

Indian summer monsoon and winter hydrographic variations over past millennia resolved by clay sedimentation

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Abstract

[1] Reconstruction of century scale Indian monsoon and winter hydrography is made from an AMS dated core located in the unique region of the SE Arabian Sea (AS) which lies in the pathways of the low salinity Bay of Bengal Waters (BBW), advecting during NE winter monsoon (NEM). Based upon clay mineral analyses we, therefore, identify chlorite and kaolinite as specific clays supplied by Bay of Bengal Waters and local fluvial flux (by the SW monsoon (SWM) precipitation from the Peninsular India) respectively along the SW continental margin of India. An evaluation of clay flux and $\delta^{18}\text{O}$ in *G. ruber* during ~450-650 yr, ~1000 yr, and 1800-2200 cal yr BP portray century- scale weaker SWM precipitation events. Kaolinite wt% and flux were found to be low during all these events, though chlorite has a persistent or enhanced flux. From the enhanced flux of chlorite and reduced K/C ratio, during weaker phases of SWM, we deduce a stronger NEM (winter) implying an inverse coupling between the summer and the winter monsoon.

1. Introduction

[2] Being regulated by reversal of winds (due to coupled heating–cooling of land–ocean), the Indian Monsoon System (IMS), comprising of the South West (SWM) and the North East monsoons (NEM), is the main source of precipitation in the Indian Subcontinent. Regional variability in precipitation and wind regime associated with IMS shapes a host of marine processes in the Northern Indian Ocean. For example, a large hydrological imbalance due to precipitation – evaporation (P-E) and fluvial influx associated with hydrometeorological regimes in two adjacent basins (the Bay of Bengal, $P \gg E$ due to higher fluvial runoff and precipitation; the Arabian Sea, excess evaporation and loss of fresh water; $E \gg P$) leads to an inter-basin transfer. During boreal summer (June through September), Indian Monsoon Current advects high salinity Arabian Sea Waters into BOB [Vinayachandran *et al.*, 1999]. Upon cessation of SWM, during NEM (November through February), westward flowing North Equatorial Currents as well as the southwards flowing the East India Coastal Currents carries warm, low salinity, nutrient rich BBW into the Arabian Sea [Kumar *et al.*, 2004; Figure 1]. The SW continental margin of India is anomalous because its sea surface salinity (SSS) and productivity are influenced and regulated by SWM as well as NEM, and is highly hypoxic [Kumar *et al.*, 2004]. Understanding of the dynamics of IMS is, therefore, critical for the agrarian and maritime economy of SE Asia. However, few continuous records are available for the Late Holocene for comparison with historical or instrumental records. Derived from $\delta^{18}\text{O}$ variability from cave stalagmite, studies of Fleitmann *et al.* [2003; 2007] and Sinha *et al.* [2007] are the only annually resolved archives of SWM dynamics during the Mid-Late Holocene.

[3] Along the SW continental margin of India, associated with the presence of regional topographic high, the “Western Ghats” (Figure 1A), there is an excessive precipitation induced by condensation of moisture from the SW monsoon winds when these encounter the land. Intense precipitation (about 4800 mm; Figure 1B) during SWM reduces SSS over the entire SE Arabian Sea, which remains low during NEM as well due to intrusion of BBW into this region (values 34-33‰ during NEM ([see Levitus *et al.*, 1994]; Figure 1). The $\delta^{18}\text{O}$ variability in surface dwelling planktonic foraminifers archives a composite influence of these monsoon effects, strong SW monsoon events reduce salinity and deplete $\delta^{18}\text{O}$ in the Bay of Bengal, and this effect is recorded at this core location.

[4] As a complement to the $\delta^{18}\text{O}$ proxy, We have explored the possibility to estimate magnitude of SWM and NEM (through the strength of BBW) instating a new proxy. Because of control of geology, drainage and climate of hinterland [Weaver, 1989], clays are expected to have a specific assemblage in each of fluvial source and ocean waters [Konta, 1985]. Along the SW continental

margin of India, which is Indian Monsoon Current as well as by North East Monsoon Current, we expect to have explicit clay assemblages in BBW as well as by the the local fluvial sources solely fed by SWM. We have measured clays in the sea waters of BOB and the Arabian Sea (in and out of the of the advection path of BBW) to identify clay fluxes specific to SWM and NEM. We explore application of $\delta^{18}\text{O}$ and temporal variations in the flux rate of specific clays of SWM and NEM as potential proxies to reconstruct variability in SWM and NEM in a core located in the advection pathways of BBW (Figure 1B). We have chosen the more stable Upper Holocene (last 3 ka) period in which there is a minimal interference of global ice volume effect, and local SST and SSS are influenced mostly by IMS [Duplessy, 1982; Rostek et al., 1993; Saher et al., 2007].

