Spatial distribution of diatoms in surface sediments from the Indian sector of Southern Ocean

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A multidisciplinary scientific expedition to the Southern Ocean (Pilot Expedition to the Southern Ocean – PESO) onboard *ORV Sagar Kanya* during the austral summer of 2004 collected various physical, chemical, biological and geological data/samples. From the sediment cores collected during the expedition, six representative core-top samples were studied along a latitudinal transect from 28° to 56° south to ascertain the modern variation in distribution of siliceous microfossils called diatoms. This is the first Indian attempt to understand the latitudinal variation in the distribution of diatom species in Southern Ocean, its relationship with the changing nutrient availability and/or supply, and its utility in palaeoceanographic reconstruction. In all, 24 diatom species were identified. The diatom population seems to be dominated by seven species namely *Fragilariopsis kerguelensis*, *Fragilariopsis separanda*, *Thalassionema nitzschioides*, *Thalassiothrix* spp., *Thalassiosira lentiginosa*, *Eucampia antarctica* and *Azpeitia tabularis*. Of these, *F. kerguelensis* and *T. lentiginosa* dominate the diatom community in the Southern Ocean sediments. The spatial distribution of most of the diatoms in surface sediments seems to be controlled by physicochemical parameters like sea surface temperature, salinity, silicate, nitrate and phosphate concentrations.

Keywords: Diatoms, nutrient, sediment, sea surface temperature, Southern Ocean.

THE Southern Ocean being a sink and source for major global oceanic water masses there is lot of attention to study not only the modern changes, but also the past variability using sedimentary records. The Indian sector of the Southern Ocean is yet to be studied in detail to understand the past climatic oscillations and its implications for the future changes[1–3]. For the last several decades, scientists have extensively used faunal and floral records of Southern Ocean sediments to infer the past changes in biological productivity as well as changes in sea surface temperature (SST) and salinity[4,5]. Since the accuracy of the climatic reconstructions greatly depends on the quality of proxy database, it is necessary to assess the response of such proxies to modern environmental changes before carrying out any reconstructions. Due to the unique characteristics of Southern Ocean, the most important and predominant biogenic proxies preserved in the sedimentary records of Southern Ocean are the siliceous microfossils called 'diatoms'.

Diatoms are unicellular algae made of siliceous skeleton called frustules and are found in almost every aquatic environment including fresh and marine waters. Their usefulness in Southern Ocean is because of its extreme sensitivity to changes in salinity, temperature, nutrient supply and other environmental factors. Because their cell wall is composed of hydrated silica [$Si(H_2O)_n$], they are well preserved in the sediments. Diatoms contribute more than 70% of the primary production in Southern Ocean and play a major role in global silica and carbon cycling[6]. Their size ranges from 2 to 200 μm and they exhibit a wide variety of shapes. The preservation and abundance of diatoms in marine sedimentary records find its use in palaeoceanographic reconstruction, particularly in the reconstruction of past SST[7,8], and more recently in the estimation of past sea ice extent[9–12]. The distribution of diatoms is chiefly influenced by the presence of nutrients like silicate, nitrate, phosphate[13], SST[13,14] and the stability of the water column[15].

In the present study, we identified the distribution patterns of fossil diatoms in core-top samples recovered from the Indian sector of Southern Ocean between 28 and 55°S lat. The relative abundances of seven relevant diatom species from the core-top samples were studied to document the distribution patterns of diatoms with respect to various oceanic fronts prevalent in the Southern Ocean, its relation to the SST, salinity, nutrients as well as the extent of the winter sea-ice.

Oceanographic setting

The dynamics of the Southern Ocean is governed by the strong westerly winds resulting in the clockwise Antarctic Circumpolar Current (ACC)[16]. The ACC, sometimes called the 'great ocean conveyor', connects the three major ocean basins – Atlantic, Pacific and Indian – allowing water, heat, salt and other properties to 'flow' from one to the other.

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This region is characterized by several oceanic frontal systems of various water masses that control the physical, chemical and biological processes. Fronts are physical boundaries that mark abrupt changes in water properties like temperature and/or salinity as one move from low latitude towards high latitude and are also known to be the regions of high biological productivity[17,18].

