

Distribution and sources of organic matter in surface sediments of the eastern continental margin of India

M.S. Krishna*, S.A. Naidu, Ch.V. Subbaiah, V.V.S.S. Sarma, N.P.C. Reddy

CSIR-National Institute of Oceanography, Regional Centre, Visakhapatnam, India - 530017

ABSTRACT

The sources and distribution of organic matter (OM) in surface sediments of the eastern continental margin of India, including the region influenced by river discharge, were investigated using content, molar C:N ratios and stable isotopes of carbon and nitrogen. Despite relatively high water column integrated chlorophyll-a concentrations were found in the continental shelf than the slope, however, the lower sediment organic carbon (SOC) was found in the former than the latter region suggesting that in situ production did not play significant role on preservation of SOC in the coastal Bay of Bengal. The broad range of $\delta^{13}\text{C}$ of SOC (-23.2 to -16.7‰) suggests that OM is a broad mixture of terrestrial and marine OM. Relative contributions from terrestrial C_3 and C_4 plants and marine sources are quantified as 34%, 23%, and 43% respectively indicating that dominant source of allochthonous OM (~57%) in the coastal Bay of Bengal. Relatively higher contribution of OM from C_4 plants were found in the sediments at off river Krishna indicating that this region received detritus of agricultural crops such as jowar, bajra and sugar cane, which are dominant in its drainage basin, during SW monsoon. This study revealed that relatively high OM preserved in the slope than shelf region along the coastal Bay of Bengal and the composition of OM is primarily controlled by the type of agricultural crops and vegetation in the drainage basin of the river.

Key words: organic matter, river discharge, stable carbon, nitrogen isotopes, sediment, Bay of Bengal.

* Corresponding author; E-mail: moturi@nio.org (M.S.Krishna)

1. Introduction

Preservation of organic carbon (OC) in marine sediment is a long term sink for atmospheric carbon dioxide (CO₂) as it removes CO₂ from the atmosphere through the biosphere and store in the geosphere [Mackenzie, 1981]. More than 90% of carbon burial in the oceans occur in continental margin sediments [e.g., Premuzic *et al.*, 1982; Smith and MacKenzie, 1987; Hedges, 1992; de Haas *et al.*, 2002; Goni *et al.*, 1997] because of high biological productivity [IGBP, 1993; Carr, 2001] and high sedimentation rate. High biological production in coastal regions is due to availability of nutrients discharged by rivers. Transport of high suspended load through river discharge results in fast sedimentation that support better accumulation of OM in coastal sediments [Ittekkot *et al.*, 1991]. Recent estimates revealed that world rivers transport annually about 19×10^9 tons of suspended sediment to the ocean [Milliman and Farnsworth, 2010].

Coastal regions receive huge amount of terrestrial OM (0.4×10^{15} g C yr⁻¹) [Hedges *et al.*, 1997] through river discharge from the nearby continents [Hedges and Keil, 1995; de Haas *et al.*, 2002]. Despite numerous studies have been carried out, still, the fate of this terrestrial OM is under debate. Some studies have shown that it is primarily deposited on the continental shelves [e.g. Hedges and Parker, 1976] while the other demonstrated lateral cross shelf transport [Biscaye and Anderson, 1994; Keil *et al.*, 1998; Galy *et al.*, 2007] to the deep ocean. Therefore, studies on OM sources and its preservation in sediments of the continental margins are of global importance and are crucial for better understanding the global carbon cycle.

The coastal Bay of Bengal is strongly influenced by the southwest monsoon (June-September) driven river discharge [Unger *et al.* 2003] from the major monsoon rivers, Godavari and Krishna in southwest (SW) while the glacial rivers, Ganga, Brahmaputra and the monsoon river Mahanadi in northwest (NW) coastal Bay of Bengal. Though the Bay of Bengal accounts for 15% of the global organic carbon burial [Lanord and Derry, 1997], however, the sources and relative composition of OM buried in the sediments is not well understood, and the influence of river discharge on relative composition of OM is poorly constrained. Though some studies were reported on organic carbon in the Bay of Bengal, many of them are confined to either suspended particulate organic matter [Unger *et al.*, 2005; Fernandes *et al.*, 2006; 2009] or the deep Bay of Bengal (Bengal Fan) sediments [Lanord and Derry, 1994; Unger *et al.*, 2003; Haake *et al.*, 2005; Galy *et al.*, 2007] but no studies focused on the sediments of the western coastal Bay of Bengal which is under the influence of major monsoonal rivers Godavari, Krishna and Mahanadi. Despite the dominance of C₄ type plants such as jowar, bajra and sugar cane in the drainage basin of the rivers Krishna and Godavari, their contribution to the sediments of the western coastal Bay of Bengal is unclear. In this

study, we made an effort to understand the influence of vegetation in the catchment area of the major monsoonal rivers on sediment OM in the eastern continental margin of India. The objectives of our study are to (i) investigate relative contribution of OM from C₃ and C₄ type terrestrial plants, and (ii) spatial variations in their contribution along the western coastal Bay of Bengal. Elemental ratios, stable isotopes of carbon (C) and nitrogen (N) are used as potential tracers to elucidate the different sources of OM [Middelburg and Nieuwenhuize, 1998; Ogrinc *et al.*, 2005; Usui *et al.*, 2006; Wu *et al.*, 2007; Zhang *et al.*, 2007; Sampaio *et al.*, 2010 and references therein] and the model "IsoSource" [Phillips and Gregg, 2001; 2003; 2005] is used for estimation of relative contribution from C₃ and C₄ land plants, and marine plankton to sediments of the western coastal Bay of Bengal.

2. Study region

Bay of Bengal, the region of positive water balance where precipitation far exceeds evaporation by 80 cm yr⁻¹ [Ramanathan and Pisharoty, 1972; Prasad, 1997], and receives large quantity of fresh water ($1.625 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}$) [Subramanian, 1993] from the major rivers such as Ganges, Brahmaputra, Mahanadi, Godavari, and Krishna [Gauns *et al.* 2005] resulting in strong stratification [Varkey *et al.* 1996] leads to suppression of vertical mixing [Ku and Luo, 1994]. Furthermore, shallow photic depth due to high suspended matter (1.1×10^9 tonnes) [Milliman and Meade, 1983; Milliman and Syvitski, 1992] and cloud cover also control primary production in the Bay of the Bengal during southwest monsoon [Madhupratap *et al.*, 2003]. Hence, the Bay of Bengal is relatively a low productive region compared to its adjacent basin, the Arabian Sea. Occurrence of mild upwelling close to coast was reported along the east coast of India [Shetye *et al.*, 1991] that results in seasonal phytoplankton blooms. Sasmal [2007] reported occurrence of phytoplankton blooms off and around river mouths along the east coast of India during southwest monsoon.

Winds over the Bay of Bengal change their direction twice a year; they are from southwest during June to September and northeast during November to February and therefore called southwest (summer) and northeast (winter) monsoons respectively. Coastal circulation in the Bay of Bengal is influenced by the East Indian Coastal Current (EICC) that flows equatorward during winter and poleward during summer [Schott and McCreary, 2001]. The strong seasonal variability in wind and circulation pattern results in supply of nutrients to the surface [Wiggert *et al.*, 2005; Lévy *et al.*, 2007].

2.1 Sample collection

Surface sediment (top ca. 2cm) samples were collected onboard ORV Sagar Nidhi (# SN42; 23rd July - 10th August, 2010) along the east coast of India (Fig. 1; Table 1) using Van Veen grab. In

order to avoid mixing of recent sediment with older sediment, surface layer (~2cm) of the grab sediment was carefully taken using plastic scoop and preserved in clean plastic bags. The surface sediment represents the modern environment covering last few tens of years. Only one grab was taken at each station assuming uniform sediment distribution in the region. The samples were collected along 9 transects (KS, KN, GS, GN, VSP, VD, HD, MS and MN) and each transect is perpendicular to the coast covering both shelf and slope (water column depth: 25 – 1000 m) regions. The region of our study extends from off river Krishna in the south to off river Mahanadi in the north of the east coast of India. In this study, continental shelf sediments are operationally defined as the sediments within the water column depth of <200m.

In addition to sediments from the coastal region, both C₃ and C₄ land plants were collected from drainage basin of the river Godavari in order to assess their contribution to the sediments of the study region. The leaf, stem, and root of these plants were collected separately for stable isotope measurement.

3. Materials and Methods

Sediments were dried at 60°C and ground to fine powder using a mortar and pestle in order to obtain the homogeneity in sediment sample for chemical and isotopic analysis. A subsample of the sediment was used directly in tin cups for determination of content and isotope ratio of total nitrogen (TN). For analyses of organic carbon (OC) and its isotope ratios, sediment was taken in silver cups (Thermo, Germany), about 50 µl of 10% high purity HCl was added to convert inorganic carbon into carbon dioxide and dried them at 60°C in the oven. The same procedure is repeated until entire inorganic carbon is removed. The cups were folded like a ball and are injected to the Elemental Analyzer (Flash EA, Thermo) coupled to the Isotope Ratio Mass Spectrometer (IRMS, Delta V Plus, Thermo Electron, Germany) via Conflow IV interface to measure content and isotopic ratios of C and N. After thorough cleaning with distilled water, plant material was cut into small pieces, dried at 50°C, ground to powder and then small aliquot is taken into tin cups and were injected to EA-IRMS couple for content and stable isotopic analysis. Content is reported as wt.% and stable isotope ratios in δ notation calculated as given below.

$$\delta R = \left(\frac{X_{sam}}{X_{std}} - 1 \right) \times 1000 \text{ ‰}$$

Where, R is ¹³C for carbon and ¹⁵N for nitrogen. X_{sam} is ¹³C/¹²C and ¹⁵N/¹⁴N of sample for carbon and nitrogen respectively. The IAEA standards and internal standards, such as glutamic acid,

alanine, and Organic Analytical Standard (OAS), were used for calibration. The long term precision of the instrument is ca. $\pm 0.2\%$ for both C and N

Total suspended matter (TSM) was determined by weight of the material retained on a $0.22\mu\text{m}$ polycarbonate filter (Millipore) after passing ca. 1-2 l of water under a moderate vacuum. Chlorophyll-a is estimated by filtering ca. 2-5 l of sample through glass fiber (GF/F; Whatman, 47mm diameter; $0.7\mu\text{m}$ pore size) filter and material retained on the filter was extracted to N, N, dimethyl formamide at 4°C in the dark for 12 h. The fluorescence in the extract was determined using spectrofluorophotometer (Cary Eclipse, Varian) following *Suzuki and Ishimaru* [1990]. The analytical precision was $\pm 4\%$. Sediment grain size analysis was done by standard pipette analysis method [*Folk*, 1974].