2. Methodology

[5] For determining specific temporal variations in the magnitude of SWM and NEM, an appropriate site is a prerequisite. However, except for the even inner shelf (~30 m), the entire uneven mid-outer shelf of the SE Arabian Sea has coarse and unconsolidated relict carbonate detritus (age > 8 ka; [Vora et al., 1996]). Furthermore, the most of the Western Margin of India is known to witness mass gravity transfer, [Chauhan and Almeida, 1993], which curtails possibility of obtaining several, suitable, high sedimentation, and turbidity free cores from the location which receives intense orographically enhanced precipitation induced fluvial flux and lies also in the advection path of BBW. During several expeditions of the RV *Gaveshani*, and the ORV *Sagar Kanya*, ~ 23 cores have been collected along the SW continental margin of India. Core RVG 167/1 (# 3904; latitude 08° 07.9' N; Longitude 76° 01.8' E; water depth 1400 m; Figure 1) has been chosen for the present study, because: (i) it lies in an area receiving orographically enhanced SWM precipitation, (ii) located in advection path of BBW, beyond the shelf break (area not influenced by any anomalous clay flux through bed load), (iii) the overlying waters are anoxic, and expected to retard bioturbation or smoothening of fine resolution signature [Qasim, 1977], and (iv) has the highest rate of sedimentation. We have obtained 44 sub-samples in upper 58 cm of the core.

[6] For attaining a better control on flux rate estimation, a closer interval age control is a prerequisite. The core was dated at 4-6 cm intervals (8 levels) by conventional ^{14}C method (Table 1). Carbonate bulk ages suffer mostly from contamination from older carbonates. The Western continental margin of India has massive carbonates on the outer shelf [Vora et al., 1996], which may be a potential source of contamination in the study area. In order to mitigate influence of any possible contamination from older carbonate. The ages were obtained on hand picked, unbroken mixed planktonic foraminifera species. We have strengthened our age model by additional four AMS ages

obtained on specific events of reduced precipitation (Poznan radio carbon laboratory, Poland) on *G. ruber* (250-415 μm size). The ages are converted to the calendar years after necessary correction of 400y for reservoir effect [Stuiver and Braziunas, 1993] using Calib programme (<http://calib.qub.ac.uk/calib/>). Narrower interval measurements (4-6 cm) have helped us to overcome chronometric error out of interpolation between longer core intervals (Figure 2), and to estimate mass accumulation rates for specific events with better control. Density variations are important input for the flux estimation. In order to aid estimation of flux rates, density was measured at 4-6 cm intervals. Average density is measured from mass/volume relation [Read, 1970] Sediment samples (known volume) were weighed after drying at 50°C. Dry bulk density is obtained from: dry weight/wet volume data [Curry and Lohmann, 1986].

[7] The $\delta^{18}\text{O}$ ($(^{18}\text{O}/^{16}\text{O})_{\text{sample}}/(^{18}\text{O}/^{16}\text{O})_{\text{standard}} - 1$) of the 25-35 tests of white *G. ruber* (size 315-400 μm , crushed, ultrasonic cleaned in ethanol) were determined against the Peedee Belemnite (PDB) standard at NGRI, Hyderabad and the University of Kiel. The results have a standard deviation of 0.04‰ for oxygen. Determined using three daily measurements of an internal calcitic standard (Z-Carrara), the external precision on $\delta^{18}\text{O}$ measurement is better than $\pm 0.1\%$. In order to ascertain source specific clays during SWM and NEM (in the load of BBW), suspended load (TSM) and clays at 18 stations (4 located in the Bay of Bengal; 12 along the study area; 2 in the area farther north with similar SWM precipitation regime but not in the advection path of BBW), were collected from the inner shelf - the upper slope (Figure 1, Table 2) during November of 2007 (NEM) and July of 2009 (SWM) under auspices of National Initiative of the Space Application Center, Indian Space Research Organization (ISRO), Govt. of India to estimate the influence of fluvial flux on marine processes. Conventionally, sea water is filtered through a 0.45 μm membrane filter paper to estimate TSM. In addition we have used six feet, Prep/Scale TFF regenerated cellulose cartridge (No. CDUF 006 Lm) and a tangential flow filtration system of Millipore to separate particulate matter (size 0.02 μm) from sea water. We have estimated clay abundance in carbonate and organic matter free 2 μm size fractions as described in Chauhan *et al.* [2006]. Accuracy of the analyses is ± 8 per cent for smectite and ± 5 per cent for other clays.

[8] Normally, the weighted per cent of clay species are used for climate reconstruction [Chauhan *et al.*, 2000 and references therein]. Sirocko and Lange [1991] have however, estimated flux rates for determining the strength of SWM. In order to estimate accumulation of clays specifically during SWM, we have, in addition, estimated also the flux rate of clays. The flux of individual clay is determined from:

$$\text{Flux (cl)} = \text{LSR} \times \text{D} \times \text{Wt}$$

Where Flux (cl) = flux of the individual clay ($\text{mg cm}^2 \text{ky}^{-1}$), LSR=linear sedimentation rate (cm ky^{-1}), D= dry density, Wt = weight percent of an individual clay mineral.

