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V Ramaswamy
National Institute of Oceanography, India

Birgit Gaye
University of Hamburg

P V. Shirodkar
National Institute of Oceanography, India

P S. Rao
National Institute of Oceanography, India

Allan Chivas
University of Wollongong, toschi@uow.edu.au

See next page for additional authors

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Total organic carbon (TOC), total nitrogen (TN) and their $\delta^{13}C$ and $\delta^{15}N$ values were determined from 110 sediment samples from the Ayeyarwady (Irrawaddy) continental shelf, northern Andaman Sea to decipher the concentration and source of organic matter. Comparatively higher TOC and TN concentrations are found in the inner-shelf mud belt, and on the continental slope sediments, whereas the outer-shelf sediments, composed mostly of relict sands, are low in TOC. The TOC contents are positively correlated with the abundance of fine-grained sediments. The TOC:TN ratios and $\delta^{13}C$ and $\delta^{15}N$ values show low variability within the modern inner-shelf mud belt and Gulf of Martaban, indicating similar source. The TOC:TN ratios are mostly between 6 and 8 in the inner-shelf mud belt and these values are similar to the suspended sediments in the Ayeyarwady and Salween rivers. The $\delta^{13}C$ values of organic matter increase from − 25‰ in the Gulf of Martaban to about − 22‰ in the slope regions indicating decreasing terrestrial input away from the coast. The $\delta^{15}N$ values on the Ayeyarwady shelf are rather low (+ 3.3 to + 4.8‰), especially off the mouths of the Ayeyarwady River mouths, reflecting greater influence of freshwater and terrigenous sediment discharge. A simple two end-member carbon mixing model applied to the Ayeyarwady shelf region indicates that terrigenous sources contribute more than 70% of the organic carbon in the modern mud belt in the inner shelf and Gulf of Martaban. Terrigenous organic carbon percentages reduce gradually offshore, reducing to less than 60% near the continental shelf edge. A strong terrigenous signal is preserved in the inner shelf and Gulf of Martaban sediments probably because organic matter from the source region is not subject to intensive processing and replacement in the floodplains and deltaic regions as well as rapid burial at sea.

Keywords

GeoQUEST

Disciplines

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Authors

V Ramaswamy, Birgit Gaye, P V. Shirodkar, P S. Rao, Allan Chivas, David J. Wheeler, and Swe Thwin

Distribution and sources of organic carbon, nitrogen and their isotopic signatures in sediments from the Ayeyarwady (Irrawaddy) continental shelf, northern Andaman Sea

V. Ramaswamy[a]* , Birgit Gaye[b], P.V. Shirodkar[a], P.S. Rao[a], Allan R. Chivas[c], David Wheeler[c], Swe Thwin[d].

[a] National Institute of Oceanography, Dona Paula, Goa 403004, India

[b] Institute of Biogeochemistry and Marine Chemistry, University of Hamburg,
Bundesstraße 55, D-20146 Hamburg, Germany

[c] GeoQuEST Research Centre School of Earth and Environmental Sciences,
University of Wollongong, NSW, 2522, Australia

[d] Department of Marine Science, University of Mawlamyine, Mawlamyine, Myanmar

*Corresponding author: Tel: +91 8322450429 Fax: +91 8322450602

E-mail address: rams@nio.org (V. Ramaswamy)

Abstract

Total organic carbon (TOC) and total nitrogen (TN) and their $\delta^{13}C$ and $\delta^{15}N$ values were determined from 110 sediment samples from the Ayeyarwady (Irrawaddy) continental shelf, northern Andaman Sea to decipher the concentration and source of the organic matter. Comparatively higher TOC and TN concentrations are found in the inner shelf mud belt, and on the continental slope sediments, whereas the outer shelf sediments, composed mostly of relict sands, are low in TOC. The TOC contents are positively correlated with the abundance of fine-grained sediments. The TOC:TN ratios and $\delta^{13}C$ and $\delta^{15}N$ values show low variability within the modern inner shelf mud belt and Gulf of Martaban, indicating similar source. The TOC:TN ratios are mostly between 6 and 7 in the inner shelf mud belt and these values are similar to the suspended sediments in the Ayeyarwady and Salween rivers. The $\delta^{13}C$ values of organic matter increase from -25‰ in the Gulf of Martaban to about –22‰ in the slope regions indicating decreasing terrestrial input away from the coast. The $\delta^{15}N$

values on the Ayeyarwady shelf are rather low (+3.3 to +4.8‰), especially off the mouths of the Ayeyarwady River mouths, reflecting greater influence of freshwater and terrigenous sediment discharge. A simple two end-member carbon mixing model applied to the Ayeyarwady shelf region indicates that terrigenous carbon constitutes about 80% of the organic carbon in the modern mud belt in the inner shelf and Gulf of Martaban reducing to less than 60 % near the shelf edge. A strong terrigenous is preserved in the inner shelf and Gulf of Martaban sediments probably because organic matter from the source region is not subject to intensive processing and replacement in the flood plains and deltaic regions as well as rapid burial at sea.

Key words: Ayeyarwady continental shelf, organic carbon, total nitrogen, stable isotopes, North Andaman Sea.

1. Introduction

Preservation of organic matter in coastal marine sediments is an important process in the global cycle of carbon and other bioactive elements as more than 90% of the carbon buried in the oceans occurs in continental margin sediments. (e.g., Berner, 1982; Hedges, 1992; Emerson and Hedges, 1988; Premuzic et al., 1982; Smith and MacKenzie, 1987; Hedges and Keil, 1995; de Haas et al., 2002; Goni et al., 1997; Walsh, 1991). In coastal regions, organic matter can be supplied both from marine and terrestrial sources. Better constraints on the sources of organic matter in marine sediments is needed to understand the processes responsible for its preservation (e.g. Keil et al., 1997; Hedges and Keil, 1995; Mayer, 1994; Calvert and Pedersen, 1992; Tyson, 1995;). Stable carbon and nitrogen isotope ratios ($\delta^{13}C$ and $\delta^{15}N$, respectively) and TOC: TN ratios have been widely used to elucidate the source and fate of organic matter in the marine environment (Hedges and Parker, 1976; Peters et al., 1978; Torgersen and Chivas, 1985; Wada et al., 1987; Thornton and McManus, 1994; Ogawa and Ogura, 1997; Gordon and Goni, 2003; Goni et al., 2003; Wu et al., 2007; Zhang et al., 2007) and also as a proxies in paleoclimatic studies (Chivas et al., 2001; Lamb et al., 2006). Continental margin sediments are significant sites for organic carbon burial because they have high sedimentation rates and biological productivity. Off major river mouths, continental margins also receive significant amounts of organic matter of terrestrial origin (Hedges and Keil, 1995; de Haas et al., 2002). Some studies show that fluvial terrigenous organic carbon is currently deposited primarily on the inner continental shelves (eg. Hedges and Parker, 1976) while other investigations (e.g., Bauer and Druffel, 1998; Gagosian et al., 1987; Prahl and Muehlhausen, 1989; Ramson et al., 1998; Schlunz et al., 1999; Galy et al., 2007) indicate that a significant amount of the organic matter delivered to continental slope and deep-sea pelagic sediments is of terrestrial origin.

The worlds 10 largest rivers contribute about 40% of the organic carbon burial in deltaic and coastal environments (Meybeck, 1982; Hedges and Kiel, 1995), There is a need to evaluate the terrestrial contribution of organic matter to the ocean sediments from different oceanic settings particularly off major rivers which deliver huge amounts of freshwater and sediments to the ocean (Nittrouer et al., 1995). The Himalayan rivers are particularly important as high rainfall and erosion rates in the source regions generate high sedimentation rates in continental margins leading to higher burial efficiency of organic matter in the oceans (Galy et al., 2007).

At present, the Ayeyarwady (formerly known as Irrawaddy) is the third largest river in the world in terms of suspended sediment discharge and together with the Salween (also known as Thanlwin) contributes annually more than 600 MT of sediment (Robinson et al., 2007). The Ayeyarwady-Salween river system transports 5.7–8.8 MTC y^{-1}r of organic carbon, suggesting that presently it may be the second largest point source of organic carbon to the global ocean after the Amazon (Bird et al., 2007).

The Ayeyarwady delta and inner-shelf mud belt is a potentially major repository of carbon of global significance, yet there is very little information available on organic matter distribution in this region. The main objectives of the present study are to map the distribution of organic carbon and nitrogen on the Ayeyarwady shelf and to determine the factors controlling their distribution and accumulation. The relative contribution of allochthonous (terrigenous) and autochthonous (marine plankton) sources of organic matter is assessed by using TOC:TN ratios and isotopic signatures of C and N.

