Evaluation of the sedimentary records of dinoflagellate cyst assemblages from the South-West coast of India

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Abstract

Long term changes in the dinoflagellate cyst assemblages evaluated through the analysis of sediment cores collected from four different locations along the South-West coast of India is presented. The sedimentation rate and age of the sediment cores were estimated by ^{210}Pb dating. Evaluation of the cyst assemblages from Harmful Algal Blooms (HABs) point of view indicates that the cyst types such as *Alexandrium affine*, *A*. *minutum*, *A*. *tamarense*, *Cochlodinium* cf. *polykrikoides*, *Gonyaulax spinifera, Lingulodinium polyedrum*, *Protoceratium reticulatum* and *Scrippsiella trochoidea* were present earlier to 19th century. Heterotrophic forms dominated the cyst assemblages at most of the locations especially in the last 2-3 decades. Two of the locations, Mangalore and Cannanore indicated considerable supply of allochthonous organic matter during 1300-1700 AD whereas Goa and Karwar were dominated by autochthonous organic matter. In the cores collected off Mangalore and Cannanore, predominance of *Gonyaulax spinifera* cysts, an autotrophic form was evidenced during 1300-1700 AD. Subsequent to this peak, the cyst abundance drastically reduced during 1800-2007 AD and this period was influenced by autotochthonous organic matter. The allochthonous input in the region is influenced by the intensity of monsoon and perturbations to this event can influence the population of dinoflagellates.

Keywords: Cysts; Blooms; Dating; Heterotrophic; South-West coast of India

1. Introduction

Dinoflagellates are one of the major groups of phytoplankton and have received attention due to their toxin producing abilities and their role in Harmful Algal Blooms (HABs). As part of their sexual life cycle, some species of dinoflagellates form resting cysts which can settle in sediments and remain dormant for long periods. Many species produce cysts which are preservable/preserved in sediments (Head, 1996; Dale, 2001). The cyst wall in most species is thick, and very resistant, being composed of organic matter (sporopollenin). Organic cyst walls are extremely resistant to natural decay, and can therefore persist in the sediments, providing an integrated time record of the cyst producing dinoflagellates and potentially their history of blooms.

For example, an intensive bloom of *Pyrodinium bahamense* var. *compressum* has occurred in Manila bay, Philippines since the late 1980's, probably due to environmental changes (Furio et al., 1996). Although a few resting cysts of *P. bahamense* var. *compressum* were recovered from sediments dated to around 1958. On the other hand, McMinn et al. (1997) concluded that since the cysts of *Gymnodinium catenatum* Graham from Tasmania, Australia, were first detected in sediments from around 1975, which is just before this species started producing intensive blooms. It was confirmed that *G. catenatum* might have been artificially introduced in Tasmanian waters. The introduction of harmful dinoflagellates to new environments via ships ballast water is one such possibility. India being one of the major maritime countries is susceptible to ship mediated bioinvasion (Anil et al., 2002).

Assessment of the vertical distribution of dinoflagellate cysts in sediment will provide information about the history of cyst deposition during different time periods. In the present study, which is the first of its kind for the region, sediment core samples were collected from four coastal locations along the South-West coast of India (Goa, Karwar, Mangalore and Cannanore) for analysis of dinoflagellate cysts assemblages. These data is coupled with geochronology using ^{210}Pb dating and geochemical analysis of organic carbon content, its isotopic nature ($\delta^{13}C_{org}$ and $\delta^{15}N$) and the C_{org}:N ratio to identify the origin and nature of the organic matter preserved in the sediment.

3. Material and methods

3.1 Study area

The continental margin of the eastern Arabian Sea i.e. west coast of India, is seasonally dynamic and influenced by South-West (SW) monsoon and upwelling from June-September that leads to prevalence of hypoxic conditions in sub-surface waters during late September-October (Naqvi et al., 2000). The subsequent winter months, November-January experience reversal of surface currents and return of oxic conditions. February-May period is warmer and characterized by low nutrient concentrations. The upwelling process brings cold, nutrient-rich waters from a few hundred meters depth into the surface and fuels the biological productivity in the euphotic zone. Naturally occurring seasonal enrichment in nutrients has been reported along the South-West coast of India where upwelling during the South-West monsoon results in high nutrient conditions triggering high primary production (de Souza et al., 1996).

3.2. Sample collection

Sampling was carried out onboard Coastal Research Vessel (CRV) *Sagar Shukti* (Cruise numbers: SaSu 89 and SaSu125). Sediment cores ranging from 62 to 130 cm were collected from coastal locations along the west coast of India using a Gravity corer of 63 mm diameter. In total 4 sediment cores were collected from coastal location off Goa (G1), Karwar (K1), Mangalore (M1) and Cannanore (Cn1)). These cores were collected away from the mouth of rivers i.e. Sal river (G1 core), Kali river (K1 core), Netravati River (M1 core) and Valapattanam River (Cn1 core). The depth of the water column varied between 19 and 33 m. The details and locations of the cores are given in Table 1 and Fig. 1.

After sampling, the sediment cores were hauled vertically; the sediment samples were extruded from the cores and sectioned at 2cm interval for 0-50 cm sediment depth and then further 5cm interval for more than 50 cm sediment depth. These cores were sectioned and stored in airtight plastic bags at 4°C in the dark until further analysis.

3.3. ^{210}Pb dating and Sedimentation Rate

^{210}Pb activities of dried and powdered samples of sediment cores were obtained indirectly by measuring vertical distribution of its excess granddaughter ^{210}Po. The measurements were carried out more than 6 months after sampling to ensure that secular equilibrium has been reached. The sediment sample was spiked with known volume of calibrated tracer ^{208}Po to determine the extraction and counting efficiencies. Polonium was extracted from the sediment and treated by chemical treatments (reacted sequentially with HCl, HNO_3, HF and H_2O_2) and deposited on a silver disk. The alpha activity of Polonium was counted on Silicon surface barrier detector coupled with plus height multi channel detector.

The ^{210}Pb excess activity ($^{210}Pb_{exc}$) was plotted logarithmically against each sediment depth. The $^{210}Pb_{exc}$ shows an exponential decrease with depth, which is due to radioactive decay with time. The Sedimentation rates have been estimated from the depth profile of $^{210}Pb_{exc}$ activity in a core assuming the Constant Initial Concentration models (Koide et al., 1972; Krishnaswami and Lal, 1978). Based on the sedimentation rate estimated, the apparent age of the cores was calculated.

3.4. Sediment processing and analysis of dinoflagellate cysts

Sediment samples were processed by palynological technique (Matsuoka and Fukuyo, 2000). These samples were used for dinoflagellate cyst analysis and determination of Water Content. In the palynological procedure, sediment samples were treated with Hydrochloric (10%) and Hydrofluoric (40%) acid solutions to remove Calcium Carbonate and Silicate materials respectively. The samples were washed with distilled water 3 times to remove acid. The chemically treated samples were sieved through 100 and 20 μm mesh-size to remove coarse and fine materials. The residue retained on the 20 μm mesh was transferred into a vial and suspended in 10 ml distilled water. For observation, a 0.5 ml aliquot of the processed sample was diluted with distilled water. Observations were carried out under a light microscope at 100 and 200 times magnification. Dinoflagellate cysts were identified based on published descriptions (Wall and Dale, 1968; Bolch and Hallegraeff, 1990; Lewis, 1991; Nehring, 1997; Sonneman and Hill, 1997; Godhe et al., 2000; Matsuoka and Fukuyo, 2000; Wang et al., 2004; Orlova et al., 2004). When species-level identification was not possible, identification was done at genus level. Water Content was determined by oven-drying a fixed amount of sediment at 70^{o}C for 24 h. Cyst concentration is expressed as cysts g^{-1} dry sediment.