3.1 Quantification of OM contributions from terrestrial and marine sources

Relative contributions of OM from terrestrial C_3 plants, which follow RuBisCo carboxylation mechanism (Calvin-Benson cycle) for photosynthesis of OM [$\delta^{13}\text{C}$: -30 to -23% ; *Smith and Epstein*, 1971], C_4 plants that follow phosphoenolpyruvate (PEP) carboxylation (Hatch-Slack cycle) mechanism for synthesis OM [-17 to -9% ; *Smith and Epstein*, 1971; *Gearing*, 1988; *Sackett*, 1989], and marine phytoplankton [-22 to -19% ; *Fry and Sherr*, 1984] were calculated from the three end-member simple mixing model using isotope mass balance equation of

$$\delta^{13}\text{C}_{\text{sample}} = f_1(\delta^{13}\text{C}_3) + f_2(\delta^{13}\text{C}_4) + f_3(\delta^{13}\text{C}_{\text{MOM}}) \quad \text{--- eq (1)}$$

where f_1 , f_2 , and f_3 represents the fractional contribution of OM from C_3 , C_4 land plants and marine phytoplankton respectively. The $\delta^{13}\text{C}_3$, $\delta^{13}\text{C}_4$, and $\delta^{13}\text{C}_{\text{MOM}}$ stands for isotope ratios of three end-members of C_3 , C_4 plants and marine OM respectively. The $\delta^{13}\text{C}_{\text{sample}}$ is the measured $\delta^{13}\text{C}$ ratio of a given sample. Assuming these three are the major sources, the sum of the three fractions should be equal to unity. Therefore,

$$f_1 + f_2 + f_3 = 1 \quad \text{--- eq (2)}$$

Unique solution for equations 1 and 2 is underdetermined mathematically as they involve three variables in two equations. However, most feasible solution can be obtained by using source partitioning mixing model, IsoSource, developed by *Phillips and Gregg* [2001, 2003, and 2005] based on isotope mass balance equation. The program IsoSource is a freely available software package (<http://www.epa.gov/wed/pages/models.htm>) that calculates ranges of most feasible proportional contributions from different sources to a mixture when the number of sources is too many to permit a unique solution. The model, IsoSource was tested successfully and used for OM

source apportionment in several instances [e.g., *Newsome et al.*, 2004; *Benstead et al.*, 2006; *Gibbes*, 2008, *Wildhaber et al.*, 2012).

The program "IsoSource" (version 1.3) was used here to calculate relative contributions of OM from C₃ and C₄ terrestrial plants, and marine phytoplankton to sediments of the western coastal Bay of Bengal. Mean $\delta^{13}\text{C}$ values of C₃ plants (-25.7‰) and C₄ plants (-13.0‰) collected from the Godavari drainage basin were taken as C₃ and C₄ end-members, respectively. The mean $\delta^{13}\text{C}$ ratio of particulate organic matter (-20.6‰) collected from bloom region off the river Godavari during the same cruise (our unpublished data) was taken as marine end-member. The model IsoSource gives a range of feasible source contributions. For graphical representation of the data, the mean (50 percentile) value of the range of feasible contributions from each source was taken for every sample. Measurement error of $\pm 0.2\text{‰}$ in $\delta^{13}\text{C}$ analysis of sample and each end members (C₃, C₄ and marine) was included in the calculation of most feasible source contributions by setting the mass balance tolerance of 0.1‰ [*Phillips and Gregg 2001*] in the model. The software, Ocean Data View (ODV) was used for graphical representation of the data and VG gridding was used for extra/interpolation.

4. Results

4.1. OC and TN content

Sediment organic carbon (SOC) ranged from 0.63 to 1.64% (Fig. 2a), with a mean of 1.04% in the shelf region along the coastal Bay of Bengal. Relatively lower content (mean 0.73% range: 0.63- 0.89%) was observed in the shelf off river Mahanadi. Relatively higher SOC was observed in the slope sediments (mean 1.40%; range 0.85-1.99%) than in the shelf (1.04%). The range of SOC found in this study (0.63 - 1.99%; for both shelf and slope) was similar to those reported for surface sediments off the Krishna-Godavari (KG) basin, east coast of India [*Mazumdar et al.*, 2007; *Ramana et al.*, 2009] and surface sediments from the Irrawaddy continental shelf, northern Andaman Sea, Bay of Bengal [*Ramaswamy et al.*, 2008]. A similar range of SOC was also reported elsewhere in the marginal sediments of several regions, for example, continental margin of the northern and western Gulf of Mexico, the north coast of Alaska and the Niger Delta [*Gearing et al.*, 1977], surface sediments from the Beaufort shelf, Beaufort Sea [*Goni et al.*, 2000], coastal sediments from the Gulf of Trieste, N Adriatic Sea [*Ogrinc et al.*, 2005], and the shelf and slope sediments off Tokachi, western North Pacific [*Usui et al.*, 2006]. Total nitrogen content is also lower (mean 0.06%; range: 0.02 - 0.13%) in the shelf than the slope (0.11%; 0.05 - 0.18%) sediments along the coast (Fig. 2b). Relatively higher elemental C:N ratios (SOC:TN) were observed in the shelf (range: 9.2 - 46.6; mean: 20.2) compared to that of the slope sediments (9.9 - 18.6; 13.4) (Fig. 2c). Integrated Chl-a in

the upper 50m of the water column (euphotic zone) ranged from 19.1 to 85.9 mg m⁻² (mean: 43.3 mg m⁻²) in the shelf while from 15.8 to 91.0 mg m⁻² (33.2 mg m⁻²) in the slope along the coast (Fig. 2d). Total suspended matter in surface water ranged from 6.5 to 41.8 mg l⁻¹ (mean 19.7 mg l⁻¹) in the shelf and from 7.0 to 42.7 mg l⁻¹ (16.1 mg l⁻¹) in the slope regions. Relative mean proportions of sand, silt, and clay in sediments are 4%, 38% and 58% in the shelf and 1%, 33% and 66% in the slope regions respectively.

4.2. Stable isotopes of SOC ($\delta^{13}C$) and TN ($\delta^{15}N$)

The $\delta^{13}C$ of SOC ranged from -23.3 to -16.7‰ in the shelf and -21.4 to -17.6‰ in the slope sediments (Fig. 3a) without much difference in mean ratios between the shelf (-20.8‰) and the slope (-20.4‰) sediments. A similar range of $\delta^{13}C$ ratios was also reported for surface sediments from the Mississippi and Atchafalaya river margin (-22.6 to -20.2‰) [Gordon and Goni, 2004], the shelf off Tokachi (western north Pacific; -23.6 to -20.6‰) [Usui *et al.*, 2006] and the Arabian Sea (-21.0‰) [Maya *et al.*, 2011]. However, relatively enriched $\delta^{13}C$ ratios were observed off the river Krishna (mean -18.8‰; range -20.7 to -16.7‰). The $\delta^{15}N$ varied between 3.7 and 13.5‰ (mean 7.3‰) in the shelf whereas only between 4.9 and 8.3‰ (5.9‰) in the slope sediments (Fig. 3b). Relatively enriched $\delta^{15}N$ ratios were observed in sediments very close to the coast compared to offshore.

5. Discussion

5.1 Organic carbon preservation: Difference between shelf and slope sediments

Continental shelf sediments are relatively low in SOC (1.04±0.30%) compared to that of the slope (1.40±0.27%) sediments along the coast. The shelf-slope contrast was more profound in the NW (shelf: 0.73±0.11%; slope: 1.24±0.11%) than SW region (shelf: 1.15±0.23%; slope: 1.50±0.34%) of the coast. Such differences in distribution of SOC between shelf and slope were previously reported in marginal sediments elsewhere [Biscaye and Anderson, 1994; Keil *et al.*, 1998]. Some investigators attributed accumulation of SOC in the slope region to lateral transport of OM from shelf [Biscaye and Anderson, 1994; Keil *et al.*, 1998] while the others attributed to existence of favourable conditions for OM preservation in slope regions [Dow, 1978; Summerhayes, 1987; Ittekkot *et al.*, 1991; Paropkari *et al.*, 1993; Hedges and Keil, 1995].

