

High resolution climatic records of the past ~489 years from Central Asia as derived from benthic foraminiferal species, *Asterorotalia trispinosa*

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Abstract

Speciation in foraminifera is a function of their ecology and habitat. Thus, their extreme sensitivity and specific responses to specific set of physio-chemical conditions in their environment, has led to their extensive application in palaeoclimatic studies. During the study of Recent benthic foraminiferal distribution on the Ayeyarwaddy Delta Shelf off Myanmar, the occurrence of the species *Asterorotalia trispinosa* was very conspicuous. Though many previous workers have reported the occurrence of the species *A. trispinosa* as a major constituent in foraminiferal assemblages from different regions, its ecological significance has never been studied before. The present work on the surface distribution of *A. trispinosa* species in the study area, establishes its preference for low salinity. The ecological preferences of *A. trispinosa* make the species an useful proxy for the delineation of wet and dry periods of the past. The downcore variation in the abundances of *A. trispinosa*, its reproductive behaviour viz. its MPS and stable isotopic values were analysed, in sediments of the core GC-5 collected at 37 m water depth on the delta front. Downcore variations in the abundance and MPS of *A. trispinosa* indicate two significant climatic conditions in the study area since 1513 AD; a dry climate prior to 1650 AD and warm and wet climate since 1650 to present. They also reveal that since 1650, 3 major freshwater pulses are recorded in the core at ~1675, 1750 and 1850 AD. The multi-proxy data also support these findings. This high-resolution palaeoclimatic data representing the past 489-years, may be the Asian signatures of the European Little Ice Age. The present work shows extreme relevance with the interest of workers around the world, trying to understand the dramatic events in global climates over the past 500 years.

Key Words: Foraminifera; *Asterorotalia trispinosa*; Ayeyarwaddy Delta Shelf; salinity; freshwater pulse; high-resolution data; Little Ice Age

1. Introduction

Foraminiferal species inhabit a wide range of marine environments. The distribution of individual taxa is a function of their ecology and habitat and often quite distinctive. Knowledge of ecological behaviour of single foraminiferal species has been used extensively to draw palaeoclimatic interpretations. For example, Nigam and Setty (1982) identified the applicability of *Virgulinitella pertusa* as an indicator of sandy substrates with low organic carbon. The influence of cold to temperate waters have been repetitively identified with the help of *Hyalinea balthica* (Bock, 1970; Collen, 1974; Ross, 1984). Nigam and Rao (1987) used the mean proloculus size (MPS) and Nigam and Khare (1992) used the coiling direction in species *Rotalidium annectans* as an indicator of varying salinity. Diameters of *Orbulina universa* and *Globorotalia menardii* (Bhonsle, 2005) are directly proportional to varying temperatures, and the peaked abundances of *Epistominella exigua* indicate increased seasonal food supply (Gooday, 1988, 1993, 1994; Hayward et al., 2004; Saraswat et al., 2005).

Although *Asterorotalia trispinosa* (Thalman, 1933) (Fig. 1) has been recognized as an important component in demarcating biofacies within different sedimentary basins (Frerichs, 1970; Subbarao et al., 1979; Lambert, 2003), its ecological preferences that control its distribution have never been ascertained. In the present study, the distribution of *A. trispinosa*, in a large number of samples collected off Myanmar (the former Burma) coast, on the continental shelf characterized by the Ayeyarwaddy River Delta, have specifically been studied to understand its ecological niche and its probable utility in palaeoclimatic reconstructions.

1.1 Previous reports on the occurrence of *Asterorotalia trispinosa*

Benthic foraminiferal species *A. trispinosa* ranges from the Pliocene to Holocene where it is often an important index fossil. For example, it is reported from the lowermost part of the Pleistocene Toukoshan formation of western Taiwan (Huang, 1964) where it defines a very important regional biostratigraphic horizon.

In Recent sediments, Thalman (1933) reported *A. trispinosa* in fine-grained sediments off the coast of Java. He hypothesized that its long spines provided buoyancy to the test, which would let them remain suspended above settling sediments for a longer time. Bhatia and Bhalla (1959) reported rare occurrences of this species in beach sands from Puri, Orissa (East Coast of India), which was the first report of the taxa from the Indian region. Ghose (1966) carried out a morphometric analysis on 88 specimens collected from beach sands at Digha, the east coast of India, and determined that this common species was referable to *A. trispinosa* and not *A. pulchella* as

previously reported (Hofker, 1951). In an analysis of the distribution of benthic foraminifera Frerichs (1970), probably misidentified his species as *Asterorotalia pulchella*, which made up 37% of his assemblage. Occurrences of *A. trispinosa* have been widely reported subsequently by many researchers (e.g., Rao, 1998; Lambert, 2003; Mellis and Violanti, 2006) ranging in abundance from rare (e.g., Subbarao et al., 1979) to abundant (e.g., Rao, 1998; Gandhi, 1999; Rana, 2009) primarily from shallow coastal waters (~11-55 m). Recent occurrences have been summarised in table 1.

2. Materials and Methods

As part of the 'India-Myanmar Joint Oceanographic Studies', 13 gravity cores and 124 surface sediment samples were collected in April 2002 on the Ayeyarwaddy Delta Shelf at water depths ranging from 10-1030 m. (Fig. 2) on board the ORV Sagar Kanya. Conductivity-temperature-depth (CTD) profiles were obtained at few select stations to assess the temperature and salinity variability in the area (Fig. 3). The geographic co-ordinates, depth of collection, the grain size distribution, temperature and salinity corresponding to each sample station are shown in table 2.

2.1 Surface Samples

~15 g of sediments from each of the 124 surface samples was dried overnight at 60°C. Each dried sample was weighed and soaked in distilled water. They were subsequently treated with 10 ml of 10% sodium hexa-metaphosphate to dissociate the clay particles followed by 5 ml of 10% hydrogen peroxide to oxidise the organic matter, if present. The treated samples were wet sieved through 63 µm (250 mesh) size sieve. The sand residue retained over the sieve was dried at 60°C to get the weight of the sand fraction. The filtrate collected in a measuring cylinder was used for pipette analysis to determine the silt and clay fraction in each sample. .

The sand fraction was coned and quartered to obtain a representative aliquot from which a minimum of 300 benthic foraminiferal specimens were picked to obtain statistically adequate numbers to portray the faunal distribution (Ujjie, 1962; Dennison and Hay, 1967; Chang, 1967). They were mounted on micropalaeontological slides and percentages of the individual benthic species were calculated. From these picked benthic foraminifera, specimens of *A. trispinosa*, a particular species under discussion in this study, were sorted. Its occurrence was seen only in 39 surface samples and their abundances in those samples are tabulated in table 3.

2.2 Statistical Analysis

Linear correlation coefficients (r) among various water and sedimentological parameters and the abundance of *A. trispinosa* recorded at different sampling stations in the study area, showing at least some abundance, were computed individually. Looking at the trends in the abundance pattern,

the complete dataset (also including zero abundances), was subjected to stepwise regression by removing outliers in the model by using Sigmastat for Windows (ver. 3.5). As a measure of goodness of fit, the values of the coefficient of determination (R^2) were calculated. To ensure the statistical significance of the computed regression coefficients, they were subjected to a detailed t-test statistical analysis.

2.3 Sub-surface Samples

For studying the sub-surface signatures, core GC-5 with a length of 178 cm was selected. It was collected at the delta front at a water depth of 37 m (Fig. 2, location same as that of surface sample no. SK-175/22). Four sub-samples were obtained from the first 10 cm of the core and the rest was sub-sampled at every two cm interval. Thus, 88 sub-samples were used for the sub-surface studies. All the procedures carried out on surface sediments for foraminiferal studies were also repeated for sub-surface samples. However, for reconstructing past environmental events in this region, a multiple proxy approach was adopted. The downcore variation in foraminiferal distribution was supplemented with the morphometric analysis of the species *A. trispinosa*, stable isotopic (Oxygen) and elemental (Mg/Ca and Sr/Ca) studies.

Results of all downcore parameters were plotted along with their three-point running averages in order to smoothen large variations.

2.3.1 Morphometric Analysis

Of the picked fauna, the downcore variation in the abundance of the species *A. trispinosa* was recorded. The size of the proloculus for each specimen of *A. trispinosa* picked was measured using an Olympus stereozoom microscope 'SZX12', with a maximum magnification of 180x and a precision of $\pm 3 \mu\text{m}$, by keeping the specimens in dorsal view. A total of 1,398 specimens from 88 samples were thus measured. A value for abundance and mean proloculus size (MPS) was derived nearly for every 2 cm interval (No specimen of *A. trispinosa* was found at level 72 cm within the core). These values were plotted to understand their downcore variation. The ecological information of this species derived from its surface distribution has been used to interpret the downcore data in GC-5.

2.3.2 Stable Oxygen Isotopic Ratios

As the abundance and morphometric plots of *A. trispinosa* were showing interesting downcore variations, the same species was used to generate stable isotopic ratios throughout the length of GC-5. Approximately 5-8 specimens of *A. trispinosa* were picked from every sub-sample of the core and subjected to standard sample preparation procedures. The stable isotopic analysis was

performed at the newly set up facility at the Freie Universitat, Berlin, Germany on “Finnigan MAT 253 Isotope Ratio Mass Spectrometer” coupled to an automatic carbonate preparation device (Kiel I). All measurements were normalised to VPDB (Vienna Pee Dee Belemnite) using Laaser Mamor (internal standard), NBS-18 and NBS- 19 and IAEA-CO-1 (international standards). The values are given in δ -notation versus VPDB. Precision of oxygen isotope measurements based on repeat analysis of a laboratory standard was better than 0.05‰.

2.3.3 Elemental studies

Elemental (Ca-Mg-Sr) concentrations were measured on 20-25 specimens of *Hanzawaia concentrica* (per sub-section) to determine the variations in temperature (Mg/Ca) and salinity (Sr/Ca) in core GC-5, using the VISTA-MPX ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometer) at Geo Forschung Zentrum (GFZ) Potsdam, Germany. This species was chosen because it was available in enough numbers throughout the length of the core. Mg/Ca analysis requires a systematic cleaning procedure which includes 5 important steps: (rinse, reduction, oxidation, chelation and leaching) (Martin and Lea, 2002; Barker et al., 2003). It has been established and reported (Martin et al., 1999; Martin and Lea 2002) that there is no difference in the mean Sr/Ca values measured from samples subjected to the simplest procedure (rinse and leach) versus those subjected to more aggressive cleaning. However, the reproducibility of the measurement improves with rigorous cleaning. Because rigorous cleaning does not introduce any artefact into Mg/Ca and Sr/Ca data sets, it is acceptable to use the full trace metal cleaning protocol (Martin and Lea, 2002). Thus the same samples were used for simultaneous measurements of Mg/Ca and Sr/Ca because they gave the advantage of measuring more parameters on the same sample. Results were obtained as an average of three replicate measurements of the samples which gave a mean reproducibility of ± 0.03 Mg/Ca mmol/mol and ± 0.05 Sr/Ca mmol/mol.

2.4 Chronology

Pb-210 dating of the top of core GC-5 done at the Geochronology Lab at the National Institute of Oceanography, Goa, revealed that the top was intact. Two radiocarbon AMS dates were obtained on Recent foraminiferal specimens picked at different levels within the core GC-5, at the Leibniz Labor für Altersbestimmung und Isotopenforschung, Christian-Albrechts-Universität Kiel, the details of which are included in table 4. As no reservoir age exists for the Ayeyarwaddy Shelf, those previously used for the Andaman region, i.e. Delta R value 12 (± 34) years, reported for Stewart Sound (13°N 93°E), North Andaman (Dutta et al., 2001) have been used to calibrate all samples. The conventional radiocarbon ages were calibrated using the Marine-04 dataset by Hughen et al. (2004)

as used by the online version of the standard radiocarbon calibration program CALIB 5.0.2 (Stuiver and Reimer, 1993). Considering the fact that the top was intact on the basis of Pb-210 activity in the top of the core, it was assigned to the year 2002 (year of collection). On the basis of the two AMS dates obtained the ages for the remaining levels within the core were interpolated (Fig. 4). Thus, in the top 82 cm length of the core, the resolution is 7.95 years/sub-section and 3.38 years/sub-section for the rest of the core. Consequently, the core represents 489 years BP and can be calibrated to represent time since 1513 to 2002 AD. This chronology has been used to describe the different climatic events reflected in core GC-5. However, the calibrated dates suggest an error of ± 48 and ± 46 years respectively, for the two dated samples in the core. Whilst referring to the climatic events described herein, due consideration needs to be given to the range of errors in calibrated ages mentioned.

3. Results

Depending upon the samples, the results are presented under two different subheadings: ecology of *A. trispinosa* and subsurface signatures of palaeoclimate.

3.1 Ecology of *Asterorotalia trispinosa*

Presence of *A. trispinosa* was observed in 39 of the 124 surface sediment samples with abundances ranging from ~1 to 43% (Table 3). Figure 5 clearly indicates the preference of *A. trispinosa* for fine-grained substrates. Its maximum abundances are seen at stations characterized by silty-clays in contrast to meagre abundances at stations underlain by coarse substrate (Fig. 6). Based on the station wise occurrence of this species, three prominent abundance zones can be delineated on the Ayeyarwaddy Delta Shelf (Fig. 7). Very close to the mouths of the Ayeyarwaddy, maximum abundances of *A. trispinosa* ranging between 20 to 40% are observed. Away from the coast, abundances reduce irrespective of depth, but generally correspond to the occurrence of fine grained substrates. This abundance pattern corresponds to the accretion pattern of the Ayeyarwaddy Delta and the sediment distribution pattern as proposed by Rao et al. (2005).