3.5. Carbon analyses

Total Carbon (TC) and total Nitrogen (TN) contents of subsample (7-8 mg) of dried, crushed and homogenized sediment samples were determined with a CNS elemental analyser (NCS 2500, CE instruments). The accuracy of the analyses was found to be better than 0.02% for TC and 1.2% for TN using BBOT [2, 5-Bis

(5 tert-butyl-benzoxazol-2-yl) thiophene] standard. The reproducibility of the measurements was ± 0.1%, as checked by running replicates of the samples.

Total Inorganic Carbon (TIC) content was analyzed using a CM 5014 CO_2 Coulometer following acidification of the samples and CO_2 extraction. Calcium carbonate was used as reference standard. The accuracy of analysis for this standard was 2% and the reproducibility of the measurements is ±0.5% for samples. Total Organic Carbon (C_{org}) content was calculated as the difference between total and inorganic carbon ($C_{org} = TC - TIC$). To express TIC as a percentage Calcium carbonate ($CaCO_3$), the following equation was used: $CaCO_3 (\%) = TIC \times 8.33$. Based on Total Organic Carbon (C_{org}) and Total Nitrogen (TN) values, the C_{org}:N ratios were calculated for the samples and expressed as molar ratios.

The carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopic compositions was analyzed with the Thermo Finnigan Delta V plus Isotope Ratio Mass Spectrophotometer coupled with the elemental analyzer. Before the isotopic analysis, sediment samples were acidified with 1N Hydrochloric acid to remove carbonates and were then dried, crushed and homogenized. The precision of the analysis was found to be better than 0.3% for $\delta^{13}C$ and 0.03% for $\delta^{15}N$ using Sucrose and Ammonium sulphate standards. The reproducibility of the measurements of replicate sediment sample for $\delta^{13}C$ and $\delta^{15}N$ is ± 0.1 and 0.3 %.

We have used C_{org}:N and $\delta^{13}C_{org}$ ratios to characterize organic matter sources in the sediment samples. The amount and type of organic matter in marine sediment reflect the supply and preservation of organic materials from marine plankton (autochthonous) and terrigenous (allochthonous) sources. C_{org}:N ratios <10 is considered to be indicative of marine source (Parsons, 1975) whereas for terrestrial organic matter, it varies from 20 to 200 (Hedges et al., 1986). The $\delta^{13}C_{org}$ from marine zones record values of -18.5 to -21.5 ‰ reflecting the heavier isotopic signature of marine organic matter whereas lighter $\delta^{13}C_{org}$ values (-25 to -29.3‰) reflecting organic matter from terrestrial C_3 plants (Sackett, 1989; Tyson, 1995).

3.6. Data analysis

The square root transformed species data of dinoflagellate cyst abundance were used to construct a lower triangular similarity matrix using Bray-Curtis Coefficients (Bray and Curtis, 1957) and subjected to clustering and ordination technique using the software PRIMER (version 5).

POLPAL 2004 program was used to plot the pollen diagrams for species distribution based on relative abundance (%) of dinoflagellate cysts in sediment cores (Nalepka and Walanus, 2003).

4. Results

4.1. Goa core (G1)

The profile of $^{210}Pb_{exc}$ activity for G1 core decreased exponentially with increasing depth, indicating a radioactive decay. Based on $^{210}Pb_{exc}$ activity profile, sedimentation rate of 3.36±0.5 cm/yr has been estimated for this core (Fig. 2). Using this estimated rate, the core represents a time span of about 17 yrs (1987-2004 AD).

A total of 25 species (11 autotrophic and 14 heterotrophic) of dinoflagellate cysts were recorded in this core. The cyst abundance ranged from 122-917 cysts g^{-1} dry sediment. Downcore variations in dinoflagellate cyst abundance were observed (Fig. 3). Based on this 3 zones were identified, Zone-1: higher cyst abundance of 411-917 cysts g^{-1} dry sediment was recorded in the upper part of the core i.e. from 2004 to 2002 AD; Zone-2: three fold decrease in cyst abundance (122-199 cysts g^{-1} dry sediment) was observed from 2000 to 1993 AD and Zone-3: increase in cyst abundance of 367-475 cysts g^{-1} dry sediment was observed from 1990 to 1987 AD.

It can be observed from species cluster analysis that seven frequently occurring species grouped together at 50% Bray-Curtis similarity (Fig. 4). The species composition of dinoflagellate cysts have been provided in Fig. 5. The heterotrophic forms dominated throughout the G1 core and contributed 50-94% of the total cyst assemblages. *Protoperidinium oblongum* and *P. leonis* dominated the heterotrophic cyst assemblages. Presence of *Polykrikos kofoidii* was recorded in the sediment core from 2002 AD. Increase in the abundance and frequency of harmful forms of dinoflagellate cysts have occurred mostly after the year 2000 AD. Cysts of *Cochlodinium polykrikoides* and *Protoceratium* *reticulatum* were observed in the more recent years i.e. from 2003 to 2004 AD whereas *Lingulodinium polyedrum* were recorded only during 2000 AD.

In G1 core, profiles for C_{org}, TN, $CaCO_3$, C_{org}:N ratios, $\delta^{13}C_{org}$ and $\delta^{15}N$ isotopes are shown in Fig. 3. Zone 1 showed a gradual increase in C_{org} and TN values from 2001 AD. The $\delta^{13}C_{org}$ and C_{org}:N ratios appear to reflect similar trends, where the source of organic matter in this core has been mainly from marine origin.

4.2. Karwar core (K1)

In the K1 core, the $^{210}Pb_{exc}$ profiles elucidate that the upper few centimeters (0-4cm) of the core is disturbed. However, 4 to 12 cm shows an exponential decay (Fig. 2). This yields a sedimentation rate of 0.10±0.02 cm/yr and with this rate estimated, the core represents a time span of ~1200 yrs (806-2006 AD).

A total of 28 species of dinoflagellate cysts (13 autotrophic and 15 heterotrophic) were recorded in this core. The cyst abundance ranged from 71-1191 cysts g^{-1} dry sediment in this core. Based on downcore variations in dinoflagellate cyst abundance, the K1 core was classified into 2 zones. Zone 1: higher cyst abundance with a maximum of 1190 cysts g^{-1} dry sediment was recorded in the upper part of the core with 2 maximum peaks observed during 1926 and 1966 AD. Zone 2: minor fluctuations in cyst abundance (71-438 cysts g^{-1} dry sediment) were recorded in the lower part of the core (Fig. 3).