The SOC in marginal sediments is known to be controlled by primary productivity in the overlying water column [Parrish, 1982; Calvert, 1987; Pedersen and Calvert, 1990; Calvert *et al.*, 1991; Calvert and Pederson, 1992; Pedersen *et al.*, 1992], low oxygen conditions in subsurface water [Dow, 1978; Demaison and Moore, 1980; Bralower and Thierstein, 1987; Summerhayes, 1987; Paropkari *et al.*, 1993], rate of sedimentation or mineral ballast [Ittekkot *et al.*, 1991; Hedges

and Keil, 1995], texture of sediments [Calvert *et al.*, 1995] and dilution by terrigenous material [Rullkötter, 2006]. Despite nearly similar integrated Chl-a concentrations are observed in the shelf ($43.3 \pm 18.4 \text{ mg m}^{-2}$) and the slope ($33.2 \pm 17.9 \text{ mg m}^{-2}$), however, relatively lower SOC was found in the former than in the latter region suggesting that the strong influence of other factors on distribution of SOC in the study region. Strong influence of factors other than productivity on preservation of SOC was reported elsewhere; for example, oxygen minimum zone on the western continental slope of India [Paropkari *et al.*, 1993], total suspended matter in the Bay of Bengal [Ittekkot *et al.*, 1991], grain size (texture) of sediments on the continental slope of the Arabian Sea [Calvert *et al.*, 1995]. Total suspended matter (TSM) concentrations were similar in the shelf ($19.7 \pm 9.5 \text{ mg l}^{-1}$) and the slope ($16.1 \pm 8.6 \text{ mg l}^{-1}$) indicating that rate of sedimentation and dilution by terrigenous material may not be responsible for better SOC accumulation in the slope sediments. Clayey and silty-clay sediments were reported to contain relatively high SOC than sandy sediments [Calvert *et al.*, 1995] as clay and silt particles provide large surface area and good binding sites for organic carbon preservation, and less porosity for oxygen penetration. In the present study, similar contents of clay and silt are observed in the shelf (clay: 58%; silt: 38%) and the slope (66%; 33%) sediments. Further, SOC correlated neither with clay ($r^2=0.001$; $p=0.858$; Fig. 4a) nor silt content ($r^2=0.11$; $p=0.059$; Fig. 4b) in the sediment suggesting that texture of the sediments has no control on the OM accumulation in sediments of the study region. Recently Sarma *et al.* [2013] reported occurrence of ca. 400 m thick (depth 100-500 m) intense oxygen minimum zone (OMZ) with undetectable levels of DO in the NW region and ca. 200 m thick OMZ with DO concentration $<5 \mu\text{mol kg}^{-1}$ in the SW region during SW monsoon. Along the western margin of the Bay of Bengal, Sardesai *et al.* [2007] also reported a thick minimum oxygen layer in the intermediate and deep waters during the SW monsoon, whereas low oxygen water were confined to NW region during fall inter-monsoon season [Sardesai *et al.*, 2007]. Therefore, higher SOC in the slope sediment could be due to low oxygen conditions in the intermediate and deeper water that result in less modification of OM in the water column and better accumulation in sediments. Paropkari *et al.* [1993] also reported that SOC in the western continental slope of India is mainly controlled by OMZ in the intermediate depths rather than biological production in the euphotic zone.

TN showed a weak positive correlation with SOC in the shelf ($r^2=0.22$; $p=0.008$; Fig. 5a) suggesting that C and N pools are rather decoupled and contributed by different sources. On the other hand, a strong positive correlation between TN and SOC ($r^2=0.73$; $p<0.001$; Fig. 5b) in the slope sediment indicates that C and N pools are rather controlled by a similar mechanism. A weak correlation in the shelf and strong positive correlation in the slope could also be due to preferential

deposition of C-rich and N-poor terrestrial OM such as waterlogged woody particles and vascular plant debris, which are relatively coarser and denser, on the shelf by the hydrodynamic sorting process during the seaward transport of particulate matter. This hydrodynamic sorting process has previously been used to explain the chemical composition of SOC off the Washington margin [Keil *et al.* 1994; Prahl *et al.* 1994], Amazon [Goni, 1997], Bengal fans [Lanord and Derry, 1994], and Gulf of Mexico [Goni *et al.* 1997]. Other possible reason could be preferential removal of N-rich protein compounds during degradation of OM in the shelf and less modification of OM in the slope sediments.

5.2 Organic matter sources

The range of $\delta^{13}\text{C}$ ratios (-23.3 to -16.7‰) in our study indicate that possible contribution from terrestrial C_3 ($\delta^{13}\text{C}$: -25.7‰; this study) [-23 to -30‰; Smith and Epstein, 1971] and C_4 plants (-13.0‰; this study) [-17 to -9‰; Gearing, 1988; Sackett, 1989], and marine phytoplankton (-20.6‰; this study) [-22 to -19‰; Fry and Sherr, 1984]. Contribution of OM from terrestrial C_3 and C_4 plants can be explained by the riverine transport of debris of the dominant agricultural crops and vegetation in drainage basin of the river. Major portion of the cultivable land in drainage basin of the river Krishna and its tributaries is occupied by jowar (sorghum) and bajra (millet), which follow PEP (Phosphoenolpyruvate) carboxylation mechanism for photosynthesis (C_4 plants), with a minor contribution from cotton and rice which follow RuBisCo carboxylation mechanism for OM synthesis (C_3 plants), as depicted in Fig. 6. In case of the Godavari and its tributaries, the upper portion of the drainage basin is occupied by jowar and bajra (C_4 type plants), and cotton and pulse (C_3 type plants). On the other hand, the lower portion is mostly occupied by rice (C_3 plants; Fig. 6). Further, sugar cane, which is also a C_4 type plant, is one of the major agricultural crops in the catchment area of both the rivers Krishna and Godavari (Fig. 6). The catchment area of the river Mahanadi and its tributaries is dominated by the forest and scrub (C_3 type plants) and sugar cane (C_4 type plants) (Fig. 6). Therefore, C_4 type vegetation is significant in catchment area of the major monsoonal rivers, Krishna, Godavari, and Mahanadi. These rivers transport OM derived from detritus of the C_3 and C_4 type plants and erosion of agricultural lands (soil OM) to the western coastal Bay of Bengal during southwest monsoon, when peak discharge occurs. In surface sediments from the shelf and slope regions of the Gulf of Mexico, Goni *et al.* [1997] also reported $\delta^{13}\text{C}$ ratios between -21.7 and -19.7‰ and interpreted the results in terms of a significant contribution from terrestrial OM produced by erosion of extensive C_4 grassland soils (-17 to -9‰) [Smith and Epstein, 1971; Gearing, 1988; Sackett, 1989] rather than OM of marine origin [-22 to -19‰; Fry and Sherr, 1984]. It was demonstrated that highly re-worked and recalcitrant soil OM derived from the C_4 vegetation was

transported to offshore regions in the Gulf of Mexico in the form of fine particulates (non-woody; detritus of leaves and grass) [Goni *et al.*, 1997].

The shelf sediments showed a broad range of $\delta^{15}\text{N}$ ratios from 3.7 to 13.5‰ compared to the slope (from 4.9 to 8.3‰; Fig. 3b) suggesting that nitrogen in sediments of the former region is contributed by range of sources with different $\delta^{15}\text{N}$ ratios. However, most of the enriched $\delta^{15}\text{N}$ ratios (>8.0‰) were observed very close to the coast (water depth of 25m) than offshore. Recently, Sarma *et al.* [2012] also reported $\delta^{15}\text{N}$ ratios up to 14.7‰ in surface sediments of the tropical Godavari estuary. Thus, enriched $\delta^{15}\text{N}$ ratios at stations close to the coast are attributed to transport of ^{15}N rich estuarine sediments to the coasts. This could also be due to diagenesis of sedimentary OM during transportation and/or at the sediment-water interface as re-suspension of surface sediment is more rigorous close to the coast.

Excluding these stations, the mean $\delta^{15}\text{N}$ ratios in the shelf ($6.4\pm 2.0\text{‰}$) are not distinctly different from that of the slope ($6.0\pm 1.0\text{‰}$) sediments as in the case of $\delta^{13}\text{C}$. These ratios are in the range of $\delta^{15}\text{N}$ of marine (7.5‰; this study) [5 - 7‰; Brandes and Devol 2002; Lamb *et al.*, 2006; Altabet, 1996], C_3 plants (3.6‰; this study), C_4 plants (5.4‰; this study) and terrestrial derived OM (1.8 to 3.5‰; Peters *et al.*, 1978; Wada *et al.*, 1987; Thornton and Mcmanus, 1994] and therefore, suggesting the possible contribution of OM from both the terrestrial and marine sources, as revealed by $\delta^{13}\text{C}$ results.

Broad range of molar C:N ratios were observed in the shelf (9 to 47) compared to the slope (10 to 19) sediments that followed the difference in $\delta^{13}\text{C}$ (shelf: -23.2 to -16.7‰; slope: -21.4 to -17.6‰) and $\delta^{15}\text{N}$ (shelf: 3.7 – 13.5‰; slope: 4.9 to 8.3‰). The mean C:N ratio in the shelf (20) as well as in the slope (13) sediment are relatively higher than the typical marine OM (ca. 5 - 8) [Meyers, 1997] and in the range of terrestrial OM (>12) [Hedges *et al.*, 1997; Lamb *et al.*, 2006]. Relatively higher C:N (>20) ratios observed in the sediments close to the coast could be due to either contribution from nitrogen poor terrestrial vascular plant material, or diagenetic alterations in nitrogen content [Bordovskiy, 1965; Prahl *et al.*, 1980]. The $\delta^{15}\text{N}$ of terrestrial OM ranges between 1.8 and 3.5‰ [Thornton and Mcmanus, 1994], however, the relatively enriched $\delta^{15}\text{N}$ in the sediments close to coast rules out the potential contribution from terrestrial OM. Therefore, higher C:N ratios in the sediments close to the coast are attributed to diagenetic alterations in N as preferential decomposition of N-rich labile compounds occurs during early diagenesis of OM.

5.3 Quantification of OM contribution from terrestrial and marine sources

Quantification of relative contributions from different OM source materials is extremely important for better understanding the biogeochemistry of OM in the coastal ocean. In the present study, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ results suggest that OM in sediment of the western coastal Bay of Bengal was contributed by both terrestrial OM derived from C_3 and C_4 type plants and marine OM derived from in-situ biological production (marine OM). Relative contribution from each of these sources to the sediment of the region was quantified. The most feasible contribution from C_3 and C_4 plants, and marine OM were found to be in the range of 15 to 65% (Fig. 7a), 10 to 61% (Fig. 7b), and 24 to 50% (Fig. 7c), respectively. The mean relative contribution from C_3 plants decreased from 37% in the shelf to 30% in the slope sediments while marine OM increased from 41% in the shelf to 47% in the slope indicating that decreasing influence of terrestrial OM and increasing dominance of marine OM towards offshore region. Maximum contribution from C_4 plants (39%) was recorded in sediment off the river Krishna compared to rest of the region (mean 19%). This is attributed to the dominance of agricultural crops of C_4 type (jowar and bajra) in its entire drainage basin except a small portion in the lower region where rice, forest and scrub (C_3 plants) are dominant (Fig. 6). The terrestrial OM in sediment off the river Godavari is contributed by 39% from C_3 and 19% from C_4 plants indicating that contribution of OM from both agricultural fields of C_4 plants (jowar and bajra) in the upper region and C_3 plants (rice, forest and scrub) in the lower region of the drainage basin of the river Godavari and its tributaries. Therefore, it seems that the relative composition of OM transported by a river to the coastal region is strongly controlled by the type of agricultural crops and vegetation in its drainage basin. As a whole, the OM in sediment of the western coastal Bay of Bengal is contributed by about 43% from in-situ marine sources, 34% from terrestrial C_3 plants, and 23% from terrestrial C_4 plants. The higher total terrestrial contribution (57%) than the marine contribution (43%) suggest that the OM in sediments of the eastern continental margin of India is dominated by allochthonous terrestrial OM transported by monsoonal rivers from the peninsular India.