Temperature and salinity was not collected for each station during sampling. However, CTD profiles obtained at a few stations are presented (Fig. 3) to demonstrate the compatibility of observed measurements with the datasets obtained from Levitus Climatology (NOAA/PMEL TMAP FERRET Ver. 5.22, Dataset: levannual.ac). The station-wise annual average bottom water temperature and salinity values obtained from Levitus Climatology could be reliably used as they were comparable with the CTD profiles obtained onboard. From the XY-scatter of *A. trispinosa* abundances versus corresponding salinities, it is evident that maximum abundances of *A. trispinosa* (20-40%) are seen

at stations with salinities ranging from 31.78 to 33.10 psu (Fig. 8) and temperatures from 26.6 to 27.77°C (Table 2). Drop in abundance of this species away from the river mouths suggests that this species prefers low salinity regimes. Ramaswamy et al. (2008) have reported station-wise total organic carbon (TOC) ranging from 0.4-1.0%. They observed higher organic matter percentages associated with fine-grained sediments in the inner-shelf mud belt and on the continental slope. However, *A. trispinosa* does not show a significant correlation with TOC values (Table 5).

An XY-scatter of its abundances versus corresponding depths was plotted. Though it occurs within a wide depth range, its maximum abundances are seen at depths between 18 to 40 m (Fig. 9). Thus, it seems that in the present study area *A. trispinosa* preferentially inhabits this depth zone. To substantiate the observations in this study results were compared with previous distributional reports for this species (Table 1).

The linear correlation analysis revealed, a significant positive correlation between *A. trispinosa*, silt, mud and temperature. On the other hand, it was negatively correlated with depth, sand and salinity. Some of the other parameters were also correlated with each other (Table 5). The statistical model derived through the regression of all the parameters (Table 6) revealed that a cumulative impact of all the parameters could cause about 58% variability in the abundance of *A. trispinosa*. However, multi-co-linearity amongst the independent variables with large values (>10) of VIF (Variance Inflation Factors) might induce error in the statistics and indicates independent variables not be correlated amongst themselves. Therefore, it was required to eliminate one or more variables from the equation. To this end, a refined stepwise regression model (Ryan, 1997) was used to identify the best indicators of abundance. The forward stepwise regression indicated that the dependent variable *A. trispinosa* can be predicted from a linear combination of the independent variables salinity and sand. About 48% variability in *A. trispinosa* could be attributed the combined effect of salinity and sand only. However, a similar equation derived after taking into consideration the outliers in the entire dataset, revealed that salinity and sand contributed to about 60% variability in *A. trispinosa*. The remaining variables did not significantly add to the ability of the equation to predict *A. trispinosa* and were not included in the final optimized equation.

3.2 Subsurface signatures of palaeoclimate

3.2.1 Total Foraminiferal Number

The total foraminiferal number (TFN) varies between a maximum of 65,185 at ~1779 AD and a minimum of 470 at ~1708 AD (Fig. 10.a). The abundances show a distinct ascent in numbers after ~1700 AD. Before 1700 AD the abundances have remained lower than ~30,000 and

fluctuations have been very minor (amplitudes range between 10-30%). Since 1700 AD to 2002 the fluctuations are higher in amplitude and significant.

3.2.2 Planktonic and benthic foraminiferal abundance

Both, planktonic as well as benthic foraminiferal abundances are significantly low prior to 1700 AD after which they show large fluctuations in abundance (Fig. 10b and 10c). Thus ~1700 AD apparently is an environmental boundary. Comparing the relative percentage abundance of benthic and planktonic foraminifera (Fig. 11a and 11b), it is seen that both show this climatic boundary at ~1650 AD. Prior to 1650 AD, both planktonic and benthic foraminifera show smaller changes in amplitude. This period is characterised by relatively higher planktonic percentages corresponding to lower benthic percentages (as compared to their abundances in the younger portion of the core). This change in foraminiferal distribution could be a climatic boundary. Post 1650 AD there are frequent and large variations in planktonic as well as benthic abundances.

3.2.3 Generic distributions

The TFN is largely composed of benthic foraminifera, which is largely constituted by low salinity assemblages on the Ayeyarwaddy Delta Shelf. Panchang (2008) statistically established the inverse relationship of four genera, namely *Asterorotalia*, *Hanzawaia*, *Ammonia* and *Elphidium* with salinity. This low salinity assemblage was found to be characteristic of low salinity regimes in the study area (as revealed by the cluster analysis). Thus, in order to assess the downcore variation in the relative abundances of the low-salinity assemblages their collective percentage abundances were also plotted (Fig. 12). This assemblage makes up about 50% of the total benthic foraminiferal assemblage in the core. After ~1650 AD, these assemblages show significant fluctuations in their amplitude. On three occasions post, at ~1675, ~1750 and ~1840-1880 AD, the low salinity assemblage constitutes ~70% of the total assemblage. These events are marked as I, II and III and are suggestive of periods of freshwater influx.

3.2.4 Distribution of *Asterorotalia trispinosa* and its application of as an indicator of palaeomonsoons

As observed in all the downcore abundances discussed above, even the *A. trispinosa* abundances (Fig. 13a) shows a marked difference in its abundance patterns in the older and younger part of the core. Abundances of *A. trispinosa* vary between a maximum of ~31% at 1835 AD and a minimum of 0.8% at 1820 AD. Its abundances are nearly constant at ~5% abundances prior to 1675 AD after which the abundances fluctuate with large amplitudes. Figure 13b illustrates the downcore variation in the MPS, which varies between 37.55 μm at ~1810 AD and ~19 μm at ~1650. The

description of the distribution of *A. trispinosa* in the study area and the statistical stepwise regression analysis (presented in section 3.1), suggests that, species *A. trispinosa* prefers low salinity regimes. Thus, it is proposed that higher abundances of *A. trispinosa* are indicative of low salinity events of the past i.e. periods of higher freshwater influx or stronger monsoons. To test the proposed hypothesis, downcore abundances of *A. trispinosa* were plotted (Fig. 13a). Mean Proloculus Sizes in foraminifera are indicative of their reproductive behaviour that is extremely sensitive to climatic changes (Bradshaw, 1955 and 1957; Boltovskoy and Wright, 1976; Nigam, 1986; Nigam and Rao, 1987; Nigam and Khare, 1992; Saraswat et al., 2005). Even the downcore MPS values of *A. trispinosa* were plotted (Fig. 13b). The fluctuations in the values of MPS are almost synchronous with those in abundances of *A. trispinosa*. Their signatures throughout the length of core GC-5 are suggestive of changing climates over the past ~489 years in the study area.

As larger abundances of *A. trispinosa* are taken as an indicator of lower salinities, its lower abundances seem to indicate dry climates, with increased salinities in the study area. Maximum fluctuations are seen between ~1675 to 1850 AD, within which two events of opposite extremities are recorded:

- Highest salinity and thus lowest fresh water influx indicated by lowest abundance of *A. trispinosa* at ~1710 AD (indicated as 'A' in Fig. 13a)
- Lowest salinity and highest freshwater influx, indicated by highest abundances of *A. trispinosa* between 1827 and 1850 AD (indicated as 'B' in Fig. 13b)

A. trispinosa abundances fluctuate throughout the length of the core GC-5, with varying amplitudes. These climatic events or freshwater pluses are better reflected in the reproductive behaviour of *A. trispinosa* i.e. the downcore variation in MPS (Fig. 13b). However, 3 significant events occur after 1650 AD. Approximately the periods around 1675, 1765 and 1850 AD are characterised by peaked fresh water pulses in the study area indicated by the annotations I, II and III in figure 13a. Two other peaks of lesser significance are recorded at ~1900 and 1938 AD indicated as IV and V.

3.2.5 Elemental Ratios

The Mg/Ca and Sr/Ca plots are illustrated in figures 14a and b respectively. As seen in all the other parameters, even Mg/Ca and Sr/Ca ratios show significant fluctuations in the warmer phase i.e. prior to ~1650 AD. The Mg/Ca ratios have remained constant at ~4 mmol/mol and the Sr/Ca values have a very narrow range between 1.33 and 1.37 mmol/mol for most part of the core. Highest Mg/Ca ratios and the lowest Sr/Ca values are observed between ~1800 and 1850 AD. Mg/Ca ratios rise by about 2 mmol/mol at ~1710 AD and significantly by 3 to 3.5 mmol/mol between 1800 to 1850 AD.

Similarly, approximately at 1710 AD the Sr/Ca ratios drop significantly by ~0.10 mmol/mol and between ~1800 to 1850 AD shows the maximum drop in values by ~0.15 mmol/mol.

3.2.6 Oxygen Isotope Ratios

5 sub-samples were merged to get a single measurement between 40 and 50 cm of the core as enough specimens were not available. The oxygen isotopic ratios vary between -2.4 and -3.25‰. Similar to the foraminiferal plots, the core shows an initial prolonged dry phase, followed by significant warm events (characterised by lower $\delta^{18}\text{O}$ values) characterised by 3 major fluctuations (Fig. 15). The $\delta^{18}\text{O}$ values remain constantly at ~-2.6‰ and above for a major portion of the drier phase. Most prominent between 1550 and 1600 AD, the driest event is seen at ~1575 AD. The transition from dry to wet can be fixed at ~1650 AD after which the highly fluctuating $\delta^{18}\text{O}$ values have remained lower than -2.8‰. Significant drop in the $\delta^{18}\text{O}$ values (about 0.3 to 0.4‰) is seen at approximately 1675, 1765 and 1875 AD, reinforcing the major fresh water pulses implied by the *A. trispinosa* abundances.

4. Discussion

The discussion is divided into two parts. In the first part, the palaeo-ecological significance of species *A. trispinosa* is established. In the second, the past climatic events are discussed.

4.1 Ecological preferences of *Asterorotalia trispinosa*

The results of the statistical analysis clearly indicates the preference of *A. trispinosa* to low salinities and finer substrates (Table 5 and Fig. 5). After a thorough review of the previous studies on the distribution of *A. trispinosa* in modern environments (Table 1), we suggest that salinity is a major governing factor on its occurrence, with optimum salinity ranges being ~31 to 33 psu. Rao (1998) reported large total abundances (live + dead) of *A. trispinosa* in all four seasons, though the species was most abundant in January when the salinity was least (31-32 psu) and least abundant in April when the salinity was highest (34-35 psu). These observations reinforce the observations made herein that *A. trispinosa* prefers low-salinity regimes.

Another governing factor on the distribution of *A. trispinosa* is texture of the substrate as the species has always been reported from clays and mud. Thalmann (1933) hypothesized that the long spines of *A. trispinosa* were perhaps an adaptation to avoid burial in high sedimentation areas. Rao (1998) reported *A. trispinosa* from a depth range of 38 to 55 m and observed that it consistently exhibits a distinct preference for substrates with relatively higher mud content. While summarizing the distribution and ecology of living benthic foraminifera, Murray (1973) concluded that no single

species is specific of deltas. However, based on the results presented here and previous work, it is probable that *A. trispinosa* may be exclusively endemic to fine grained sediments of the Indo-Pacific deltaic regimes that are characterized by high sedimentation rates. The absence of this species from similar deltaic environments elsewhere, however, is problematic [absent from, e.g. the Mississippi River delta (Phleger, 1955; Lankford, 1959) and the Colorado River delta in the Atlantic region (Barbieri, 2001); the Fraser River delta in British Columbia (Jonasson and Patterson, 1992); the Rhone (Blanc-Vernet, 1969; Vangerow, 1974) and Ebro Deltas of Europe (Scrutton, personal communication in Murray, 1973); the Shatt Al-Arab Delta in the Arabian Gulf (Al-Zamel and Cherif, 1998); and the Pacific region (Inoue, 1989)]. Salinity may therefore be the additional controlling factor on the distribution of the species. Although the deltas described above are also characterized by high rates of sedimentation, they are characterized by higher salinities ranging from 34-36 psu and up to 37 psu (Ebro Delta, Spain) in contrast to the ~ 32 psu characterizing the present study area. *A. trispinosa* thus holds promise as a palaeosalinity indicator in palaeoclimatic reconstructions. Due to the sensitivity of this species to salinity variations, the abundance of this species in sub-surface sediments can be used as an indicator of fluctuating river discharge and thus as a proxy for generating high resolution records for palaeo-monsoon in the study area. Lambert (2003) used the distribution of *A. trispinosa* in shallow cores as one of the indicator species of the outer delta front while reconstructing the Holocene deltaic regression patterns in the Mahakam Delta in the Eastern Kalimantan, Indonesia.

4.2 Palaeoclimatic reconstruction

The climatic events indicated by *A. trispinosa* abundances and MPS are also well reflected by the additional proxies. A climatic transition from dry to wet as well as three major fresh water pulses, are reflected well in all the foraminiferal parameters discussed above in section 3.2.

Modern trends suggest a multi proxy approach towards palaeoclimatic studies, especially supplementation with geochemical data which provide quantitative, reliable and precise measurements of climatic events. In order to confirm the wet and dry events suggested by the foraminiferal studies, elemental and stable isotopic ratios were obtained on the same core. The analytical methods have been explained above in section 2.

The long residence times of Mg, Ca (~1Ma each) and Sr (~5 Ma) (Broecker and Peng, 1982), suggests that there should be very limited variability of seawater Sr/Ca on the relatively short timescales of glacial-interglacial change (Martin et al., 1999) or even less on very high resolution records of the Holocene. Therefore, variations in Sr/Ca recorded in marine carbonates on the short

timescales have been attributed to environmental parameters (Elderfield et al., 2000). Coupled numerical models of the Sr and Ca budgets of the ocean reveal that large changes in river fluxes and carbonate accumulation rates can produce seawater Sr/Ca variations that approximate both the shape and amplitude of foraminiferal Sr/Ca variations. Mg/Ca in marine carbonates varies with latitude suggesting temperature dependence.