The variations in temperature and salinity observations along the 45°E transect during the PESO reveal four major frontal systems[19] (Figure 1, Table 1). They include: Agulhas Return Front (ARF) between 40°15′ and 41°15′S with a width of ~ 110 km marked by a change in temperature from 19 to 17°C and a change in salinity from 35.54 to 35.39‰ at the surface; Subtropical Front (STF) between 41°15′ and 42°15′S with a width of ~ 110 km marked by a rapid decrease in surface temperature from 17 to 10.6°C and salinity from 35.35 to 34.05‰; Subantarctic Front (SAF) between 42°30′ and 47°S with a width of ~ 500 km with a change in surface temperature from 9.7 to 6.3°C and change in surface salinity from 34.0 to 33.85‰ and Polar Front (PF) between 48° and 52°S with a width of ~ 440 km characterized by a fall in surface temperature from 5.5 to 2.7°C.

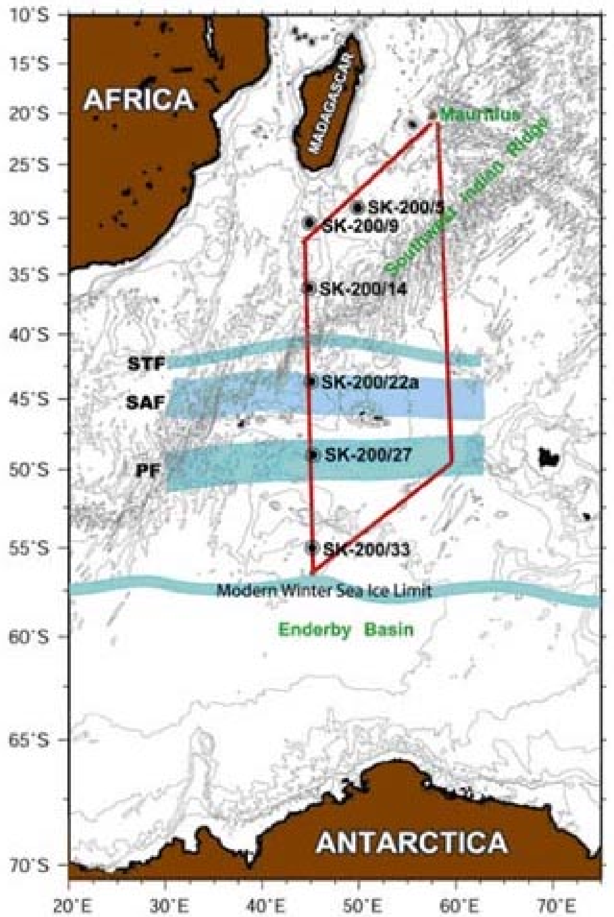

Figure 1. Location map showing the core sites and various frontal systems. STF, Subtropical Front; SAF, Subantarctic Front; PF, Polar Front.

Materials and methods

During the expedition to the Southern Ocean (200th Expedition – January to March 2004), several piston/gravity sediment cores were recovered along the 45°E latitudinal transect between 28° and 55°S within the Indian sector of Southern Ocean (Figure 1; Table 1). The sediments were examined onboard for lithological variations. The samples were brought to National Centre for Antarctic and Ocean Research (NCAOR), Goa and were processed for various sedimentological and microfossil (floral and faunal) analysis. This study deals with the distribution of diatoms along the 45°E transect in the six representative core-top (top 0–1 cm portion of the core) sediments of the Indian sector. The water column samples were also collected at different depths for nutrient concentration. This was done using the facility onboard 'Autoanalyser' (Skalar) and following standard methods for sea water analysis and other details of salinity and SST are published elsewhere[19].

Diatom analysis, sediment treatment and slide preparation followed the method by Battarbee[20]. About 0.1 g of the sample was taken in a 200 ml beaker and 20 ml hydrogen peroxide (H_2O_2) was added. All the organic matter was removed by heating the contents on a hotplate. Few drops of hydrochloric acid (50%) were added subsequently to remove the remaining H_2O_2 as well as any carbonates present. After cooling, the contents were transferred to centrifuge tubes and were centrifuged at 1500 rpm for 5 min. The supernatant solution was decanted and the washing process repeated four times. Clay was removed in the final wash by adding few drops of very weak ammonia solution (1%) to the sample. The diatom suspension was diluted to a suitable concentration and a few drops of the above suspension were allowed to settle overnight in coverslips. Proper care was taken to avoid the contamination by dust and other foreign particles into the coverslips. Once the coverslips were dried, they were mounted on a glass slide with a drop of ZRAX (diatom mountant – Refractive Index > 1.7) using toluene as solvent. The slides were kept over a hotplate to dry off the toluene in the ZRAX and allowed to cool. All slides were analysed at 1000X under a Nikon Eclipse E600 POL microscope for diatom identification and quantification.