2. Material and methods

2.1 Study Area:

The Ayeyarwady continental shelf is part of a complex geological setting in the Andaman Basin (Curray et al., 1979). The shelf width is about 170 km off the Ayeyarwady River mouths and increases to more than 250 km in the centre of the Gulf of Martaban (Fig. 1). A N–S trending 120 km wide bathymetric depression is present towards the southern end of the continental shelf and the Martaban submarine canyon lies within this depression (Rao et al., 2005).

Sediment dispersal on the Ayeyarwady continental shelf is strongly dependent on tidal currents and the seasonally reversing monsoon currents (Ramaswamy et al., 2004; Rao et al., 2005). The northern Indian Ocean, including the Andaman Sea and Gulf of Martaban, is characterized by the seasonally reversing Asian monsoon (Wyrtki, 1973). The southwest monsoon is active between mid-May and the end of September while the northeast monsoon is active between December and February. In response to the monsoons, the oceanic flow in the Andaman Sea changes direction twice a year with a cyclonic flow in spring and summer and anti-cyclonic for the rest of the year (Potemra et al., 1991). Tidal ranges in the Gulf of Martaban are around 6 m (Indian Tide Tables, 2002). The highest tidal range of nearly 7 m is recorded in the western Gulf of Martaban. The mouths of the Ayeyarwady River have a tidal range between 2 and 4 m while the lower Rakhine coast (west coast of Myanmar) has a tidal range less than 2 m. During spring tide, tidal currents of 2.5–3 m s^{-1} have been observed in the Gulf of Martaban (Bay of Bengal Pilot, 1978).

The main source of freshwater and suspended sediment to the northern Andaman Sea is from the Ayeyarwady and Salween Rivers which have a length of ~2000 and

~2800 km respectively. Minor contributions are from the Sittang and Tavoy rivers. The Salween has virtually no flood-plain while the Ayeyarwady has an extensive floodplain and large delta having substantial cover of mangrove swamps. The Ayeyarwaddy annual freshwater discharge is 411 ± 53 Km^3 which transports between 226 to 334 million tons (MT) of suspended sediment. More than 90% of the freshwater and suspended load is delivered between mid-June and mid-November. The annual freshwater flux of Salween river is approximately 211 km^3, which transports 188–206 MT of suspended load (Bird et al., 2007; Robinson et al., 2007), with smaller rivers like the Sittang located close to the coast between the Ayeyarwady and Salween transporting an additional 47 $km^3 y^{-1}$ of water and 27–43 MT of sediment (Robinson et al., 2007). The Ayeyarwady transports 2.2–4.3 million tons carbon (MTC) every year as particulate organic carbon (POC) while the Salween transports an additional 2.4–3.4 MTC y^{-1}. The high organic carbon yields are likely to be the result of (i) a strongly monsoonal climate, (ii) the large area of highly productive forest present on steep slopes in a region of active tectonism, and (iii) the comparatively small area of floodplain in the catchments.

The $\delta^{13}C$ values of POC range between -24.1‰ to -25.8‰ for the Ayeyarwady with a weighted average $\delta^{13}C$ value of -24.8‰. The source of POC to this river is mainly from forest and alpine C3 carbon during lean flow season and is augmented with C4 savannah vegetation from the central arid plains during the high flow season. The $\delta^{13}C$ of Salween has a narrower range between -25.0 and -25.8 during high and low flow seasons.

The Ayeyarwady continental shelf and the Gulf of Martaban are covered by a modern inner-shelf mud belt while the outer shelf is covered with relict sands and carbonates (Rodolfo, 1969; Rao et al., 2005). Because of the macro-tidal setting, high suspended sediment concentration is a perennial feature in the Gulf of Martaban and Ayeyarwady continental shelf (Ramaswamy et al., 2004). Major changes in suspended sediment concentrations (SSC) on the Ayeyarwady shelf are related to spring-neap tidal cycles with a maximum aerial extent of the turbid zone (45,000 km^2) during spring tide and minimum (~15,000 km^2) during neap tide. Most of the suspended sediment discharged by the Ayeyarwady River is transported eastward and deposited in the Gulf of Martaban. A smaller fraction is transported into the eastern Bay of Bengal from October to December. Evidence of suspended sediment transport as bottom flows directly into the deep Andaman Sea via the Martaban Canyon is also seen (Ramaswamy, 2004).

2.2 Sample collection

A hundred and ten surface sediment and cores-top samples, collected from the Ayeyarwady continental margin shelf and adjoining areas during the low river discharge period of April–May 2002 (Fig. 1), were chosen for this study. The spacing between sampling stations was generally 25 km. The stations were restricted to water depths greater than 20 m except for five samples collected on the way to and returning from Yangon Port. Representative samples of sediments from grab and core tops were collected in plastic bottles and immediately stored in a cold room between 2ºC and 4ºC. A small aliquot of the sample was dried onboard at 45ºC in a hot-air oven and stored in sealed plastic bags for further analysis.

2.3 Organic carbon and total nitrogen analysis:

The samples were ground to a fine powder with an agate pestle and mortar and carbonate abundances determined by a digital gasometer (precision ±1%). Total carbon and nitrogen percentages were measured by a Carlo Erba Nitrogen Analyser 1500 (Milan, Italy). The precision of this method is 0.05% for carbon and 0.005% for nitrogen. Organic carbon was calculated as the difference between total and carbonate carbon.

2.4 Stable isotopes

The $\delta^{15}N$ values were determined using a Finnigan MAT 252 mass spectrometer after high-temperature flash combustion in a Carlo Erba NA-2500 elemental analyzer at 1100°C. Pure tank N_2 calibrated against the reference standards International Atomic Energy Agency IAEA-N-1 and IAEA-N-2 was used as a working standard. The $\delta^{15}N$ is given as the per mil deviation from the N-isotope composition of atmospheric N_2. Analytical precision was better than 0.1 ‰ based on replicate measurements of a reference standard. Duplicate measurements of samples resulted in a mean deviation of 0.2 ‰. The $\delta\ ^{13}C$ was measured after removal of carbonate with 1N hydrochloric acid and is given as the per mille deviation from the isotopic composition of the PDB standard. Working standards were IAEA-CH6 and saccharose with a $\delta\ ^{13}C$ of -26.3 ‰. Replicate measurements had mean deviations of 0.2 ‰ for the standards and 0.3 ‰ for samples.

3. Results

3.1 Total organic carbon (TOC) and total nitrogen (TN) distribution and ratios

The TOC(%), TN (%), TOC:TN ratios are presented in Table 1, and their spatial variation on the Ayeyarwady shelf are shown in Figures 2 to 4. TOC shows a wide range between 0.07 to 1.40% except for one sample which has a TOC concentration of 2.66%. TN values also show a wide range (0.01 to 0.23%) and a distribution pattern similar to TOC. The lowest values of TOC and TN are found in the outer shelf relict sands (TOC of 0.18 to 0.5%) and higher values on the continental slope and inner shelf silty clays. Elevated TOC (> 0.75%) and TN content are found at the head of the Martaban canyon. TOC > 0.75% is also found off the Tavoy River. TOC:TN ratios range between 7 and 9 off the Rakine coast (Fig. 4). Off the Ayeyarwady river mouths and Gulf of Martaban TOC:TN ratios values lie mostly between 6 and 8 with a few values between 8 and 9. On the south-eastern part of the study area their values are much higher and range between 9 and 20.

3.2 Carbon and nitrogen isotopes

The $\delta^{13}C$ values on the Ayeyarwady shelf vary mostly between -21 and -25‰ except for one sample which is less than -21‰ and 4 samples greater than -25‰ (Fig. 5, Table 1). The highest $\delta^{13}C$ values are found in continental slope sediments whereas the lowest values are found near the river mouth of the Ayeyarwady and in the Gulf of Martaban. The $\delta^{15}N$ values showed a spread between +3.4 and +5‰ (Fig. 6). The lowest values are found off the mouths of the Ayeyarwady River.

4. Discussion

4.1 Distribution of organic matter on the Ayeyarwady continental margin.

The range of TOC (0.4 to 1%) on the Ayeyarwady shelf is similar to those found off major rivers in high tidal regimes like the Amazon, Changjiang, Pearl River etc. (Showers and Angle, 1986; Schlunz et al., 1999; Wu et al., 2003; Hu et al., 2006). In the study area, higher organic matter contents are associated with fine-grained sediments in the inner shelf mud-belt and on the continental slopes. A good correlation is seen between the proportion of the mud fraction (silt and clay) and TOC content (Fig 7). Organic matter is known to be associated with fine-grained sediments because of the larger surface area which provides good binding sites for organic matter (Kiel et al., 1994; Mayer, 1994). In the adjacent Bay of Bengal Fan sediments higher carbon content is associated with fine-grained sediments but the organic carbon is mostly in the form of organic particles or aggregates protected by terrigenous mineral matrix (Galy et al., 2007; 2008). The relict-sand dominated outer-shelf areas on the Ayeyrawady shelf has low TOC and TN content. Areas of localized higher TOC and TN contents in the Martaban Canyon imply a pathway for channeling fine-grained sediments and associated organic matter from the Ayeyarwady shelf to the deep-sea. In high energy environment, like the Gulf of Martaban and off the Ayeyarwady River mouths, TOC and TN concentrations are comparatively low because of dilution by the high supply of terrigenous material and oxidation of part of the organic matter due to constant tidal resuspension. (Fig 2).