Taking advantage of the fact that all three elements have longer residence times and could thus give reliable signatures for fresh water discharge in the region, simultaneous measurements of Ca, Mg and Sr were done by the technique described above. ~1800 to ~1850 AD is the period when *A. trispinosa* shows highest abundances (Fig. 13a) and thus lowest salinity. Thus, the elemental concentrations support the hypothesis that *A. trispinosa* can be effectively used as an indicator of freshwater influx.

The higher Mg/Ca ratios and lower Sr/Ca ratios at these intervals seem to indicate a significant warming resulting in heavy fresh water discharge causing significant drop in salinities. As stated above, because these elements have a extremely long residence times, significant environmental changes / salinity gradients are required to cause a variation in their amplitude over smaller time scales. Thus, in the present study large amplitude changes are seen only during the warming events.

Oxygen isotopic concentrations of foraminiferal shells serve as a measure of ambient water temperatures. However, these can also vary because of fresh water influx (glacial ice melt or evaporation-precipitation), especially in the study area where the marine environment is largely governed by high gradients in the salinity regimes.

The climatic events documented by *A. trispinosa* are not only evidenced by foraminiferal assemblages, but also reinforced by geochemical proxies namely, stable isotopic and elemental ratios. Thus, the present study does not only successfully demonstrate the reliability of the species *A. trispinosa* as a proxy for palaeomonsoons but also validates the climatic interpretations drawn and discussed.

4.2.1 Cyclicity

Major freshwater pulses in the study area are at ~1675, 1765 and 1850 AD. They occur at an interval of 90 and 85 years respectively and are clearly evidenced in the dataset. However, the data set does also show several smaller fluctuations, especially in the older part of the core. These minor fluctuations are better reflected by the downcore variations in the reproductive behaviour of *A. trispinosa*, abundance of the low-salinity assemblage and the oxygen isotope ratios. Thus, in order to

verify if any cyclicity exists in climatic events, the MPS data of *A. trispinosa* was analysed for cyclicity using the software Redfit 3.8. The same parameter has been used by previous workers to document cyclicity in monsoons in the past few hundred years (Nigam and Khare, 1995). The MPS data revealed a ~93 year cyclicity at a 90% level of reliability (Fig 16).

Cycles of almost similar length have been noticed in different climatic records. They include phenomenon such as changes in the flooding of the River Nile (Fairbridge, 1984) and monsoon variations along the central west coast of India (Nigam et al., 1995). Variations in the radius of the sun are believed to modulate these cycles at a periodicity of 80 (± 10) years, known as the 'Gleissberg Cycle'.

4.2.2 Asian signatures of the Little Ice Age (LIA)

The Intergovernmental Panel on Climate Change (IPCC-2001), describes the Little Ice Age as "a period of modest cooling between the ~16th and the mid 19th century of the Northern Hemisphere during which the temperature was 1°C less than that of the present" (UNEP/GRID-Arendal). It was initially believed that the LIA only impacted the European climate. Later there were reports of this phenomenon from many other parts of the globe, including those from the Southern Hemisphere [North America (Jacoby et al., 1988; Jacoby and D'Arrigo, 1989; and many more), Western Greenland and Subtropical North Atlantic (Mann, 2002), China and Korea (Kim, 1984 ; Kim and Choi, 1987; Wang and Wang, 1990; Wang, 1991), Japan (Meijina and Tagami, 1983), South America (Villalba, 1990; Boninsegna, 1992), New Zealand (Salinger, 1979), etc]. Bradley and Jones (1993) reported it as a period of both, warm and cold climatic anomalies, which varied in importance geographically. Unlike the true ice ages of the Pleistocene which were marked by a substantial lowering of global temperatures (2°C to 3°C below current levels), the 13th to 19th century was generally colder, quite variable in timing from region to region and in most cases punctuated with intermittent periods of warmth (Bradley and Jones, 1993; Pfister, 1995). In the Northern Hemisphere, the coldest interval was between ~1570 to ~1730 and through most of the nineteenth 19th century, though not all records show this pattern. Though there is no agreed consensus on the date of its beginning, it is agreed that the LIA ended at ~1850 AD after which warming began. It is also agreed that during the LIA there were three sunspot minima beginning at ~1650, 1770 and 1850 AD, each separated by slight warming intervals (Mann et al., 1999; Website of the NASA Earth Observatory; UNEP/GRID-Arendal).

Coincidentally the present data set collected on the Ayeyarwaddy Delta Shelf off Myanmar offers very high-resolution climatic records of the 16th to the 19th Century and seems to document

Asian signatures of the Little Ice Age. It is worth exploring if this phenomenon affected the present study area in any way. Changes in the incoming energy from the sun to the earth, due to changes in the radius of the sun and/or number of sunspots have been reported to bring about climatic variations, including monsoonal rains over India (thus the fresh water discharge through rivers) and adjoining areas (Nigam et al., 1995; Gupta et al., 2005; Khare and Nigam, 2006, Saraswat et al., 2007). It is most logical to attribute the three fresh water pulses recorded at ~1675, 1765 and 1850 AD (Fig. 12 and Fig. 13a-b) in the current data set, to the three sunspot minima reported during this period. However, the authors refrain from doing so because there is much speculation over the causes of these significant climatic fluctuations within the past 500 years (increased volcanic activity, sunspot activity, ENSO and change in ocean circulation patterns, etc). Researchers trying to understand the climate dynamics within this period stress upon the need for reporting high resolution and calibrated proxy records from different parts of the globe (Bradley and Jones, 1993; Mann, 2002). The present work is an attempt to report such data and comparable phenomena from Central Asia and account for the regional hiatus in data. However, it would be interesting to ascertain the causes of these high amplitude climatic events reported here.

5. Conclusions

The highlight of this study is that this data set offers high resolution records for the past 489 years; a resolution of ~4 years since 1513 to 1676 AD and since then ~8 years resolution unto Present.

1. Downcore variations in the abundance and MPS of *A. trispinosa* indicate:
 - Two significant climatic conditions in the study area since 1513 AD; a dry climate prior to 1650 AD and warm and wet climate since 1650 to present.
 - The period between 1800-1850 AD experienced maximum rainfall / fresh water influx; Mg/Ca and Sr/Ca values well support this result.
 - Since 1650, 3 major freshwater pulses are recorded in the core at ~1675, 1750 and 1850 AD.
 - MPS data shows a 93.86 year cyclicity in climatic events in the study area which falls into the scope of the Gleissberg Cycle (viz. 80 ± 10 years).
2. The records seem to represent the Asian signatures of the climatic events of the Little Ice Age, i.e. the duration from the 16th to the mid 19th century.
3. These freshwater pulses seem to be the signatures of the warming events associated with the Little Ice Age.

4. Though the applicability of *A. trispinosa* as a palaeoclimatic proxy is limited to the Indo-pacific region, the results of this study are of global importance and significant to workers who are trying to understand the climate dynamics of the past 500 years.

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References:

- Al-Zamel, A.Z., Cherif, O.H., 1998. Subtidal foraminiferal assemblages of the western part of the Shatt Al-Arab Delta, Kuwait, Arabian Gulf. *Jour. Foram. Res.* 28 (4), 327-344.
- Barbieri, R., 2001. Taphonomic implications of foraminiferal composition and abundance in intertidal mud flats, Colorado River delta (Mexico). *Micropalaeontol.* 47, 73-86.
- Barker, S., Greaves, M., Elderfield, H., 2003. A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry. *Geochem. Geophys. Geosyst.* 4, doi: 10.1029/2003GC000559.
- Bhatia, S.B., Bhalla, S.N., 1959. Recent Foraminifera from beach sand at Puri, Orissa. *Jour. Palaeontol. Soc. India* 4, 78-81.
- Bhonsle, S., 2005 (Unpublished Results). Planktonic foraminiferal approach to assess palaeo-environmental conditions of Equatorial Indian Ocean: Preliminary Results. M.Sc. Dissertation, Goa University, 67 p.
- Blanc-Vernet, L., 1969. Contribution à l'étude des Foraminifères de Méditerranée. *Recl. Trav. Stn mar.* Endoume 48, 5-281.
- Bock, W.D., 1970. *Hyalinea balthica* and the Plio-Pleistocene Boundary in the Caribbean Sea. *Science* 170 (3960), 847-848.

- Boltovskoy, E., Wright, R., 1976. Recent Foraminifera. Dr. W. Junk Publishers, The Hague, pp.515.
- Boninsegna, J.A., 1992. South American dendroclimatological records in R.S. Bradley and P.D. Jones eds. Climate since A.D. 1500, London, Routledge, 446-462. Bradley, R.S., Jones, P.D., 1993. Little Ice Age summer temperature variations: their nature and relevance to recent global warming trends. Holocene 3 and 4, 367-376.
- Bradshaw, J.S., 1955. Preliminary laboratory experiments on ecology of foraminiferal populations. Micropalaeontol. 1, 351-358.
- Bradshaw, J.S., 1957. Laboratory studies on the rate of growth of foraminifera. Jour. Palaeontol. 31, 1138-1147.
- Broecker, W.S., Peng, T.H., 1982. Tracers in the Sea. Lamont-Doherty Geological Observatory, Palisades, New York, pp. 690.
- Chang, Y.M., 1967. Accuracy of fossil percentage estimation: Jour. Palaeontol. 41, 500-502.
- Climate Change 2001: The Scientific Basis. UNEP/GRID-Arendal
http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg1/
- Collen, J.D., 1974, *Hyalinea balthica* from the Pliocene sediments, New Zealand. Jour. Geol. Geophys. 17 (4), 907-912.
- D'Arrigo, R.D., Jacoby, G.C., Jr., 1989. Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. Climatic Change 14, 39-59.
- Dennison, J.M., Hay, W.W., 1967. Estimating the needed sampling area for subaquatic ecologic studies. Jour. Palaeontol. 41, 706-708.
- Dutta, K., Bhushan, R., Somayajulu, B.L.K., 2001. ¹⁴C reservoir ages and ΔR correction values for the northern Indian Ocean. Radiocarbon 43, 483-488.
- Elderfield, H., Cooper, M., Ganssen, G., 2000. Sr/Ca in multiple species of planktonic foraminifera: implications of reconstructions of seawater Sr/Ca. Geochem. Geophys. Geosys. 1, 1999GC000031, ISSN:1525-2027.
- Fairbridge, R.W., 1984. The Nile floods as a global climatic/solar proxy. Climatic Changes on a Yearly to Millennial Basis, 181-190.
- Frerichs, W.E., 1970. Distribution & Ecology of Benthonic Foraminifera in the sediments of the Andaman Sea. Contrib. Cush. Found. Foram. Res. 21 (4), 123-147.
- Gandhi, S.M., 1999 (Unpublished results). Micropalaeontological (benthic foraminifera) study on the depositional environment of Palk Strait, east coast of India. Ph.D. Thesis, Tamil University, Tanjavur, 192 p.
- Ghose, B.K., 1966. *Asterorotalia trispinosa* (Thalman), a spinose rotalid from Digha Beach, Southeastern Bengal. Contrib. Cush. Found. Foram. Res. 17 (3), 104-108.
- Gooday, A.J., 1988. A response by benthic foraminifera to the deposition of phytodetritus in the deep sea. Nature 332, 70-73.

- Gooday, A.J., 1993. Deep-sea benthic foraminiferal species which exploit phytodetritus: characteristic features and controls on distribution. *Mar. Micropaleontol.* 22, 187–205.
- Gooday, A.J., 1994. The biology of deep-sea foraminifera: a review of some advances and their significance in paleoecology. *Palaios* 9, 14–31.
- Gupta, A.K., Das, M., Anderson, D.M., 2005. Solar influence on the Indian summer monsoon during the Holocene. *Geophys. Res. Lett.* 32:L17703, doi:10.1029/2005GL022685.
- Hayward B.W., Grenfell, H.R., Carter, R., Hayward, J.J., 2004. Benthic foraminiferal proxy evidence for the Neogene palaeoceanographic history of the Southwest Pacific, east of New Zealand. *Mar. Geol.* 205, 147-184.
- Hofker, J., 1951. The Foraminifera of the Siboga Expedition, pt. 3, Ordo Dentata: Siboga expeditie, Mon. IVa, 513 p.
- Huang, T., 1964. “Rotalia” group from the upper Cenozoic of Taiwan. *Micropalaeontol.* 10 (1), 1-3.
- Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C., Blackwell, P.G., Buck, C.E., Burr, G., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., McCormac, F.G., Manning, S., Ramsey, C.B., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Marine04 Marine Radiocarbon Age Calibration, -0-26 Cal Kyr BP. *Radiocarbon* 46, 1059-1086.
- Inoue, Y., 1989. Northwest Pacific foraminifera as palaeoenvironmental indicators. *Science Reports of the Institute of Geoscience, University of Tsukuba*, 10, 57-162.
- Jacoby, G.C., Jr., Ivanciu, I.S., Ulhan, L.D., 1988. A 263-year record of summer temperature for northern Quebec reconstructed from tree-ring data and evidence for major climatic shift in the early 1800s. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 64, 69-78.
- Jonasson K.E., Patterson R.T., 1992. Preservation potential of salt marsh foraminifera from the Fraser River delta, British Columbia. *Micropalaeontol.* 38 (3), 289-301.
- Khare, N., Nigam, R., 2006. Can the possibility of some linkage of monsoonal precipitation with solar variability be ignored? Indications from foraminiferal proxy records. *Curr. Sci.* 90 (12), 1685-1688.
- Kim, Y.O., 1984. The Little Ice Age in Korea: an approach to historical climatology. *Geography Education* 14, 1-16 (in Korean with English abstract).
- Kim, G.S., Choi, I.S., 1987. A preliminary study on long-term variation of unusual climatic phenomena during past 1000 years in Korea in D. Ye, C. Fu, J. Chao, and Yoshino eds. *The climate of China and global climate*. China Ocean Press, Beijing, 30-37.
- Lambert, B., 2003. Micropaleontological investigations in the modern Mahakam delta, East Kalimantan (Indonesia). *Carnets de Geologie/Notebooks on Geology*, Article 2003/02, 1-21.
- Lankford, R.R., 1959. Distribution and ecology of Foraminifera from East Mississippi delta margin. *Bull. Amer. Assoc. Pet. Geol.* 43, 2068-2099.
- Levitus, S., and Boyer, T., 1994, *World Ocean Atlas 1994 Volume 4: Temperature*. NOAA Atlas NESDIS 4, U.S. Department of Commerce, Washington, D.C., <http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94/>