Based on species cluster analysis, nine frequently occurring species grouped together at 50% Bray-Curtis similarity (Fig. 4). Downcore variations of species composition of dinoflagellate cysts is shown in Fig. 5. The K1 core was mainly dominated by cysts of heterotrophic forms that contributed to nearly 57-100% of the total dinoflagellate cyst assemblages. Among the heterotrophic forms, the species that dominated the cyst assemblages were *P. latissimum*, *P. oblongum* and *Protoperidinium* spp (round brown cysts). Autotrophic forms were dominated by cysts of *Gonyaulax scrippsae* and *G. spinifera*. In this core, cysts of harmful dinoflagellates such as *Alexandrium affine* were recorded in 2006 AD and *C. polykrikoides* in 1926 and 2006 AD.

The profiles for C_{org}, TN, $CaCO_3$, C_{org}:N ratios, $\delta^{13}C_{org}$ and $\delta^{15}N$ isotopes did not show much variations except on two occasions where the values peaked during 900 and 1926 AD (Fig. 3). Based on C_{org}:N ratios and $\delta^{13}C_{org}$, the major source of organic matter is from marine origin in K1 core except on one occasion during 1926 AD where the C_{org}:N ratio of 20.46 was more towards terrestrial input.

4.3. Mangalore core (M1)

In the core M1, the $^{210}Pb_{exc}$ activity from surface to 17cm decreases exponentially (Fig. 2). The estimated sedimentation rate from this profile is 0.18±0.01 cm/yr. Based on estimated sedimentation rate, M1 core represents a time span of ~700 yrs (1313-2007 AD).

A total of 27 species of dinoflagellate species, 11 autotrophic and 16 heterotrophic were recorded in this core. Dinoflagellate cyst abundance showed a remarkable change through the core and recorded a maximum cyst abundance of 19,880 cysts g^{-1} dry sediment during the period 1451 AD (Fig. 3). Based on cyst abundance, 2 zones can be clearly demarcated. Zone 1: the abundance remained almost constant from 1800-2007 AD and recorded a moderate cyst abundance of 177-676 cysts g^{-1} dry sediment in the upper part of the core. Zone 2: very high cyst abundance of 3,684-19,880 cysts g^{-1} dry sediment was recorded in the lower part of the core that corresponded to 1300-1700 AD. During this period three maximum peaks of high abundance were observed during the period 1451, 1507 and 1751 AD. Drastic reduction in cyst abundance was recorded from 1800 AD onwards.

Based on species cluster analysis, six frequently occurring species grouped together at 50% Bray-Curtis similarity (Fig. 4). Among the autotrophic forms, *Gonyaulax spinifera* (GnxSp) being frequently occurring species did not group together with other species. Downcore variations in species composition of dinoflagellate cysts were recorded in this core (Fig. 5). The upper part of the core (Zone 1) was mainly dominated by cysts of *Protoperidinium* species (15-85%) and *G. spinifera* (4-78%). The lower part of the core (Zone 2) was remarkably dominated by cysts of *Gonyaulax spinifera* (autotrophic forms) that contributed 97-100% of the total dinoflagellate cyst assemblages. *Alexandrium minutum* and *A. affine* were recorded from the period 1500 to 1900 AD. Cysts of *C. polykrikoides* were reported as rarely occurring during the 2 particular periods i.e.

1885 and 1929 AD. Presence of *P. reticulatum* cysts were observed more frequently in the past (during 1300-1700 AD) than in the recent years whereas *L. polyedrum* was recorded only during 1700 AD. Calcareous cysts of *S. trochoidea* were recorded from 1700 to 1900 AD.

For M1 core, the profiles for C_{org}, TN, $CaCO_3$, C_{org}:N ratios, $\delta^{13}C_{org}$ and $\delta^{15}N$ isotopes showed remarkable changes in Zone 1 and 2 that reflected on dinoflagellate cyst assemblages (Fig. 3). The $CaCO_3$ content was higher (20-61%) in the upper part of the core during 1800-1900 AD where C_{org} and TN content were reduced in this core. This is mainly due to high deposition of broken pieces of bivalves, gastropods, scallops and tusk shells. The C_{org} (1.96-3%) and TN (0.15-0.25%) content showed an increasing trend in the upper part of the core (Zone 1) as compared to lower part of the core (Zone 2). Stable isotopes ($\delta^{13}C_{org}$ and $\delta^{15}N$) and C_{org}:N ratio profiles indicates an enhanced input of marine organic matter prevailed during 1818-2007 AD (Zone 1) whereas strong supply of terrestrial organic matter during 1313-1796 AD (Zone 2).

4.4. Cannanore core (Cn1)

The $^{210}Pb_{exc}$ activity decreases from the surface to 10cm of Cn1 core. The estimated sedimentation rate of the core is 0.15±0.02 cm/yr (Fig. 2). Assuming the constant rate through the core, time span of this core represents ~700 yrs (1334-2007 AD).

A total of 28 species of dinoflagellate cysts (12 autotrophic and 16 heterotrophic) were recorded in this core. The cyst abundance in Cn1 core ranged from 63 to 1039 cysts g^{-1} dry sediment. This core can be categorized into 2 zones based on changes in dinoflagellate cyst abundance. Zone1: the cyst abundance in the upper part of the core gradually decreased and fluctuated between 167-438 cysts g^{-1} dry sediment from 1504 to 2007 AD; except during 1980 AD where the cyst abundance was reduced to 63 cysts g^{-1} dry sediment (Fig. 3). Zone 2: the lower part of the core has been characterized by higher dinoflagellate cyst abundance of 548-1039 cysts g^{-1} dry sediment recorded during 1374 to 1504 AD.

It was observed from species cluster analysis that eight frequently occurring species grouped together at 50% Bray-Curtis similarity (Fig. 4). The variations in species composition of dinoflagellate have been recorded in Cn1 core (Fig. 5). This core was mainly dominated by cysts of heterotrophic forms such as *P. latissimum* and *Pyrophacus steinii* with the exception during the period 1374-1440 AD and 1507-1574 AD where cysts of autotrophic forms such as *G. spinifera* dominated. Occurrence of *A. tamarense* cysts (potential PSP producer) were reported only once during the period 1674 AD whereas cysts of *Cochlodinium polykrikoides* was reported on two occasions during 1967 and 1994 AD. Cysts of *G. spinifera* have the longest history whereas *C. polykrikoides* were recently recorded.

In Cn1 core, profiles for C_{org}, TN, $CaCO_3$, C_{org}:N ratios, $\delta^{13}C_{org}$ and $\delta^{15}N$ isotopes are shown in Fig. 3. The C_{org} content was higher in the upper most part of the core. Based $\delta^{13}C_{org}$ and C_{org}:N ratios, the upper part of the Cn1 core comprised of a mixture of marine and terrestrial organic matter whereas downcore, it showed a shift more towards terrestrial source.