4.2 Source of organic matter on the Ayeyarwady shelf:

4.2.1 TOC:TN ratios:

The TOC:TN of undegraded marine phytoplankton is generally close to 6.7 while vascular plants are N-depleted and have TOC:TN ratios exceeding 12 (Hedges et al., 1997; Tyson, 1995; Meyers 1994; Lamb et al., 2006). Terrestrial plant material can have a wide range of TOC:TN ratios; characteristic ranges are 175-400 for wood, 20-50 for tree leaves, and 25-80 for grass and herbaceous plants (Hedges, et al., 1986). On the Ayeyarwady shelf, the range for TOC:TN ratios (between 5 and 14) is much lower than that of terrestrial plants and more similar to marine organic particles. The inner shelf and Gulf of Martaban sediments, where the maximum river influence and terrigenous contribution is expected, the TOC:TN ratios are close to or lower than the Redfield ratio for marine plankton. Sediments with TOC:TN ratios lower than the Redfield Ratio have been reported from other tropical river mouths (Ruttenberg and Goni, 1997; Wu et al., 2003; Hu et al., 2006). The low TOC:TN ratios in these areas have been ascribed to anthropogenic influence or natural causes like preferential sorption of inorganic N or a bacterially derived component of organic matter in the sediment (Ruttenberg and Goni; 1997). In marine sediments, normally N is preferentially remineralised leading to an increase in TOC:TN ratios. However, in N-rich coastal environments, the TOC:TN ratio can decrease due to N immobilization to supply the relative N-deficit in sediments (Tyson, 1995). The comparatively low TOC:TN ratio in the Ayeyarwady shelf could also be due to supply of suspended sediments having low TOC:TN ratios by rivers. Bird et al., (2007) observed low TOC:TN in the Ayeyarwady (6 to 10) and Salween (9 to 14) rivers. Summer monsoon wet season TOC:TN ratios of the Salween are comparatively lower and similar to the Ayeyarwady. Low TOC:TN ratios in these rivers have been ascribed to higher portion of soil-derived organic carbon. Algal-derived carbon, which has a higher C:N ratio, is likely to be a minor component of POC due to the turbid conditions that exist throughout the wet and dry seasons in both rivers. Hedges and

Oades (1997) also suggest that soils organic matter derived from soils can have low TOC:TN ratios because soil microbes are nitrogen rich and bacterial and fungal dominated populations can have TOC:TN ratios of 5:1 and 15:1 respectively.

4.2.2 Distribution of $\delta^{13}C$ values of TOC

The $\delta^{13}C$ value of marine particulate organic matter typically range from -22‰ to -18‰ (Peters et al., 1978; Wada et al., 1987; Middelburg and Nieuwenhuize, 1998) while fluvial $\delta^{13}C$ is a mixture of freshwater phytoplankton (-25 to -30‰) and particulate terrestrial organic matter (-25 to -33‰) (e.g. Salomons and Mook, 1981; Barth et al., 1998; Middelburg and Nieuwenhuize, 1998). Typical fluvial organic carbon has $\delta^{13}C$ values between –24 and –28‰ (Lamb et al., 2006; Raymond and Bauer, 2001)).

The spatial distribution of $\delta^{13}C$ values of TOC in the Ayeyarwady shelf sediments (Fig. 5) indicate a significant terrestrial source, the influence of which decreases steadily away from the coast. The entire shelf, having a width of more than 170 km, shows TOC $\delta^{13}C$ values distinctly depleted compared to typical marine values indicating influence of terrestrial organic matter over the entire continental shelf. The lowest $\delta^{13}C$ values, in the Gulf of Martaban are similar to that of the Ayeyarwady and Salween rivers (Table 1).

4.2.3 Distribution of $\delta^{15}N$: values of TN

Marine organic matter usually has mean $\delta^{15}N$ values of 5 to 7 as derived from phytoplankton which normally use dissolved nitrate (Brandes and Devol, 2002; Lamb et al., 2006; Altabet, 1996). Some marine phytoplankton like *Trichodesmium* use nitrogen fixed from the atmosphere, hence the $\delta^{15}N$ value of the organic matter derived from them is close to zero (Altabet, 1996). Organic matter derived from nitrogen fixing land plants has $\delta^{15}N$ values around zero, whereas plants using only mineral N from soil ($NO3^-$ or $NH4^+$) have usually positive $\delta^{15}N$ values . The range of $\delta^{15}N$ values in the Ayeyarwady continental margin sediments (Fig. 6) is distinctly lower than normally found in typical marine sediments (5-7‰).

The main reason for the low $\delta^{15}N$ values of TN in the study area is probably because of input of river suspension having low $\delta^{15}N$ values as well as biological assimilation of low $\delta^{15}N$ riverine dissolved organic and inorganic nitrogen by marine organisms. This is supported by the fact that lowest $\delta^{15}N$ values are observed off the Ayeyarwady River mouth and in low productivity mid-shelf areas. The macro-tidal and highly productive Gulf of Martaban has comparatively higher $\delta^{15}N$ values (between 4 and 5‰) compared to the river mouths of the Ayeyarwady ($\delta^{15}N$ values <4‰; Fig 6). Literature survey shows that the $\delta^{15}N$ values of TN in sediments from the equatorial Indian Ocean and southern Bay of Bengal are close to mean oceanic values, but $\delta^{15}N$ values in the northern part of the Bay of Bengal are relatively low, which could be due to the enormous river input (Schafer and Ittekkot, 1995; Gaye-Haake et al., 2005; Unger et al., 2006). River suspension can have quite variable $\delta^{15}N$ values (Maksymowska et al., 2000) and generally, they are lower than oceanic values (Altabet, 1996). River-derived suspended matter collected off the mouth of Ganges-Brahmaputra during November/December 1997 had $\delta^{15}N$ values of +3.7 to +3.8‰ (Unger et al., 2006), which is in the range of other tropical rivers (Jennerjahn et al., 2004). We are not aware of any systematic study or reports of $\delta^{15}N$ values of the Ayeyarwady River. Analysis of a few samples of bedload and suspended sediments in the estuarine part of Salween and Yangon River (a distributary of the Ayeyarwady River), collected during peak discharge periods, show $\delta^{15}N$ values between 3.3 and 4.3‰ (Table 1). Low $\delta^{15}N$ in these rivers could be due to contributions from forest and soil nitrogen as terrestrial plant ecosystems have low $\delta^{15}N$. During the cruise we observed a huge bloom of *Trichodesmium* covering an area of more than 10000 km^2 on the Ayeyarwady shelf (Unpublished cruise report of Sagar Kanya Cruise – SK175) and the contribution of these nitrogen fixing blooms to the δ15N values in the Ayeyarwady sediments needs to be assessed.

4.2.4 Terrestrial carbon

To assess the relative proportions of terrestrial and marine organic carbon present in the sediments a simple $\delta^{13}C$-based two end-member mixing model based on the model derived by. Calder and Parker (1968) and Schultz and Calder (1976); taken from Hu et al., (2006) and Schlunz et al., (1999) has been applied to this region. The equation used is as follows.

$$\text{TC \%} = \frac{\delta^{13}C_{\text{marine}} - \delta^{13}C_{\text{org}}}{\delta^{13}C_{\text{marine}} - \delta^{13}C_{\text{terrestrial}}} \times 100$$

Where TC is the terrestrial carbon
$\delta^{13}C_{\mathbf{org}}$ is the measured $\delta^{13}C$ of a given sample
$\delta^{13}C_{\mathbf{marine}}$ is the marine end member = -20.5‰
$\delta^{13}C_{\mathbf{terrestrial}}$ is the terrestrial end member = -27‰

The TOC:TN ratios and $\delta^{15}N$ values are not considered in the estimation of the terrigenous contribution to marine organic matter because they correlate very poorly with $\delta^{13}C$ (Fig. 8). The marine end-member was taken as -20.5 ‰ (average value of marine POM -19 to -22‰) which is close to average $\delta^{13}C$ values of core tops in deep Andaman Sea range (range between -19.99 and -21.2‰ with a average of -20.55‰ Fontugne and Duplessy, 1986). Calculations made with marine end member values between 20 and 21‰ does not show significant changes with variations less than 5%. The mixing equation is however, very sensitive to the $\delta^{13}C$ value of the terrigenous end member which can vary considerably for various Himalayan rivers; between -20.3‰ for the Ganges (Aucour et al., 2006) and -28‰ for the Changjiang (Zhang et al., 2007). The terrigenous end member was taken as -25.1 ‰ which is the average of the $\delta^{13}C$ values of POC of Ayeyarwady and Salween rivers (Bird et al., 2007). Equal weightage was given to both the rivers as the POC contribution from both the rivers are similar (Bird et al., 2007).