- Maejima, I., Tagami, Y., 1983. Climate of Little Ice Age in Japan. Geographical Reports of the Tokyo Metropolitan University 18, 91-111.
- Mann, M.E., 2002. Little Ice Age. The Earth system: physical and chemical dimensions of global environmental change-Volume 1 in M.C. MacCracken and J.S. Perry eds. Encyclopedia of Global Environmental Change. John Wiley and Sons Ltd., Chichester, 504-509.
- Mann, M.E., Bradley, R.S., Hughes, M.K. (1999). Northern Hemisphere temperature patterns and climate forcing over the past six centuries. *Nature*, 392, 779-787.
- Martin, P.A., Lea, D.W., Mashiotta, T.A., Papenfus, T., Sarnthein, M., 1999. Variation of Foraminiferal Sr/Ca over Quaternary Glacial-Interglacial Cycles: Evidence for changes in mean ocean Sr/Ca? *Geochem. Geophys. Geosys.* 1, 1999GC0006, ISSN:1525-2027.
- Martin, P.A., Lea, D.W., 2002. A simple evaluation of cleaning procedures on fossil benthic foraminiferal Mg/Ca. *Geochem. Geophys. Geosys.* 3, 8401.
- Mellis, R., Violanti, D., 2006. Foraminiferal biodiversity and Holocene evolution of the Phetchaburi coastal area (Thailand Gulf). *Mar. Micropaleontol.* 61 (1-3), 94–115.
- Murray, J.W., 1973. *Distribution and Ecology of Living Benthic Foraminiferids*: Heinemann Educational Books, London, pp. 274.
- Nigam, R., 1986. Dimorphic forms of Recent foraminifera: an additional tool in paleoclimatic studies. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 53, 239-244.
- Nigam, R., Khare, N., 1992. The reciprocity between coiling direction and dimorphic reproduction in benthic foraminifera. *Jour. Micropalaeontol.* 11 (2), 221-228.
- Nigam, R., Khare, N., 1995. Significance of correspondence between river discharge and proloculus size of benthic foraminifera in paleomonsoonal studies. *Geo-Mar. Lett.* 15 (1), 45-50.
- Nigam, R., Rao, A.S., 1987. Proloculus size variation in recent benthic foraminifera: Implications for paleoclimatic studies. *Estuar. Coast. Shelf Sci.* 24, 649-655.
- Nigam, R., Setty, M. G. A. P., 1982. Ecological regimen and distribution of *Virgulinitella spp.* in the inshore sediments of western India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 38, 57-61.
- Nigam, R., Khare, N., Nair, R. R., 1995. Foraminiferal evidences for 77-year cycles of droughts in India and its possible modulation by the Gleissberg solar cycle. *Jour. Coast. Res.* 11 (4), 1099-1107.
- Panchang, R., 2008 (Unpublished results). *Distribution and ecology of benthic foraminifera off Myanmar*. Ph.D. Thesis, Goa University, Goa, India. pp. 445, pl. 42.
- Pfister, C., 1995. Monthly temperature and precipitation in Central Europe 1525-1979: quantifying documentary evidence on weather and its effects, in *Climate Since A.D. 1500*, revised edition, eds. R.S. Bradley and P.D. Jones, Routledge, London, 118-142.
- Phleger, F.B., 1955. Ecology of Foraminifera in south-eastern Mississippi Delta area. *Bull. Amer. Assoc. Petrol. Geol.* 39, 712-752.
- Ramaswamy, V., Gaye, B., Shirodkar, P.V., Rao, P.S., Chivas, A.R., Wheeler, D., Thwin, S., 2008. Distribution and sources of organic carbon, nitrogen and their isotopic signatures in sediments from the Ayeyarwaddy (Irrawaddy) continental shelf, northern Andaman Sea. *Mar. Chem.* 111 (3-4), 137-150.

- Rana, S.S., 2009 (Unpublished results). Surface and sub-surface distribution of foraminifera from Central East Coast of India and its palaeo-ecological significance. Ph. D. Thesis, Goa University.
- Rao, N.R., 1998 (Unpublished results). Recent foraminifera from the inner shelf sediments of the Bay of Bengal, Off Karikkattukuppam, near Madras, South India. Ph. D. Thesis, Madras University.
- Rao, P.S., Ramaswamy, V., Swe Thwin, 2005. Sediment texture, distribution and transport on the Irrawaddy continental shelf, Andaman Sea. *Mar. Geol.* 216, 239-247.
- Ross, R., 1984. *Hyalinea balthica* and its late Quaternary palaeoclimatic implications. *Strait of Sicily. Jour. Foram. Res.* 14 (2), 134.
- Ryan, P.T., 1997. Modern regression methods. John Wiley and Sons. Inc, New York. Salinger, M.J., 1979. New Zealand climate: the temperature record, historical data and some agricultural implications. *Climatic Change* 2, 109-126.
- Saraswat, R., Nigam, R., Barreto, L., 2005. Palaeoceanographic implications of abundance and mean proloculus diameter of benthic foraminiferal species *Epistominella exigua* in sub-surface sediments from distal Bay of Bengal fan. *Jour. Earth Sys. Sci.* 114 (5), 453-458.
- Saraswat, R., Nigam, R., Weldeab, S., Mackensen, A., 2007. A tropical warm pool in the Indian Ocean and its influence on ENSO over the past 137, 000 yrs BP. *Curr. Sci.* 92 (8), 1153-1156.
- Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C Age calibration program. *Radiocarbon* 35 (1), 215-230.
- Subbarao, M., Vedantam, D., Nageshwar Rao, J., 1979. Distribution and Ecology of Benthic Foraminifera in the Sediments of the Vishakhapatnam shelf, East Coast of India. *Paleogeogr. Paleoclimatol. Paleoecol.* 27, 349-369.
- Thalman, H.E., 1933. Zwei neue Vertreter der Foraminiferen – Gattung *Rotalia* Lamark 1804, *R. cubana* nom. nov. und *R. trispinosa* nom. nov.: *Eclogae Geologicae Helveticae*, 26 (2), 248-251.
- Ujjié, H., 1962, Introduction to statistical foraminiferal zonation: *Jour. Geol. Soc. Japan* 803, 431-450.
- Vangerow, E.F., 1974. Récentes observations écologiques des foraminifères dans la zone saumâtre de l'embouchure du Rhône. *Rev. de Micropaléontol.* 17, 95-196.
- Villalba, R., 1990. Climatic fluctuations in northern Patagonia during the last 1000 years as inferred from tree ring record. *Quat. Res.* 34, 346-360.
- Wang, S., Wang, R., 1990. Seasonal and annual temperature variations since 1470 A.D. in East China. *Acta Meteorologica Sinica* 4, 428-239.
- Wang, S., 1991. Reconstruction of temperature series of North China from 1380s to 1980s. *Sci. China. Ser. B* 34, 751-759.
- Website of the NASA Earth Observatory;
<http://eobglossary.gsfc.nasa.gov/Library/glossary.php3?xref=Little%20Ice%20Age>

Captions to Figures

Fig.1: Benthic foraminiferal species *Asterorotalia trispinosa* (a) ventral view; (b) dorsal view. Scale bar = 500 μm

Fig. 2: Map of the study area showing the sampling locations and bathymetry

Fig. 3: Temperature and salinity profiles recorded through CTD operations during the cruise SK-175 on board ORV Sagar Kanya in April 2002 on the Ayeyarwaddy Delta Shelf off Myanmar. Profiles a and b were obtained at deep station 18; Profiles c and d were obtained at station 46; and Profiles e and f at station 48; both the shallow stations have comparable depths (20 and 22 m, respectively) but show significant differences from the top to the bottom.

Fig. 4: Interpolation of dates within Core GC-5 on the basis of Pb-210 dating and ^{14}C AMS dates. X axis represents age in cal. Yrs.

Fig. 5: Ordination diagram showing the relationship of *A. trispinosa* with the sediment characteristics. Silt is directly and most closely linked with *A. trispinosa* in contrast to sand, which forms the farthest cluster.

Fig. 6: Ternary plot of sediment characteristics in samples showing presence of *A. trispinosa*. Most samples, especially those with higher frequencies of *A. trispinosa* lie in the silty-clay zone.

Fig. 7: The shaded regions represent different zones based on the abundance of *A. trispinosa* in the region

Fig. 8: An X-Y plot of *A. trispinosa* abundances versus salinity indicates that the maximum abundance of this species occurs within a range of 31.70 to 33.10 psu in the study area

Fig. 9: An X-Y plot of *A. trispinosa* abundances versus depth. The shaded portion indicates that the maximum abundance of this species occurs within a depth range of 18-40 m.

Fig. 10a-c: Downcore abundances of (a) Total Foraminiferal Number (b) Benthic and (c) Planktonic foraminifera in GC-5

Fig 11a-b: Comparison of the downcore percentage abundances of (a) Benthic and (b) Planktonic foraminifera

Fig. 12: Downcore variation in the collective percentage abundances of the low salinity species viz. *Ammonia*, *Asterorotalia*, *Elphidium* and *Hanzawaia*. I, II and III indicate the 3 major events of fresh water pulses in the study area.

Fig. 13a-b: Downcore variations in (a) abundance of *A. trispinosa* (b) MPS. 'A' indicates the period of lowest freshwater influx and 'B' indicates the period of highest freshwater influx in the study area. The low salinity periods are matched 'crest-to-crest' in the two parameters and shaded in grey.

Fig. 14a-b: Downcore variation of (a) Mg/Ca ratios and (b) Sr/Ca ratios obtained on benthic foraminiferal species *Hanzawaia concentrica*

Fig. 15: Downcore variation in stable oxygen isotopic ratios obtained on foraminiferal species *A. trispinosa*. A climatic boundary is seen at 1650 AD; I, II and III indicate the 3 major events of fresh water pulses in the study area.

Fig. 16: Plot of varied cyclicities obtained from analysis of MPS of *A. trispinosa*. Only the cyclicity of 93.86 years is indicated at a very high level of significance.

Table Captions

Table 1: Comparison of statistics related to *A. trispinosa* reported from different regions of the world

Table 2: Sampling details and environmental data, collected/generated on the surface sediments used in the study

Table 3: Percentage abundance of *A. trispinosa* as encountered at various stations

Table 4: Details of sub-surface samples dated and AMS dates obtained

Table 5: Correlation between various parameters and *A. trispinosa* abundance

Table 6: Statistical model expressing relationship between *A. trispinosa* abundance and various parameters recorded at different sampling locations