6. Conclusion

The distribution, preservation and sources of OM in surface sediments of the eastern continental margin of India were investigated using content and stable isotopic ratios of carbon and nitrogen. Contents of both organic carbon and total nitrogen were relatively low in the shelf than in the slope sediments along the coast in general and in the NW region in particular. This is attributed to low oxygen conditions in the intermediate depths of the water column. Remarkably broad range of $\delta^{13}\text{C}$ ratios (from -23.2 to -16.7‰) suggest that major contribution of OM from terrestrial C_3 and C_4 plants, and in-situ produced marine OM. The sediment OM in the coastal Bay of Bengal is

contributed by ~43% of marine OM followed by ~34% and ~23% of terrestrial C₃ and C₄ plants respectively. These results demonstrate that (i) a predominance of allochthonous terrestrial OM (57%) rather than autochthonous marine OM (43%) in sediments of the eastern continental margin of India, (ii) the strong influence of river discharge on the relative composition of sediment OM through transportation of terrestrial OM from the peninsular India. The relative composition of terrestrial OM (contribution from C₃ versus C₄ plants) transported by a river to the study region is seem to be governed by the type of agricultural crops and vegetation in the drainage basin of the river. The preservation of OM is governed by the low oxygen levels in the water column resulted from strong stratification caused by river discharge. Therefore river discharge has significant impact on quality and quantity of OM brought to the coastal Bay of Bengal and its preservation in the sediments.

7 Acknowledgements

We thank the Director, National Institute of Oceanography (NIO), Goa, and the Scientist-In-Charge, NIO-Regional Centre, Visakhapatnam for their support and encouragement. The work is part of the Council of Scientific and Industrial Research (CSIR), Government of India funded Supra Institutional Project (SIP). We also thank master and crew of the Sagar Nidhi for help during the voyage (No. 42). This is NIO contribution number

References

- Altabet, M. A. (1996), Nitrogen and carbon isotopic tracers of the source and transformation of particles in the deep sea. In: Ittekkot, V., P. Schaefer, S. Honjo, and P. J. Depetris, (Eds.) Particle Flux in the Ocean. *SCOPE, Vol. 57*, Wiley & Sons, Chichester, pp. 155-184.
- Benstead, J. P., J. G. March, B. Fry, K. C. Ewel, and C. M. Pringle (2006), Testing Iso-source: Stable isotope analysis of a tropical fishery with diverse organic matter sources, *Ecology*, *87*, 326–333.
- Biscaye, P. E., and R. F. Anderson (1994), Fluxes of particulate matter on the slope of the southern Mid-Atlantic Bight: SEEP-II, *Deep Sea Research II*, *41*, 459–509.
- Bordovskiy, O. K. (1965), Accumulation and transformation of organic substances in marine sediment, *Marine Geology*, *3*, 114.
- Bralower, T. J., and H. R. Thierstein (1987), Organic carbon and metal accumulation rates in Holocene and mid-Cretaceous sediments: palaeoceanographic significance. In: Brooks, J., and A. J. Fleet (Eds.), Marine Petroleum Source Rocks. *Geological Society Special Publication*, *26*, 345-369.
- Brandes, J. A., and A. H. Devol (2002), A global marine-fixed nitrogen isotopic budget: implications for Holocene nitrogen cycling, *Global Biogeochemical Cycles*, *16*, 1120, doi: 10.1029/2001GB001856.

- Calvert, S. E. (1987), Oceanographic controls on the accumulation of organic matter in marine sediments. In: Brooks, J., and A. J. Fleet (Eds.), *Marine Petroleum Source Rocks. Geological Society Special Publication, 26*, 137-151.
- Calvert, S. E., and T. F. Pedersen (1992), Organic carbon accumulation and preservation in marine sediments: How important is anoxia? In: Whelan, J. K., and J. W. Farrington (Eds.), *Productivity, Accumulation and Preservation of Organic Matter in Recent and Ancient Sediments*. Columbia Univ. Press, New York, pp. 231-263.
- Calvert, S. E., R. E. Karlin, L. J. Toolin, D. J. Donahue, J. R. Southon, and J. S. Vogel (1991), Low organic carbon accumulation rates in Black Sea sediments, *Nature, 350*, 692-695.
- Calvert, S. E., T. F. Pederson, P. D. Naidu, and U. von Stackelberg (1995), On the organic carbon maximum on the continental slope of the eastern Arabian Sea, *Journal of Marine Research, 53*, 269-296.
- Carr, M. (2001), Estimation of potential productivity in Eastern Boundary Currents using remote sensing, *Deep Sea Research, 49*, 59-80.
- de Haas, H., T. C. E. van Weering, and H. de Stigter (2002), Organic carbon in shelf seas: sinks or sources, processes and products, *Continental Shelf Research, 22*, 691-717.
- Demaison, G. J., and G. T. Moore (1980), Anoxic environments and oil source bed genesis. *Organic Geochemistry, 2*, 9-31.
- Dow, W. J. (1978), Petroleum source beds on continental slopes and rises. *American Association of Petroleum Geology, 62*, 1584-1606.
- Fernandes, F., F. D'Souza, S. G. P. Matondkar, and N. B. Bhosle (2006), Amino sugars in suspended particulate matter from the Bay of Bengal during the summer monsoon of 2001, *Journal of Earth System Science, 115*, 363-370.
- Fernandes, F., N. B. Bhosle, S. G. P. Matondkar, and R. Bhushan (2009), Seasonal and spatial distribution of particulate organic matter in the Bay of Bengal. *Journal of Marine Systems, 77*, 137-147.
- Folk, R. L. (1974), *The petrology of sedimentary rocks*: Austin, Tx, Hemphill Publishing Corporation. pp. 182
- Fry, B., and E. B. Sherr (1984), $\delta^{13}\text{C}$ measurements as indicators of carbon flow in marine and freshwater ecosystems, *Contributions in Marine Science, 27*, 13-47.
- Galy, V., C. F. Lanord, O. Beyssac, P. Faure, H. Kudrass, and F. Palhol (2007), Efficient organic carbon burial in the Bengal fan sustained by the Himalayan erosional system, *Nature, 450*, 407-410.
- Gauns, M., M. Madhupratap, N. Ramaiah, R. Jyothibabu, V. Fernandes, J. T. Paul, and S. P. Kumar (2005), Comparative accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and the Bay of Bengal, *Deep Sea Research II, 52*, 2003-2017.
- Gearing, J. N. (1988), The use of stable isotope ratios for tracing the nearshore-offshore exchange of organic matter. Lecture notes on coastal and estuarine studies, vol. 22. In: Jansson, B. O. (Ed.), *Coastal Offshore Ecosystem Interactions*. Springer-Verlag, New York, pp. 69-101.
- Gearing, P., F. Plucker, and P. L. Parker (1977), Organic carbon stable isotope ratios of continental margin sediments, *Marine Chemistry, 5*, 251-266.

- Gibbs, M. M. (2008), Identifying source soils in contemporary estuarine sediments: a new compound-specific isotope method, *Estuaries and Coasts*, 31, 344–359.
- Goni, M. A. (1997), In: Flood, R. D., D. J. W. Piper, A. Klaus (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Report, 155*, 519–530.
- Goni, M. A., K. C. Ruttenberg, and T. Eglinton (1997), Sources and contribution of terrestrial organic carbon in the Gulf of Mexico, *Nature*, 389, 275-278.
- Goni, M., M. Yunker, R. Macdonald, and T. Eglinton (2000), Distribution and sources of organic biomarkers in arctic sediments from the Mackenzie River and Beaufort Shelf, *Marine Chemistry*, 71, 23-51.
- Gordon, E. S., and M. A. Goni (2004), Controls on the distribution and accumulation of terrigenous organic matter in sediments from the Mississippi and Atchafalaya river margin, *Marine Chemistry*, 92, 331-352.
- Haake, B. G., N. Lahajnar, K. Emeis, D. Unger, T. Rixen, A. Suthhof, V. Ramaswamy, H. Schulz, A. L. Paropkari, M. V. S. Gupta, and V. Ittekkot (2005), Stable nitrogen isotopic ratios of sinking particles and sediments from the northern Indian Ocean, *Marine Chemistry*, 96, 243-255.
- Hedges, J. I. (1992), Global biogeochemical cycles - progress and problems, *Marine Chemistry*, 39, 67-93.
- Hedges, J. I., and P. L. Parker (1976), Land-derived organic matter in surface sediments from the Gulf of Mexico, *Geochimica et Cosmochimica Acta*, 40, 1019-1029.
- Hedges, J. I., and R. G. Keil (1995), Sedimentary organic matter preservation: an assessment and speculative synthesis, *Marine Chemistry*, 49, 81–115.
- Hedges, J. I., R. G. Keil, and R. Benner (1997), What happens to terrestrial organic matter in the ocean? *Organic Geochemistry*, 27, 195-212.
- International Geosphere Biosphere Program (IGBP) (1993), Land-Ocean interactions in the coastal zone, *Science Plan. IGBP of ICSU, Report no. 25*, Stockholm, 50pp.
- Ittekkot, V., R. R. Nair, S. Honjo, V. Ramaswamy, M. Bartsch, S. Manginini, and B. N. Desai (1991), Enhanced particle fluxes in Bay of Bengal induced by injection of fresh water, *Nature*, 351, 385-387.
- Keil, R. G., E. Tsamakis, C. B. Fuh, J. C. Giddings, and J.I. Hedges (1994), Mineralogical and textural controls on the organic composition of coastal marine sediments: hydrodynamic separation using SPLITT-fractionation, *Geochimica et Cosmochimica Acta*, 58, 879–893.
- Keil, R. G., E. Tsamakis, J. C. Giddings, and J. I. Hedges (1998), Biochemical distributions (amino acids, neutral sugars and lignin phenols) among size-classes of modern marine sediments from the Washington Coast, *Geochimica et Cosmochimica Acta*, 62, 1347-1364.
- Ku, T-L., and S. Luo (1994), New appraisal of Radium 226 as a large-scale oceanic mixing tracer, *Journal of Geophysical Research*, 99, 10,255-10,273.
- Lamb, A. L., G. P. Wilson, and M. J. Leng (2006), A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}\text{C}$ and C/N ratios in organic material, *Earth Science Reviews*, 75, 29-57.
- Lanord, C. F., and L. A. Derry (1994), d^{13}C of organic carbon in the Bengal Fan: source evolution and transport of C_3 and C_4 plant carbon to marine sediments. *Geochimica et Cosmochimica Acta*, 58, 4809–4814.