3. Results and Discussions

[9] In our core $\delta^{18}\text{O}$ varies between 2.79-2.29‰ (Figure 2), and heavier incursions have been observed at 450-650 (~0.24‰), ~1000 (0.45‰), 1800-2200 (0.51‰) cal yr B.P. (Figure 2). Based upon the criterion of *Sarkar et al.* [2000], these incursions signify SSS or SST variability of $> 1\text{‰}$ or $> 1^{\circ}\text{C}$. During past 3 ka, the SST variations in the Arabian Sea are rather insignificant [*Rostek et al.*, 1993; *Saher et al.*, 2007]. We link these incursions, therefore, with SSS enhancements. Even though *G. ruber* is surface dwelling and proliferates throughout the year [*Saher et al.*, 2007], SWM had been considered to be the regulator of its $\delta^{18}\text{O}$ [*Sarkar et al.*, 2000; *Tiwari et al.*, 2006 and references therein]. Owing to advection of low salinity BBW waters, the $\delta^{18}\text{O}$ variability in our core will be a composite of SWM as well as NEM SSS. Like all other available studies [*Sarkar et al.*, 2000, *Tiwari et al.*, 2006], our reconstruction is based also upon overall salinity variability by BBW and SWM, perhaps subdued by the low salinity of BBW, the heavier incursions of $\delta^{18}\text{O}$, therefore, stem from SSS reduction associated with a weaker SWM at 2200-1800, ~ 1000 and 650-450 yr B.P. We attain support to our reconstruction from archived precipitation minima and reduced run off at 2200-1900, 1000 and 650-450 yr B.P. in the fluvial runoff records of the River Indus [*von Rad et al.*, 1999]. A weaker SWM at 2200-2300 yr has also been reported from BOB [*Chauhan and Suneethi*, 2001]. Farther north, *Tiwari et al.* [2006] have found a weaker SWM at 550, 1100 and 2000 yr B.P. from $\delta^{18}\text{O}$ viabilities in *G. ruber*, first of these is observed also in the annually resolved records of stalagmite from the core monsoon region of India [*Sinha et al.*, 2007]. We find further endorsement to our reconstruction from the enhanced fluvial flux of the Indus during 1200-1700 and 2600 yr B.P. [*von Rad et al.*, 1999], and a stronger SWM during < 400 y and 600-1200 y B.P. from wind induced upwelling proxies of the Western Arabian Sea [*Anderson et al.*, 2002; *Gupta et al.*, 2003] concurrent with stronger SWM archived in our studies. We therefore infer that heavier incursions in our studies epitomize regional weaker SWM phases.

[10] We have attained support to our reconstruction from clay mineral flux. Clays (~ 2 μm in size) have an ability to be transported for long distances. Being a weathering residue, their production and supply is dependent on geology, drainage and climate [*Weaver*, 1989], and therefore these have potential to be used as climate proxy and geo-tracers [*Biscaye*, 1965; *Weaver*, 1989; *Chauhan and*

Gujar, 1996; Chauhan et al., 2000; Chauhan et al., 2006]. Chlorite is the clay produced under arid, cold climate, and is mostly found in the rivers having catchment in the glaciated region of the Himalayas [*Konta, 1985*]. The climate of the study area being humid – tropical, local production of chlorite is unlikely, and it is generally absent in soil, estuarine and shelf sediments [*Chauhan and Gujar, 1996*]. It is implausible, therefore, that this clay shall be supplied from the local mountains through fluvial flux. Kaolinite and gibbsite are the specific clays known to be produced under tropical humid climate by intense chemical weathering (*Weaver, 1989; Chauhan and Gujar, 1996*). The climate of the SW Peninsular India is tropical humid, and about 80% of precipitation in the region occurs during SWM. We, therefore, expect contribution of SWM climate specific clays kaolinite and gibbsite from the Peninsular Source.

[11] We have evaluated the surficial clay mineral distribution and physiography of the shelf water to get further clues on the source and dispersal pathways of the clays. *Chauhan and Gujar [1996]* have found that the middle and the outer shelf are completely devoid of any clay size detritus. The shelf has rugged and uneven physiography with exposed relic reef (age > 8 ka; [*Vora et al., 1996*]), which implies that the mid-outer shelf is not an active depocenter of modern clays from the suspended as well as bed load, despite an intense SWM precipitation. In order to affirm further, we have evaluated TSM and clays at 12 stations (Figures 3-4; Table 2) from this area. TSM varies significantly during SWM and NEM in the inland waters (122-46 mg l⁻¹), but it is found low, beyond 30 m of water depth (28 to 14 mg l⁻¹; Figure 3-4; Table 2). A low TSM in the offshore (> 40 m) affirms further a deficient supply into the deeper waters. We attribute this to the prevalent alongshore hydrography (Figure 1), which inhibits across shelf advection of TSM. An entrapment of fines by infragravity edge waves in the coastal waters [*Tatavarti and Narayana, 2006* and references therein] impede further supply of fines into the deeper region of the mid - outer shelf.