Diatom counting followed the reference convention developed by Schrader and Gersonde[21] and Armand[22]. Each slide was traversed horizontally until at least 300 valves were counted. In order to avoid overestimation, only valves > 50% intact were counted. For elongate species (i.e. *Thalassionema nitzschioides* and *Thalassiothrix* spp.), only end species (one end of the frustule) were counted. Diatoms were identified to species level. Girdle bands of *Dactyliosolen antarcticus* were counted in all the samples but were not used in the estimation of relative abundances due to constraints in estimation of the total number of girdle bands making up a species. Many species observed do

Table 1. Core location details along with water depth and oceanic regime

Core no.	Water depth (m)	Location		Oceanic regime
		Lat. °S	Long. °E	
SK-200/5	2296	28°19′	48°44′	Tropical region
SK-200/9	2256	30°56′	44°52′	Tropical region
SK-200/14	2730	36°07′	44°50′	Subtropical region, Agulhas Return Front
SK-200/22A	2720	43°42′	45°04′	Subantarctic region
SK-200/27	4389	49°00′	45°13′	Antarctic Polar Front
SK-200/33	4204	55°01′	45°09′	Polar region

not reach to the statistically required numbers and were not detailed in the present study. Taxonomic identification was followed after Castracane[23], Mereschkowsky[24], Hustedt[25], Fryxel and Hasle[26,27], Hasle and Semina[28], Priddle *et al.*[29], Fryxel and Prasad[30], Armand and Zielinski[31].

For scanning electron microscope (SEM) analysis of the diatoms, a small portion of the cover slip containing the sample was placed on a double sided carbon tape which was mounted on a sample stub and coated with platinum (100 Å) in a sputter coater and were scanned, using a JEOL 6360 LV scanning electron microscope at the SEM–EDS facility at NCAOR.

Results and discussion

The diatoms in the core-top sediments show significant variations in distribution from low to high latitudes. The samples recovered between 28°19′S and 36°07′S lat. before the Subtropical Front (STF) (SK 200/5, 9 and 14) were poorly represented by diatoms (Figure 2 *a*). On the other hand, the samples recovered between 43°42′S and 55°01′S lat. i.e. around Subantarctic Front (SAF) and southwards (SK 200/22A, 27 and 33) are well represented by diatoms. The major diatom species identified in the core-top samples are listed and briefly discussed below whereas minor species are only listed.

Fragilariopsis kerguelensis (O'Meara) Hust.[25] *(Figure 3h; Figure 4h, i)*

Fragilariopsis kerguelensis under light microscope appears as solitary frustules with elliptical valves. Two rows of alternating areolae within the heavily silicified valves and punctuate interstitial membranes are the chief features that facilitate identification of the species. *F. kerguelensis* has been described as the most abundant diatom in Antarctic Seas[32], which is confirmed in the Indian sector of Southern Ocean as well. The distribution pattern of *F. kerguelensis* shows inverse relationship with temperature and salinity. South of the STF, *F. kerguelensis* increase in abundance from 48.1% at 43°42′S (SK 200/22A) to 71.7% at 55°01′S (SK 200/33). The present study supports the view that maximum abundance is observed between the maximum winter sea–ice edge and the PF[33]. The temperature falls gradually from 26.3°C to 2.2°C as we move from mid to high latitudes. The occurrence of *F. kerguelensis* with respect to modern SST shows greatest abundance at temperatures of 2.2°C at 55°01′S lat. (SK 200/33) where it constitutes more than 71% of the total diatom population. Further, at higher temperatures, the abundance decreases significantly and it reaches zero at a temperature of 21.1°C at 36°07′S latitude (SK 200/14). *F. kerguelensis* dominates the diatom population between the sub tropical front (STF) in the North and the PF in the south, thus registering itself as an endemic species of Southern Ocean waters[1]. This increase in *F. kerguelensis* distribution is due to the high silicate availability at 55°01′S lat. The low values of silicate and phosphate concentrations at SK 200/22A and 27 may be due to large scale utilization of these nutrients during the spring diatom bloom. *F. kerguelensis* abundance in sediments shows more or less similar relationship with the concentration of nitrates. As the concentration of nitrate increases from low to high latitudes, there is a relative increase in the *F. kerguelensis* population. The abundance of *F. kerguelensis* between STF and PF may be related to dissolution of weakly silicified diatom spicules resulting in the preservation of heavily silicified forms[1,34].