Contours of terrestrial organic carbon (TC) (Fig. 9) show that the Ayeyarwady shelf is dominated by terrestrially derived carbon with more than 80% of the organic carbon in the Gulf of Martaban and inner shelf sediment is derived from land. There is a gradual decrease of terrigenous contribution away from the coast, and deep-water continental slope sediments have terrigenous carbon less than 60%. The terrigenous contribution is relatively higher on the eastern side of the continental shelf showing that most of the sediment and terrigenous POC transport is towards the south and east.

A strong terrestrial organic carbon source is seen in the inner shelf and Gulf of Martaban sediments because of the rapid burial of the fluvial carbon due to high sedimentation rates (Rodolfo, 1969; Rao et al., 2005) and refractory nature of fluvial terrestrial carbon which is dominated by soil carbon (Bird et al., 2007). Perennial turbidity in the Gulf of Martaban and off the river mouths of the Ayeyarwady due to (Ramaswamy et al., 2004) hinder marine productivity and enhance the terrestrial carbon signature. On the outer shelf and continental slope, sedimentation rates are comparatively low and the marine contribution becomes more dominant. On the Ayeyarwady shelf, processes favoring high terrestrial carbon accumulation are rapid burial due to high sedimentation (Rao et al., 2005) and high turbidity near the river mouth and Gulf of Martaban (Ramaswamy et al., 2004) which suppresses marine productivity. The seasonal supply of sediment and organic matter to the continental shelf during summer monsoon should enhance preservation of carbon due to rapid burial as more than 80% of the annual POC and sediment fluxes are delivered to sea during the summer monsoon period between June and September.

4.2.5 Comparison with other continental shelves

The POC contribution of the Ayeyarwady-Salween river systems is comparable to large rivers like Amazon, Ganges-Brahmaputra and Changjiang (Bird et al., 2007). Like the other large rivers, the Ayeyarwady and Salween originate in tectonically active high mountainous regions having high erosion rates with the source region being dominated by C3 plants.

In many large rivers, the carbon from the source region undergoes substantial modifications in the flood plains (Blair et al., 2004; Galy et al., 2008). POC of Chinese rivers originating in the Himalaya, like Yangtse, Pearl, etc. are dominated by

C3 plants near the source region (Wu et al., 2007, Zhang et al., 2007). However, contribution from deltas (C4 plants salt marshes) and urbanization has lead to elevated $\delta^{13}C$ values by 2 to 4‰. Similarly, the Ganges-Brahmaputra has elevated $\delta^{13}C$ values and lower C3 plant contribution due to significant recycling of the organic carbon pool during the deposition-erosion cycles in the plain (Aucour et al., 2006; Galy et al., 2008). The catchment area of the Amazon is from highly forested regions dominated by C3 plants in the uplifted terrain of the Andes which is augmented by 10% of C4 plants and is further extensively processed in the floodplains before discharge to the sea . The organic matter in the AS differs from the other major rivers in having a higher C3 dominated forest and soil carbon with comparatively low processing or replacement by floodplain or deltaic carbon (Bird et al., 2007). The Salween does not have a significant deltaic or floodplain contribution as it flows mostly in narrow gorges while the flood plain of the Ayeyarwaddy is located in a tectonically active central arid plain with relatively low sediment contribution from floodplain albeit contribution from C4 plants during the monsoon. Another major difference is the comparatively low anthropogenic carbon contribution of the Ayeyarwady and Salween due to low population, agriculture and industrialization.
The AS contrast strongly with GB or Changjian where the river flows through some of the densely populated and heavily agricultural regions of the world. Overall the $\delta^{13}C$ values of the AS rivers are enriched compared to the Changjiang or Amazon due to predominance of soil carbon but is distinctly depleted compared to the Ganges-Brahmaputra river systems.

A number of studies have shown that continental margins, especially the inner-shelf mud belt are significant repositories or terrestrial organic matter. In the Amazon and Changjian continental shelf, terrestrial carbon dominance can be seen for a distance of about a few hundred km from the river mouth. Elevated organic carbon accumulation rates are observed within the Changjiang Estuary and inner shelf sediments on the East China Shelf due to the rapid burial of organic matter as a result of high fluvial sediment discharge (Deng et al., 2006). The average TOC content of superficial sediments on the Amazon shelf is 0.66 +_ 0.2% of which 69% is from terrestrial sources (Showers and Angle, 1986). On the inner shelf muds the core tops show δ^{13}C values of -26 to -23 with a sharp difference at -22 which is the boundary between modern muds and relict sands. The Amazon has a high terrigenous contribution of >85% near river mouth which decreases to around 60% 600 km away from river mouth (Showers and Angle, 1986). Due to modifications by shelf processs, terrestrial carbon is replaced by marine carbon (Aller and Blair, 2006). The Ayeyerwady shelf is similar to other large rivers in having high Ter OM in the inner shelf with decreasing terrigenous organic matter contribution away from the coast. Unlike the Amazon or Changjiang where the sediments are carried out along the shelf for long distances, a major portion of sediment deposited on the continental shelf and adjacent GOM (Rao et al., 2005). This leads to rapid burial and greater preservation of terrestrial carbon . The carbon accumulation pattern may be similar to the GB river system where high sedimentation rates limit the time terrestrial carbon spends in the upper layers (oxic and rapid turnover) of the sediments and help preserve the marine signature (Galy et al., 2007 2008).

5. Conclusions

The TOC:TN ratios, δ^{13}C and δ^{15}N values of organic matter show low variability within the modern mud belt of the Ayeyarwady continental shelf indicating a similar source. Organic matter content correlates well with grain size and comparatively higher organic matter content is present in the fine-grained inner shelf sediments and GOM and lower organic matter content in the outer-shelf relict sands . TOC:TN rations are less than 10 on the Ayeyarwady shelf and does not correlate well with δ^{13}C, the other proxy for terrestrial organic matter, because of differences in cycling of carbon and nitrogen in the oceans. δ^{15}N values are lower than typical marine values probably because of higher fluvial nitrogen input.

The inner shelf and GOM sediment have is dominated by terrestrial organic carbon (>80) delivered by the AS rivers whereas on the outer shelf the contribution of marine productivity derived carbon is dominant. Comparatively low rates of processing of soil carbon from the source region in floodplains and deltaic regions and rapid burial on the shelf leads to better preservation of terrestrial carbon in the continental shelf sediments. The burial efficiency of terrestrial carbon is enhanced by seasonal supply in sediment discharge and high turbidity in Gulf of Martaban which inhibits marine productivity. On the outer shelf and continental slope, the ter organic carbon is diluted by marine carbon, which is reflected in less depleted $\delta^{13}C$ values.

Acknowledgements

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List of Tables

Table 1. Station numbers, location, water depth, total organic carbon (TOC) and total nitrogen (TN) content, $\delta^{13}C$ and $\delta^{15}N$ values in surface sediment samples from the Ayeyarwady continental shelf, northern Andaman Sea. River values from bird et al. 2007.

Figure captions

Fig. 1. Sampling locations (black dots) overlain on a bathymetric map of the northern Andaman Sea and Gulf of Martaban. Contour values are in meters. Dashed line shows the approximate boundary between the inner shelf silty clays and the outer shelf relict sands.

Fig. 2. Spatial variation of total organic carbon content (TOC) in surface sediments of the Ayeyarwady continental shelf.

Fig. 3. Spatial variation of total nitrogen (TN) content in surface sediments of the Ayeyarwady continental shelf.

Fig. 4 Spatial variation in TOC:TN ratios in surface sediments of the Ayeyarwady continental shelf.

Fig. 5. Spatial variation in $\delta^{13}C$ values of TOC in surface sediments of the Ayeyarwady continental shelf.

Fig. 6. Spatial distribution of in $\delta^{15}N$ surface sediments of the Ayeyarwady continental shelf.

Fig. 7. Relationship between total organic carbon content and grain size in surface sediments of the Ayeyarwady continental shelf

Fig. 8. Correlation between a) TOC and TN b) $\delta^{15}N$ of TN and $\delta^{13}C$ of TOC and c) TOC:TN and $\delta^{13}C$ values, of sediments from the Ayeyarwady continental shelf.