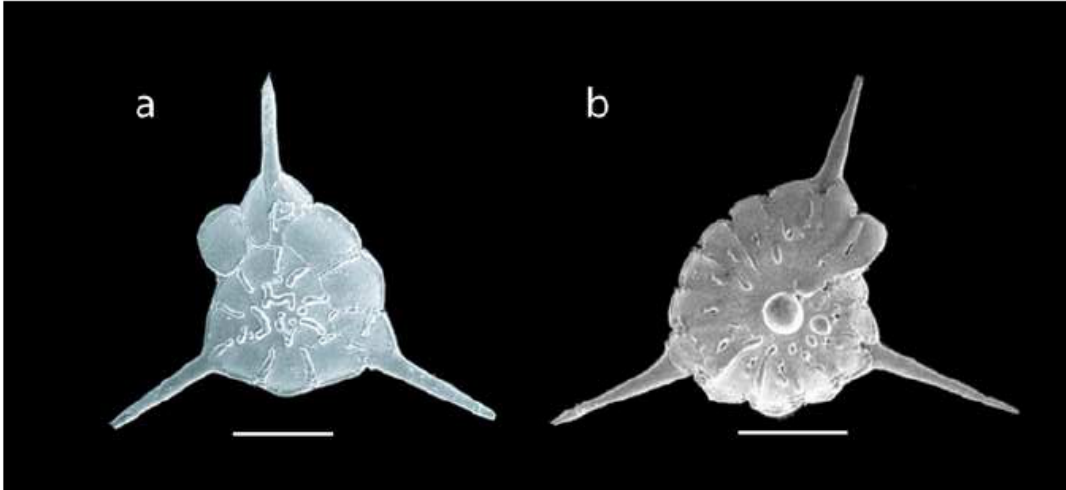


Fig.1

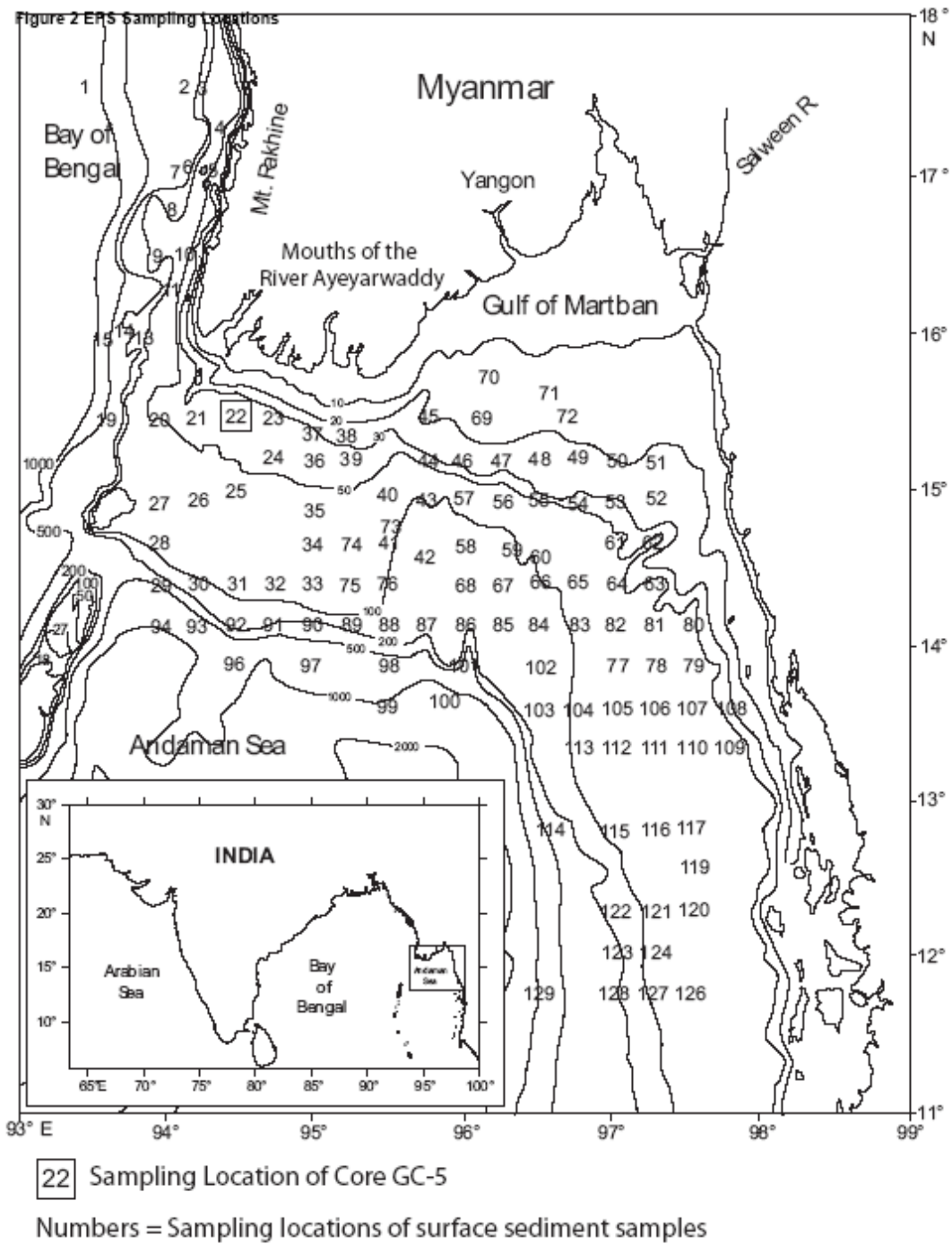


Fig.2

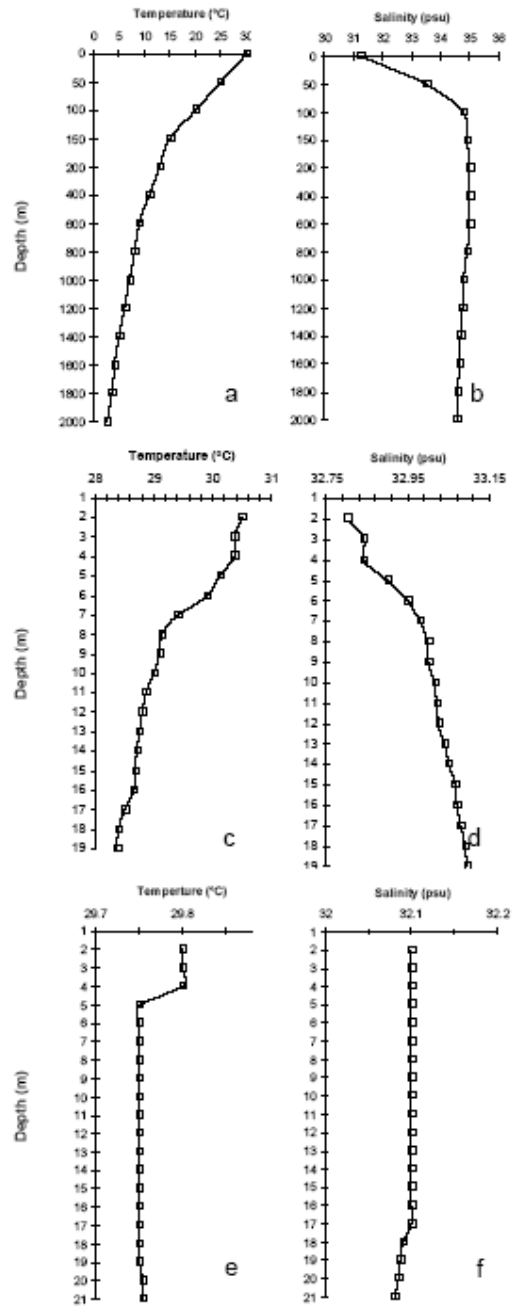


Fig.3

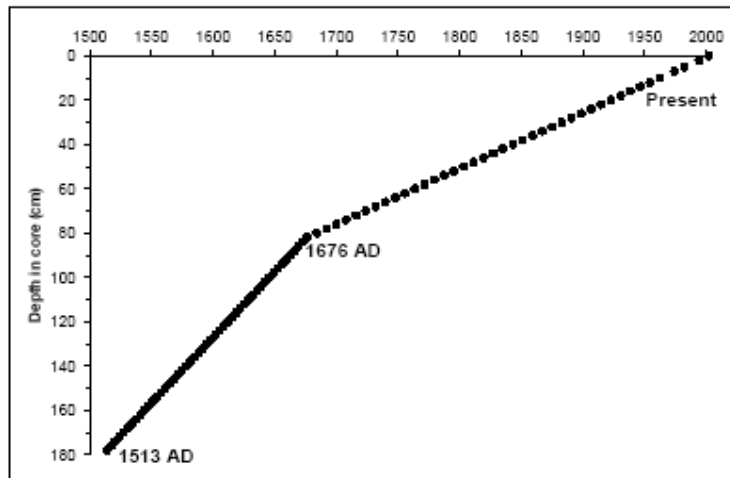


Fig.4

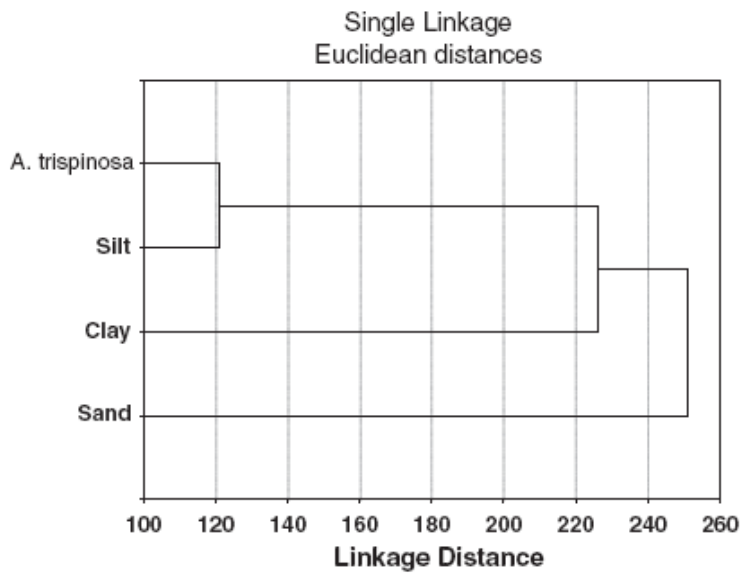


Fig.5

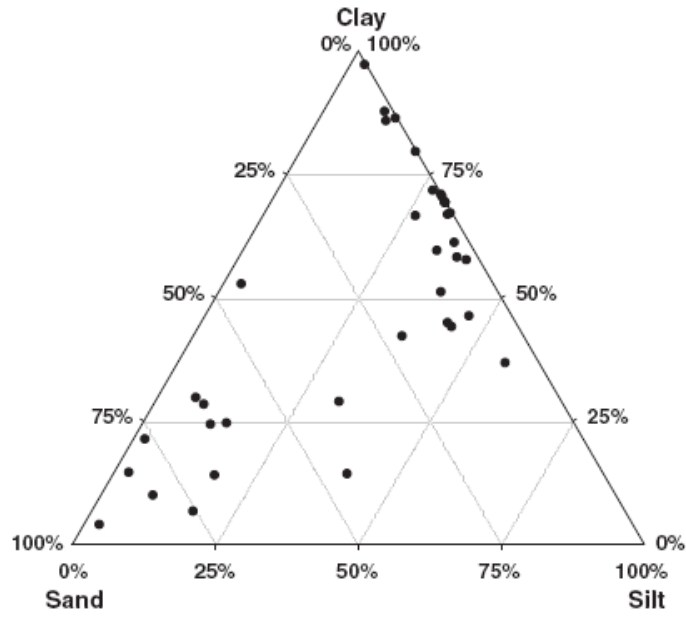


Fig.6

Figure 7 EPS *Trispinosa* abundance zones

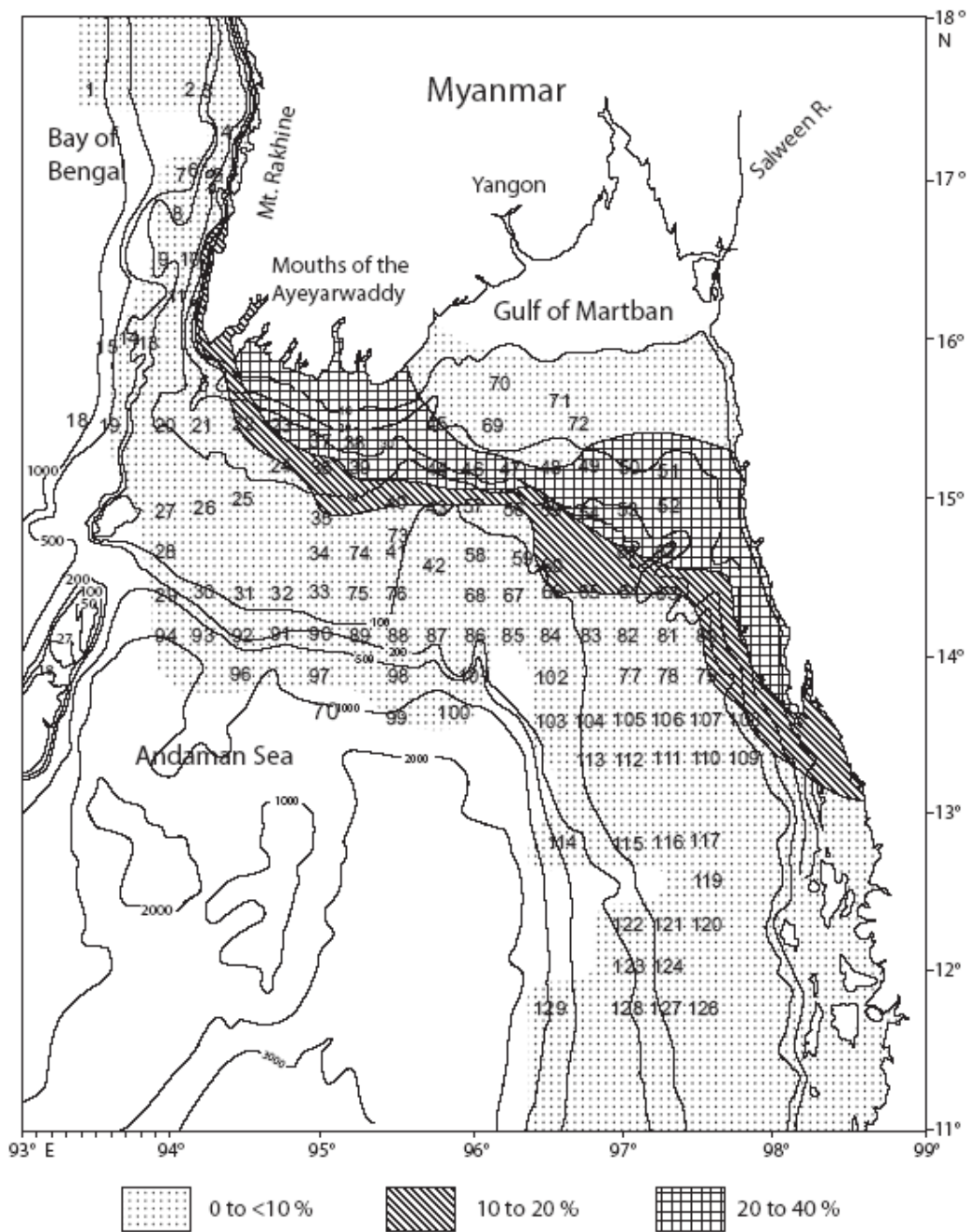


Figure 8 DOC Trispinosa Vs Salinity

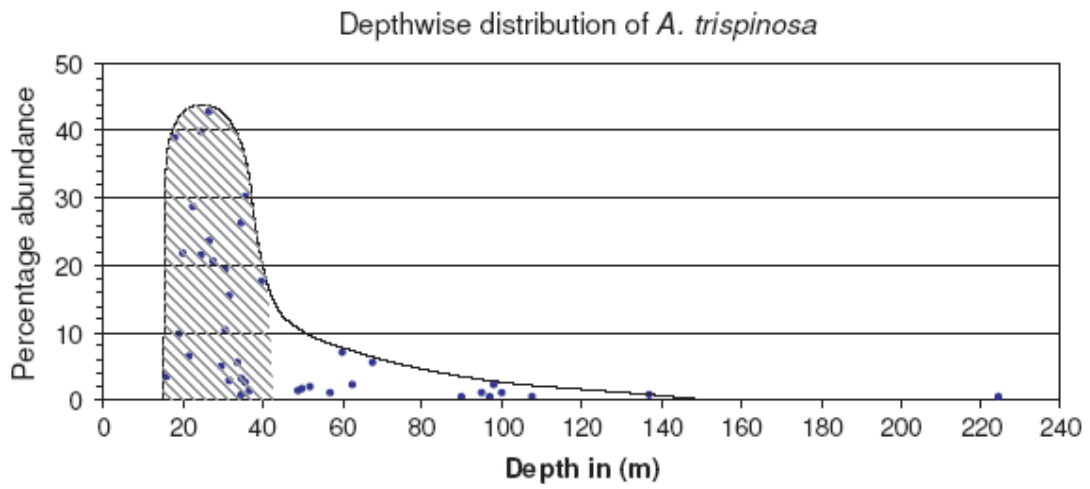
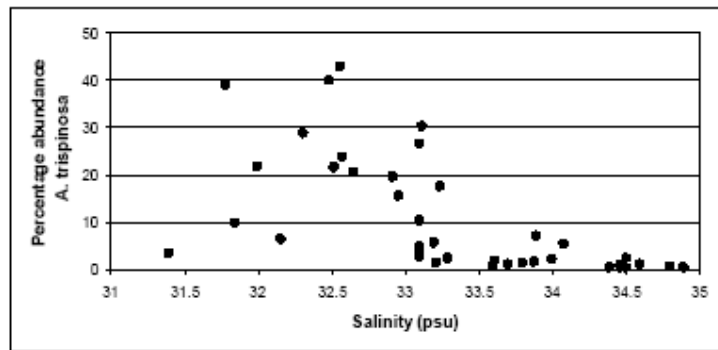