Thalassiosira lentiginosa (Janisch)[26] *(Figures 3 a; 4a)*

Thalassiosira lentiginosa is a discoid diatom with flat and circular valve. The areolation is usually fasciculate and the marginal internal openings are slit-like, with radial orientations. They are present in all the samples collected within the frontal zones and show a decrease in abundance from 17% within the STF to 11% near the winter sea–ice edge. However, its abundance in sediments remains obscure irrespective of its resistance to dissolution and increased presence in the sediments[34,35]. Our study supports the earlier studies that reported highest abundances of *T. lentiginosa* from sediments from the Permanent Open Ocean Zone (POOZ) to the Polar Front Zone (PFZ)[1,36,37–40].

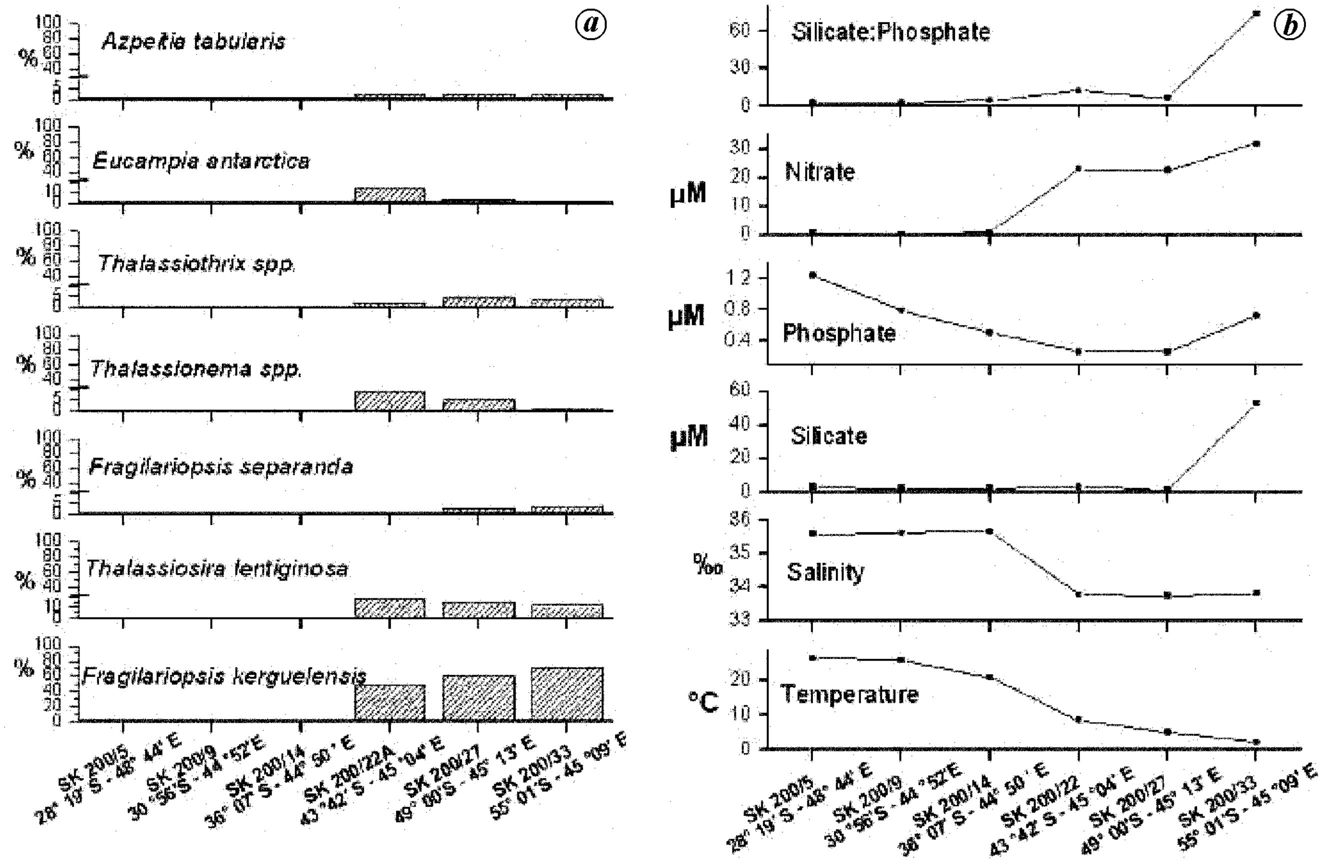

Figure 2. ***a***, Latitudinal distribution of various diatom species; Note the break in the *Y*-axis of all the species except for *Fragilariopsis kerguelensis*; ***b***, Sea surface temperature, salinity and nutrient distribution in the study region.