Fig. 9 Spatial variation in proportion of terrigenous organic matter (in percent) on the Ayeyarwady continental shelf.

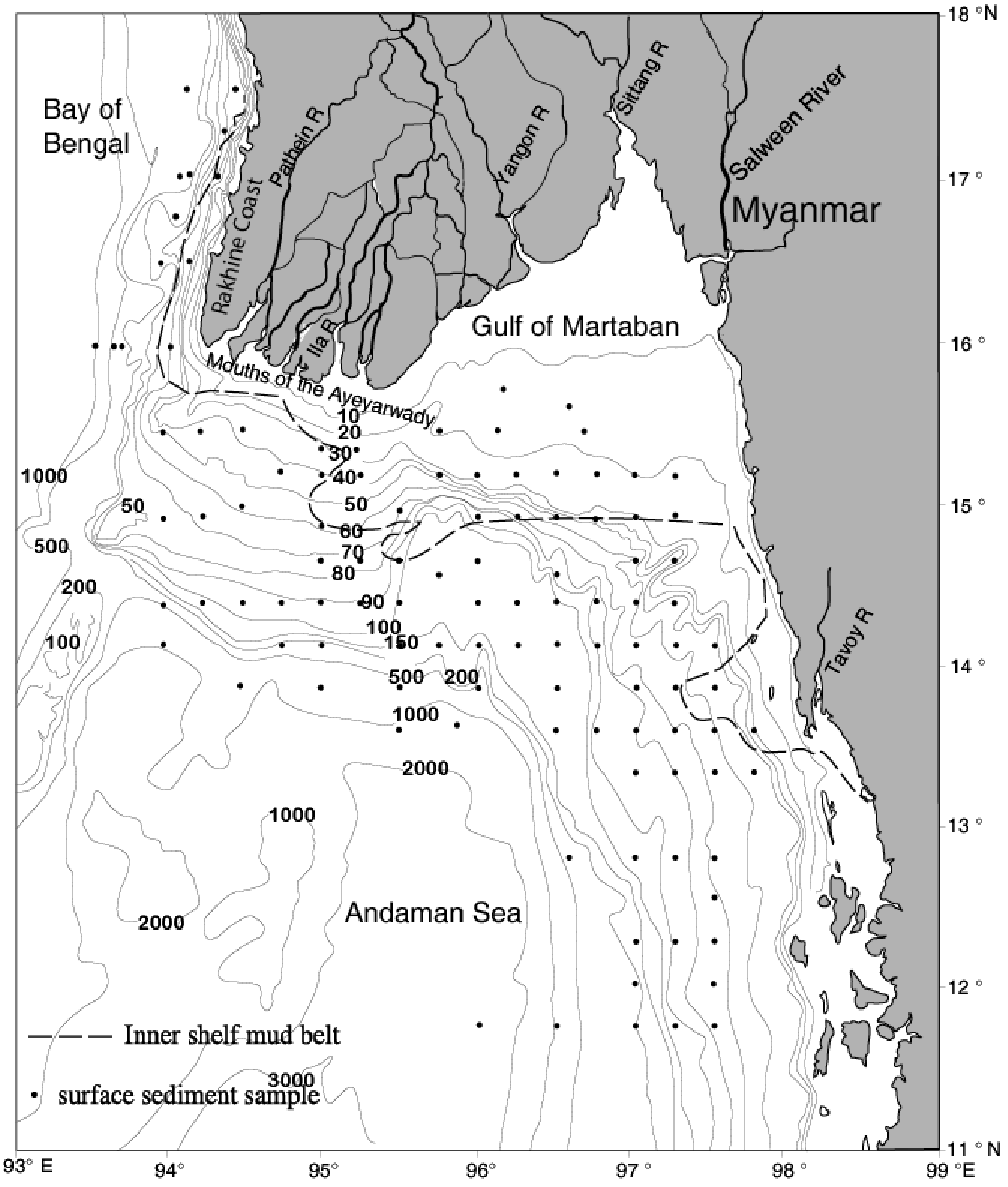

Bay of Bengal
Myanmar
Gulf of Martaban
Andaman Sea
Rakhine Coast
Pathein R
Ila R
Yangon R
Sittang R
Salween River
Tavoy R
Mouths of the Ayeyarwady
10
20
30
40
50
60
70
80
90
100
150
200
500
1000
2000
3000
Inner shelf mud belt
surface sediment sample
18 °N
17 °
16 °
15 °
14 °
13 °
12 °
11 °N
93° E
94°
95°
96°
97 °
98 °
99 °E

Fig. 1

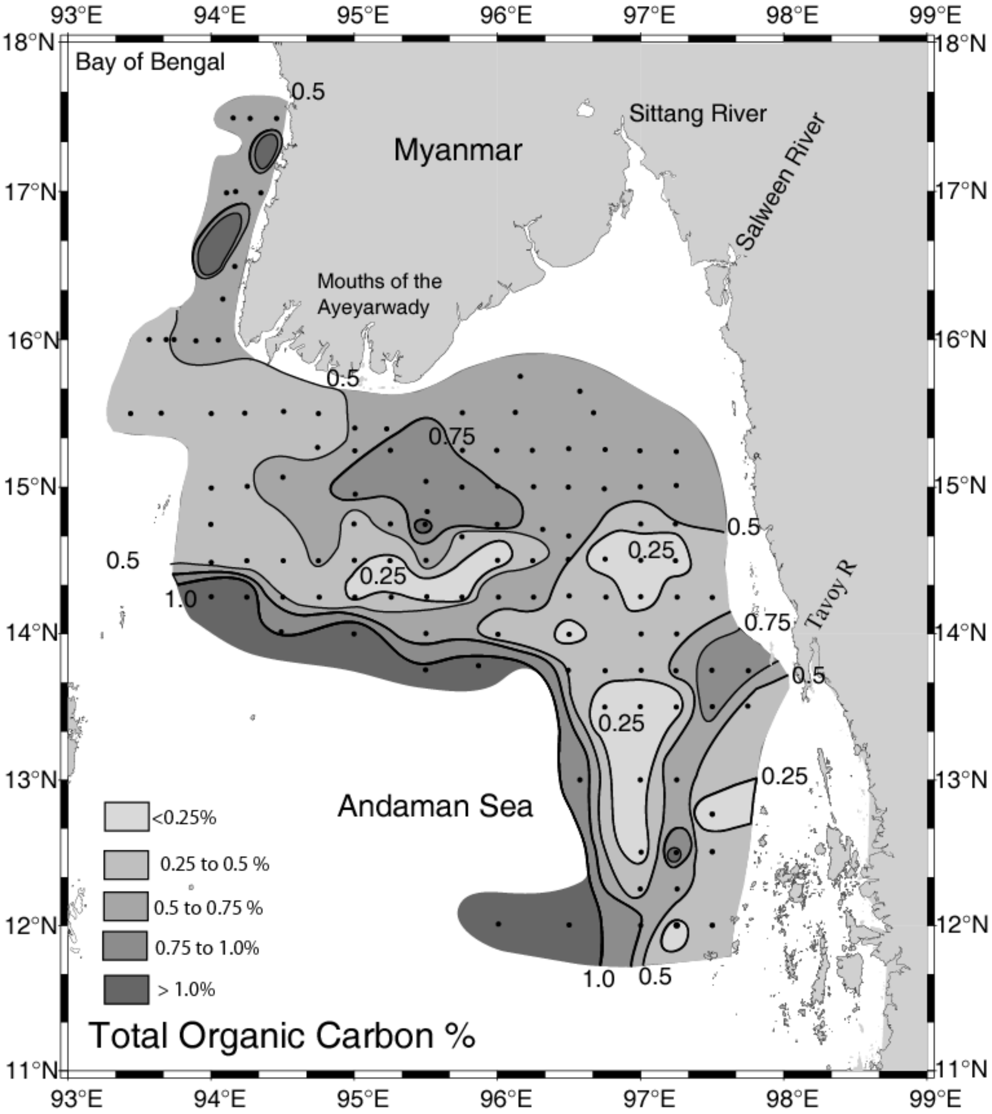

93°E
94°E
95°E
96°E
97°E
98°E
99°E
18°N
17°N
16°N
15°N
14°N
13°N
12°N
11°N
Bay of Bengal
Myanmar
Sittang River
Salween River
Mouths of the Ayeyarwady
Tavoy R
Andaman Sea
0.5
0.75
0.25
1.0
<0.25%
0.25 to 0.5 %
0.5 to 0.75 %
0.75 to 1.0%
> 1.0%
Total Organic Carbon %