Fig.9

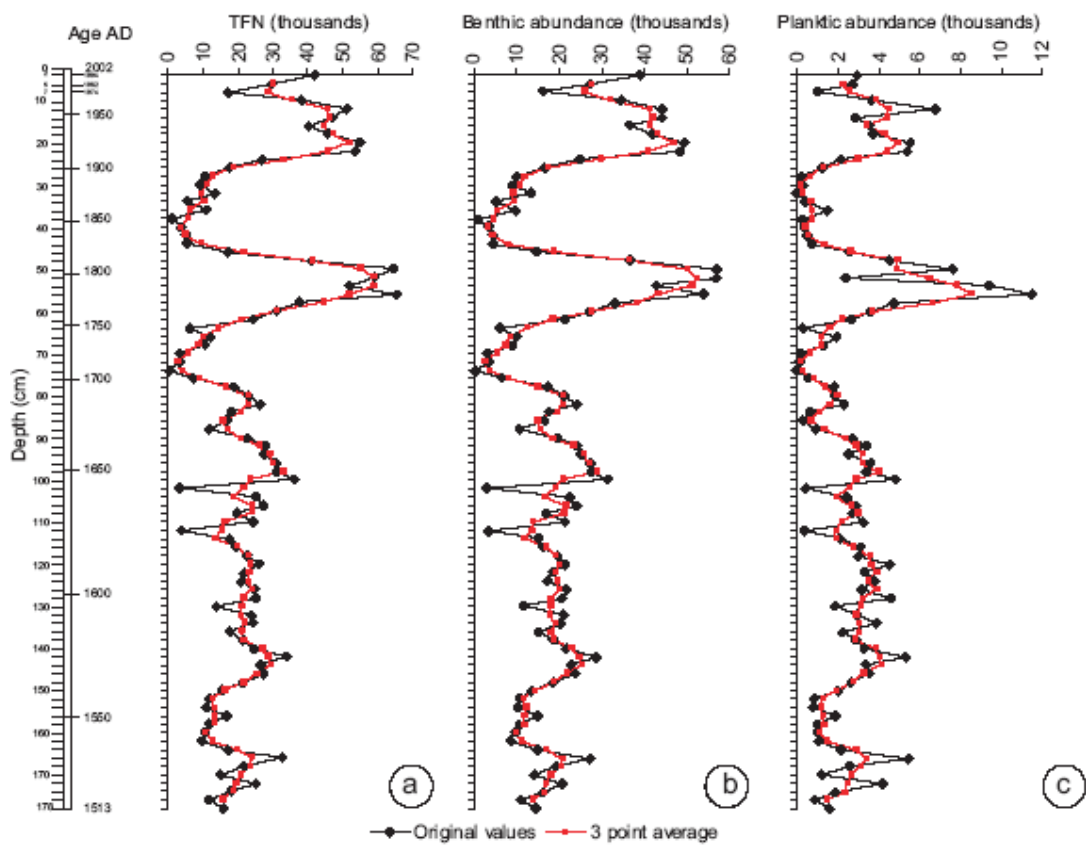


Fig. 10

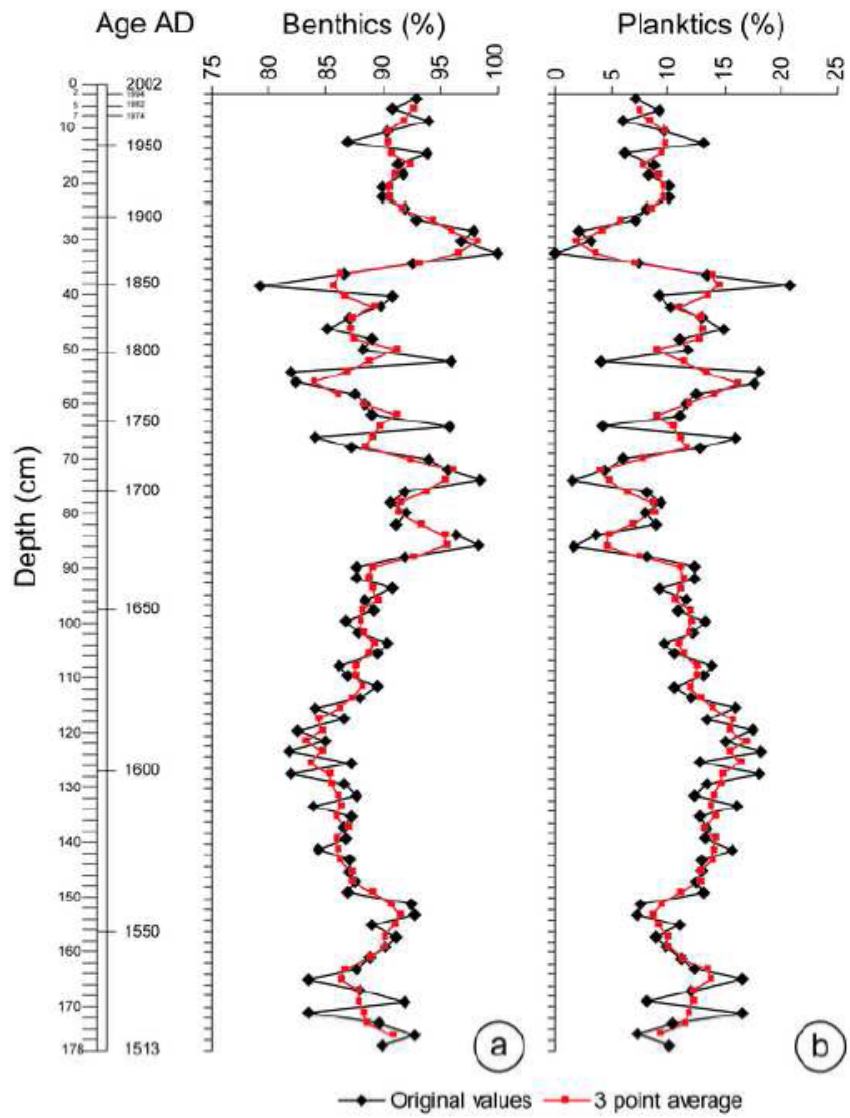
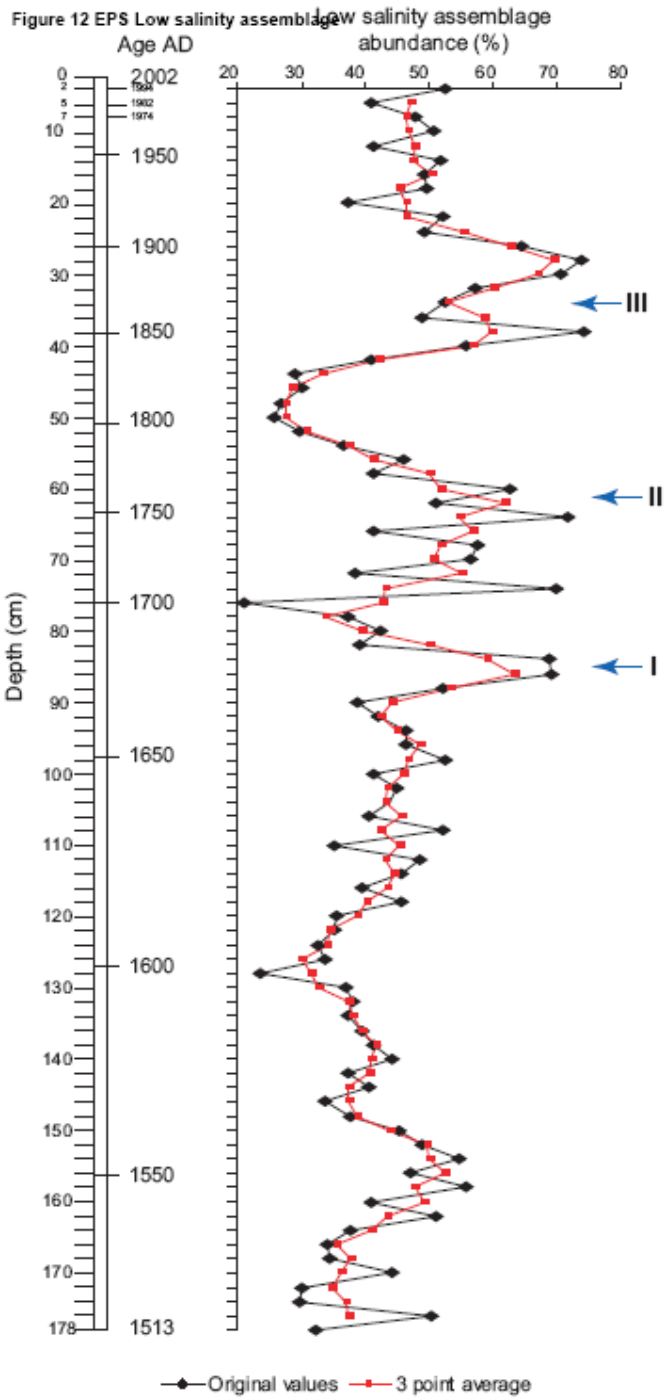