[12] The clay assemblage and representative X-ray diffractograms in the seawater samples during NEM and SWM from the Arabian Sea and BOB are presented in Figures 3-5. The surficial distribution of clays during SWM and NEM are markedly different. During SWM, kaolinite is the predominant clay with illite and gibbsite as minor clays on the entire inner shelf. In contrast, the outer shelf - slope waters were found with kaolinite, illite, smectite as significant clays with minor gibbsite (Figure 3), which is very close to clay assemblage reported in the homogenized surficial sediments in this region [*Chauhan and Gujar, 1996*]. We have found similar assemblage at two other stations located farther northwards (not in the advection pathways of BBW; Figure 1; Table 2),

and affirm absence of chlorite along the entire SE Arabian Sea during SWM. Conspicuous absence of chlorite is attributed to the unsuitable climate of the SW Peninsular India.

[13] During NEM, we found occurrence of chlorite in sea waters of all the offshore stations from the study area, though it remains absent at the stations not in the pathways of BBW (Figure 1; Table 2). Because chlorite is conspicuous by its absence over the entire shelf during SWM, we infer its specific contribution through BBW. This inference is derived also from the occurrence of illite and chlorite in the sea water samples of BOB during NEM as well SWM (Table 2). We deduce, therefore, that the contribution of chlorite is from BBW, though illite may have multiple sources. Similarly, kaolinite, which is produced by intense chemical weathering induced by SWM precipitation under tropical, humid climate, is contributed from the adjacent the Peninsular India, and its supply is equated with the magnitude of the SWM precipitation. The temporal variability in kaolinite and chlorite, therefore, appears linked with SWM and NEM respectively. Because a higher (lower) abundance/flux of kaolinite (chlorite) is related with SWM (NEM), we have used kaolinite/chlorite (K/C) ratio also as an index of the magnitude of SWM/NEM.

[14] The total flux of clays is found to be highly variable. In general, the flux is about 17.2-18.9 g cm² ky⁻¹. However, during 450-650, 1000 and 1800 – 2200 cal yr B.P. contrary to an over all reduction in kaolinite and in total flux of clays (~13.5 -10.29 g cm² ky⁻¹), an enhanced flux of chlorite has been observed (Figure 2). Concordant with lighter $\delta^{18}\text{O}$ (lower SSS and enhanced SWM) kaolinite flux is found to be enhanced during > 2200, 1800-1100, 900-650 and < 400 y cal yr BP, though it dwindles during all the heavier incursion episodes (reduced SWM precipitation) of 2200-1800, ~ 1000 and 650-450 y cal BP. During a reduced precipitation regime, the fluvial discharge is expected to be diminished with considerable decrease of (i) production and supply of fine detritus, (ii) carrying capacity, and (iii) overall sedimentation. The enhanced flux of chlorite, when, overall clays, SSS and kaolinite flux are reduced (Figure 2), is anomalous to this dictum. We propose that an increased chlorite during weaker SWM (reduced kaolinite and heavier $\delta^{18}\text{O}$) appears to stems from the persistence of BBW. In order to validate this thesis, we have obtained lithogenic flux rates (from the residue remained after treatment of bulk sediments with 10% acetic acid) and compared it with that of $\delta^{18}\text{O}$, overall flux of chlorite and kaolinite and K/C ratio (Figure 2). We find reduced lithogenic and clay flux during all the events of heavier $\delta^{18}\text{O}$ incursions (Figure 2). Conspicuously, there is an augmentation of chlorite (kaolinite and K/C ratio; Figure 2) during these times. From lower lithogenic, kaolinite, total clay flux rates and heavier $\delta^{18}\text{O}$ during these events, we deduce a prolonged and substantial reduction in the SWM precipitation curtailing yield of terrigenous detritus

and fluvial discharge. An enhanced or persistent flux of chlorite, a clay contributed exclusively by BBW during NEM only at these times stem from sustained contribution from BBW. The observed antiphase behaviour among kaolinite and chlorite endorses, an inverse coupling between the SWM precipitation and this westward flow of Bay of Bengal water that occurs during the NE winter monsoon.

Acknowledgements

[15] Authors are thankful to the Director the National Institute of Oceanography, Dona Paula, Goa for providing the facilities. We acknowledge Professor Vincent Salters and the Associated Editor and two anonymous referees for very efficient review processes and for constructive comments which have improved the science in the manuscript. We thank the Space Application Center, and IGBP-ISRO, Ahmedabad for financial grants for TSM and clays mineral studies in offshore waters of AS and BOB. We acknowledge the support of the Indian Coast Guard in collection of sea water samples. Kumud K. Singh, E. Vogelsang and M. Saranthein helped with carbon and oxygen analysis & interpretation. NIO Contribution no XXXX.