Fig 2

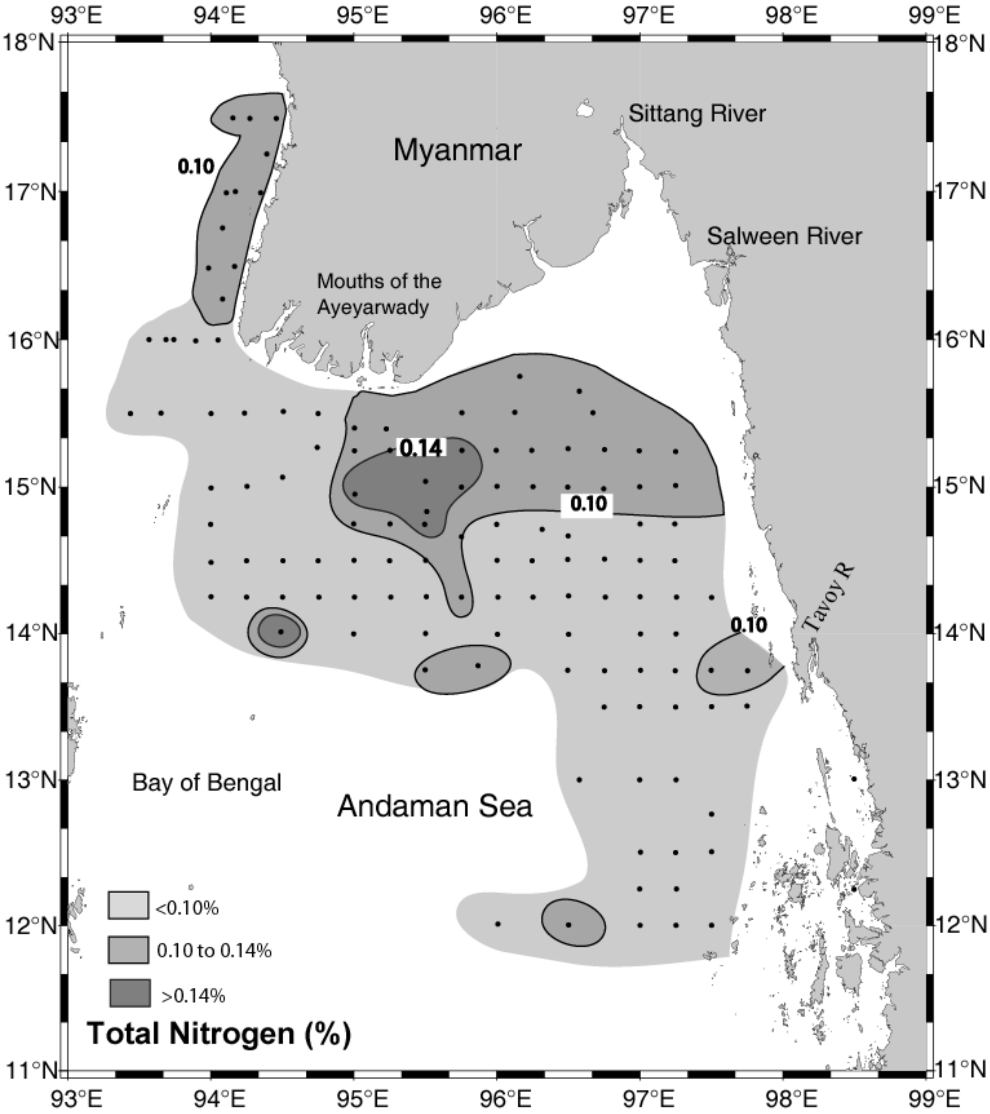
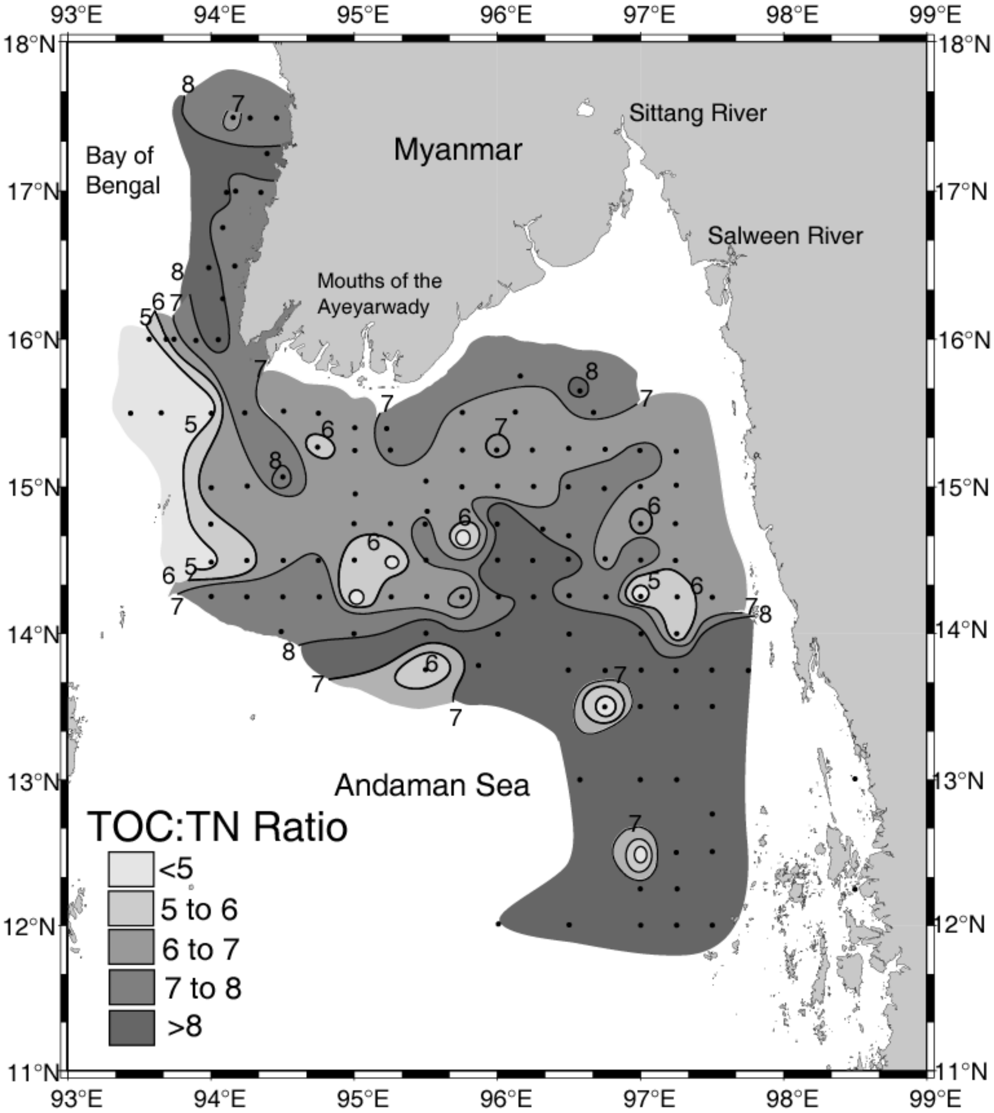

93°E
94°E
95°E
96°E
97°E
98°E
99°E
18°N
17°N
16°N
15°N
14°N
13°N
12°N
11°N
Myanmar
Sittang River
Salween River
Mouths of the Ayeyarwady
Tavoy R
0.10
0.14
0.10
0.10
Bay of Bengal
Andaman Sea
<0.10%
0.10 to 0.14%
>0.14%
Total Nitrogen (%)

Fig 3



93°E
94°E
95°E
96°E
97°E
98°E
99°E
18°N
17°N
16°N
15°N
14°N
13°N
12°N
11°N
Bay of Bengal
Myanmar
Sittang River
Salween River
Mouths of the Ayeyarwady
Andaman Sea
TOC:TN Ratio
<5
5 to 6
6 to 7
7 to 8
>8