Fig.11



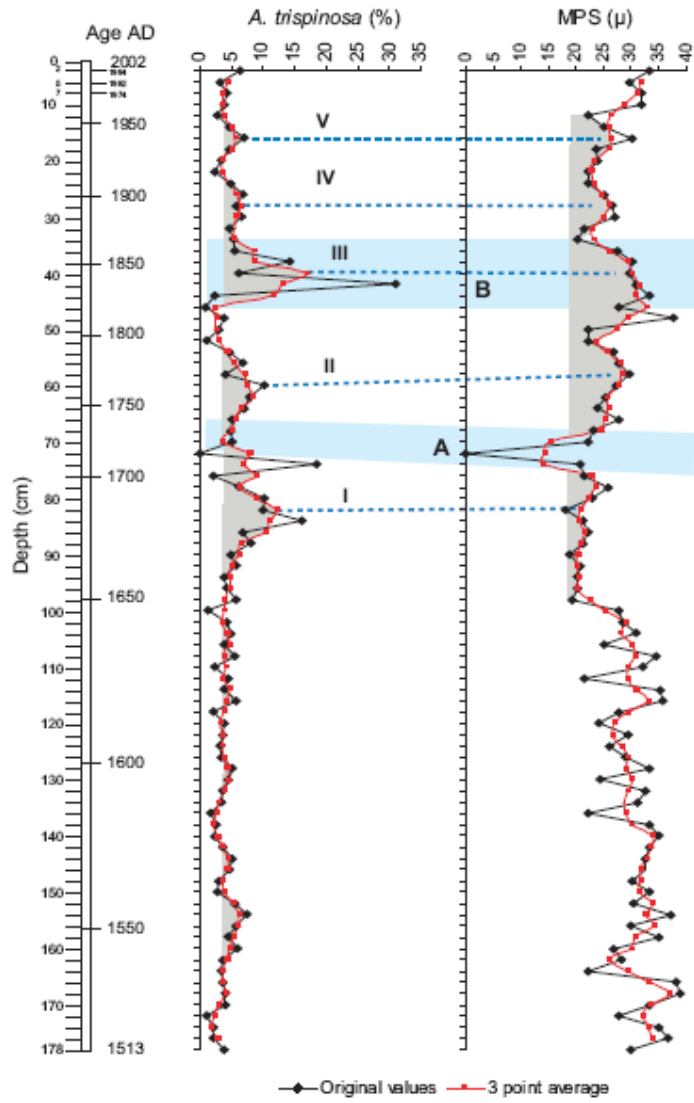


Fig.13

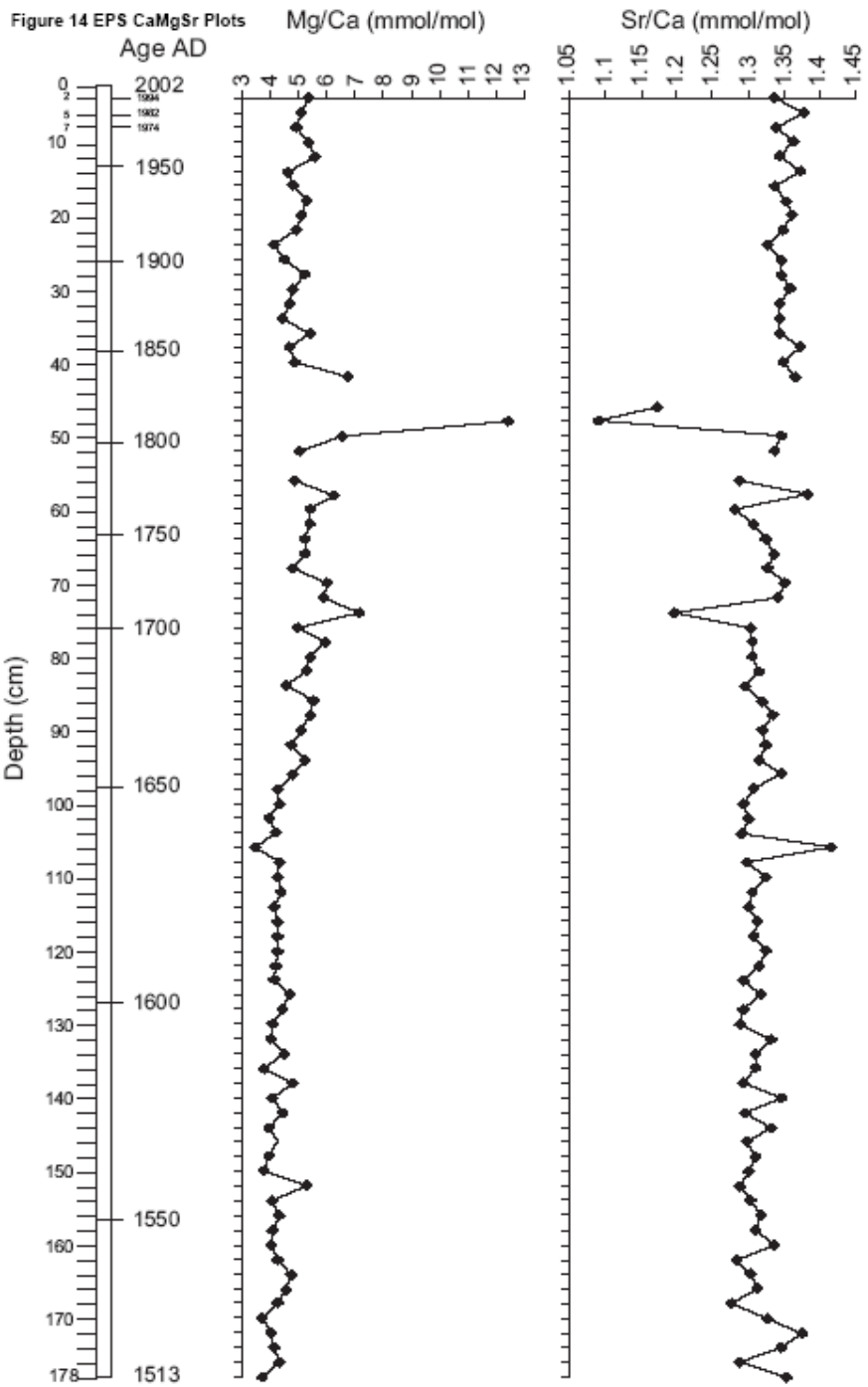
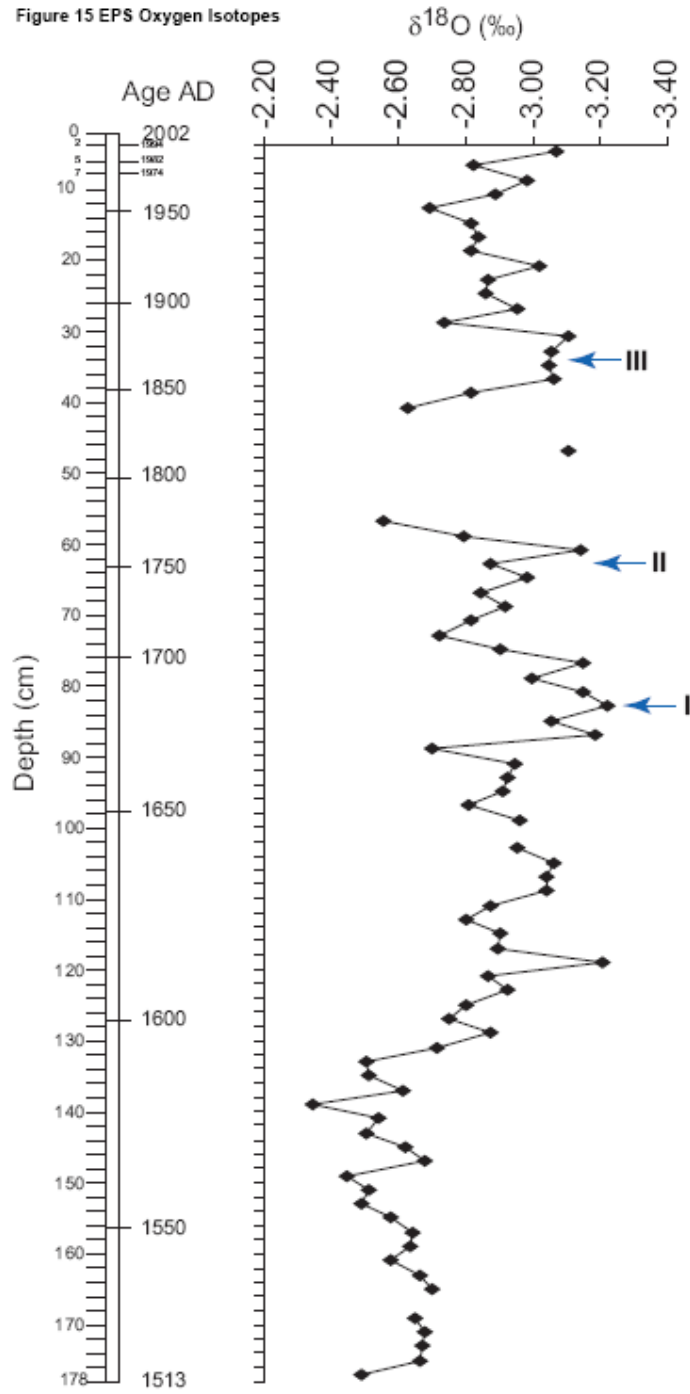


Figure 15 EPS Oxygen Isotopes



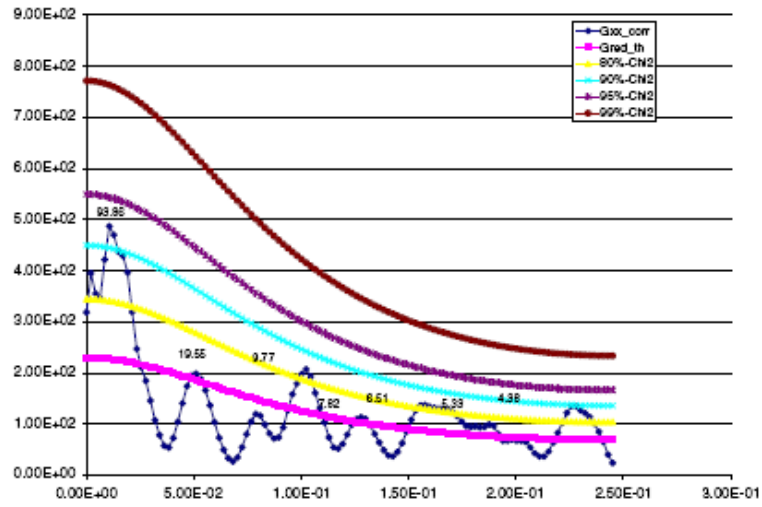


Fig.16

Table 1: Comparison of statistics related to *A. trispinosa* reported from different regions of the world

Region	Reported by	Maximum abundance	Depth (m)	Salinity (psu)	Temperature (°C)
Java	Thalman, 1933 Hofker, 1951	–	–		
Puri, Orissa, India	Bhatia and Bhalla, 1959	Rare	Beach sands		
Digha, Bengal	Ghose, 1966	Well represented	Beach sands		
Andaman Sea	Frerichs, 1970	37%	20–32	32.32–33.07	26.44–27.01
Visakhapatnam Shelf, East Coast of India	Subbarao et al., 1979	6%	20	32.6–32.8	27.5–27.9
Shelf region off Madras, East Coast of India	Rao, 1998	36–38%	38–55	32.48–32.90	24.2–24.5
Palk Strait, Southeast Coast of India	Gandhi, 1999	41–53%	11		
Mahakam Delta, East Kalimantan (Indonesia)	Lambert, 2003	70–100%	2–4	33.3–33.5	28.7–28.9
Central East Coast of India	Rana, 2009				
Eastern Bay of Bengal and Andaman Sea	Present work	38–43%	18–40	31.78–32.56	27.20–27.77

Table 2: Sampling details and environmental data, collected/generated on the surface sediments used in the study

Sample no.	Depth (m)	Latitude (°N)	Longitude (°E)	Salinity ^a (psu)	Temperature ^a (°C)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	TOC ^b (%)
SK-175/2	137	17.49	94.27	34.80	18.00	44.88	40.73	14.38	55.11	0.75
SK-175/3	49	17.49	94.45	33.80	26.80	43.97	3.22	52.80	60.90	0.762
SK-175/4	36	17.25	94.39	33.30	27.20	6.69	26.69	66.60	89.99	1
SK-175/5	34	16.99	94.34	33.20	27.20	2.64	36.12	61.22	97.70	0.932
SK-175/6	75	17.00	94.17	34.34	25.50	1.20	29.13	70.86	99.50	0.87
SK-175/7	125	16.99	94.10	34.80	18.90	2.05	21.49	76.45	97.94	0.75
SK-175/8	96	16.75	94.08	34.76	22.40	2.07	16.29	81.63	97.92	1.016
SK-175/9	132	16.48	93.38	34.85	18.90	1.83	19.47	78.69	98.16	1
SK-175/10	31	16.49	94.16	33.10	27.40	3.68	37.96	58.35	96.31	0.5
SK-175/11	32	16.27	94.08	33.10	27.35	7.38	46.22	46.39	92.61	0.5
SK-175/12	30	15.99	94.04	33.10	27.50	10.13	38.77	51.09	89.86	0.5
SK-175/13	76	15.99	93.89	34.28	23.50	9.83	13.03	77.13	90.16	0.75
SK-175/14	160	16.00	93.73	34.90	16.50	63.54	0.29	36.16	36.45	0.725
SK-175/15	29	16.00	93.68	32.98	27.46	N.A	N.A	N.A	N.A	0.4
SK-175/19	90	15.50	93.65	34.70	21.90	12.67	13.35	73.96	87.31	0.4
SK-175/20	33	15.49	94.00	32.94	27.50	N.A	N.A	N.A	4.40	0.078
SK-175/21	32	15.50	94.23	32.92	27.48	81.15	5.20	13.63	18.83	0.4
SK-175/22 ^c	37	15.51	94.50	33.22	27.15	63.60	6.57	29.81	36.38	0.28
SK-175/23	25	15.5	94.75	32.52	27.62	11.67	44.15	44.16	88.31	0.28
SK-175/24	35	15.16	94.45	33.10	27.15	68.21	17.66	14.11	57.90	0.282
SK-175/25	47	15.06	94.50	33.66	26.55	55.26	7.11	37.66	44.77	0.638
SK-175/26	66	15.00	94.25	34.23	25.00	21.36	30.81	47.81	78.62	0.491

Sample no.	Depth (m)	Latitude (°N)	Longitude (°E)	Salinity ^a (psu)	Temperature ^a (°C)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	TOC ^b (%)
SK-175/27	70	14.99	94.00	34.21	25.20	80.04	5.03	14.92	19.95	0.4
SK-175/28	76	14.74	93.99	34.21	25.10	52.81	24.89	22.28	47.17	0.49
SK-175/29	105	14.48	94.00	34.65	23.90	86.24	0.65	13.09	13.74	0.49
SK-175/30	93	14.50	94.24	34.64	21.30	66.00	12.49	21.50	33.99	0.48
SK-175/31	90	14.50	94.50	34.57	21.19	63.15	15.83	21.01	36.84	0.48
SK-175/32	93	14.49	94.75	34.56	21.00	15.91	50.59	33.45	84.04	0.6
SK-175/33	88	14.50	94.99	34.55	20.90	64.77	14.92	20.30	35.22	0.3
SK-175/34	60	14.74	94.99	33.86	26.40	46.85	1.58	51.56	53.14	0.431
SK-175/35	50	14.95	95.00	33.88	26.40	1.46	10.59	87.94	98.53	0.75
SK-175/36	32	15.24	95.00	32.96	27.35	21.36	36.61	42.24	99.00	0.924
SK-175/37	23	15.40	95.00	32.31	27.68	5.91	57.24	36.83	92.60	0.535
SK-175/38	18	15.39	95.22	31.78	27.77	11.87	43.22	44.89	88.80	0.599
SK-175/39	25	15.25	95.25	32.49	27.58	0.87	32.14	66.97	99.11	1
SK-175/40	63	15.04	95.50	34.00	25.30	0.23	2.41	97.35	99.70	0.827
SK-175/41	95	14.74	95.49	34.46	21.60	2.34	11.77	85.88	99.20	1.053
SK-175/42	100	14.66	95.75	34.60	21.30	100.00	N.A	N.A	50.20	0.282
SK-175/43	98	15.25	95.75	34.50	21.00	0.20	13.19	86.14	99.33	1
SK-175/44	35	15.30	95.45	33.10	27.08	6.98	35.94	63.27	99.80	0.737
SK-175/45	16	15.25	95.99	31.40	27.68	82.97	2.46	14.56	100.00	0.74
SK-175/46	20	15.25	96.24	32.00	27.60	0.21	30.38	69.39	99.80	0.71
SK-175/47	19	15.26	96.49	31.85	27.60	0.08	30.47	69.43	100.00	0.688
SK-175/48	22	15.26	96.49	32.16	27.54	0.02	28.99	71.00	100.00	0.718
SK-175/49	22	15.25	96.75	31.92	27.50	0.01	27.53	72.46	99.99	0.664
SK-175/50	20	15.24	96.99	31.90	27.46	0.06	7.36	92.62	99.98	0.735
SK-175/51	20	15.24	97.25	31.88	27.42	0.14	15.97	83.88	99.85	0.712