Thalassionema nitzschioides (Grunow) Mereschk.[24] *(Figure 3k; Figure 4e and f)*

Thalassionema nitzschioides are linear, tapering diatom with rounded apices and flat surfaces with marginal areolae. They are widely distributed in Southern Ocean sediments. Several varieties of *T. nitzschioides* have been identified namely *T. nitzschioides* var. *parva, T. nitzschioides* var. *lanceolata* and *T. nitzschioides* var *capitulata. T. nitzschioides* var. *lanceolata* dominated in the subantarctic and subtropical zones. Their abundance varied from 8.2% in SK 200/22A at mid latitude (43°42′S) to 1.1% in SK 200/33 at high latitudes (55°01′S).

Thalassiothrix spp. group Schimper ex Karsten[28]*. (Figure 3 l; Figure 4 g)*

Thalassiothrix spp. are needle-like, straight diatoms with a single marginal row of areolae. This group is represented in the sediments by *Thalassiothrix antarctica* and *Thalassiothrix longissima*. Since these species are identical to each other and are difficult to differentiate under light microscope, they have been counted in this study as a combined group (*Thalassiothrix* spp). Moreover, *Thalassiothrix* spp. group specimens are very long and narrow and the valves present in the sediments are generally broken into many parts. They are typical of POOZ and PFZ[1]. This study shows that maximum abundance (~ 4.1%) of *Thalassiothrix* spp. is encountered at 49°00′S (SK 200/27) latitude located within the PF. North of the PF, its abundance decreases gradually to zero north of STF. The same pattern of distribution is reported from the Pacific and Atlantic sectors of the Southern Ocean[33,41]. Its abundance in the sediments of the Indian sector of Southern Ocean clearly indicates the preferential preservation of strongly silicified diatom frustules.

Eucampia antarctica (Castrac.) Mangin var. recta (Mangin)[30] *(Figure 3 e, f)*

Eucampia antarctica appears as solitary cells with elliptical valves and has a solitary labiate process and two marginal areolae. *E. antarctica* is present in the Antarctic and sub-Antarctic regions of the Southern Ocean. *E. antarctica* shows significant variations in abundance[42]. The abundance decreases from 12.9% at 43°42′S (SK 200/22A) latitude