5. Discussion

Inferences drawn from dinoflagellate cyst assemblages recorded in the cores from the study area indicate dominance of heterotrophic forms of *Protoperidinium* species in the last 2-3 decades. With respect to the scenario dating back to 1300-1700 AD, one can notice marked predominance of autotrophic forms in Mangalore and Cannanore cores (Fig. 3). The predominance of *Gonyaulax spinifera* was observed during 1300-1700 AD. Subsequent to predominance of *G. spinifera*, the cyst abundance decreased and cysts of heterotrophic species became abundant. Matsuoka (1999) suggested that increased diatom production was the main reason for increase in heterotrophic dinoflagellates in Tokyo bay whereas Dale (2001) linked the increase to reduced production of autotrophic dinoflagellates due to reduced light penetration. Abundance of heterotrophic dinoflagellate cysts suggests nutrient-rich conditions (Harland et al., 2006). In addition, dominance of different heterotrophic taxa reflects different nutrient enrichment levels based on their specific modes of feeding and preferences for prey (Matsuoka et al., 2003). Increase in the proportion of heterotrophic dinoflagellates and *Polykrikos* from 2000 AD onwards in G1 core can be possibly related to increased nutrient loading.

Cyst assemblages from all the major coastal upwelling systems (NW Africa, the Angola/Benguela, SW Africa, Chile, Peru and southern California) are greatly dominated by heterotrophic *Protoperidinium* species (Marret and Zonneveld, 2003 and references therein; Pospelova et al., 2008). Matsuoka et al. (2003) found *Polykrikos* cysts contributing up to 40% of the cyst assemblage in surface sediments in heavily eutrophic areas of the Tokyo Bay. Cysts of heterotrophic dinoflagellate species dominated the cyst assemblages in the 3 cores except for M1 core, the most abundant cysts being of Protoperidinoid type.

Changes in cyst assemblages can also be influenced by the environmental characteristics. The drastic reduction in cyst abundance in M1 core during 1700 AD may be possibly related to changes in the supply of nutrients or organic matter. The amount and type of organic matter in marine sediment cores reflect the supply and preservation of organic materials from marine and terrestrial sources. Continental margin sediments are significant sites for organic carbon burial because of high sedimentation rates and biological productivity. Off major river mouths, continental margins receive significant amounts of organic matter of terrestrial orgin (Hedges and Keil, 1995; de Haas et al, 2002). Based on $\delta^{13}C$ analysis and C_{org}:N ratios, the major source of organic matter supplied during 1300-1700 AD is from terrestrial input whereas from 1800-2007 AD, changes in supply of organic matter occurred where it consisted of a mixture of marine organic matter and terrestrial supply. The input of terrigenious material to the Arabian Sea is related to monsoon intensity and varies on a regional scale across the Arabian Sea (Sirocko, 1989). The changes in cyst ssemblages can thus be related to possible changes in monsoon related influences or increase in anthropogenic activities. Due to absence of specific quantifiable data regarding monsoon intensity and inputs of nutrients, this aspect will need further detailed investigation. The drastic reduction in dinoflagellate cyst assemblage in M1 core coincides with high deposition of broken pieces of shells during 1800-1900 AD. This material deposited at coastal location off Mangalore, may be due to erosion of this material from intertidal area where changes or shift in this area might have occurred in the past years. As a result, these shells in the sediment might have caused a barrier for resuspension of *G. spinifera* cysts.

According to Dale et al. (1999) and Matsuoka (1999), strong eutrophication tends to increase heterotrophic dinofagellates over the gonyaulacoid species while mild eutrophication may increase the occurrence of *Lingulodinium polyedrum*. It is possible that shifts in nutrient availability account for some of the species successions, e.g. the change in species dominance from *G. spinifera* to *Protoperidinium* species recorded in M1core. The relative number of cysts in relation to the motile stages of the dinoflagellate species is a complex issue. For example *Gonyaulax digitale* and Protoperidinioid species are much less prolific cyst producers (1:500 and 1:120, cyst:theca ratio). *Lingulodinium polyedrum* and *Alexandrium tamarense* produce relatively few cysts (ca. 4:1000) (Lewis, 1988; Anderson and Keafer, 1985). Inspite of the low cyst:theca ratio, cysts of *G. spinifera* prevailed in large numbers during 1300-1700 AD and this indicates *G. spinifera* formed recurrent blooms.

Several incidents of Harmful Algal Blooms (HABs) have occurred in Indian waters during the last decades (Subramanyan, 1954; Karunasagar et al., 1989; Karunasagar and Karunasagar, 1992). Paralytic Shellfish Poisoning (PSP) outbreaks have been reported at Mangalore (Karunasagar et al., 1984; Segar and Karunasagar 1989). The core data from this study suggests that cysts of harmful types prevailed much earlier to 19th century. The presence of cysts in sediment reveals that vegetative cells of this species do occur in the plankton and there may be potential risk for outbreaks of toxicity or harmful events associated with these species in future. History of dinoflagellate blooms from sedimentary records requires a good understanding about the relationship between the magnitude of a motile dinoflagellate bloom population and the abundance of resting cysts produced by that population. Further studies to elucidate this task are needed.

6. Conclusion

Sedimentary records of dinoflagellate cyst assemblages from a unique tropical environment influenced by monsoon provided a basis for tracking the changes that have taken place in the past. The observed predominance of the autotrophic forms and their subsequent reduction; with dominance of heterotrophic species in the recent years indicate that the region has undergone considerable changes.

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Legends to tables

Table 1

Details of core locations (latitude and longitude), sampling date, water depth and core length of sediment cores collected along the South-West coast of India.

Table 2

Dinoflagellate cyst species recorded in sediment cores collected along the South-West coast of India.

Legends to figures

Fig. 1 Location map of sediment cores collected along the South-West coast of India.

Fig. 2 Profiles of $^{210}Pb_{exc}$ activity (dpm/g) plotted logarithmically against sediment depth (cm) for G1, K1, M1 and Cn1 cores. The sedimentation rate is determined from the slope of $^{210}Pb_{exc}$ values plotted versus depth.

Fig. 3 Downcore variations of dinoflagellate cyst abundance of total, autotrophic and heterotrophic cysts (cysts g^{-1} dry sediment), Organic Carbon (% C_{org}), Isotope of Organic Carbon (‰ $\delta^{13}C_{org}$), Total Nitrogen (% TN), Isotope of

Nitrogen (‰ $\delta^{15}N$), Organic Carbon:Total Nitrogen ratio (C_{org}:N molar ratio) and Calcium Carbonate (% $CaCO_3$) in G1, K1, M1 and Cn1 cores.

Fig. 4 Cluster dendrogram of dinoflagellate species based on cyst abundance using Bray-Curtis similarity coefficient index and group average method. The species codes are presented in Table 2. The frequently occurring species (FOS) are mainly highlighted in the cluster.

Fig. 5 Downcore variations representing changes in species composition (%) of dinoflagellate cysts. The species codes are presented in Table 2. The harmful forms are marked by asterick (*)

Table 1
Details of core locations (latitude and longitude), sampling date, water depth and core length of sediment cores collected along the South-West coast of India.

Sediment Cores	Codes for cores	Latitude (°N)	Longititude (°E)	Sampling date	Water depth (m)	Core length (cm)
Goa	G1	15°08'	73°51'	04 March 2005	19	68
Karwar	K1	14°49'	73°54'	31 December 2006	33	125
Mangalore	M1	12°54'	73°39.34'	01 January 2007	30	130
Cannanore	Cn1	11°51.48'	75°11.15'	01 January 2007	29	100

Table 2
Dinoflagellate cyst species recorded in sediment cores along the South-West coast of India.