- Lanord, C. F., and L. A. Derry (1997), Organic carbon burial forcing of the carbon cycle from Himalayan erosion, *Nature*, *390*, 65–67.
- Levy, M., D. Shankar, J. -M. Andre, S. S. C. Shenoi, F. Durand, and M. C. de Boyer (2007), Basin-wide seasonal evolution of the Indian Ocean's phytoplankton blooms, *Journal of Geophysical Research*, *112*, C12014, doi:10.1029/2007JC004090.
- Mackenzie, F. T. (1981), Flux of Organic Carbon by Rivers to the Ocean. Likens, G. E. et al.(Eds.) 360–384 (US Department of Energy, Washington DC).
- Madhupratap, M., M. Gauns, N. Ramaiah, S. P. Kumar, P. M. Muraleedharan, S. N. de Sousa, S. Sardesai, and U. Muraleedharan (2003), Biogeochemistry of the Bay of Bengal: Physical, chemical and primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001, *Deep Sea Research Part II*, *50*, 881–896.
- Maya, M. V., S. G. Karapurkar, H. Naik, R. Roy, D. M. Shenoy, D.M., and S. W. A. Naqvi (2011), Intra-annual variability of carbon and nitrogen stable isotopes in suspended organic matter in waters of the western continental shelf of India, *Biogeosciences*, *8*, 3441-3456.
- Mazumdar, A., A. L. Paropkari, D. V. Borole, B. R. Rao, N. H. Khadge, S. M. Karisiddaiah, M. Kocherla, and H. M. Joao (2007), Pore-water sulfate concentration profiles of sediment cores from Krishna-Godavari and Goa basins, India, *Geochemical Journal*, *41*, 259-269.
- Meyers, P. A. (1997), Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes, *Organic Geochemistry*, *27*, 213-250.
- Middelburg, J. J., and J. Nieuwenhuize (1998), Carbon and nitrogen stable isotopes in suspended matter and sediments from the Schelde estuary, *Marine Chemistry*, *60*, 217-225.
- Milliman, J. D., and R. H. Meade (1983), World-wide delivery of river sediment to the oceans, *Journal of Geology*, *91*, 1-21.
- Milliman, J. D., and J. P. M. Syvitski (1992), Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers, *Journal of Geology*, *100*, 525-544.
- Milliman, J. D., and K. M. Farnsworth (2010), River discharge to the coastal ocean: A global synthesis. Cambridge University Press
- Newsome, S. D., D. L. Phillips, B. J. Culleton, T. P. Guilderson, and P. L. Koch (2004), Dietary reconstruction of an early to middle Holocene human population from the central California coast: insights from advanced stable isotope mixing models, *Journal of Archaeol Science*, *31*, 1101–1115
- Ogrinc, N., G. Fontolan, J. Faganeli, and S. Covelli (2005), Carbon and nitrogen isotope compositions of organic matter in coastal marine sediments (the Gulf of Trieste, N Adriatic Sea): indicators of sources and preservation, *Marine Chemistry*, *95*, 163-181.
- Paropkari, A. L., C. Prakash Babu, and A. Mascarenhas (1993), New evidence for enhanced preservation of organic carbon in contact with oxygen minimum zone on the western continental slope of India, *Marine Geology*, *111*, 7-13.
- Parrish, J. T. (1982), Upwelling and petroleum source beds, with reference to Paleozoic. *American Association of Petroleum Geology*, *6*, 750-774.
- Pedersen, T. F., and S. E. Calvert (1990), Anoxia vs. Productivity: What controls the formation of organic-carbon-rich sediments and sedimentary rocks? *AAPG Bulletin*, *74*, 454-466.

- Pedersen, T. F., G. B. Shimmield, and N. B. Price (1992), Lack of enhanced preservation of organic matter in sediments under the oxygen minimum on the Oman Margin, *Geochimica et Cosmochimica Acta*, 56, 545-551.
- Peters, K. E., R. E. Sweeney, and I. R. Kaplan (1978), Correlation of carbon and nitrogen stable isotope ratios in sedimentary organic matter, *Limnology and Oceanography*, 23, 598-604.
- Phillips, D. L., and J. W. Gregg (2001), Uncertainty in source partitioning using stable isotopes, *Oecologia*, 127, 171-179. (see also erratum, *Oecologia* 128:204)
- Phillips, D. L., and J. W. Gregg (2003), Source partitioning using stable isotopes: coping with too many sources, *Oecologia*, 136, 261-269
- Phillips, D. L., and J. W. Gregg (2005), Combining sources in stable isotope mixing models: alternative methods, *Oecologia*, 144, 520-527.
- Prahl, F. G., J. T. Bennett, and R. Carpenter (1980), The early diagenesis of aliphatic hydrocarbons and organic matter in sedimentary particulates from Dabob Bay, Washington, *Geochimica et Cosmochimica Acta*, 44, 1967-1976.
- Prahl, F. G., J. R. Ertel, M. A. Goni, M. A. Sparrow, and B. Eversmeyer (1994), Terrestrial organic carbon contributions to sediments on the Washington margin, *Geochimica et Cosmochimica Acta*, 58, 3035-3048.
- Prasad, T. G (1997), Annual and seasonal mean buoyancy fluxes for the tropical Indian Ocean, *Current Science*, 73, 667-674.
- Premuzic, E. T., C. M. Benkovitz, J. S. Gaffney, and J. J. Walsh (1982), The nature and distribution of organic matter in the surface sediments of world oceans and seas, *Organic Geochemistry*, 4, 63-77.
- Ramana, M. V., T. Ramprasad, A. L. Paropkari, D. V. Borole, B. R. Rao, S. M. Karisiddaiah, E. Desa, M. Kocherla, H. M. Joao, P. Lokabharati, M. -J. Gonsalves, J. N. Pattan, N. H. Khadge, C. P. Babu, A. V. Sathe, P. Kumar, and A. K. Sethi (2009), Multidisciplinary investigations exploring indicators of gas hydrates occurrence in the Krishna-Godavari basin offshore, east coast of India, *Geo-Marine Letters*, 29, 25-38.
- Ramanathan, K. R., and P. R. Pisharoty (1972), Water balance- Indian Ocean. World Water Balance, pp. 39-41, International Association of Hydrological Science, Gentbrugge, Belgium.
- Ramaswamy, V., B. Gaye, P. V. Shirodkar, P. S. Rao, A. R. Chivas, D. Wheeler, and S. Thwin (2008), Distribution and sources of organic carbon, nitrogen and their isotopic signatures in sediments from the Ayeyarwady (Irrawaddy) continental shelf, northern Andaman Sea, *Marine Chemistry*, 111, 137-150.
- Rullkotter, J. (2006), Organic matter: The driving force for early diagenesis. In: *Marine Geochemistry*, Schulz, H. D., and M. Zabel (Eds.), Springer-Verlag Berlin Heidelberg. pp. 125-168.
- Sackett, W. M. (1989), Stable carbon isotope studies on organic matter in the marine environment. In: *Handbook of Environmental Isotope Geochemistry*, Fritz, P., and J. C. Fontes (Eds.), Elsevier, New York, pp. 139-169.
- Sampaio, L., R. Freitas, C. Maguas, A. Rodrigues, and V. Quintino (2010), Coastal sediments under the influence of multiple organic enrichment sources: An evaluation using carbon and nitrogen stable isotope, *Marine Pollution Bulletin*, 60, 272-282.