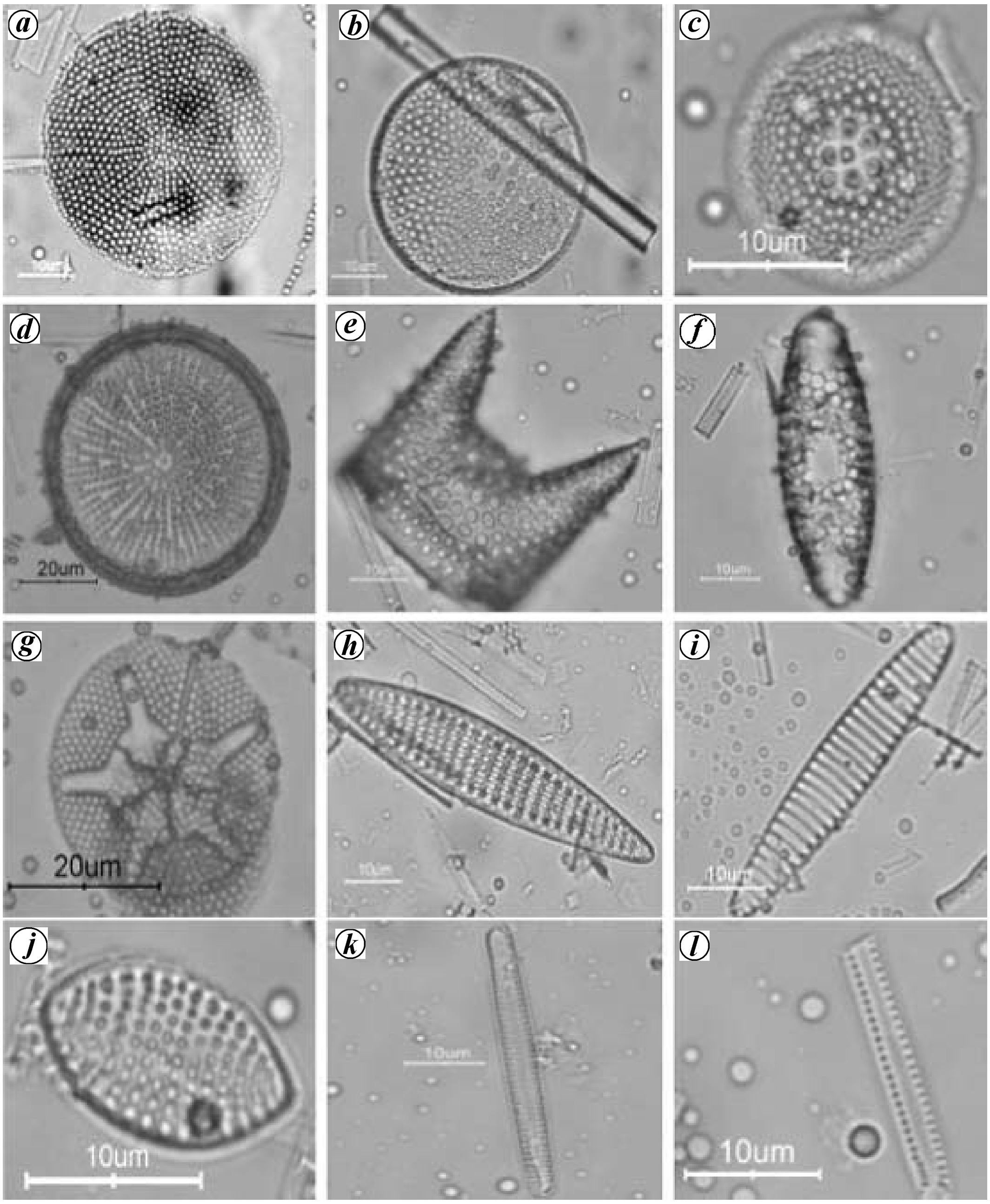

Figure 3. Light microscope photomicrographs of the diatom species in the study area. ***a***, *Thalassiosira lentiginosa*; ***b***, *Azpeitia tabularis* (the long 'diatom' is a broken piece of *Thalassiothrix* spp.); ***c***, *Thalassiosira gracilis*; ***d***, *Actinocyclus actinochilus*; ***e***, *Eucampia antarctica* (Terminal valve); ***f***, *Eucampia antarctica* (Intercalary valve); ***g***, *Asteromphalus parvulus*; ***h***, *Fragilariopsis kerguelensis*; ***i***, *Fragilariopsis ritscheri*; ***j***, *Fragilariopsis separanda*; ***k***, *Thalassionema nitzschioides* var. *lanceolata*; ***l***, *Thalassiothrix* spp.

to 1.8% at 55°01′S (SK 200/33) latitude. Our observation confirms that *E. antarctica* shows significant fluctuations in their distribution in Southern Ocean sediments as reported elsewhere[37]. *E. antarctica* is a widely used palaeo proxy and shows pronounced increase at the frontal boundary which is marked by high productivity, indicating its preference for nutrient-rich waters.

Fragilariopsis separanda Hust.[25] *(Figure 3j; Figure 4 j)*

These are solitary, elliptical to lanceolate species with interstitial membranes perforated by one row of short tube-like poroids. *Fragilariopsis separanda* and *F. kerguelensis* show similar distribution pattern although the latter is