Fig. 4

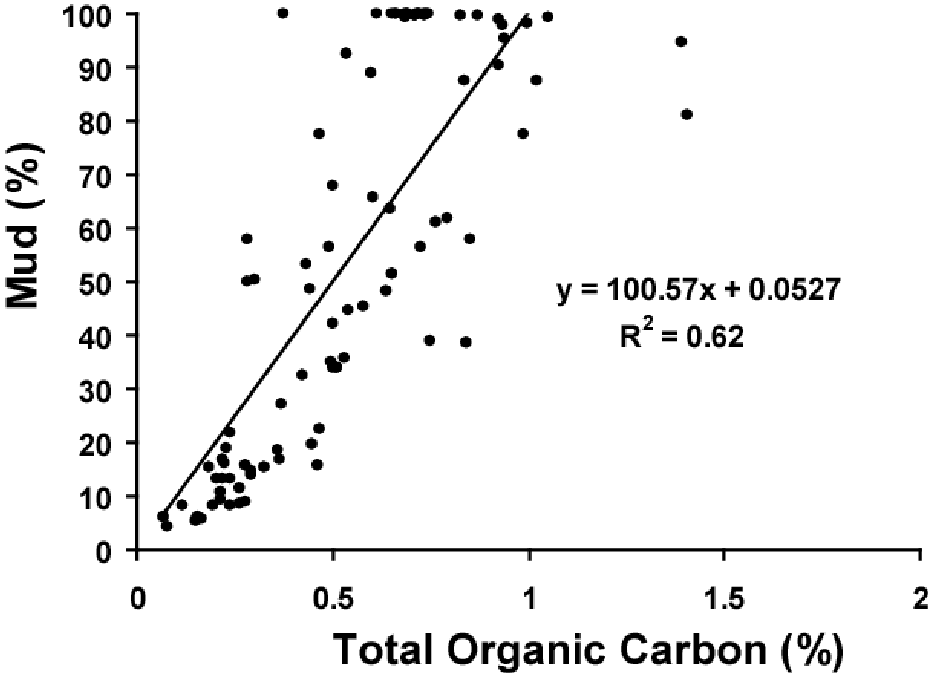
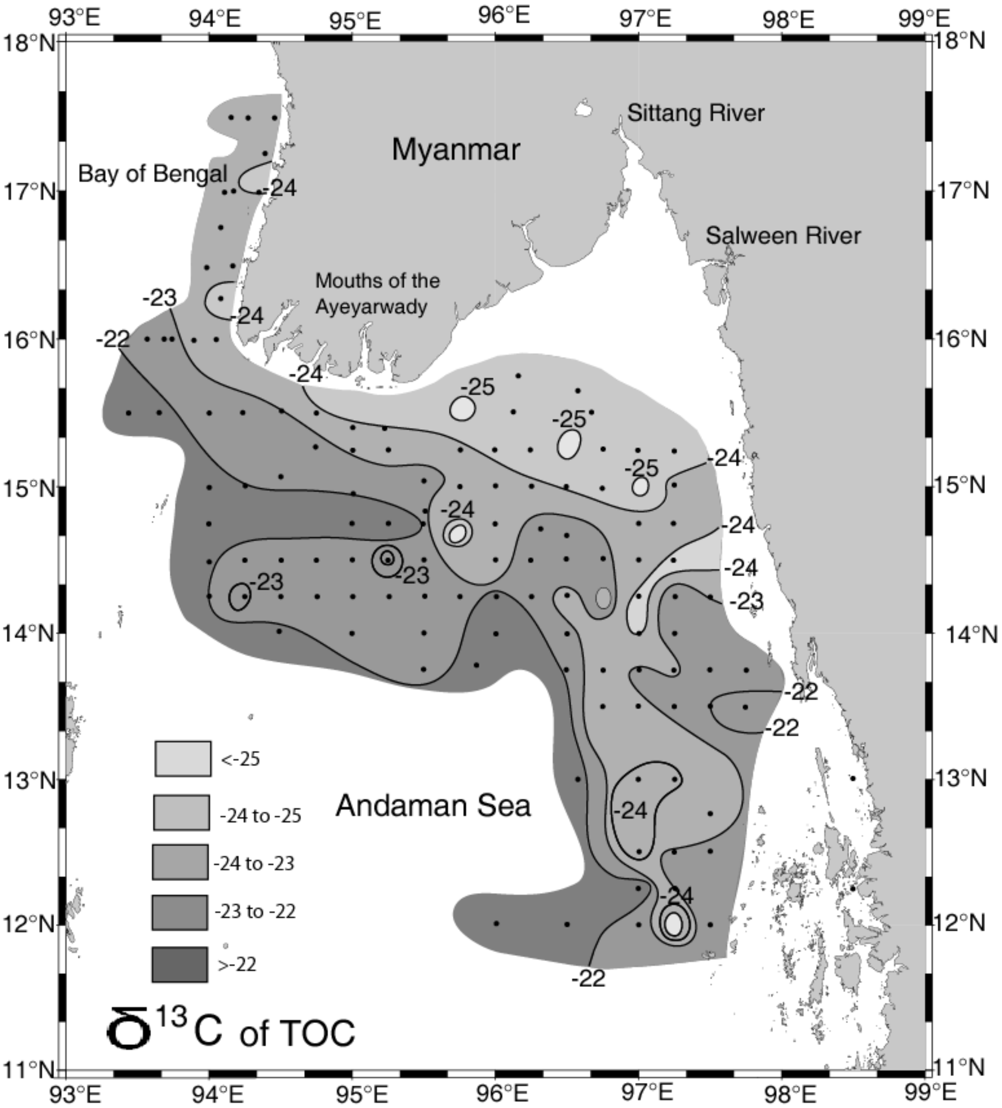

100
90
80
70
60
50
40
30
20
10
0
Mud (%)
0
0.5
1
1.5
2
Total Organic Carbon (%)
y = 100.57x + 0.0527
R2 = 0.62

Fig. 5


93°E
94°E
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15°N
14°N
13°N
12°N
11°N
Myanmar
Sittang River
Salween River
Bay of Bengal
Mouths of the Ayeyarwady
Andaman Sea
-22
-23
-24
-25
<-25
-24 to -25
-24 to -23
-23 to -22
>-22
δ^{13}C of TOC

Fig. 6

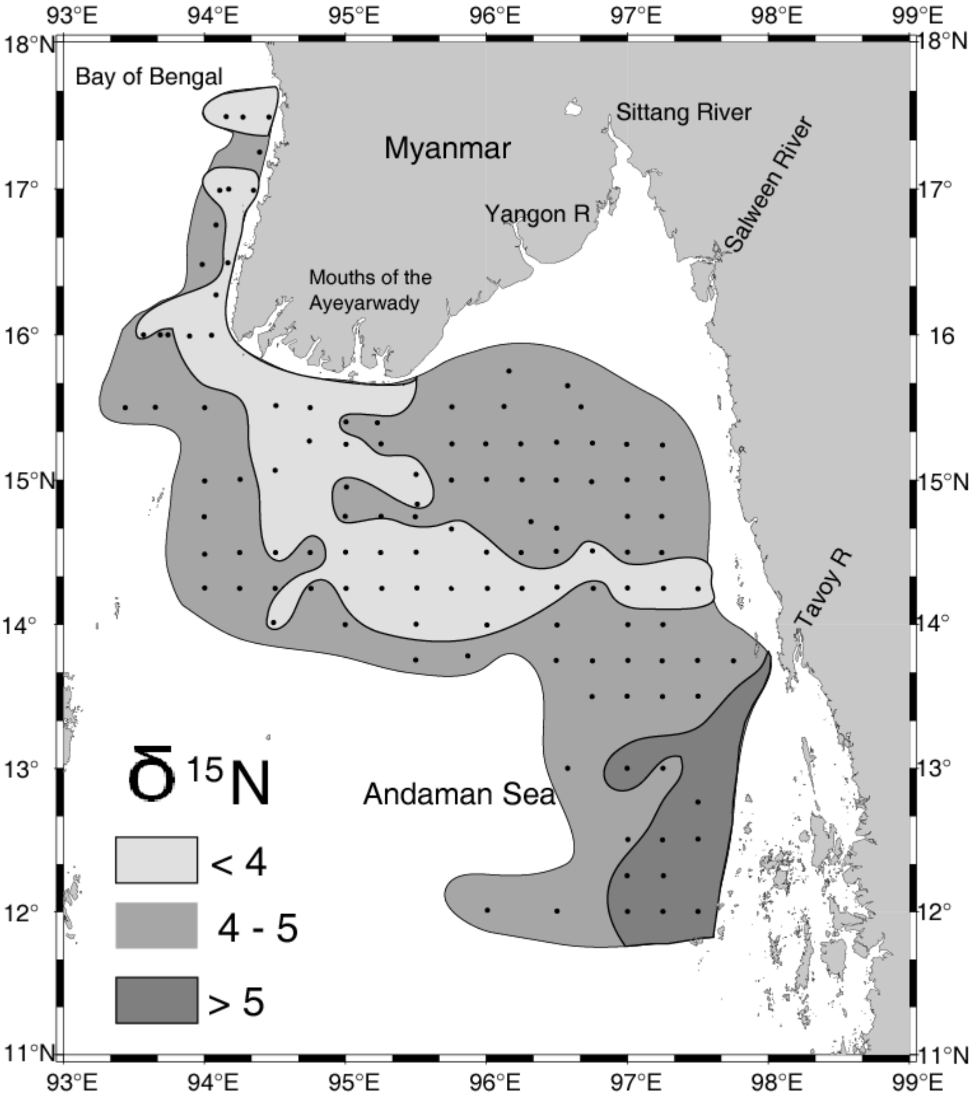
93°E
94°E
95°E
96°E
97°E
98°E
99°E
18°N
17°
16°
15°N
14°
13°
12°
11°N
16
Bay of Bengal
Myanmar
Sittang River
Salween River
Yangon R
Mouths of the Ayeyarwady
Tavoy R
Andaman Sea
δ15N
< 4
4 - 5
> 5