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Figure Captions

Figure 1. Location of core and sea water samples from BOB (B1-B4) and the Arabian Sea (A-N; refer Figure 3 for individual location of water samples # A-L marked as a box in (A)), and regional sea surface salinity (p.s.u) during (A) NEM (December) and (B) SWM (August) together with prevalent hydrography [Levitus *et al.*, 1994]. Regional topographic features the “Western Ghats” (data source: <http://web.ics.purdue.edu/~braile/edumod/sv/1down.htm>) along the West Coast of India (which induces orographic influence on SWM precipitation) is shown in panel A. The measured precipitation during SWM at selected locations is shown in panel B.

Figure 2 Temporal variations in (A) $\delta^{18}\text{O}$ of *G. ruber* together with and ^{14}C ages vs depth, (B) kaolinite (flux and wt%), (C) chlorite (flux and wt%), (D) total clay flux rates and linear sedimentation rates (LSR) (E) K/C ratio and lithogenic flux. Positive relation among heavier $\delta^{18}\text{O}$, kaolinite, K/C ratio during weaker SWM at 450-650, 1000 and 1800-2200 yr B.P. during enhanced BBW (higher chlorite) are marked with gray shades.

Figure 3. Sampling locations (A-L) and spatial distributions of TSM and clays measured in surficial sea waters during SWM. Note conspicuous absence of chlorite in the entire study area.

Figure 4. Spatial distributions of TSM and clays measured in surficial sea waters during NEM. Specific occurrence of chlorite in the offshore samples in the study area though found in BOB, but not in other locations of the Arabian Sea (refer Table 2 also) is a conspicuous feature.

Figure 5. Selected X-ray diffractograms from the Bay of Bengal and the Arabian Sea during SWM and NEM. For stations (A, E, H, L, M, B1) refer Fig1A, 3 and Table2. Note absence of chlorite in all the samples (i-v) from the Arabian Sea during SWM.

Table 1: Calibrated ^{14}C (conventional and AMS) ages for core 167/1 [*Stuiver and Braziunas*, 1993; <http://calib.qub.ac.uk/calib/>].

Mid level (cm)	Sample Lab ID	Material	^{14}C Age (y BP)	Calibrated Age (y BP)	1 s.d. (y)
10	RG1673904/1	Foraminifers*	840	460	90
13	POZ-22003	<i>G.ruber</i>	950	590	50
14	POZ-22021	<i>G.ruber</i>	1050	630	40
15	RG1673904/2	Foraminifers	1160	710	30
20	RG1673904/3	Foraminifers	1440	960	110
24	RG1673904/4	Foraminifers	1600	1140	100
28	RG1673904/5	Foraminifers	1760	1300	30
30	RG1673904/6	Foraminifers	1870	1370	40
38	RG1673904/7	Foraminifers	2190	1730	110
42	POZ-22062	<i>G.ruber</i>	2450	2020	50
46	POZ-22064	<i>G.ruber</i>	2730	2350	30
50	RG1673904/8	Foraminifers	2940	2600	130