Sample no.	Depth (m)	Latitude (°N)	Longitude (°E)	Salinity ^a (psu)	Temperature ^a (°C)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	TOC ^b (%)
SK-175/52	28	15.01	97.25	32.66	27.10	0.94	27.11	71.94	99.20	0.684
SK-175/53	27	15.00	96.99	32.56	27.20	0.20	20.16	79.63	99.90	0.662
SK-175/54	27	14.98	96.74	32.58	27.40	0.35	32.45	67.18	99.80	0.688
SK-175/55	31	15.00	96.49	32.92	27.10	0.18	30.53	69.28	99.90	0.718
SK-175/56	60	15.00	96.25	33.90	26.35	0.03	29.47	70.49	100.00	0.691
SK-175/57	68	15.00	95.99	34.08	24.70	2.28	40.84	58.93	99.90	0.745
SK-175/58	108	14.74	95.99	34.50	19.30	62.93	8.64	28.41	57.90	0.85
SK-175/59	140	14.77	96.31	34.80	15.30	29.94	28.00	42.04	70.04	0.25
SK-175/60	94	14.4	96.30	34.49	20.30	47.97	20.09	31.92	52.01	0.645
SK-175/61	40	14.74	97.00	33.24	26.40	60.78	14.44	24.77	48.40	0.444
SK-175/62	36	14.74	97.24	33.12	26.60	36.00	N.A	N.A	67.90	0.499
SK-175/63	35	14.49	97.24	33.60	26.70	93.16	2.65	4.18	5.30	0.152
SK-175/64	52	14.50	97.00	33.61	25.60	81.00	9.00	10.00	18.90	0.227
SK-175/65	71	14.50	96.75	34.19	23.90	80.50	0.53	18.92	19.45	0.214
SK-175/66	97	14.50	96.49	34.46	20.60	76.66	1.81	21.52	42.00	0.501
SK-175/67	97	14.50	96.24	34.49	20.30	85.65	3.92	10.42	14.34	0.374
SK-175/68	110	14.30	96.00	34.56	20.80	88.57	2.38	9.03	11.41	0.219
SK-175/69	103	15.50	96.12	34.56	20.30	0.00	21.66	78.33	99.99	0.69
SK-175/70	16	15.75	96.15	31.29	27.59	0.05	23.31	76.63	99.94	0.615
SK-175/71	10	15.65	96.58	30.70	27.60	0.04	38.95	60.99	99.94	0.651
SK-175/72	11	15.50	96.67	30.80	27.58	0.04	37.50	62.49	99.99	0.718
SK-175/73	14	14.83	95.51	31.60	27.74	26.31	9.38	64.29	73.67	1
SK-175/74	71	14.74	95.25	34.23	24.80	27.11	16.25	56.62	72.87	0.601
SK-175/75	73	14.49	95.24	34.20	24.70	78.64	6.81	14.53	21.34	0.205
SK-175/76	90	14.50	95.50	34.52	20.60	58.94	17.84	23.21	41.05	0.538
SK-175/77	78	14.00	97.00	34.12	23.80	75.00	10.14	14.77	24.91	0.465
SK-175/78	58	14.00	97.25	33.76	25.90	67.01	8.87	24.11	32.98	0.368

Sample no.	Depth (m)	Latitude (°N)	Longitude (°E)	Salinity ^a (psu)	Temperature ^a (°C)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	TOC ^b (%)
SK-175/79	57	14.00	97.50	33.70	25.20	63.58	11.94	24.47	33.80	0.511
SK-175/80	50	14.24	97.50	33.82	25.65	79.58	0.16	20.24	20.40	0.446
SK-175/81	53	14.25	97.25	33.82	25.85	83.09	0.30	16.60	16.90	0.28
SK-175/82	62	14.25	97.00	33.82	27.95	85.75	0.61	13.62	14.23	0.222
SK-175/83	90	14.25	96.75	34.46	20.30	68.45	9.47	22.06	31.53	0.497
SK-175/84	105	14.25	96.50	34.46	20.20	87.81	1.32	10.88	12.20	0.325
SK-175/85	125	14.25	96.25	34.66	17.20	88.11	0.11	11.77	11.88	0.212
SK-175/86	150	14.25	96.00	34.80	15.30	70.44	13.72	15.82	29.54	0.53
SK-175/87	165	14.25	95.75	34.80	14.00	49.71	27.74	22.53	50.27	0.751
SK-175/88	110	14.25	95.50	34.50	20.60	87.75	3.02	9.22	12.24	0.237
SK-175/89	90	14.25	95.25	34.51	20.60	86.03	6.22	7.74	13.96	0.25
SK-175/90	90	14.25	95.00	34.39	22.50	75.51	17.71	6.76	21.90	0.241
SK-175/91	103	14.25	94.75	34.60	21.00	82.81	4.89	12.28	17.17	0.365
SK-175/92	97	14.25	94.50	34.60	21.21	90.51	0.89	8.59	9.48	0.5
SK-175/93	122	14.25	95.26	34.70	17.40	85.35	3.23	11.40	14.63	1
SK-175/94	670	14.25	94.00	35.00	8.76	15.29	24.43	61.26	85.69	1.404
SK-175/96	550	14.01	94.48	35.00	9.74	25.28	47.74	28.97	76.71	0.989
SK-175/97	600	14.00	94.99	35.25	8.10	12.49	36.52	50.97	87.50	1.024
SK-175/98	230	14.00	95.50	34.97	12.25	39.53	34.23	26.22	60.45	0.654
SK-175/99	1080	13.75	95.49	34.94	6.04	2.31	38.73	58.95	97.68	0.998
SK-175/100	818	13.78	95.86	34.95	7.86	7.08	39.34	53.56	92.90	1.394
SK-175/101	225	13.99	96.00	34.90	12.20	38.81	32.09	29.09	77.40	0.469
SK-175/102	110	14.49	97.24	34.40	20.20	89.95	0.02	9.32	9.34	0.165
SK-175/103	138	13.75	96.49	34.80	15.20	55.41	25.83	18.74	44.57	0.503
SK-175/104	101	13.75	96.75	34.42	20.30	N.A	N.A	N.A	N.A	0.294

Sample no.	Depth (m)	Latitude (°N)	Longitude (°E)	Salinity ^a (psu)	Temperature ^a (°C)	Sand (%)	Silt (%)	Clay (%)	Mud (%)	TOC ^b (%)
SK-175/105	92	13.75	97.00	34.42	20.30	86.84	0.60	15.55	16.15	0.294
SK-175/106	70	13.75	97.24	34.11	23.60	72.14	8.76	19.08	27.84	0.511
SK-175/107	63	13.75	97.49	33.60	25.95	6.27	21.48	72.24	93.72	0.938
SK-175/108	46	13.75	97.75	33.51	25.95	9.52	14.01	76.46	90.47	0.922
SK-175/109	51	13.50	97.75	33.51	26.00	41.92	17.49	40.17	57.66	0.425
SK-175/110	72	13.50	97.50	34.01	23.40	58.23	9.33	32.43	41.76	0.795
SK-175/111	73	13.50	97.24	34.02	23.60	86.84	1.73	11.41	13.14	0.218
SK-175/112	85	12.50	97.00	34.44	20.40	86.72	2.01	11.24	13.25	0.153
SK-175/113	88	13.50	96.74	34.44	20.30	87.96	1.02	11.00	12.02	0.117
SK-175/114	1140	13.00	96.33	35.50	5.98	Nil	Nil	Nil	Nil	Nil
SK-175/115	245	13.00	96.35	34.92	11.84	7.50	48.55	43.93	92.48	0.837
SK-175/116	96	13.00	96.99	34.42	20.30	86.09	2.86	11.03	13.89	0.194
SK-175/117	98	13.00	97.25	34.44	20.30	73.00	7.77	19.21	26.98	0.581
SK-175/118	83	13.00	98.49	34.00	23.50	84.93	0.15	14.90	15.05	0.46
SK-175/119	72	12.76	97.50	34.00	23.30	89.38	0.56	10.03	10.59	0.183
SK-175/120	80	12.50	97.50	34.02	23.30	N.A	N.A	N.A	11.50	0.262
SK-175/121	93	12.50	97.25	34.43	20.30	N.A	N.A	N.A	12.10	1.012
SK-175/122	198	13.99	96.50	34.90	12.70	N.A	N.A	N.A	5.90	0.067
SK-175/123	175	12.25	96.99	34.95	13.90	N.A	N.A	N.A	18.50	0.359
SK-175/124	92	12.25	97.25	34.48	20.30	89.96	1.89	8.14	10.03	0.25
SK-175/125	78	12.25	98.49	34.00	23.30	N.A	N.A	N.A	9.00	0.277
SK-175/126	75	12.00	97.49	34.03	23.30	N.A	N.A	N.A	8.50	0.264
SK-175/127	92	12.00	97.25	34.49	20.30	82.03	3.30	14.66	17.96	0.238
SK-175/128	232	12.00	97.00	35.40	12.35	73.97	8.70	17.32	26.02	0.842
SK-175/129	1060	12.00	96.49	34.94	5.87	10.74	18.44	70.81	89.25	2.658

^a Salinity and temperature data were obtained from NOAA/PMEL TMAP FERRET Ver. 5.22; Data Set: levannual.nc.

^b TOC data were procured from Ramaswamy et al., 2008.

^c Sampling location with which coring location coincides.

Table 3: Percentage abundance of *A. trispinosa* as encountered at various stations

Sample no.	Percentage of <i>A. trispinosa</i>
SK-175/2	0.47
SK-175/3	1.23
SK-175/4	2.35
SK-175/5	5.49
SK-175/10	10.29
SK-175/11	2.58
SK-175/12	4.73
SK-175/22	1.30
SK-175/23	21.48
SK-175/24	3.14
SK-175/35	1.45
SK-175/36	15.40
SK-175/37	28.65
SK-175/38	38.88
SK-175/39	39.75
SK-175/40	1.99
SK-175/41	0.77
SK-175/42	0.91
SK-175/43	2.16
SK-175/44	26.30
SK-175/45	3.28
SK-175/46	21.71
SK-175/47	9.67
SK-175/48	6.30
SK-175/52	20.51
SK-175/53	42.72
SK-175/54	23.56
SK-175/55	19.36
SK-175/56	6.93
SK-175/57	5.30
SK-175/58	0.30
SK-175/61	17.53
SK-175/62	30.00
SK-175/63	0.75
SK-175/64	1.78
SK-175/66	0.24
SK-175/79	0.89
SK-175/90	0.29
SK-175/101	0.28

Table 4: Details of sub-surface samples dated and AMS dates obtained

Depth in core (cm)	¹⁴ C age (yr. BP)	Calibrated age
80–82	635 ± 30 BP	1676 (±48) AD
176–178	800 ± 25 BP	1513 (±46) AD

Table 5: Correlation between various parameters and *A. trispinosa* abundance

	Depth	Sand	Silt	Clay	TOC	Mud	Salinity	Temp.	<i>A. trispinosa</i>
Depth	1.00	0.29 ^{ns}	-0.16 ^{ns}	-0.21 ^{ns}	-0.01 ^{ns}	-0.27 ^{ns}	0.82**	-0.98**	-0.48**
Sand		1.00	-0.59**	-0.89**	-0.61**	-0.87**	0.33**	-0.32 ^{ns}	-0.44*
Silt			1.00	0.15 ^{ns}	0.08 ^{ns}	0.50**	-0.33*	0.18 ^{ns}	0.48**
Clay				1.00	0.67**	0.79**	-0.14 ^{ns}	0.24 ^{ns}	0.28 ^{ns}
TOC					1.00	0.69**	-0.03 ^{ns}	0.00 ^{ns}	0.12 ^{ns}
Mud						1.00	-0.42*	0.28 ^{ns}	0.40*
Salinity							1.00	-0.78**	-0.62**
Temp.								1.00	0.44**
<i>A. trispinosa</i>									1.00

ns=non-significant.

** Significant at p<0.01.

* Significant at p<0.05.

Table 6: Statistical model expressing relationship between *A. trispinosa* abundance and various parameters recorded at different sampling locations

Variables	Equations	R ²
All	$A. trispinosa = 267.89 - (0.14 \times \text{Depth}) + (2.02 \times \text{Sand\%}) + (2.37 \times \text{Silt}) + (2.31 \times \text{Clay}) + (3.88 \times \text{TOC\%}) - (0.27 \times \text{Mud\%}) - (11.65 \times \text{Salinity p.s.u.}) - (2.69 \times \text{Temp } ^\circ\text{C})$	0.58
Optimised model	$A. trispinosa = 261.73 - (0.12 \times \text{Sand\%}) - (7.46 \times \text{Salinity p.s.u.})$	0.48
Optimised model after removing outliers	$A. trispinosa = 211.21 - (5.93 \times \text{Sand\%}) - (0.10 \times \text{Salinity p.s.u.})$	0.60