Cyst species (paleontological name)	Motile species (biological name)	Species code	Sediment cores			
			G1	K1	M1	Cn1
Autotrophic						
-	*Alexandrium affine* (Inoue et Fukuyo) Balech[a]	AxA		+	+	+
-	*Alexandrium minutum* Halim[a]	AxM		+	+	+
-	*Alexandrium tamarense* (Lebour) Balech[a]	AxT				+
-	*Cochlodinium* cf. *polykrikoides* Margalef[a]	CocP	+	+	+	+
-	*Cochlodinium* sp.	Cocs	+	+		+
Spiniferites bentori Rossignol	*Gonyaulax digitalis* (Pouchet) Kofoid	GnxD	+		+	
Spiniferites bulloideus Deflandre et Cookson	*Gonyaulax scrippsae* Kofoid	GnxSc	+	+		+
Spiniferites	*Gonyaulax spinifera* (Claparède *et* Lachmann) complex[a]	GnxSp	+	+	+	+
-	*Gonyaulax* sp.	Gnxs			+	
-	*Gyrodinium impudicum* Fraga et Bravo	GyrI		+		
Lingulodinium machaerophorum Deflandre et Cookson	*Lingulodinium polyedrum* (Stein) Dodge[a]	LngP	+	+	+	+
-	*Pentapharsodinium dalei* Indelicato *et* Loeblich	PenD	+			+
-	*Phaeopolykrikos hartmannii* (Zimmermann) Matsuoka et Fukuyo	PheH	+	+		
Operculodinium centrocarpum Deflandre et Cookson	*Protoceratium reticulatum* (Claparède *et* Lachmann) Bütschli[a]	PcerR	+	+	+	+
Tuberculodinium vancampoae Rossignol	*Pyrophacus steinii* (Schiller) Wall et Dale	PyhS	+	+	+	+
-	*Scrippsiella trifida* Lewis	ScTr			+	
-	*Scrippsiella trochoidea* (Stein) Loeblich III[a]	ScT	+	+	+	+
-	*Scrippsiella* sp.	Scs		+		
Heterotrophic						
-	*Diplopelta parva* (Abé) Matsuoka	DplP				+
-	*Lebouraia minuta* Abé	LebM	+			
-	*Polykrikos kofoidii* Chatton	PoK	+	+	+	+
-	*Polykrikos schwartzii* Butschli	PoS		+	+	+
Votadinium spinosum Reid	*Protoperidinium claudicans* Paulsen	PpCla	+	+	+	+
Stelladinium stellatum (Wall et Dale) Reid	*Protoperidinium compressum* (Abé) Balech	PpCom	+			+
Selenopemphix quanta (Bradford)	*Protoperidinium conicum* (Gran) Balech	PpC	+	+	+	+
Brigatedinium sp.	*Protoperidinium denticulatum* (Gran et Braarud)	PpDe		+	+	+
-	*Protoperidinium latissimum* (Kofoid) Balech	PpLa	+	+	+	+
Quinquecuspis concreta Reid	*Protoperidinium leonis* (Pavillard) Balech	PpL	+	+	+	+
-	*Protoperidinium minutum*	PpM		+	+	
Votadinium calvum Reid	*Protoperidinium oblongum* (Aurivillius) Balech	PpO	+	+	+	+
Trinovantedinium applanatum (Braford) Bujak and Davies	*Protoperidinium pentagonum* (Gran) Balech	PpP			+	
-	*Protoperidinium* cf. *pentagonum* Gran	PpcfP	+	+	+	+
Selenopemphix nephroides Benedeck	*Protoperidinium subinerme* (Paulsen) Loeblich III	PpS	+	+	+	+
Stelladinium robustum Zonneveld	*Protoperidinium* sp.1	Pps1	+	+	+	+
Lejeunecysta concreta	*Protoperidinium* sp.2	Pps2	+	+	+	+
-	*Protoperidinium* spp.	Pps	+	+	+	+
Dubridinium caperatum Reid	*Zygabikodinium lenticulatum* (Paulsen) Loeblich et Loeblich	ZyLen	+	+	+	+
Total no of species			25	28	27	28
No of autotrophic species			11	13	11	12
No of heterotrophic species			14	15	16	16