*Unbroken mixed planktonic foraminifers

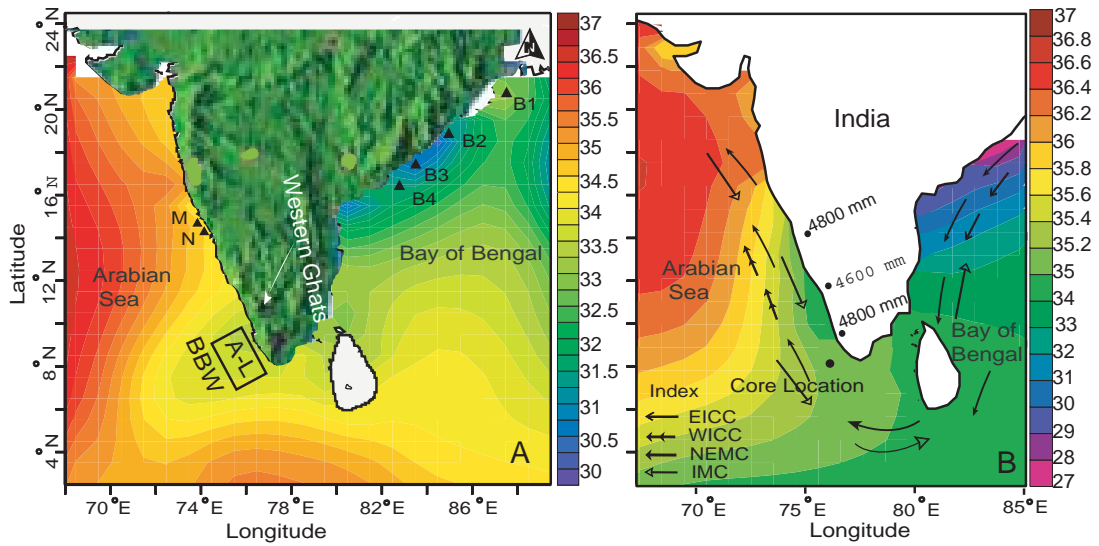


Figure 1. Location of core and sea water samples from BOB (B1-B4) and the Arabian Sea (A- L; refer Figure 3 for individual location of water samples # A-L marked as a box in (A)), and regional sea surface salinity (p.s.u) during (A) NEM (December) and (B) SWM (August) together with prevalent hydrography [Levitus et al., 1994]. Regional topographic features the "Western Ghats" (data source: <http://web.ics.purdue.edu/~braile/edumod/sv/1down.htm>) along the West Coast of India (which induces orographic influence on SWM precipitation) is shown in panel A. The measured precipitation during SWM at selected locations is shown in panel B.

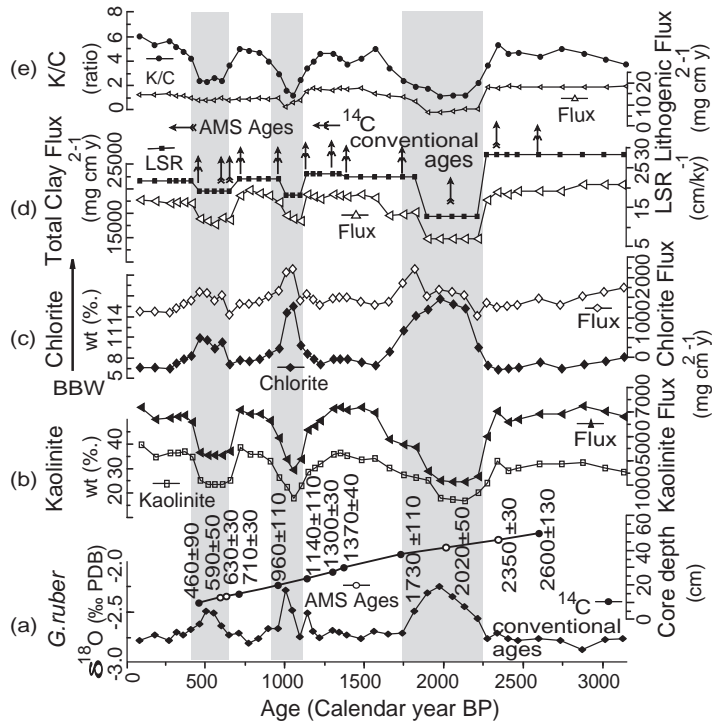


Figure 2. Temporal variations in (A) $\delta^{18}\text{O}$ of *G. ruber* together with age vs depth model, (B) kaolinite (flux and wt%), (C) chlorite (flux and wt%), (D) total clay flux rates and linear Sedimentation rates (LSR), (E) K/C ratio and Lithogenic flux rate. Positive relation among heavier $\delta^{18}\text{O}$, kaolinite, K/C ratio during weaker SWM at 450-650, 1000 and 1800-2200 yr BP during enhanced BBW (higher chlorite) are marked with gray shades.