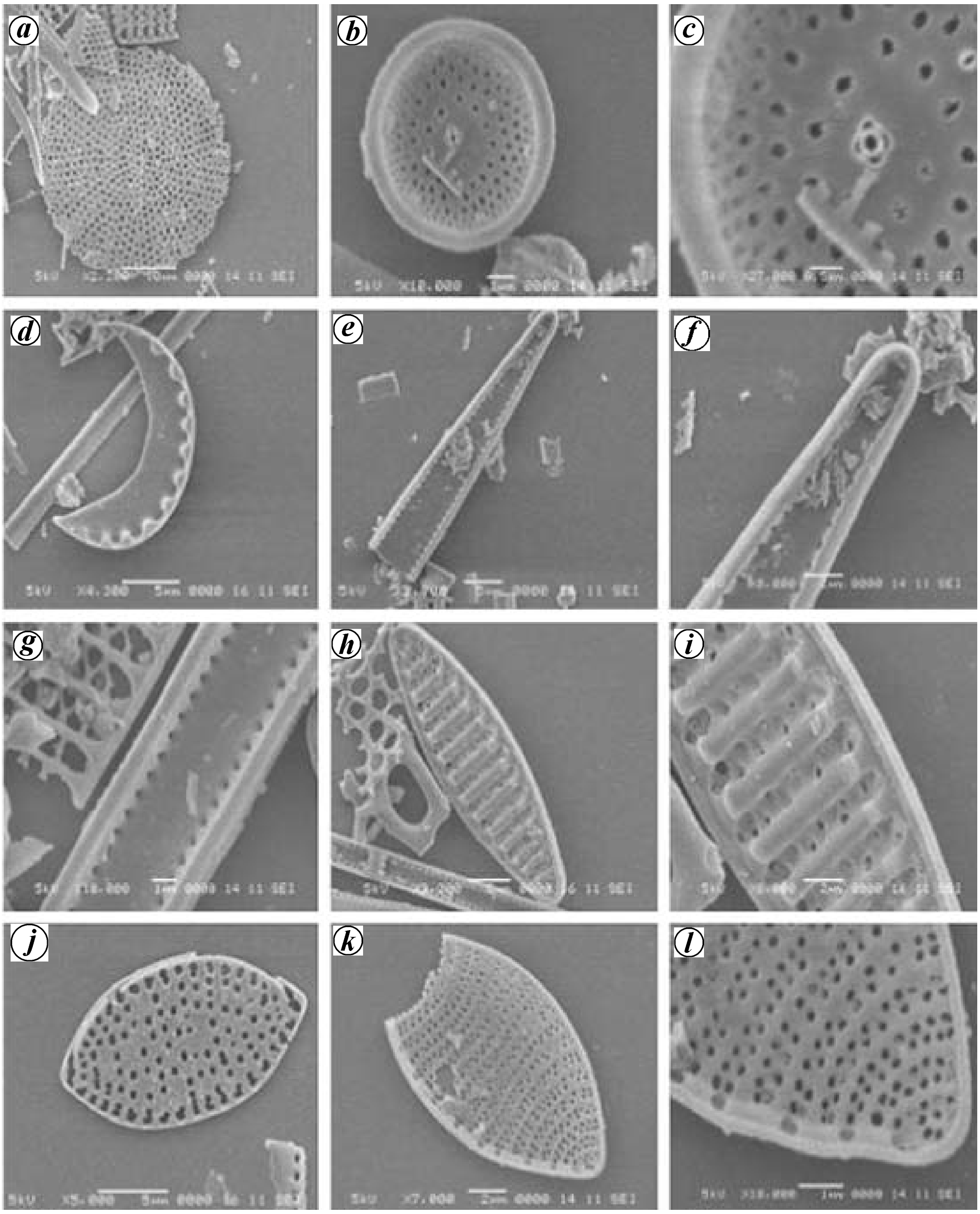

Figure 4. SEM photomicrographs. ***a***, *Thalassiosira lentiginosa*; ***b***, *Thalassiosira gracilis*, Internal valve view; ***c***, *T. gracilis*, enlarged view; ***d***, A part (girdle band) of the diatom *Dactyliosolen antarcticus*; ***e***, *Thalassionema nitzschioides*; var. *lanceolata*; ***f***, *T. nitzschioides* enlarged; ***g***, *Thalassiothrix* (enlarged view); ***h***, *Fragilariopsis kerguelensis*; ***i***, *F. kerguelensis* enlarged view; ***j***, *Fragilariopsis separanda*; ***k***, *Fragilariopsis rhombica*. Internal valve view; ***l***, *F. rhombica* enlarged showing two rows of poroides in between two transapical costae.

more abundant. They show an increase in abundance in the PFZ where it constitutes 4% of the total diatom population.

Azpeitia tabularis (Grunow) G. A. Fryxell & P. A. Sims[43] (Figure 3 b)

These are solitary discoid diatoms with flat, circular valves having fasciculate areolae in radial rows. Like other diatoms, *A. tabularis* also show significant variation in distribution at the fronts. At the frontal boundary, its abundance increases to 3.1% at 43°42′S (SK 200/22A) latitude and further south its abundance decreases marginally to 2.1% at 55°01′S (SK 200/33) latitude.