- Sardessai, S., N. Ramaiah, P. Kumar, and D. Sousa (2007), Influence of environmental forcings on the seasonality of dissolved oxygen and nutrients in the Bay of Bengal, *Journal of Marine Research*, *65*, 301-316.
- Sarma, V. V. S. S., J. Arya, Ch. V. Subbaiah, S. A. Naidu, L. Gawade, P. P. Kumar, and N. P. C. Reddy (2012), Stable isotopes of carbon and nitrogen in suspended matter and sediments from the Godavari estuary, *Journal of Oceanography*, *68*, 307-319.
- Sarma, V. V. S. S., M. S. Krishna, R. Viswanadham, G. D. Rao, V. D. Rao, B. Sridevi, B. S. K. Kumar, V. R. Prasad, Ch. V. Subbaiah, T. Acharyya, and D. Bandopadhyay (2013), Intensified oxygen minimum zone on the western shelf of Bay of Bengal during summer monsoon: influence of river discharge, *Journal of Oceanography*, *69*, 45-55.
- Sasmal, S. K. (2007), On a 16°N chlorophyll plume along the east coast of India, *International Journal of Remote Sensing*, *28*, 4671-4675.
- Schott, F. A., and J. P. McCreary (2001), The monsoon circulation of the Indian Ocean, *Progress in Oceanography*, *51*, 1-123.
- Shetye, S. R., S. S. C. Sheno, A. D. Gouveia, G. S. Michael, D. Sundar, and G. Nampoothiri (1991), Wind-driven coastal upwelling along the western boundary of the Bay of Bengal during the southwest monsoon, *Continental Shelf Research*, *11*, 1397-1408.
- Smith, B. N., and S. Epstein (1971), Two categories of $^{13}\text{C}/^{12}\text{C}$ ratios for higher plants, *Plant Physiology (Bethesda)*, *47*, 380-384.
- Smith, S. V., and F. T. MacKenzie (1987), The oceans as a net heterotrophic system: implications from carbon geochemical cycle, *Global Biogeochemical Cycles*, *1*, 187-198.
- Subramanian, V. (1993), Sediment load of Indian rivers, *Current Science*, *64*, 928-930.
- Summerhayes, C. P. (1987), Organic-rich Cretaceous sediments from the North Atlantic. In: Marine Petroleum Source Rocks, Brooks, J., and A. J. Fleet (Eds.), *Geological Society Special Publication*, *26*, 301-316.
- Suzuki, R., and T. Ishimaru (1990), An improved method for the determination of phytoplankton chlorophyll using N,N-dimethyl formamide, *Journal of Oceanography*, *46*, 190-194.
- Thornton, S. F., and J. McManus (1994), Application of organic carbon and nitrogen stable isotope and C/N ratios as source indicators of organic matter provenance in estuarine systems: evidence from the Tay Estuary, Scotland, *Estuarine Coastal and Shelf Science*, *38*, 219-233.
- Unger, D., V. Ittekkot, P. Schafer, J. Tiemann, and S. Reschke (2003), Seasonality and interannual variability of particle fluxes to the deep Bay of Bengal: influence of riverine input and oceanographic processes, *Deep-Sea Research II*, *50*, 897-923.
- Unger, D., V. Ittekkot, P. Schafer, and J. Tiemann (2005), Biogeochemistry of particulate organic matter from the Bay of Bengal as discernible from hydrolysable neutral carbohydrates and amino acids, *Marine Chemistry*, *96*, 155-184.
- Usui, T., S. Nagao, M. Yamamoto, K. Suzuki, I. Kudo, S. Montani, A. Noda, and M. Minagawa (2006), Distribution and sources of organic matter in surficial sediments on the shelf and slope of Tokachi, western North Pacific, inferred from C and N stable isotopes and C/N ratios, *Marine Chemistry*, *98*, 241-259.
- Varkey M. J., V. S. N. Murty, and A. Suryanarayana (1996), Physical oceanography of the Bay of Bengal and Andaman Sea, *Oceanography Marine Biology Annual Review*, *34*, 1-70.

- Wada, E., M. Minagawa, H. Mizutani, T. Tsuji, R. Imaizumi, and K. Karasawa (1987), Biogeochemical studies on the transport of OM along the Otsuchi River watershed, Japan, *Estuarine Coastal and Shelf Science*, *25*, 321–336.
- Wiggert, J. D., R. Hood, K. Banse, and J. Kindle (2005), Monsoon driven biogeochemical processes in the Arabian Sea, *Progress in Oceanography*, *65*, 176–213.
- Wildhaber, Y. C., R. Liechti, and C. Alewell (2012), Organic matter dynamics and stable isotope signature as tracers of the sources of suspended sediment, *Biogeosciences*, *9*, 1985–1996.
- Wu, Y., J. Zhang, S. M. Liu, Z. F. Zhang, Q. Z. Yao, G. H. Hong, and L. Cooper (2007), Sources and distribution of carbon within the Yangtze River system, *Estuarine Coastal and Shelf Science*, *71*, 13-25.
- Zhang, J., Y. Wu, Jennerjahn, V. Ittekkot, and Q. He (2007), Distribution of organic matter in the Changjiang (Yangtze River) estuary and their stable carbon and nitrogen isotopic ratios: Implications for source discrimination and sedimentary dynamics, *Marine Chemistry*, *106*, 111-126.

Figure Captions:

- Fig. 1: Map showing study region in the western coastal Bay of Bengal. Filled dark circles in the enlarged map shows stations of sediment collection.
- Fig. 2: Spatial distribution of (a) sediment organic carbon (SOC; %), (b) total nitrogen (TN; %), (c) elemental C:N ratio, and (d) integrated chlorophyll-a (mg m^{-2}) in sediments from the western coastal Bay of Bengal
- Fig. 3: Spatial distribution of (a) stable isotope ratios of organic carbon ($\delta^{13}\text{C}$; ‰), (b) isotope ratios of total nitrogen ($\delta^{15}\text{N}$; ‰) in surface sediments of the western coastal Bay of Bengal
- Fig. 4: Relationship of SOC with (a) clay and (b) silt content in sediments of the western coastal Bay of Bengal
- Fig.5: Relationship of SOC with TN in sediments of (a) shelf and (b) slope region of the western coastal Bay of Bengal
- Fig.6: Map showing major agricultural crops in India (Source: Perry Castenada Map Library at the University of Texas; <http://origins.osu.edu/article/65/maps>). Major monsoonal rivers, Krishna, Godavari and Mahanadi are shown by solid thin line. Drainage basins of river Krishna (••••••••), Godavari (— — —) and Mahanadi (====) are also shown.
- Fig.7: Spatial distribution of relative contribution from (a) C_3 plants (C_3 , %), (b) C_4 plants (C_4 , %), and (c) marine organic matter (MOM; %) to the organic matter in surface sediments of the western coastal Bay of Bengal.

Table Captions

Table 1: Station name, Longitude ($^{\circ}\text{E}$), Latitude ($^{\circ}\text{N}$), water depth (m), $\delta^{13}\text{C}$ (‰) of organic carbon, sediment organic carbon (wt.%), integrated chlorophyll-a (mg m^{-2}), $\delta^{15}\text{N}$ (‰) of total nitrogen, total nitrogen (wt. %), elemental C:N ratio, total suspended matter (TSM; mg l^{-1}), contribution of organic matter from terrestrial C_3 plants (%), C_4 plants (%) and marine organic matter (%) to the sediments of the western coastal Bay of Bengal.

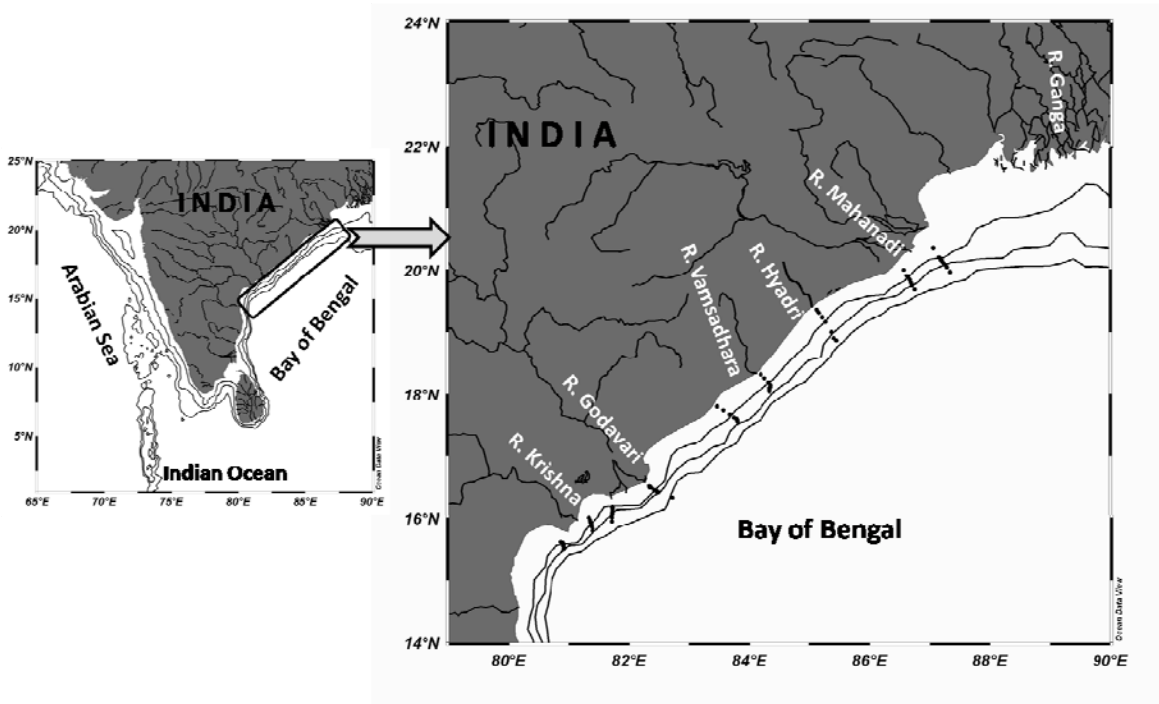
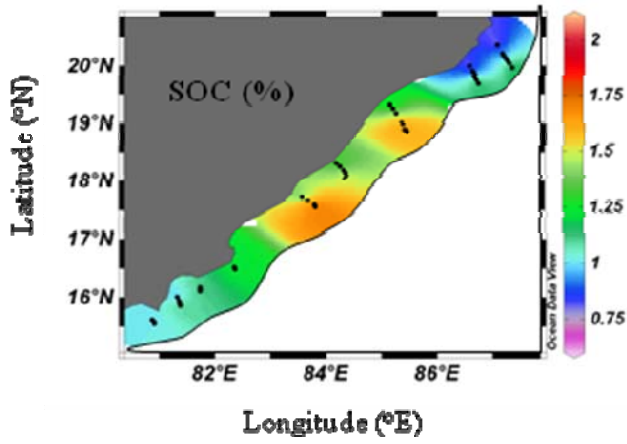
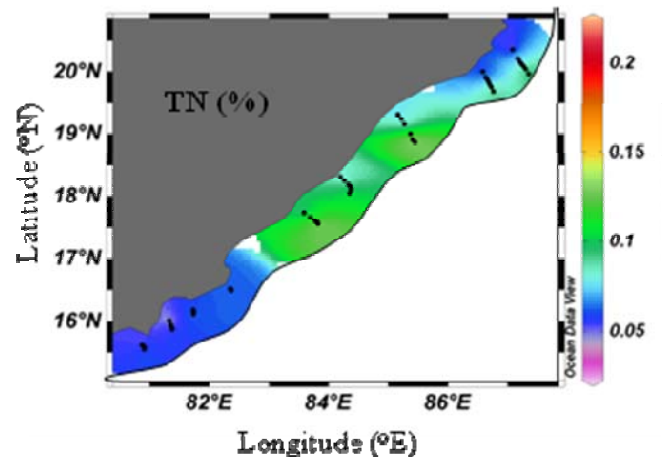