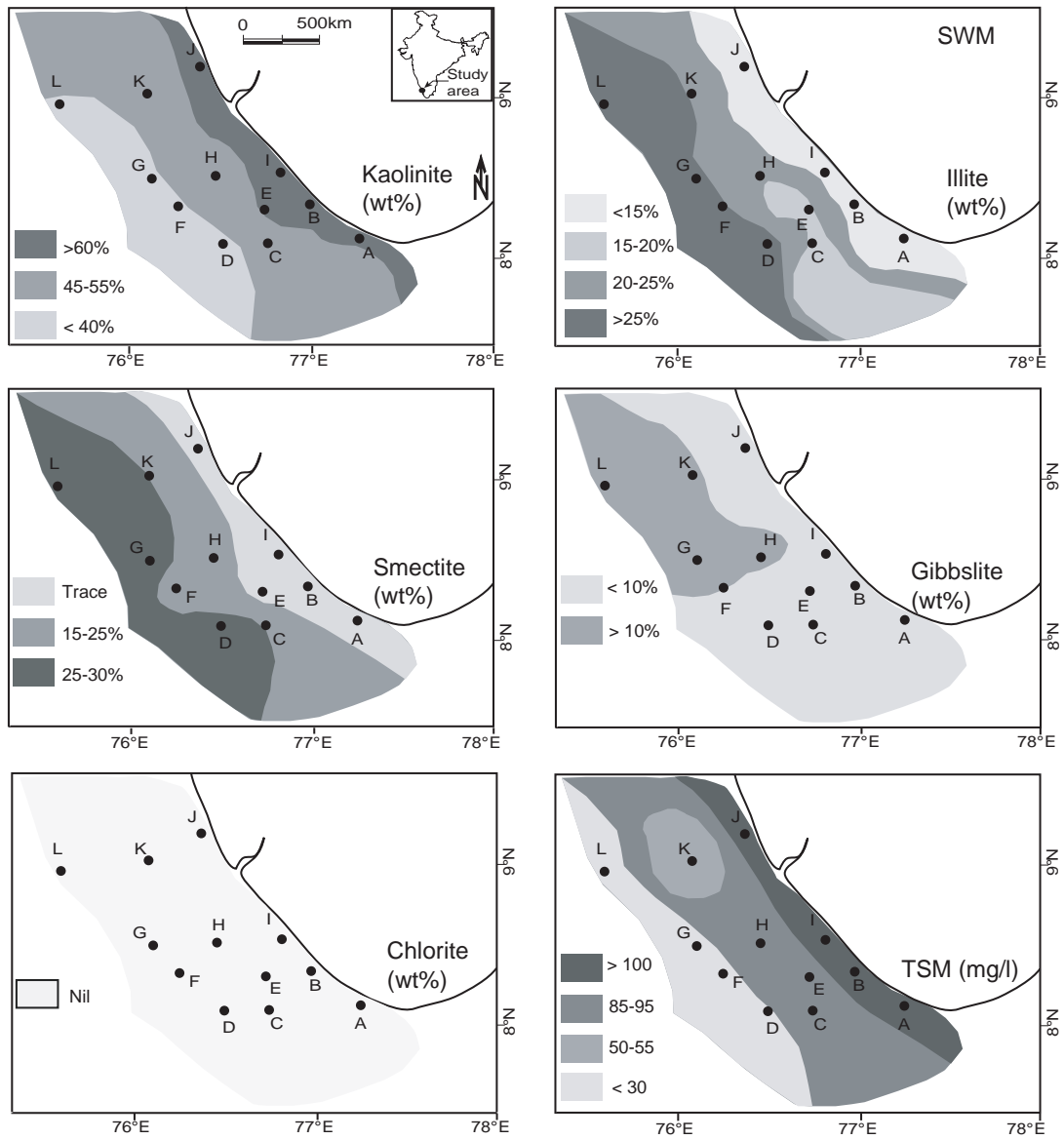


Figure 3. Sampling locations (A-L) and spatial distributions of TSM and clays measured in surficial sea waters during SWM. Note conspicuous absence of chlorite in the entire study area.