[a] Harmful species

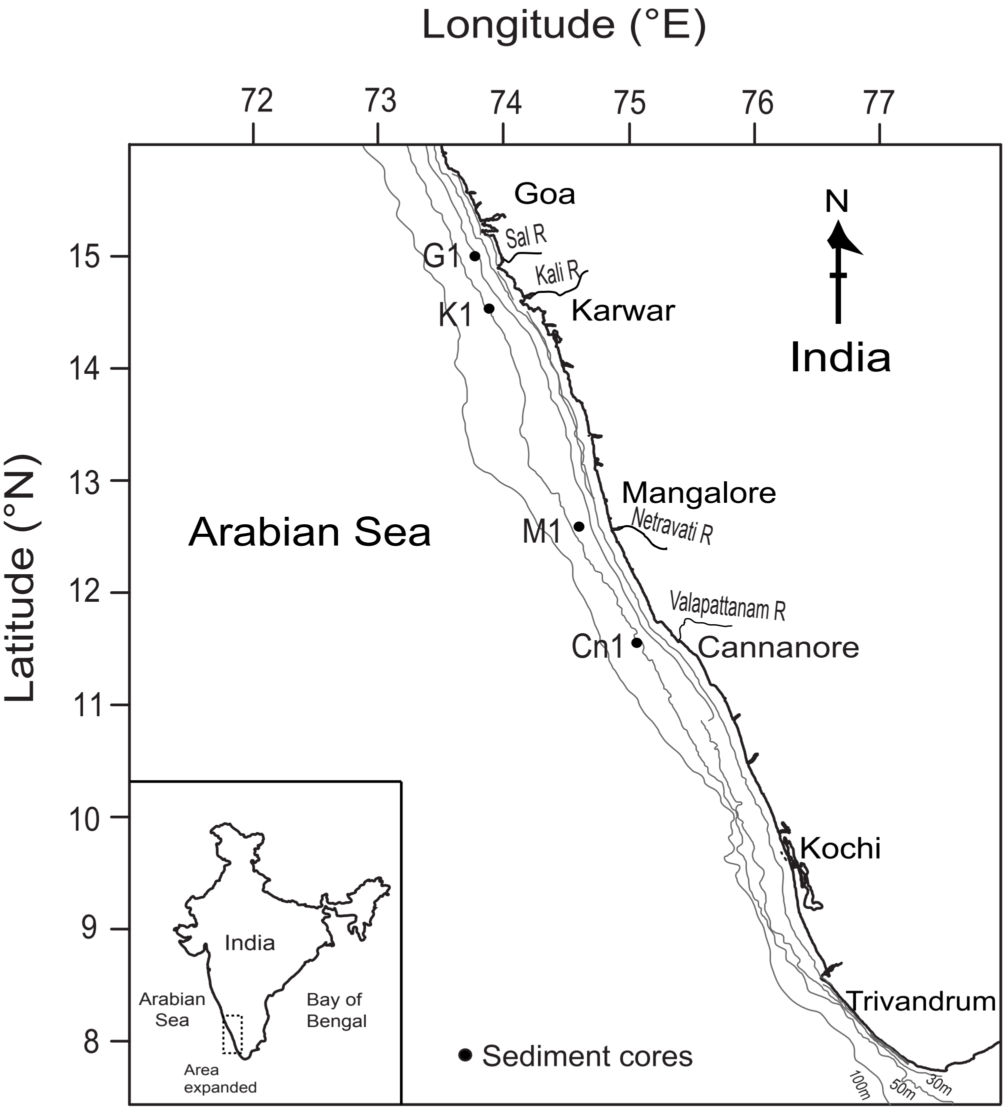
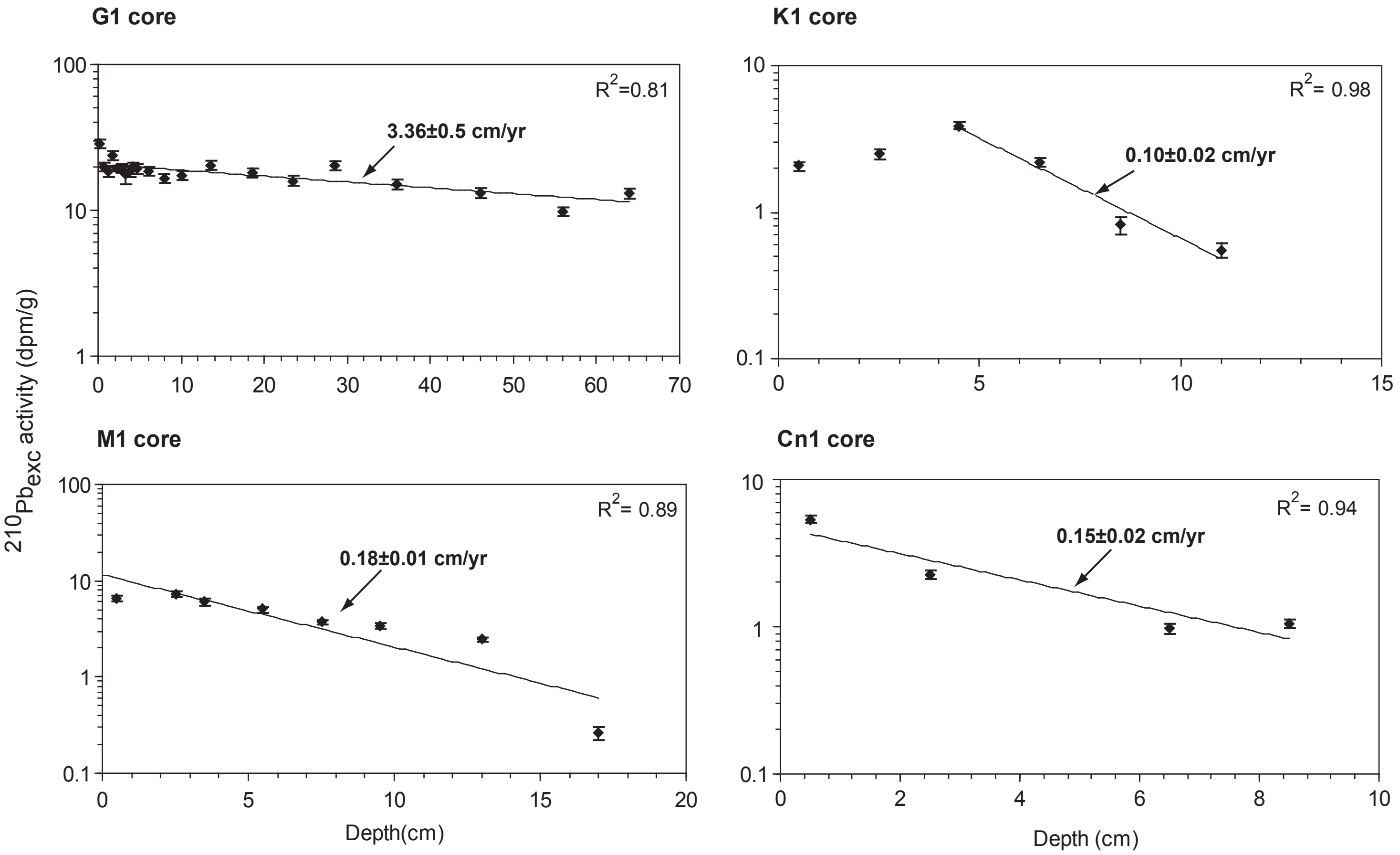

Longitude (°E)
72
73
74
75
76
77
Latitude (°N)
15
14
13
12
11
10
9
8
Goa
Sal R
G1
Kali R
K1
Karwar
Mangalore
Netravati R
M1
Arabian Sea
Valapattanam R
Cn1
Cannanore
Kochi
Trivandrum
100m
50m
30m
N
India
● Sediment cores
India
Arabian Sea
Bay of Bengal
Area expanded

