180.

Tréguer P., D.M. Nelson, S. Gueneley, C. Zeyons, J. Morvan, A. Buma (1990). The distribution of biogenic and lithogenic silica and the composition of particulate organic matter in the Scotia Sea and the Drake Passage during autumn, 1987. *Deep-Sea Res.* **37**, 833-851

Tsunogai S., S. Noriki, K. Harada, Y. Wanatabe, M. Maedaa (1986). Large but variable particulate flux in the Antarctic Ocean and its significance for the chemistry of Antarctic Water. *J. Oceanogr. Soc. Japan.* **42**, 83-90.

Varkey M.J. (1986). Salt balance and mixing in the Bay of Bengal. *Ph.D thesis*, Univ. Kerala, India.

Varkey M.J., V.S.N. Murty, A. Suryanarayana (1996). Physical oceanography of the Bay of Bengal and Andaman Sea. In: *Oceanography and Marine Biology: an Annual Review*, vol. 34, A.D. Ansell, R.V. Gibson, eds., UCL Press, 1-70.