Fig. 1

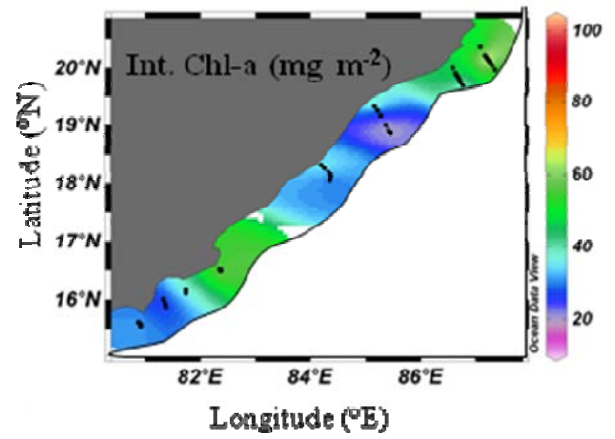
(a)



(b)



(d)



(c)

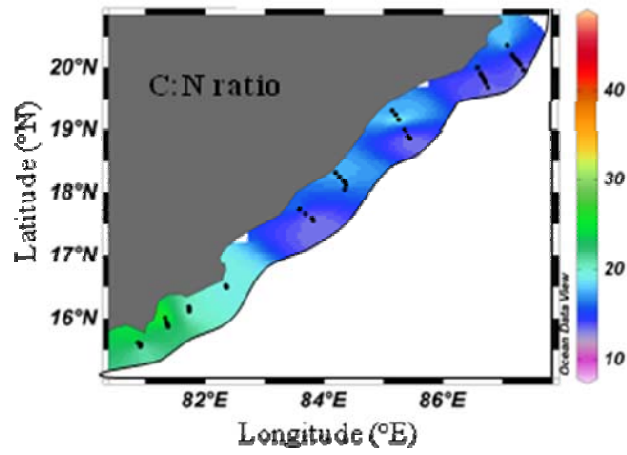


Fig. 2

(a) (b)

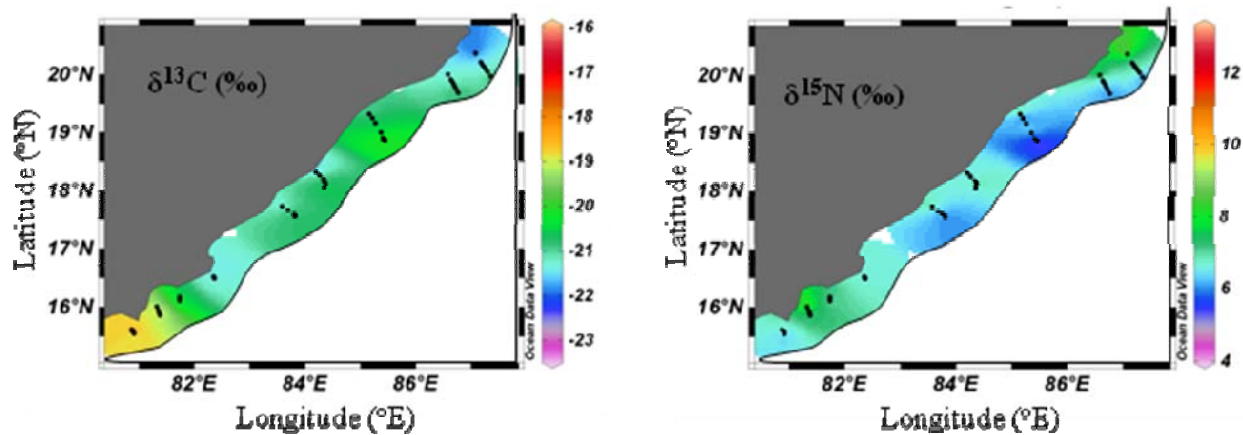


Fig. 3

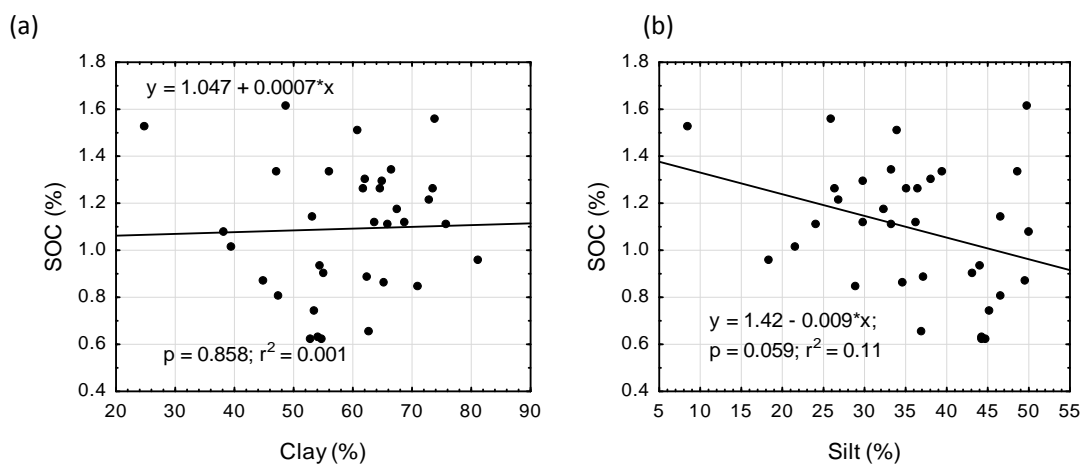


Fig. 4

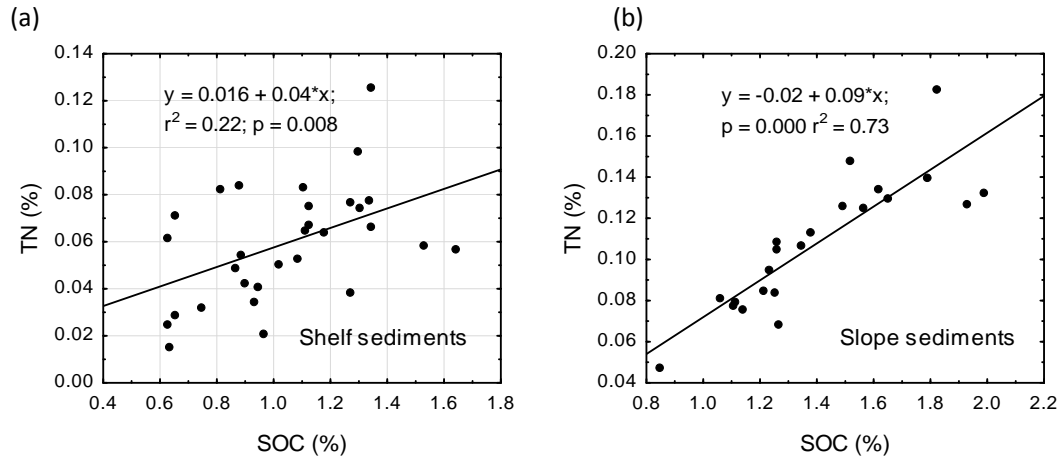


Fig. 5

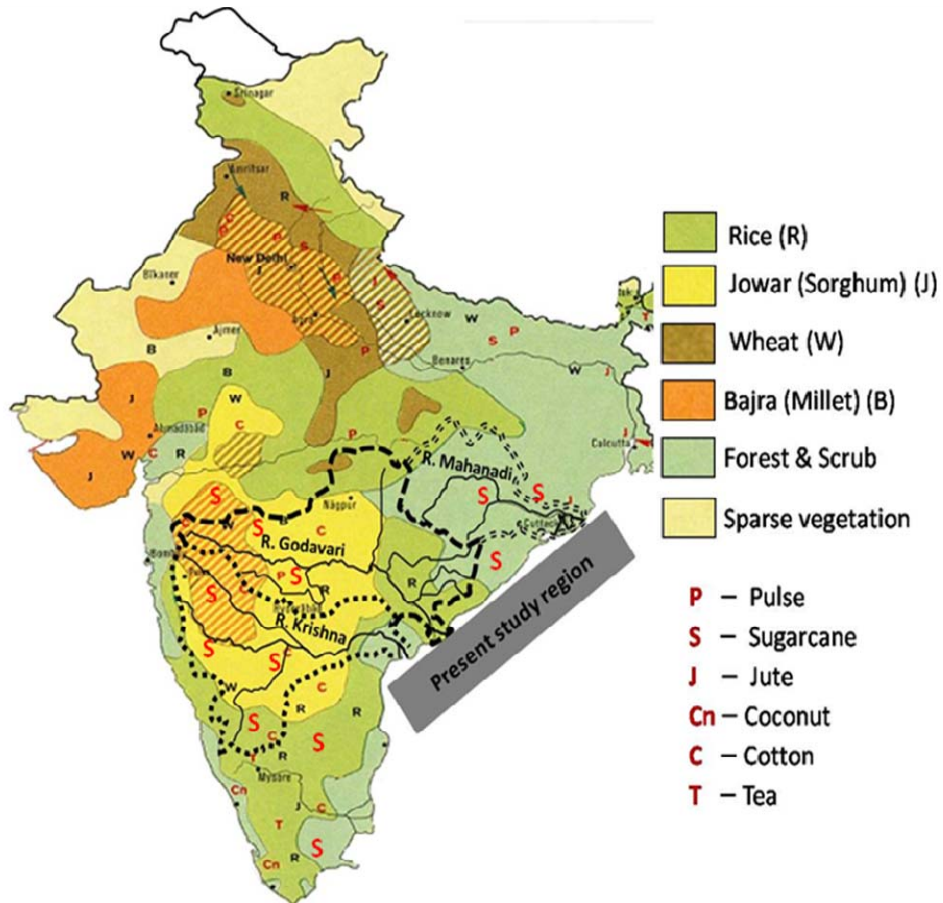
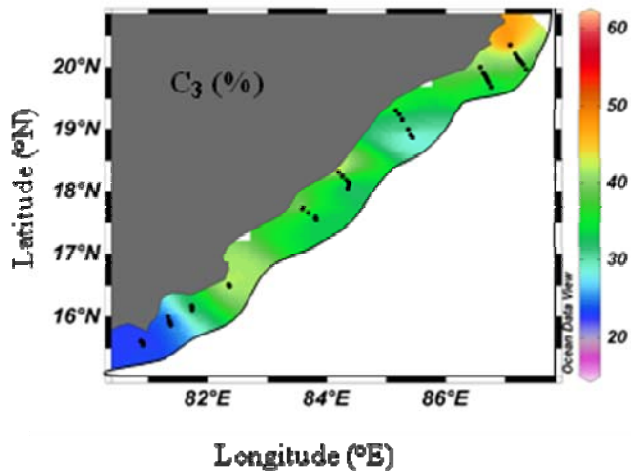
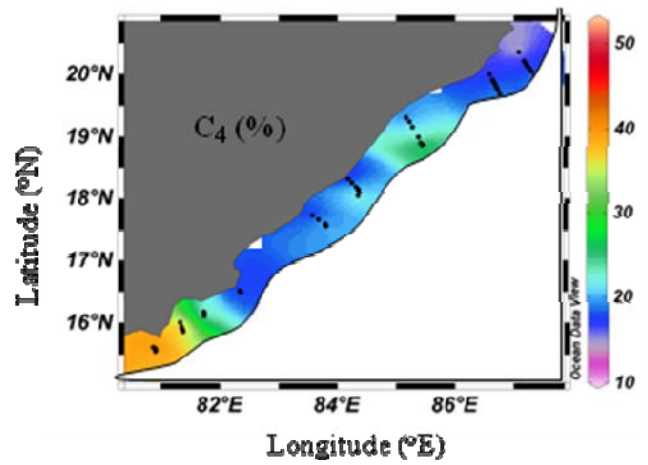