Fig. 7

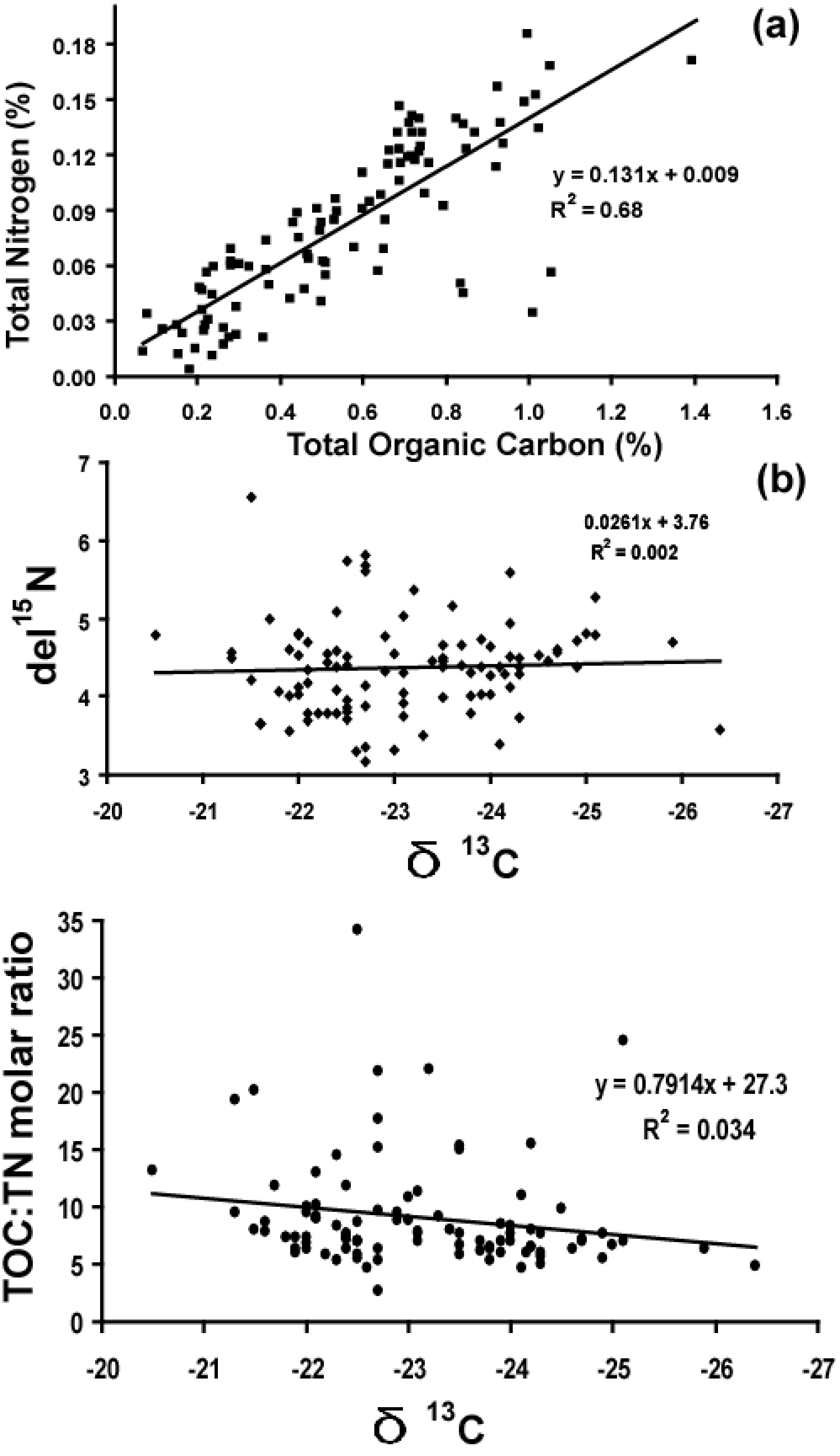
(a)
Total Nitrogen (%)
0.00
0.03
0.06
0.09
0.12
0.15
0.18
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Total Organic Carbon (%)
y = 0.131x + 0.009
R^2 = 0.68
(b)
del^{15}N
3
4
5
6
7
-20
-21
-22
-23
-24
-25
-26
-27
δ ^{13}C
0.0261x + 3.76
R^2 = 0.002
TOC:TN molar ratio
0
5
10
15
20
25
30
35
-20
-21
-22
-23
-24
-25
-26
-27
δ ^{13}C
y = 0.7914x + 27.3
R^2 = 0.034

Fig. 8

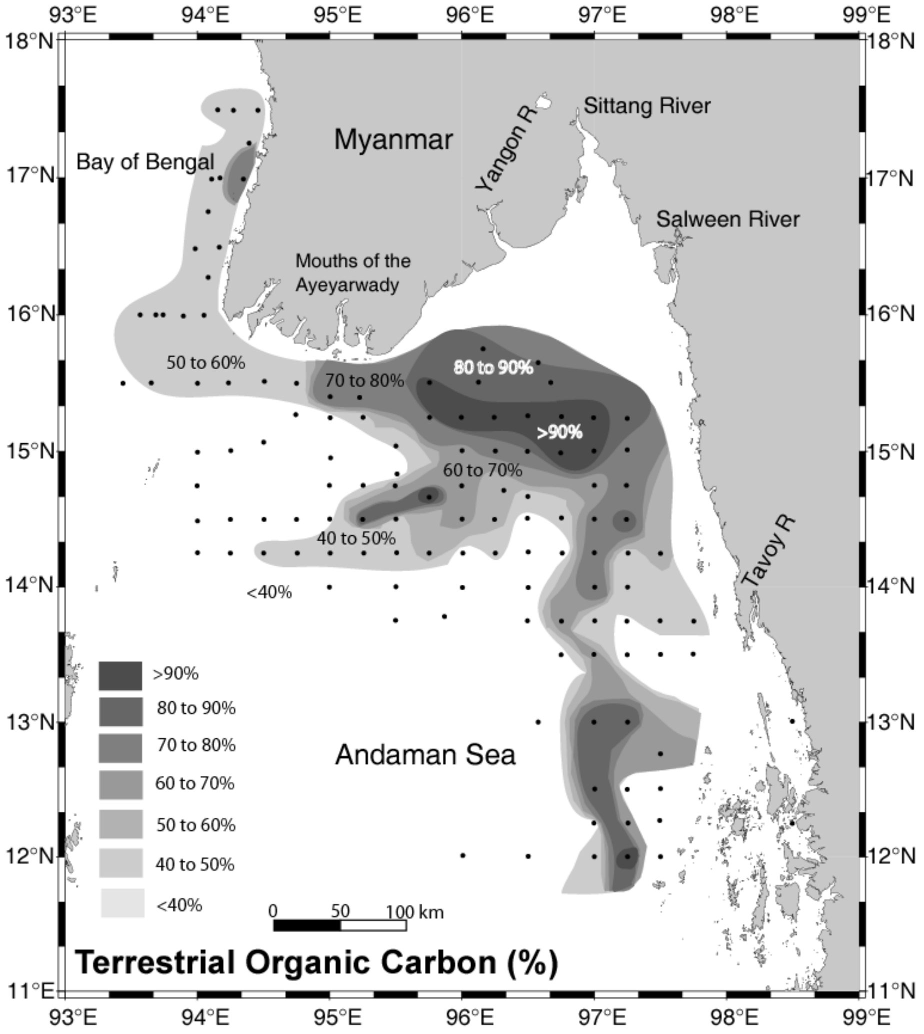
93°E
94°E
95°E
96°E
97°E
98°E
99°E
18°N
17°N
16°N
15°N
14°N
13°N
12°N
11°E
11°N
Myanmar
Bay of Bengal
Yangon R.
Sittang River
Salween River
Mouths of the Ayeyarwady
Tavoy R
Andaman Sea
50 to 60%
70 to 80%
80 to 90%
>90%
60 to 70%
40 to 50%
<40%
>90%
80 to 90%
70 to 80%
60 to 70%
50 to 60%
40 to 50%
<40%
0
50
100 km
Terrestrial Organic Carbon (%)

Fig. 9