Fig. 1


G1 core

K1 core

M1 core

Cn1 core

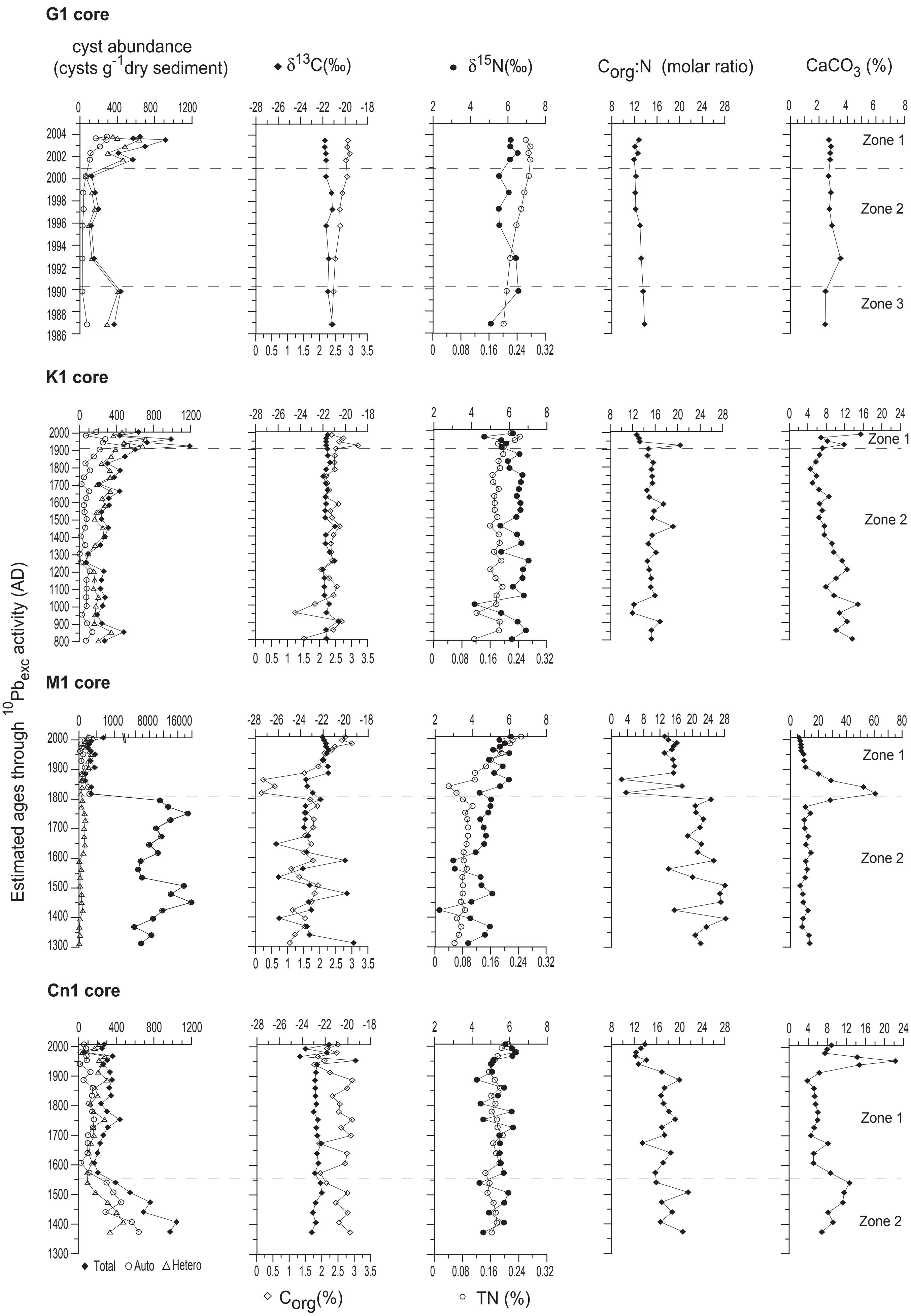

G1 core
cyst abundance (cysts g-1 dry sediment)
δ13C(‰)
δ15N(‰)
Corg:N (molar ratio)
CaCO3 (%)
0 400 800 1200
-28 -26 -24 -22 -20 -18
2 4 6 8
8 12 16 20 24 28
0 2 4 6 8
2004 2002 2000 1998 1996 1994 1992 1990 1988 1986
0 0.5 1 1.5 2 2.5 3 3.5
0 0.08 0.16 0.24 0.32
Zone 1
Zone 2
Zone 3
K1 core
0 400 800 1200
-28 -26 -24 -22 -20 -18
2 4 6 8
8 12 16 20 24 28
0 4 8 12 16 20 24
2000 1900 1800 1700 1600 1500 1400 1300 1200 1100 1000 900 800
0 0.5 1 1.5 2 2.5 3 3.5
0 0.08 0.16 0.24 0.32
Zone 1
Zone 2
M1 core
0 1000 8000 16000
-28 -26 -24 -22 -20 -18
2 4 6 8
0 4 8 12 16 20 24 28
0 20 40 60 80
2000 1900 1800 1700 1600 1500 1400 1300
0 0.5 1 1.5 2 2.5 3 3.5
0 0.08 0.16 0.24 0.32
Zone 1
Zone 2
Cn1 core
0 400 800 1200
-28 -26 -24 -22 -20 -18
2 4 6 8
8 12 16 20 24 28
0 4 8 12 16 20 24
2000 1900 1800 1700 1600 1500 1400 1300
0 0.5 1 1.5 2 2.5 3 3.5
0 0.08 0.16 0.24 0.32
Zone 1
Zone 2
Estimated ages through 10Pbexc activity (AD)
◆ Total ○ Auto △ Hetero
◇ Corg(%)
○ TN (%)