Fig.6

(a)



(b)



(c)

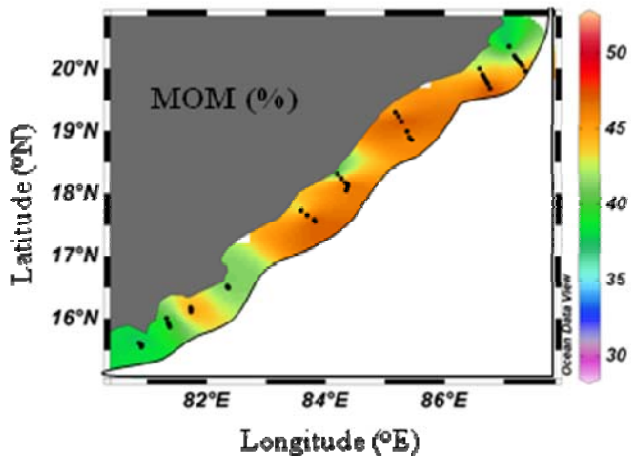


Fig.7

Station Name	Longitude (° E)	Latitude (°N)	Water depth (m)	$\delta^{13}\text{C}$ (‰;VPDB)	SOC (%)	Int. Chl a (mg m ⁻²)	$\delta^{15}\text{N}$ ‰	TN (%)	C:N ratio	TSM (mg l ⁻¹)	C ₃ (%)	C ₄ (%)	MOM (%)
<i>Shelf sediments</i>													
KS1	80.86847	15.61422	24.9	-19.1	0.96	31.6	9.1	0.02	46.6	41.8	24	36	40
KS2	80.89463	15.59907	54.3	-18.5	1.12	33.55	5.2	0.08	14.9	36	22	42	36
KS4	80.90783	15.58903	123.2	-17.9	0.86	28.05	5.3	0.05	17.7	25.8	19	48	33
KN1	81.32548	16.00637	27.18	-19.8	0.63	21.8	13.5	0.02	40.4	16.9	26	28	46
KN3	81.35397	15.93487	77.5	-18.5	0.90	19.1	6.1	0.04	21.1	41	22	42	36
KN4	81.36163	15.91237	103.9	-16.7	1.27	27.85	5.6	0.04	32.8	24.6	15	61	24
GS1	81.73282	16.17433	28.1	-21.8	0.93	43.75	9.3	0.03	27.0	23.1	46	16	38
GS2	81.73612	16.1643	60.8	-20.2	1.11	46.95	6.0	0.06	17.1	14.7	28	24	47
GS4	81.73553	16.14883	110.2	-20.3	1.27	39.1	6.3	0.08	16.5	27.3	29	23	48
GN1	82.34767	16.52057	28.1	-22.6	1.08	29.1	6.6	0.05	20.5	24	57	12	31
GN2	82.35803	16.5122	61.8	-20.3	1.35	50.2	6.4	0.07	20.3	29.7	29	23	48
GN3	82.35363	16.4951	83.4	-20.6	1.18	77.1	6.2	0.06	18.5	25.6	30	20	50
GN4	82.36493	16.48943	135.7	-22.2	1.30	76.2	7.3	0.07	17.4	25.6	52	14	35
VSP2	83.58568	17.73277	55.1	-22.4	0.94	-	8.9	0.04	23.0	22.3	54	13	33
VSP3	83.69073	17.66413	81.5	-20.8	1.34	-	5.2	0.13	10.7	19	32	19	49
VSP4	83.7615	17.61617	110.3	-	-	-	7.8	0.04	-	15.9			
VD1	84.20042	18.31223	31.9	-23.2	1.34	35.15	6.6	0.08	17.1	13.8	65	10	25
VD2	84.265	18.2505	60.3	-20.9	1.02	49.45	5.8	0.05	20.1	11.9	34	19	47

VD3	84.3341	18.181	80.2	-20.6	1.30	37.3	6.1	0.10	13.1	17.4	30	20	50
VD4	84.3658	18.14463	110.5	-20.4	1.53	25.2	8.2	0.06	26.0	14.9	29	22	49
HD2	85.17022	19.30887	53.7	-21.5	1.12	56.5	8.6	0.07	16.7	10.6	42	17	41
HD3	85.22603	19.2411	82.7	-20.5	1.10	24.06	3.7	0.08	13.2	6.5	30	21	49
HD4	85.27773	19.1602	117.3	-20.4	1.64	20.35	6.8	0.06	28.9	12.7	29	22	49
MS1	86.5829	20.00083	34.6	-22.1	0.65	35.85	11.1	0.03	22.3	7	50	14	36
MS2	86.6334	19.90918	58.9	-20.6	0.63	55.1	4.1	0.06	10.2	11.7	30	20	50
MS3	86.643	19.89473	79.1	-21.3	0.65	68.05	4.7	0.07	9.2		39	17	44
MS4	86.65287	19.8821	110.2	-22.1	0.89	44.55	10.0	0.05	16.2	8	50	14	36
MN1	87.08008	20.35493	30.9	-22.8	0.63	29.1	11.2	0.02	25.1	16.9	60	11	29
MN2	87.17198	20.213	58.6	-21.1	0.81	59.6	5.0	0.08	9.8		36	18	46
MN3	87.2022	20.16473	78.4	-21.1	0.88	61	5.2	0.08	10.5	18.3	36	18	46
MN4	87.22367	20.13823	110.2	-22.9	0.74	85.9	13.1	0.03	23.2	8.2	61	11	28
<i>Slope sediments</i>													
GS5	81.73602	16.1117	263.5	-20.6	1.14	20.75	6.3	0.08	15.1	21.8	18	51	31
VSP5	83.80822	17.58932	269.7	-20.7	1.93	-	5.6	0.13	15.2	17.9	31	20	49
VSP6	83.81327	17.58013	519.3	-21.0	1.51	-	5.7	0.15	10.2	13.8	23	38	39
VSP7	83.81288	17.56387	766.8	-20.8	1.99	-	5.4	0.13	15.1	14.8	31	20	49
VSP8	83.81933	17.55427	1056.2	-20.2	1.82	-	5.6	0.18	9.9	13.8	30	20	50
VD5	84.3664	18.1117	262.5	-20.8	1.56	22.95	8.1	0.13	12.5	11.5	31	20	49

VD8	84.34872	18.05183	1209.7	-19.9	1.65	26.1	5.0	0.13	12.7	10.5	35	18	47
HD5	85.37742	18.99407	263.0	-20.9	1.62	15.8	7.3	0.13	12.0	13.9	32	19	49
HD6	85.41583	18.89768	512.3	-19.8	1.79	17.35	5.0	0.14	12.8		28	24	47
HD8	85.45442	18.86233	1192.3	-19.9	1.49	22.1	4.9	0.13	11.8	9.1	32	19	49
MS5	86.68162	19.8398	282.3	-21.0	1.10	43.3	5.3	0.08	14.2	14.3	27	28	45
MS6	86.7007	19.79933	523.5	-20.7	1.25	29.75	6.1	0.08	14.9	7	34	19	47
MS7	86.7223	19.75427	772.4	-20.5	1.23	30.6	5.9	0.10	12.9	10.4	26	28	46
MS8	86.76162	19.68682	1012.4	-20.6	1.34	32.55	5.6	0.11	12.6	8.7	27	28	45
MN5	87.23997	20.1163	289.1	-21.4	1.06	90.95	6.0	0.08	13.1	31.8	35	18	47
MN6	87.2631	20.09043	509.2	-21.0	1.26	52.05	5.2	0.11	12.0	10.7	31	20	49
MN7	87.29968	20.04147	756.9	-20.5	1.26	52.75	5.5	0.11	11.5	10.5	30	21	49
MN8	87.35322	19.96558	1045.2	-20.3	1.38	28	5.1	0.11	12.2	14.7	30	20	50
<i>Plant samples from Godavari drainage basin</i>													
C ₃ plants			-	-25.3		-	3.6			-	-	-	-
C ₄ plants			-	-13.0		-	5.4			-	-	-	-

Table 1