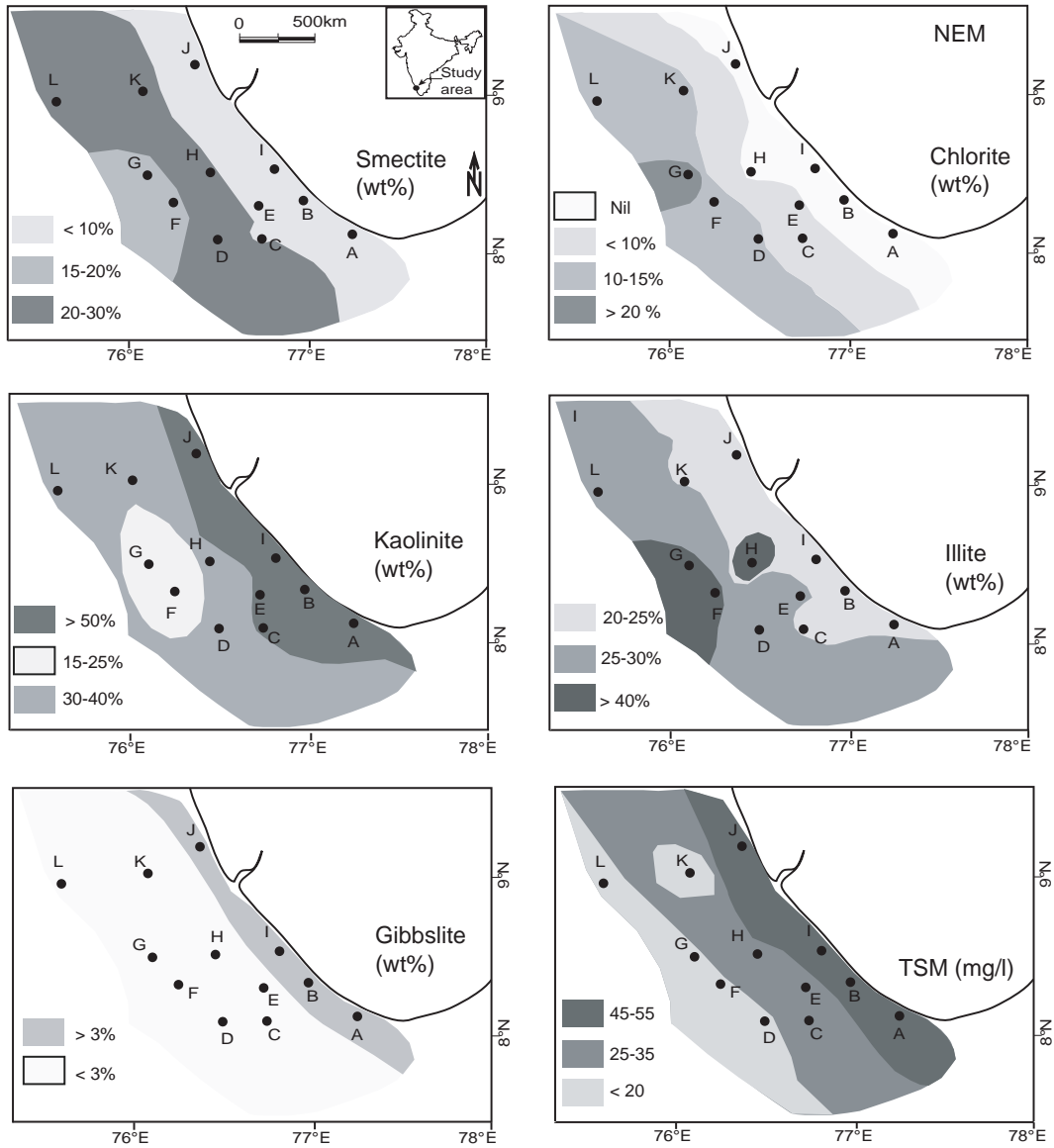


Figure 4. Spatial distributions of TSM and clays measured in surficial sea waters during NEM. Specific occurrence of chlorite in the offshore samples in the study area though found in BOB, but not in other locations of the Arabian Sea (refer Table 2 also) is a conspicuous feature.

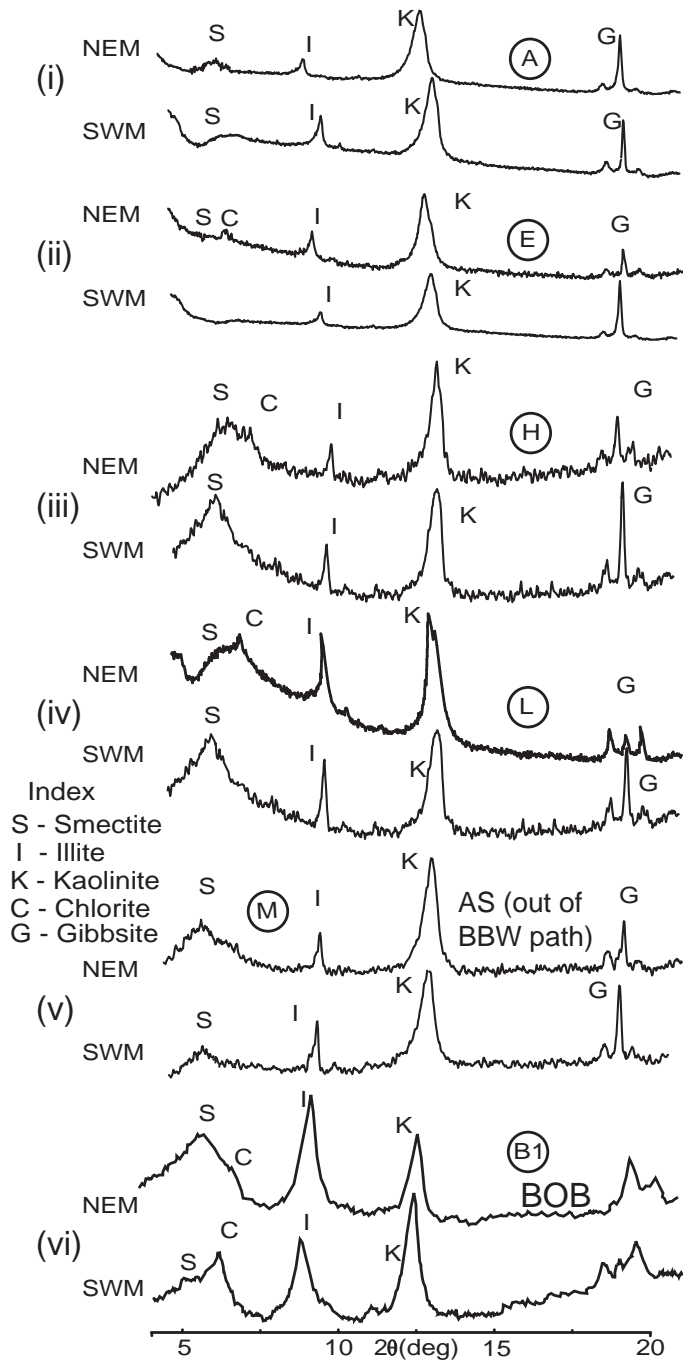


Figure 5. Selected X-ray diffractograms from the Bay of Bengal and the Arabian Sea during SWM and NEM. For stations (A, E, H, L, M, B1) refer Fig 1, 3 and Table 2. Note absence of chlorite in all the samples (i-v) from the Arabian Sea during SWM.