In addition to the above, several other species were identified and quantified for the present study. The relative abundances of these species were found to be < 2% and are listed below: *Asteromphalus parvulus* Karster (Figure

3 *g*); *Actinocyclus actinochilus* (Ehrenberg) Simonsen. (Figure 3 *d*); *Chaetoceros* spp.; *Dactyliosolen antarcticus* Castrac. (Figure 4 *d*); *Fragilariopsis rhombica* (O'Meara) Hust. (Figure 4 *k*, *l*); *Fragilariopsis ritscheri* Hust. (Figure 3 *i*); *Fragilariopsis obliquecostata* (vanHeurck) Heiden; *Fragilariopsis curta* (vanHeurck) Hust.; *Hemidiscus karstenii* Jousé; *Melosira* spp.; *Nitzschia* spp.; *Pseudo-nitzchia* stellata; *Roperia tessalata* (Roper) Grunow; *Synedropsis fragilis* (Manguin) Hasle; *Trichotoxon* spp.; *Thalassiosira trifulta* G.A. Fryxell; *T. gracilis* (G. Karst.) Hust. var. *gracilis* (Figure 3 *c*; Figure 4 *b*, *c*).

In order to understand the controlling factors, the distribution of diatoms within the modern sediments was compared with the various physicochemical parameters measured during the expedition (Figure 2). Ideally, one should compare the sea-floor diatom relative abundances with annual nutrient concentrations and not with the seasonal data. However, there is complete lack of annual or even seasonal nutrient data within the proximity of our cores and even the World Ocean Circulation Experiment (WOCE) tracks have not covered this region. From our preliminary data, it is evident that the latitudinal distribution of diatoms within the study area is controlled by the variations in SST, salinity, as well as the dissolved nutrients like silicate, phosphate and nitrates. Diatoms normally dominate the phytoplankton community, accounting for 70% or more in the community, given sufficient nutrients and silicate concentration higher than a threshold concentration of approximately 2 μM silicate[44].

The silicate concentration in the study area varied from 1.7 to 3.2 μM north of the PF and shows abrupt increase to about 52.8 μM towards south in the polar waters, indicating that the water south of the frontal region is conducive for the growth of diatoms. The effect of such high concentration of silicate in surface waters on the growth of diatom communities is reflected by the dominance of highly silicified diatoms like *F. kerguelensis* and *T. lentiginosa* in silica-rich waters of high latitude oceans. Nitrate reveals a steady increase in concentration from low to high latitudes, varying from 0.77 μM at 28°19′S (SK 200/5) to 31.81 μM at 55°01′S (SK 200/33) latitude. Significant increase in nitrate concentration is observed between 36°07′S (SK 200/14) and 43°42′S (SK 200/22A) latitudes that shows an increase in concentration from 1.02 μM to 22.97 μM, respectively. The phosphate concentration decreases gradually from 1.24 μM at 28°19′S (SK 200/5) to 0.25 μM at 49°00′S (SK 200/27) and again increases to 0.72 μM at 55°01′S (SK 200/33) latitude. These variations in the concentrations of phosphate may be due to enhanced utilization of nutrients by the phytoplankton during the preceding spring bloom. The diatom abundance at these locations may be attributed to higher concentration of nitrate and silicate. Studies also suggested that the silicate, nitrate and phosphate concentration of the water mass play an important role in the growth of diatoms[44–46] provided there is enough supply of iron[47,48]. In lower latitudes, the nitrate and silicate concentrations are extremely low and therefore, the diatoms are nearly absent in the surface sediments collected from these waters.

Summary and conclusions

Preliminary study on the modern geographic distributions of major diatom species in six core-top samples collected along a transect from the Indian sector of the Southern Ocean, revealed the dominance of *F. kerguelensis*, *T. lentiginosa*, *T. nitzschioides* and *Thalassiothrix* spp. within the diatom community. The spatial distribution of diatoms in surface sediments is well correlated with respect to the frontal changes and related nutrient availability. The study indicates that the distribution of diatoms does not solely depend on nutrient distribution and/or concentration, but depends a lot on physical parameters like the SST and salinity conditions. The extent of silicification of the diatom frustules seems to play a major role in the preservation with the heavily silicified forms dominating the diatom community compared to the less silicified diatoms.

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