Fig. 3

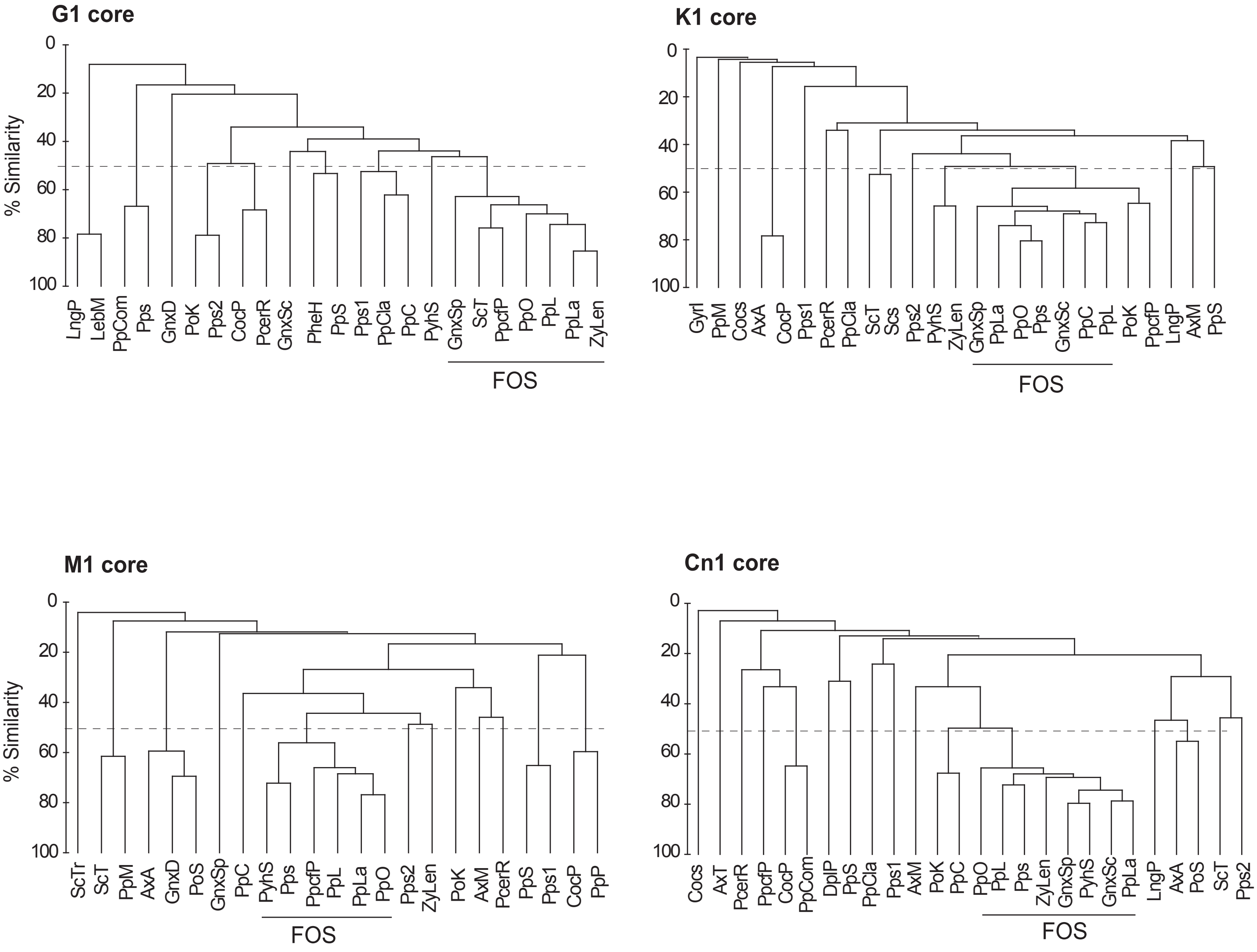

G1 core
% Similarity
0
20
40
60
80
100
LngP
LebM
PpCom
Pps
GnxD
PoK
Pps2
CocP
PcerR
GnxSc
PheH
PpS
Pps1
PpCla
PpC
PyhS
GnxSp
ScT
PpcfP
PpO
PpL
PpLa
ZyLen
FOS
K1 core
0
20
40
60
80
100
GyrI
PpM
Cocs
AxA
CocP
Pps1
PcerR
PpCla
ScT
Scs
Pps2
PyhS
ZyLen
GnxSp
PpLa
PpO
Pps
GnxSc
PpC
PpL
PoK
PpcfP
LngP
AxM
PpS
FOS
M1 core
% Similarity
0
20
40
60
80
100
ScTr
ScT
PpM
AxA
GnxD
PoS
GnxSp
PpC
PyhS
Pps
PpcfP
PpL
PpLa
PpO
Pps2
ZyLen
PoK
AxM
PcerR
PpS
Pps1
CocP
PpP
FOS
Cn1 core
0
20
40
60
80
100
Cocs
AxT
PcerR
PpcfP
CocP
PpCom
DplP
PpS
PpCla
Pps1
AxM
PoK
PpC
PpO
PpL
Pps
ZyLen
GnxSp
PyhS
GnxSc
PpLa
LngP
AxA
PoS
ScT
Pps2
FOS

Fig. 4

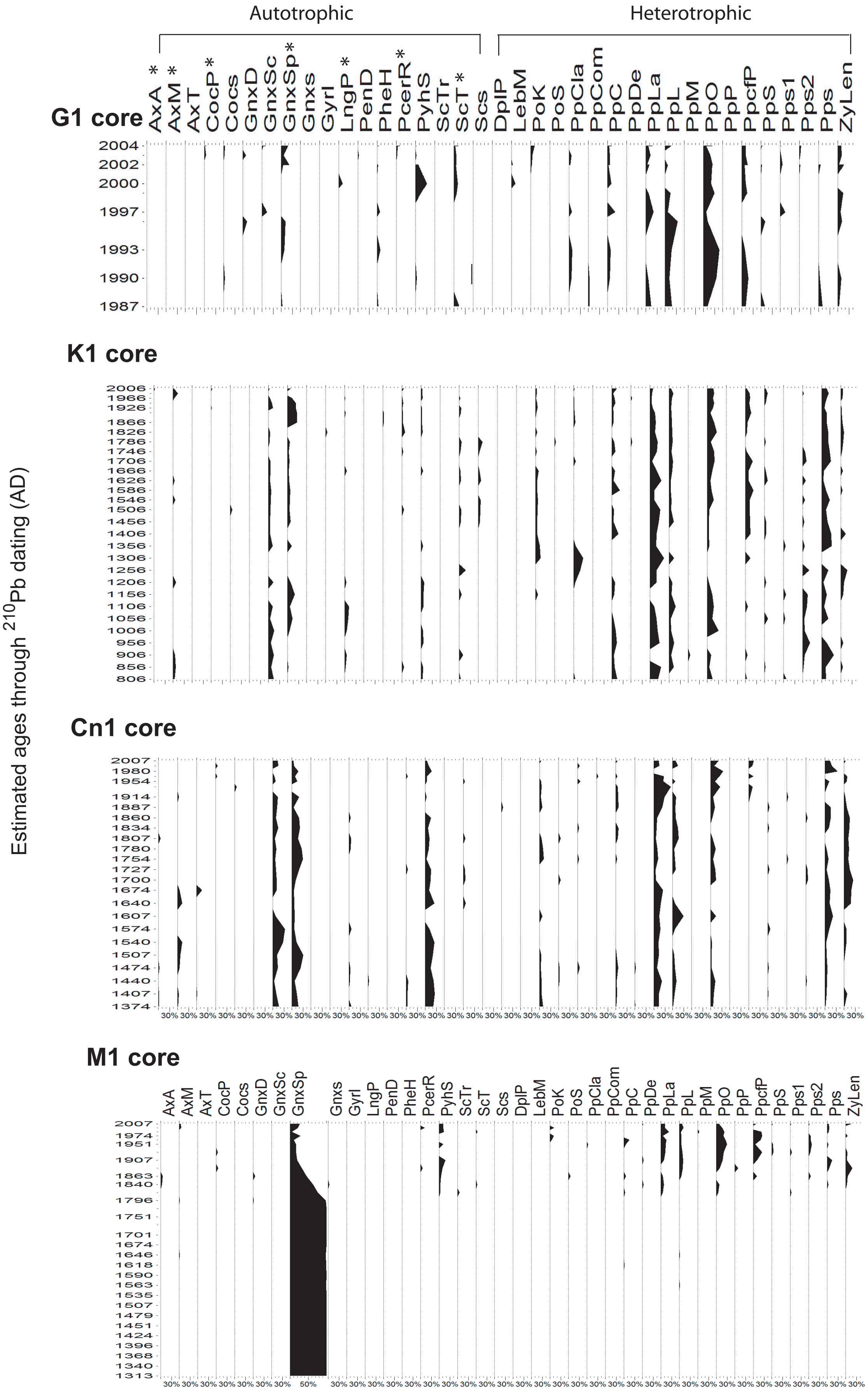

Autotrophic
Heterotrophic
G1 core
AxA *
AxM *
AxT
CocP *
Cocs
GnxD
GnxSc
GnxSp*
Gnxs
GyrI
LngP *
PenD
PheH
PcerR*
PyhS
ScTr
ScT *
Scs
DplP
LebM
PoK
PoS
PpCla
PpCom
PpC
PpDe
PpLa
PpL
PpM
PpO
PpP
PpcfP
PpS
Pps1
Pps2
Pps
ZyLen
2004
2002
2000
1997
1993
1990
1987
K1 core
2006
1966
1926
1866
1826
1786
1746
1706
1666
1626
1586
1546
1506
1456
1406
1356
1306
1256
1206
1156
1106
1056
1006
956
906
856
806
Estimated ages through ^{210}Pb dating (AD)
Cn1 core
2007
1980
1954
1914
1887
1860
1834
1807
1780
1754
1727
1700
1674
1640
1607
1574
1540
1507
1474
1440
1407
1374
30%
M1 core
AxA
AxM
AxT
CocP
Cocs
GnxD
GnxSc
GnxSp
Gnxs
GyrI
LngP
PenD
PheH
PcerR
PyhS
ScTr
ScT
Scs
DplP
LebM
PoK
PoS
PpCla
PpCom
PpC
PpDe
PpLa
PpL
PpM
PpO
PpP
PpcfP
PpS
Pps1
Pps2
Pps
ZyLen
2007
1974
1951
1907
1863
1840
1796
1751
1701
1674
1646
1618
1590
1563
1535
1507
1479
1451
1424
1396
1368
1340
1313
30%
50%

Fig. 5